Project No./(Center No.) E-21-610 (R6262-0A0)  
Project Director: P. G. Steffes  
Sponsor: GTE Spacenet Corporation  

Agreement No.: Research Project Agreement dated 1/20/87, No. C-10070
Award Period: From 1/20/87 To 1/19/89 (Performance) 1/31/89  
Sponsor Amount: New With This Change Total to Date
Contract Value: $ 28,854
Funded: $ 28,854

Cost Sharing No./(Center No.) N/A  
Cost Sharing: $  

Title: Research in Development of Satellite Interference Location System (SILS)  

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Military Security Classification:
(or) Company/Industrial Proprietary: N/A  
ONR Resident Rep. is ACO: Yes No  
Defense Priority Rating:

REstrictions
See Attached Supplemental Information Sheet for Additional Requirements.
Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.
Equipment: Title vests with  

COMMENTS:
An advance payment of $7,213 has been received from the sponsor.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

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Closeout Notice Date 06/29/90

Project No. E-21-610  Center No. R6262-0A0

Project Director STEFFES P G  School/Lab EE

Sponsor GTE SPACENET CORP/

Contract/Grant No. C-10070  Contract Entity GTRC

Prime Contract No.

Title RESEARCH IN DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS)

Effective Completion Date 900629 (Performance) 900629 (Reports)

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Closeout Actions Required: | Y/N | Date Submitted
---|---|---
Final Invoice or Copy of Final Invoice | Y | ___
Final Report of Inventions and/or Subcontracts | N | ___
Government Property Inventory & Related Certificate | N | ___
Classified Material Certificate | N | ___
Release and Assignment | N | ___
Other | N | ___

Comments

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Subproject Under Main Project No.

Continues Project No.

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Distribution Required:

- Project Director: Y
- Administrative Network Representative: Y
- GTRI Accounting/Grants and Contracts: Y
- Procurement/Supply Services: Y
- Research Property Management: Y
- Research Security Services: N
- Reports Coordinator (OCA): Y
- GTRC: Y
- Project File: Y
- Other: N
REPORT

TO

GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #1

for

Contract C-10070

RESEARCH IN DEVELOPMENT OF SATELLITE INTERFERENCE
LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

January 20, 1987 through March 30, 1987

Submitted by

Professor Paul G. Steffes
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1. INTRODUCTION AND SUMMARY

Over the past two months, initial work has begun on our program to design, develop, and analyze a Satellite Interference Location System (SILS) at Georgia Tech. As was outlined in the Proposal for this project, "Research in Development of Satellite Interference Location System (SILS) at Georgia Tech" (November 1986), the goal of this project is to design, develop, and analyze a working SILS by early 1989 (24 months ARC). Our initial steps in this effort have included study of the Techniques and Expected Performance for the system and Hardware Definition for the system.

Overall, the initial work seems to have gotten off to a good start and substantive progress is expected for the next two month period. It is hoped that some initial hardware tests can be conducted before the end of June.

2. TECHNIQUES AND EXPECTED PERFORMANCE

As described in the Proposal for the project, two different techniques will be used in determining the location of interfering signals. The first is the Time Difference of Arrival (TDOA) system which compares the propagation time for the interfering signal through the satellite to which it is causing interference with the propagation time through an adjacent satellite. The difference in time-of-arrival at the SILS over the two different paths localizes the position of the interfering transmitter to an arc segment on the earth's surface. Since the use of this technique requires a two channel receiving system capable of estimating differential time delays to very high accuracy (better than 80 nsec) and capable of receiving very weak signals on the "adjacent satellite" path, it was felt that the first year of this project would concentrate on development and characterization of a SILS using only
TDOA techniques. However, since the same components of the SILS which are used in TDOA measurements would also be used for the interferometric measurements which were scheduled for the second year of the project, we are conducting studies of the interferometric techniques at this time with specific interest in the relationship between hardware performance and system performance. (Note: Some results from these studies are included in attached appendices.) In this way, we hope to procure the best hardware possible (amplifiers, mixers, oscillators, etc.) for locating interfering signals using either technique.

3. HARDWARE DEFINITION

Both the TDOA and interferometric techniques for the locating of interfering signals involve comparison of two signals: one which is fairly strong, and one which is very weak. In the case of the interferometric technique, the strong signal is due to the interfering signal received through a copolarized feed and repeated by the satellite, and the weak signal is due to reception of the interfering signal through a cross-polarized feed, and then repeated through the satellite. By comparing the phases of the two signals and knowing the separation of the phase centers of the receiver antenna feeds on the spacecraft, it is possible to determine the angle-of-arrival of the interfering signal relative to the spacecraft. While it is true that the carrier-to-noise ratio (CNR) on the copolarized channel would be much stronger than on the cross-polarized channel, our analysis of the correlation-type phase detector has shown that CNR must be maximized on both channels in order to obtain the best estimate of differential phase. Thus, it is just as important to optimize the CNR on the relatively strong copolarized channel as on the
relatively weak cross-polarized channel. This same result also applies to our analysis of the time delay estimations for the TDOA technique.

As a result, we have sought to optimize the performance of both our 6.1 meter antenna/receiver system and our 3.1 meter system. The 6.1 meter system exhibits an antenna gain of 55.4 dB and has a low-noise converter (LNC) which serves as front-end and converts the incoming 11.7-12.2 GHz signals down to 3.566-4.066 GHz. Since its equivalent noise temperature is 180 K, the resulting G/T is 32.9 dB/K. For our 3.1 meter system, we have recently procured a low-noise block converter (LNB) which converts the incoming 11.7-12.2 GHz signals down to 950-1450 MHz. The noise figure of this LNB is a remarkable 150 K, resulting in a system G/T of 27 dB/K. Thus, because of its superior G/T, the 6.1 meter system is used for the weaker signal channel.

In our first satellite experiment, we plan to prove the operational feasibility of the TDOA method for locating interfering signals. As shown in the accompanying figure (Appendix 1), the 3.1 meter receiver system will be pointed at the GSTAR 1 satellite. The 6.1 meter receiver will be pointed at the GSTAR 2 satellite. The 3.1 meter receiver will be tuned to a video signal on GSTAR 1 and the 6.1 meter receiver will be tuned to the corresponding transponder on GSTAR 2, which will be unoccupied, except for the sidelobe signal from the FM video transmitter aimed at GSTAR 1. Because of the extreme weakness of the signal from GSTAR 2, direct FM detection of that video signal will not be possible. Instead, the output from the low-noise converter (in the 3.566-4.066 GHz range) will be fed directly to a microwave spectrum analyzer. The analyzer will be manually tuned to the frequency of the signal and a linear detector will be used. Our previous tests have shown that when using such a configuration, both IF bandwidths as low as 3 MHz and video
filtering can be employed, while still retaining the "time marks" or synchronization pulses of the FM video signal. The result is a drastic improvement over the detected signal-to-noise ratio which would be obtained using a standard IF bandwidth (30-50 MHz) and an FM demodulator. As with the 6.1 meter receiving system, a spectrum analyzer will be connected directly to the output of the front-end down converter of the 3.1 meter receiving system. The video signal from this spectrum analyzer will be displayed along with the video from the 6.1 meter system, and the differential time delay between the two will be determined. The observed differential time delay will be related to the position of the transmitter, as well as to differential delays through the two satellite transponders and the two receiving systems. The contributions from the transponders and the receivers can be "calibrated out" if the location of the transmitter is well known, and possible locations of other transmitters can then be computed.

4. CONCLUSION

During the first two months of Contact C-10070, studies of the TDOA (Time Difference of Arrival) and interferometric techniques for locating the sources of Ku-band satellites have begun. These studies have already yielded valuable data as to the optimal equipment configuration for planned experiments, and the first satellite test has been planned, using the TDOA technique. In the next two months, we hope to complete the first satellite tests, as well as to proceed with software and hardware development for conversion of time delay measurements to positive arcs on the surface of the earth.
Angle of Incidence

Interferometric Baseline

Electrical Angle = \frac{\pi T 2d \cos(\text{Incident Angle})}{\lambda}

GSTAR

Satellite Feeds

HORZ \quad \text{VERT}

Possibilities

Interferometric Geometry

19 March 1987

Report 1 / Appendix 2
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #2

for
Contract C-10070

RESEARCH IN DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

March 31, 1987 through May 30, 1987

Submitted by
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1. INTRODUCTION

Since the March 30 report, we have made progress in the modeling of TDOA and interferometric techniques, and we have acquired the hardware necessary to implement our second Ku band receiving station.

2. TDOA

As part of modeling the Time Delay of Arrival (TDOA) method of determining the location of the source of a satellite signal, we have derived the equations relating geographic location to differential time of arrival. These equations have been implemented in a computer program which iteratively evaluates, then plots lines of equal delay upon areas of interest on Earth. Appendix 1 contains a map showing a specific example relating differential delays through GTE's GSTAR 1 and GSTAR 2 satellites. Maximum differential delays across the continental United States are approximately +/-240 microseconds for this case.

Since the form of these equations takes the geographic location as its input to produce a non-unique differential delay as its output, some sort of iterative numerical method is required to uniquely determine the location of a signal source given a set of time delays and some other piece of information. Specific to this case, this other piece of information can come from differential delays between any other pair of satellites or interferometric information. We will provide computational methods for both situations.

However, we experience a large amount of time required to numerically generate the delay contours for the example included in this report. To speed up computations, the use of a large table of initial estimations for the iterative procedure to determine geographic locations suggests itself.
3. INTERFEROMETRY

We have received the satellite hardware information from GTE describing the GSTAR series satellite microwave feed locations and phase centers. Thank you for providing this data.

We have concluded that the interferometric baseline does not pass through the center of CONUS as is implied in one of the drawings of our last report. The actual baseline does not intersect Earth. From this we conclude an asymmetry in the contours of equal phase as related to the TDOA constant delay contours. This will assist in uniquely locating geographic solutions to the satellite signal source problem. However, the mathematical generalization for a sphere intersecting a randomly placed cone of constant phase is not trivial and will provide further modeling and computational challenges.

We plan to also look at the possibility of using interferometry between two separate satellites to increase the resolution of a solution provided by one of the two methods mentioned above. Note that this method cannot be used to provide an initial unique solution over an area the size of the United States because it provides multiple solutions due to its multiple wavelength baseline.

4. HARDWARE

We have acquired a commercially available Ku band input LNB, feed, and receiver for our newly acquired and mounted 3.1 meter reflector. At the time of the writing of this report, we are performing initial alignment and testing of the 3.1 meter system. We are presently investigating surmountable installation problems such as mechanical alignment of the dish and the compatibility between our donated reflector geometry and the "look angle" of our acquired Ku band feed.
We are presently hampered by activities surrounding the replacement of the 25 year old roof on our building where these satellite antennas are located. Currently, these activities do not allow us to permanently install the delicate microwave components, coax feeds, or control cables connecting the outdoor antenna and the indoor receiving equipment. Therefore, we have been routing the cables at night or on weekends when the roofing work is not going on, then removing our materials before the construction begins again. An example is the case where after a day of roofing activities, we found our quarter degree beamwidth 6.1 meter reflector to not be pointing at GSTAR 1 as it was the previous day. We hope to be able to resume normal rooftop activities by the end of June.

5. PLANS

We are presently working on the installation of our new Ku band receiving station. Upon successful operation, we plan to begin making time delay measurements between multiple path signals with the same source to facilitate TDOA method confirmation. We have previously viewed a data signal intended for GSTAR 1 through both GSTAR 1 and GSTAR 2 using our 6.1 meter dish system with a spectrum analyzer performing the final conversion to baseband. The use of the spectrum analyzer greatly facilitates this sort of "fishing" amongst the transponders because of its adjustable IF and baseband bandwidths and its simultaneous baseband output.

We have viewed through GSTAR 1 transponders several commercial TV news stations using microwave dish equipped vans to provide the equivalent of their six o'clock news shows with remote feeds. Because of the known format of NTSC video, we will attempt to use these signals to perform TDOA tests; however, this requires our happening to find an empty corresponding transponder on
GSTAR 2. We will most probably request GTE's services to arrange for the use of two matching transponders and a test pattern transmission from one of the GTE uplink facilities.

We are also working on the interferometric models with goals of providing plots similar to the TDOA graphics included in this report. This will be followed by computer integration of the TDOA and interferometry schemes to provide unique geographic solutions given phase and delay information.

However, we first need to determine the cross- and co-polarized characteristics of both the satellite and ground equipment. Experiments are being generated to acquire this data. We may again require the services of a GTE uplink site to provide signals of varying polarizations.
APPENDIX 1

DELAY CONTOURS

Figure 1 is an illustration of constant delay contours of 20 microseconds overlayed on a Mercator projection of an outline of the continental United Stabes. This geometry is specific to the case of a signal delayed through the GSTAR 1 and GSTAR 2 satellite pair. The grid shows multiples of ten degrees of longitude and latitude.

The delay contour which appears to be vertical (straight North-South) is closest to being half-way between the subsatellite points of GSTAR 1 and GSTAR 2 (104 degrees west longitude). This contour corresponds to a normalized delay of zero between the two received signals. Given the appropriate reference frame, moving the transmitter site to the west can be considered a positive delay with eastern movement corresponding to negative delays.

Note that these are "normalized" delay contours. The fixed delays between the two satellites of interest have been removed. These fixed delays will be different for different SILS sites. However, once the delays have been determined and integrated into the calculations for determining the signal source, they will remain "calibrated out" and constant as long as the satellites do not appreciably move. Of course, we will determine the effects of satellite motion on the desired results so as to determine what is "appreciable" motion.
Contours of 20 [uSec] For GSTAR1(103W) and GSTAR2(105W)
REPORT TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #3

for
Contract C-10070

RESEARCH IN DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

June 1, 1987 through July 31, 1987

Submitted by
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ABSTRACT

A system is currently being developed for inferring the position of uplink ground stations using existing domestic satellites with minimal disruption of normal satellite operation. The system operates by measuring differential time delays of a single uplink signal through two adjacent spacecraft to infer the relative position of the uplink transmitter. A system for measurement of such differential time delays and its performance in inferring positional data are described. Since this technique alone does not provide an unambiguous determination of uplink transmitter location, the use of an interferometer to resolve such ambiguities is discussed.
1. INTRODUCTION

The locations of transmitters which serve as sources of interference to or unauthorized operation of domestic geosynchronous satellite communications systems are difficult to determine. This is because of the wide range of potential locations of the interfering transmitters and because most satellite Earth stations direct their transmitted power away from the surface of the Earth which makes detection with terrestrial receivers difficult except at relatively short ranges. Alternate location approaches include aircraft-based detection of interfering signals or detection from low altitude spacecraft. Both have the difficulty of requiring a fairly long response time and extreme expense. The use of adaptive antennas aboard domestic spacecraft (i.e., movable "spot beams") to either locate the source of the unwanted signals or to minimize the effects of such signals is feasible, but requires additional cost for spacecraft construction and launch. The fleet of existing domestic satellites are not so equipped. The technique of physically moving a spacecraft so that the edge of its principle receiving beam scans past the undesired transmitter has been tried, but has the disadvantages of disrupting the traffic through other transponders on the same satellite and of consuming propellant. Therefore, it becomes clear that alternate techniques which require only minimal disruption of normal spacecraft operation and which can operate using the fleet of existing domestic satellites are preferable.

One alternative is a Time Difference of Arrival (TDOA) system by which the propagation time for the uplink signal through a satellite is compared with that through an adjacent satellite. Given that the position of the two spacecraft relative to the receiving station is precisely known, the difference in time of arrival over the two different paths will localize the uplink transmitter location to a curve on the Earth's surface. Realization of such a
system requires a two channel receiving system capable of accurately estimating the differential delay between the two paths. Similarly, since the level of the uplink signal through the adjacent satellite path is typically 30 to 40 dB lower than through the primary satellite, high sensitivity equipment is required for the adjacent satellite downlink. This also requires that the corresponding transponder aboard the adjacent satellite be unoccupied so as not to interfere with the relatively weak signal from the source of interest. Such a TDOA system holds the promise of locating the source of signals regardless of their purpose without the need for disrupting normal communications through the spacecraft nor requiring any additional spaceborne hardware.

The TDOA approach can be used to locate the sources of a wide range of signal types. Almost any modulated signal (video, audio, digital, etc.) can be located based on the measurement of the differential time delay of some unique portion of its waveform. Even pseudo-random noise type signals can be located using a variable time delay correlator to infer the differential time delay between the two satellite paths. However, continuous wave (CW) signals present a special problem. Unless the differential time delay through the two paths is less than 1/f (where f is the frequency of the CW signal), it becomes impossible to unambiguously identify the location of the source of the CW signal.

Since the TDOA technique described only localizes the position of the uplink transmitter to an arc segment on the Earth's surface, some additional technique is required to resolve the position of the ambiguity. Initially, it was thought that the ambiguity could be resolved by making a second TDOA measurement using an adjacent third spacecraft to form another signal path pair. Then the position of the uplink in question could be determined by finding the intersection of the two resulting arcs. Unfortunately, as we
discuss in Section 2, such intersections are almost colinear within the continental United States for most domestic geosynchronous satellites of interest. Likewise, the question of locating CW signal sources is not addressed.

One technique for resolving the positional ambiguity (which also could be used with CW signals) is interferometry, or the comparison of phases of two incoming signals at two different antenna locations. In order to make unambiguous interferometric measurements of the direction of an incoming signal transmitted from within the continental United States as viewed from a geosynchronous satellite, a space between the two antennas of no more than about 100 wavelengths can be used. Thus, at Ku band frequencies, the space between the two receiving antennas must be less than 2.2 meters, making use of adjacent geosynchronous satellites infeasible. However, the distance between the phase centers of the feeds used for the two orthogonal polarizations aboard a single satellite is usually smaller than this. Thus, a measurement of the differential phase of the uplink signal as measured by ground stations through each of two orthogonally polarized feeds aboard the spacecraft could be used to infer the angle of arrival and, thus, an arc of possible locations of the uplink signal source. Of course, since the signal level through the cross-polarized transponder would be much weaker (approximately -30 dB based on manufacturers' data for typical ground antenna cross-polarization isolation) than through the primary transponder, a more sensitive receiver is required for that signal. Combining the TDOA and interferometric techniques can localize the uplink transmitter's position by determining the intersection of the two arcs. This has the added advantage of requiring only two satellite paths.
In this paper, we provide analysis and evaluation of the TDOA technique for locating uplink transmitter positions, and describe a developmental system which is being used to make such measurements. We also describe initial results obtained using the system. We conclude by suggesting improvements for such a system in order to enhance the accuracy of the inferred uplink transmitter position, and we discuss the approaches for incorporating interferometric measurements in order to resolve the positional ambiguities inherent with the TDOA technique.

2. TIME DIFFERENCE OF ARRIVAL (TDOA) TECHNIQUES

The key disciplines involved in the application of the TDOA techniques for locating of Earth stations include: RF budget analysis, geometry, and signal processing. This paper predominately deals with the geometric aspects leaving the other areas to future work.

Whether friendly or not, the typical satellite uplink user is attempting to illuminate only one satellite at any one time. For several reasons, however, the uplink may be illuminating multiple satellites with enough power so that a receiving ground station may be able to detect the presence of the source station on adjacent satellites in addition to the uplink's goal satellite. Reasons for this include poor dish alignment procedures or equipment, marginal antenna aperture sizes which may not generate appropriately small beamwidths, sidelobes intrinsic to the uplink antenna, and a smaller apparent angle between satellites which are at low elevation angles relative to an uplink location. This last effect has been made more noticeable by the reduction of geosynchronous satellite spacing from three to two degrees.
The TDOA location method being presented depends on our ability to determine relative time delays due to different lengths of two satellite signal paths as perceived by a receiving station. Given this time delay, the location of the receiving station, and the positions of the two satellites of interest, a curve on the Earth's surface containing the location of the signal's source may be determined. It is not unusual for satellite operators to know at all times the position of their satellites to within a few meters via the use of radio signal processing techniques or laser reflections obtained off cube-corner mirrors aboard the satellite.

Figure 1 presents a two-dimensional view of the geometry pertinent to the TDOA technique. As illustrated, the positions of the two satellites, the location of the TDOA receiver site, and thus the distances from the satellites to the TDOA receiver site are known. The unknowns are the two remaining distances from each of the two satellites to the unknown uplink station.

If the receiver site monitors the signal through both satellites, a relative time delay between the two paths may be measured. Given this and a knowledge of the speed of the signal propagation through space, the difference in path distances may be deduced. Subtracting out the known downlink distances from the satellites to the TDOA receiver site leaves the remaining differential distance between the two unknown uplink distances. In the two-dimensional case, this differential distance determines two potential points for the location of the uplink station by solving for the intersections of the Earth's circle and the two branches of the hyperbolas made up from the two paths of equal length plus the inferred delay distance. Holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two intersections is the uplink location.
Figure 2 depicts the three-dimensional case. Only the unknown uplink portions of the signal path are illustrated since the distances from the satellites to the TDOA receiver site are assumed to be known. Extending from the two-dimensional case, the surfaces of constant delay between the satellites form two shallow hyperbolic bowls centered along the axis of the line segment connecting both satellites and opening away from its center point. The two intersections of these hyperbolic branch surfaces with the sphere of the Earth provide terrestrial curves of constant delay which include the location of the uplink station. As in the two-dimensional case, holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two curves contains the uplink location. However, unlike the two-dimensional case, we now have one less known input than required to support the dimension of our desired solution. Therefore, our solution is one dimension higher than desired, and another piece of information is required to acquire a unique solution.

Figure 3, illustrating another viewpoint of the three-dimensional case, determines the terrestrial curves of constant delay by looking at the intersections of circles around the subsatellite points of the effected satellite pair. Let the radii of these circles be determined by considering all distances from the satellite to Earth of sizes ranging from the subsatellite distance (shortest possible) to the pole distance (longest possible). Attach the measured delay distance to one of these lengths, then construct the circles around each subsatellite point corresponding to the intersections of this longer path length with the Earth's sphere. Then if the satellite-to-Earth lengths are swept over their realizable ranges, the intersections of the constructed circles will provide the curves of constant delay.
In both cases, the goal is to relate the differential distance which is inferred from time delay measurements and known geometric information to a curve along the Earth's surface which contains the unknown uplink's location. The second viewpoint for the three-dimensional case lends itself to a triangle construction which provides trigonometric equations that generate a latitude and longitude given a delay distance and the known geometric information. Using a computer program to sweep the appropriate variables, a table of geographic points of constant time delay may be generated. Then sweeping through different time delays generates sets of curves which are terrestrial curves of constant differential delay.

Figure 4 shows curves of constant delay with 20 microseconds separation for GTE's geosynchronous GSTAR 1 (103 degrees West) and GSTAR 2 (105 degrees West) satellites projected onto a mercator projection of the CONUS (CONtinental United States) area. Equations 1 and 2 relate the known geometry and the measured delay to longitude and latitude for a fixed satellite-Earth distance. Sweeping the eastern and western subsatellite distances over their realizable ranges with one distance incorporating the delay generates one constant delay curve along the intersections of the two subsatellite circles.

\[
\varepsilon = \tan^{-1} \left[ \frac{d_{tw}^2 - r_p^2 - (alt + r_p)^2}{d_{tw}^2 - r_p^2 - (alt + r_p)^2} \right] \text{cos}(\Delta \text{long})
\]

(1)

\[
\text{lat} = \cos^{-1} \left[ \frac{d_{te}^2 - r_p^2 - (alt + r_p)^2}{-2(alt + r_p)r \text{cos}(\Delta \text{long})} \right]
\]

(2)

where:
\[
\begin{align*}
\text{dte} & = \text{[km]} \text{ distance from eastern satellite to eastern subsatellite circle} \\
\text{dtw} & = \text{[km]} \text{ distance from western satellite to western subsatellite circle} \\
\text{rp} & = \text{[km]} \text{ radius of planet} \\
\text{alt} & = \text{[km]} \text{ distance from surface to geosynchronous orbit} \\
\text{Along} & = \text{[deg]} \text{ angular distance between eastern and western satellites} \\
\epsilon & = \text{[deg]} \text{ longitude difference between eastern satellite and subsatellite circle intersection (eastern satellite longitude + } \epsilon = \text{ subsatellite circle intersection longitude)} \\
\text{lat} & = \text{[deg]} \text{ magnitude of latitude of subsatellite circle intersection.}
\end{align*}
\]

Based on the use of the GSTAR satellites, these equations, and subtracting out any additional delays for an arbitrary TDOA receiving location site, delays range from a magnitude of about 200 microseconds for the east and west coasts of the United States to zero along the western Great Plains beneath the satellites.

Note that the geometry of Figure 4 implies that the curves of constant delay associated with one pair of satellites would be almost colinear with the curves of another nearby pair of satellites for a large part of CONUS. However, due to RF constraints, any other satellite pair employed for TDOA measurements must be close to the primary satellite. Thus, some technique other than this form of TDOA must be used to determine the missing dimension which is required to uniquely locate an uplink station.
3. SYSTEM ARCHITECTURE

Through the courtesy of GTE Spacenet Corporation, we chose to use signals through GTE's GSTAR 1 and GSTAR 2 satellites in our time delay measurement experiments. Two sets of Earth station receiving facilities, located atop the Electrical Engineering building on the Georgia Tech campus, were used for the experiments. One includes a 6.1 meter Harris reflector with appropriate feeds for simultaneous transmission and reception of a standard Ku band signal set. A 180 K Harris 6312 low noise block (LNB) converter amplifies and shifts the incoming signal from Ku band down to a C band IF (3.566 to 4.066 GHz) from which our Harris 6531 receiver produces a 70 MHz IF and FM demodulated baseband NTSC video and audio. The second employs generic Ku band TVRO components. It includes a smaller fiberglass 3.1 meter reflector, a 180 K LNB converter which converts to the TVRO industry standard "B band" IF of 950 to 1450 MHz. From here, a Drake model ERS 324S receiver generates a 70 MHz IF and demodulated baseband video and audio.

Although digital or analog correlation would allow the time displacement measurement of a pair of almost any type of signal, we chose to use a dual trace oscilloscope to view a pair of wideband FM television signals. Reasons for the use of TV signals include the variety of available source qualities and locations, the ease of demodulation, and the features of the signal. The use of the oscilloscope provides real time feedback to those performing the measurements. For the preliminary experiments, demodulation and the low level signal detection has been performed by using two HP 8558B spectrum analyzers. These devices provide great flexibility in the degrees of freedom which they give a user such as variable IF bandwidths from 3 KHz to 3 MHz, variable baseband lowpass filtering, IF frequency centering control, and logarithmic versus linear output.
Figure 5 shows the equipment configuration for the time delay measurements. The spectrum analyzers take the 70 MHz IF signals from both receivers and provide a baseband signal by using the analyzers' internal IF bandpass filter to perform slope detection on the frequency modulated video signal. The characteristics of the baseband output is a function of the selected IF bandwidth and the analyzers' controllable low pass filter on the baseband output.

4. DEVELOPMENTAL SYSTEM PERFORMANCE

Many signal pairs have been observed with this equipment configuration. The best results have been sourced by remote evening news transmissions from mobile satellite terminals. These signals are uplinked from vehicles equipped with microwave transmitters and a reflector of minimal aperture size which is quickly erected, activated, and aimed upon arrival at the news site. Many times this is done too quickly as real time observations through multiple satellites confirm.

Antenna misalignment, multiple sidelobes, or a large main beam due to a small aperture size or a road weary dish contribute to signals appearing on transponders of adjacent satellites. At our site, we search with our 3.1 meter system for a potential signal through GSTAR 2 which takes the role of the primary satellite. Although this video signal is available for full demodulation and viewing on a studio monitor, this is only done to ease and confirm signal acquisition. If a potential candidate is found (this is confirmed by viewing the content of the signal), we then begin searching, with our 6.1 meter reflector system, the output of the corresponding transponder on GSTAR 1, which is only 2 degrees away and becomes the adjacent satellite. If we are fortunate and the GSTAR 1 transponder is not heavily occupied (with
another TV signal, wideband data, or assorted small carriers), then we go back to the GSTAR 2 signal and use a spectrum analyzer to slope detect the FM video signal. This baseband output is fed to a Tektronix 2215 dual trace oscilloscope and used as the trigger source by either generic triggering or the Tektronix specific TV frame-triggering mode. The spectrum analyzer's IF and baseband filters and center frequency tuning are then optimized to facilitate the cleanest triggering of the oscilloscope. Then the GSTAR 1 transponder's spectrum is searched for any vestige of the spectrum viewed through GSTAR 2.

There are many pieces of frequency modulated video to be found. Potential ripples in the GSTAR 1 transponder spectrum being searched are slope detected by another spectrum analyzer, then routed to the other channel of the dual trace oscilloscope for visual correlation. With the oscilloscope's sweep rate set to show about one horizontal NTSC line on the GSTAR 2 trace, the presence of another video signal in the noise from the GSTAR 1 trace is readily noticeable. If the GSTAR 1 video signal is not from the same source as the GSTAR 2 video signal, it is apparent by the relative drifting of the synchronization pulses between the two video signals due to different time base sources. But if clock rates are close and the user believes that he is viewing the same signal through both receivers, reducing the sweep rate to that of one vertical period (1/60 sec) will show the relative positions of the vertical retrace fields. If the fields are not almost aligned, then these are two different signals because the maximum delays expected are on the order of 200 microseconds. However, if the same signal is being viewed through both satellites, there will be no apparent drift and a vertical retrace investigation will show a maximum vertical sync field misalignment of only a few horizontal lines.
Our adjacent satellite signal observations have included the barest vestiges of signals plucked from the noise of busy transponders with the skilled use of IF and baseband bandwidth and tuning controls. But other observations have included signals which were more than 4 dB above the noise floor on empty transponders, thus almost reaching the direct FM demodulation threshold.

Photo 1 shows an oscilloscope photograph of two differentially-delayed signals for the specific case of KARE's remote evening news uplink from Mankato, MN (50 miles southwest of Minneapolis), taken on 6 August 1987 at about 6:20 p.m. EDT. Note that the GSTAR 1 signal can be seen to be about 7 microseconds ahead of the GSTAR 2 signal with the sweep rate of 10 microseconds per time division. However, due to the repetitive nature of the horizontal lines, we could be misaligned by an integer number of lines. Photo 2 shows that the vertical retrace intervals are indeed close to alignment with the sweep rate set to 2 milliseconds per time division. Photo 3 shows a close-up view of the transition from vertical retrace pulses to video line sync pulses (about 200 microseconds per time division). Note that a delay of 235 microseconds must be subtracted from this measured delay to remove the satellites-to-Atlanta differential delay specific to our receiver location. Table 1 lists calculated time delays for a variety of locations within CONUS.

5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

By using the methods and equipment configuration described above, we have been able to measure differential satellite path delays. This enables us to deduce part of the solution to the problem of locating an uplink station given only its signal through the uplink's intended satellite in addition to some
vestige of this signal through an adjacent satellite. However, our observations were of uplink stations with fairly large sidelobe levels. With the limitations of our present 6.1 meter reflector and 180 K low noise amplifier, we were unable to detect sidelobes of many of the higher quality uplink facilities which typically employ large well-aligned reflectors at fixed locations. A larger receiver antenna with a lower noise temperature front-end will be required.

Our future activities include the investigation and characterization of the use of analog and digital correlators to measure the differential delay for RF, IF, or baseband signals. The most difficult issue appears to be determining methods for producing useful variable delays for the analog correlators. We also plan to pursue the investigation and characterization of interferometric (differential phase) methods to determine another set of terrestrial curves of possible uplink station locations. The two orthogonally polarized feeds aboard the GSTAR spacecraft provide adequate separation for phase detection and a baseline which is the center of a conic surface of constant differential phase. The intersection of this cone with the Earth's surface provides another set of curves which can identify an uplink's location when combined with curves from another source such as the TDOA conclusions. While the terrestrial intersections of TDOA and interferometric curves are not necessarily orthogonal, they provide better geographic uplink location discrimination than the almost colinear curves which result from using multiple and necessarily nearby pairs of adjacent satellites for TDOA deductions. Phase stability of system components and noise relationships are expected to become key issues of the interferometric investigation.
LIST OF TABLE CAPTIONS

Table 1: Calculated delays

LIST OF FIGURE CAPTIONS

Figure 1: Two-dimensional TDOA geometry, hyperbolic intersections
Figure 2: Three-dimensional TDOA geometry, hyperbolic intersections
Figure 3: Three-dimensional TDOA geometry, triangle constructions
Figure 4: Curves of constant differential delay

LIST OF PHOTO CAPTIONS

Photo 1: Single video line oscilloscope photo, showing uSec delay
Photo 2: Single video frame oscilloscope photo, showing aligned vertical retrace fields
Photo 3: Single video frame oscilloscope photo, showing close up of aligned vertical retrace fields
### TABLE 1: Calculated Delays

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<th>GSTAR I (km)</th>
<th>GSTAR II (km)</th>
<th>GSTAR I - GSTAR II (km)</th>
<th>Time (μSec)</th>
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Primary Satellite

Adjacent Satellite

Unknown Distance

Unknown Distance

Unknown Uplink Site

Uplink Positional Solutions

Two Dimensional View of TDOA Geometry

Figure 1

Axis of Hyperbolic Surfaces

of Constant Delay

Uplink Positional Solutions

Figure 2  Three Dimensional View of TDOA Geometry
Arc of Possible Solutions

Sub-Satellite Points

East Satellite

Known Distance

West Satellite

Figure 3

Construction of Curves of Constant Delay

Figure 4

Contours of 20 uSec for GSTAR 1 (103°W) and GSTAR 2 (105°W)
Figure 5

Adjacent Satellite

6.1m Dish

180K LNC

3.566-4.066 GHz

Harris Receiver

Ku

70 MHz

HP Spectrum Analyzer

Tektronix Dual Trace Oscilloscope

Primary Satellite

3.1m Dish

180K LNB

950-1450 MHz

Drake Receiver

Unknown Uplink Site
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #4

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator
August 1, 1987 through September 30, 1987

Submitted by
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1. Introduction and Summary

Since the June/July report period, we have made RF characterization measurements on our new 3.1 meter dish receiving system which is used to receive signals from the TDOA primary satellites and the copolarized signal for interferometry work. We have also refined and submitted our paper on TDOA techniques to *IEEE Transactions on Aerospace, and Electronic Systems*. Included with this report is a table showing characteristics of available receiving systems and a copy of the manuscript which was sent to IEEE.

We are arranging our research priorities as discussed in the 9 October 1987 telephone conversation between Paul Steffes (Georgia Tech) and Bill Kinsella (GTE). In order to facilitate the design of uplink locating abilities into "next generation" spacecraft, we are delaying our refinement of TDOA techniques to investigate the general interferometric scheme with immediate attention to the usefulness of placing extra feed horns on the satellite for differential phase measurements of uplink signals. When TDOA work continues, we are prepared to apply digital sampling to a baseband conversion of signals from both the afflicted and adjacent satellites and use digital correlation and other digital signal processing techniques to accurately determine the differential delay between signals.

2. Design Suggestions for Future Spacecraft

The Satellite Interference Location System (SILS) development project has focused on developing a system which could locate the position of uplink transmitters using existing, on-orbit satellites such as GSTAR 1 and GSTAR 2. However, as new satellites are designed, it is possible that some relatively simple and low-cost changes in spacecraft antenna design may further facilitate the location of uplink signal sources.

As mentioned in previous Bimonthly Progress Reports, a significant source of difficulty for both TDOA and interferometric techniques lies with the fact that one of the two signal channels required for each technique carries an especially low level signal. In the case of the TDOA technique, this occurs because one of the two satellites being used for the time delay measurement is being illuminated only by a low level sidelobe from the uplink transmitter. Two approaches to increasing the level of the sidelobe signal received through what we have previously called the "adjacent" satellite can be used. The first is simply to increase the G/T of the ground station which receives the sidelobe signal. While this is an effective solution, the overall carrier-to-noise ratio (CNR) of this signal is ultimately limited by the "uplink" CNR, which is related to the spacecraft G/T. Therefore, any approach for increasing the G/T of the "adjacent" spacecraft would be helpful. It is noteworthy that the antenna systems used with the GSTAR spacecraft actually contain 13 separate beams. In the transmit mode, six of these beams can be used as an "Eastern-US spot beam". The remaining seven can form a "Western-US spot beam".

1
All 13 can be summed to form a continental US (CONUS) beam.[4] However, in receive mode, all 13 beams are presently automatically combined to form a single CONUS beam.

One effective way to increase the G/T of the spacecraft receiver for SILS purposes would be to allow access by a tunable test transponder to any one of the 13 individual receiving beams. This requires the addition of RF switches between the feeds and the electronics. Because of the smaller beam size and effective higher gain, the resulting G/T would be significantly higher. A typical scenario would be that an interfering signal appears on GSTAR 2 transponder 6. The adjacent enhanced GSTAR 1 then sets its tunable transponder to channel 6 and scans through each of 13 beams until the best CNR from the sidelobe of the interfering signal is obtained as received by the SILS site. Not only does this facilitate the TDOA/SILS process, but it narrows the possible locations of interfering signal by beam position selection. However, this still requires that transponder 6 on the "adjacent" satellite (GSTAR 1) not be illuminated by an uplink from the same geographic region as the interfering signal. Evaluation of the overall cost effectiveness of adding this capability is beyond the scope of this discussion, but will be pursued in future discussions.

One cost effective method for improving the ability of a single spacecraft to make "interferometric" measurements of uplink transmitter location, such as will be conducted in the second year of the current SILS program, involves placing additional feed horns on the spacecraft. As currently envisioned, interferometric measurements of the position of an uplink transmitter will be made by using the vertically polarized and horizontally polarized feeds as the two elements of the interferometer. However, because one of the feeds should be orthogonally polarized to the incoming signal, the received signal can be extraordinarily weak, making phase comparison by the SILS ground station difficult. This is the basis of our present interferometric technique which uses existing hardware to look at the signals incident on the satellite's copolarized and orthogonally polarized feeds. However if additional copolarized feeds were available, interferometric measurements could be made without nearly as much difficulty. It should be noted that the feed horns used for interferometry need not be nearly as large and complex as the 13 horn arrays used for the regular communications CONUS beams. This is because only the phase of the incoming signal needs to be measured. Any amplitude variations across the beam would have little effect on the resulting interferometric measurement.

Thus we propose that in addition to the 16 feed horns used for each polarization on the current GSTAR spacecraft, an additional horn should be available which capable of providing a very wide beam (covering CONUS) for each polarization. The two horns (one for each polarization) should be switchable to the inputs of any transponder so as to make improved interferometric measurements possible.

For example, an interfering signal is observed on transponder 5 of an upgraded GSTAR 1. (The example signal is vertically polarized and is at a frequency of 14.280 GHz.) Now
the "additional" vertically polarized horn can be connected to the input of transponder 13, which normally receives only horizontally polarized signals. Thus, two channels of information can be downlinked at 11.980 GHz, one with horizontal polarization (output of transponder 5) and one with vertical polarization (output of transponder 13), and each will carry the interfering signal. However, one will carry the interfering signal as received with the normal 13 beam CONUS array, and another with the single horn beam. The difference in the phases of the receiving signals can be used to infer uplink station position. In fact, if yet an additional horn providing full CONUS coverage could be added for each polarization (a total of 4 horns, see Figure [1]), then a second baseline would exist, whereby the exact location of the interfering signal could be deduced (see Figure [2]). It should be noted that the spacing between the "additional horns" and the main feed arrays are limited by the focal range of the individual reflectors. When using the orthogonally polarized feeds for the baselines, the spacing between the orthogonally polarized reflectors also contributes to the baselines. Further studies of this issue will be forthcoming.

3. Uplink and Downlink dish size relationships for link CNR

A current limitation of the Georgia Tech hardware for uplink station locating using the TDOA technique is that 5 meters is the maximum uplink ground station reflector diameter from which useable sidelobe levels can be obtained. In an attempt to evaluate how the system would improve if larger receiving antennas were used (such as the 13 meter antennas at the TT&C sites), we have developed a relation between the reflector size for the interfering station and the minimum reflector size required for a SILS ground station in order to successfully complete a SILS measurement.

Equation 1 describes the relationship between link CNR and the uplink and downlink reflector diameters. This is derived from measurements taken and assumes:

- Worst case uplink reflector sidelobe compliance with the FCC 29-251og(θ) rule,
- Our worst case mobile Earth station measurements have originated from the minimum legal 4.5 meter dish size,
- Operation on Ku Band frequency pairs,
- Uplink reflector efficiencies of 50% during measurements,
- Linear operation of the adjacent satellite’s transponder.

\[
\text{Link CNR [dB]} = 10 \log \left(289 \frac{\lambda_r}{d_\text{X}} \right)^{2.5} + 10 \log \left( \frac{P_c}{P_\text{X}} \frac{d_\text{X}}{d_\text{Y}} \right)^2 - 58.2
\]

EQN (1)

Table 1 lists the link CNR for various dish diameters assuming 50% reflector efficiencies at both Earth stations and the appropriate Ku Band frequencies (14 GHz up, 12 GHz down).
Conclusions from Table 1 include the intuitively appealing notion that the detectable signal threshold occurs when the downlink reflector diameter approaches that of the uplink reflector. However, closer inspection of the equation shows that the uplink station will eventually have the advantage as dish sizes increase. Equation 2 relates the 0 dB CNR level for Ku Band frequencies with reflector sizes in meters and efficiencies of 50%. Table 2 lists CNR values computed from Equation 2 for a variety of dish sizes, and Figure 3 is a plot relating transmit and receive dish sizes for 0 dB CNR (detectability threshold).

\[
\frac{J_k^{2.5}}{J_r^2} = 2.897 \quad \text{EQN (2)}
\]

where:  
\( J_k \) = uplink transmitter reflector diameter  
\( J_r \) = downlink receiver reflector diameter

4. Conclusions

At least two terrestrial arcs containing the location of an uplink site are required to uniquely identify an uplink's transmitter location with preference to maximally orthogonal sets of arcs. We now have several possible methods available for locating these arcs which include:

1) TDOA - Requires the use of two transponders aboard two satellites to generate differential time delay - depends on detecting noise level signals (existing hardware)
2) Interferometry - Cross polarized feeds aboard one satellite - depends on detecting noise level signals (existing hardware)
3) One additional horn for each polarization - (new hardware)
4) Two additional horns for each polarization - Allows a single satellite to generate two terrestrial arcs, thus uniquely identifying the uplink location (new hardware)
5) Switchable Spot Beams - Does not generate arcs but enhances signal acquisition and CNR for other methods (new hardware)

While the last three methods will increase cost, they will greatly ease the process of locating an uplink because we will not be dealing with signals which are at least 20 dB below the CNR of an intentional link. Of course, this assumes that we will be successful in our examination of SILS methods.
TABLE 1 - Characteristics of Available Systems

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<td>GT 6.1m</td>
<td>31.6 240</td>
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<tr>
<td>GTE now</td>
<td>---</td>
<td>---</td>
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* hypothetical system noise temperature
SA = Scientific Atlanta
GT = Georgia Tech

TABLE 2 - CNR versus Uplink and Downlink Reflector Diameters
(Table of Equation 2)

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<th>[meters]</th>
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Above Demodulation Threshold
RF Detection Not Detectable

References


Horizontally Polarized Antenna-Feedhorn Array Configuration

Figure 1
Satellite

Feedhorn Assembly

Terrestrial Arcs
of constant differential phase

Figure 2
Figure 3

Uplink vs Downlink Dish Diameters
for Link CNR = 0 dB

\[ l = \frac{d_{up}}{d_{down}} \]

\[ 2.897 = \frac{d_{up}^{2.5}}{d_{down}^{2}} \]  (Eqn 2)
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #5

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

October 1, 1987 through November 30, 1987

Submitted by
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1. Introduction

Since the last report, we have defined some of the hardware which we shall build to support our satellite interferometry experiments which use the two cross-polarized feeds on a single spacecraft to form an interferometer. We have also added analog to digital conversion capability to a microcomputer system in order to support time correlation experiments on satellite signal pairs from our Time Difference of Arrival work.

2. Digital Correlation

Determination of differential time delays between signals traverse different satellite signal paths is a prerequisite to using the TDOA method for locating uplink stations. Until now, we have measured our differential time delays by manually observing two demodulated time domain signals on an oscilloscope. This process and the ambient conditions which are typically rather dynamic require that the equipment operator be quick and completely aware of his job. In order to be more responsive to the realities of our end goal, we are introducing computer correlation to provide the differential time measurement.

We have taken a commercially available Metrabyte analog to digital converter accessory board and installed it in a Hewlett Packard Vectra microcomputer (an IBM PC/AT compatible computer). This software polled hardware can presently sample each of two channels at a rate of 25 kilosamples/second/channel (or a single channel at 50 kilosamples/second). A fixed length frame of analog samples is taken from each channel and correlated in software in order to produce a time domain graph where the maxima indicates the time of best correlation. The time of this maxima should correspond to the sought after differential time delay.

Cross correlation is performed by a Turbo C program which directly evaluates Equation 1 over the acquired data frames.

Cross Correlation Equation

(Eqn 1) \[ c(T) = \sum_{\forall t} \left[ x(t) \times y(t+T) \right] \]

where: \( x, y \in \) acquired data frames
\( c \in \) resulting data frame

Performing this correlation takes about 32 seconds on our present computer using a frame length of 1024 samples with a dynamic range of 12 bits/sample.
A reader familiar with the mathematics of digital signal processing or Fourier analysis may notice that a more rapid response can be had by multiplying in the transform domain (convolving) the two incoming data frames if one of the frames is reversed in time. We are aware of this and can implement Fast Fourier Transforms when we are satisfied with our results and have the resources. The availability of data in the frequency domain will also provide the additional opportunity for our making use of various digital filtering techniques.

Figure 1 is a graph of a time domain “chirp” which is used as an input signal test pattern for our software. This 1024 sample frame has been auto-correlated to generate Figure 2. Figure 3 is an actual sampling of a slope demodulated satellite FM television signal which had a received CNR of approximately 10 dB. The picture content consisted of a colorbar test pattern. In this case, the sample frame length is 512 samples taken at a rate of about 50 kilosamples/second. Note the two local peaks in the sampled signal which correspond to the 60 Hz vertical retrace portion of the television signal. Another frame was immediately sampled. These two frames were cross-correlated to produce the data of Figure 4. Note that the distance between the two peaks corresponds to the length in time of one television vertical retrace interval. As one would predict, one television frame appears similar to the next to the cross-correlation software.

In the context of observing satellite channel video signals, the present sampling rate is adequate to determine relationships between video frames. A much faster sampling rate than the present 25 kilosamples/second/channel is desired to determine the differential time delay measurements to the microsecond resolution (within individual video lines) required to acquire the most accurate spatial TDOA results. Speeds of up to 50 kilosamples/second/channel may be had by implementing DMA techniques on the present hardware. However, the desired 100 to 1000 kilosamples/second rates require specialized hardware. As in the case of applying transforms, we can implement the faster sampling when we are satisfied with our results and have the resources.

3. Interferometry

Analogous to determination of differential time measurements for TDOA techniques is the determination of differential phase between a satellite’s crosspolarized feeds for interferometric spatial determination of an uplink’s location. Our present two channel Ku band satellite receiving system provides a 70 MHz IF for each channel which can be mixed to provide the DC differential phase output that follows from classical analysis of frequency multiplication. This is illustrated in Figure 5.

However, this technique of differential phase determination requires identical receiver processing of each channel. This requirement includes all intermediate mixing stages be phase
locked to the same sources in both receiving systems. Since we have two different receiving systems, it is unlikely that the results of all the intermediate mixing stages of the two systems will lead to frequency and phase locked 70 MHz IFs with center frequencies within the required fraction of one Hertz necessary to provide a DC measure of differential phase.

There are several solutions to this problem. One is to phase lock all the intermediate local oscillators to the same sources. This is difficult but possible with our present hardware as Figure 6 shows. We shall need to modify our present Ku band LNB on our 3.1 meter receiver by adding a local oscillator locked to our 6.1 meter receiving system's Ku to C band downconverter. We shall also have to distribute the intermediate local oscillators of our 6.1 meter system's Harris receiver to another (available) Harris receiver of slightly different vintage. This will require our modification of various pieces of the second receiver's mixing stages.

Another solution is illustrated in Figure 7. This method uses the resulting differential frequency between the two paths as feedback which is injected in a further mixing stage to cancel out the effects of all the different local oscillators of intermediate mixing stages. If the spectral purity of the received signal is not sufficient to guarantee unambiguous use of one error product for further mixing, an injected reference signal may be used along with a phase locked loop to generate the error signal. We plan to investigate both methods and construct at least one piece of hardware to perform the differential frequency measurement.

Conclusion

A lot of work still lies ahead on this project. We wish to fulfill the promise that digital correlation can automatically provide higher resolution time delay measurements. Issues include fast A/D converters and software transformation techniques. Differential phase determination issues include the difficulty of phase and frequency locking of the two receiving systems, the effects of noncoherent observed signals versus locally injected reference signals for the feedback method, and the level of crosstalk between the crosspolarized signals at the satellite (hopefully high) and at our receiving antennas (hopefully low).

Our PhD student, Whit Smith, plans to have finished all his coursework and his PhD Qualifying exams by late April 1988, thus removing distractions and increasing his time on this research. We have heard no response from the IEEE Transactions on Aerospace and Electronic Systems concerning the publication of the manuscript which you received with our last report. Our first annual report to GTE is due in January. This will contain a synopsis of work done and future plans.
Figure 1
"Chirp" Test Pattern
correlated result

Figure 2

Auto-Correlation of "Chirp" Test Signal
Filtered Correlated Result

Figure 4
Cross-Correlated TV Signal
REPORT

to

GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #6

for

Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

February 1, 1988 through March 31, 1988

Submitted by

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1. Introduction

In order to broaden our Satellite Interference Location System investigation, we have changed our focus from the Time Difference of Arrival to the interferometric method of signal source location determination. We have defined the requirements for successful implementation of this method and are presently attempting to determine the adequacy of the various hardware elements in the signal paths.

2. Interferometry Investigation

The interferometric technique for uplink transmitter location requires:

1) Two receiving antennas with well known locations
2) Sufficient signal strength into each antenna to facilitate a phase comparison

Given the presently available GSTAR satellite antenna mechanical diagrams and some additional information concerning phase center location, we can determine the locations of the two cross-polarized satellite feeds and their apparent phase centers in some useful reference frame. This allows us to develop a model for relating the resulting cones of measured constant differential phase to their intersection with the sphere of the Earth which is our final goal.

Our system assumes that the unknown uplink's signal will contain some detectable cross-polarization component. However, we must determine that the differential phase which we measure is actually due to imperfections in the polarization purity of the uplink in question. To be confident of this, we must learn of the polarization purity of the other locations in the system where polarization impurity may be introduced. Sources of cross-polarization impurity include:

1) The unknown uplink (we desire impurity)
2) The satellite receive antenna (desire purity)
3) The satellite transmit antenna (desire purity)
4) The SILS Site receive antenna (desire purity)

We have developed experiments to determine the purity of the various portions of an interferometric system. They involve the use of signals of various polarizations sent through various combinations of transponders which may or may not have an
associated cross-polarized transponder.

As an example of a signal through two collocated (in frequency) cross-polarized transponders, Figure 1 shows a plot of relative received signal strength versus the polarization of our Harris 6.1 meter receiving system. The signal strength is measured in dB above the local noise floor for a video signal feature downlinked through GSTAR 1 transponders 5 (horizontal) and 12 (vertical) at approximately 11950 MHz. Even when using our spectrum analyzer's lowest resolution signal power scale, we could still detect the cross-polarized signal in the "polarization null" which is 90 degrees from the desired polarization. In this case, it is desired that the observed cross-polarized component originates in the uplink's antenna system. Results from single transponder experiments with CW signals will allow us to determine the polarization isolation of various portions of the system.

Once we have determined the polarization purity of the various segments of our overall system, we will attempt to determine the phase stability of our receiving hardware. Preliminary tests will include the use of an available laboratory grade phase locked frequency counter to provide a signal for modulation and transmission through our two receiving paths. Comparison of the down-converted signals will show the overall frequency and phase stability.

Should we find that our two systems are not sufficiently phase locked, we have the alternatives of either altering the hardware in each receiving chain to be sourced by the same oscillators or employing some form of feedback. Once the system is phase locked, we can calibrate out any unknown phase shifts between the satellite feeds and our terrestrial phase detector by using test signals originating from two or more known Earth locations.

3. Conclusion

Because further pursuit of the Time Difference of Arrival technique requires further theoretical study and better hardware and because we cannot easily generate the required delays of up to 500 microseconds for cross-correlation by any method other than by digital sampling, we will need to further study the finer points of digital sampling and signal processing. Further analysis of the effects of noise on differential time measurements and determination of adequate dynamic range and sampling rates to suit the proposed digital signal processing techniques will be required.

The present digital hardware is limited by the speed of a
borrowed A/D conversion board. We would like to move from our present 50 kHz sampling rate to a more desirable 1 MHz sampling rate to facilitate further experimentation and higher cross-correlation resolution of differential time measurements. We have access to several Hewlett-Packard 60 MHz digital sampling oscilloscopes which are IEEE-488 compatible. Given enough time to complete the interface programming and a needed IEEE-488 card for our computer, we should be able to realize a faster sampling rate.

Our PhD student, Whit Smith, passed his PhD Qualifying Examination on April 1. He has also finished his desired graduate classes. Therefore, he may now attach most of his time to the Satellite Interference Location project. The publishers of IEEE Transactions on Aerospace and Electronic Systems have yet to accept or return our manuscript, Time Difference of Arrival Techniques. However, we have received confirmation of their receipt of our paper. One must note that they are four months behind in their Transactions publication.

We look forward to working with signals from GTE’s satellite control facilities in our cross-polarization experiments, some transponder time, and a visit from Bill Kinsella.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #8

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF A SATELLITE INTERFERENCE
LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

April 1, 1988 through May 31, 1988

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1. Introduction

We are presently pursuing the interferometric method of terrestrial uplink position determination. As discussed in previous reports, the use of the physically separated dual polarization feeds aboard GSTAR series satellites may allow the measurement of the differential phase of a received signal between the two feeds which source the satellite transponder inputs. These signals may then be independently relayed to a SILS site via individual downlink channels. A differential phase measurement referenced to the satellite antenna feeds is then made which is related to possible uplink locations. "Realizability" issues include the signal level of each of the two polarization components in question into the satellite antenna feeds, the polarization isolation of each component of the system, and the phase stability of all components between the satellite antenna input feeds and the SILS site receiver outputs.

2. Interferometry Hardware Issues

For our purposes, polarization purity is determined at four points in the system: the unknown uplink's antenna, the satellite receiving and transmitting antenna, and the SILS site antenna. One can argue that the satellite antenna's polarization purity will be the best for a typical scenario because of the offset reflector with polarization grid design which is employed in the present GSTAR series satellites. The Georgia Tech Harris Delta Gain antenna also boasts a high degree of polarization purity. However, we have made a series of measurements which are designed to determine the polarization purity of the different parts of the system.

These polarization purity measurements were made by measuring received CW signal powers at our Georgia Tech site for various polarization rotations of our antenna. One of GTE's Tracking, Telemetry and Control (TT&C) stations transmitted a set of CW signals with polarizations offset 0, 30, 60, and 90 degrees from the nominal polarization, through a portion of a transponder which has no overlapping cross-polarized transponder. This set of transmissions of various polarizations was repeated for a segment of a transponder with an overlapping cross-polarized transponder. There were some problems with leakage of a cross-polarization component in the supposedly single channel portion of the transponder passband due to the realistic filter characteristics, however, the polarization integrity of the spacecraft and the Georgia Tech ground station were as expected.

Although we have yet to measure the polarization purity of typical uplink signals, we have frequently observed cross-polarization components from a variety of sources. To illustrate an atypical but worst case example, we recently demodulated and
observed on both polarizations what appeared to be a mobile satellite terminal video transmission.

We have also attempted to characterize the frequency and phase stability of the receivers at the Georgia Tech site. During a recent full loop transmission originated at Georgia Tech, we observed the received CW signal which was locally sourced from a microwave phase locked frequency counter to drift more than 50 kHz over a 30 second period. Although we expect upon examination to find one local oscillator which is causing most of the drift, this drift is far too unstable for performing the desired differential phase measurements. This local oscillator stability examination process has been simplified by the loan of one of GTE's test translators so as to avoid using satellite transponder time to operate the full uplink/downlink loop. If we are unable to adequately stabilize or phase lock all our oscillators together, then a feedback approach will be attempted to lock the output of our receiving system to a reference signal. This approach has the benefit of not depending on the required hardware to lock a large number of oscillators to a single source. If we find this to be unrealizable, then the GTE TT&C site facilities may be employed because of their intrinsic frequency stability.

3. Interferometric Geographical Solutions

We have determined the relationship between measured electrical phase of signals at the GSTAR satellite feeds to the terrestrial solutions for possible uplink locations. Figure 1 shows the geometric construction used to relate the angle of a signal incident upon a GSTAR series satellite and its associated interferometric baseline to the desired terrestrial curves. Note that this geometry will differ for a satellite with a different mechanical feed configuration. Figure 2 is the desired result which illustrates curves of constant electrical differential phase across CONUS. This should be contrasted with Figure 3 which shows similar results for the Time Difference of Arrival method.

The simultaneous use of both the TDOA (via GSTAR 1 and 2) and Interferometric (via GSTAR 1) methods is illustrated in Figure 4. The curves of constant differential delay and phase form intersections which are the three dimensional solutions to the uplink location problem. Although the intersections are not necessarily orthogonal over all of CONUS and their intersections will be an area of size determined by signal-to-noise ratios and geometry determined by the noise statistics, they give much better solutions than an overlap of two sets of differential delay or two sets of differential phase measurement results.

To facilitate rapid determination of the intersections of the time delay and interferometric curves, a set of solutions may
be generated off-line for rapid recall or a iterative numerical approach may be used. Based on the difficulty in determining both the TDOA and Interferometric terrestrial curves, we do not suggest that one attempt to find a closed form solution for the intersection of these curves.

4. Conclusion

During our most recent reporting interval, we received a visit from Mr. Bill Kinsella of GTE Spacenet (McLean, VA) on May 18 and 19, and Dr. Alireza Shoamanesh of Telesat Canada on Thursday May 19. During the visit, we demonstrated the Time Difference of Arrival method by blindly locating a San Francisco uplink station using signal paths through GSTAR 1 and GSTAR 2. Mr. Kinsella arranged for the loan of a test translator to facilitate full link testing without using transponder time. His visit and insights have been helpful and enlightening.

Our immediate plans involve the actions discussed above which include reduction and analysis of the cross-polarization isolation measurements, the further examination our equipment for frequency and phase stability, and exploration of a closed loop frequency stabilizing circuit. Eventually, we plan to submit another paper for journal publication when we adequately understand the issues involved in the interferometric technique. Enclosed is a copy of our revised paper which has been accepted for publication by IEEE Transactions on Aerospace and Electronic Systems.
Figure 1
Construction of Curves of Constant Differential Phase
Figure 2

Contours of Constant Differential Phase for Geosync Satellite over 133.0 W
Figure 3

Contours of 20 µSec for Satellite Locations 103.0W and 105.0W
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #9

for

Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

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June 1, 1988 through July 31, 1988

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Introduction

We are continuing our pursuit of the interferometric method for terrestrial uplink position determination. As discussed in previous reports, the use of the offset dual polarization feeds aboard the GSTAR series satellites may facilitate the measurement of the differential phase of a received signal between these two feeds which are connected to the satellite transponder inputs. These signals may then be independently relayed to a SILS site via the orthogonally polarized downlink channels. A differential phase measurement referenced to the satellite antenna feeds is then made which is related to geographic solutions corresponding to possible uplink locations. (A map of CONUS with calculated curves of constant differential phase for GSTAR 1 appears in our last Bimonthly report.)

Realizability issues include the signal level of each of the two polarization components in question into the satellite antenna feeds, the polarization isolation of each component of the system, and the phase stability of all components between the satellite antenna input feeds and the SILS site receiver outputs. These issues have been previously discussed. We are presently focusing on characterizing the phase stability of our available system. Since evidence suggests that our available hardware is not stable enough to make uncompensated "open loop" differential phase measurements between arriving Ku Band signals, we are pursuing electronic methods for performing closed loop differential frequency and phase locking of our two receiving systems.

Polarization Purity Measurements

Received signal isolation due to polarization purity is determined at several points in the system: the unknown uplink's antenna, the satellite receiving antenna, the satellite transmitting antenna, and the SILS site receiving antennas. Poor uplink station polarization purity and perfect polarization isolation elsewhere is desired for SILS purposes. One can argue that the satellite antenna's polarization purity will be the best for a typical scenario because of the offset reflector with polarization grid design which is employed in the present GSTAR series satellites. The Georgia Tech Harris Delta Gain antenna also boasts a high degree of polarization purity. However, we have made a series of measurements which are designed to determine the polarization purity of the different parts of the available hardware.

Our goal has been to test the satellite and our own antenna's cross-polarization characteristics with the assumption
that a carrier sourced by GTE's Tracking, Telemetry, and Control (TT&C) station has the best polarization purity in the system. To test our own antenna, it was necessary to guarantee that there exist no cross-polarization component radiating from the satellite. Therefore, a signal was uplinked into a portion of a transponder which shares no overlapping cross-polarized transponder. Once our own antenna's polarization characteristics were determined, the GTE sourced carrier was moved in frequency to a portion of a transponder passband which shares an overlapping cross-polarized transponder to observe the satellite antenna's polarization purity.

These polarization purity measurements were made by measuring received CW signal powers with the Georgia Tech 6.1 meter reflector system for various polarization rotations of our antenna during four hours on 11 May 1988. GTE's Colorado TT&C station first transmitted a set of CW signals received at 12193 MHz with polarization angles of 0, 30, 60, and 90 degrees from the nominal satellite input polarization through a portion of transponder 16 on GSTAR 2 which has little overlapping cross-polarized transponder throughput. This set of transmissions of various polarizations was repeated at a received frequency of 12157 MHz which is in a segment of transponder 16 which overlaps cross-polarized transponder 8. Figure 1 shows the relationships between the transponder frequency band plan and the carrier frequencies employed.

Plots 1 through 8 illustrate the received CNR levels for four TT&C polarization rotations through the overlapping and non-overlapping transponder passband segments. Although there were some problems with leakage of a cross-polarization component in the supposedly single channel portion of the transponder 16 passband due to the realistic filter characteristics through transponder 8, the results were as expected.

The critical results are related to the depths of the notches in Plot 1 and Plot 4 which respectively illustrate the cases of single transponder carrier transmission for a best aligned (copolarized) uplink station and a worst aligned (cross-polarized) uplink station. For the scenario where power is transmitted from the satellite in only one polarization, we would like to see zero power reception for an orthogonally rotated SILS receiving antenna in both cases. Although Plot 1 shows a drop from about 40 dB to a 10 dB CNR carrier at the receiving antenna cross-polarization angle providing the least power transmission, this may be attributed to some combination of imperfect orthogonal transponder rejection and imperfect polarization purity in our receiving antenna. The complete loss of signal (less than 1/2 dB CNR measured) for the worst uplink polarization alignment angle (where the GTE sourced signal is 90 degrees from copolarized) illustrated in Plot 4 suggests that the best polarization purity is in the satellite antenna. The other plots illustrate expected results for overlapping transponders.
Differential Phase Measurements

Figure 2 shows our two receiving systems with an emphasis on the frequency sources and mixing scheme. Notice that frequency sources include several oscillator technologies: temperature compensated crystal locked, room temperature crystal locked, digital synthesizer with a crystal source, LC tuned circuit, and an open loop DC tuned varactor based oscillator. Thus, there are a multiplicity of sources for phase and frequency drift between the two systems for reasons including temperature changes, DC voltage stability, and signal dependent circuit loading.

In an attempt to determine the phase stability of our receiving system, we have made frequency drift measurements of various embedded oscillators using a temperature compensated crystal oscillator based RF/microwave frequency counter. With one exception, all measured crystal oscillators in our exciter's upconverter and two Harris C band receivers were found to be stable with a measured frequency drift of less than 16 Hertz per minute. These measurements led us to discover and repair several problems with our Harris 6531 C band receiver's synthesizer oscillator. The Drake "domestic-use" receiver which we use with our smaller 3.1 meter reflector was found to have an elegantly simple design which is well suited to receiving a wideband FM television signal. However, frequency stability is not one of its strong points. Unmodulated carriers may be observed jumping around at up to one megahertz per second as a function of noise on the tuning voltage entering and internal to the varactor tuned frequency conversion stage. This problem may be solved by altering the DC tuning circuits.

Another problem which has been encountered is that our frequency counter has been found to be sensitive to carrier-to-noise levels (with the variance of the measured frequency rising with lowering CNR). We are having problems isolating the signal whose frequency we wish to measure amongst the background noise, spurs, and other signals which we inadvertently inject. So, we are presently constructing an RF circuit, illustrated in Figure 3, which will isolate a single carrier by mixing our microwave receiver's 70 MHz IF down to a lower intermediate frequency, passing the desired signal through a narrowband IF filter, then mixing this signal back up to our 70 MHz IF. Using this circuit, we can complete frequency stability tests with realistic signals applied over a full uplink/downlink loop which includes our microwave exciter, power transmitter, test translator, and receiver.

We are finding that the combination of unlocked frequencies between our two receiving systems and the drifts of our various oscillators does not allow for direct differential phase
measurements or some sort of "open loop" measurement which may be corrected by analytic means after the observations. Therefore, Figure 4 illustrates the approach of our plan to continue, by building an RF circuit which provides the frequency difference of an externally injected test carrier between the two receiving systems. This error frequency will then be regenerated via a phase locked loop and mixed into one of the signal paths in order to produce a pair of signals at the same frequency relative to the test carrier. Now, phase measurements may be made between filter selected pairs of signals from one receiver and the frequency corrected transponder passband of another.

Conclusion

The experimental result of a complete loss of signal for a cross-polarized uplink into a single polarization transponder channel indicates that we have enough polarization purity in a full link using our 6.1 meter receiving system to allow us to isolate a sufficiently strong cross-polarized component of an unknown signal for differential phase measurements. We know that uplinked signals with substantial cross-polarization components exist because we have observed and sometimes directly demodulated them. We can also conclude that better polarization isolation in the ground hardware at a SILS site may provide potentially better cross-polarization signal resolution than our present equipment affords. The results of viewing typical interfering signal cross-polarization levels and the requirements of the phase detection circuitry will influence the receiving system polarization isolation requirements.

We are presently constructing various mixing and filtering circuits to perform the signal isolation functions described above. Present construction goals include isolation and amplification of received signals of various levels. We will then build the phase locked loop circuit which locks to our locally provided test carrier that appears in the microwave receiver's 70 MHz IF passband. The dynamics of the phase locked loop's VCO filter will be determined by the dynamics of the frequency changes of our complete receiving systems. Some form of limiting or signal amplitude normalization will be required in order to remove DC gain and offsets from the final differential phase measurement. We are also looking at analytic methods of differential phase measurement of signals at two different frequencies which may incorporate digital signal processing. Should we determine that our frequency correcting hardware cannot be realized with reasonable effort, then we will attempt to find a completely phase locked receiving system to facilitate our differential phase measurements.
Figure 1
Downlink Frequency Band Plan for GSTAR Satellites

Non-Overlapping Transponder Signal
Overlapping Transponder Signal
Frequency Synthesis and Mixing for both Georgia Tech Ku Band Receiving Systems

Figure 2
Crowded and Noisy
Received Signal

Mixing Signal from Tunable VFO

Narrowband IF Filter

Isolated Output Signal

Single Carrier Isolator Circuit

Figure 3
61 m

Harris

70 MHz IF

PLL Circuit

70 MHz

Signal Selection Filters

Differential Phase

70 MHz

IF Band Frequency Shifting Circuit

Figure 4
Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

Uplink Angle from Best CoPolarization: 0°

Single / Dual Transponder
Plot 2

Uplink Angle from Best CoPolarization: 30°

Single/Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 60°

Single / Dual Transponder
Plot 4

Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

CNR, dB

Uplink Angle from Best CoPolarization: 90°

Single / Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

CNR, dB

Plot 5

Uplink Angle from Best CoPolarization: $90^\circ$  
Single / Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 30°

Single / Dual Transponder
Plot 7

Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

CNR, dB

Uplink Angle from Best CoPolarization: 65°

Single / Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 90°

Single / Dual Transponder
REPORT

TO

GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #10

for

Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

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August 1, 1988 through September 31, 1988

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Introduction

We are focusing our efforts upon the signal processing aspects of the interferometric method for terrestrial uplink position determination. As discussed in previous reports, the use of the offset dual polarization feeds aboard the GSTAR series satellites may facilitate the measurement of the differential phase of a received signal between these two feeds which are connected to the satellite transponder inputs. These signals may then be independently relayed to a SILS site via the orthogonally polarized downlink channels. A differential phase measurement referred to the satellite antenna feeds is then made which is mapped into geographic solutions corresponding to possible uplink locations.

Realizability issues include determination of the available signal power of each of the two polarization components in question into the satellite antenna feeds, the polarization isolation of each component of the system, and the phase stability of all components between the satellite antenna input feeds and the SILS site receiver outputs. Signals with more than adequate strength have been observed simultaneously occupying both orthogonally polarized transponders. The experimental results from our polarization purity test are presented in our last report (Bimonthly Report number 9). Experiments with locally generated CW signals from a relatively stable source indicate that the phase stability of our equipment is not adequate for performing uncompensated "open loop" differential phase measurements between the 70 MHz IF outputs derived from the pair of locally received Ku-Band signals. Therefore, we are pursuing differential phase measurement techniques which employ electronic methods to compensate for the phase and frequency corruption. This report discusses these methods.

Differential Phase Measurement Obstacles

There are two problems to overcome before acquiring a differential phase which may be mapped into the desired terrestrial curves of possible uplink locations. A frequency offset of the received spectra at our IF output ports is the first problem. The second involves interpretation of a differential phase measurement between two broadband signals versus the phase measurement between a monochromatic signal and a signal of arbitrary bandwidth.

The goal is to perform a remote differential phase measurement referred to the two cross-polarized feeds aboard the afflicted satellite. Figure 1 shows the two signal paths from
Signal Paths from Orthogonally Polarized Satellite Feeds to Receiver IF Ports Illustrating Frequency and Phase Variation Sources

Figure 1
satellite antenna to terrestrial IF output at 70 MHz with an emphasis on the frequency sources of the mixing schemes. Notice that frequency sources include several oscillator technologies: temperature compensated crystal locked, ambient temperature crystal locked, digital synthesizer with a crystal source, LC tuned circuit, and an open loop DC tuned varactor based oscillator. The twin local oscillators aboard the satellite which shift each polarization’s bank of transponder signals from the 14 GHz uplink passband to the desired 12 GHz downlink passband are not locked together. Thus, there are a multiplicity of sources for phase and frequency drift between the two systems for reasons including temperature changes, DC voltage stability, and signal dependent circuit loading. Therefore, there will exist some offset frequency between the two spectra presented at the receivers’ IF outputs.

Even if the received and downshifted spectra were perfectly aligned, there exists the problem of interpreting the definition of differential phase for the situation where each signal occupies some finite bandwidth. For the trivial case of monochromatic signals, a mixer output provides a DC component which is related to the differential phase between the input signals. However, a typical GSTAR signal is broadband data or frequency modulated television signal.

Frequency Corrections for Offset Spectra

Several methods of correcting for the offset IF spectra have been proposed. One "total" digital signal processing solution involves shifting some portion of the spectrum of each signal close to baseband to facilitate the bandlimiting and sampling of a portion of each of two broadband transponder signals. The sampled frames from each signal path are transformed into the frequency domain. These digitally represented spectra are cross-correlated in order to determine their frequency offset by choosing the correlation maximum as the offset frequency. One spectrum is shifted accordingly then the phase measurement is performed.

Drawbacks to the described DSP system include a lack of error frequency resolution due to both the minimum frequency increments of the discrete spectra and the potential broadness of a cross-correlation peak which would depend upon signal content. Were the frequency offset between spectra to exceed the filtered sampling bandwidth, a correction would be beyond the abilities of this method.

Other methods for acquiring an offset frequency combine both analog and digital techniques or are completely analog. One proposed method takes advantage of the DC maximum or the AC minimum which should occur when two similar spectra are
multiplied with each other and aligned in frequency. Any deviation from the DC maximum or AC minimum out of a mixer’s output should indicate non-overlapping spectra. This is effectively analog cross-correlation in the frequency domain. The mixer output signals can be used to drive an oscillator in order to generate an offset frequency which may be employed for spectrum shifting.

We have experimented with the mixing of two identically sourced but slightly offset 70 MHz IF spectra while trying to manually tune to for the best spectrum alignment. We observed what appeared to be only the wideband noise of the mixing products of the two spectra for any frequency offsets not near spectral alignment. Although we could see a falling AC magnitude near spectral alignment, the instabilities of our total system and coarseness of our manual tuning capabilities did not allow us to observe an obvious DC maximum or a total nulling of the AC component.

Each of the described methods involves some form of cross-correlation between the two received signals. Therefore, the addition of a relatively powerful and known reference carrier into each signal path at the satellite antenna’s input increases the cross-correlation peak. The addition of this reference carrier can also be employed in the geographic calibration of the entire system.

Figure 2 illustrates another method by which a circuit determines the frequency difference between injected reference carriers in the IF passbands. The two IF signals are mixed to generate an output which should feature prominently an error signal whose frequency is the difference between the injected carriers. This error signal is regenerated by a phase locked loop in order to minimize phase noise and to facilitate tracking as the various frequency determining components of the hardware drift.

A 70 MHz local oscillator generates a CW signal which is mixed with first of the two IF signals in order to produce a DC voltage corresponding to the phase difference between the 70 MHz local oscillator and the selected portion of the first IF passband. A second CW signal which is offset above (or below) the first CW signal by the error frequency is generated by quadrature mixing of the error and the 70 MHz local oscillator signals. This second offset CW signal is then mixed with the second IF signal in order to produce a DC voltage corresponding to a phase difference. Because the spectrum of the second signal is offset from the first spectrum by the error frequency, the mixing of the second CW signal with the second signal provides a phase measurement at a frequency equal to the frequency of the phase measurement in the first signal’s spectrum before the frequency shifting induced by the different sets of signal processing hardware. Thus the two resulting DC voltages
Figure 2
Differential Phase Measurement Apparatus
with Compensation for Offset Spectra

Error Frequency

\[ \cos \]

\[ \sin \]

Quadrature

Mixing

\(^{-70 \text{ MHz}} + \text{Error}\)

Differential Phase Measurement Apparatus
with Compensation for Offset Spectra

IF Port 2

70 MHz + Error

140 MHz + Error

Error Frequency + Noise

Phase Locked Loop for
Regenerating Error Frequencies

~70 MHz Local Oscillator

Limiting Amplifiers

Easily Performed in Software

\[ \frac{1}{T} \int_{0}^{T} dt \]

Differential Phase
correspond to two phase measurements between the two spectrally aligned signals and some carrier. These DC levels may be combined to determine an absolute differential phase between the two aligned spectra at a frequency chosen by the frequency of the CW signal.

This method avoids the mixing of two broadband signals by mixing each signal with a monochromatic signal. Because the signal contents may cause varying amounts of power to be present over time at the phase measurement frequency, limiting amplifiers should be used to guarantee that the phase detector mixers receive adequate signal levels so that amplitude variations will not be interpreted as phase information. Integration in time of the DC voltages should increase the accuracy of the overall phase measurement.

Local Hardware Limitations

We have two receiving systems as is required in order to simultaneously view both polarizations and perform the earlier Time Difference of Arrival measurements. One of our present receiving systems is composed of studio quality, phase locked oscillator referenced Harris components, whereas, the other is made from residential consumer TVRO components (See Figure 1). Although the consumer system works well as a satellite FM television receiver, it has exceptionally poor frequency stability for our purposes. Received signals have been observed to experience random spectral shifts of more that 500 kHz per second. Thus we are experiencing the problem of having only one acceptably stable receiving system.

One solution involves using our relatively stable Harris 6522 auxiliary C-Band receiver. We need to modify the output from our existing Ku-Band LNC, which produces an unlocked L-Band output (950-1450 MHz), in order to produce the required C-Band input into the receiver, or we need to acquire a Ku-to-C band LNC. Both possibilities require equipment expenditures. A phase locked Ku-to-C Band LNC similar to that found in our better receiving system is desirable but more expensive.

Another solution would be to use an existing phase locked receiving system such as those available at GTE’s Tracking, Telemetry, and Control facilities. Although we would rather solve the problems locally using finesse, due to financial and time considerations, we have requested information through Bill Kinsella concerning the availability of the GTE’s equipment.
Conclusion

We are continuing our differential phase measurement effort by constructing a hardware realization of the method described last and illustrated in Figure 2. These circuits generate a pair of CW signals which are offset by the frequency error induced by the differences between each signal path. These CW signals are independently mixed with the appropriate IF channel in order to generate a pair of DC voltage differential phase measurements which are combined to generate an overall differential phase measurement. Although we have been designing and building iteratively many of our signal processing modules, we shall attempt to purchase available off-the-shelf assemblies where such purchases will wisely facilitate our chronological and economic goals.

Whit Smith, our Ph.D. candidate who is participating in this project, is presently completing his dissertation proposal.

We are talking with Bill Kinsella and other GTE Spacenet technical personnel concerning the availability of access to phase locked receiving systems and information which provides some characterization of the phase stability of the spacecraft's onboard oscillators. Myound Kim has told us that the initial frequency stability tests performed on the GSTAR satellites after launch indicate a peak sinusoidal onboard oscillator frequency drift of less than 2.3 kHz per 24 hour period which is probably attributed to the change in direction of incident solar radiation during a day.

Although the proposed hardware solution to the offset spectra problem circumvents the problem concerning interpretation of the mixing product of two broadband signals, Radio Astronomers have been using these sorts of interferometric signal processing schemes to produce one and two dimensional images from broadband celestial signal sources. Therefore, we shall be investigating the usefulness of Radio Astronomy techniques and results for our acquisition of a differential phase measurement referred to the satellite antenna's feeds.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #11

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

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October 1, 1988 through November 30, 1988

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Introduction

Over the past two month period, we have continued to focus our efforts upon the signal processing aspects of the interferometric method for terrestrial uplink position determination. As discussed in previous reports, the use of the offset dual polarization feeds aboard the GSTAR series satellites can facilitate the measurement of the differential phase of a received signal between these two feeds which are connected to the satellite transponder inputs. These signals may then be independently relayed to a SILS site via the orthogonally polarized downlink channels. A differential phase measurement referred to the satellite antenna feeds is then made which is mapped into geographic solutions corresponding to possible uplink locations.

Overall system realizability issues have been discussed in previous reports. Our attention is presently directed towards the construction of RF signal processing equipment which performs differential phase measurements and employs electronic methods to compensate for the phase and frequency corruption due to our signals traversing different paths.

There are two problems to overcome before acquiring the desired differential phase measurement. A frequency offset between the received spectra at our two IF output ports due to different hardware (e.g. transponders or receivers) in the two signal paths is the first problem. The second involves interpretation of a differential phase measurement between two broadband signals versus the phase measurement between a monochromatic signal and a signal of arbitrary bandwidth.

In order to facilitate a minimum of signal distortion due to differing equipment in the two signal paths, we have acquired the use of two phase-locked receiving systems courtesy of GTE Spacenet. Of this equipment, we presently have the pair of Miteq Ku-to-70 MHz downconverters mounted in racks and a Hewlett-Packard model 8656A synthesizer, which serves as local oscillator for the downconverters, awaiting the addition of Ku-Band LNAs and the appropriate interconnections.

Figure 1 illustrates our method of correcting for the offset spectra and making a differential phase measurement. A circuit determines the frequency difference between an injected reference carrier in the 70 MHz IF passband outputs from our dual Ku-Band receiving system. The two IF signals are mixed to generate an output which should feature prominently an error signal whose frequency is the difference between the injected carriers.

A user tuned 70 MHz local oscillator generates a CW signal
Differential Phase Measurement Apparatus with Compensation for Offset Spectra

Figure 1
which is mixed with the first of the two IF signals in order to produce a DC voltage corresponding to the phase difference between the 70 MHz local oscillator and the selected portion of the first IF passband. A second CW signal which is offset above (or below) the first CW signal by the error frequency is generated by having a phase locked loop lock to the sum of the local oscillator and error frequencies. The use of this phase locked loop facilitates low phase noise and tracking of the error frequency from which the second CW signal is derived. This second offset CW signal is then mixed with the second IF signal in order to produce a DC voltage corresponding to a phase difference.

Because the spectrum of the second signal is offset from the first spectrum by the error frequency, the mixing of the second CW signal with the second IF signal provides a phase measurement at a frequency equal to the frequency of the phase measurement in the first signal's spectrum before the frequency shifting induced by the different signal paths. Thus the two resulting DC voltages correspond to two phase measurements between the two spectrally aligned signals and some arbitrary carrier. These DC levels may be combined to determine an absolute differential phase between the two aligned spectra at a frequency chosen by the user controlled local oscillator.

This method avoids the mixing of two broadband signals by mixing each broadband IF signal with a monochromatic signal. Because varying amounts of signal power may be present over time at the phase measurement frequency, limiting amplifiers are used to guarantee that the phase detector mixers receive adequate signal levels so that amplitude variations will not be interpreted as phase information. Integration (in time) of the DC voltages should increase the accuracy of the overall phase measurement.

Status of Offset Spectra Corrector

We are presently constructing the electronic circuits which will realize the block diagram that is illustrated in Figure 1. The hardware has been broken into several modules which are being realized as RF components mounted on printed circuit boards and housed within RF tight, diecast aluminum boxes that are interconnected via BNC jumper cables. These modules will be mounted in industry standard 19 inch rack mounted enclosures.

At the time of this writing, we have completed several modules. One is a dual IF pre-amplifier strip and mixer. Two are a pair of differential phase detectors preceded by limiting amplifiers.

The work remaining includes the computer interface, the computer programming for combining the two differential phase
measurements, and the admittedly difficult phase locked loop portion of the electronics. The phase locked loop circuit will have to isolate and regenerate the error signal between the two incoming IF spectra. A critical characteristic is the loop circuit's ability to handle the possibly low signal-to-noise ratios between the error product and the noise product due to transponder background noise and low cross-polarization component received power levels.

Conclusion

We are continuing our differential phase measurement effort by constructing a hardware realization of the offset spectra correction method described above and illustrated in Figure 1. Note that the circuit has become slightly simpler since our last BiMonthly report. We are experiencing and surmounting problems typical of high gain, small signal, VHF circuits. The phase locked loop circuit remains the largest obstacle to completed offset spectra correction hardware.

Whit Smith, our Ph.D. candidate who is participating in this project, presents his dissertation proposal at 2:00 PM on Tuesday 13 December 1988. We look forward the possibilities of a visit by Bill Kinsella and our attending a demonstration of the Interferometrics pre-detection TDOA correlator.

We await the arrival of the Ku-Band LNAs which will complete the dual receiving system. Upon their receipt, we shall be able to perform "open loop" differential phase measurements of signals observed through cross-polarized transponders. Upon completion of the offset spectra corrector and its associated laboratory tests and characterization, we shall be requesting transponder time and assistance from GTE's TT&Cs to provide remotely sourced terrestrial CW signals for system calibration. These tests should confirm or allow us to correct the mapping of phase information to terrestrial location curves which we have determined from our knowledge of the antenna feed locations and attitude of the satellite. These tests should also allow us to characterize the usefulness of the interferometric SILS approach in a realistic environment.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #13

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE
LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

January 1, 1989 through February 28, 1989

Submitted by
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Introduction

During this reporting period, we have continued to focus our efforts upon the signal processing aspects of the interferometric method for terrestrial uplink position determination. This involves inferring the position of uplink transmitters by performing differential phase measurements referred to the orthogonally polarized antenna feeds aboard a satellite as is discussed in previous reports.

We have also been in contact with GTE personnel, while attempting to infer uplink transmitter locations during real interference events, and for planning future SILS activities within GTE.

Interferometry

As is discussed in detail in BiMonthly Report 11, the remaining problems for the interferometric method of terrestrial transmitter location determination appear to be twofold. First we must realign the received spectra corresponding to each of the two orthogonally polarized signals received at the satellite antenna feeds which are offset by the difference in frequency of the two local oscillators aboard the spacecraft. Secondly, after realigning the spectra, we must determine how to interpret a differential phase measurement between two broadband signals. Once these two tasks have been accomplished, we can feed the measured differential phase to a computer program which maps this information into terrestrial contours of constant differential phase.

The method proposed in BiMonthly Report 11 and again illustrated in Figure 1 determines the frequency differential by mixing the two received spectra and searching for the product of a reference CW carrier which is purposely injected somewhere into the passband of the afflicted transponders of each polarization by a cooperating SILS transmitter. This offset frequency is then used to generate locally offset CW signals which may be locally tuned to any desired portion of the afflicted passband to perform a pair of differential phase measurements between our CW signals and the incoming broadband signals. These two phase measurements are then handed to a computer which generates an overall differential phase measurement from the combination of the two intermediate differential phase measurements.

As we have determined, this method has two problems. First, one must detect the product of the reference CW signal amongst the summed products of all the other signal components. Therefore, the injected CW signal must be substantially greater in power level than the rest of the contents of the transponder's passband. Secondly, the phase locked loop which generates this
Figure 1

Differential Phase Measurement Apparatus with Compensation for Offset Spectra using a Single Phase Locked Loop
difference frequency may be required to lock to any beat frequency corresponding to the differential frequency between the spacecraft oscillators which may range from zero to more than 2 kHz. One finds much difficulty in designing a phase locked loop which can operate down to zero frequency.

In order to solve this problem and answer some of his own questions about our signal processing techniques, graduate student Whit Smith has spent several weeks investigating several other methods. During this time, he pursued a method which involved phase measurements between various quadrature components of the incoming signals. However, we were able to prove that these methods give us no extra information in that we are already limited in the number of measurable parameters available in the incoming signal.

However, Figure 2 illustrates a method which we are presently pursuing and in which we have more confidence. In order to refrain from having to mix the two incoming spectra to determine differential frequency products, we are employing two phase locked loops to regenerate the injected reference carriers in each transponder's received spectra. These regenerated CW signals are then combined using RF signal processing components (mixers and filters) with a locally tuned CW signal to produce a second local CW signal which tracks the first locally tuned CW signal by a frequency offset equal to that between the two received spectra. Each of these two locally tunable CW signals is then mixed with the appropriate incoming broadband signal to produce a pair of intermediate differential phase measurements. The results of these two measurements are then combined in software to produce one overall differential phase measurement.

As with the method presented in BiMonthly Report 11, this method retains the desirable characteristics of not requiring a differential phase measurement between two broadband signals. However, it has the additional benefit of allowing the uplinked reference CW signal to be located away in frequency from the portion of the band which is experiencing the interfering signal as long as each of the two cross-polarized signals have experienced the effects of the satellite's two different local oscillators. This allows reference carriers to exist on transponders different from the afflicted ones, and thus not alert a jammer of pending location determination activities.

Much of the hardware required for the method illustrated in Figure 2 has already been constructed. We are presently building the phase locked loops and plan to add them to the existing equipment. We shall then test our equipment on locally generated and offset CW signals in various signal-to-noise environments. If local testing proves successful, we shall then request transponder time and a dual polarization CW transmission from one of GTE's TT&C sites for further testing including geographic and total system phase offset calibration.
Differential Phase Measurement Apparatus with Compensation for Offset Spectra Using Dual Phase Locked Loops
SILS Support of GTE Interference Location Efforts

On Tuesday 28 February, Dr. Steffes of Georgia Tech was contacted by Bill Kinsella of GTE concerning an interfering signal on GSTAR 1 transponder 2. The interfering signal, which was later found to be the digital preamble for a recently installed video teleconferencing installation in Raleigh, NC, consisted of either a carrier or a 50 percent duty cycle square wave on-off transmission with no other noticeable modulation and a frequency of about 2 kHz.

Professor Steffes assembled the collection of test equipment and various operating modules from the incomplete interferometric hardware necessary to perform crude TDOA and wideband, uncompensated differential phase measurements, and he found the interfering signal to be present on the cross-polarized transponder of GSTAR 1 and some vestige to be seen on the co-polarized transponder of GSTAR 2. Because the available phase measuring modules lack RF signal amplitude compensation or bandlimiting, Professor Steffes took reference measurements of the DC levels output from the phase measuring modules using the interfering signal present on the cross-polarized transponders in question. GTE then transmitted a reference carrier atop the interfering signal from which Professor Steffes then made another voltage observation corresponding to a differential phase.

The difference in DC voltages which corresponds to differences in phases between the two measurements was found to indicate that the jammer should be slightly south of the almost east-west curve of constant differential phase on which the supporting GTE Grand Junction TT&C lies.

Our 3.1 meter antenna was then directed to the afflicted satellite, GSTAR 1, and we aligned our 6.1 meter antenna with the adjacent satellite, GSTAR 2. As per our previous TDOA measurements, we routed the received IF signals from the afflicted and adjacent satellite paths to spectrum analyzers for tuning and demodulation to baseband. The resulting two signals were then routed into a dual trace oscilloscope for manual determination of the time difference between the signal pair.

The difference in time of arrival of the periodic signal was observed to be about 200 microseconds west of the terrestrial longitude bisector between satellites. Mapping this into terrestrial geography indicates a north-south curve located on the United States' west coast. Combining this with the southern approximation from the differential phase attempt led to a suggestion of the San Francisco Bay area as a possible uplink location. We later realized that the almost 500 microsecond time between edges of the uplinked square wave modulated carrier would
provide a time correlation peak every 500 microseconds and offset west from the satellite longitude bisector by 200 microseconds. Therefore, another terrestrial solution would occur slightly inland of the United States' east coast and slightly south of the curve of constant differential phase which includes Grand Junction. This alternate solution turned out to be the case.

Although we do not plan to make broadband signal measurements, the above measurements were performed with the entire IF bandwidths of our receivers being introduced into the ports of the phase detector module. Some sort of phase information is being discerned from the incoming signals because we can change lengths of cable between one receiver and the phase detector module and get predictable DC output shifts thus indicating a net phase change. Although we have yet to determine how to model the phase measurement between two wideband signals, we believe that we can at least observe terrestrial background radiation as viewed through the orthogonally polarized antennas aboard the spacecraft in question.

To prevent phase measurements between broadband noise in the "open loop" mode of performing measurements and to prevent wideband noise from interfering with the phase locked loops presented in Figure 2, we have ordered pairs of 5 and 20 MHz wide passband filters centered around our receiver's 70 MHz IF.

Conclusion

We are continuing our differential phase measurement effort by acquiring filters and constructing a hardware realization of the offset spectra phase measuring device described above and illustrated in Figure 2. We appreciate GTE's hardware support and provision of signal sources. We also look forward to visiting the Grand Junction, Colorado TT&C site to support SILS hardware installation as we have discussed with Bill Kinsella.

As earlier BiMonthly reports discuss, we are investigating the problem analogous to that of our offset spectra which is experienced by the Radio Astronomy community in the form of doppler shifts induced upon the spectra of signals received at antennas separated by our planet's diameter when astronomical very long baseline interferometry (VLBI) is performed. A sampling of both the literature and conversations with various Radio Astronomy authorities indicates that the offset spectra problem is resolved by either an a priori knowledge of the induced offset frequency and an open loop change in one receiver's (atomic clock referenced) local oscillator or the offset is determined from hours of off-line cross-correlation between long samples of the two received non-coherent signals. Neither method is desired for our application.
REPORT

TO

GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #14

for

Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

March 1, 1989 through April 30, 1989

Submitted by

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Introduction

We are continuing to direct our efforts towards the signal processing aspects of the interferometric method for terrestrial uplink position determination. This involves inferring the position of uplink transmitters by performing differential phase measurements referred to the orthogonally polarized antenna feeds aboard a satellite as is discussed in previous reports. Most of our recent efforts concern the construction and testing of RF signal processing equipment which realigns the spectra of the two orthogonally received signals which are processed by transponders sharing the same input frequency passband but employ two different local oscillators with slightly different frequencies thus producing slightly offset output spectra. In order to perform differential phase measurements, these spectra must be realigned in the domain in which the measurement occurs.

At the time of this writing, we are close to performing a "proof-of-concept" experiment to demonstrate the validity of the offset spectra correction hardware which is key to the performance of an interferometric SILS system with our present satellite hardware. This hardware has been discussed in detail in previous reports, and its status is reviewed in this report.

Status of Offset Spectra Correction Hardware

Figure 1 illustrates the RF signal processing paths and components in our present realization of offset spectra correction hardware. All of the major modules in Figure 1 have been built which include:

2 limiting phase detectors
2 50-90 MHz manually tunable phase locked loops
a combiner module which generates the phase measurement frequencies for each input spectrum
various mixer, filter, and amplifier modules to facilitate laboratory creation of the expected spectra

Each of the modules works. They are presently being integrated into the overall system illustrated in Figure 1.

The phase locked loops work. They will lock to the pair of downlinked reference signals corresponding to each polarization's transponder and provided by a cooperating terrestrial SILS transmitter. They have been successfully locked for periods of hours to SCPC reference CW signals visible on GSTAR satellites thus indicating their ability to lock to and track signals in a transponder environment containing other signals and noise.
Differential Phase Measurement Apparatus with Compensation for Offset Spectra Using Dual Phase Locked Loops
Because the reference signal in one received passband is expected to be only a few kilohertz above the reference signal in the other passband, the following locking procedure is facilitated by our hardware. One loop is considered to be a master to which the slave loop is locked. The master loop is tuned to a reference signal in one receiver's passband. The slave loop's input is then released from the master's signal and connected to the other passband where it is easily locked to the second passband's nearby reference signal.

The combiner module which generates the offset phase measurement frequencies does indeed provide an offset between the locally tuned "phase observation frequencies" by the difference between the two input reference frequencies. Great care has been observed in testing the output frequencies and signal levels because the differences in frequencies at points of interest is on the order of a few kilohertz in the 70 MHz environment. Various mixing products with lower signal amplitudes appear in the offset output from the combiner module which may be rejected by a third phase locked loop that reproduces only the desired output CW signal.

"Proof-of-Concept" Experiment

Figure 2 illustrates the "proof-of-concept" experimental hardware configuration which we are using to provide laboratory signals similar to those expected in the satellite environment. Two signal generators are employed to provide the equivalent of transponder input signals. The 19 MHz oscillator is considered to be the cooperative SILS reference carrier. The 20 MHz oscillator is considered to be the non-cooperative unknown signal of interest whose phase we are trying to determine. These signals are summed as illustrated in order to produce the equivalent of inputs into two transponders aboard a satellite. One of the paths from the 20 MHz "unfriendly" oscillator is connected to a variable length transmission line in order to simulate varying differential phase shifts and thus varying angles of incidence for the corresponding "unfriendly" radiation arriving the satellite antenna.

The simulated transponder inputs at about 20 MHz are then mixed with approximately 50 MHz outputs of another pair of signal generators which are purposefully set to have frequency differences of about 0 to 10 kHz. These two signal generators with their slight offsets correspond to the two unlocked local oscillators aboard the satellite which feed the two sets of transponders associated with the two orthogonally polarized antenna feeds.

The outputs from this pair of mixers provides a pair of spectra like that expected at the 70 MHz IF output ports for each
Phase Measurement Hardware Testing Configuration

Figure 2

19 MHz

Variable Length Line

20 MHz

5100 MHz

About 10 kHz Difference

5101 MHz

Resulting Spectra into "Transponders"

70.00 MHz

70.01 MHz

Local Tuning x MHz

PLL

PLL

x MHz

x + 0.01 MHz

Performing in Software

Offset Spectra Correction

and Phase Measurement
of our orthogonally polarized receiving channels. Each spectrum should consist of a reference and an "unfriendly" CW signal. These spectra are then fed into the offset spectrum correction RF hardware where a locally tuned oscillator selects the frequency within one passband for one phase measurement. This hardware also generates the second frequency for a phase measurement in the second passband which is offset by the difference in frequency between the SILS reference carriers.

Because we are expecting interference from broadband modulated signals (FM TV, PSK), this system is designed to allow tuning into a broadband signal. Therefore for experimental purposes, the "unfriendly" 20 MHz signal will be frequency modulated to give it a non-zero bandwidth. Should we choose to look at an "unfriendly" CW carrier, we shall need another phase locked loop in lieu of the locally tuned phase detector mixing signal. For experimental purposes, this signal can be realized by independently mixing the 20 MHz "unfriendly" source with one of the 50 MHz "transponder" oscillators to produce a tuning signal which is aligned in frequency with itself for phase detection in one passband. The offset correction hardware will generate the other signal necessary for the phase measurement in the offset passband.

The choice of 19 and 20 MHz for the simulated uplinked signals was motivated by the availability of signal generators. Although microwave signals could be used and fed into our receivers, the results at the 70 MHz intermediate frequency are the primary concern.

Conclusion

We are close to being able to demonstrate working offset spectra correction hardware and the associated differential phase measurement. This success will be followed by the generation of a system calibration procedure. Calibration will occur in three stages. First, phase offsets in the spectra correction hardware must be taken into account. Second, offsets due to other portions of our Georgia Tech Earth station must be determined. These two calibrations should be realized with the use of locally injected signals. Last, the orientation and location of constant phase centers for the satellite antenna system must be determined. This should require CW signals emitted from two geographically separated transmitting sites. For this procedure, we shall be calling on various GTE TT&C resources.

We look forward to visiting the Grand Junction, Colorado TT&C site in late June. We are happy to have received the March 1989 issue of IEEE Transactions on Aerospace and Electronic Systems which contains our Time Difference of Arrival SILS paper.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #15

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

May 1, 1989 through June 30, 1989

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Introduction

During the last two months, we have traveled to the GTE Grand Junction TT&C where successful TDOA measurements were made, and we have performed preliminary experiments with our apparatus for differential phase measurement and offset spectra correction. The experiments appear to indicate that the equipment performs its desired goal. With these positive results in hand, we are continuing to direct our efforts towards the signal processing aspects of the interferometric method for terrestrial uplink position determination as discussed in previous reports.

Interferometry Hardware

Past reports discuss the details of our proposed hardware which performs the dual phase measurements at a user chosen frequency given the two spectra which have been received after being offset by the independent local oscillators associated with the cross-polarized sets of transponders onboard the satellite. We have completed enough of the hardware to make manual measurements in the laboratory.

However, in order to make the laboratory measurements, we also needed to generate two sets of signals with a frequency offset typical of that found at the IF outputs of our two satellite receivers. Figure 1 illustrates the test configuration with the pseudo-transponders occupying the upper half of the illustration and the actual phase measurement hardware occupying the lower half.

As was discussed in the last report, two signal generators are employed to provide the equivalent of transponder input signals. The 19 MHz oscillator is considered to be the cooperative SIILS reference carrier. The 20 MHz oscillator is considered to be the non-cooperative unknown signal of interest whose phase we are trying to determine. These signals are summed as illustrated in order to produce the equivalent of inputs into two transponders aboard a satellite. One of the paths from the 20 MHz "unfriendly" oscillator is connected to a variable length transmission line (ganged trombone sections or different lengths of coaxial cable) in order to simulate varying differential phase shifts and thus varying angles of incidence for the corresponding "unfriendly" radiation arriving at the satellite antenna. The angle of incidence for the SIILS reference carrier's radiation is assumed to be known because we know the location of the SIILS uplink site and the orientation of the spacecraft.

The simulated transponder inputs at about 20 MHz are then mixed with approximately 50 MHz outputs from another pair of signal generators which are purposefully set to have frequency differences of about 0 to 10 kHz. These two signal generators
Figure 1
Experimental Interferometry Hardware

SILS Reference

Jammer Source

Transponder 1 LO

Transponder 2 LO

70.00 Mc

50.01 Mc

50.01 Mc

70 Mc

19 MHz

20 MHz

Variable Phase

Cal 70.01 71.01

-10 kc

70 71

Pseudo-Transponder

Spectra Realignment/Phase Measurement

Diff Phase

Cal

Computer

PLL

70 Mc

70 Mc

PLL

70.01 Mc

70 Mc
with their slight offsets correspond to the two unlocked local oscillators aboard the satellite which feed the two sets of transponders associated with the two orthogonally polarized antenna feeds. These two oscillators are expected to have frequency differences of less than 3 kHz.

The outputs from this pair of mixers provides a pair of spectra like that expected at the 70 MHz IF output ports for each of our orthogonally polarized receiving channels. Each spectrum should consist of a reference and an "unfriendly" CW signal. These spectra are then fed into the offset spectrum correction RF hardware where a locally tuned oscillator selects the frequency within one passband for one phase measurement. This hardware also generates the second frequency for a phase measurement in the second passband which is offset by the difference in frequency between the SILS reference carriers.

For purposes of our experiment, the locally tuned oscillator used to select the signal for phase comparison is replaced by a feed from the already known "unfriendly" signal source. In operational hardware, this would be a VFO for a wideband signal or a phase locked loop which is manually locked to a received CW signal of interest.

Two useful sets of experiments have been performed. The first employed the trombone section as a variable phase element in one of the "unfriendly" signal paths. Although the ganged trombone hardware borrowed from one of our undergraduate electromagnetics labs provides a change in phase of only 5 degrees at 20 MHz, we were able to acquire composite measurements of about 3.1 to 6.6 degrees.

Because the nature of the DC output from the phase detectors implies that a noisy measurement or a no-signal measurement should look like a small angular result, a second set of measurements were acquired by switching in and out short and long sections of coaxial cable. With a goal of an approximately 90 degree change, the computed difference in phase at 20 MHz for our cables is 84 degrees and we acquired composite measurements of about 67 to 74 degrees.

Although these results happily indicate that phase is being measured, we have several areas where improvement is available. These results do not take into account an observed scaling factor which is unique to each of our phase detectors. Because each of these composite measurements are manually performed using an oscilloscope to view at least four noisy outputs ranging from about 1 to 1000 millivolts over a half hour period during which module level calibrations are occasionally made by hand, a lot of drift from the various signal generators and RF processing components is expected. If the signal paths are broken as during the removal and insertion of different lengths of cable, then the phase locked loops lose lock, and lock on the appropriate carrier
must be manually re-established. We have also identified several points in the RF signal paths where different signal power levels would produce better results. The output of the module which generates the offset CW signal for phase measurement in the "shifted" spectrum contains several components in addition to the desired result, therefore, we would like to insert another phase locked loop to regenerate the desired output CW signal.

Bill Kinsella of GTE has agreed to provide to us a computer interface board that will give us analog-to-digital measurement and digital interface capabilities which will allow us to perform the on-line calibrations and measurements in seconds instead over large fractions of an hour. We anticipate that the use of statistical techniques for the sampled voltage signals and the rapidity of the switching between the various calibration signals will allow us to overcome various drifts and noise problems while also speeding the characterization of our system.

**Computer Controlled TDOA**

All of our TDOA measurements to date have been acquired by slope demodulating frequency modulated television signals observed on an adjacent satellite with a manually tunable spectrum analyzer which is also employed to observe the afflicted transponder's output spectrum for the signal of interest. This adjacent baseband signal is compared with that from the primary satellite which is similarly detected or from a satellite television receiver to determine the time difference between signals. This measurement is then mapped into a geographic curve containing the possible uplink locations.

These measurements are presently performed by having a user manually tune some combination of satellite receivers and spectrum analyzers and then view both baseband signals on a dual trace oscilloscope to generate the differential time measurement which is then typed into a computer to be evaluated by a program.

There exist several possibilities to facilitate automating the TDOA measurement process at the Grand Junction TT&C site. One route involves buying commercially available test equipment and connecting it via existing computer interface busses. Because the site already has one Hewlett Packard HP8566B spectrum analyzer, which is fully controllable over the digital IEEE-488 (GPIB or HPIB) interface, a second identical spectrum analyzer may be acquired and the pair used as two digitally controllable tuners for producing a pair of baseband outputs. These outputs can be fed to a pair of analog-to-digital converters which are realizable as a multiple trace digital oscilloscope. Such oscilloscopes are available as full test instruments with their own front panel and displays or as outboard data acquisition modules which must be connected to a host computer for user
interface. Should two identical spectrum analyzers be used, the locking together of each of their oscillators is desirable to guarantee that they are observing the same signal.

If the features of a second $57000 HP8566B spectrum analyzer are not required, a computer controlled downconverter followed by a bank of computer switched filters for slope demodulation similar to that which occurs in the presently available spectrum analyzer can produce the baseband signal from the primary satellite signal. This more custom configuration may be better tailored to suit the application. The adjacent satellite baseband signal can be produced from the existing spectrum analyzer.

Visit to the Grand Junction TT&C

On June 19th, Bill Kinsella of GTE and Professor Paul Steffes and Whit Smith of Georgia Tech traveled to GTE's Grand Junction, Colorado GSTAR TT&C site. Our goal was to observe the available equipment and determine any additional equipment requirements necessary to perform SILS operations from the site.

During our stay, we employed the large reflector antennas to acquire several differential time measurements between primary and adjacent satellite signals which have not been possible from our Georgia Tech site because of our smaller antenna reflectors. These TDOA measurements were successful and confirm a previously theorized relationship between unknown transmitter antenna size and SILS site antenna size.

We used our detection of signals to illustrate the methods for performing the differential time measurements to the operational staff at the TT&C site. We provided software and maps which are useful in determining geographic locations from a variety of satellite pairs, SILS site locations, and differential time measurements. The staff was able to perform the TDOA SILS technique when we left.

In order to perform TDOA measurements and in anticipation of future interferometric measurements, we recommend the following changes to the Grand Junction TT&C site which will allow differential time measurements to be performed using enhancements to the existing automatic test equipment facility (ATEF).

The downlink antenna LNA feeds are presently routed to a central switch which selects one antenna, amplifies its signal, and routes it across the room to the ATEF hardware. Although the chosen signal is computer selectable, only one may be viewed at any given time. Because two different antenna signals must be simultaneously observed in order to perform the required differential time measurement for TDOA and to perform the
required differential phase measurement for interferometry, we recommend that a second computer selectable switch, amplifier with a gain of about 30 dB, and the associated cabling, elliptical waveguide or heliax, be installed to provide a second signal path from the antennas to the ATEF hardware.

Some method of detecting this second signal must be employed. As is discussed above, the hardware to perform this function can vary depending on whether we expect to continue to perform TDOA measurements manually or under computer control. To facilitate manual measurements, we recommend the acquisition of another spectrum analyzer in addition to the existing HP8569B.

Because many of our signals of interest for SILS purposes will be generic FM satellite television, we recommend the acquisition of a LNB, a satellite television receiver, and the associated video monitor and speaker. Our experience shows that the ability to view the signal contents aids in performing the TDOA measurements. This equipment can also cheaply provide a baseband video output from the primary satellite signal.

Should a decision be made to perform the TDOA measurements automatically, equipment as is discussed above is required. An additional IEEE-488 controllable spectrum analyzer and digital oscilloscope fill the requirement if off-the-shelf equipment is desired. The custom hardware option may provide more economy and different features.

Although the TT&C has the best equipment available at the time of its construction, lower noise figure LNAs are presently available at Ku band frequencies. We recommend the acquisition of the lower noise 150 to 180 K LNAs which will improve adjacent satellite signal observation in addition to facilitating daily activities of the TT&C site.

Conclusion

The differential phase measurement hardware appears to function properly. We look forward to computerizing this measurement and further refining the characterization of our system. Subsequently, we shall begin measurements of actual spacecraft signals.

We enjoyed our trip to the Grand Junction TT&C site and the hospitality which we received from the GTE personnel. We look forward to seeing routine SILS activity at this site. As requested by employees at the Grand Junction site, we have sent them copies of our IEEE Transactions paper describing our early TDOA efforts and shall send modified TDOA software as it is produced. We would like to assist in efforts to install facilities for performing SILS measurements.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #16

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

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July 1, 1989 through August 31, 1989

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Introduction

During the last reporting period, we have continued our pursuit of the interferometric SILS method. We have confirmed our ability to measure differential phase between CW signals which are in offset spectra. We are currently employing a computer interface board with digital and analog capabilities which has consistently allowed us to perform the above mentioned measurements to a accuracy of better than two degrees of phase under a variety of laboratory conditions.

Interferometry Hardware

Past reports discuss the details of our proposed hardware which performs the dual phase measurements given the two spectra which have been received after being offset by the independent local oscillators associated with the cross-polarized sets of transponders onboard the satellite.

Our last report (Bimonthly Report number 15) describes the laboratory configuration which is used to generate a pair of offset spectra containing a "friendly" CW reference and an "unfriendly" CW signal with a user variable phase ability incorporated into the "unfriendly" signal. These offset spectra are used to emulate the pair of signals which would be received from each of the two orthogonally polarized transponder outputs aboard the afflicted satellite. These spectra are then injected into our offset correction and phase measurement hardware. As of our last report, we had completed enough of the hardware to make initial manual measurements in the laboratory. We have now automated much of the measurement process. Figure 1 illustrates the present hardware which now incorporates some computer control.

The Metrabyte interface card which GTE provided to us is used in an IBM XT compatible computer to sample the outputs of the two phase detectors and to control the phase detector calibration circuitry. Note that the phase detectors are RF mixers which have been optimized to provide a larger DC output to facilitate phase measurement. The outputs from the phase detectors are low pass filtered to about 1 kHz by an analog circuit. This low frequency signal is then oversampled by the computer. The computer integrates (averages) over thousands of samples to determine the average DC level out of the phase detector which is proportional to the phase difference between signals entering the phase detector.

Because the average DC level out of the phase detector is proportional to not only the desired phase difference but also
Figure 1

Experimental Interferometry Hardware

19 MHz

SILS Reference

Jammer Source

20 MHz

Variable Phase

Transponder 1 LO

Transponder 2 LO

50.00 Mc

50.01 Mc

70 Mc

Cal 70.01

Jam 71.01

10 kc

70 71

Pseudo-Transponder

Spectra Realignment/Phase Measurement

70 Mc

PLL

Diff Phase

70 Mc

PLL

Diff Phase

Computer

Cal

Cal
the entering signal amplitudes, we need a method for removing these possibly unknown amplitudes from the formula for computing the desired numerical phase angle. This is traditionally done in interferometric DF systems by hard limiting both incoming channels to a known power or amplitude then mixing the two signals to achieve a DC voltage which corresponds to the desired phase angle. We took a different approach.

We remove our signal amplitude ambiguities by alternately inserting and removing a known length of cable into one of the entering signal paths. This induces a known phase shift at our known frequency of measurement. By taking the average DC measurements both with and without the extra cable length inserted, we can use these two numbers to solve numerically the underlying non-linear equations for both signal amplitude and phase difference. The computer software controls both the phase detector output sampling and cable switching. We have used this method to achieve a phase accuracy of better than one degree over a greater than 20 dB dynamic range for one of the incoming signals.

The addition of computer controlled measurements has reduced the time to make the measurements from a manual time of about a half hour to a few seconds with judicious adjustment of the sampling frequency, number of samples, and the analog filter characteristics. Other changes in the RF hardware include the introduction of a few amplifier stages at points where signal strengths had been reduced to marginal levels by earlier processing stages.

We are presently performing experiments with non-monochromatic signals to confirm our ability to deduce phase differences between broadband signals such as FM SCPC, phase modulated data, or FM television signals. We should then like to move on to live satellite signal phase measurements.

Satellite Measurements

In order to employ our interferometric SILS method, we need to know the location of our interferometric baseline. For the most general geometric case, we should need to know the three dimensional locations of the two orthogonally polarized phase centers of the receiving antennas onboard the satellite of interest to determine absolutely the location of the baseline. However, the mechanical diagrams for the GSTAR spacecraft show the receiving horns for each polarization to be in the spacecraft's XZ plane. This is the plane which contains a line connecting the satellite and the subsatellite point and a line connecting the Earth's poles. Thus the interferometric baseline must lie in the spacecraft's XZ plane which intersects Earth as the line of longitude above which the spacecraft resides. This
Figure 2

Location of Interferometric Baseline in Spacecraft XZ Plane
is illustrated in Figure 2.

This terrestrial interpretation of the plane containing the interferometric baseline and the resulting contours of constant differential phase is lost if there is any significant rotation of the spacecraft. However, this condition implies the beginning of a catastrophic failure of the satellite system. We do not anticipate significant angular displacements based on our observations of the spacecraft's fraction-of-a-degree pointing telemetry during our initial trip to the GTE McLean facility.

Now that the interferometric baseline has been restricted to a plane, only a single angle need be deduced. This is determined by learning the locations of the phase centers for each of the cross-polarized receiving horns aboard the spacecraft. However, phase offsets between channels are induced not only by the spatially displaced phase centers but also by the possibly different signal paths through the satellite RF hardware, ground receiving RF hardware which may change with experimental configuration, and different downlink propagation paths which may change with time. Therefore, we believe it to be difficult if not impossible to determine these phase offsets in an open loop fashion given such information as the spacecraft mechanical configuration. Thus we should initially like to calibrate out these offsets by transmitting signals from known terrestrial sites through the spacecraft to determine the angle of our interferometric baseline.

We propose the use of transmitters at two different sites. GTE's Colorado and east coast TT&C sites should work based on our initial computations. Each site will transmit a CW signal on both polarizations (or rotated 45 degrees off either polarization) through the cross-polarized pair of transponders participating in the experiment. The signals need only be far enough apart in frequency so that they are uniquely identifiable. Each site's location is known, and their relative phases will be measured. Using the extra degree of freedom given by knowing the extra terrestrial location will provide the angle of interferometric baseline in the spacecraft's XZ plane.

Although we have been successful in measuring phase between laboratory generated CW signals in offset spectra, we have been using an upconverted version of the "unfriendly" input signal as the tuning signal which picks the frequency in each spectra at which the phase measurement occurs. This tuning signal source guarantees that the tuning signal is at the same frequency as the "unfriendly" signal of interest. For the case of the live satellite signal measurements, we shall need to regenerate the non-reference signal with a third phase locked loop which will then be treated as the tuning signal.
Conclusion

The computerized differential phase measurement hardware appears to function properly with CW signals. We are presently attempting to perform similar measurements between broadband signals. We plan to follow this with live satellite measurements. At his request, we sent Bill Kinsella ten reprints of our paper concerning our TDOA experiments which appeared in the March 1989 issue of IEEE Transactions on Aerospace and Electronic Systems. We look forward to a visit by Mr. Kinsella later in September.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #17

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

September 1, 1989 through October 31, 1989

Submitted by
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Introduction

Since the last reporting period, we have continued our pursuit of the interferometric SILS method. We have reduced the complexity of our interferometry circuit for broadband signals. We have found that the phase measurement accuracy with our present hardware which we estimated to be within 2 degrees in Bimonthly Report #16 was in error based on measurements over a small change in phase. The actual accuracy of our present hardware is about +/- 10 degrees over the entire 360 degree range. However, we have approaches for decreasing this error. A major source of this error has been the noise in our test circuits which simulate the transponder frequency offset problem. This noise was traced to locking problems within the phase locked loops which are being solved as of the writing of this report.

Simplified Circuit Topology

We have built and tested with CW signals the hardware shown in Bimonthly Report #15. This topology depends on our making a pair of phase measurements between the received signal of interest and a locally derived CW signal. However, when performing phase measurements between a CW and a broadband signal, the resulting energy within the passband of the mixer’s product output can be small enough to elude simple detection. This is particularly true of a FM signal where the carrier may be viewed as being swept through the passband of the mixer’s low pass output filter thus producing a signal characterized by a low power per unit bandwidth (Watts/Hertz).

Therefore, one must mix a pair of broadband signals together in order to perform a phase measurement between them. Although it is possible that over large fractional bandwidths the phase would vary between time delayed signals, small fractional bandwidths can produce useful results. We have shown this to be true in laboratory measurements between frequency modulated signals occupying hundreds of kilohertz centered near 70 MHz. Therefore, as in the original problem presented by the unlocked oscillators aboard the cross-polarized transponders of our satellites of interest, we attempt to realign the offset spectra.

Figure 1 shows a solution along with the equipment available to perform the differential phase measurement from a pair of satellite signals. The transponder signals are being generated artificially in the laboratory until we are satisfied with the quality of the results. Again we use a pair of reference CW signals which come from a friendly terrestrial source to realign the spectra. Each of the orthogonally polarized signals is received and each reference carrier is regenerated by a PLL.
Figure 1 - Experimental Hardware for SILS Interferometric Measurement
The output of each PLL is offset by the frequency and phase error associated with each transponder oscillator's frequency offset and the angle of arrival of the reference signal at the satellite antenna. We can know the angle of arrival of our friendly reference signal and thus the resulting differential phase between received channels. Any additional phase and the frequency offsets are due to elements in the signal processing path which signals from any other source must experience.

Therefore, to realign the resulting spectra, we upconvert each channel's received spectrum by the regenerated reference carrier derived from the other channel's received spectrum. We mix the output of the vertical channel's PLL reference generated carrier with the spectra of the received horizontal channel to produce a desired product spectra at a higher frequency. The same is done for the other channel.

Now the differences in frequency between the two resulting higher frequency spectra are canceled out. These two spectra are band pass filtered to isolate a signal of interest. They are then mixed to produce a product which has a DC component proportional to the phase between the input spectra which may be measured and integrated by a computer. The known phase offset due to the angle of arrival of the reference carrier is then subtracted out along with any known fixed offsets to produce the desired resulting differential phase between the chosen signals. This phase may then be mapped into a terrestrial map to produce a curve of constant differential phase on which the chosen signal's source must reside.

Problems

Our claims of achievable differential phase accuracy in our last Bimonthly Report were incorrect. In our experiments, we used a variable length coaxial trombone section to generate an adjustable differential delay. The trombone section was chosen to facilitate our retaining phase lock between measurements which would have been lost were we to disconnect a section of coaxial cable to insert a different length of cable to produce a different signal delay and thus a different phase. Unfortunately, these are the same trombone sections which are rather "beaten" due to their use in our undergraduate laboratories. After writing the last Bimonthly Report, we found that mechanical distortions cause the characteristics of the transmission line to vary with length which effects the desired phase measurements. This was discovered by observing another portion of the Voltage Output versus Phase Input cosine curve. A series of more reliable measurements were performed using carefully measured lengths of coaxial cable to generate the +/- 10 degree accuracy over the entire possible input phase range as mentioned above in the Introduction.
The phase locked loops in our system were believed to be working properly based on our viewing their output spectra with a spectrum analyzer. However, after finding intermittent undesired frequencies in the output of our phase detector, we looked closely at the outputs of our PLLs by mixing the PLL outputs with a copy of a CW input signal. The resulting products showed that the PLLs were hovering within a few kilohertz of exact locking, but that they were never in phase lock.

After much circuit work and analysis, we discovered that the "perfect integrator" circuit employed by our loops works best when it's output is less than a few millivolts. We had been allowing the integrator to ramp up to the about 5 volts required to tune our VCOs to the desired 70 MHz range. We have since changed the circuit to provide tuning by the summing of a manually controlled DC voltage. Performing the experiment described in the previous paragraph shows that we are now indeed locked in frequency and that the phase is constant to within a reproducible noise level.

Although we are pressing forward without presently attempting to improve further the accuracy of the differential phase measurement modules, we see several possible methods to increase greatly the accuracy of the phase measurement hardware. Measurement of the input signal strength should facilitate the use of an AGC loop to produce an input signal with an average level for which further phase measurement hardware is best characterized. The use of approximately 45 and 90 degree switchable transmission lines would allow software to chose among four samples in the voltage versus phase cosine curve. Therefore, the software could compute the phase from the points in the steeper portion of the cosine curve which maps into a more accurate phase measurement.

Conclusion

We have one more PLL to alter before again performing laboratory tests using pseudo-transponder generated signals. When we are pleased with the performance of our equipment in these tests, we should like to perform the same test using live satellite signals.

We enjoyed our visit by Tom Wirth of GTE on September 28th. We have been communicating with Mr. Wirth and look forward to assisting in his efforts to build a working, automated Time Difference of Arrival (TDOA) facility at GTE's Grand Junction, Colorado TT&C site.
REPORT TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #18

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

November 1, 1989 through December 31, 1989

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Introduction

Since the last reporting period, we have continued our pursuit of the interferometric SILS method. We have reached a point in our interferometry experiments where we would like to perform experimental differential phase measurements upon real satellite signals which are transmitted from at least two different geographical locations.

Live Interferometric Satellite Experiment

We have performed laboratory differential phase measurements employing the configuration shown in Figure 2 which produces the offset spectra similar to that which is expected to be received from the two orthogonally polarized satellite transponders and contains the phase offset which we wish to measure. We are consistently able to perform repeatable phase measurements with our laboratory hardware.

Figure 1 shows the total signal path topology which we are presently assuming with the two paths of interest being that of the reference and the interfering signals. This topology is discussed at length in Bimonthly Report # 17. As has been previously discussed, this method of locating an interfering unknown uplink signal requires that an additional reference signal be present nearby in frequency. Because we are hardware limited in our abilities to transmit and receive on two polarization, we would like to have GTE supply the satellite signals.

In order to determine whether the interferometry method is indeed working, we need to have the interfering signal to be transmitted from at least two geographically separate sites to induce a substantial phase difference between the orthogonally polarized antenna feeds aboard the satellite of interest. The Grand Junction, Colorado and Woodbine, Maryland TT&C sites of GTE should present a sufficient differential phase to suit the purposes of this experiment.

Figure 3 shows the desired CW signals which we would like to have transmitted from each of the two different sites during the two different portions of the experiment. Each signal should appear on frequency overlapping transponders in each polarization as is illustrated in in the example shown in Figure 4. The lower frequency signal is to be the reference CW signal with the higher frequency signal being the unknown or interfering signal. Due to the limitations of our experimental hardware, we need to have the signals separated by no less than 5 MHz and no more than 10 MHz and would like to have as much power as is possible in each
Figure 1 - Experimental Hardware for SILS Interferometric Measurement
Figure 2 - Hardware for Simulating Frequency Offset Transponders
Figure 3

Site 1

Experiment 1: Jammer at Site 1

No Signal

5 < f(jam) - f(ref) < 10 MHz

Site 2

Experiment 2: Jammer at Site 2

f(ref) f(jam)

No Signal
Each Signal Needs to Appear on Both Polarizations
Example: GSTAR 1

Figure 4

Ref  Jam

4H  5H  6H

12V  13V  14V
signal. We shall lock to the reference CW signals with our phase locked loops, realign the offset spectra, then mix the two interfering signals to produce the desired differential phase.

There are two experiments. For the first experiment, the reference and interfering signal should come from the same uplink site. For the second experiment, the interfering signal should come from a geographically different site. Our knowing the location of both sites should allow us to observe a difference in phase between the two sites and determine any satellite specific phase shifts.

We would like to have at least a half hour of each set of signals at whatever time is convenient to GTE. We shall be glad to coordinate transmission beginning and endings with your engineers via telephone or operate at specifically scheduled times.

We would like to emphasize that the accuracy of these measurements greatly depends on the phase purity and signal-to-noise ratio of the reference CW signal, therefore, we would like to have the reference signal be as powerful and pure as is possible.

Problems and Solutions

In our last report, we mentioned our difficulties in acquiring accurate phase lock with our phase locked loop hardware. We have since solved this problem and have been able to lock simultaneously with both PLLs to SCPC carriers.

To determine that both loops are indeed locked to the same signal, we mix their outputs to see if we can get the DC output which should indicate that they are locked to the same signal. Because of the interference of nearby SCPC data signals and the other noises experienced in the spectrum of a busy transponder, this is an experiment which we would like to repeat in the much cleaner spectral environment of the above mentioned experiment with a relatively powerful reference CW signal.

At this writing we have not yet completely determined the relationship between the measured phase detector output voltages and the desired angles in degrees, however, we are making consistent measurements of the phase of our interfering signal in our laboratory test hardware. This problem appears to be one of determining a scaling factor which may be a function of net power into the phase detector.

Figure 1 shows a pair of 140 MHz band pass filters preceding the inputs to the phase detectors and a series of amplifiers throughout the received signal processing hardware. We presently lack the filters and some of the amplifiers. However, we believe
that our present hardware should allow us to prove our system in the experiment described above. The mixing product that the 140 MHz band pass filters should reject consists of the pair of received spectra which have been offset in frequency by twice their original error offset and thus should not correlate to produce a DC term within the phase detector. However, their energy is present in the phase detector, therefore, a cleaner output would result by the removal of these undesired signals.

Conclusion

We have continued communicating with Mr. Wirth and look forward to assisting in his efforts to build a working, automated Time Difference of Arrival (TDOA) facility at GTE’s Grand Junction, Colorado TT&C site.

We look forward to testing our interferometry hardware with satellite signals as soon as is convenient for GTE.
REPORT

TO

GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #19

for

Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

January 1, 1990 through February 28, 1990

Submitted by

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Introduction

Since the last reporting period, we have performed two experiments which indicate that the interferometric SILS technique does indeed discriminate between terrestrial uplink sites as a function of the phase angle between the satellite's orthogonally polarized antenna feeds.

Live Interferometric Satellite Experiment

After GTE informed us that we would be using GSTAR 3 as the satellite for our interferometric tests, we plotted the associated contours of constant differential phase to learn the expected differential phase measurement results between the probable uplink sites. Figure 2 shows this plot against a Mercator projection of the continental United States with cross marks at the approximate locations of Grand Junction, Colorado, Atlanta, Georgia, and Washington, DC.

Our first experiment occurred on Thursday 15 February 1990 between 9 and 11 pm EST. GTE offered to provide the signals requested in the desired experimental procedure which is outlined in Bimonthly Report # 18 from Grand Junction and the Washington, DC area with the Grand Junction uplink site providing the reference signal in addition to the signal whose position was to be measured. The Washington signal originated with GTE's Satellite News Gathering (SNG) truck which was parked outside the McLean, Virginia facility and operated by GTE's Bill Kinsella and Tom Wirth. Our second experiment occurred a week later on Thursday 22 February 1990 between 8:30 and 10:16 pm EST. Again, the Grand Junction site provided both reference and "unknown" signals with the second site being an Atlanta located and based Ku-band SNG truck belonging to WXIA Channel 11 (Gannett Broadcasting, Inc.). The WXIA SNG truck was operated by a combination of the WXIA personnel and Professor Paul Steffes of Georgia Tech.

This choice of satellite and uplink locations results in several interesting observations. First, the predicted phase difference between Grand Junction and Washington is on the order of one degree or less while that between Atlanta and Grand Junction is about 12 degrees. Thus, one should expect to measure the same differential phase from the Grand Junction and Washington signals assuming our model of the constant differential phase contours is correct.

A second point worth noting is that GSTAR 3 suffered an accident during its trip to geosynchronous orbit which has, amongst other things, resulted in its presently inclined orbit.
Figure 2
Curves of Constant Differential Phase for GSTAR 3
This orbit requires that a terrestrial observer track the satellite through a celestial "figure eight" pattern during a 24 hour period. Because the satellite recently appears to a terrestrial observer to be moving at its maximum northwesternly angular velocity at about 10 pm EST, all involved terrestrial antennas were required to constantly realign their azimuths and elevations in order to maintain relatively constant received power levels. To a lesser degree, polarization purity is effected by the satellite moving out of the main radiation lobe of a linearly polarized terrestrial antenna and thus into a region of the antenna's pattern where some power from each of the spatially orthogonal polarization components may be emitted or detected.

On each of the above mentioned evenings, GTE's Grand Junction TT&C began transmitting a pair of CW signals at 14030 and 14035 MHz with the lower frequency signal being the reference and the other signal being the "unknown" uplink signal whose position was to be measured. These signals were transmitted from a linearly polarized antenna which had been rotated approximately 45 degrees from either of GSTAR 3's horizontal or vertical polarization orientations. These signals were received by GSTAR 3, amplified and converted by the pair of onboard oscillators to signals at approximately 11730 and 11735 MHz then retransmitted back to Earth.

As Figure 1 illustrates, each orthogonally polarized pair of signals was received at our dual feed 6.1 meter antenna, amplified by a pair of Ku-band LNAs, then fed at Ku-band frequencies to an identical pair of phase locked downconverters which mixed the signals down to 65 and 70 MHz. Phase locked loops were then locked to the now 65 MHz reference signals. The regenerated CW pair of signals were employed to realign the spectra from each received polarization which had become slightly offset due to the independent local oscillators onboard the satellite. SAW filters were employed to isolate the "unknown" 70 MHz signals from the reference signal and other noise components in the received passband. The spectra realignment process resulted in the pair of 70 MHz "unknown" signals being centered at about 135 MHz where they were mixed together to produce DC voltages related to their phase offsets.

A computer controlled sampling process was used to remove the amplitude ambiguity and integrate out any remaining AC components in the voltage measurement. A computer program then inferred the phase difference between the two RF channels. These measurements were made continuously for periods of many minutes with results being intermittently written to the computer's hard disc.

Mean differential phases and variances of the accumulated data from each of the four transmissions (Grand Junction and McLean on 15 February, Grand Junction and Atlanta on 22 February)
Figure 1 - Experimental Hardware for SILS Interferometric Measurement
were generated as a function of lowering received power thresholds. The mean angles from the data sets with the lower variances were subtracted to determine the differential phase. For the first experiment, a differential phase angle of less than one degree was measured. The second experiment resulted in a differential phase angle of about 22 degrees which is a 2.8% error from the expected 12 degree result out of a possible 360 degree measurement.

The results from the first experiment reflect the expected small differential angle between the Grand Junction and McLean sites. Although the second experiment did result in the desired non-zero measured angle between Grand Junction and Atlanta, there are several explanations for the discrepancy between the expected 12 and the measured 22 degrees of differential phase. First, our model assumes certain locations for the phase centers of the antenna onboard GSTAR 3 which were derived from the mechanical specifications for the antennas onboard the GSTAR satellite series. This may not necessarily be the case for the electrical phases. Second, we have yet to remove all amplitude dependent effects from our phase measurement hardware. Third, there may exist mechanical or electronic effects of which we are unaware resulting from the accident experienced by GSTAR 3 during its trip to orbit.

Recommendations for an Operational System

Better phase detection hardware is recommended for future interferometric SILS systems. The problem with the present phase detector stems mainly from saturation of the amplifiers preceding the mixer which produces the DC voltages related to the desired differential phase. In order to maintain linear amplifier operation and thus minimum phase distortion over a wide dynamic range, an automatic gain control loop consisting of RF power couplers and electronically variable attenuators is suggested.

The present phase detector also takes pairs of DC measurements between RF paths containing switched lengths of transmission line which purposely introduce an additional fractional wavelength time delay into one of the incoming signal paths. Knowing these pairs of voltages, the measurement frequency, and the difference in lengths of transmission line allows for numerical solution of the differential phase angle independent of the incoming signal amplitude. Because this hardware is more sensitive to noise errors in certain parts of its voltage versus differential phase characteristic, this method could be optimized to operate in the lower error portions of the mentioned characteristic.

We have been generating geographic plots of constant differential phase contours in an open loop fashion by assuming the locations of phase centers of the onboard satellite antenna
system. We would recommend that a survey be taken by having signals transmitted from many different geographic sites. This could be accomplished by having a SNG truck drive north from the southern tip of Texas while stopping occasionally to perform a transmission in conjunction with another facility such as that available at Grand Junction. A more practical method of performing such a survey would be to accumulate data from "targets of opportunity" such as SNG customers over a several week period by having them transmit some signal in conjunction with reference signals from a GTE site as a part of their uplink initiation procedure.

Conclusion

We are pleased with the results of the two experiments described above. Whit Smith is now working on his dissertation which, as is stated in our contract, will serve as the final report describing both the TDOA and interferometric SILS methods. We are open to any observations or suggestions concerning any of the SILS methods and would like to cooperate in sharing related information that is desired by GTE.

Bill Kinsella has given us permission to return the equipment that we have borrowed to perform the interferometric measurements. However, should GTE personnel visit Georgia Tech in the near future and wish to see a demonstration of the interferometric hardware, there exists a reasonable probability of our re-acquiring the needed equipment.

Whit Smith has been in contact with Tom Wirth who is working with hardware which is destined to become a part of GTE's Grand Junction TDOA SILS system. They are planning to meet to integrate the hardware and generate the software necessary to control and process the received signals necessary to generate the desired geographic results from the TDOA method for uplink location.
REPORT
TO
GTE SPACENET CORPORATION

BIMONTHLY PROGRESS REPORT #20

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE
LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

March 1, 1990 through April 30, 1990

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Introduction

Since the last reporting period, we have continued working to analyze data from the successful demonstration experiments of the interferometric SILS technique conducted on February 15 and February 22, 1990. Below we describe the nature of the data set obtained and its statistical variation.

Experimental Results - Live Signal Tests

During the live satellite signal tests, attempts were made to equalize the received reference and "jammer" signal CNRs. However, the constant angular motion of GSTAR 3 required periodic antenna realignment at each of the participating Earth stations. Thus the received signal powers and therefore CNRs appeared to change with time. The phase locked loops were able to remain locked to the reference signals throughout all of their power level changes during all experiments except for one instance when all GSTAR 3 signals were lost while attempting to realign the Georgia Tech antenna.

The "jammer" signal emitted during the transmission from the GTE SNG truck at the McLean, Virginia site was observed on a spectrum analyzer at the Georgia Tech site to occupy about 100 kHz as compared to the relatively low phase noise CW (narrowband) signals which were experienced for all other portions of the experiments. The equipment performed equally well with the wideband signal as with the carriers.

From the measured and averaged voltage values taken during the live satellite experiments, angles and powers were inferred as is discussed in previous reports. From these results, mean differential phases and variances of the accumulated data from each of the four transmissions (Grand Junction, McLean, Grand Junction, and Atlanta) were generated. These statistical results are presented in Tables 4.1 through 4.4 with data included as a function of lowering received power thresholds. The last column in the table indicates the percentage of the available data which had an inferred power level greater than the listed power threshold. As the actual measured voltage values for these two experiments would require a minimum of 100 pages to print, this data is not listed in this report.
Table 4.1
Reduced Data from First Grand Junction Transmission

Mean, Standard Deviation, and Percent of Data Used versus Power Threshold

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Table 4.3
Reduced Data from Second Grand Junction Transmission

Mean, Standard Deviation, and Percent of Data Used versus Power Threshold

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Table 4.4  
Reduced Data from Atlanta, GA Transmission  
Mean, Standard Deviation, and Percent of Data Used versus Power Threshold

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Tables 4.1 and 4.2 show the reduced data sorted by inferred IF power threshold for the first experiment which was a measurement of the phase angle between Grand Junction and McLean. The standard deviation of the inferred angles for the samples above the higher -3.0 dBm power threshold is not the minimum deviation listed in the table. Thus, to choose a mean value to use as the estimated angle, a lower threshold was chosen which has a relatively low standard deviation for the included data. This was done in lieu of choosing the most powerful few samples or all the samples because this better removes transients (high power signals) or periods when the computer continued to take samples but there were no desired signals present (low power signals).

Choosing the power threshold of -8.0 dBm for both the Grand Junction and McLean data gives mean angle values of 4.3 and 3.6 degrees respectively for the first day of measurements. Thus, a differential phase angle of less than one degree was acquired. Similarly choosing a power threshold of -3.0 dBm to minimize the standard deviation for the data of the second set of measurements resulted -27 and -50 degrees for Grand Junction and Atlanta respectively. This data is listed in Tables 4.3 and 4.4 and produced a differential phase angle of about 23 degrees which is a 3.1% error from the expected 12 degree result out of a possible 360 degree measurement.

Values of 4.3 and -27 degrees were measured for similar
signals originating from Grand Junction for the two experiments. During the week between the experiments, parts of the hardware at the Georgia Tech site were reconfigured. This and other changes elsewhere along the signal paths may explain the difference in measured values. The absolute estimates are expected to vary with time. The differential estimates are the values of most interest.

The results from the first experiment reflect the expected small differential angle between the Grand Junction and McLean sites. Although the second experiment did result in the desired non-zero measured angle between Grand Junction and Atlanta, there are several explanations for the discrepancy between the expected 12 and the estimated 23 degrees of differential phase. First, the employed geometric model assumes certain locations for the phase centers of the antenna onboard GSTAR 3 which were derived from the mechanical specifications for the antennas onboard the GSTAR satellite series. This may not necessarily be the case for the electrical phases. Second, all amplitude dependent effects had yet to be removed from the phase measurement hardware. Third, there may exist unknown mechanical or electronic effects resulting from the accident experienced by GSTAR 3 during its trip to orbit.

Tables 4.1 through 4.4 show a variety of inferred power levels for the different sets of data. Table 4.5 lists various signal CNR maximums and minimums which were recorded during the experiments. There appears to be no correlation between the standard deviations inferred from the measured voltages and the listed CNRs. The reference signal source was Grand Junction for all experiments.

Table 4.5

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The spectra were offset by 1091 Hz at 9:53 pm EST on the evening of the first experiment and by 1043 Hz at 10:16 pm EST on the evening of the second experiment. These values were acquired by inserting the reference carriers, which had been regenerated by the phase locked loops, into a pair of frequency counters which were phase locked to the same temperature compensated crystal oscillator. The two displayed values were subtracted to produce the frequency differences.

**Conclusion**

This analysis shows that satellite-based interferometry can be a robust technique for characterizing the relative angle of arrival of uplink signals even under low carrier-to-noise conditions. This increases our belief in the realizability of such a technique for use in an operational SILS system.

At this point, Whit Smith is completing his doctoral dissertation which will serve as the Final Report for this project. However, we believe that realization of the operational TDOA system (currently under construction at the GTE, Grand Junction, Colorado site) for which we have provided consultation and design support will soon be followed by realization of an operational interferometric SILS system.
REPORT
TO
GTE SPACENET CORPORATION

ANNUAL REPORT

for
Contract C-10070

RESEARCH IN DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

January 20, 1987 through January 31, 1988

Submitted by
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Atlanta, Georgia 30332-0250
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I. INTRODUCTION AND SUMMARY

The locations of transmitters which serve as sources of interference to or unauthorized operation of domestic geosynchronous satellite communications systems are difficult to determine. This is because of the wide range of potential locations of the interfering transmitters and because most satellite Earth stations direct their transmitted power away from the surface of the Earth which makes detection with terrestrial receivers difficult except at relatively short ranges. Alternate location determination approaches include aircraft-based detection of interfering signals or detection from low altitude spacecraft. Both have the difficulty of requiring a fairly long response time and extreme expense. The use of adaptive antennas aboard domestic spacecraft (i.e., movable "spot beams") to either locate the source of the unwanted signals or to minimize the effects of such signals is feasible, but requires additional cost for spacecraft construction and launch [1]. The fleet of existing domestic satellites are not so equipped. The technique of physically moving a spacecraft so that the edge of its principle receiving beam scans past the undesired transmitter has been tried, but has the disadvantages of disrupting the traffic through other transponders on the same satellite and of consuming propellant [2]. Therefore, it becomes clear that alternate techniques which require only minimal disruption of normal spacecraft operation and which can operate using the fleet of existing domestic satellites are preferable.

One alternative is a Time Difference of Arrival (TDOA) system by which the propagation time for the uplink signal through a satellite is compared with that through an adjacent satellite. Given that the position of the two
spacecraft relative to the receiving station is precisely known, the difference in time of arrival over the two different paths will localize the uplink transmitter location to a curve on the Earth's surface. Realization of such a system requires a two channel receiving system capable of accurately estimating the differential delay between the two paths (see Figure 1). Similarly, since the level of the uplink signal through the adjacent satellite path is typically 30 to 40 dB lower than through the primary satellite (for example, see [3,4] for uplink sidelobe performance), high sensitivity equipment is required for the adjacent satellite downlink. This also requires that the corresponding transponder aboard the adjacent satellite be unoccupied so as not to interfere with the relatively weak signal from the source of interest. Such a TDOA system holds the promise of locating the source of signals regardless of their purpose without the need for disrupting normal communications through the spacecraft nor requiring any additional spaceborne hardware.

The TDOA approach can be used to locate the sources of a wide range of signal types. Almost any modulated signal (video, audio, digital, etc.) can be located based on the measurement of the differential time delay of some unique portion of its waveform. Even pseudo-random noise type signals can be located using a variable time delay correlator to infer the differential time delay between the two satellite paths. However, continuous wave (CW) signals present a special problem. Unless the differential time delay through the two paths is less than 1/f (where f is the frequency of the CW signal), it becomes impossible to unambiguously identify the location of the source of the CW signal.
Since the TDOA technique described only localizes the position of the uplink transmitter to a curve on the Earth's surface, some additional technique is required to resolve the ambiguity. Initially, it was thought that the ambiguity could be resolved by making a second TDOA measurement using an adjacent third spacecraft to form another signal path pair. Then the position of the uplink in question could be determined by finding the intersection of the two resulting arcs. Unfortunately, as we discuss in Section II, such intersections are almost colinear within the continental United States for most domestic geosynchronous satellites of interest. Likewise, the question of locating CW signal sources is not addressed.

One technique for resolving the positional ambiguity (which also could be used with CW signals) is interferometry, or the comparison of phases of two incoming signals at two different antenna locations. In order to make unambiguous interferometric measurements of the direction of an incoming signal transmitted from within the continental United States as viewed from a geosynchronous satellite, a space between the two antennas of no more than about 100 wavelengths can be used. Thus, at Ku band frequencies, the space between the two receiving antennas must be less than 2.2 meters, making use of adjacent geosynchronous satellites infeasible. However, the distance between the phase centers of the feeds used for the two orthogonal polarizations aboard a single satellite is usually smaller than this. Thus, a measurement of the differential phase of the uplink signal as measured by ground stations through each of two orthogonally polarized feeds aboard the same spacecraft could be used to infer the angle of arrival and, thus, a curve of possible locations of the uplink signal source. Of course, since the signal level through the cross-polarized transponder would be much weaker (approximately
-30 dB based on manufacturers' data for typical ground antenna cross-polarization isolation) than through the primary transponder, a more sensitive receiver is required for that signal. Combining the TDOA and interferometric techniques can localize the uplink transmitter's position by determining the intersection of the two curves. This has the added advantage of requiring only two satellite paths.

Over the past year, we have analyzed and demonstrated the feasibility of the TDOA technique for locating uplink transmitter positions, and have built a developmental Ku band system which is being used to make such measurements. In this report we describe this work, along with our initial studies of interferometric techniques for resolving the positional ambiguities inherent in the TDOA technique. In addition to describing and characterizing the performance of our developmental Satellite Interference Location System (SILS), we project the performance of future ground systems using larger antennas, and make suggestions for designs of "next generation" spacecraft in order to increase their effectiveness in locating, or avoiding, interference from unwanted uplink signals. We conclude by describing plans for the next contract year during which we plan to incorporate the interferometric techniques into our developmental system, which is expected to lead to a system capable of unambiguously locating the geographic position of Ku band uplink sites within the continental United States.

II. TIME DIFFERENCE OF ARRIVAL (TDOA) TECHNIQUES

The key disciplines involved in the application of the TDOA techniques for locating of Earth stations include: RF budget analysis, geometry, and signal processing. While we have addressed all three areas, we begin with the geometric study.
Whether friendly or not, the typical satellite uplink user is attempting to illuminate only one satellite at any one time. For several reasons, however, the uplink may be illuminating multiple satellites with enough power so that a receiving ground station may be able to detect the presence of the source station on adjacent satellites in addition to the uplink's goal satellite. Reasons for this include poor dish alignment procedures or equipment, marginal antenna aperture sizes which may not generate appropriately small beamwidths, sidelobes intrinsic to the uplink antenna, and a smaller apparent angle between satellites which are at low elevation angles relative to the uplink location. This last effect has been made more noticeable by the reduction of geosynchronous satellite spacing from three to two degrees.

The TDOA location method developed depends on the ability to determine relative time delays due to different lengths of two satellite signal paths as perceived by a receiving station. Given this time delay, the location of the receiving station, and the positions of the two satellites of interest, a curve on the Earth's surface containing the location of the signal's source may be determined. It is not unusual for satellite operators to know at all times the position of their satellites to within a few meters via the use of radio signal processing techniques or laser reflections obtained off cube-corner mirrors aboard the satellite.

Figure 1 presents a two-dimensional view of the geometry pertinent to the TDOA technique. As illustrated, the positions of the two satellites, the location of the TDOA receiver site, and thus the distances from the satellites to the TDOA receiver site are known. The unknowns are the two remaining distances from each of the two satellites to the unknown uplink station.
If the receiver site monitors the signal through both satellites, a relative time delay between the two paths may be measured. Given this and a knowledge of the speed of the signal propagation through space and the equivalent distance of any non-negligible signal processing time, the difference in path distances may be deduced. Subtracting out the known downlink distances from the satellites to the TDOA receiver site leaves the remaining differential distance between the two unknown uplink distances. In the two-dimensional case, this differential distance determines two potential points for the location of the uplink station by solving for the intersections of the Earth's circle and the two branches of the hyperbolas made up from the two paths of equal length plus the inferred delay distance. Holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two intersections is the uplink location.

Figure 2 depicts the three-dimensional case. Only the unknown uplink portions of the signal path are illustrated since the distances from the satellites to the TDOA receiver site are assumed to be known. Extending from the two-dimensional case, the surfaces of constant delay between the satellites form two shallow hyperbolic bowls centered along the axis of the line segment connecting both satellites and opening away from its center point. The two intersections of these hyperbolic branch surfaces with the sphere of the Earth provide terrestrial curves of constant delay which include the location of the uplink station. As in the two-dimensional case, holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two curves contains the uplink location. However, unlike the two-dimensional case, we now have
one less known input than is required to support the dimension of our desired solution. Therefore, our solution is one dimension higher than desired, and another piece of information is required to acquire a unique solution.

Figure 3 illustrates another viewpoint of the three-dimensional case where terrestrial curves of constant delay are determined by showing the intersections of concentric circles around the subsatellite points of the effected satellite pair. We let the radii of these subsatellite circles be determined by considering a general satellite-to-Earth distance (dte and dtw in Figure 3) which will be greater than or equal to the satellite-to-subsatellite point distance. Note that if the differential delay to the two satellites from a given uplink station is considered as a differential distance equal to the difference between the two uplink-to-satellite paths, then the uplink station must lie on the intersection of the two subsatellite circles.

From this construction, a family of curves of terrestrial solutions to the uplink location problem may be determined for various delays between satellite signal pairs. For a particular differential delay, the corresponding differential distance is computed. A reference uplink-to-satellite distance is chosen. The other uplink-to-satellite distance differs in length by the differential distance. A subsatellite circle is constructed for both distances. The intersections of these circles are a point on a curve of potential uplink locations for the given differential delay.

The entire curve is constructed by sweeping the reference uplink-to-satellite distance from its minimum at the subsatellite point to its maximum near the Earth's poles. The intersections form the entire curve for the given differential delay. A family of curves may be generated by performing this iteration over a number of different differential delays.
In both the hyperbolic intersection and the subsatellite circle constructions, the goal is to relate time delay measurements and known geometric information to a curve along the Earth's surface which contains the unknown uplink's location. The subsatellite circle viewpoint for the three-dimensional case lends itself to a triangle construction which provides trigometric equations that generates a latitude and longitude given a delay and the known geometric information. Using a computer program to sweep the appropriate variables generates a family of terrestrial curves of constant differential delay. Figure 4 shows these curves with 20 microsecond separation for GTE's geosynchronous GSTAR 1 (103 degrees West) and GSTAR 2 (105 degrees West) satellites projected onto a Mercator projection of the CONUS (CONtinenental United States) area. Equations 1 through 7 relate the known geometry and the measured delay to a longitude and latitude for a fixed Earth-to-satellite distance. Sweeping over this distance generates one of the constant delay curves.

\[ \Delta \text{long} = |\text{longw} - \text{longe}| \]  
(1)

\[ \Delta t = \text{time of arrival of (eastern signal - western signal)} \]  
(2)

\[ \Delta \text{distance} = \Delta t \cdot c \]  
(3)

\[ \Delta \text{distance} = \Delta t \cdot c \]  
(4)

\[ \epsilon = \tan^{-1} \left[ \frac{\Delta t^2 - r^2 - r_{\text{sat}}^2}{\sqrt{\Delta t^2 - r^2 - r_{\text{sat}}^2}} \cdot \sin(\Delta \text{long}) \right] \]  
(5)

\[ \text{long} = \text{longe} + \epsilon \quad \text{if} \quad \Delta t > 0 \quad \text{uplink west of satellites} \]  
(7)

\[ \text{longw} - \epsilon \quad \Delta t < 0 \quad \text{uplink east of satellites} \]
\[
\text{lat} = \cos^{-1}\left[ \frac{dte^2 - r_p^2 - r_{\text{sat}}^2}{-2 r_{\text{sat}} r_p^2 \cos(\text{Along})} \right]
\]  

(8)

where:

\[dte\] = [km] distance from eastern satellite to eastern subsatellite circle

\[dtw\] = [km] distance from western satellite to western subsatellite circle

\[r_{\text{sat}}\] = [km] radius of satellite orbit

\[r_p\] = [km] radius of planet

\[\text{Along}\] = [deg] angular distance between eastern and western satellites

\[\varepsilon\] = [deg] offset longitude between subsatellite circle intersection

\[\text{lat}\] = [deg] magnitude of latitude of subsatellite circle intersection.

Based on the use of the GSTAR satellites (using these equations and subtracting out any additional delays for an arbitrary TDOA receiving location site), delays range from a magnitude of about 200 microseconds for the east and west coasts of the United States to zero along the western Great Plains beneath the satellites.

Note that the geometry of Figure 4 implies that the curves of constant delay associated with one pair of satellites would be almost colinear with the curves of another nearby pair of satellites for a large part of CONUS. However, due to signal level constraints, any other satellite pair employed for TDOA measurements must be close to the primary satellite. Thus, some technique other than this form of TDOA must be used to lower the dimension of the solution which uniquely locates an uplink station.
III. INTERFEROMETRIC TECHNIQUES

As described in Section I, the use of interferometry to resolve the positional ambiguities inherent with the two-spacecraft TDOA method is very attractive. The basic technique to be used involves comparing the phase of the uplink signal as measured through the horizontally polarized and vertically polarized feeds of the spacecraft. Since, for the GSTAR-series spacecraft, the effective phase centers for the vertically polarized antenna are spaced approximately 5 inches apart, the difference in phase obtained by measuring a signal received using the vertically polarized antenna versus the horizontally polarized antenna can be used to infer the angle-of-arrival of the incoming signal relative to the "baseline." (The baseline is defined as a line which intersects the phase centers of the receiving antennas.) This effect is shown in a simple schematic form in Figure 5. As shown in Figure 6, the angle-of-arrival relative to the spacecraft baseline defines an arc of possible uplink transmitter positions on the earth. The intersection of this arc with the position arc determined by the TDOA technique uniquely identifies the uplink transmitter location. In Section IV.C, we discuss the implementation of ground station equipment needed to make such measurements.

IV. THE GEORGIA TECH DEVELOPMENTAL SATELLITE INTERFERENCE LOCATION SYSTEM (SILS)

A. Architecture

The Georgia Tech Developmental Satellite Interference Location System (SILS) has been built so as to demonstrate the operational feasibility of the TDOA and interferometric techniques described in the previous sections. Work
in the first year of this contract has focused on developing an operational TDOA system. Experiments have been conducted using GTE Spacenet Corporation's GSTAR 1 (103° W) and GSTAR 2 (105° W) spacecraft, operating on the Ku satellite band (downlink frequencies - 11.7 to 12.2 GHz, uplink frequencies - 14.0 to 14.5 GHz). The dual Ku band receiver system is located atop the Electrical Engineering building on the Georgia Tech campus. One receiver includes a 6.1 meter Harris reflector with appropriate feeds for simultaneous transmission and reception of a standard Ku band signal set. A 180 K Harris 6312 low noise block (LNB) converter amplifies and shifts the incoming signal from Ku band down to a C band IF (3.566 to 4.066 GHz) from which our Harris 6531 receiver produces a 70 MHz IF and FM demodulated baseband NTSC video and audio. The second receiver employs generic Ku band TVRO components. It includes a smaller 3.1 meter fiberglass reflector, a 180 K LNB converter which converts to the TVRO industry standard "B band" IF of 950 to 1450 MHz. From here, a Drake model ERS 324S receiver generates a 70 MHz IF and demodulated baseband video and audio.

Although digital or analog correlation would allow the time displacement measurement of a pair of almost any type of signal, we initially chose to use a dual trace oscilloscope to view a pair of wideband FM television signals. Reasons for the use of TV signals include the variety of available source qualities and locations, the ease of demodulation, and the features of the signal. The use of the oscilloscope provides real time feedback to those performing the measurements. For the preliminary experiments, demodulation and the low level signal detection were performed by using two HP 8558B spectrum analyzers. These devices provide great flexibility in the degrees of freedom which they allow a user such as variable IF bandwidths from 3 KHz to
3 MHz, variable baseband lowpass filtering, IF frequency centering control, and logarithmic versus linear output.

Figure 7 shows the equipment configuration for the time delay measurements. The spectrum analyzers take the 70 MHz IF signals from both receivers and provide a baseband signal by using the analyzers' internal IF bandpass filter to perform slope detection of the frequency modulated video signal. The relevant characteristics of the baseband output are a function of the selected IF bandwidth and the analyzers' controllable low pass filter on the baseband output.

Determination of differential time delays between signals traversing different satellite signal paths is a prerequisite to using the TDOA method for locating uplink stations. Initially, we measured our differential time delays by manually observing two demodulated time domain signals on an oscilloscope. This process and the ambient conditions which are typically rather dynamic require that the equipment operator be quick and completely aware of his job. In order to be more responsive to the realities of our end goal, we are introducing computer correlation to provide the differential time measurement.

We have taken a commercially available Metrabyte analog-to-digital converter accessory board and installed it in a Hewlett Packard Vectra microcomputer (an IBM PC/AT compatible computer). This software, polled hardware can presently sample each of two channels at a rate of 25 kilosamples/second/channel (or a single channel at 50 kilosamples/second). A fixed length frame of analog samples is taken from each channel and correlated in software in order to produce a time domain graph where the maxima indicates the time of best correlation. The time of this maxima should correspond to the sought after differential time delay.
Cross-correlation is performed by a Turbo C program which directly evaluates Equation (9) over the acquired data frames.

Cross-Correlation Equation

\[ c(T) = \sum_{t} [x(t) \ast y(t+T)] \]

where:

\( x, y \) \( \in \) acquired data frames
\( c \) \( \in \) resulting data frame.

Performing this correlation takes about 32 seconds on our present computer using a frame length of 1024 samples with a dynamic range of 12 bits/sample.

A reader familiar with the mathematics of digital signal processing or Fourier analysis may notice that a more rapid response can be had by multiplying in the transform domain (convolving) the two incoming data frames if one of the frames is reversed in time. We are aware of this and can implement Fast Fourier Transforms when we are satisfied with our results and have the resources. The availability of data in the frequency domain will also provide the additional opportunity for our making use of various digital filtering techniques.

Figure 8 is a graph of a time domain "chirp" which is used as an input signal test pattern for our software. This 1024 sample frame has been auto-correlated to generate Figure 9. Figure 10 is an actual sampling of a slope demodulated satellite FM television signal which had a received carrier-to-noise ratio (CNR) of approximately 10 dB. The picture content consisted of a colorbar test pattern. In this case, the sample frame length is 512 samples taken at a rate of about 50 kilosamples/second. Note the two local peaks in
the sampled signal which correspond to the 60 Hz vertical retrace portion of
the television signal. Another frame was immediately sampled. These two
frames were cross-correlated to produce the data of Figure 11. Note that the
distance between the two peaks corresponds to the length in time of one
television vertical retrace interval. As one would predict, one television
frame appears similar to the next to the cross-correlation software.

In the context of observing satellite channel video signals, the present
sampling rate is adequate to determine relationships between video frames.
A much faster sampling rate than the present 25 kilosamples/second/channel is
desired to determine the differential time delay measurements to the micro-
second resolution (within individual video lines) required to acquire the most
accurate spatial TDOA results. Speeds of up to 50 kilosamples/second/channel
may be had by implementing DMA techniques on the present hardware. However,
the desired 100 to 1000 kilosamples/second rates require specialized hardware.
As in the case of applying transforms, we can implement the faster sampling
when we are satisfied with our results and have the resources. We have
obtained the use of an H-P 60 M-sample/second digital oscilloscope. Coupling
this unit to our P-C based correlator system could provide an extremely high
resolution TDOA measurement.

Analogous to determination of differential time measurements for TDOA
techniques is the determination of differential phase between a satellite's
cross-polarized feeds for interferometric spatial determination of an uplink's
location. Our present two channel Ku band satellite receiving system provides
a 70 MHz IF for each channel which can be mixed to provide the DC differential
phase output that follows from classical analysis of frequency multiplication.
This is illustrated in Figure 12.
However, this technique of differential phase determination requires identical receiver processing of each channel. This requirement includes all intermediate mixing stages be phase locked to the same sources in both receiving systems. Since we have two different receiving systems, it is unlikely that the results of all the intermediate mixing stages of the two systems will lead to a frequency and phase locked at 70 MHz IFs with center frequencies within the required fraction of one Hertz necessary to provide a DC measure of differential phase.

There are several solutions to this problem. One is to phase lock all the intermediate local oscillators to the same sources. This is difficult but possible with our present hardware as Figure 13 shows. We shall need to modify our present Ku band LNB on our 3.1 meter receiver by adding a local oscillator locked to our 6.1 meter system's Harris receiver to another (available) Harris receiver of slightly different vintage. This will require our modification of various pieces of the second receiver's mixing stages.

Another solution is illustrated in Figure 14. This method uses the resulting differential frequency between the two paths as feedback which is injected in a further mixing stage to cancel out the effects of all the different local oscillators of intermediate mixing stages. If the spectral purity of the received signal is not sufficient to guarantee unambiguous use of one error product for further mixing, an injected reference signal may be used along with a phase locked loop to generate the error signal. We plan to investigate both methods and construct at least one piece of hardware to perform the differential frequency measurement.

A good deal of development still lies ahead on this project. We wish to fulfill the promise that digital correlation can automatically provide higher
resolution time delay measurements. Issues include fast A/D converters and software transformation techniques. Differential phase determination issues include the difficulty of phase and frequency locking of the two receiving systems, the effects of noncoherent observed signals versus locally injected reference signals for the feedback method, and the level of cross-talk between the cross-polarized signals at the satellite (hopefully high) and at our receiving antennas (hopefully low).

B. Performance

Many signal pairs have been observed with this equipment configuration. The best results have been sourced by remote evening news transmissions from mobile satellite terminals. These signals are uplinked from vehicles equipped with microwave transmitters and a reflector of minimal aperture size which is quickly erected, activated, and aimed upon arrival at the news site. Many times this is done too quickly as real time observations through multiple satellites confirm. Antenna misalignment, multiple sidelobes, a large main beam due to a small aperture size, or a "road-weary" dish contribute to signals appearing on transponders of adjacent satellites.

At our site, we search with our 3.1 meter system for a potential signal through GSTAR 2 which takes the role of the primary satellite. Although this video signal is available for full demodulation and viewing on a studio monitor, this is only done to ease and confirm signal acquisition. If a potential candidate is found (this is confirmed by viewing the content of the signal), we then begin searching, with our 6.1 meter reflector system, the output of the corresponding transponder on GSTAR 1, which is only 2 degrees away on the geosynchronous arc and becomes the adjacent satellite. If we are
fortunate and the GSTAR 1 transponder is not heavily occupied, we return to
the GSTAR 2 signal and use a spectrum analyzer to slope detect the FM video
signal. This baseband output is fed to a Tektronix 2215 dual trace oscillo-
scope and used as the trigger source by either generic triggering or the
Tektronix specific TV frame-triggering mode. The spectrum analyzer's IF and
baseband filters and center frequency tuning are then optimized to facilitate
the cleanest triggering of the oscilloscope. Next, the GSTAR 1 transponder's
spectrum is searched for any vestige of the spectrum viewed through GSTAR 2.

Generally, there are many vestiges of frequency modulated video to be
found. Potential ripples in the GSTAR 1 transponder spectrum being searched
are slope detected by another spectrum analyzer, then routed to the other
channel of the dual trace oscilloscope for visual correlation. With the
oscilloscope's sweep rate set to show about one horizontal NTSC line on the
trace containing the signal from GSTAR 2, the presence of another video signal
in the noise from the GSTAR 1 trace is readily detectable. If the GSTAR 1
video signal is not from the same source as the GSTAR 2 video signal, it
becomes apparent by the relative drifting of the synchronization pulses
between the two video signals due to different time base sources. But if
clock rates are close and the user believes that he is viewing the same signal
through both receivers, reducing the sweep rate to that of one vertical period
(1/60 sec) will show the relative positions of the vertical retrace fields.
If the fields are not almost aligned, then these are two different signals
because the maximum delays expected are on the order of hundreds of
microseconds. However, if the same signal is being viewed through both
satellites, there will be no apparent drift and a vertical retrace investi-
gation will show a maximum vertical sync field misalignment of only a few
horizontal lines.
Our adjacent satellite signal observations have included the barest vestiges of signals plucked from the noise of busy transponders with the skilled use of IF and baseband bandwidth and tuning controls. But other observations have included signals which were more than 4 dB above the noise floor on empty transponders, thus almost reaching the direct FM demodulation threshold.

Photo 1 shows an oscilloscope photograph of two differentially-delayed signals for the specific case of television station KARE's remote evening news uplink from Mankato, MN (50 miles southwest of Minneapolis), taken on 6 August 1987 at about 6:20 p.m. EDT. Note that the GSTAR 1 signal can be seen to be about 7 microseconds ahead of the GSTAR 2 signal with the sweep rate of 10 microseconds per time division. However, due to the repetitive nature of the horizontal lines, the delay could be greater by an integer number of horizontal line periods. Photo 2 shows that the vertical retrace intervals are indeed close to alignment with the sweep rate set to 2 milliseconds per time division. Photo 3 shows a close up view of the transition from vertical retrace pulses to video line sync pulses (about 300 microseconds, given 200 microseconds per time division). Note that a delay of 235 microseconds must be subtracted from this measured delay to remove the differential delay specific to our receiver location. Table 1 lists calculated time delays for a variety of locations within CONUS. Numerous other successful tests have been made, and the differential delays measured have been consistent with the location of the uplink transmitter.

For example, for a video signal being transmitted through transponder 14 of the GSTAR 2 spacecraft (1/11/88), the differential time delay of the sidelobe signal as received through transponder 14 of GSTAR 1 was -480 micro-
seconds (i.e., the signal received through GSTAR 1 led that received through GSTAR 2 by 480 microseconds). Since -235 microseconds of this delay is due to the position of our receiving site in Atlanta, the results is a net delay of -245 microseconds. Since the site of the uplink transmitter was Wheeling, West Virginia, this result was within 5 microseconds of the expected value, as can be seen by inspection of Figure 4. This result was especially gratifying in that the time delay measurement was made using the oscilloscope. Even better accuracies can be obtained using the digital correlator techniques.

Another test which has been conducted with our system was for its ability to receive signals which are uplinked to a cross-polarized transponder without receiving interference from the same signal being transmitted through a copolarized transponder. This is required in order to make interferometric measurements using a single spacecraft. This also requires that the polarization isolation of the SILS receiver which monitors the cross-polarized transponder must better than that of the uplinking station.

To test our system, we monitored a video signal being uplinked to transponder 5 on GSTAR 1 at a frequency of 14.289 GHz, using our 3.1 meter antenna/receiver operating at 11.989 GHz. We then monitored the same signal through orthogonally polarized transponder 13, using our 6.1 meter antenna/receiver. To be certain that the signal being received was actually from transponder 13
and not simply a cross-polarized signal from transponder 5, the polarization of the 6.1 meter receiving antenna was varied ±5°. Had the received signal been a cross-polarized signal from transponder 5, a sharp increase in signal level would have been noticeable as the polarization were shifted away from vertical. As it was, little variation in the signal amplitude occurred, suggesting that the signal was indeed vertically polarized, and therefore, from transponder 13. Subsequent demodulation of the signal showed it to be the same as that being received from transponder 5, thus supporting the feasibility of this technique.

V. EXPECTED PERFORMANCE FOR FUTURE SYSTEMS

By using the methods and equipment configuration described above, we have been able to measure differential satellite path delays. This enables us to deduce part of the solution to the problem of locating an uplink station given only its signal through the uplink's intended satellite in addition to some vestige of this signal through an adjacent satellite. However, our observations were of uplink stations with fairly large sidelobe levels. With the limitations of our present 6.1 meter reflector and 180 K low noise amplifier, we were unable to detect sidelobes of many of the higher quality uplink facilities which typically employ large well-aligned reflectors at fixed locations. A larger receiving antenna with a lower receiving system noise temperature will be required.

A current limitation of the Georgia Tech hardware for an uplink station location using the TDOA technique is that 5 meters is the maximum uplink ground station reflector diameter from which useable sidelobe levels can be obtained. In an attempt to evaluate how the system would improve if larger
receiving antennas were used (such as the 13 meter antennas at the TT&C sites), we have developed a relation between the reflector size for the interfering station and the minimum reflector size required for a SILS ground station in order to successfully complete a SILS measurement.

Equation (10) describes the relationship between link CNR and the uplink and downlink reflector diameters. This is derived from measurements taken and assumes:

- Worst case uplink reflector sidelobe compliance with the FCC 29-25 log (θ) rule;
- Our worst case mobile Earth station measurements have originated from the minimum legal 4.5 meter dish size;
- Operation on Ku band frequency pairs;
- Uplink reflector efficiencies of 50% during measurements;
- Linear operation of the adjacent satellite's transponder.

\[
\text{Link CNR [dB]} = 10 \log(289 \frac{\lambda_t}{d_t \rho_t})^{2.5} + 10 \log \left( \frac{\eta d \sqrt{\rho}}{\lambda r} \right) - 58.2 \quad (10)
\]

where:

\[d_t = \text{uplink transmitter reflector diameter}\]
\[d_r = \text{downlink receiver reflector diameter}\]
\[\rho_t = \text{efficiency of (uplink) antenna}\]
\[\rho_r = \text{efficiency of receiving (downlink) antenna}\]

Table 2 lists the link CNR for various dish diameters assuming 50% reflector efficiencies at both Earth stations and the appropriate Ku band frequencies (14 GHz up, 12 GHz down).
Conclusions from Table 2 include the intuitively appealing notion that the detectable signal threshold occurs when the downlink reflector diameter approaches that of the uplink reflector. However, closer inspection of the equation shows that the uplink station will eventually have the advantage as dish size increases. Equation (11) relates the 0 dB CNR level for Ku band frequencies with reflector sizes in meters and efficiencies of 50%.

\[
\frac{d_t^{2.5}}{d_r^2} = 2.897
\]

Equation (11) relates the 0 dB CNR level for Ku band frequencies with reflector sizes in meters and efficiencies of 50%.

(Table 2 lists CNR values computed from Equation (11) for a variety of dish sizes.) Figure 15 is a plot relating transmit and receive dish sizes for 0 dB CNR (detectability threshold).

VI. DESIGN CONSIDERATIONS FOR FUTURE SPACECRAFT

The Satellite Interference Location System (SILS) development project has focused on developing a system which could locate the position of uplink transmitters using existing, on-orbit satellites such as GSTAR 1 and GSTAR 2. However, as new satellites are designed, it is possible that some relatively simple and low-cost changes in spacecraft antenna design may further facilitate the location of uplink signal sources.

As mentioned in previous Bimonthly Progress Reports, a significant source of difficulty for both TDOA and interferometric techniques lies with the fact that one of the two signal channels required for each technique carries an especially low level signal. In the case of the TDOA technique, this occurs because one of the two satellites being used for the time delay measurement is being illuminated only by a low level sidelobe from the uplink transmitter.
Two approaches to increasing the level of the sidelobe signal received through what we have previously called the "adjacent" satellite can be used. The first is simply to increase the G/T of the ground station which receives the sidelobe signal. While this is an effective solution, the overall CNR of this signal is ultimately limited by the "uplink" CNR, which is related to the spacecraft G/T. Therefore, any approach for increasing the G/T of the "adjacent" spacecraft would be helpful. It is noteworthy that the antenna systems used with the GSTAR spacecraft actually contain 13 separate beams. In the transmit mode, six of these beams can be used as an "Eastern US spot beam." The remaining seven can form a "Western US spot beam." All 13 can be summed to form a continental US (CONUS) beam. However, in receive mode, all 13 beams are presently automatically combined to form a single CONUS beam.

One effective way to increase the G/T of the spacecraft receiver for SILS purposes would be to allow access by a tunable test transponder to any one of the 13 individual receiving beams. This requires the addition of RF switches between the feeds and the electronics. Because of the smaller beam size and effective higher gain, the resulting G/T would be significantly higher. A typical scenario would be that an interfering signal appears on GSTAR 2 transponder 6. The adjacent enhanced GSTAR 1 then sets its tunable transponder to channel 6 and scans through each of the 13 beams until the best CNR from the sidelobe of the interfering signal is obtained as received by the SILS site. Not only does this facilitate the TDOA/SILS process, but it narrows the possible locations of interfering signal by beam position selection. However, this still requires that transponder 6 on the "adjacent" satellite (GSTAR 1) not be illuminated by an uplink from the same geographic
region as the interfering signal. Evaluation of the overall cost effectiveness of adding this capability is beyond the scope of this discussion, but will be pursued in future discussions.

One cost effective method for improving the ability of a single spacecraft to make "interferometric" measurements of uplink transmitter location, such as will be conducted in the second year of the current SILS program, involves placing additional feed horns on the spacecraft. As currently envisioned, interferometric measurements of the position of an uplink transmitter will be made by using the vertically polarized and horizontally polarized feeds as the two elements of the interferometer. However, because one of the feeds is orthogonally polarized to the incoming signal, the received signal can be extraordinarily weak, making phase comparison by the SILS ground station difficult. This is the basis of our present interferometric technique which uses existing hardware to look at the signals incident on the satellite's co-polarized and orthogonally polarized feeds. However, if additional co-polarized feeds were available, interferometric measurements could be made without nearly as much difficulty. It should be noted that the feed horns used for interferometry need not be nearly as large and complex as the 13 horn arrays used for the regular communications CONUS beams. This is because only the phase of the incoming signal needs to be measured. Any amplitude variations across the beam would have little effect on the resulting interferometric measurement.

Thus, we propose that in addition to the 16 feed horns used for each polarization on the current GSTAR spacecraft, an additional horn should be available which is capable of providing a very wide beam (covering CONUS) for each polarization. The two horns (one for each polarization) should be
switchable to the inputs of any transponder so as to make improved interferometric measurements possible.

For example, an interfering signal is observed on transponder 5 of an upgraded GSTAR 1. (The example signal is vertically polarized and is at a frequency of 14.280 GHz.) Now the "additional" vertically polarized horn can be connected to the input of transponder 13, which normally receives only horizontally polarized signals. Thus, two channels of information can be downlinked at 11.980 GHz, one with horizontal polarization (output of transponder 5) and one with vertical polarization (output of transponder 13), and each will carry the interfering signal. However, one will carry the interfering signal as received with the normal 13 beam CONUS array, and another with the single horn beam. The difference in the phases of the receiving signals can be used to infer uplink station position. In fact, if yet an additional horn providing full CONUS coverage could be added for each polarization (a total of 4 horns, see Figure 16), then a second baseline would exist, whereby the exact location of the interfering signal could be deduced (see Figure 17). It should be noted that the spacing between the "additional horns" and the main feed arrays are limited by the focal range of the individual reflectors. When using the orthogonally polarized feeds for the baselines, the spacing between the orthogonally polarized reflectors also contributes to the baselines.

VII. CONCLUSION AND PLANS FOR YEAR 2

In the first year of the contract, we have demonstrated the feasibility of the TDOA technique for determining the longitudinal position of Ku bank uplink transmitters within the continental United States. We have built a
developmental Satellite Interference Location System (SILS) with which we have made TDOA measurements both manually, using a dual-trace wide bandwidth oscilloscope, and digitally, using a PC-based sample-correlator system. While we would like to pursue the development of a high-resolution digital sampler-correlator for the TDOA system during the second year of the contract, our main thrust will be to develop a working spacecraft interferometry system, in order to determine uplink station latitude, and therefore, determine a unique solution for uplink station location. This will require a high level of effort on the part of the investigators, but is expected to lead to a working, demonstrable system by the end of the contract term.
VIII. REFERENCES


IX. TABLES, FIGURES, AND PHOTOS
TABLE 1: Calculated Delays

<table>
<thead>
<tr>
<th>Site</th>
<th>GSTAR I [km]</th>
<th>GSTAR II [km]</th>
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\( \Delta t = \text{time of arrival of (eastern signal - western signal)} \)
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<td>4.6</td>
<td>2.8</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

Above Demodulation Threshold | RF Detection | Not Detectable
Figure 1

Two Dimensional TDOA Geometry
Hyperbolic Intersections
Figure 2
Three Dimensional TDOA Geometry
Hyperbolic Intersections
Contours of 20 uSec Differential Delay for GSTAR 2 (105°W) and GSTAR 1 (103°W)

Figure 4
Figure 5
SILS Interferometry Technique at Satellite Antenna
Figure 6

SILS - Geometry of Interferometry
Figure 7
TDOA Developmental System Hardware Configuration

Adjacent Satellite

6.1m Dish

Primary Satellite

Unknown

Uplink Site

3.1m Dish

180K LNB

180K LNC

3.566-4.066 GHz

Harris Receiver

3.1m Dish

950-1450 MHz

Ku

Drake Receiver

180K LNB

950-1450 MHz

70 MHz

HP Spectrum Analyzer

Tektronix Dual Trace Oscilloscope

70 MHz
"Chirp" Test Pattern

Figure 8
correlated result

Auto-Correlation of "Chirp" Test Signal

Figure 9
Figure 10

Sampled TV Signal
Filtered Correlated Result

Figure 11
Cross-Correlated TV Signal
Figure 12
Figure 13
Figure 14

Receiver 1
70MHz IF

Receiver 2
70MHz IF

70MHz

70MHz + e

AC Error
Component e

70MHz + e + e
70MHz + e - e

DC Phase

Figure 14
Figure 15

Uplink vs Downlink Dish Diameters for Link CNR = 0 dB

\[ \frac{d_{\text{up}}}{d_{\text{down}}} = 2.5 \]

\[ 2.897 = \frac{d_{\text{up}}}{d_{\text{down}}^2} \quad \text{(Eqn 2)} \]
Horizontally Polarized Antenna-Feedhorn Array Configuration

Figure 16
Terrestrial Arcs

of constant differential phase

Figure 17
Photo 1

Horizontal Video Sync Pulse
(10 μSec/Div)

Photo 2

Vertical Video Sync Pulse
(1 mSec/Div)

Photo 3

Vertical Video Sync Pulse
Close-Up
(~300μSec/Div)
REPORT
TO
GTE SPACENET CORPORATION

ANNUAL REPORT
(INCLUDES BIMONTHLY PROGRESS REPORT #12)

for
Contract C-10070

RESEARCH AND DEVELOPMENT OF A SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

Paul G. Steffes, Principal Investigator

January 20, 1988 through January 19, 1989

Submitted by
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1. Introduction and Summary

During the second year of contract C-10070 (20 January 1988 through 19 January 1989), we have continued our work on the development of a Satellite Interference Location System (SILS) for inferring the location of terrestrial satellite uplink stations using existing geosynchronous civilian repeater-type satellites with minimal disruption to normal satellite operation. Two methods have been developed which together can produce a unique positional solution.

The first method is the Time Difference of Arrival (TDOA) technique in which the propagation time for the uplink signal to a particular satellite is compared with the propagation time to an adjacent satellite. Given that the positions of the two spacecraft relative to the receiving station are precisely known, the difference in time of arrival over the two different paths isolates the possible uplink transmitter location to a one dimensional curve on the Earth's surface. Figures 1 and 2 show the two and three dimensional cases. Realization of such a system requires a two channel receiving system capable of accurately estimating the differential delay between the two paths as illustrated in Figure 3. Because the level of the uplink signal through the adjacent satellite path is typically 30 to 40 dB lower than through the primary satellite, high sensitivity equipment is required for the adjacent satellite downlink. The low signal levels also impose a requirement that the corresponding transponder aboard the adjacent satellite be
Time Difference of Arrival (TDOA)

Two Dimensional Geometry

Hyperbolic Intersections

Figure 1
3-D TDOA Geometry

Axis of Hyperbolic Surfaces of Constant Delay

Primary Satellite

Adjacent Satellite

Uplink Positional Solutions

Unknown Uplink Site

TDOA Receiver Site

Figure 2
Figure 3

Developmental System Hardware Configuration for TDOA and Interferometry

- High Gain
- Low Gain
- Low Noise Amplifiers
- Ku Band Receivers
- 70 MHz IF
- 70 MHz IF
- Spectrum Analyzers (Slope Demodulation)
- Differential Time Measurement
- Differential Phase Measurement
only lightly occupied so as not to interfere with the relatively weak signal from the source of interest.

The TDOA approach can be used to locate the sources of a wide range of signal types. Almost any modulated signal (video, audio, digital, etc.) can be located by using a measurement of the differential time delay between some unique portions of the two received waveforms. Even pseudo-random noise signals can be located using a variable time delay correlator to infer the differential time delay between the two satellite paths. However, continuous wave (CW) signals present a special problem. Unless the differential time delay through the two paths is less than $1/f$ (where $f$ is the frequency of the CW signal), it becomes impossible to identify unambiguously the location of the source of the CW signal. Figure 4 shows a Mercator projection map of the Continental United States (CONUS) illustrating the family of curves of constant differential delay for GTE's GSTAR 1 (103 degrees west) and GSTAR 2 (105 degrees west) satellites.

In the first year of contract C-10070 (20 January 1987 through 19 January 1989), we analyzed and demonstrated the feasibility of the TDOA technique for locating uplink transmitter positions and built the developmental Ku-Band system which is being used to make such measurements. This work is described in the first Annual Report for contract C-10070, submitted January 1988, and in a paper to be published in the IEEE Transactions on Aerospace and Electronic Systems [1].

Another technique for producing a one dimensional solution
Curves of Constant Differential Delay
for GSTAR 1 and GSTAR 2

Contours of 20 [uSec] For GSTAR1(103W) and GSTAR2(105W)

Figure 4
is Interferometry, or the comparison of phases of an incoming signal at two spatially separated antenna locations. Given a differential electrical phase measurement made between two known and separate locations, one can determine the angle of arrival of incident radiation relative to an interferometric baseline formed by the line connecting the two receiving antennas. Figure 5 illustrates the relevant geometry for a dual antenna receiving system, and Equation 1 relates the desired geometric angle to the antenna separation, wavelength of the incoming signal, and the measured differential phase between the antennas. This technique may be used with CW or modulated signals.

In order to employ this technique for a SILS effort, we need to have two antennas in a location which facilitates a useful terrestrial solution. A distance between the two antennas of no more than about 100 wavelengths should be used to make unambiguous interferometric measurements of the direction of an incoming signal transmitted from within CONUS as viewed from a geosynchronous satellite. At the Ku-Band frequencies used by some domestic satellites the space between the two receiving antennas must be less than 2.2 meters, thus making use of adjacent geosynchronous satellites infeasible. However, the distance between the phase centers of the feeds used for the two orthogonal polarizations aboard a single satellite is usually smaller than this. Thus, a measurement of the differential phase of the uplink signal as measured by ground stations through each of the two orthogonally polarized feeds aboard the spacecraft could be used to infer the angle of arrival of incident radiation.
Figure 5

\[ \Delta \Phi = \frac{2nd \cos(\theta)}{\lambda} \]  
(Equation 1)

Phased Array Equation for Interferometry
upon the satellite. This measured differential phase can be mapped into a terrestrial curve of possible locations of the uplink signal source.

Figure 6 illustrates the antenna feed locations aboard a GSTAR series satellite and relates this geometry to an interferometric baseline. Figure 7 shows the resulting cone of constant differential phase around the interferometric baseline and its terrestrial intersection. Figure 8 shows a Mercator projection map of CONUS illustrating the family of curves of constant differential phase for GTE's GSTAR 1 (103 degrees west) satellite. Because the signal level through the cross-polarized transponder would be much weaker than that through the primary transponder (approximately -30dB based on manufacturers' data for typical ground antenna cross-polarization isolation), a more sensitive receiver is required for that signal.

Employing some combination of the TDOA and Interferometric techniques can localize the uplink transmitter's position through the determination of the intersection of the two curves. Figure 9 shows a map with overlaid curves of constant delay and differential phase for the TDOA and Interferometric methods specific to the GSTAR satellite case. The use of these two methods has the added advantage of requiring only two satellite paths and holds the promise of locating the source of signals regardless of their purpose without the need for disrupting normal communications through the spacecraft nor requiring any additional spaceborne hardware.
Figure 6

Interferometric Geometry at the Satellite
Figure 7
Interferometric Cone of Constant Differential Phase Intersecting Earth

Terrestrial Curve of Constant Differential Phase

Cone of Constant Differential Phase

θ_{cone}

Interferometric Baseline
Interferometric Curves of Constant Differential Phase

Figure 8

Contours of Constant Differential Phase for Geosync Satellite over 103.0 W
TDOA and Interferometric Curves of Constant Differential Delay and Phase

Figure 9

(Delay in Microseconds)
In this report, we describe the work conducted over the past year in theoretically characterizing and in demonstrating the feasibility of the Interferometric method for determining ground station positions, using our developmental Ku-Band system. In addition to describing the hardware developed for use in interferometric measurements, we have made suggestions for designs of "next generation" spacecraft in order to increase their effectiveness in locating, or avoiding, interference from unwanted uplink signals. We conclude by describing plans for the next contract year during which we plan to complete development and characterization of the Georgia Tech demonstration SILS system so as to assist GTE in possible implementation of an operational SILS system at one of its Tracking, Telemetry, and Control (TT&C) sites. We are also expecting the completion of Mr. Smith's doctoral dissertation which will serve as the final report for this project, as well as completion of software which assists the SILS operator in determining the location of the interfering transmitter.

2. Summary of Work Completed

2.1 TDOA

In the first year of contract C-10070, we successfully demonstrated the feasibility of the TDOA system. Mr. Smith and Professor Steffes have also authored a paper which has been accepted for publication in IEEE Transactions on Aerospace and Electronic Systems [1], which contains a description of the theoretical conclusions, developmental hardware, and empirical
results of actual TDOA measurements. Better TDOA results have been achieved since the composition of the mentioned paper, and live demonstrations have been presented to a representative of the GTE Spacenet Corporation.

While we have successfully shown the feasibility of the TDOA system, our limited resources do not allow us to maintain a constantly operating TDOA system because the hardware is shared with Interferometry research and scheduled uplink and downlink sessions. Were our goal to maintain an operational TDOA system, we should like to upgrade further our signal processing software, to acquire faster analog-to-digital conversion hardware, and to investigate various methods of signal correlation that differ from our present post-demodulation measurement of differential delays which employs human measurement on an oscilloscope display.

2.2 Interferometry

As discussed in the Bimonthly Progress Reports submitted over the past year, the theoretical issues for the Interferometric method of uplink location include geometry, RF budget analysis, and signal processing. The geometry has been determined as a closed form expression which allows the generation of terrestrial curves of constant differential phase given the known position of a satellite, the known spatial locations of the dual polarization offset transponder feed phase centers, and a measured electrical phase. This relationship is illustrated in Figure 8 using curves of constant differential
phase for GSTAR 1 at Ku-Band frequencies overlaid upon a Mercator projection map of CONUS. Because there will be a multiplicity of difficult-to-determine fixed phase shifts throughout the system, offset corrections will be implemented after calibration with signals from several known terrestrial sources.

RF realizability issues include determining the signal level of each of the two polarization components in question into the satellite antenna feeds, the polarization isolation purity of each component of the system, and the phase stability of all components between the satellite antenna input feeds and the SILS site receiver outputs.

Received signal isolation which corresponds to polarization purity is determined at several points in the system: the unknown uplink's antenna, the satellite receiving antenna, the satellite transmitting antenna, and the SILS site receiving antennas. Poor uplink station polarization purity and perfect polarization isolation elsewhere are desired for SILS purposes. One can argue that the satellite antenna's polarization purity will be the best for our typical scenario because of the offset reflector with polarization grid design which is employed in the present GSTAR series satellites. The Georgia Tech/Harris Delta Gain antenna also boasts a high degree of polarization purity [2]. However, we have made a series of measurements which are designed to determine the polarization purity of the different parts of the available hardware.

To test our own antenna, it was necessary to guarantee that
there exist no cross-polarization component radiating from the satellite. Therefore, a signal was uplinked into a portion of a transponder which shares no overlapping cross-polarized transponder. Once our own antenna's polarization characteristics were determined, the GTE sourced carrier was moved in frequency to a portion of a transponder passband which shares an overlapping cross-polarized transponder to observe the satellite antenna's polarization purity.

These polarization purity measurements were made by measuring received CW signal powers with the Georgia Tech 6.1 meter reflector system for various polarization rotations of our antenna during four hours on 11 May 1988. GTE's Colorado TT&C station first transmitted a set of CW signals received at 12193 MHz with polarization angles of 0, 30, 60, and 90 degrees from the nominal satellite input polarization through a portion of transponder 16 on GSTAR 2 which has little overlapping cross-polarized transponder throughput. This set of transmissions of various polarizations was repeated at a received frequency of 12157 MHz which is in a segment of transponder 16 which overlaps cross-polarized transponder 8.

Plots 1 through 8 illustrate the received CNR levels for four TT&C polarization rotations through the overlapping and non-overlapping transponder passband segments. Although there were some problems with leakage of a cross-polarization component in the supposedly single channel portion of the transponder 16 passband due to the realistic filter characteristics through transponder 8, the results were as expected.
The critical results are related to the depths of the notches in Plot 1 and Plot 4 which respectively illustrate the cases of single transponder carrier transmission for a best aligned (co-polarized) uplink station and a worst aligned (cross-polarized) uplink station. For the scenario where power is transmitted from the satellite in only one polarization, we would like to see zero power reception for an orthogonally rotated SILS receiving antenna in both cases. Although Plot 1 shows a drop from about 40 dB to a 10 dB CNR carrier at the receiving antenna cross-polarization angle providing the least power transmission, this may be attributed to some combination of imperfect orthogonal transponder rejection and imperfect polarization purity in our receiving antenna. The complete loss of signal (less than 1/2 dB CNR measured) for the worst uplink polarization alignment angle (where the GTE sourced signal is 90 degrees from co-polarized) illustrated in Plot 4 suggests that the best polarization purity is in the satellite antenna. The other plots illustrate expected results for overlapping transponders.

These experimental results indicate that our equipment has enough polarization purity in a full link using our 6.1 meter receiving system to allow us to isolate a sufficiently strong cross-polarized component of a signal for differential phase measurements. We know that uplinked signals with substantial cross-polarization components exist because we have observed and sometimes directly demodulated them. We can also conclude that better polarization isolation in the ground hardware at a SILS
site may provide potentially better cross-polarization signal resolution than our present equipment affords. The results of viewing typical interfering signal cross-polarization levels and the requirements of the phase detection circuitry will influence the receiving system polarization isolation requirements.

3. Summary of Work Currently Being Conducted and Planned for the Next Contract Year

The predominant short-term unsatisfied experimental goals are the performance of a differential phase measurement and the reference of this measurement to the satellite's antenna feeds. Issues here include understanding the phase stability of our available receiving equipment, correcting any equipment induced phase measurement errors which can come from a multitude of unlocked local oscillators used in the mixing processes of receiving, and removing the error induced by the various local oscillators aboard the satellite.

3.1 Interferometry

Because evidence suggests that our available hardware is not stable enough to make uncompensated "open loop" differential phase measurements between arriving Ku-Band signals, we are investigating three possible methods to overcome our equipment shortcomings. The first involves using dual phase locked receiving systems in which all the local oscillators are locked to a common reference source. We have obtained, on loan from GTE Spacenet, two Miteq (model DN 8012S/7300-1) Ku-to-70 MHz downconverters and two Microwave Systems Engineering (model KLA-
We have also obtained a Hewlett-Packard (model 8656A) synthesizer which will serve as a common local oscillator for both receivers. This "brute force" approach will guarantee the relative phase stability between the two receiving paths from our site's terrestrial antennas to our receiver's IF output ports. However, phase and frequency offsets caused by different local oscillators associated with the two sets of orthogonally polarized transponders aboard the spacecraft used in this measurement must be accounted for and corrected. A second method involves using a locally injected reference carrier and Digital Signal Processing (DSP) techniques to remove any frequency shifting from sampled portions of the signal passbands. We have yet to pursue seriously this option. The third method, which we are actively pursuing, employs electronic methods for performing closed loop differential frequency and phase locking of our two receiving systems.

Figure 10 illustrates this electronic frequency correction approach. We are building an RF circuit which provides the frequency difference between the two receiving systems of an externally injected test carrier. This error frequency will then be regenerated via a phase locked loop and mixed into one of the signal paths in order to produce a frequency and phase locked set of image carriers in some intermediate frequency passband. Phase measurements may then be made between filter selected pairs of signals from one receiver and the frequency corrected transponder passband of another. We are presently constructing the various
Differential Phase Measurement Apparatus with Compensation for Offset Spectra

Figure 10
RF signal processing circuit necessary to achieve this goal.

Once electrical phase measurements have been acquired, these numbers are processed by a computer program to provide a curve of constant differential phase. If a global system phase calibration is required, these results will also be presented to the computer program. The result of the Interferometric method combined with some combination of TDOA or other Interferometric results may be used to determine the unknown uplink location as is illustrated in Figure 9.

We have already developed a generalized software package for the TDOA technique which allows the operator to input the location of the TDOA receiving site, locations for any two geosynchronous satellites used for the measurement, and the measured differential time delay. The program then traces a curve showing possible locations of the uplink transmitter. (A preliminary version of this program has already been provided to Mr. Kinsella for evaluation.) Similar software is being developed for the Interferometric technique.

3.2 Noise Analysis

Smith and Steffes [1] derived an empirical relationship between adjacent satellite carrier-to-noise ratio (CNR) and geographical error across the center of CONUS specific to the Georgia Tech TDOA hardware. This was accomplished by determining an error from multiple oscilloscope based time difference observations of a satellite signal under user variable noise level conditions and then mapping these results into miles across
the center of CONUS.

Note that these results depend on the oscilloscope method for performing the time delay determination. Should any hardware change be made, such as the use of analog or digital correlation to determine the signal delays, these methods would need to be characterized and then mapped onto the Earth's surface as described above.

At this time, only preliminary phase measurements are being attempted. Therefore, no data exists from which to infer empirical noise characteristics. However, the literature (for example [3-4]) provides several equations which present theoretical bounds upon differential time and phase measurement accuracy as a function of signal-to-noise levels. Therefore, a determination of worst case CNR for a specific hardware configuration can be related to geographic error. One must note that signal CNRs will depend on site specific parameters such as antenna reflector sizes, low noise amplifier noise levels, and phase and delay measurement hardware techniques.

Regardless of the method of parameter measurement, if a stochastic description of the noise characteristics can be acquired, then this can be mapped through the deterministic equations which relate differential delay or phase to terrestrial curves into geographic error probability regions. Thus, for example, the terrestrial intersection of the first sigma region for a TDOA measurement and that of a Interferometry measurement may be found to occupy an oval area of 400 square miles which contains the potential uplink site.
We do not plan to perform such mappings based on analytic noise characterizations for the differential time or phase measurements of our particular SILS hardware. However, plans do include producing an empirically derived table of geographical errors (in miles or some other useful units) similar to that produced for the TDOA results.

4. Design Considerations for Future Spacecraft

In the previous Annual Report for Contract C-10070 (pages 22-25), we described at length potential modifications to spacecraft design which would optimize the ability to locate uplink transmitter positions. The primary suggestion was the addition of 4 feedhorns to the existing 32 feeds currently used aboard GSTAR-series spacecraft. These feeds would each cover the continental United States and would not provide communications quality (equalized) beam patterns. Instead, they would provide two antennas on each of the two interferometric baselines and would be co-polarized with the interfering signals, thus allowing for an interferometric measurement of both latitude and longitude of the interfering signal. Also, a much higher signal-to-noise ratio would be obtained with this arrangement since a cross-polarized antenna would no longer be used as part of the receiving array. This would result in a far more accurate determination of the uplink transmitter location. Because we do not anticipate the Interferometric method as being sensitive to signal amplitudes (only relative phase), the variations in
antenna gain over the beam of these "additional" feeds would not affect the ability to measure accurately the uplink position. As discussed in our previous Annual Report, this added capability requires, in addition to the four feedhorns, a switch matrix which allows connection of the "SILS" feedhorns to any of the transponders.

Over the past year, we have also discovered that an independent local oscillator is used for each set of cross-polarized transponders aboard each spacecraft. This complicates the required hardware for interferometric measurement, because the specification for oscillator stability allows drifts between these two oscillators of up to 2300 Hz per day. We understand that the use of independent local oscillators is desirable so that a single oscillator failure would only disable a single set of commonly polarized transponders. However, the accuracy of the Interferometric method is certainly compromised by this architecture. As an alternative, we suggest a spacecraft design that employs independent oscillators for each transponder group which are locked to a common master reference. Should the common reference fail, each oscillator would be able to lock to an internal reference, as per the current design. Thus, the only added components in the "upgraded" spacecraft, beyond those required for the antenna feed system, will be an additional common master reference oscillator, and circuits within each local oscillator to switch from the master reference to the internal local oscillator reference in the event of a failure. These design changes will make it possible to locate the position
of any uplink station, regardless of modulation type, polarization purity of the uplink signal, or sidelobe signal levels.

5. Summary

In the second year of Contract C-10070 (20 January 1988 through 19 January 1989), we have completed the theoretical analysis of the Interferometric method for uplink transmitter site location. We have also constructed a system for making the required differential phase measurements, and have begun initial testing. In the next year of the contract, we hope to demonstrate a working Interferometric system which, when teamed up with the TDOA system already developed, will clearly demonstrate the feasibility of the combined approaches for uniquely identifying the location of the uplink transmitter sites. We shall also study the capabilities of this technique, as well as completed the software for use in computing ground station position from TDOA and Interferometric techniques. Finally, we intend to assist GTE in development of an operational Satellite Interference Location System, which can provide a full-time capability for uplink transmitter site location.
References


Plot 1

Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

Uplink Angle from Best CoPolarization: 0°

Single/Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 30°

Single/Dual Transponder
Plot 3

Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 60°

[Single]/ Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

Uplink Angle from Best CoPolarization: 90°
Unlink Angle from Rest CoPolarization: 0°
Plot 6

Polarization Angle of the Ga Tech 6.1 m Receiver System

Degrees

CNR, dB

Unlink Angle from Best CoPolarization: $30^\circ$

Single / [Dual Transponder]
Plot 7

Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

Unlink Angle from Best CoPolarization: 25°

Single / Dual Transponder
Polarization Angle of the Ga Tech 6.1 m Receiver System

Uplink Angle from Best CoPolarization: 90°

Single/Dual Transponder
REPORT
TO
GTE SPACENET CORPORATION

FINAL REPORT

for
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RESEARCH AND DEVELOPMENT OF SATELLITE INTERFERENCE LOCATION SYSTEM (SILS) AT GEORGIA TECH

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January 20, 1987 through June 30, 1990

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Dedication

Benefits resulting from this dissertation are dedicated to all the friends, teachers, employers, mentors, and mostly to my parents who have done the tremendous jobs of putting up with me and making it possible for me to get to a point in life where I may contribute something back into this world.
Acknowledgments

I should like to thank my dissertation advisor, Professor Paul G. Steffes, for his assistance, teachings, and patience. I should also like to thank the faculty members who served on the various committees which are required to produce another Ph.D. student. I should specifically like to thank the following Georgia Tech professors for their technical and moral support:

Aubrey Bush
John Dorsey
Bob Feeney
Dave Hertling
Bob Roper
Bill Sayle
Steve Wicker

I should like to thank Mr. William P. Kinsella of the GTE Spacenet Corporation of McLean, Virginia for his moral support and for his company's financial support of this project.

I should like to thank Ms. Diana Fouts for her help and provision of resources for preparing much of the graphic content of this dissertation.

Finally, I thank Mr. Jim Norman and Dr. Sheila Azdell for being out there.
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Summary

This dissertation describes the design and development of a system for inferring the position of terrestrial satellite uplink stations using existing domestic satellites with minimal disruption to normal satellite operation. Two methods are presented by which a quantity measured at a terrestrial receiving site is mapped into a curve of possible uplink locations on the Earth’s surface. One method involves measuring differential time delays of a single uplink signal observed through two adjacent spacecraft. Another method uses a short baseline interferometer composed of the two cross-polarized and spatially separated antenna feeds aboard an affected satellite. A unique location or two dimensional solution is obtained by employing an appropriate combination of the two presented methods. A system for measurement of the required differential delays and phases is described in addition to the experimental work performed to demonstrate the feasibility of these location methods.
1. Problem Statement and Potential Solutions

The objective of this research has been the development of a Satellite Interference Location System (SILS) for inferring the location of terrestrial satellite uplink stations using existing geosynchronous civilian repeater-type satellites with minimal disruption to normal satellite operation. Two methods are presented which together can produce a unique positional solution. Each method has been tested experimentally.

The first method is the Time Difference of Arrival (TDOA) system in which the propagation time for the uplink signal to a particular satellite is compared with the propagation time to an adjacent satellite. Given that the positions of the two spacecraft relative to the receiving station are precisely known, the difference in time of arrival over the two different paths isolates the possible uplink transmitter location to a one dimensional curve on the Earth's surface. Figures 1.1 and 1.2 show the two and three dimensional cases. Such a system requires a two channel receiving system capable of accurately estimating the differential delay between the two paths, as is illustrated in Figure 1.3. Because the level of the uplink signal through the adjacent satellite path is typically 30
Primary Satellite
Unknown Distance
Unknown Distance
Unknown Uplink Site

Adjacent Satellite
Unknown Distance
Unknown Distance

TDOA Receiver Site

Uplink Positional Solutions

Two Dimensional TDOA Geometry
Hyperbolic Intersections

Figure 1.1
Three Dimensional TDOA Geometry

Hyperbolic Intersections

Figure 1.2
Adjacent Satellite
GSTAR 2

Jammed Satellite
GSTAR 1

Georgia Tech
6.1 M Dish
Gain = 55.4 dB

Ku DownLink
11.7 < Ku < 12.2 GHz
g/T = 32.8 dB/K

HP8558B
Spectrum
Analyzers

LNB 180K
Harris 6312 LNB
Pseudo C Band IF
3.566 < IF < 4.066 GHz

ABW
Base Band
Dual Trace Scope
with Variable Delay

Transmit Site

Georgia Tech
3.1 M Dish
Gain = 48.8 dB

g/T = 27 dB/K

EchoStar LNB
LNB 150K

"B" Band IF
950 < IF < 1450 GHz
to 40 dB lower than that through the primary satellite (for example, see [13,14] for uplink sidelobe performance), high sensitivity equipment is required for the adjacent satellite downlink. The corresponding transponder aboard the adjacent satellite should be only lightly occupied so as not to interfere with the relatively weak signal from the source of interest. Figure 1.4 shows a Mercator projection map of the Continental United States (CONUS) illustrating the family of curves of constant differential delay for GTE’s GSTAR 1 (103 degrees west) and GSTAR 2 (105 degrees west) satellites.

The TDOA approach can be used to locate the sources of a wide range of signal types. Almost any modulated signal (video, audio, digital, etc.) can be located by using a measurement of the differential time delay between some unique portions of the two received waveforms. Even pseudo-random noise signals can be located using a variable time delay correlator to infer the differential time delay between the two satellite paths. However, unmodulated continuous wave (CW) signals present a special problem. Unless the differential time delay through the two paths is less than 1/f (where f is the frequency of the CW signal), it becomes impossible to identify unambiguously the location of the source of the CW signal.

Another technique for producing a one dimensional solution is interferometry, or the comparison of phases of
an incoming signal at two spatially separated antenna locations. Given a differential electrical phase measurement made between two known and separate locations, one can determine the angle of arrival of incident radiation relative to an interferometric baseline formed by the line connecting the two receiving antennas. Figure 1.5 illustrates the relevant geometry for a dual antenna receiving system to relate the desired geometric angle to the antenna separation, wavelength of the incoming signal, and the measured differential phase between the antennas. This technique may be used with CW signals.

To employ this technique for a SILS effort, two antennas are required in a location which facilitates a useful terrestrial solution. The distance between adjacent geosynchronous satellites is too large to make unambiguous interferometric measurements of the direction of an incoming signal transmitted from within CONUS as viewed from a geosynchronous satellite. At the Ku-band frequencies used by some domestic satellites the distance between feeds used for the two orthogonal polarizations aboard a single satellite is usually smaller than one meter. Thus, a measurement of the differential phase of the uplink signal as measured by ground stations through each of the two orthogonally polarized feeds aboard the spacecraft may be used to infer the angle of arrival of incident radiation
Electrical Angle = $\frac{\pi 2d \cos(\theta)}{\lambda}$

Figure 1.5
Radio Interferometer Geometry and Equation

Figure 1.6
Interferometric Geometry at the Satellite

Figure 1.7
Interferometric Cone Intersecting the Earth
upon the satellite. This measured differential phase can be mapped into a terrestrial curve of possible locations of the uplink signal source.

Figure 1.6 illustrates the antenna feed locations aboard a GSTAR series satellite and relates this geometry to an interferometric baseline. Figure 1.7 shows the resulting cone of constant differential phase around the interferometric baseline and terrestrial intersection between this cone and the sphere of the Earth. Figure 1.8 shows a Mercator projection map of CONUS illustrating the family of curves of constant differential phase for GTE’s GSTAR 1 (103 degrees west) satellite. Because the signal level through the cross-polarized transponder would be much weaker than that through the primary transponder (approximately -30dB based on manufacturers’ data for typical ground antenna cross-polarization isolation), a more sensitive receiving system is required for that signal.

Employing a combination of the TDOA and interferometric techniques can localize the uplink transmitter’s position through the determination of the intersection of the two curves. Figure 1.9 shows a map with overlaid curves of constant delay and differential phase for the TDOA and Interferometric methods specific to the case where time difference is measured between GSTAR 1 and GSTAR 2 and phase difference is measured between the orthogonally polarized
Contours of Constant Differential Phase for Geosync Satellite over 103.0 W

Figure 1.8
Contours of Constant Differential Phase and Delay
antenna feeds aboard GSTAR 1. The combination of these two methods has the added advantage of requiring only two satellite paths and provides for locating the source of signals regardless of their purpose without disrupting normal communications through the spacecraft or requiring any additional spaceborne hardware.

Because the GTE Spacenet Corporation sponsored most of this research and GTE allowed the Georgia Tech investigators the use of much equipment and their GSTAR series of satellites, most of the examples and experiments presented herein are oriented around the use of the specific satellites GSTAR 1, GSTAR 2, and GSTAR 3. These are polarization re-use, repeater-type, Ku-band, geosynchronous United States domestic communications satellites located at longitudes 103, 105, and 93 degrees west respectively.

Both the Time Difference of Arrival and Interferometric techniques were successfully tested experimentally. The TDOA experiments were performed by measuring delays of "target-of-opportunity" signals. Because the interferometric tests required more elaborate signals and more complex processing schemes, a pair of experiments were performed using signals originating from Atlanta, Georgia and two GTE sites. The details of various experiments are discussed herein.
2. History

On 27 April 1986, someone operating under the title of "Captain Midnight" overwhelmed the Home Box Office commercial television C-band uplink signal between Hauppauge, Long Island and the geosynchronous Hughes Galaxy I satellite located over the Pacific at 134 degrees west longitude. The "Captain Midnight" incident [1-3] is relatively unique in that it received much press attention. However, intentional or inadvertent interference from man-made sources to satellite communications channels is a frequent occurrence. During the local evening television news time slots, one can find examples of poorly directed uplink radiation patterns from mobile satellite terminals striking more than their intended satellite target. In uplink transmitter hardware, radio frequency leakage into some intermediate frequency circuitry outside of the intended information passband may show up as unknown noise in an unintended satellite transponder. Many occurrences of illegal transponder usage also exist.

Most cases of interference may be corrected by taking action at the originating uplink station. However, a receiving station cannot typically determine the source of the uplink unless there is some easily demodulated and
identified artifact in the interfering signal. The
satellite operators usually have no more information than an
afflicted user, and an intentional jammer will not be trying
to assist an identification effort.

The locations of unknown uplink stations are difficult
to determine because of the wide range of potential
locations of the interfering transmitters and because most
satellite uplink stations direct their transmitted power
away from the surface of the Earth, making detection with
terrestrial receivers difficult except at relatively short
ranges. Alternate approaches to location determination
include detection from aircraft or low altitude spacecraft.
Both share the difficulties of fairly long response times
and extreme expense. The use of adaptive antennas aboard
domestic spacecraft (i.e., movable "spot beams") either to
locate the source of the unwanted signals or to minimize the
effects of such signals is feasible, but requires the
additional cost for spacecraft construction and launch [4].
The existing fleet of domestic satellites are not so
equipped. The technique of physically moving a spacecraft
so that the edge of its principle receiving beam scans past
the undesired transmitter has been tried, but has the
disadvantages of disrupting the traffic through other
transponders on the same satellite and of consuming
propellant [5]. Preferable are alternate techniques which
use the existing fleet of domestic satellites and require only a minimal disruption to normal spacecraft operation.

There are several possible signal processing methods for uplink station location which require no modification to spaceborne hardware. In cases where there is relative motion between the satellite and some combination of the receiver and transmitter, the knowledge of a satellite's orbital geometry and the propagation time changes or doppler shifts may be employed. Several satellites currently exist (i.e. the SARSAT series) whose mission is to find (by using doppler shifts) an activated Emergency Locator Transmitter (ELT) of the type carried aboard commercial aircraft. If the spacecraft has no motion relative to the receiver and transmitter as in the case of geosynchronous satellites, then remaining methods include the use of TDOA and interferometry as described above.

From investigations of the literature, Chestnut [6] appears to be the first to have discussed the TDOA method in the refereed press although he refers to other sources in his paper. To this author's best knowledge, single spacecraft short baseline interferometry was first described by Professor Paul Steffes of Georgia Tech in 1986. A short history of both the TDOA and interferometric methods follows with editorial emphasis on the underlying motivations of the participants.

Richard Harris and Reed Burkhart of Hughes Aircraft released a TDOA "review package" dated 7 April 1986. The paper briefly discusses the TDOA method in the context of an interference locating system and primarily focuses on the error analysis presented by Chestnut.

In the Summer of 1986, Professor Paul Steffes presented a proposal for SILS research to Hughes Aircraft. They initially appeared to be interested in sponsoring research. However, their final response was negative. They stated that all external research had been halted after their corporate acquisition by General Motors.

In October of 1986, Professor Steffes and Smith presented a similar proposal for SILS research to the GTE Spacenet Corporation. GTE was interested and provided funding beginning in January 1987. This gave Georgia Tech access to GTE resources which include their various ground control facilities and their GSTAR series of Ku-band domestic geosynchronous communications satellites. The Georgia Tech Earth station facility had already been using the GSTAR series of satellites as part of the institute’s regular AMCEE/NTU distribution of live and videotaped
Burkhart and Harris presented a reorganization of their 1986 TDOA review package as a conference paper [7] on 9 February 1987 in the context of a navigation system for providing an uplink operator's location with the implicit cooperation of the transmitting station and the employed transponder's owners. In their paper, the authors do not claim to have made any actual measurements and deal mostly with the error analysis in the style of Chestnut. The authors refer to the use of a third satellite to form another pair of signal paths from which a second set of terrestrial curves of constant differential delay may be determined whose intersection will contain the unknown uplink station. This discussion appears to imply that they had not made any actual measurements because the mathematical findings within this dissertation show that the intersections of these two sets of curves are almost tangential for useful adjacent satellite locations. The empirical discovery of the signal-to-noise levels on typical adjacent satellites as observed by the Georgia Tech researchers reduces the differential time measurement accuracy to a point where typical intersections of these two sets of noisy tangential curves can have intersections occupying not a well defined point but an area of thousands of square miles.
In the Spring of 1987, the Amateur Radio experimenter's publication, QEX, published plans by AMSAT president Vern Riportella to invoke a form of "Techno-Sports" which would include a determination of the location of an "unknown uplinker" employing doppler shifts through one of the OSCAR (Orbiting Satellite Carrying Amateur Radio) series of non-geosynchronous satellites. This author has since been contacted to model mathematically such an activity.

The June 1987 issue of Telecommunications magazine ran a short overview article by Dr. Michael J. Marcus of the FCC which discusses satellite security [4]. Marcus hints at ground electronics techniques for uplink locating but states, "There are legitimate reasons for avoiding public discussion of the technical details of these techniques..." This was written some time after an extensive telephone conversation in September of 1986 with Professor Steffes concerning satellite interference location techniques. Dr. Marcus led the investigation of the "Captain Midnight" incident during the summer of 1986.

In November 1987, Smith and Steffes submitted a manuscript concerning their theoretical and experimental Ku-band TDOA efforts to IEEE Transactions on Aerospace and Electronics Systems [8]. This paper included a discussion of the relevant theory, a closed form equation for determining the terrestrial curves of constant differential
delay, a system architecture description, and the Georgia Tech developmental system performance with an experimental case result consisting of oscilloscope photographs of propagation-delayed demodulated television using real unplanned signals, the computed possible locations, and the actual location of the signal source. After an unintentional delay in an associate editor’s office, this paper was accepted for publication after peer review in the Spring of 1988 and published in March 1989. Note that this paper was presented as part of this author’s Ph.D. Qualifying Examination on 1 April 1988.

The Georgia Tech researchers received a visit from the sponsor, Mr. Bill Kinsella of GTE Spacenet (McLean, VA), on 18 and 19 May 1988. Dr. Alireza Shoamanesh of Telesat Canada also appeared at Georgia Tech on Thursday 19 May 1988 with Mr. Kinsella. During the visit, Steffes and Smith demonstrated the Time Difference of Arrival method by blindly locating a San Francisco uplink station using signal paths through GSTAR 1 and GSTAR 2.

On 8 June 1988, a meeting consisting of representatives of the FCC, Georgia Tech (Professor Steffes), Hughes Aircraft, GTE Spacenet, AT&T, Intelsat, Comsat, and other satellite operating companies was held in Washington, DC concerning SILS activities. A decision was made to hold formal operating and technical meetings later in July. Mike
Marcus of the FCC verbally requested that Georgia Tech not publish information concerning satellite interference locating capabilities, giving as the reason his wish not to inform potential adversaries. The Georgia Tech investigators gracefully declined the censorship offer stating that the publication concerning the TDOA efforts had already been accepted by *IEEE Transactions on Aerospace and Electronics Systems* and that this research activity had been taken on only after written guarantees as to the freedom to publish all results were given.

The 22 July 1988 meeting, consisting of a similar group, presented two revelations. A restricted-distribution communication dated 29 January 1988 from Hughes to the FCC was revealed which included a report entitled "Transmitter Location System." This report describes the Hughes TDOA C-band experimental effort. Although Hughes did not appear to have achieved any better accuracy in their later geographical results as compared to that of the Georgia Tech team, they seem to have significant advantages in equipment, software, and manpower. Their experiments were performed under controlled conditions using large receiving reflectors and previously arranged uplink signals (video test patterns) from known uplink stations. The signals were processed digitally using Tektronix hardware and purchased software. In contrast, the Georgia Tech experiments used available
equipment and "targets-of-opportunity" which were discovered as various transponders of various satellites were examined.

In addition, the Interferometrics Corporation, which was represented at the meeting, released a report indicating their desire to build and maintain a SILS site which would perform TDOA measurements for the satellite operator community. They proposed an approach where direct pre-detection radio frequency correlation of the two incoming signals would be performed to determine the required differential delay. They claimed that this would have the benefit of better noise immunity in the presence of another transponder signal when compared to post-detection correlation. Direct RF correlation has been discussed at Georgia Tech, and the post-detection method of correlation was found to require less hardware and economic commitment, thus facilitating more rapid results. The key requirements for the former method involve the acquisition of sufficiently fast analog-to-digital converters or variable digital or analog delay hardware.


On Tuesday 3 April 1990, Smith spoke with Reed Burkhart of Hughes at the National Association of Broadcasters
convention in Atlanta, Georgia. Mr. Burkhart told Mr. Smith that Hughes had presently ceased their pursuit of the TDOA method for financial and resource commitment considerations.

Most of this information has been gathered by discussions with members of the interested satellite operations community. Most parties who are interested in this subject tend to keep their information proprietary. An on-line abstract search (including the TECHDATA and Georgia Tech library databases) which accumulated more than one megabyte of keyword related abstracts failed to produce any other relevant documents.

To the knowledge of this author, there exists no available system which performs a similar signal source location function.
3. Time Difference of Arrival (TDOA) Techniques

The Time Difference of Arrival (TDOA) system is a technique by which the propagation time for the uplink signal to a particular satellite is compared with the propagation time to an adjacent satellite. Given that the positions of the two spacecraft relative to the receiving station are precisely known, the difference in time of arrival over the two different paths isolates the possible uplink transmitter location to a one-dimensional curve on the Earth's surface. The key disciplines involved in the application of the TDOA techniques for locating Earth stations include geometry, RF link analysis, and signal processing.

Geometric issues include a determination of the relationship between the location of the receiving SILS site, the location of the primary and adjacent satellites, a measured differential delay between the signals traversing the two different paths, and a curve of constant differential delay. A set of equations which facilitate numerical generation of a geographic set of curves of constant differential delay as a function of satellite position were developed and are described below. Appendix A discusses the derivation of these equations, and Appendix B
lists a computer program for generation of various families of curves of constant delay.

RF link analysis issues include the determination that sufficient power and Carrier-to-Noise ratio (CNR) exist through both the primary and adjacent satellite signal paths to perform the desired differential delay measurement at a SIFS receiver site. Receiving antenna dish sizes, typical transmitting antenna sidelobe strengths, and transponder loading become the important factors.

Signal processing issues involve the recovery of the differential time information between the two received signals. Possibilities include coherent versus non-coherent demodulation of an incoming RF signal, digital versus analog measurements of the time delay, and the practicality of the methods of choice.

3.1. TDOA Geometry:
Terrestrial Curves of Constant Differential Delay

Whether friendly or not, the typical satellite uplink user is attempting to illuminate only one satellite at any one time. For several reasons, however, the uplink may be illuminating multiple satellites with enough power so that a receiving ground station may be able to detect the presence of the source station on adjacent satellites in addition to the uplink's goal satellite. Reasons for this include poor dish alignment procedures or equipment, a marginal antenna
aperture size which may not generate appropriately small beamwidths, sidelobes intrinsic to the uplink antenna, and a smaller apparent angle between satellites which are at low elevation angles relative to the uplink location. This last effect has been made more noticeable by the recent reduction of geosynchronous satellite spacing from three to two degrees.

The TDOA location method being presented depends on the ability to determine relative time delays due to the different lengths of two satellite signal paths as perceived by a receiving station. A curve on the Earth's surface containing the location of the signal's source may be determined given this time delay (which can be measured by simultaneously observing each of the two relevant satellites with receiving systems), the location of the receiving station, and the positions of the two satellites of interest. It is not unusual for satellite operators to know at all times the position of their satellites to within a few meters via the use of laser reflections obtained off cube-corner mirrors aboard the satellite or more typically from radio signal processing techniques.

The previously presented Figure 1.1 shows a two-dimensional view of the geometry pertinent to the TDOA technique. As illustrated, the positions of the two satellites, the location of the TDOA site, and thus the
distances from the satellites to the TDOA receiver site are known. The unknowns are the two remaining distances from each of the satellites to the unknown uplink station.

If the receiver site has two antennas connected to two receiving systems which can simultaneously monitor the signal through each satellite, a relative time delay between the two paths may be measured. Given this delay, a knowledge of the speed of the signal propagation through space, and the equivalent distance of any non-negligible signal processing time, the difference in path distances may be deduced. Subtracting out the known downlink distances and any other system offsets from the satellites to the TDOA receiver site leaves the remaining differential distance between the two unknown uplink distances. In the two-dimensional case, this differential distance determines two potential points for the location of the uplink station. These points are found by solving for the intersections of the Earth's circle and the two branches of the hyperbolas made from the two paths of equal length plus the inferred delay distance. Holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two intersections is the uplink location.

Previously presented Figure 1.2 depicts the three-dimensional case. Only the unknown uplink portions of the
signal path need to be considered because the distances from the satellites to the TDOA receiver site are assumed to be known. As an extension of the two-dimensional case, the surfaces of constant delay between the satellites form a hyperboloid of two sheets centered along the axis of the line segment connecting both satellites and opening away from the segment's center point. The two intersections of these hyperbolic branch surfaces with the sphere of the Earth provide terrestrial curves of constant delay which include the location of the uplink station. As in the two-dimensional case, holding one arrival time as fixed and considering whether the other signal is leading or lagging this fixed time uniquely determines which of the two curves contains the uplink location. However, unlike the two-dimensional case, there is one less known input than is required to support the dimension of the desired solution. Therefore, the solution is one dimension higher than desired, and another piece of information is required to acquire a unique solution.

Figure 3.1 illustrates another viewpoint of the three-dimensional case where terrestrial curves of constant delay are determined by the locus of the intersections of concentric circles around the subsatellite points of the effected satellite pair. Let the radii of these subsatellite circles be determined by considering a general
Earth's North Pole

Arc of Possible Solutions

SubSatellite Point

3 Dimensional TDDA Geometry for Triangle Constructions

Geosynchronous Arc
satellite-to-Earth distance (dte and dtw in Figure 3.1) which will be greater than or equal to the satellite-to-subsatellite point distance. Note that if the differential delay to the two satellites from a given uplink station is considered as a differential distance equal to the difference between the two uplink-to-satellite paths, then the uplink station must lie on the intersection of the two subsatellite circles.

From this construction, a family of curves of terrestrial solutions to the uplink location problem may be determined for various delays between satellite signal pairs. For a particular differential delay, the corresponding differential distance is computed. A reference uplink-to-satellite distance is then chosen. The other uplink-to-satellite distance is chosen to differ in length by the differential distance. A subsatellite circle is constructed for both distances. The intersections of these circles are a point or a pair of points on a curve of potential uplink locations for the given differential delay.

The entire curve is constructed by sweeping the reference uplink-to-satellite distance from its minimum at the subsatellite point to its maximum near the Earth’s poles. The intersections form the entire curve for the given differential delay. A family of curves may be generated by performing this iteration over a number of
different differential delays.

In both the hyperbolic intersection and the subsatellite circle constructions, the goal is to relate time delay measurements and known geometric information to a curve along the Earth's surface which contains the unknown uplink's location. The subsatellite circle viewpoint for the three-dimensional case lends itself to a triangle construction which provides trigonometric equations that generate a latitude and longitude given a delay and the known geometric information. Details of this construction are discussed in Appendix A. Using a computer program similar to that found in Appendix B to sweep the appropriate variables generates a family of terrestrial curves of constant differential delay. Figure 1.4 showed these curves with 20 microsecond separation for GTE's geosynchronous GSTAR 1 (103 Degrees West) and GSTAR 2 (105 Degrees West) satellites projected onto a Mercator projection of the CONUS (CONtinental United States) area. Equations 3.1 through 3.4 relate the known geometry and the measured delay to a longitude and latitude for a fixed Earth-to-satellite distance. Sweeping over this distance generates one of the constant delay curves.
Equation 3.1
\[
e = \arctan \left[ \frac{(dtw^2 - r_p^2 - r_{sat}^2)}{(dte^2 - r_p^2 - r_{sat}^2)} - \cos(\text{difflong}) \right] - \frac{\sin(\text{difflong})}{\text{[degrees]}}
\]

Equation 3.2
Longitude =
longe + e [degrees] if T>0 (Uplink west of satellites)
longe - e [degrees] if T<0 (Uplink east of satellites)

Equation 3.3
\[
\text{Latitude} = \arccos \left[ \frac{r_p^2 + r_{sat}^2 - dte^2}{2 * r_p^2 * r_{sat}^2 * \cos(\ e \ )} \right] \text{[degrees]}
\]

Equation 3.4
\[
T = \frac{(dte - dtw)}{c} \text{[seconds]}
\]

where:
longe = [degrees] Longitude of eastern satellite
longw = [degrees] Longitude of western satellite
difflong = [km] Absolute value of (longw - longe)
dte = [km] Swept distance from eastern satellite to eastern subsatellite circle
dtw = [km] Swept distance from western satellite to western subsatellite circle
r_{sat} = [42162 km] Radius of Earth geosynchronous orbit
r_p = [6378 km] Radius of Earth
\( \theta = [\text{degrees}] \) Intermediate offset longitude between subsatellite circle intersection and satellite longitude
T = [seconds] Differential time of arrival
\( \text{Eastern Signal} - \text{Western Signal} \)
c = [2.997925x10^{8} \text{ m/sec}] Speed of Light
Assuming the use of the GSTAR 1 and 2 satellites, these equations, and subtracting out any additional delays for an arbitrary TDOA receiving location site, delays range over a magnitude of about 200 to 300 microseconds for the west and east coasts of the United states to zero along the western Great Plains beneath the satellites. Note that the latitude values should be taken as both positive and negatives as the resulting curves are symmetric about the equator. However, the antenna beam pattern GSTAR series satellites enforces only northern hemisphere service, therefore, the southern solutions would be unlikely uplink location candidates.

Note that the geometry of Figure 1.4 implies that the curves of constant delay associated with one pair of satellites would be almost tangential to the curves of another nearby pair of satellites for a large part of CONUS. Thus, the intersection from the TDOA curves of two nearby satellite pairs will not provide a high resolution solution due to the large areas of the intersections of terrestrial curves induced by signal noise. However, due to signal level constraints, any other satellite pair employed for TDOA measurements must be close to the primary satellite. Therefore, some technique other than this form of TDOA must be used to lower the dimension to a solution which uniquely locates an uplink station.
3.2 RF Link Analysis - Power Budgets

The satellite experiencing an interfering signal will usually be illuminated by an adequate amount of power to facilitate easy detection of the interfering signal (or else it would not be a interference problem). Therefore, the power critical signal path for TDOA purposes is that from the unknown uplink location through the adjacent satellite and back down to the SILS receiving site.

There are many possible scenarios by which a satellite may receive enough illumination to cause interference. An Earth station operator may incorrectly aim his dish antenna out of the plane containing geosynchronous satellites thus causing one or more satellites to experience his antenna's first sidelobe as he increases his transmission power. Most operators vary their output power level to adequately illuminate their target satellite to facilitate varying attenuation conditions. The antenna's pattern may be distorted due to mechanical distortions in the reflector or misalignment of the feeds at the reflector's focus. There also exist cases where there is inadequate illumination of an adjacent satellite for TDOA purposes.

The following example presents a simple link analysis for a typical scenario where GSTAR 1 is the afflicted satellite and GSTAR 2 is the adjacent satellite. This
example illustrates some of the points germane to TDOA operations. The goal is to determine how well a TDOA operator may be able to measure a delay from which he may infer a terrestrial curve of constant differential delay.

An operator in Atlanta, Georgia is using a Scientific-Atlanta Series 8060 6-meter antenna [13] in an attempt to saturate a Ku-band transponder aboard GSTAR 1 (103 degrees west) with a 32 MHz wide frequency modulated television signal. The antenna is correctly aimed at GSTAR 1 and needs an adequate amount of power at 14.25 GHz from its high power microwave amplifier to achieve the published [22] transponder input saturation flux density of -95.6 dBW/meter$^2$ at the satellite. (Although not realistic, this example assumes 100% efficiencies for all reflectors.)

Equation 3.5 [25]  
\[
\text{Flux Density} = \frac{\text{EIRP}}{4 \pi r^2}
\]

Equation 3.6 [25]  
\[
\text{EIRP} = P_t \times G_t
\]

Where:  
$P_t$ = Power from transmitter into antenna  
$G_t$ = Antenna Gain = 57.2 dBi @ 14.25 GHz = 524800  
$r$ = Distance to GSTAR 1 = 37369 km

Solving for power gives a required 9.2 watts or 9.6 dBW into the antenna and an EIRP for GSTAR 1 of 4.8 megawatts or 66.8 dBW.

To find the power level illuminating GSTAR 2 which is 2 degrees further west at 105 degrees longitude, one must
compute the sidelobe power levels emitted from this antenna. Part 25.209 of the Federal Communications Commission regulations [24] requires that a satellite uplink antenna have a sidelobe performance with emissions below an envelope defined by:

\[ \text{Equation 3.7} \quad \text{Emitted Power [dBi]} = 29 - 25 \times \log(\theta) \]
\[ \text{for } 1 \leq \theta \leq 7 \text{ [degrees]} \]

Scientific-Atlanta advertises that their 6-meter antenna meets or is better than this specification. Ignoring the slight angular offset due to parallax and assuming a worst case sidelobe performance at 2 degrees off boresite gives a power difference from the main lobe peak of 21.5 dB. Thus the apparent EIRP in the direction of GSTAR 2 is 45.3 dBW or 34 kilowatts which produces a flux density of 1.9 picowatts/m² or -117 dBW/m² at the satellite.

However, the absolute powers are less important than the link carrier-to-noise (CNR) ratios which determine the quality of the received RF signal. A CNR value should be contrasted to a signal-to-noise (SNR) value. A low CNR value may map into a higher SNR value for the communicated information content due to a processing gain achieved by a modulation or coding scheme such as the frequency modulation used to transmit television or voice through satellite
channels. CNR refers only to the final modulated RF carrier power to RF noise levels. CNR (which is a unit-less ratio as is SNR) may be defined as:

Equation 3.8 [25] \[ \text{CNR} = \frac{\text{EIRP} \cdot L_p \cdot G_r \cdot \frac{1}{k} \cdot \frac{1}{T_{eq} \cdot \text{BW}}} \]

where: \( k = \) Boltzmann's Constant = 1.379 \times 10^{-23} \text{ W/K/Hz} = -228.6 \text{ dBW/K/Hz}

\( G_r \) = Gain of Receiving Antenna
\( T_{eq} \) \( [\text{K}] \) = Equivalent Noise Temperature of the Receiving Antenna System
\( \text{BW} \) \( [\text{Hz}] \) = Bandwidth of Interest
\( L_p \) = "Space Loss" attenuation over distance from the Friis Transmission Equation if the transmitting and receiving antenna gains are removed and is given by:

Equation 3.9 [12] \[ L_p = \frac{(\text{wavelength})^2}{(4 \cdot \text{Pi} \cdot r)^2} \]

\( r = \) Distance (to GSTAR 2 = 37440 km)

At the uplink frequency of 14.25 GHz (wavelength = 2.1 cm) with GSTAR 2 being 37440 km from Atlanta, the "space loss" is found to be -206.8 dB from Equation 3.9. From this information, assuming a receiver bandwidth of 32 MHz, and the published \( G_r/T_{eq} \) of the satellite of 2.5 for Atlanta [22], uplink CNR is found to be -5.5 dB.

Downlink CNR is determined in the same way. The same model 6-meter dish with an equivalent noise temperature of
180 K is assumed to be used by the SILS receiving site which is also in Atlanta. The published gain of the aforementioned Scientific-Atlanta antenna is 55.9 dBi at the 12 GHz downlink frequency resulting in a receiver $G_r/T_{eq}$ of 33.4 dB/K. The "space loss" for the downlink is a slightly different -205.5 dB due to the difference between uplink and downlink frequencies. Using the same bandwidth gives a downlink CNR of 2.6 dB. The uplink and downlink CNRs are combined (as are paralleled resistors) as shown in Equation 3.10 to give a total link CNR$_T$ of -5.9 dB.

Combining Link CNRs

Equation 3.10 [25] \[ (\text{CNR}_T)^{-1} = (\text{CNR}_{up})^{-1} + (\text{CNR}_{dn})^{-1} \]

As the noise is 5.9 dB stronger than the desired signal, this link CNR does not facilitate a differential measurement by observing a demodulated signal with an oscilloscope. Intuitively, one would observe only the channel noise floor were one to view this received signal with a spectrum analyzer. Inserting such an FM signal into a slope demodulator will produce only noise at its output. A typical extended CNR threshold satellite television receiver requires a CNR of at least 8 dB before it can lock onto the signal.

Fortunately, the SILS site need not recover the entire
modulated signal. The SILS requirement for TDOA is only that some time discernible feature of the signal be detectable for cross-correlation or direct delay observation.

The previous link analysis assumes the SILS site is attempting to recover the full 32 MHz wide frequency modulated television signal. If this goal is abandoned and only a 4.5 MHz portion of the signal is accepted via the use of bandpass filters, then a total link CNR of 2.4 dB is achieved.

Although the entire television signal is no longer available, this is not as great a loss as one may initially believe. A NTSC signal contains much timing information. The 15.75 kHz horizontal synchronization pulses and the 60 Hz vertical frame retrace information should be easily detectable by tuning through various portions of the original 32 MHz signal.

This reduced passband may now be slope demodulated to produce a signal which is visible on an oscilloscope or available to a cross-correlation device. This demodulated adjacent satellite signal may now be compared with the easily demodulated primary satellite signal for delay measurement purposes. Measurement of delays within television signals is particularly easy because of the consistent features available in the timing information.
Such measurements were successfully performed on a variety of television signals as is discussed throughout this dissertation.

3.3 Signal Processing

Signal processing issues involve the recovery of the differential time information between the two received signals. Possibilities include the demodulation of an incoming RF signal, digital versus analog cross-correlation to measure a time delay, and the practicality of the methods of choice.

The method chosen to perform the signal demodulation employed a pair of available HP 8558B spectrum analyzers to slope demodulate frequency modulated carriers such as satellite television or audio SCPC signals. Slope demodulation is facilitated in these devices by halting the sweeping of the local sweep oscillator and manually tuning it to the edge of the signal of interest. Thus any frequency modulation would show up as the amplitude information which drives the Y-axis of the spectrum analyzer's display. Such analyzers have ports available which provide voltage outputs proportional to the Y-axis information. Thus the slope demodulated information is available in analog form. The variable baseband and IF filters within these spectrum analyzers also facilitate a
manual ease of tuning. For these reasons, the spectrum analyzers were used as demodulators for this investigation.

Determination of differential time delays between signals traversing different satellite signal paths is required when using the TDOA method for locating uplink stations. The delay measurements were performed by manually observing the two spectrum analyzer demodulated time domain signals on an oscilloscope. This process and the ambient conditions which vary substantially require that the equipment operator be quick and completely aware of his job. To be more responsive to the realities of the end goal, attempts were made to employ computer correlation to provide the differential time measurement.

3.3.1 Cross-correlation: Digital Signal Processing Techniques

A commercially available Metrabyte analog-to-digital (ADC) converter accessory board was installed in a Hewlett Packard Vectra microcomputer (an IBM PC/AT compatible computer). This system sampled each of two channels at a rate of 25 kilosamples/second/channel (or a single channel at 50 kilosamples/second). A fixed length frame of analog samples was taken from each channel and correlated in software to produce a time domain graph where the maxima indicates the time of best correlation. The time of this
maxima corresponds to the differential time delay.

Cross correlation was performed by a "Turbo C" program which directly evaluates Equation 3.11 over the acquired data frames.

Cross Correlation Equation

Equation 3.11 \[ c(T) = \sum_{t} [ x(t) * y(t+T) ] \]

where: \( x, y \) acquired data frames
\( c \) resulting data frame
\( T \) index of delay

Performing this correlation required about 32 seconds on the computer using a frame length of 1024 samples with a dynamic range of 12 bits/sample.

The reader may notice that a more rapid response can be obtained by multiplying in the transform domain. (This is the equivalent of convolving the two incoming data frames if one of the frames is reversed in time.) The availability of data in the frequency domain would also provide the additional opportunity for employing various digital filtering techniques.

Figure 3.2 is a graph of a time domain "chirp" which is used as a input signal test pattern for the software. This 1024 sample frame has been auto-correlated to generate Figure 3.3. Figure 3.4 is an actual sampling of a slope
Figure 3.2
Auto-correlated Chirp Test Signal

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Page 43
Digitized Slope-Demodulated Television Signal
Filtered Correlated Result

Cross-Correlated Television Signal
demodulated satellite FM television signal which had a received CNR of approximately 10 dB. The picture content consisted of a color-bar test pattern. In this case, the sample frame length was 512 samples acquired at a rate of about 50 kilosamples/second. Note the two local peaks in the sampled signal which correspond to the 60 Hz vertical retrace portion of the NTSC video signal. Another frame was immediately sampled. These two frames were cross-correlated to produce the data of Figure 3.5. Note that the distance between the two peaks corresponds to the length in time of one television vertical retrace interval. As one would predict, successive television frames are interpreted similarly by the cross-correlation software.

In the context of observing satellite channel video signals, the 25 kilosamples/second/channel sampling rate is adequate to determine relationships between video frames. However, a much faster sampling rate than this is desired to determine the differential time delay measurements to the microsecond resolution (within individual video lines) required to acquire useful spatial TDOA results. Although speeds of up to 50 kilosamples/second/channel may have been acquired by implementing DMA techniques on the available hardware, the desired 100 to 1000 kilosamples/second rates require specialized hardware.

As such resources were not easily available and human
observations of oscilloscope displays provided a simple method for delay measurement, it was decided that work in this area will be pursued at a later time.

3.3.2. Cross-correlation:

Analog Signal Processing Techniques

There are also several analog options for performing the cross-correlation function to determine the desired delay value. An analog cross-correlator may be realized by mixing two incoming signals where one of the signal paths contains a variable delay element. The DC component of the mixer output would peak as the variable delay was set to equal the actual delay between the signals. Were this to be done with the incoming RF without any form of demodulation, nulls would appear at every half wavelength. However, the voltage peaks would contain the desired cross-correlation information. A simple analog peak detector circuit with a discharge time constant appropriate to the delay sweep rate could provide a voltage related to the desired cross-correlation output.

The problem with this approach is constructing the delay circuit. Variable delay times of from -500 to +500 microseconds are required. Although dual-in-line-pin (DIP) package lumped element or transmission line delay devices are economically available in the tens of nanosecond ranges, their inherent distortions do not allow them to be cascaded
for the required delay lengths. Two other solutions are switched lengths of transmission line and surface acoustic delay devices.

Switched lengths of coaxial cable could produce the required delay. However, RG-58 50 ohm coaxial cable, which has a typical velocity factor of 66\% (Belden 8259 [23]), would require a 99 km cable length to achieve a delay of 500 microseconds. This is obviously not a useful solution. Although a similar length of optical fiber requires a volume of less than a cubic meter, either type of cable would be expensive and present substantial amplitude losses.

Another method to realize such delays employs surface acoustic wave (SAW) delay devices. Also realizable as filters, these devices transform an incoming electrical waveform into a mechanical wave which propagates through a material medium at speeds substantially less than that of light. There may exist multiple taps for transforming the mechanical waves back into electrical signals at various distances from the input launching point thus realizing a multiply tapped delay line. The delay and phase distortions of SAW devices are well characterized by their manufacturers. The Sawtek Corporations sells a series of devices which would be useful in this application. Although these devices cost between $10 and $100 in single quantities, they better facilitate a compact electronic
design as their package size is less than that of a 40 pin DIP IC package.

3.4. Experimental Apparatus and Procedures

The choice was made to use Ku-band signals transmitted through GTE's GSTAR 1 and GSTAR 2 satellites for the differential time delay measurements because of the availability of these satellites through the courtesy of the GTE Spacenet Corporation. Two sets of Earth station receiving facilities located atop the Electrical Engineering building on the Georgia Tech campus were used for the experiments. One included a 6.1 meter Harris reflector with appropriate feeds for simultaneous transmission and reception of a standard Ku-band signal set as shown in Figure 3.6. A 180 K Harris 6312 low noise block converter (LNB) amplified and shifted the incoming signal from Ku-band down to a C band IF (3.566 to 4.066 GHz) from which the Harris 6531 receiver produced a 70 MHz IF and FM demodulated baseband NTSC video and audio. The second receiving system employed generic Ku-band TVRO components. It includes a smaller fiberglass 3.1 meter reflector, a 180 K LNB converter which converts to the TVRO industry standard "L band" IF of 950 to 1450 MHz. From here, a Drake model ERS 324S receiver generated a 70 MHz IF and demodulated baseband video and audio.

Although digital or analog correlation allows
Adjacent Satellite

- GSTAR 2

Jammed Satellite

- GSTAR

- GSTAR 1

Georgia Tech
6.1 M Dish
Gain = 55.4 dB

Ku DownLink
11.7 < Ku < 12.2 GHz
g/T = 32.8 dB/K

Georgia Tech
3.1 M Dish
Gain = 48.8 dB
g/T = 27 dB/K

Harris 6312 LNB

Pseudo C Band IF
3.566 < IF < 4.066 GHz

LNB 180K

EchoStar LNB

LNB 150K

Dual Trace Scope with Variable Delay

ABW

HP8558B Spectrum Analyzers

Base Band

Base Band

Transmit Site
measurement of the time displacement between pairs of most
types of signals, a dual trace oscilloscope was chosen to view a pair of wideband FM television signals. Reasons for the use of TV signals included the variety of available source qualities and locations, the ease of demodulation, and the time domain features of an NTSC video signal. The use of the oscilloscope provided real time feedback to those performing the measurements. Demodulation and low level signal detection was performed by using two HP 8558B spectrum analyzers as slope detectors. These devices provided great flexibility in the degrees of freedom which they allow a user such as variable IF bandwidths from 3 kHz to 3 MHz, variable baseband lowpass filtering, IF frequency centering control, and logarithmic or linear amplitude demodulation.

Figure 3.6 shows the equipment configuration for the time delay measurements. The spectrum analyzers take the 70 MHz IF signals from both receivers and provide a baseband signal by using the analyzers' internal IF bandpass filter to perform slope detection of the frequency modulated video signal. The relevant characteristics of the baseband output are a function of the selected bandwidths of the analyzers' IF and baseband output filters.

Many signal pairs have been observed with this equipment configuration. The best results have been sourced
by remote evening news transmissions from mobile satellite terminals. These signals are uplinked from vehicles equipped with microwave transmitters and a reflector of minimal aperture size which is quickly erected, activated, and aimed upon arrival at the news site. Many times this is done too quickly as real time observations through multiple satellites confirm. Antenna misalignment, multiple sidelobes, a large main beam due to a small aperture size, or a "road-weary" dish contribute to signals appearing on transponders of adjacent satellites.

The Georgia Tech operators searched with the 3.1 meter system for a potential signal through GSTAR 2 which took the role of the primary satellite. Although any received video signal was available for full demodulation and viewing on a studio monitor, this was done only to ease and confirm signal acquisition. If a potential candidate was found (this was confirmed by viewing the content of the signal), searching began with the 6.1 meter system on the output of the corresponding transponder on GSTAR 1 which was only 2 degrees away on the geosynchronous arc and becomes the adjacent satellite. If the operator was fortunate and the GSTAR 1 transponder was not heavily occupied, he returned to the GSTAR 2 signal and used a spectrum analyzer to slope detect the RF video signal. This baseband output was fed to a Tektronix 2215 dual trace oscilloscope and was used as the
trigger source. The spectrum analyzer’s IF and baseband filters and center frequency tuning were then optimized to facilitate the cleanest triggering of the oscilloscope. Next, the GSTAR 1 transponder’s spectrum was searched for any vestige of the spectrum viewed through GSTAR 2.

Generally, there were many vestiges of frequency modulated video to be found. Potential ripples in the GSTAR 1 transponder spectrum being searched were slope detected by another spectrum analyzer, then routed to the other channel of the dual trace oscilloscope for visual correlation. With the oscilloscope’s sweep rate set to show about one horizontal NTSC line (64 microseconds) on the trace containing the signal from GSTAR 2, the presence of another video signal in the noise from the GSTAR 1 trace was readily detectable. If the GSTAR 1 video signal was not from the same source as the GSTAR 2 video signal, then one observed relative drifting of the synchronization pulses between the two video signals due to different time base sources. But if clock rates were close and the user believed that he was viewing the same signal through both receivers, then reducing the oscilloscope’s sweep rate to about one vertical period (1/60 second) showed the relative positions of the vertical retrace fields. If the fields were not nearly perfectly aligned, then these were two different signals because the maximum delays expected were on the order of
hundreds of microseconds. However, if the same signal was being viewed through both satellites, one would have observed no apparent drifting over time between the two signals, and a vertical retrace observation would have shown a maximum vertical sync field misalignment of only a few horizontal lines.

Adjacent satellite signal observations have included the barest vestiges of signals plucked from the noise of busy transponders with the skilled use of IF and baseband bandwidth and tuning controls. But other observations have included signals which were more than 4 dB above the noise floor on empty transponders, thus almost reaching a typical satellite receiver's direct FM demodulation threshold.

Figure 3.7 (Photo 1) shows an oscilloscope photograph of two differentially-delayed signals for the specific case of television station KARE's remote evening news uplink from Mankato, MN (50 miles southwest of Minneapolis), taken on 6 August 1987 at about 6:20 p.m. EDT. Note that the GSTAR 1 signal can be seen to be about 7 microseconds ahead of the GSTAR 2 signal with the sweep rate of 10 microseconds per time division. However, due to the repetitive nature of the horizontal lines, the delay could differ by an integer number of horizontal line periods. Figure 3.8 (Photo 2) shows that the vertical retrace intervals were indeed close to alignment with the sweep rate set to 2 milliseconds per
Oscilloscope Photographs for TDOA Example
Figures 3.7, 3.8, and 3.9

Page 50
time division. Figure 3.9 (Photo 3) shows a close up view of the transition from vertical retrace pulses to video line sync pulses (about 300 microseconds, given 200 microseconds per time division). This compares favorably to the analytically computed delay of about 339 microseconds from Mankato, MN which includes the satellite-to-Atlanta differential delay. Note that a delay of 235 microseconds must be subtracted from this measured delay to remove the fixed differential delay specific to the Atlanta, Georgia receiver location. Table 3.1 lists calculated time delays for a variety of locations within CONUS.

Table 3.1: Calculated Delays within CONUS

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance to GSTAR I [km]</th>
<th>Distance to GSTAR II [km]</th>
<th>Differential Distance [km]</th>
<th>Time [uSec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>37369.5</td>
<td>37440.2</td>
<td>-70.7</td>
<td>-235.8</td>
</tr>
<tr>
<td>Van Buren</td>
<td>38996.0</td>
<td>39091.6</td>
<td>-95.6</td>
<td>-318.9</td>
</tr>
<tr>
<td>Seattle</td>
<td>38411.2</td>
<td>38358.7</td>
<td>52.5</td>
<td>175.2</td>
</tr>
<tr>
<td>San Diego</td>
<td>37148.8</td>
<td>37110.8</td>
<td>48.0</td>
<td>160.1</td>
</tr>
<tr>
<td>Dallas</td>
<td>37012.1</td>
<td>37038.8</td>
<td>-22.6</td>
<td>-88.8</td>
</tr>
<tr>
<td>Greenbay</td>
<td>38049.8</td>
<td>38098.2</td>
<td>-48.5</td>
<td>-161.7</td>
</tr>
<tr>
<td>Detroit</td>
<td>38014.6</td>
<td>38079.9</td>
<td>-65.3</td>
<td>-217.8</td>
</tr>
<tr>
<td>Mankato</td>
<td>37914.3</td>
<td>37945.1</td>
<td>-30.8</td>
<td>-102.8</td>
</tr>
</tbody>
</table>

Differential Time = time of arrival of (eastern signal - western signal)
3.5 TDOA Results

3.5.1 Mapping of Measurement Error

Because the delay measurement is a non-deterministic value with its own set of statistics, this random variable may be mapped from the measurement domain into the desired geographic contour domain. To do this in a mathematically rigorous form, the functions describing the mapping from the measurement to the geographic domains are required. Although these are given for computational purposes in Equations 3.1 through 3.4, they are non-linear and do not facilitate an easy mapping of the random variable's statistics.

The following example is included to facilitate an intuitive understanding of the relationship between the measurement statistics and the geographic consequences. After a series of measurements and data reduction, a typical TDOA delay measurement may be considered to be a gaussian random variable with a particular mean value of 235 microseconds with a standard deviation of 10 microseconds. Mapping this measured mean and the sum and difference of the standard deviations gives the three geographic contours shown projected onto the map of Figure 3.10. The enclosed area may be considered to be the statistical first sigma region for this particular measurement.
Delta-t = -236.5 [\mu\text{Sec}] \pm 10 [\mu\text{Sec}]
The literature provides several theoretical bounds for differential time and phase measurement accuracy as a function of signal-to-noise levels (for example [10-11]). Therefore, a determination of worst case CNR for a specific hardware configuration can be related to geographic error. One must note that CNRs will depend on site specific parameters such as antenna reflector sizes, amplifier noise levels, and phase and delay measurement hardware techniques.

3.5.2 Geographic Error versus CNR

Table 3.2 presents an empirically derived relationship between carrier-to-noise ratio, delay measurement error, and CONUS geographical error. This information was empirically derived because of the difficulty in mathematically manipulating the inherent non-linear mappings of noise statistics through the slope demodulation technique and the mapping from differential delay to a terrestrial curve of constant differential delay. Smith and Steffes [8] derived this relationship between adjacent satellite carrier-to-noise ratio (CNR) and geographical error across the center of CONUS specific to the Georgia Tech TDOA hardware. The table lists this relationship between adjacent satellite carrier-to-noise ratios, the measured differential time delay error, and the approximate east-west geographic error across a latitude of 40 degrees north which is about the
center of CONUS. This table was generated by taking a known frequency modulated television signal with a carrier-to-noise ratio of greater than 15 dB (high CNR) and comparing a slope demodulated copy with another attenuated (low CNR) then slope demodulated copy. These measurements were performed using the same equipment and the same procedure by which the differential time delay measurements were made.

Table 3.2

Empirically Derived Differential Time and Geographic Error versus Adjacent Satellite Carrier-to-Noise Ratio

<table>
<thead>
<tr>
<th>CNR</th>
<th>Observed Differential Time Measurement Error</th>
<th>Geographic Error Across Center of CONUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>dB</td>
<td>Microseconds</td>
<td>Miles</td>
</tr>
<tr>
<td>2.2</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>1.8</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>1.4</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>0.8</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>0.7</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>0.5</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>0.4</td>
<td>60</td>
<td>300</td>
</tr>
<tr>
<td>0.3</td>
<td>70</td>
<td>350</td>
</tr>
</tbody>
</table>

Note that these results depend on the oscilloscope observation method for performing the time delay determination. Should any hardware change be made, such as the use of analog or digital correlation to determine the
signal delays, the errors inherent in these methods would need to be characterized and then mapped onto the Earth's surface as described above.

3.5.3. Uplink and Downlink dish size relationships for link CNR

Equation 3.12 describes the relationship between link CNR and the interfering uplink transmitter and SILS downlink site reflector diameters. This is derived from measurements taken and assumes:

- Worst case uplink reflector sidelobe compliance with the FCC 29-25log(θ) rule,
- The strongest measured uplink signals originated from the minimum legal 4.5 meter dish [17],
- Operation on Ku Band frequency pairs,
- Uplink reflector efficiencies of 50%,
- Linear operation of the adjacent transponder.
- The adjacent satellite is 2 degrees from the primary satellite.

\[
\begin{align*}
\text{LINK CNR (dB)} & = 10 \log\left( \frac{289}{d_t} \times \frac{L_t}{\left( d_t \times p_t \right)^{1/2}} \right)^{2.5} + 10 \log\left( \frac{\pi d_r}{L_r} \right)^2 \times p_t + 58.2 \\
\end{align*}
\]

Equation 3.12

where:  
- \( d_t \) = uplink transmitter reflector diameter  
- \( d_r \) = downlink receiver reflector diameter  
- \( p_t \) = efficiency of uplink antenna  
- \( p_r \) = efficiency of downlink antenna  
- \( L_t \) = transmitting wavelength  
- \( L_r \) = receiving wavelength

Table 3.2 lists the link CNR for various dish diameters assuming 50% reflector efficiencies at both Earth stations.
and the appropriate Ku Band frequencies.

Conclusions from Table 3.3 and Figure 3.11 include the intuitively appealing notion that the detectable signal threshold occurs when the downlink reflector diameter approaches that of the uplink reflector. However, closer inspection of the equation shows that the uplink station will eventually have the advantage as dish sizes increase. Equation 3.14 relates the 0 dB CNR level for Ku Band frequencies for reflector sizes in meters with 50\% efficiencies.

Equation 3.14 \[
\frac{d(xmit)^2}{d(recv)^2} = 2.9
\]

Table 3.3: CNR vs Uplink and Downlink Reflector Diameters
(This table is derived from Equation 3.13)

<table>
<thead>
<tr>
<th>Diameter in meters</th>
<th>4.5</th>
<th>6.1</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(uplink)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>-1.9</td>
<td>-5.2</td>
<td>-6.3</td>
<td>-12</td>
<td>-13</td>
<td>-18</td>
</tr>
<tr>
<td>4.5</td>
<td>1.4</td>
<td>-1.9</td>
<td>-3.4</td>
<td>-8.4</td>
<td>-10</td>
<td>-15</td>
</tr>
<tr>
<td>6.1</td>
<td>4.0</td>
<td>0.7</td>
<td>-0.8</td>
<td>-5.7</td>
<td>-7.5</td>
<td>-12</td>
</tr>
<tr>
<td>7</td>
<td>5.2</td>
<td>1.9</td>
<td>0.4</td>
<td>-4.5</td>
<td>-6.3</td>
<td>-11</td>
</tr>
<tr>
<td>11</td>
<td>9.1</td>
<td>5.8</td>
<td>4.3</td>
<td>-0.6</td>
<td>-2.4</td>
<td>-7.1</td>
</tr>
<tr>
<td>13</td>
<td>11</td>
<td>7.3</td>
<td>5.8</td>
<td>0.9</td>
<td>-1.0</td>
<td>-5.6</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>11</td>
<td>9.5</td>
<td>4.6</td>
<td>2.8</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

Above Demodulation Threshold RF Detection Detectable
Graph Relating Uplink and Downlink Dish Diameters

Figure 3.11
4. Interferometry

Polarization re-use is a typical method employed in the satellite industry for doubling the available bandwidth of a given allocated frequency band. Typical domestic communications satellites use orthogonal linear polarization to achieve this doubling of capacity. To suit this end, there exists a pair of cross-polarized multi-horn beam-forming antenna feed assemblies at the focus of a typical satellite reflector antenna assembly. These feed assemblies are spatially offset from each other by a few inches.

Because of uplink antenna system imperfections or less than optimal operation of a transmitting site, uplinked radiation arriving at the intended satellite typically has some measurable cross-polarization component. Strong cross-polarization video transmissions were observed by the Georgia Tech investigators. Occasionally these signals were strong enough to facilitate direct demodulation.

The use of the offset dual polarization feeds aboard the GSTAR series satellites facilitates the measurement of the differential phase of a received signal between these two feeds which are connected to separate satellite transponder inputs. These cross-polarized signals are independently relayed to a SILS site via the orthogonally
polarized downlink channels. A differential phase measurement referenced to the satellite antenna feeds is then performed. This measurement is related to geographic solutions corresponding to possible uplink locations. A map of CONUS with calculated curves of constant differential phase for GSTAR 1 appears in Figure 4.1.

As discussed in the introduction, the theoretical issues for the interferometric method of uplink location include geometry, RF budget analysis, and signal processing. The geometry has been determined as a closed form expression which allows the generation of terrestrial curves of constant differential phase given the known position of a satellite, the known spatial locations of the dual polarization offset transponder antenna feeds, and the measured electrical phase. This relationship is illustrated in Figure 4.1 using curves of constant differential phase for GSTAR 1 at Ku-band frequencies overlaid upon a Mercator projection map of CONUS. Because there are a multiplicity of difficult-to-determine fixed phase shifts throughout the system, offset corrections are best implemented after calibration with signals from several known terrestrial sources.

The RF link analysis issues include determination of the signal level of each of the two polarization components in question into the satellite antenna feeds, the
Contours of Constant Differential Phase for Geosync Satellite over 103.0 W
polarization isolation of each component of the system, and the phase stability of all components between the satellite received antenna feeds and the SILS site receiver outputs.

Signal processing issues involve the recovery of the carrier differential phase information as measured between the two cross-polarized feeds aboard the afflicted satellite. Although a simple mixing process between the two received cross-polarized channels would appear to produce a voltage related to the desired value, there are other effects for which there must be an accounting. Ku-band signals are typically uplinked at about 14 GHz then down-converted within the satellite to a downlink frequency of about 12 GHz. A pair of independent 2.3 GHz local oscillators are used for each polarization’s set of 8 transponders on the GSTAR series of satellites. Because these oscillators are not locked to each other, the frequency shift in the spectra on the horizontal polarization’s signals will rarely be exactly the same as the shift in the vertical polarization’s signals. Calibration of the system to compensate for this net frequency offset requires the introduction into the transponder’s passband of a reference carrier which is sourced from a cooperating and known site.
4.1 Geometry

4.1.1 Locating the Satellite’s Interferometric Baseline

To employ the interferometric SIIS method, the location of the interferometric baseline must be known. For the most general geometric case, one should know the three-dimensional locations of the two orthogonally polarized phase centers of the receiving antennas onboard the satellite of interest to determine absolutely the location of the baseline. The mechanical diagrams for the GSTAR spacecraft show the receiving horns for each polarization to be in the spacecraft’s XZ plane. This is the plane which contains both a line connecting the satellite and the subsatellite point and Earth’s spin axis. Thus, the interferometric baseline must lie in the spacecraft’s XZ plane that intersects Earth as the line of longitude above which the spacecraft resides. This is shown in Figure 4.2.

Once the interferometric baseline is restricted to a
plane, only a single angle need be deduced. This was determined by learning the locations of the phase centers for each of the cross-polarized receiving horns aboard the spacecraft. This was done by reviewing the original GSTAR series antenna assembly mechanical drawings. However, phase offsets between channels are induced not only by the spatially displaced phase centers but also by the different signal paths through the satellite RF hardware, ground receiving RF hardware (which may change with experimental configuration), and through different downlink propagation paths which may change with time. Since it would be difficult to determine these phase offsets in an open loop fashion given the spacecraft mechanical configuration, it would be better to calibrate out these offsets by transmitting signals from known terrestrial sites through the spacecraft so as to determine the actual angle of the interferometric baseline.
Location of Interferometric Baseline in Spacecraft XZ Plane

Interferometric Baseline in the Spacecraft XZ Plane

Figure 4.2

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4.1.2 Terrestrial Curves of Constant Differential Phase

The relationship between measured electrical phase of signals at the GSTAR satellite feeds and possible uplink locations has been determined. Figure 1.7 shows the geometry relating the angle of a signal incident upon a GSTAR series satellite (and its associated interferometric baseline) to the desired terrestrial curve. Note that this geometry will change for a satellite with a different antenna feed configuration. Previously presented Figure 4.1 shows the desired result which illustrates curves of constant electrical differential phase across CONUS. This should be contrasted with previously presented Figure 1.4 which shows similar results for the Time Difference of Arrival method.

4.2. RF Link Analysis

The RF power budgets for each of the two signal paths of interest to the interferometry technique are similar and equally significant to that for the TDOA technique. However, the isolation between the two cross-polarized signals which traverse the cross-polarized paths from the "interfering" uplink station to the satellite and then to the SILS receiving antenna is a dominant factor in determining the realizability of the interferometric method. Therefore, experiments were performed to determine the
acceptability of the polarization isolation.

4.2.1. Cross-Polarization Isolation Experiment

One requirement for the proper operation of the interferometric system is that the unknown uplink signal contains some detectable cross-polarized component. Likewise, one must determine that the differential phase which is measured is actually due to imperfections in the polarization purity of the uplink in question. To be confident of this, the polarization purity of the other locations in the system where some polarization impurity may be introduced must be determined. Sources of cross-polarization impurity include:

1) The unknown uplink (desire impurity)
2) The satellite receive antenna (desire impurity)
3) The satellite transmit antenna (desire purity)
4) The SILS Site receive antenna (desire purity)

The satellites of interest typically employ a single antenna system for both the transmitters and receivers. Therefore, the desired purity of the satellite transmitting antenna will induce the same in the satellite receiving antenna if they are the same hardware. Thus, the most desired polarization impurity would be in the unknown uplink transmission system.

Experiments were developed to determine the polarization purity of the various portions of the hardware available to produce an interferometric system. They
involved the use of signals of various polarizations sent through various combinations of transponders some of which did or did not have an associated cross-polarized transponder.

As an example of a signal sent through two collocated (in frequency) cross-polarized transponders, Figure 4.3 shows a plot of relative received signal strength versus the polarization of the Georgia Tech Harris 6.1 meter receiving system. The signal strength was measured in dB above the local noise floor for a video signal feature downlinked through GSTAR 1 transponders 5 (horizontal) and 12 (vertical) at approximately 11950 MHz. Even when using a HP8558B spectrum analyzer's lowest resolution signal power scale to observe the Georgia Tech Harris 6531 receiver's 70 MHz IF output, the cross-polarized signal remained detectable in the "polarization null" which is 90 degrees from the desired polarization. In this case, it was desired that the observed cross-polarized component originate in the uplink's antenna system. Results from single transponder experiments with CW signals allowed determination of the polarization isolation for various portions of the system.

One can argue that the satellite antenna's polarization purity will be the best for the Georgia Tech experiments because of the offset reflector with polarization grid design which is employed in the present GSTAR series
satellites. The Georgia Tech Harris Delta Gain antenna also boasts a high degree of polarization purity [17] because of its unique feed design. However, a series of measurements were made which were designed to determine the polarization purity of the different parts of the available hardware.

An experimental goal was to test the satellite and the local SILS site receiving antenna’s cross-polarization characteristics with the assumption that a carrier sourced by GTE’s Tracking, Telemetry, and Control (TT&C) station had the best polarization purity in the system. To test the local antenna, it was necessary to guarantee that there existed no significant cross-polarization component radiating from the satellite. Therefore, a signal was uplinked into a portion of a transponder which shares no overlapping cross-polarized transponder. Once the local antenna’s polarization characteristics were determined, the GTE sourced carrier was moved in frequency to a portion of a transponder passband which shares an overlapping cross-polarized transponder to observe the satellite receiving antenna’s polarization purity. No signals originated at Georgia Tech because transmitter feed polarization and receiver feed polarization cannot be independently adjusted with the Georgia Tech system.

These polarization purity measurements were made by measuring received CW signal powers with the Georgia Tech
6.1 meter reflector system for various polarization rotations of the Georgia Tech antenna during four hours on 11 May 1988. GTE's Colorado TT&C station first transmitted a set of CW signals received at 12193 MHz with polarization angles of 0, 30, 60, and 90 degrees from the nominal satellite input polarization through a portion of transponder 16 on GSTAR 2 which has little overlapping cross-polarized transponder throughput. This set of transmissions of various polarizations was repeated at a received frequency of 12157 MHz which is in a segment of transponder 16 that overlaps cross-polarized transponder 8. Figure 4.4 shows the relationships between the transponder frequency band plan and the carrier frequencies employed.

Plots 1 through 8 (Figures 4.5 through 4.12) illustrate the received CNR levels for four TT&C polarization rotations through the overlapping and non-overlapping transponder passband segments. Although there were some problems with leakage of a cross-polarized component in the supposedly single channel portion of the transponder 16 passband due to the realistic filter characteristics of transponder 8, the results were as expected. CNR levels were measured by observing the difference in dB between the noise floor and CW signal peaks on a HP8558B spectrum analyzer which monitored the 70 MHz IF output of the Harris 6531 satellite receiver. The IF bandwidth of the spectrum analyzer was set
to 100 kHz. The Harris receiver's AGC system was temporarily defeated to facilitate impeding receiver induced changes in the observed noise floor.

The critical results are related to the depths of the notches in Plot 1 and Plot 4 (Figures 4.5 and 4.9) which respectively illustrate the cases of single transponder carrier transmission for a best aligned (co-polarized) uplink station and a worst aligned (cross-polarized) uplink station. For the scenario where power is transmitted from
Figure 4.4
Satellite Polarization Purity Experiment Frequency Plan

Downlink Frequency Band Plan for GSTAR Satellites

Non-Overlapping Transponder Signal

Overlapping Transponder Signal

12110 MHz
12130 MHz
12157 MHz
12193 MHz
12198 MHz
1206 MHz
12130 MHz
12157 MHz
12184 MHz
Uplink 0 Degrees from Best Copolarization
Single Transponder Transmission
Figure 4.5 - plot 1
Uplink 30 Degrees from Best Copolarization
Single Transponder Transmission
Figure 4.6 - plot 2

Polarization Angle of the Ga Tech 6.1 m Receiver System
Degrees

C/N, dB
Figure 4.7 - Plot 3
Single Transponder Transmission
Uplink 60 Degrees from Best Copolarization

Polarization Angle of the Ga Tech 6.1 m Receiver System
Figure 4.8 - Plot 4

Single Transponder Transmission

Uplink 90 degrees from best copolarization
Polarization Angle of the Ga Tech 6.1 m Receiver System Degrees
Figure 4.12 - Plot 8
Dual Transponder Transmission
UpLink 90 Degrees from Best Copolarization

Polarization Angle of the GA Tech 6.1 m Receiver System

Degrees
the satellite in only one polarization, one would like to see zero power reception for an orthogonally rotated SILS receiving antenna in both cases. Plot 1 shows a CNR drop from about 40 dB to 10 dB at the receiving antenna cross-polarization angle providing the least power transmission. This may be attributed to some combination of imperfect orthogonal transponder rejection and imperfect polarization purity in the Georgia Tech receiving antenna. The complete loss of signal (less than 0.5 dB CNR measured) for the worst uplink polarization alignment angle (where the GTE sourced signal is 90 degrees from co-polarized) illustrated in Plot 4 suggests that the best polarization purity is in the satellite antenna. The other plots illustrate expected results for overlapping transponders.

The experimental result of a complete loss of signal for a cross-polarized uplink into a single polarization transponder channel indicates that there exists enough polarization purity in a full link using the Georgia Tech 6.1 meter SILS receiving system to allow isolation of a sufficiently strong cross-polarized component of an unknown signal for differential phase measurements. Uplinked signals with substantial cross-polarization components have been observed and sometimes directly demodulated. One may also conclude that better polarization isolation in the ground hardware at a permanent SILS site may provide
potentially better cross-polarization signal resolution than
the equipment used for these experiments affords.

4.2.2 Phase Stability of the Georgia Tech Earth Station

Originally it was hoped that there would be no
requirement to perform any sort of spectra realignment
between the received pair of cross-polarized signals.
Therefore, attempts were made to characterize the frequency
and phase stability of the receivers at the Georgia Tech
site. During a full loop transmission originating from
Georgia Tech, the received CW signal which was locally
sourced from a microwave frequency counter phase locked to a
temperature compensated crystal oscillator was observed to
drift more than 50 kHz over a 30 second period. This drift
is far too large for performing the desired differential
phase measurements. This local oscillator stability
examination process was simplified by the loan of one of GTE
Spacenet's test translators so as to avoid using satellite
transponder time to operate the full uplink/downlink loop.
There were numerous local oscillators involved in the full
loop test to which the observed drift may be attributable.
Some of these are in the Georgia Tech transmission path or
the test translator which would not effect the receive paths
of an interferometry system. Because of the inability to
adequately stabilize or phase lock all the local oscillators
together, a feedback approach was employed which uses a
reference signal.

4.3 Signal Processing

The paramount issues for the signal processing portion of the interferometric technique include the spectral realignment of the signals received from each polarization, the measurement of a differential phase between these two realigned signals, and the removal of any phase offsets induced by the paths traversed by these signals.

4.3.1. The Offset Spectra Problem

There is a spectra misalignment problem to overcome before acquiring a differential phase which may be mapped into the desired terrestrial curves of possible uplink locations. The goal is to perform a remote differential phase measurement referred to the two cross-polarized feeds aboard the afflicted satellite. Figure 4.13 shows the two signal paths from satellite antenna to terrestrial IF outputs at 70 MHz with an emphasis on the frequency sources for the receiver's mixing schemes. The frequency sources include several oscillator technologies: temperature compensated crystal locked, ambient temperature crystal locked, and digital synthesizer with a crystal source. The twin local oscillators aboard the satellite which shift each polarization's bank of transponder signals from the 14 GHz uplink passband to the desired 12 GHz downlink passband are
Interferometry System Block Diagram

Figure 4.13

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not locked together. Thus, there are a multiplicity of sources for phase and frequency drift between the two signal paths. Therefore, there will exist some offset frequency between the two spectra presented at the receivers' IF outputs.

Even if the received and downshifted spectra were perfectly aligned, there exists the problem of interpreting the definition of differential phase for the situation where each signal occupies some non-zero bandwidth. For the trivial case of monochromatic signals, a mixer output provides a DC component which is related to the differential phase between the input signals. However, a typical satellite signal is often a broadband data or frequency modulated television signal.

4.3.1.1 Digital Signal Processing Approach

Several methods of correcting for the offset spectra have been proposed. One "total" digital signal processing solution involves shifting some portion of the spectrum of each signal close to baseband to facilitate the bandlimiting and digital sampling of a portion of each of two broadband transponder signals. The sampled frames from each signal path are transformed into the frequency domain. These digitally represented spectra are cross-correlated to determine their frequency offset by choosing the correlation
maximum as the offset frequency. One spectrum is shifted accordingly then the phase measurement is performed. The introduction of a known reference signal would greatly enhance this technique.

Drawbacks to the described DSP system include a lack of error frequency resolution due to both the minimum frequency increments of the discrete spectra and the potential broadness of a cross-correlation peak which would depend upon signal content. Were the frequency offset between spectra to exceed the filtered sampling bandwidth, a correction would be beyond the abilities of this method.

A problem analogous to that of the offset spectra is experienced by the Radio Astronomy community in the form of doppler shifts induced upon the spectra of signals received at antennas separated by this planet’s diameter when astronomical Very Long Baseline Interferometry (VLBI) is performed. A sampling of both the literature and conversations with various Radio Astronomy authorities indicated that their offset spectra problem is resolved by either an a priori inference of the induced offset frequency and an open loop change in one receiver’s (atomic clock referenced) local oscillator or the offset is determined from hours of off-line cross-correlation between long samples of the two received signals. Neither method was desirable for the SILS application.
4.3.1.2 Analog Spectra Realignment

Measurement of differential phase between two signals can be accomplished by directly comparing the phase of the two signals or by comparing the phase of each with a reference carrier. When performing phase measurements between a (reference) carrier and a broadband signal, the resulting energy within the passband of the mixer's product output can be so small as to elude simple detection.

Thus, it is preferable to mix a pair of broadband signals together to perform a phase measurement between them. Although it is possible that over large fractional bandwidths the phase would vary between time delayed signals, small fractional bandwidths produce consistent results. This was shown to be true in laboratory measurements between frequency modulated signals occupying hundreds of kilohertz centered near 70 MHz.

To facilitate the mixing of two broadband signals to determine their phase difference, the spectral misalignment or frequency offset induced by the two unlocked oscillators aboard the spacecraft must be removed before the phase measurement is performed.

Figure 4.15 shows the RF signal processing configuration used to perform the differential phase measurement between a pair of simulated satellite signals. A reference CW signal which would normally originate from a
Simulated Satellite Signal Generation with Offset Spectra Correction Hardware for the Interferometric SILS Technique

Figure 4.15
friendly terrestrial source is used to realign the spectra. This signal is transmitted so as to be received by the satellite on each of the two cross-polarized feeds. At the terrestrial SILS receiving site, each reference carrier is regenerated by a phase locked loop (PLL).

The output of one PLL differs in frequency and phase from the other PLL by the difference induced by each transponder oscillator's frequency offset and the angle of arrival of the reference signal at the satellite antenna. One can know the angle of arrival of the friendly reference signal and thus the resulting differential phase between received channels. Any additional phase and the frequency offsets are due to elements in the signal processing path which signals from any other source must also experience.

Therefore, to realign the resulting spectra, each channel's received spectrum is upconverted by the regenerated reference carrier derived from the other channel's received spectrum. The output of the vertical channel's PLL reference generated carrier is mixed with the spectra of the received horizontal channel to produce a desired product spectra at a higher frequency. The same is done for the other channel.

Thus, the differences in frequency between the two resulting higher frequency spectra are canceled out. These two spectra are band pass filtered to isolate a signal of
interest. They are then mixed to produce a product which has a DC component related to the phase between the input spectra which may be measured and integrated by a computer. The known phase offset due to the angle of arrival of the reference carrier is then subtracted out along with any known fixed offsets to produce the desired resulting differential phase between the chosen signals. This phase may then be mapped into a terrestrial map to produce a curve of constant differential phase on which the chosen signal's source must reside.

4.3.2 Phase Budgets

Figure 4.14 shows the signal paths relevant to the interferometric method from the satellite receiving antenna to the terrestrial SILS interferometric phase detector with an emphasis on the elements which effect frequency and phase. Radiation from both the interfering and reference uplink sources was present at the antenna. The incident radiation's geometric angle at the antenna induced an electrical phase difference between the cross-polarized receive feeds. Thus, the independent vertical and horizontal paths contained both signals but corresponding signals had different geometry dependent phases at points 1 and 2 in Figure 4.14. To facilitate the hardware which is later described, both signals are assumed to be unmodulated
Phase and Frequency Control Elements for the Interferometric SLIS System

Figure 4.14
carriers, and the frequency difference between the reference and interfering signals is assumed to be 5 MHz with the reference signal being the lower.

Throughout the following equations, this notation holds:

- \( r \): refers to the reference carrier
- \( s \): refers to the interfering signal
- \( h \): refers to the horizontally polarized channel
- \( v \): refers to the vertically polarized channel
- \( L \): refers to the SILS site downconverter local oscillator

**Incident Reference and Interfering Radiation**

\[
\text{Equation 4.1: } \quad r_i = A_{ir} \cos(\omega_{rt}) \\
\text{Equation 4.2: } \quad s_i = A_{is} \cos(\omega_{st})
\]

where:
- \( \omega_r \): Reference uplink frequency
- \( \omega_s \): Interfering uplink frequency
- \( A_x \): Various signal amplitudes
- \( \theta_x \): Various signal phases
- \( r_i \): Incident Reference Carrier
- \( s_i \): Incident Interfering Signal

**Signals at Point 1**

\[
\text{Equation 4.3: } \quad r_1 = A_{r1} \cos(\omega_{rt} + \theta_{rv}) \\
\text{Equation 4.4: } \quad s_1 = A_{s1} \cos(\omega_{st} + \theta_{sv})
\]

**Signals at Point 2**

\[
\text{Equation 4.5: } \quad r_2 = A_{r2} \cos(\omega_{rt} + \theta_{rh}) \\
\text{Equation 4.6: } \quad s_2 = A_{s2} \cos(\omega_{st} + \theta_{sh})
\]

The signals next experienced the mixing stage for conversion from the 14 GHz uplink band to the 12 GHz downlink band. Because the two independent onboard oscillators were not locked, the spectra at points 3 and 4
in Figure 4.14 are now offset in frequency by the difference between the 2300 MHz oscillators. The microwave filters following the mixing stage rejected the higher mixing product and the other products developed from the typically saturated amplifier used by full transponder signals.

Signals at Point 3

Equation 4.7: \[ r_3 = A_{r3} \cos[(w_r - w_v)t + \theta_{rv} - \theta_v] \]
Equation 4.8: \[ s_3 = A_{s3} \cos[(w_s - w_v)t + \theta_{sv} - \theta_v] \]

Signals at Point 4

Equation 4.9: \[ r_4 = A_{r4} \cos[(w_r - w_h)t + \theta_{rh} - \theta_h] \]
Equation 4.10: \[ s_4 = A_{s4} \cos[(w_s - w_h)t + \theta_{sh} - \theta_h] \]

where: \( w_v \) = Vertical transponder LO frequency
\( w_h \) = Horizontal transponder LO frequency
\( \theta_v \) = Vertical transponder LO phase
\( \theta_h \) = Horizontal transponder LO phase

The signals were then transmitted back to Earth where they were collected and amplified at the SILS site and downconverted in a pair of phase locked downconverters. These downconverters generated their internal microwave local oscillator frequencies by multiplying an externally generated and shared VHF signal. The received signals appear at the output of the downconverters at points 5 and 6 in an intermediate frequency band centered at 70 MHz. The SILS site local oscillator is tuned to center the
interfering signal at 70 MHz and the reference signal at 65 MHz. The channels retained their frequency offset from each other by the difference between the satellite's local oscillators.

**Multiplied Local Oscillator before Mixing in the Downconverter**

Equation 4.11: \[ \text{LO} = A_{LO} \cos(\omega_L t + \theta_L) \]

**Signals at Point 5**

Equation 4.12: \[ r_5 = A_{r5} \cos[(\omega_r - \omega_v - \omega_L) t + \theta_{rv} - \theta_v - \theta_L] \]
Equation 4.13: \[ s_5 = A_{s5} \cos[(\omega_s - \omega_v - \omega_L) t + \theta_{sv} - \theta_v - \theta_L] \]

**Signals at Point 6**

Equation 4.14: \[ r_6 = A_{r6} \cos[(\omega_r - \omega_h - \omega_L) t + \theta_{rh} - \theta_h - \theta_L] \]
Equation 4.15: \[ s_6 = A_{s6} \cos[(\omega_s - \omega_h - \omega_L) t + \theta_{sh} - \theta_h - \theta_L] \]

where: \( \omega_L = \text{SILS LO frequency} \)
\( \theta_L = \text{SILS LO phase} \)

The phase locked loops regenerated only the 65 MHz reference carriers. Therefore, only the CW reference carriers appeared at points 7 and 8 following the PLLs.

**Signals at Points 7 and 8**

Equation 4.16: \[ r_7 = A_{r7} \cos[(\omega_r - \omega_v - \omega_L) t + \theta_{rv} - \theta_v - \theta_L] \]
Equation 4.17: \[ r_8 = A_{r8} \cos[(\omega_r - \omega_h - \omega_L) t + \theta_{rh} - \theta_h - \theta_L] \]

Helical resonator and SAW Bandpass filters centered at
70 MHz isolated the interfering signal. Thus the interfering signals appeared alone at points 9 and 10.

Signals at Points 9 and 10

Equation 4.18: \[ s_9 = A_s9 \cos[(w_s-w_v-w_L)t + \theta_{sv}-\theta_v-\theta_L] \]

Equation 4.19: \[ s_{10} = A_{s10} \cos[(w_s-w_h-w_L)t + \theta_{sh}-\theta_h-\theta_L] \]

The interfering signal at point 9 was mixed with the the regenerated reference signal at point 8. The higher product is retained by the following filter. This adds all the accumulated phases and shifts the frequency from earlier stages to produce the signal at point 11. The same is done with the signals at points 7 and 10 to produce the signal at point 12.

Signals at Points 11 and 12

Equation 4.20: \[ s_{11} = A_{s11} \cos[(w_s-w_v-w_L+w_r-w_h-w_L)t + (\theta_{sv}-\theta_v-\theta_L+\theta_{sr}-\theta_h-\theta_L)] \]

Equation 4.21: \[ s_{12} = A_{s12} \cos[(w_r-w_v-w_L+w_s-w_h-w_L)t + (\theta_{sr}-\theta_v-\theta_L+\theta_{sh}-\theta_h-\theta_L)] \]

Each of the signals at points 11 and 12 had the same frequency. Therefore, this pair of signals was mixed and lowpass filtered to produce a DC term which contained an unknown amplitude, a known reference differential phase, and the desired but unknown interfering signal's differential
phase. This final amplitude consisted of the phase detector’s losses and the amplitudes of the signals entering the phase detector. Section 4.3.3 discusses the removal of the unknown amplitude. This leaves only the desired unknown differential phase from the interfering uplink transmitter.

The Resulting DC Term at Point 13

Equation 4.22: \[ V_{13} = A_{13} \times \cos[ (\theta_{rh} - \theta_{rv}) + (\theta_{sv} - \theta_{sh}) ] \]

where:
- \( V_{13} \) = The measurable (known) mixer output voltage
- \( A_{13} \) = An unknown scaling factor due to losses and earlier signal amplitudes
- \( (\theta_{rh} - \theta_{rv}) \) = The known electrical phase induced by the known incident angle of the reference signal
- \( (\theta_{sv} - \theta_{sh}) \) = The unknown electrical phase induced by the unknown incident angle of the interfering signal

4.3.3. Amplitude Independent Phase Measurement

A Metrabyte interface card provided by GTE was used in an IBM XT compatible computer to sample digitally the voltage output of the phase detector and to control the phase detector calibration circuitry. Note that the phase detector employed is a stock RF mixer which has been optimized to provide a larger DC output to facilitate phase measurement. The output from the phase detector was low pass filtered to about 1 kHz by an analog circuit to facilitate digital sampling and removal of higher mixing products. This low frequency signal was then oversampled by
the computer. The computer integrated (averaged) over thousands of samples to determine the average DC level output from the phase detector which was related to the phase difference between signals entering the phase detector.

Because the average DC level output from this type of phase detector is related to not only the desired phase difference but also the entering signal amplitudes, a method was needed for removing these possibly unknown amplitudes from the formula for computing the desired numerical phase angle. This is traditionally done in interferometric direction finding (DF) systems by hard limiting both incoming channels to a known power level and then mixing the two signals to achieve a DC voltage which corresponds to the desired phase angle. The SILS system employed a different approach.

The RF signal amplitude ambiguities were removed by alternately inserting and removing a known length of cable into and from one of the entering RF signal paths to induce a specific phase shift at the known frequency of measurement. This provides two equations for the two unknowns of differential phase and amplitude. By measuring the mixer's lowpassed DC outputs both with and without the extra cable length inserted, it is possible to solve numerically the underlying non-linear equations for both
signal amplitude and phase difference. This is illustrated below.

A pair of voltage signals are modeled as:

Equation 4.23 \[ V_1 = A_1 \cos(w_1t + p_1) \] [volts]

Equation 4.24 \[ V_2 = A_2 \cos(w_2t + p_2) \] [volts]

where: \( V \) = [volts] Measurable voltage
\( A \) = [volts] Amplitude
\( w \) = [rad/sec] Angular frequency
\( t \) = [sec] Time
\( p \) = [rad] Phase

Ignoring higher mixing products by assuming that a mixer is a perfect multiplier, the mixing of this pair of signals gives at the mixer output:

\[ V_{\text{mix}} = A_1 A_2 A_{\text{mix}} \left( \cos[(w_2+w_1)t + p_2+p_1] + \cos[(w_2-w_1)t + p_2-p_1] \right) \]

If the frequencies are the same \((w_1 = w_2)\), then:

\[ V_{\text{mix}} = A_1 A_2 A_{\text{mix}} \left( \cos[(2w_1)t + p_2+p_1] + \cos[p_2-p_1] \right) \]

Lowpass filtering to remove the double frequency product term gives:
Equation 4.27

\[ V_{\text{mix|lpf}} = A_1 A_2 A_{\text{mix}} A_{\text{lpf}} \cos(p_2 - p_1) \] [volts]

\[ = A_T \cos(p_2 - p_1) \] [volts]

where:  
- \( A_1 \) = Signal 1’s original voltage amplitude  
- \( A_2 \) = Signal 2’s original voltage amplitude  
- \( A_{\text{mix}} \) = Amplitude changes attributable to the mixer  
- \( A_{\text{lpf}} \) = Amplitude changes attributable to the lowpass filter  
- \( A_T \) = The combined total amplitude

The signal amplitudes, mixer losses, and lowpass filter losses will all vary depending on the strength of the incoming signals and variations in the RF signal processing components. Thus, the measurable voltage, \( V_{\text{mix|lpf}} \), is related to not only the desired differential phase, \( p_2 - p_1 \), but is also proportional to the unknown total amplitude \( A_T \).

The insertion and removal of the known length of transmission line at one of the mixer inputs produces a phase shift, \( p_L \) which depends on the known frequency of the mixer’s input signals. Now two equations are available. One relates a measurable mixer output voltage to the differential phase without the line inserted. The other relates the measurable voltage to the phase difference plus the additional phase induced by the additional transmission line length. The new equations are:

Equation 4.28  
\[ V_{\text{short}} = A_T \cos(p_2 - p_1) \] [volts]

Equation 4.29  
\[ V_{\text{long}} = A_T \cos(p_2 - p_1 + p_L) \] [volts]
Finding $p_2 - p_1$ requires the solution of Equations 4.28 and 4.29. Because they are non-linear, the following equation is numerically solved for $p_2 - p_1$ knowing $V_{\text{long}}$, $V_{\text{short}}$, and $p_L$:

$$V_{\text{long}} \cos(p_2 - p_1) = V_{\text{short}} \cos(p_2 - p_1 + p_L)$$

Equation 4.30

Computer software solved these equations and controlled both the phase detector output sampling and cable switching. The addition of computer controlled measurements reduced the time to make the measurements from a manual time of about a half hour to a few seconds with judicious adjustment of the sampling frequency, number of samples, and the analog filter characteristics.

4.4 Experimental Apparatus and Procedures

To test the offset spectra correction and other signal processing hardware, a series of laboratory tests were performed. This was done before attempting the more expensive live satellite tests. The laboratory tests required the generation of a pair of frequency shiftable spectra containing a reference carrier and a phase shiftable broadband or CW "interfering" signal. The satellite tests required signal transmissions from geographically separated pairs of locations which provided sufficient phase differences to illustrate desirable operation of the
4.4.1 Differential Phase Measurements with Laboratory Signals

To make laboratory measurements to test the interferometric technique, there was a need to generate two sets of signals with a frequency offset typical of that found at the IF outputs of the pair of satellite receivers local to the SILS site. Figure 4.15 illustrated the test configuration with the pseudo-transponders occupying the upper half of the illustration and the actual phase measurement hardware occupying the lower half.

Two signal generators are employed to provide the equivalent of transponder input signals. The 19 MHz oscillator is considered to be the cooperative SILS reference carrier. The 20 MHz oscillator is considered to be the non-cooperative unknown signal of interest. These signals are summed as illustrated to produce the equivalent of inputs into two transponders aboard a satellite. One of the paths from the 20 MHz "unfriendly" oscillator is connected to a variable length transmission line (ganged trombone sections or different lengths of coaxial cable) to simulate varying differential phase shifts and thus varying angles of incidence for the corresponding "unfriendly" radiation arriving at the satellite antenna. The angle of
incidence for the SILS reference carrier's radiation is assumed to be known because the location of the SILS uplink site and the orientation of the spacecraft is known.

The simulated transponder inputs at about 20 MHz are then mixed with approximately 50 MHz outputs from another pair of signal generators which are purposefully set to have frequency differences of about 0 to 10 kHz. These two signal generators with their slight offsets correspond to the two unlocked local oscillators aboard the satellite which feed the two sets of transponders associated with the two orthogonally polarized antenna feeds. The two spacecraft oscillators are expected to have frequency differences of less than 3 kHz.

The outputs from this pair of mixers provided a pair of spectra like that expected at the 70 MHz IF output ports for each of the orthogonally polarized receiving channels at a SILS site. Each spectrum consisted of a reference and an "unfriendly" CW signal.

Because interference is expected from broadband modulated signals (FM TV, PSK), the "unfriendly" source signal had the ability to be frequency modulated to give it a substantial bandwidth. The choice of 19 and 20 MHz for the simulated uplinked signals was motivated by the availability of signal generators. Although microwave signals could be used and fed into the receivers, the
results at the 70 MHz intermediate frequency are the primary concern for laboratory test of the offset spectra correction and phase measuring hardware.

4.4.2 Differential Phase Measurement with Live Satellite Signals

Figure 4.13 showed the total satellite signal path topology assumed with the two paths of interest being that of the reference and the interfering signal. As was previously discussed, this method of locating an interfering unknown uplink signal requires that an additional reference signal be present nearby in frequency. Because the Georgia Tech Earth station was hardware limited in its ability to transmit and receive simultaneously on two polarizations, it was requested that GTE supply the satellite signals.

To determine whether the interferometry method was indeed working, the "interfering" signal needed to be transmitted from at least two geographically separate sites to induce a substantial phase difference between the orthogonally polarized antenna feeds aboard the satellite of interest. The Grand Junction, Colorado TT&C site and the McLean, Virginia site of GTE presented a sufficient difference in the differential phase measured between the two spacecraft antenna feeds to demonstrate the effectiveness of this system if either GSTAR 1 (103 degrees west longitude) or GSTAR 2 (105 degrees west longitude) was
used and the model which generates the illustrated curves of constant differential phase was correct. However, this was not true for the case of GSTAR 3 which was located at 93 degrees west longitude and should have nearly identical differential phase shifts for signals originating at the Grand Junction and McLean sites.

After being informed by GTE that GSTAR 3 would be the satellite used for the interferometric tests, plots of the associated contours of constant differential phase were generated to learn the expected differential phase measurement results between the probable uplink sites. Figure 4.16 shows this plot against a Mercator projection of the continental United States with cross marks at the approximate locations of Grand Junction, Colorado, Atlanta, Georgia, and McLean, Virginia.

Figure 4.17 illustrates the CW signals which were transmitted from each of the two different sites during the two different portions of the experiment. Each signal appeared on frequency overlapping transponders in each polarization as is shown in the example of Figure 4.17. The lower frequency signal served as the reference CW signal with the higher frequency signal being the unknown or interfering signal. Due to the limitations of the experimental hardware, the signals needed to be separated by no less than 5 MHz and no more than 10 MHz and were to be as
powerful as is possible. The reference CW signals were locked with the phase locked loops, the offset spectra were realigned, then the two interfering signals were mixed together to produce the desired differential phase.

Each experiment involved two measurements. For the first measurement, the reference and interfering signal came from the same uplink site. For the second measurement, the interfering signal came from a geographically different site with the reference signal continuing to originate from the previous site. A knowledge of the location of both sites provided for observations of a difference in phase between the two sites and determination of any satellite specific phase shifts.

The experiments were planned so that one half hour was allocated to each pair of signals from each site. The accuracy of these measurements greatly depended on the phase purity and signal-to-noise ratio of the reference CW signal, therefore, the cleanest and most powerful reference carrier was requested.

Figure 4.13 shows a pair of band pass filters centered at 140 MHz preceding the inputs to the phase detector. These filters were not included in the experimental hardware. Fortunately, the mixing product that these filters should reject consists of the pair of received spectra which have been offset in frequency by twice their
Site 1                Site 2

Experiment 1: Jammer at Site 1

- f(ref)
- f(jam)

No Signal

Experiment 2: Jammer at Site 2

- f(ref)
- f(jam)

5 < f(jam) - f(ref) < 10 MHz

Desired Transmissions for Interferometry Experiment

Figure 4.17

Page 113
GSTAR 3 Signals for Interferometry Experiment
Both Signals Should Appear on Each Polarization

Figure 4.18
original error offset and thus should not correlate to produce a DC term within the phase detector.

The first experiment occurred on Thursday 15 February 1990 between 9 and 11 pm EST. GTE offered to provide the signals requested as is described above from Grand Junction and the McLean site with the Grand Junction uplink site providing the reference signal in addition to an "unknown" signal. The McLean signal originated with GTE's Ku-band Satellite News Gathering (SNG) truck which was parked outside their McLean, Virginia facility (immediately outside of Washington, DC). The second experiment occurred a week later on Thursday 22 February 1990 between 8:30 and 10:16 pm EST. Again, the Grand Junction site provided both reference and "unknown" signals with the second site being an Atlanta located and based Ku-band equipped SNG truck belonging to the local WXIA Channel 11 television station.

These choices of satellite and uplink locations result in several interesting observations. First, the predicted phase difference between Grand Junction and McLean was on the order of one degree or less while that between Atlanta and Grand Junction was about 12 degrees. Thus, one would expect to measure about the same differential phase between the Grand Junction and McLean signals assuming the differential phase contour model is correct.

A second point worth noting is that GSTAR 3 suffered an
accident during its trip to geosynchronous orbit which, amongst other things, resulted in its occupying an inclined orbit. This orbit requires that a terrestrial observer track the satellite through a celestial "figure eight" pattern during a 24 hour period which occupies an angular box with peak-to-peak widths of about 1.5 degrees of longitude and about 5 degrees of latitude. Because the satellite appeared to a terrestrial observer to be moving at its maximum northwesternly angular velocity at about 10 pm EST at the time of these experiments, all involved terrestrial antennas were required to constantly realign their azimuths and elevations to maintain relatively constant received power levels. This caused a continuous change to the received signal CNR levels. To a lesser degree, polarization purity is effected by a satellite moving out of the main radiation lobe of a linearly polarized terrestrial antenna and thus into a region of the antenna’s pattern where some power from each of the spatially orthogonal polarization components may be emitted or detected.

On each of the above mentioned evenings, GTE’s Grand Junction TT&C began transmitting a pair of CW signals at 14030 and 14035 MHz with the lower frequency signal being the reference and the other signal being the "unknown" uplink signal. These signals were transmitted from a
linearly polarized antenna which had been rotated approximately 45 degrees from either of GSTAR 3's horizontal or vertical polarization orientations. These signals were received by GSTAR 3, amplified and converted by the pair of onboard oscillators to signals at approximately 11730 and 11735 MHz then retransmitted back to Earth.

As Figure 4.13 illustrates, each orthogonally polarized pair of signals was received at Georgia Tech's dual feed 6.1 meter antenna, amplified by a pair of Ku-band low noise amplifiers (LNAs), then transported through coaxial cable at Ku-band frequencies to an identical pair of phase locked down-converters which mixed the signals down to 65 and 70 MHz. The dual polarity feeds of the Georgia Tech 6.1 meter antenna were used to receive the pair of cross-polarized signals. Phase locked loops were then locked to the now 65 MHz reference signals. The regenerated CW pair of signals were employed to realign the spectra from each received polarization which had become slightly offset due to the independent local oscillators onboard the satellite. Two 250 kHz wide surface acoustic wave (SAW) bandpass filters, centered at 70 MHz, were employed to isolate the "unknown" 70 MHz signals from the reference signal and other noise components in the received passband. This spectral realignment process resulted in the pair of 70 MHz "unknown" signals being centered at about 135 MHz where they were
mixed together to produce DC voltages related to their phase offsets.

The computer controlled sampling process previously described was used to remove the amplitude ambiguity and integrate out any remaining AC components in the voltage measurement. A computer program then inferred the phase difference between the two RF channels. These measurements were made continuously for periods of many minutes with results being intermittently written to the computer's hard disc.

4.5. Interferometric Results

4.5.1 Experimental Results - Laboratory and Live Signal Tests

Laboratory experiments demonstrated the desired operation of the offset spectra correction and differential phase measuring hardware using the experimental configuration described above in section 4.4.1. Various lengths of transmission line were employed as the variable phase element for one of the "unfriendly" signal paths. Available trombone sections provided a change in phase of only 5 degrees at 20 MHz. Larger phase changes were realized by using various lengths of coaxial cable. However, the use of coax cables required the breaking and then acquisition of phase lock as the cables were disconnected and reconnected. The use of trombone sections
facilitated the direct observation of a change of phase as the trombone sections' lengths were changed.

During the live satellite signal tests, attempts were made to equalize the received reference and "jammer" signal CNRs. However, as is discussed above, the constant angular motion of GSTAR 3 required periodic antenna realignment at each of the participating Earth stations. Thus the received signal powers and therefore CNRs appeared to change with time. The phase locked loops were able to remain locked to the reference signals throughout all of their power level changes during all experiments except for one instance when all GSTAR 3 signals were lost while attempting to realign the Georgia Tech antenna.

The "jammer" signal emitted during the transmission from the GTE SNG truck at the McLean, Virginia site was observed on a spectrum analyzer at the Georgia Tech site to occupy about 100 kHz as compared to the relatively low phase noise CW (narrowband) signals which were experienced for all other portions of the experiments. The equipment performed equally well with the wideband signal as with the carriers.

From the measured and averaged voltage values taken during the live satellite experiments, angles and powers were inferred as is discussed in section 4.3.2. From these results, mean differential phases and variances of the accumulated data from each of the four transmissions (Grand
Junction, McLean, Grand Junction, and Atlanta) were generated. These statistical results are presented in Tables 4.1 through 4.4 with data included as a function of lowering received power thresholds. The last column in the table indicates the percentage of the available data which had an inferred power level greater than the listed power threshold. As the actual measured voltage values for these two experiments would require a minimum of 20 pages to print, this data is not listed in this report.
Table 4.1
Reduced Data from First Grand Junction Transmission
Mean, Standard Deviation, and Percent of Data Used versus Power Threshold

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Table 4.4
Reduced Data from Atlanta, GA Transmission

Mean, Standard Deviation, and Percent of Data Used versus Power Threshold

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Tables 4.1 and 4.2 show the reduced data sorted by power threshold for the first experiment which was a measurement of the phase angle between Grand Junction and McLean. The standard deviation of the inferred angles for the samples above the higher -3.0 dBm power threshold is not the minimum deviation listed in the table. Thus, to choose a mean value to use as the estimated angle, a lower threshold was chosen which has a relatively low standard deviation for the included data. This was done in lieu of choosing the most powerful few samples or all the samples because this better removes transients (high power signals)
or periods when the computer continued to take samples but there were no desired signals present (low power signals).

Choosing the power threshold of -8.0 dBm for both the Grand Junction and McLean data gives mean angle values of 4.3 and 3.6 degrees respectively for the first day of measurements. Thus, a differential phase angle of less than one degree was acquired. Similarly choosing a power threshold of -3.0 dBm to minimize the standard deviation for the data of the second set of measurements resulted -27 and -50 degrees for Grand Junction and Atlanta respectively. This data is listed in Tables 4.3 and 4.4 and produced a differential phase angle of about 23 degrees which is a 3.1% error from the expected 12 degree result out of a possible 360 degree measurement.

Values of 4.3 and -27 degrees were measured for similar signals originating from Grand Junction for the two experiments. During the week between the experiments, parts of the hardware at the Georgia Tech site were reconfigured. This and other changes elsewhere along the signal paths may explain the difference in measured values. The absolute estimates are expected to vary with time. The differential estimates are the values of most interest.

The results from the first experiment reflect the expected small differential angle between the Grand Junction and McLean sites. Although the second experiment did result
in the desired non-zero measured angle between Grand Junction and Atlanta, there are several explanations for the discrepancy between the expected 12 and the estimated 23 degrees of differential phase. First, the employed geometric model assumes certain locations for the phase centers of the antenna onboard GSTAR 3 which were derived from the mechanical specifications for the antennas onboard the GSTAR satellite series. This may not necessarily be the case for the electrical phases. Second, all amplitude dependent effects had yet to be removed from the phase measurement hardware. Third, there may exist unknown mechanical or electronic effects resulting from the accident experienced by GSTAR 3 during its trip to orbit.

Tables 4.1 through 4.4 show a variety of inferred power levels for the different sets of data. Table 4.5 lists various signal CNR maximums and minimums which were recorded during the experiments. There appears to be no correlation between the standard deviations inferred from the measured voltages and the listed CNRs. The reference signal source was Grand Junction for all experiments.
Table 4.5

Maximum and Minimum Measured Carrier-to-Noise Ratios versus "Jammer" Signal Source Location for the Interferometry Experiments

<table>
<thead>
<tr>
<th>&quot;Jammer&quot; Location</th>
<th>Reference CNR</th>
<th>&quot;Jammer&quot; CNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td></td>
<td>[dB above the noise floor]</td>
<td></td>
</tr>
<tr>
<td>Grand Junction, CO</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>McLean, VA</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Grand Junction, CO</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>

The spectra were offset by 1091 Hz at 9:53 pm EST on the evening of the first experiment and by 1043 Hz at 10:16 pm EST on the evening of the second experiment. These values were acquired by inserting the reference carriers, which had been regenerated by the phase locked loops, into a pair of frequency counters which were phase locked to the same temperature compensated crystal oscillator. The two displayed values were subtracted to produce the frequency differences.

4.5.2 Mapping of Measurement Error

As in the TDOA case, the differential phase measurement is a non-deterministic value with its own set of statistics. This random variable may be mapped from the measurement
domain into the desired geographic contour domain. To do this in a mathematically rigorous form, the functions describing the mapping from the measurement to the geographic domains are required. The relevant equations are discussed for computational map generation purposes in Appendix C. Again, they are non-linear and do not facilitate an easy mapping of the random variable's statistics.

To further complicate a mapping from the measurement domain to the geographical domain, the actual measurements for the interferometric technique are made as a pair of voltages which will each have their own statistics. Although this pair of measurements is reduced to a single differential phase value as was previously discussed, the statistics of the original voltage measurements would now need to be carried through the latter mappings as a 2-dimensional set of probability distribution functions.

For reasons similar to the case of the TDOA measurements, a characterization of the measurement's statistics and mappings between domains is not included in this dissertation. However, the following example is included to illustrate the relationship between measurement statistics and the geographic consequences. After a series of measurements, data reduction, and normalization to the electrical phase reference frame shown in earlier
projections of curves of constant differential phase onto maps, an example differential phase measurement may be considered to be a gaussian random variable with a mean value of 50 electrical degrees with a standard deviation of 10 degrees. Mapping this measured mean and the sum and difference of the standard deviations gives the three geographic contours shown projected onto the map of Figure 4.19. The enclosed area may be considered to be the statistical first sigma region for this particular measurement. Combining this geographic result with that of a TDOA measurement gives a zone of maximum likelihood in which to search for an interfering uplink station.

Because of logistics limitations, an insufficient number of experiments were performed to produce an empirical table of CNR versus geographical error as was done for the TDOA location technique.

4.5.3 Combining TDOA and Interferometric Geographic Results

The simultaneous use of both the TDOA (via GSTAR 1 and GSTAR 2) and Interferometric (via GSTAR 1) methods is illustrated in Figure 1.9. The curves of constant differential delay and phase form intersections which are the three dimensional solutions to the uplink location problem. Although the intersections are not necessarily orthogonal over all of CONUS and their intersections will be
Contours of Constant Differential Phase for Geosync Satellite over 93.0 W

Interferometric Contours of First Sigma Region

Fig. 4.19
an area of size determined by carrier-to-noise ratios and
geometry determined by the noise statistics, they give much
better solutions than an overlap of two sets of differential
delay or two sets of differential phase measurement results.
To facilitate rapid computer determination of the
intersections of the time delay and interferometric curves
for an automated scenario, a set of solutions may be
generated off-line for rapid recall or an iterative
numerical approach may be used.

5. Conclusions

As discussed above, the goal of the presented research
was to develop theoretically and to illustrate
experimentally the TDOA and interferometric methods for
locating a terrestrial satellite uplink station. In each
case, the theoretical analysis consisted of understanding
the geometry, RF signal power budget, and signal processing
issues. Experiments provided measurements of differential
delays and phases between actual satellite signals which
have been mapped into terrestrial curves corresponding to
actual uplink station locations.

The TDOA technique has been successfully performed on
numerous occasions both with Georgia Tech and GTE Spacenet
facilities to the satisfaction of technically competent
observers. All of the experimental observations to date
have been performed with the more difficult "targets-of-opportunity" as contrasted to the provision of a contrived set of signals originating from a previously designated location.

The more complicated interferometric method was successfully tested in two experiments conducted with custom built hardware. The experiments were conducted on 15 February 1990 and 22 February 1990. The results confirm the feasibility of the interferometric system. These tests were observed by Smith and Professors Steffes and Aubrey M. Bush of the Georgia Tech School of Electrical Engineering.

Regardless of the method of parameter measurement, if a stochastic description of the noise characteristics can be acquired, then this can be mapped through the deterministic equations which relate differential delay or phase to terrestrial curves into geographic error probability regions. Thus, for example, the terrestrial intersection of the first sigma region for a typical TDOA measurement with this system and that of a interferometry measurement may be found to occupy an area of 10,000 square miles which contains the potential uplink site. Figure 4.20 geographically illustrates the combination of the earlier TDOA and Interferometric statistical examples.

The originality of this work has been documented in the history (Section 2.0) presented above. The paper by Smith
and Steffes [8] is the first in the refereed press to describe theoretically and to present experimental results of an operational TDOA system. These efforts provided the first implementation of a Ku-band TDOA system. Although the Hughes documents are not clear on the dates of their C-band TDOA experiments, the Georgia Tech investigators may be the first to implement any sort of a TDOA system. This research is believed to be the first to implement spacecraft-based short baseline interferometry for location of ground stations. The Georgia Tech investigators appear to be the first to demonstrate this type of interferometry.

While the feasibility of the TDOA system has been successfully demonstrated, the Georgia Tech researchers' limited resources did not allow constant maintenance of an operating TDOA system because the hardware was shared with interferometry research and scheduled uplink and downlink sessions. Were the goal to maintain an operational TDOA system, upgrades to the system should include signal processing software, faster analog-to-digital conversion hardware, and various methods of signal correlation that differ from the presented post-demodulation measurement of differential delays employing measurement by operators via an oscilloscope display. Further suggestions are discussed in Section 6.
6. Suggestions for Further Research

This research was the first full attempt at realizing a Satellite Interference Location System. Each aspect of this system could be analyzed to the depth of an individual dissertation. However, the goal of this work was to demonstrate the global system feasibility. This has been done for the TDOA and interferometric techniques.

The following list includes a few areas for further research or modification to the existing system which should further facilitate SILS activities.

6.1 Spacecraft Modification

The Satellite Interference Location System (SILS) development project focused on developing a system which could locate the position of uplink transmitters using existing, on-orbit satellites such as GTE's GSTAR 1 and GSTAR 2. However, as new satellites are designed, it is possible that some relatively simple and low-cost changes in spacecraft antenna design may further facilitate the location of uplink signal sources.

6.1.1 Increasing G/T with Spacecraft Test Transponder

A significant source of difficulty for both the TDOA and interferometric techniques lies with the fact that one of the two signal channels required for each technique
carries an especially low level signal. In the case of the TDOA technique, this occurs because one of the two satellites being used for the time delay measurement is being illuminated only by a low level sidelobe from the uplink transmitter.

A receiving system's "G/T" ratio is a figure-of-merit employed by the microwave community which relates an antenna gain to the system noise temperature. A need for a large antenna gain and low noise temperature imply that a large G/T is desired. This quantity usually is expressed with units of dB/K which is the decibel form of the (linear) antenna gain divided by the system noise temperature in degrees Kelvin. This measure is used to specify receiving Earth stations as well as satellite receivers. For the satellite which may have a beam-forming antenna network to facilitate service to specific geographic areas, the satellite manufacturer will specify the satellite G/T as a function of terrestrial location.

Two approaches to increasing the level of the sidelobe signal received through what previously has been called the "adjacent" satellite can be used. The first is simply to increase the G/T of the ground station which receives the sidelobe signal. While this is an effective solution, the overall CNR of this signal is limited ultimately by the "uplink" CNR, which is related to the spacecraft G/T.
Therefore, any approach for increasing the G/T of the "adjacent" spacecraft would be helpful. It is noteworthy that the antenna systems used with the GSTAR spacecraft actually contain 13 separate beams. In the transmit mode, six of these beams can be used as an "Eastern-US spot beam". The remaining seven can form a "Western-US spot beam". All 13 can be summed to form a continental US (CONUS) beam [18]. However, in receive mode, all 13 beams are presently automatically combined to form a single CONUS beam.

One effective way to increase the G/T of the spacecraft receiver for SILS purposes would be to allow access by a tunable test transponder to any one of the 13 individual receiving beams. Because of the smaller beam size and effective higher gain, the resulting G/T would be significantly higher. A typical scenario would be that an interfering signal appears on GSTAR 2 transponder 6. The adjacent enhanced GSTAR 1 then sets its tunable transponder to channel 6 and scans through each of 13 beams until the best CNR from the sidelobe of the interfering signal is obtained as received by the SILS site. Not only does this facilitate the TDOA/SILS process, but it narrows the possible locations of interfering signal by beam position selection. However, this still requires that transponder 6 on the "adjacent" satellite (GSTAR 1) not be illuminated by an uplink from the same geographic region as the interfering
signal.

6.1.2 Additional Feedhorns for Spacecraft Interferometer

One very cost effective method for improving the ability of a single spacecraft to make interferometric measurements of uplink transmitter location involves placing additional feed horns on the spacecraft. Interferometric measurements of the position of an uplink transmitter are made by using the vertically polarized and horizontally polarized feeds as the two elements of the interferometer. However, because one of the feeds will be orthogonally polarized to the incoming signal, the received signal is extraordinarily weak, making phase comparison by the SILS ground station difficult. If additional co-polarized feeds were available, interferometric measurements can be made with less difficulty. It should be noted that the feed horns used for interferometry need not be nearly as large and complex as the 13 horn arrays used for the regular communications CONUS beams. This is because only the phase of the incoming signal needs to be measured. Any amplitude variations across the beam would have little effect on the resulting interferometric measurement.

Thus, in addition to the 16 feed horns used for each polarization on the current GSTAR spacecraft, an additional horn should be available which capable of providing a very
wide beam (covering CONUS) for each polarization. The two horns (one for each polarization) should be switchable to the inputs of any transponder so as to make improved interferometric measurements possible.

For example, an interfering signal is observed on transponder 5 of an upgraded GSTAR 1. (The signal is vertically polarized and is at a frequency of 14.280 GHz.) Now the "additional" vertically polarized horn can be connected to the input of transponder 13, which normally receives only horizontally polarized signals. Thus, two channels of information are downlinked at 11.980 GHz, one with horizontal polarization (output of transponder 5) and one with vertical polarization (output of transponder 13), and each will carry the interfering signal. However one will carry the interfering signal as received with the normal 13 beam CONUS array, and another with the single horn beam. The difference in the phases of the receiving signals is used to infer uplink station position. If yet an additional horn providing full CONUS coverage could be added for each polarization (a total of 4 horns), then a second baseline would exist, whereby the exact location of the interfering signal could be deduced. It should be noted that the spacing between the additional horns and the main feed arrays are limited by the focal range of the individual reflectors. When using the orthogonally polarized feeds for
the baselines, the spacing between the orthogonally polarized reflectors also contributes to the baselines.

6.1.3 Phase-Locking of the 2300 MHz Spacecraft Local Oscillators

Many of the existing domestic communications satellites employ the polarization re-use technique which is exploited by the interferometric SILS technique. The GSTAR Ku-band series of GTE satellites each have a pair of 2300 MHz oscillators which are the local oscillators for down-conversion from the 14 GHz uplink frequency band to the 12 GHz downlink frequency band. The down-converters of the vertically polarized transponders employ one local oscillator while the down-converters of horizontally polarized transponders employ the other oscillator. The use of these two independent and redundant oscillators facilitates the continued operation of half of the transponders should some portion of one of the down-conversion circuits fail.

The GSTAR spacecraft technical characteristics literature states that the oscillators will experience less than one part per million frequency drift per month [22]. This maximum frequency offset between the oscillators of 2300 Hz does not facilitate simple phase measurement by direct mixing. Therefore, it is suggested that the spacecraft local oscillators be phase locked to a common source.
One method for locking to a common source may be to treat one of the oscillators as a master and drive a second slave oscillator from the master. Should the master fail or drift out of an allowable passband, the second oscillator could continue at its own natural resonant frequency. Thus, the benefits of the redundant second oscillator are retained.

6.2 Computer Controlled TDOA

All of the TDOA measurements were acquired by slope demodulating frequency modulated television signals observed on an adjacent satellite with a manually tunable spectrum analyzer which was also employed to observe the afflicted transponder’s output spectrum for the signal of interest. This adjacent baseband signal was compared with that from the primary satellite which was similarly detected or from a satellite television receiver to determine the time difference between signals. This measurement was then mapped into a geographic curve containing the possible uplink locations.

These measurements were performed by having a user manually tune some combination of satellite receivers and spectrum analyzers and then view both baseband signals on a dual trace oscilloscope to generate the differential time measurement. The measured value was then typed into a
There exist several possibilities to facilitate automating the TDOA measurement process at a SILS site. One route involves buying commercially available test equipment and connecting it via computer interface busses. For example, a pair of Hewlett Packard HP8566B spectrum analyzers which are fully controllable over the IEEE-488 (GPIB or HPIB) digital interface bus may be used as two digitally controllable tuners for producing a pair of baseband outputs. These outputs can be fed to a pair of analog-to-digital converters which are realizable as a multiple trace digital oscilloscope. Such oscilloscopes are available as full test instruments with their own front panel and displays or as outboard data acquisition modules which must be connected to a host computer for user interface. Should two identical spectrum analyzers be used, the locking together of each of their oscillators would be desirable to guarantee that they are observing the same signal.

If the features similar to that found on a pair of $57000 HP8566B$ spectrum analyzers are not required, a computer controlled downconverter followed by a bank of computer switched filters for slope demodulation similar to that which occurs in the variable bandwidth IF sections of commercially available spectrum analyzers followed by a
video detector can produce the baseband signals. This more custom configuration may more economically suit the application.

6.3 Improved Phase Detectors

Better phase detection hardware is recommended for future interferometric based SILS systems. Some problems with the phase detector which was employed for this system appear to stem from saturation of the amplifiers preceding the mixer that produced the DC voltages that should be related to the desired differential phase. To maintain linear amplifier operation and thus minimum phase distortion over a wide dynamic range, an automatic gain control loop consisting of RF power couplers and electronically variable attenuators is suggested.

The employed phase detector also took pairs of DC measurements between RF paths containing switched lengths of transmission line which purposely introduced an additional fractional wavelength time delay into one of the incoming signal paths. A knowledge of these pairs of voltages, the measurement frequency, and the difference in lengths of transmission line allowed for numerical solution of the differential phase angle independent of the incoming signal amplitude. Because such a scheme is more sensitive to noise induced errors in certain parts of its voltage versus
differential phase characteristic, this method could be optimized to perform in the lower error portions of the mentioned characteristic by introducing a multiplicity of various length computer switched transmission line segments.

6.4 Confirmation for Curves of Constant Differential Phase

Geographic plots of constant differential phase contours were generated in an open loop fashion by assuming the locations of phase centers of the onboard satellite antenna system based on spacecraft mechanical drawings. It is recommended that a survey be taken by having signals transmitted from many different geographic sites. This could be accomplished by having a SNG truck drive north from the southern tip of Texas while stopping occasionally to perform a transmission in conjunction with another facility similar to the GTE TT&C at Grand Junction. A more practical method of performing such a survey would be to accumulate data from "targets-of-opportunity" such as SNG customers over a several week period by having them transmit some signal in conjunction with reference signals from a cooperating SILS reference site as a part of the SNG's uplink initiation procedure.
A. TDOA Equation Derivation

This section describes equations which generate a set of terrestrial curves of constant differential delay which may be projected onto a map for use with the TDOA location method. Section 3.1 above outlines a method for generating a series of points whose locus forms one of the desired curves. The relevant known quantities are the longitudes of the two geosynchronous satellites of interest, the radius of the Earth, and the altitude of the geosynchronous satellite.

To generate one curve, a differential time is assumed. Using this differential time, the corresponding differential propagation distance (at the speed of light) is determined. Two new lines, $d_{te}$ and $d_{tw}$, are generated with lengths differing by this differential distance. Each of these new lines will connect the satellite to the Earth’s surface as is illustrated in Figure A.1.

To begin, the shorter of these new lines is set equal to the altitude of one satellite. This shorter line connects one satellite to its subsatellite point. The other line connects the second satellite to the Earth but touches the Earth’s surface at some distance from the second subsatellite point. A terrestrial circle is formed around the second subsatellite point with a radius which intersects the second line.
Earth's North Pole

Arc of Possible Solutions

SubSatellite Point

East Satellite

dte

West Satellite

dtw

Geosynchronous Arc

3 Dimensional TDOA Geometry for Triangle Constructions
Triangle Construction for Generation of Terrestrial Curves of Constant Differential Delay

Figure A.2
Distances are incrementally added to each new line ($d_{te}$ and $d_{tw}$) and corresponding subsatellite circles are formed around each subsatellite point. The intersections between these two circles are the points of interest. As the distances are incrementally added to $d_{te}$ and $d_{tw}$, the locus of the intersections of the two subsatellite circles form the desired terrestrial curves.

Figure A.2 illustrates a two dimensional slice through the Earth's equatorial plane showing the relevant geometry. The known variables are:

- $alt = [35784 \text{ km}]$ altitude to the satellite
- $r_p = [6378 \text{ km}]$ radius of planet Earth
- $r_{sat} = [42162 \text{ km}]$ radius of the satellite's orbit
- $longe = $ [degrees east] longitude of the eastern satellite
- $longw = $ [degrees west] longitude of the western satellite
- $d_{te} = d_{tw} + (a \text{ fixed differential distance})$ [km]

The first goal is to solve for angle $e$ in Figure A.2. Adding angle $e$ to $longe$ gives the longitude of the intersection of the subsatellite circles. This is accomplished by application of basic triangle relationships.

From the law of cosines:

**Equation A.1:**

$$d_{te}^2 = r_p^2 + r_{sat}^2 - 2 * r_p^2 * r_{sat}^2 * \cos(a)$$

**Equation A.2:**

$$d_{tw}^2 = r_p^2 + r_{sat}^2 - 2 * r_p^2 * r_{sat}^2 * \cos(b)$$

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The relationships relating the distances between Earth's center and the planes formed by the eastern and western subsatellite circles and the angles \( a \) and \( b \) are:

Equation A.3: \[ r_e = r_p \cdot \cos(a) \]
Equation A.4: \[ r_w = r_p \cdot \cos(b) \]

Solving each equation for the common term \( r_p \) and combining Equations A.3 and A.4 to remove \( r_p \) leaves:

Equation A.5: \[ \frac{r_e}{r_w} = \frac{\cos(a)}{\cos(b)} \]

Similarly, angle \( e \) and angle \( w \) may be related to the cosines of angles \( a \) and \( b \) by the sharing of side \( z \) between two triangles.

Equation A.6: \[ r_e = z \cdot \cos(e) \]
Equation A.7: \[ r_w = z \cdot \cos(w) \]
Thus:

Equation A.8: \[ \frac{r_w}{r_e} = \frac{\cos(w)}{\cos(e)} \]

Angles \( e \) and \( w \) are related by:

Equation A.9: \[ \text{differential} = \text{longw} - \text{longe} = e + w \]
Therefore, substituting from equation A.9 into Equation A.8 gives:

Equation A.10:
\[
\frac{r_w}{r_e} = \frac{\cos(w)}{\cos(e)} = \frac{\cos(difflong - e)}{\cos(e)}
\]
\[
= \cos(difflong) \cdot \cos(e) + \sin(difflong) \cdot \sin(e) \cdot \cos(e)
\]
\[
= \cos(difflong) + \sin(difflong) \cdot \tan(e)
\]

Solving equation A.10 for \(\tan(e)\) gives:

Equation A.11:
\[
\tan(e) = \frac{\frac{r_w}{r_e} - \cos(difflong)}{\sin(difflong)}
\]

Recalling the relationship from Equation A.5 relating \(\frac{r_w}{r_e}\) to \(\cos(a)/\cos(b)\) gives:

Equation A.12:
\[
\tan(e) = \frac{\frac{\cos(b)}{\cos(a)} - \cos(difflong)}{\sin(difflong)}
\]
Again, from the law of cosines:

Equation A.13:
\[
\cos(a) = \frac{(d_{te}^2 - r_p^2 + r_{sat}^2)}{-2 \cdot r_p^2 \cdot r_{sat}^2}
\]

Equation A.14:
\[
\cos(b) = \frac{(d_{tw}^2 - r_p^2 + r_{sat}^2)}{-2 \cdot r_p^2 \cdot r_{sat}^2}
\]

Replacing \(\cos(b)/\cos(a)\) with Equations A.13 and A.14 gives:

Equation A.15:
\[
\begin{align*}
e &= \arctan \left[ \frac{(d_{tw}^2 - r_p^2 - r_{sat}^2)}{(d_{te}^2 - r_p^2 - r_{sat}^2)} \right]
\end{align*}
\]

Angle \(e\) has been found. Note that angle \(e\) is the offset from the eastern satellite longitude. Therefore, the geographic longitude is found by:
Equation A.16:

Longitude = longe + e [degrees]
    if T>0 (Uplink west of satellites)

= longe - e [degrees]
    if T<0 (Uplink east of satellites)

where: T = [seconds] Differential time of arrival
        (Eastern Signal - Western Signal)

The latitude is found by noting that:

Equation A.17: \( \cos(a) = \cos(\text{latitude}) \times \cos(e) \)

Solving for \( \cos(\text{latitude}) \) gives:

Equation A.18: \( \cos(\text{latitude}) = \cos(a)/\cos(e) \)

Substituting the relationship of Equation A.13 for \( \cos(a) \)
and solving for latitude gives:

Equation A.19

\[
\text{Latitude} = +/- \arccos \left( \frac{r_p^2 + r_{\text{sat}}^2 - d_{\text{te}}^2}{2 \times r_p^2 \times r_{\text{sat}}^2 \times \cos(e)} \right)
\]

thus providing both the latitude and longitude.

The lines \( d_{\text{te}} \) and \( d_{\text{tw}} \) are defined by:

Equation A.20: \( T = (d_{\text{te}} - d_{\text{tw}})/c \) [seconds]
Again, the variables, their units, and some of their relationships are defined to be:

\[ \text{longe} = \text{[degrees]} \text{ Longitude of eastern satellite} \]
\[ \text{longw} = \text{[degrees]} \text{ Longitude of western satellite} \]
\[ \text{difflong} = \text{[degrees]} \text{ Absolute value of (longw - longe)} \]
\[ \text{dte} = \text{[km]} \text{ Swept distance from eastern satellite to eastern subsatellite circle} \]
\[ \text{dtw} = \text{[km]} \text{ Swept distance from western satellite to western subsatellite circle} \]
\[ \text{rsat} = \text{[42162 km]} \text{ Radius of Earth geosynchronous orbit} \]
\[ \text{rE} = \text{[6378 km]} \text{ Radius of Earth} \]
\[ \theta = \text{[degrees]} \text{ Intermediate offset longitude between subsatellite circle intersection and satellite longitude} \]
\[ T = \text{[seconds]} \text{ Differential time of arrival} \]
\[ \text{Eastern Signal - Western Signal} \]
\[ c = \text{[2.997925x10}^8 \text{ m/sec]} \text{ Speed of Light} \]
\[ \text{Latitude} = \text{[degrees]} \]
\[ \text{Longitude} = \text{[degrees]} \]

One curve of constant differential delay is found by sweeping the shorter line connecting the satellite to Earth's surface from its minimum length (the satellite's altitude) to its maximum length at the limb of the Earth. The intersections of the subsatellite circles formed around the terrestrial intersections these circles and \( \text{dte} \) and \( \text{dtw} \) produce the desired curve.

A computer program may plot this curve by stepping \( \text{dte} \) and \( \text{dtw} \) over the above mentioned ranges and plotting points at the coordinates defined by the inferred longitude and latitudes. A family of such curves may be generated by assuming a set of delays then repeating the entire procedure to generate one curve for each delay. The computer program
presented in Appendix B does just this and also draws appropriate geographic, political, and cartographic boundaries.
B. TDOA Computer Program to Find Terrestrial Curves of Constant Delay

The following computer program takes as inputs a measured delay, the pair of geosynchronous satellite longitudes, and the SILS site location in latitude and longitude to generate a Mercator projection map of CONUS overlaid with the curve of constant delay appropriate to the given geometry. The additional offset between the satellite of interest and the SILS site is removed to convenience the user. The curve is generated using the equations developed in Appendix A. The program can also continue to generate a family of curves to facilitate an spatially intuitive view of the relationship between measured delays and their geographical mapping.

The program includes an interactive editor to facilitate user friendliness. A 98 kilobyte file (USA.DAT) of points is used to outline the map of the United States of America. This program was written in Borland’s Turbo Pascal version 3.01A. The use of a math co-processor is recommended.
(WHIT SMITH, 11 December 1988)
(Compute subsatellite delay circle intersections)
(Take a delta-time as an input 4 Feb 1988)
(Variable satellite longitude 7 Mar 1988)
(Make: time to sat a variable 9 Dec 1988)
   depends on variable SILS site location
save system defaults in file
help feature

PROGRAM main;

(GLOBAL DECLARATIONS)

CONST
REVISION=8;
CR=$0D;
ERRMSG=0;
WEST=-130;
EAST=-60;
NORTH=55;
SOUTH=22;

Rp=6378.;
Alt=35784.;
LONGei=103.0;
LONGwi=105.0;
Tmin=0.1193626;
SILSOFFSETi=235;
LONGsilsi=84.40;
LATsilsi=33.78;

var
rpalt, difsatlong, radsqr: real;  (intermediate variables)
cosdiflong, xmin, ymin, delx, dely: real;
coords: text;
lastx, lasty: real;
longsat1, longsat2, longe, longw, deltat: real;
silsoffset, longsils, latsils: real;

{ ************************************************************
 *
 * Trig Pack: 24 April 1987 Rev 2
 *
 ************************************************************

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Tangent
input is in radians

function tan(x: real): real;
var y: real;
BEGIN
y:=cos(x);
if y=0 then
  tan:=9.99999999E30
else
  tan:=sin(x)/y;
END;

{ *******************************************************

Arccos
output is in radians

} function arccos(x: real): real;
BEGIN
if abs(x)>1 then
  if ERRMSG=1 then
    writeln('ERROR: abs(x)>1 in arccos(x)');
if (x=0) then
  arccos:=PI/2
else
  if (x<0) then
    arccos:=PI-arctan( sqrt( abs(1/(x*x)-1) ) )
  else
    arccos:= arctan( sqrt( abs(1/(x*x)-1) ) )
END;

{ *******************************************************

Arcsin
output is in radians

} function arcsin(x: real): real;
BEGIN
if abs(x)>1 then
  if ERRMSG=1 then
    writeln('ERROR: abs(x)>1 in arcsin(x)');

if (x=0) then
  arcsin:=0
else if (x=1) then
  arcsin:=PI/2
else if (x=-1) then
  arcsin:=-PI/2
else
  if (x<0) then
    arcsin:=-arctan( sqrt(abs( 1/( 1/(x*x)-1 ) ) ) )
  else
    arcsin:= arctan( sqrt(abs( 1/( 1/(x*x)-1 ) ) ) );

END;

{ *******************************************************
*         Radians to Degrees
} function deg(rad: real): real;
BEGIN
  deg:=rad*360/2/PI;
END;

{ *******************************************************
*         Degrees to Radians
} function rad(deg: real): real;
BEGIN
  rad:=deg*2*PI/360;
END;

{ *******************************************************
{ *******************************************************

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Plot Package
Maps plot commands into 640 x 200 graphics display

procedure plton;
begin
hires;
hirescolor(white);
end;

procedure pltscale(xminarg, yminarg, xmaxarg, ymaxarg: real);
begin
xmin:=xminarg;
ymin:=yminarg;
delx:=xmaxarg-xmin;
dely:=ymaxarg-ymin;
end;

procedure pltxyc(x, y: real; color: integer);
var
u, v: real;
begin
u:=(x-xmin)/delx;
v:=(y-ymin)/dely;
if (0<=u) and (u<1) then
  if (0<=v) and (v<1) then
    plot( round(640*u), 200-round(v*200), color);
end;
procedure drawxyc(x1, y1, x2, y2: real; color: integer);

var
ul, v1, u2, v2: real;
onscreen: integer;

begin
onscreen:=0;
ul:=(x1-xmin)/delx;
v1:=(y1-ymin)/dely;
u2:=(x2-xmin)/delx;
v2:=(y2-ymin)/dely;

if (-1<=u1) and (u1<2) then
  if (-1<=v1) and (v1<2) then
    onscreen:=1;
if (-1<=u2) and (u2<2) then
  if (-1<=v2) and (v2<2) then
    onscreen:=1;

if onscreen=1 then
  draw( round(640*u1), 200-round(v1*200),
       round(640*u2), 200-round(v2*200), color);
end;

{-----------------
* axis: assume xmin and ymin > 0 for now
*}
procedure axis(xtic, ytic: real);

var
xleft, xrite, ytop, ybot: real;

begin
xleft:=xtic*(int(xmin/xtic)+1);
xrite:=xleft;
ybot:=ytic*(int(ymin/ytic)+1);
ytop:=ybot;

while (xrite+xtic)<(xmin+delx) do begin (tics)
  begin
xrite:=xrite+xtic;
drawxyc(xrite, ybot-0.02*dely, xrite, ytop+0.02*dely, white);
end;

while (ytop+ytic)<(ymin+dely) do
begin
ytop:=ytop+ytic;
drawxyc(xleft-0.02*delx, ytop, xleft+0.02*delx, ytop, white);
end;

drawxyc(xleft, ybot, xrite, ybot, white);  (axis)
drawxyc(xleft, ybot, xleft, ytop, white);

end;

{ **************************** *******************************************************
  
  procedure initplot;

  BEGIN

  plton;
  pltscale(WEST,SOUTH,EAST,NORTH);
  {size of frame to contain USA}
  lastx:=201; lasty:=201;  {nothing drawn yet}
  assign(coords, 'usa.dat');
  reset(coords);
  difsatlong:=rad(longw-longe);
  cosdiflong:=cos(difsatlong);
  rpalt:=Rp+Alt;
  rad sqr:= s quar(Rp)+s quar(rpalt);
  END;

  { **************************** *******************************************************
  
  procedure init;

  var i, j: integer;
BEGIN
clrscr;

{Initialize lat and long to GSTAR 1 and 2}
silsoffset:=SILSOFFSETi;
longe:=LONGei;
longw:=LONGwi;
longsils:=LONGsilsi;
latsils:=LATsilsi;

END;

{*******************************************************************************
200, 200 = EOF
201, 201 = continuous
202, 202 = point by point
}
procedure drawmap;

var
x, y: real;
i: integer;

BEGIN

while (not eof(coords)) and (lastx<>200) and (lasty<>200) do
begin
read(coords, x);
if (not eof(coords)) then
read(coords, y);
x:=-x; {correct for west longitudes}

if (lastx=201) or (lasty=201) then
begin
lastx:=x; lasty:=y;
end;

if (x<200) and (y<200) then
drawxyc(lastx, lasty, x, y, white);

lastx:=x; lasty:=y;
end;
gotoxy(1,1);

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write('longw = ', longw:6:1, ' longe = ', longe:6:1);

for i:=0 to 80 do {centerline between sats}
begin
    y:=i;
    x:=-(longw+longe)/2;
    pltxyc(x, y, white);
end;

for i:=0 to 80 do {east and west sats}
begin
    y:=i;
    x:=-longw;
    pltxyc(x, y, white);
    x:=-longe;
    pltxyc(x, y, white);
end;

gotoxy(77,4); {Non-scaled, map specific Long/Lat markers}
write('50');
gotoxy(77,12);
write('40');
gotoxy(77,20);
write('30');
gotoxy(69,25);
write('70');
gotoxy(11,25);
write('120');
gotoxy(1,1);

END;

procedure drawlatlong;
var
    i: integer;
BEGIN
    for i:=-13 to -6 do {longitudes}
        drawxyc(i*10,0,i*10,60,white);
    for i:=0 to 6 do {longitudes}
        drawxyc(-130,i*10,-60,i*10,white);
drawxyc(-1*longsils-0.5, latsils,
       -1*longsils+0.5, latsils, white);
drawxyc(-1*longsils, latsils-0.5, -1*longsils,
       latsils+0.5, white);

END;

function distsat(time: real): real;
BEGIN
  distsat:=299792.5*time;
END;

procedure intersect(dte, dtw: real; var lat, long: real);
var
dterad, dtwrad: real;
BEGIN

  (Unique for each iteration)
  dterad:= sqr(dte)-radsqr;
dtwrad:= sqr(dtw)-radsqr;

  long:= dtwrad/dterad - cosdiflong;
  long:= arctan( long / sin(difsatlong) );
  lat:= deg(arccos( -dterad/2/Rp/(rpalt)/cos(long) ));

  Distance to satellite [km] = f(time [sec])

  Compute northern INTERSECTION of subsat circles for
  given dsat

  Input:    dte, dtw: distance to east/west satellites
  Output:   lat, long: northern lat and diff long from
             east subsat longitude


long := deg(long);
{
 writeln('dte = ',dte:7:1);
 writeln('dtw = ',dtw:7:1);
}

END;

{ ***********************************************
* Get a differential time value
* }
procedure editor;

var
i, j, k: integer;
temp, testlonge, testlongw: real;
otyet: boolean;
testchar: char;
BEGIN
{Get SILS site longitude and latitude}
testchar:= 'N';
notyet:= TRUE;
while ((testchar='N') or (testchar='n')) do
begin
 testchar:= 'Y';
 clrscr;
 writeln('
SILS Site Location Editor');
 gotoxy(1,5);
 writeln('
Latitude = ', latsils:6:1,
 [Deg North]');
 writeln('
Longitude = ', longsils:6:1,
 [Deg West]');
 gotoxy(1,15);
 writeln('
Satisfied? (Y/N)[Y]');
 writeln;
 write(' '); 
 read(kbd, testchar);
 writeln;
 if ((testchar='N') or (testchar='n')) then
 begin
 writeln(' We'll be sticking to the CONUS region');
 writeln;
 write(' Enter SILS Latitude [Deg North] ');}
readln(testlonge);
write('  Enter SILS Longitude [Deg West] ');
readln(testlongw);

. testlonge:=abs(testlonge);
testlongw:=abs(testlongw);

if (testlonge<80) then {Good lat/long values?}
  if (testlongw<130) then
    begin
      testchar:='Y';
      latsils:=testlonge;
      longsils:=testlongw;
    end
  else
    begin
      testchar:='N';
      writeln;
      writeln('  -- Bad Latitude or Longitude Value --');
      for i:=1 to 32000 do
        for j:=1 to 8 do;
      end;
    end;
end;

{Get two satellite Longitudes}
testchar:='N';
notyet:=TRUE;
while ((testchar='N') or (testchar='n')) do
  begin
    testchar:='Y';
    clrscr;
    writeln('  Satellite Position Editor');
    gotoxy(1,5);
    writeln('  Eastern Longitude =  longe:6:1, [deg]');
    writeln('  Western Longitude =  longw:6:1, [deg]');
    gotoxy(1,15);
    writeln('  Satisfied? (Y/N)[Y]');
    writeln;
    write(' ');}
  read(kbd, testchar);
  writeln;
  if ((testchar='N') or (testchar='n')) then
    begin
      writeln('  We'll be sticking to the Western Hemisphere');
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writeln;
write('Enter 1st Longitude'); readln(testlonge);
write('Enter 2nd Longitude'); readln(testlongw);

testlonge:=abs(testlonge);
testlongw:=abs(testlongw);

if (testlonge>testlongw) then begin               {Switch east and west}
  temp:=testlonge;
  testlonge:=testlongw;
  testlongw:=temp;
end;

if (testlonge<180) then                            {Good longitude values?}
  if (testlongw<180) then begin
    testchar:='Y';
    longe:=testlonge;
    longw:=testlongw;
    end
  else begin
    testchar:='N';
    writeln; writeln('Bad Longitude Value');
    for i:=1 to 32000 do
      for j:=1 to 8 do;
    end;
  end;
longsat1:=longe;                                   {TENATIVE}
longsat2:=longw;

{Get Measured Differential Time}
deltat:=700;
while( (deltat<-600) or (100<deltat)) do begin
  clrscr;
gotoxy(10,1);
  writeln('Satellite Positions: ', longe:6:1,
          'W and ', longw:6:1, 'W');
  writeln;
  write('Enter differential time observed from');
  write(' SILS Site in microseconds');
gotoxy(20,5);
readln(deltat);
if ((deltat<-600) or (100<deltat)) then
begin
write('Delta time value of ',deltat:6:1,
     ' is out of range - try again');
for j:=1 to 10000 do
for k:=1 to 30 do;
end;
end;

END;

*******************************************************
* Display: Dish angles for Afflicted Satellite
* Adjacent Satellite
* Offset time to Satellite
*
procedure infopage;

var
costhetal, costheta2, thetal, theta2, dsatl, dsat2: real;
rsat, re: real;
az1, az2, ell, el2: real;

BEGIN

{Compute Geometry Constants}
rsat := Alt+Rp;
re := Rp;

{Fixed differential time from satellites to SILS site}
costhetal := cos( abs( rad( latsils )))
     * cos( abs( rad( longsat1-longsils)));
dsatl := sqrt( rsat*rsat + re*re
     - 2 * re * rsat * costhetal);
costheta2 := cos( abs( rad( latsils )))
     * cos( abs( rad( longsat2-longsils)));
dsat2 := sqrt( rsat*rsat + re*re
     - 2 * re * rsat * costheta2);
silsoffset := (dsat2 - dsatl) * 1000 / 2.997925e8 * 1e6;

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(Azimuth and Elevation to each satellite)

ell := arccos( (re*re + dsatl*dsatl - rsat*rsat)/(2 * re * dsatl) );

ell := deg( ell ) - 90;

azl := tan( rad(latsils))/tan(arccos(costhetal));
azl := deg( arccos(azl) ) + 180;

el2 := arccos( (re*re + dsat2*dsat2 - rsat*rsat)/(2 * re * dsat2) );
el2 := deg( el2 ) - 90;

az2 := tan( rad(latsils))/tan(arccos(costheta2));
az2 := deg( arccos(az2) ) + 180;

{report intermediate variables}

clrscr;
{
 writeln(' Intermediate Test Variables'); writeln;

 writeln(' latsils = ', latsils:5:1);
 writeln(' longsils = ', longsils:5:1);
 writeln(' longsat1 = ', longsat1:5:1);
 writeln(' longsat2 = ', longsat2:5:1);
 writeln;
 writeln(' costhetal = ', costhetal:7:3);
 writeln(' costheta2 = ', costheta2:7:3);
 writeln(' dsat1 = ', dsat1:7:3);
 writeln(' dsat2 = ', dsat2:7:3);
 writeln;
 writeln(' re = ', re:6:1);
 writeln(' rsat = ', rsat:7:1);
 readln;
}
{Report AZ/EL information}

clrscr;
writeln(' Dish Pointing Angles'); writeln(' ---------------------');
writeln(' Satellite 1');
writeln(' Satellite 2');
writeln;
writeln(' Azimuth [Deg] ,', az1:6:2, ' , az2:6:2);
writeln('Elevation [Deg] , , el1:6:2, , el2:6:2);

{Report Offset Time from SILS Site}
gotoxy(1,10);
write('

gotoxy(1,13);
writeln(' Differential Times');
writeln('-------------------');
writeln;

writeln(' SILS Site Observed Delta time = ',
       , deltat:6:1, ' [uSec]');
writeln(' ( + SILS Site offset) '
       , silsoffset:6:1);
writeln('----------');
deltat:=deltat+silsoffset;

writeln(' Satellite Observed Delta time = '
        , deltat:6:1, ' [uSec]');

gotoxy(1,22);
write('

write('');
writeln('Hit Carrige Return to generate isochron plot');
readln;

END;

{******************************************************************************
 * Scan through one delay
 * *
 }procedure onescan;

var
 lat, long: real;
delay, tuli: integer;
delt, tu1, tu2: real;

BEGIN
delt:=deltat;  \( (\text{One scan line for one delta time})\)
begin
  delt:=delt*1e-6;
  gotoxy(1,1);
  write('Delta-t = ',delt*1000000.:6:1,'[uSec] ');
for tuli:=0 to 110 do  \( (\text{steps of 100uSec over 0 to 11mSec})\)
begin
  tul:=100*tuli*1e-6;
  tu2:=delt+tul;
  intersect( distsat(tu2+Tmin), distsat(tul+Tmin), lat, long);
  \{  
  if (tul=0) then
    begin
      gotoxy(1,2);
      write('long(0) = ',long:6:1,'   ');
    end;
  long:=long+longe;
  pltxyc(-long, lat, white);
  \}
end;
write('  (Hit CR to fill out 20 [uSec] plot)')
readln; \( (\text{Pause to show only one isochron})\)
gotoxy(1,1);  \( \)write(' 
for delay:=0 to 12 do (steps of 20uSec over 0 to 240uSec)
begin
  delt:=20*delay*1e-6;
  gotoxy(1,1);
  write('Delta-t = ',delt*1000000.:6:1,'[uSec] ');
for tuli:=0 to 110 do  \( (\text{steps of 100uSec over 0 to 11mSec})\)
begin
  tul:=100*tuli*1e-6;
  tu2:=delt+tul;
  intersect( distsat(tu2+Tmin), distsat(tul+Tmin), lat, long);
  \{  
  if (tul=0) then
    begin
      gotoxy(1,2);
      write('long(0) = ',long:6:1,'   ');
    end;
  long:=long+longe;
  pltxyc(-long, lat, white);
  \}
end;
for delay:=0 to 18 do (steps of 20uSec over 0 to 360uSec)
begin
delt:=20*delay*1e-6;
gotoxy(1,1);
write('Delta-t = ',-1*delt*1000000.:6:1,'[uSec] ');
for tuli:=0 to 110 do
    (steps of 100uSec over 0 to 11mSec)
    begin
        tul:=100*tuli*1e-6;
tu2:=delt+tul;
intersect( distsat(tu2+Tmin), distsat(tul+Tmin), lat, long);
        { if (tul=0) then
            begin
                gotoxy(1,2);
                write('long(0) = ',long:6:1,' 	 I);
            end;
            long:=-long+longw;
            pltxyc(-long, lat, white);
            end;
        }
end;
gotoxy(1,1);
write(' Contours of 20 [uSec] for Satellite Locations ');
write(longe:6:1, 'W and ', longw:6:1, 'W');
END;

{ *******************************************************
* * MAIN LINE PROCEDURE
* *
} BEGIN

init;
editor;
infopage;
initplot;
drawlatlong;
drawmap;
onecan;
readln;
textmode;
END.
C. Interferometry Equation Derivation

This section describes equations which generate a set of terrestrial curves of constant differential phase which may be projected onto a map for use with the interferometric location method. The relevant known quantities are the longitude of the geosynchronous satellite of interest, Earth's radius, and the altitude of the geosynchronous satellite.

An interferometric baseline connects the satellite to Earth's spin axis as is illustrated in Figure C.1. For the case of the GSTAR satellites, this baseline is believed to be about 55 degrees below the line connecting the satellite to its subsatellite point. The desired terrestrial curves are formed by the intersections of Earth's sphere with a cone formed around the interferometric baseline with its vertex at the satellite.

To generate one curve, a geometric angle, \( \theta_{dp} \), which forms the cone around the interferometric baseline is chosen. Angle \( \theta_c \) is swept from its vertical angle of 0 degrees clockwise to about 20 degrees. The intersection of a line connecting the satellite at point S to Earth's surface at point B is thus swept across Earth's surface forming the desired curve. The challenge lies in locating the longitude and latitude of point B.
Intersection of a Cone of Constant Differential Phase and Earth's Sphere
Figure C.2

Angle Relationships for the Generation of Terrestrial Curves of Constant Differential Phase

Slice through a Subsatellite Circle
Note that there is another desired solution at the same latitude and symmetric about the satellite's longitude. This other desired solution is eclipsed by Earth in Figure 6.1. There are also two undesired solutions. These correspond to where line SB emerges on the side of Earth opposite the satellite.

The following construction relates the fixed and chosen variables to the desired latitude and longitude. The construction is broken into parts. Many of the variables are defined geometrically in Figure C.2. The given quantities necessary to determine one pair of longitudes and latitudes are:

**Given Quantities**

\[ \theta_{bl} = \text{Angle ESZ} \]
\[ \theta_{dp} = \text{Angle BSZ} \]
\[ \theta_c = \text{Angle BZY} \]
\[ r_e = \text{Radius of Earth} \]
\[ ES = \text{Earth to Satellite distance, orbital radius} \]

The quantities of interest are the angles and not the absolute lengths of the intermediate lines which are defined only to facilitate the geometric construction. Because similar triangles retain their corresponding angles.
regardless of scale, some sides of the triangles in the following construction are set equal to unity to facilitate simplicity.

C.3.1 Find $\theta_{ci}$

The first goal is to determine angle $\theta_{ci}$ between the line BS connecting the terrestrial point B with the satellite and the line ES connecting the satellite to Earth's center.

Given: $\theta_{bl}$, $\theta_{dp}$, $\theta_{c}$
Choose: Length of line $SZ = 1$

Equation C.1: $XZ = SZ * \tan(\theta_{bl}) = \tan(\theta_{bl})$
Equation C.2: $BZ = SZ * \tan(\theta_{dp}) = \tan(\theta_{dp})$

Thus, $XZ$ and $BZ$ are now known in terms of known quantities.

Equation C.3: $XB^2 = BZ^2 + XZ^2 - 2*BZ*XZ*cos(\theta_c)$

Thus, $XB$ is known in terms of known quantities.

Equation C.4: $SZ = 1 = SX * \cos(\theta_{bl})$
Equation C.5: $SZ = 1 = SB * \cos(\theta_{dp})$

Thus, $SX$ and $SB$ are known.

Equation C.6: $XB^2 = BS^2 + SX^2 - 2*BS*SX*cos(\theta_{ci})$

Thus, $\theta_{ci}$ is known in terms of known quantities.
C.3.2 Find $\theta_e$

The next goal is to find angle $\theta_e$ between the line connecting the satellite to Earth's center and the line connecting the terrestrial cone intersection point (Point B) to Earth's center.

Given: $\theta_{ci}$

Equation C.7: $BE^2 = ES^2 + BS^2 - 2*ES*BS*cos(\theta_{ci})$

Thus, Equation C.7 is found to be a quadratic in BS. The desired solution is that with the smaller magnitude. This corresponds to the solution on Earth's surface closest to the satellite. The other solution corresponds to a point on Earth which is not visible to the satellite.

Equation C.8: $BS^2 = BX^2 + SX^2 - 2*BS*SX*cos(\theta_e)$

This gives the desired angle $\theta_e$ in terms of known quantities.

C.3.3 Find $\theta_{ssc}$

The next goal is to find angle $\theta_{ssc}$ which is the angle in the subsatellite circle plane between the plane containing the satellite's line of longitude and a line connecting the terrestrial intersection point (Point B) and
the line connecting the satellite and Earth's center.

Given: \( \theta_{bl}, \theta_{ci}, \theta_{e} \)
Choose: Length of line \( AS = 1 \)

Equation C.9: \( AS = 1 = BS \cdot \cos(\theta_{ci}) \)
Equation C.10: \( AS = 1 = CS \cdot \cos(\theta_{bl}) \)

Thus, \( BS \) and \( CS \) are known.

Equation C.11: \( BC^2 = BS^2 + CS^2 - 2*BS*CS*\cos(\theta_{dp}) \)

Thus, \( BC \) is known.

Equation C.12: \( AB = AS \cdot \tan(\theta_{ci}) = \tan(\theta_{ci}) \)
Equation C.13: \( AC = AS \cdot \tan(\theta_{bl}) = \tan(\theta_{bl}) \)

Thus, \( AB \) and \( AC \) are known.

Equation C.14: \( BC^2 = AB^2 + AC^2 - 2*AB*AC*\cos(\theta_{ssc}) \)

Thus, angle \( \theta_{ssc} \) is known.

C.3.4 Find the latitude and difflong

Given: \( \theta_{e}, \theta_{ssc} \)
Choose: Length of line \( AE = 1 \)

Equation C.15: \( AB = AE \cdot \tan(\theta_{e}) = \tan(\theta_{e}) \)

Thus, \( AB \) is known.
Equation C.16: \[ AY = AB \times \cos(\theta_{ssc}) \]

Thus, AY is known.

Equation C.17: \[ AY = AE \times \tan(lat) = \tan(lat) \]

Thus, \(|lat| = |latitude|\) is known.

Note that the latitude needs to be specified as being north or south of the equator as follows:

If \(|\theta_{ssc}| > 90\) degrees
then the latitude is north of the equator
else the latitude is south of the equator.

Solving for difflong:

Equation C.18: \[ \cos(\theta_e) = \cos(difflong) \times \cos(lat) \]

Thus, difflong is known.

C.3.5 Find the longitudes

The longitude offset angle, difflong, now needs to be added to and subtracted from the satellite’s longitude to produce the final longitudes of the two terrestrial points.

Given: difflong
longsat = the longitude of the satellite

Equation C.19: western longitude = longsat + difflong
Equation C.20: eastern longitude = longsat - difflong
The final longitude values may need to be adjusted to correct to cartographic convention if the final longitude values cross through the terrestrial 0 or 180 degree longitudes. The latitude is given in Section C.3.4.

The computer program presented in Appendix D sweeps angles $\theta_{dp}$ and $\theta_c$ to produce the desired terrestrial curves.
D. Interferometry Computer Program to Find Terrestrial Curves of Constant Differential Phase

The following computer program takes as inputs the geosynchronous satellite longitude and the SILS site location in latitude and longitude to generate a Mercator projection map of CONUS overlaid with a family of curves of constant delay appropriate to the given geometry. The curves are generated using the equations developed in Appendix C.

As with the similar TDOA program, this program includes an interactive editor to facilitate user convenience. A 98 kilobyte file (USA.DAT) of points is used to outline the map of the United States of America. This program was written in Borland’s Turbo Pascal version 3.01A. The use of a math co-processor is recommended.
(WHIT SMITH, 11 May 1988)
(Interferometry: Plot lines of constant phase over CONUS)

PROGRAM main;

{GLOBAL DECLARATIONS}

CONST
REVISION=2;
CR=$0D; \quad \text{(HEX CARRIAGE RETURN)}
ERRMSG=0; \quad \text{(Error messages on if 1)}
WEST=-130; \quad \text{(Map extents, degrees of lat and long)}
EAST=-60; \quad \{-130, -60, 55, 22\}
NORTH=55;
SOUTH=22;

Rp=6378.; \quad \text{(Radius of planet – Earth=6378km)}
Re=6378.; \quad \text{(Radius of planet – Earth=6378km)}
Alt=35784.; \quad \text{(Altitude of satellite = 35784km)}
Rsat=42162.; \quad \text{(Radius of satellite = 42162km)}
Tmin=0.1193626; \quad \text{(Subsatellite prop delay in seconds )}
ANGBASELINE=55.886; \quad \text{(Interferometric baseline)}

LONGei=103.0; \quad \text{(Default East Satellite Longitude: GSTAR 1 )}
LONGwi=105.0; \quad \text{(Default West Satellite Longitude: GSTAR 2 )}
ATLOFFSET=235; \quad \text{(Default Atlanta diff delay to GSTAR pair)}

var
PI2: real;
angbl, angdp, anggp, angep, angc, angci, ange: real;
angssc, dlat, dlong, longsat, longw, longe, lat: real;

rpalt, difsatlong, radsqr: real; \quad \text{(intermediate variables)}
cosdiflong, xmin, ymin, delx, dely: real;
coords: text;
lastx, lasty: real;
deltat: real;

{ Trig Pack: 24 April 1987 Rev 2 }

* Tangent
* \text{input is in radians}
function tan(x: real): real;
var y: real;
BEGIN
  y:=cos(x);
  if y=0 then
    tan:=9.99999999E30
  else
    tan:=sin(x)/y;
END;

{ *********************************************************
 * Arccos
 * output is in radians
 * }
function arccos(x: real): real;
BEGIN
  if abs(x)>1 then
    if ERRMSG=1 then
      writeln('ERROR: abs(x)>1 in arccos(x)');
  if (x=0) then
    arccos:=PI/2
  else
    if (x<0) then
      arccos:=PI-arctan( sqrt( abs(1/(x*x)-1) ) )
    else
      arccos:= arctan( sqrt( abs(1/(x*x)-1) ) );
END;

{ *********************************************************
 * Arcsin
 * output is in radians
 * }
function arcsin(x: real): real;
BEGIN
if abs(x)>1 then
  if ERRMSG=1 then
    writeln('ERROR: abs(x)>1 in arcsin(x)');

if (x=0) then
  arcsin:=0
else if (x=1) then
  arcsin:=PI/2
else if (x=-1) then
  arcsin:=-PI/2
else
  if (x<0) then
    arcsin:=-arctan( sqrt(abs( 1/( 1/(x*x)-1 ) )))
  else
    arcsin:= arctan( sqrt(abs( 1/( 1/(x*x)-1 ) )))

END;

{ *******************************************************
  * Radians to Degrees
} function deg(rad: real): real;
BEGIN
deg:=rad*360/2/PI;
END;

{ *******************************************************
  * Degrees to Radians
} function rad(deg: real): real;
BEGIN
rad:=deg*2*PI/360;
END;

{ *******************************************************
  * Plot Package
  * Maps plot commands into 640 x 200 graphics display
}
procedure plton;
begin
hires;
hirescolor(white);
end;

{-------------------
 *                  }
procedure pltscale(xminarg, yminarg, xmaxarg, ymaxarg: real);
begin
xmin:=xminarg;
ymin:=yminarg;
delx:=xmaxarg-xmin;
dely:=ymaxarg-ymin;
end;

{-------------------
 *                  }
procedure pltxyc(x, y: real; color: integer);
var
u, v: real;
begin
u:=(x-xmin)/delx;
v:=(y-ymin)/dely;
if (0<=u) and (u<1) then
  if (0<=v) and (v<1) then
    plot( round(640*u), 200-round(v*200), color);
end;

{-------------------
 *                  }
procedure drawxyc(x1, y1, x2, y2: real; color: integer);
var
ul, v1, u2, v2: real;
onscreen: integer;
end;
begin
onscreen:=0;

ul:=(x1-xmin)/delx;
v1:=(y1-ymin)/dely;
u2:=(x2-xmin)/delx;
v2:=(y2-ymin)/dely;

if (-1<=u1) and (ul<2) then
  if (-1<=v1) and (v1<2) then
    onscreen:=1;
if (-1<=u2) and (u2<2) then
  if (-1<=v2) and (v2<2) then
    onscreen:=1;

if onscreen=1 then
  draw( round(640*ul), 200-round(vl*200),
       round(640*u2), 200-round(v2*200), color);

end;

{ *******************************************************
* 200, 200 = EOF                               
* 201, 201 = continous                        
* 202, 202 = point by point                   
* }                                               
procedure drawmap;

var
  x, y: real;
i: integer;
BEGIN

while (not eof(coords)) and (lastx<>200) and (lasty<>200) do begin
  read(coords, x);
  if (not eof(coords)) then
    read(coords, x);
  x:=-x;  (*correct for west longitudes*)

  if (lastx=201) or (lasty=201) then begin
    lastx:=x;  lasty:=y;

END.
if (x<>200) and (y<>200) then drawxyc(lastx, lasty, x, y, white);
lastx:=x; lasty:=y;
end;

gotoxy(1,1);
write('longsat = ', longsat:6:1);
for i:=0 to 80 do {east and west sats}
begin
y:=i;
x:=-longsat;
pltxyc(x, y, white);
end;
gotoxy(77,4);
write('50');
gotoxy(77,12);
write('40');
gotoxy(77,20);
write('30');
gotoxy(69,25);
write('70');
gotoxy(11,25);
write('120');
gotoxy(1,1);

END;

{ *******************************************************
 *
 *
 procedure drawlatlong;
 *

 var
 i: integer;
 longsils, latsils: real;

 BEGIN

 for i:=-13 to -6 do {longitudes}
 drawxyc(i*10,0,i*10,60,white);

 for i:=0 to 6 do {longitudes}
drawxyc(-130,i*10,-60,i*10,white);

(Insert a cross for SILS site)
longsils:=108.8; (grand junction)
latsils :=39.1;
drawxyc(-1*longsils-0.5, latsils, -1*longsils+0.5, latsils, white);
drawxyc(-1*longsils, latsils-0.5, latsils, white);

latsils:=33.8; (atlanta)
longsils :=84.5;
drawxyc(-1*longsils-0.5, latsils, -1*longsils+0.5, latsils, white);
drawxyc(-1*longsils, latsils-0.5, latsils, white);

latsils:=39.4; (woodbine)
longsils :=77.1;
drawxyc(-1*longsils-0.5, latsils, -1*longsils+0.5, latsils, white);
drawxyc(-1*longsils, latsils-0.5, latsils, white);

END;

{ *******************************************************
* Distance to satellite [km] = f(time [sec]) *
* *******************************************************
function distsat(time: real): real;
BEGIN
distsat:=299792.5*time;
END;

{ *******************************************************
* Compute northern INTERSECTION of subsat circles for *
* given dsat *
* Input:  dte, dtw: distance to east/west satellites *
* Output: lat, long: northern lat and diff long from *
* east subsat longitude
*******************************************************

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procedure intersect(dte, dtw: real; var lat, long: real);

var
dterad, dtwrad: real;

BEGIN

{Unique for each iteration}
dterad:= sqr(dte)-radsqr;
dtwrad:= sqr(dtw)-radsqr;
long:= dtwrad/dterad - cosdiflong;
long:= arctan( long / sin(difsatlong) );
lat:= deg(arccos( -dterad/2/Rp/(rpalt)/cos(long) ));
long:= deg(long);

{ writeln('dte = ',dte:7:1);
 writeln('dtw = ',dtw:7:1);
 }

END;

{*******************************************************************************
 * Get a differential time value
 * *******************************************************************************
 *}
procedure editor;

var
i, j, k: integer;
temp, testlonge, testlongw, offset: real;
notyet: boolean;
testchar: char;

BEGIN

{Get two Longitudes}

testchar:='N';
notyet:=TRUE;
while ((testchar='N') or (testchar='n')) do begin

testchar:='Y';
clrscr;
writeln(' Satellite Position Editor');
gotoxy(1,5);
writeln(' Satellite Longitude = ', longsat:5:1, '[deg]');
gotoxy(1,15);
writeln(' Satisfied? (Y/N)[Y]');
writeln;
write(' ');
read(kbd, testchar);
writeln;
if ((testchar='N') or (testchar='n')) then 
begin
writeln(' We'll be sticking to the Western Hemisphere');
writeln;
write(' Enter Longitude '); readln(testlonge);
testlonge:=abs(testlonge);
if (testlonge<180) then (Good longitude values?)
  longsat:=testlonge
else
  begin
    testchar:='N';
writeln;
    writeln(' Bad Longitude Value');
    for i:=1 to 32000 do
      for j:=1 to 8 do;
  end;
end;
end;

END;

{ **********************************************
  *
  *
  *
} function solvelatlong;

var
  radical, a, b, c, x, y, z: real;
  cosange, cosci, dsatsqr, asqr, bsqr, cosssc, dsat: real;

BEGIN
\[
\begin{align*}
\text{Satellite Sphere Geometry} & \\
c & := \tan(\text{angbl}) \\
a & := \tan(\text{angdp}) \\
bsqr & := \left(a^2 + c^2 - 2ac\cos(\text{angc})\right) \\
z & := \frac{1}{\cos(\text{angbl})} \\
y & := \frac{1}{\cos(\text{angdp})} \\
\cosci & := \frac{z^2 + y^2 - bsqr}{2yz} \\
\text{angci} & := \arccos(\cosci) \\
\end{align*}
\]

if (ERRMSG=1) then begin
write('[1]');
write('c = ',c:9:3);
write('a = ',a:9:3);
write('bsqr = ',bsqr:9:3);
write('z = ',z:9:3);
write('y = ',y:9:3);
write('cosci = ',cosci:9:3);
write('angci = ',deg(angci):9:3);
end;

\[
\begin{align*}
\text{Cone of Constant Phase Geometry} & \\
& \text{Depends on actual distances} \\
\text{radical} & := \text{Rsat}^2\text{Rsat}^2(\cosci^2 - 1) + \text{Re}^2\text{Re}^2 \\
\cosange & := 0 \\
\text{if (radical} & \geq 0 \text{) then begin} \\
& \text{begin} \\
& \text{dsat} := \text{Rsat}\cosci - \sqrt(\text{radical}); \\
& \text{cosange} := \left(\text{Rsat}\text{Rsat} + \text{Re}\text{Re} - \text{dsat}\text{dsat}\right)/(2\text{Re}\text{Re}\text{Rsat}); \\
& \text{ange} := \arccos(\cosange) \\
& \text{if (ERRMSG=1) then begin} \\
& \text{begin} \\
& \text{writeln('[2]');} \\
& \text{writeln('dsat = ',dsat:9:3);} \\
& \text{writeln('cosange = ',cosange:9:3);} \\
& \text{writeln('ange = ',deg(ange):9:3);} \\
& \text{end;} \\
& \text{end;} \\
& \text{if (cosange} \geq \cos(\text{deg(80)}) \text{) then begin} \\
& \text{begin} \\
\end{align*}
\]
{ ------------------------ Triangle Plane Projection}

\[ y := \frac{1}{\cos c} \]
\[ x := \frac{1}{\cos(\alpha_b)} \]
\[ \text{asqr} := x^2 + y^2 - 2xy \cos(\alpha_d) \]
\[ b := y \sin(\alpha_{ci}) \]
\[ c := x \sin(\alpha_b) \]
\[ \cos ss := \frac{(b^2 + c^2 - \text{asqr})}{2bc} \]
\[ \text{ang ss} := \arccos(\cos ss) \]

if (ERRMSG=1) then begin
  writeln('[3]');
  writeln('y = ',y:9:3);
  writeln('x = ',x:9:3);
  writeln('asqr = ',asqr:9:3);
  writeln('b = ',b:9:3);
  writeln('c = ',c:9:3);
  writeln('cos ss = ',cos ss:9:3);
  writeln('ang ss = ',deg(ang ss):9:3);
end;

{ ------------------------ Subsatellite Circle Geometry}

\[ b := \tan(\alpha) \]
\[ a := b \cos ss \]
\[ c := b \sin(\text{ang ss}) \]
\[ \text{dlat} := \arctan(a) \]
\[ \text{dlong} := \arccos(\cos(\alpha) / \cos(\text{dlat})) \]

if (ERRMSG=1) then begin
  writeln('[4]');
  writeln('b = ',b:9:3);
  writeln('a = ',a:9:3);
  writeln('c = ',c:9:3);
  writeln('dlat = ',deg(dlat):9:3);
  writeln('dlong = ',deg(dlong):9:3);
end;

{ ------------------------ Lat/Long Normalization}

\[ \text{dlat} := -\text{deg( dlat )} \]
\[ \text{dlong} := \text{deg( dlong )} \]
\[ \text{longw} := \text{longsat} + \text{dlong} \]
\[ \text{longe} := \text{longsat} - \text{dlong} \]
if ( abs(angssc)>(PI/2) ) then
  (Correct for latitude N/S of equator)
  lat:= dlat
else
  lat:= -dlat;
end

else
begin
  lat:=0; longe:=0; longw:=0;
end;

if (ERRMSG=1) then begin
  writeln( 1);
end;

END;

( *******************************************************
* Asssume screen already in plot mode with map in place
* )
procedure scanphase;
var
i, j: integer;
BEGIN

gotoxy(1,1);
write('Contours of Constant Differential Phase for');
write('Geosync Satellite over ');
write( longsat:5:1, " W");
readln;

gotoxy(1,1);
write('Sweep differential phase over 59 to 63.5 deg');
write(' in 1/4 degree steps');
for i:=0 to 18 do begin
  angdp:= rad(59+i/4.0);
  for j:=0 to 128 do
    ...
end;
begin
angc:= rad(j/16.0);  
(Sweep cone angle over 0 to 8 degrees)
   (in 1/16 degree steps)
solvelatlong;  
(Solve for lat and longe/longw)
angep:= 1630.5*cos(angdp); 
(Generate electrical phase angle)
while (angep>360)  
   (Normalize to [-360,360])
   angep:=angep-360;
while (angep<-360)
   angep:=angep+360;

gotoxy(10,1);
write('Diff Phase = ', angep:6:2, ' [deg] ');
write('Cone Angle = ', deg(angc):6:2, '[deg] ');
pltxyc(-longe, lat, white);  
(Plot the points)
pltxyc(-longw, lat, white);

gotoxy(1,1);
write('Contours of Constant Differential Phase for');
write(' Geosync Satellite over ');
write( longsat:5:1, ' W');
END;

{  ******************************************************
   Test
   *
   *
procedure test;
BEGIN
angbl:= rad( 55.9 );
angdp:= rad( 60 );
angc:= rad( 1 );
solvelatlong;
 writeln(' lat = ',lat:9:3);
 writeln(' longe = ',longe:9:3);
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writeln('longw = ',longw:9:3);
writeln('longsat = ',longsat:9:3);
writeln('angbl = ',deg(angbl):9:3);
writeln('angdp = ',deg(angdp):9:3);
writeln('angc = ',deg(angc):9:3);
readln;
END;

procedure initplot;
BEGIN
piton;
pltscale(WEST,SOUTH,EAST,NORTH);
(lastx:=201; lasty:=201; (nothing drawn yet)
assign(coords, 'usa.dat');
reset(coords);
difsatlong:=rad(longw-longe); (variable initialization)
cosdiflong:=cos(difsatlong);
rpalt:=Rp+Alt;
radsqr:= sqr(Rp)+sqr(rpalt);
END;

procedure init;
BEGIN
var i, j: integer;
PI2:=2*PI;
clrscr;
longe:=LONGei;  (Initialize lat and long to GSTAR 1 and 2)
longw:=LONGwi;

longsat:=LONGei; (Initialize longitude to eastern satellite)
angbl:=rad( ANGBASELINE );

END;

{ *******************************************************
*     MAIN LINE PROCEDURE
*  *
*     }
BEGIN
init;
{test;}
editor;
initplot;
drawlatlong;
drawmap;
scanphase;
readln;
textmode;
END.

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E. Interferometry Computer Program to Operate RF Hardware

The following computer program performed real-time operation of the phase detector hardware, controlled the Metrabyte analog-to-digital conversion board, and computed the desired phase angles for the interferometric experiments.

The Metrabyte board had a voltage input which came from the output of the phase detector. A TTL level output from the Metrabyte board switched the phase detector module’s additional transmission line length into and out of one of the phase detector’s inputs to facilitate the removal of amplitude ambiguities from the final inferred phase.

The program took a pair of voltage measurements and inferred the phase and an input amplitude and thus power into an assumed 50 ohm load. This was displayed to the experimenter. These measured voltages and their times of measurement were also written to a disc file to facilitate later processing. These files were used to generate the mean and standard deviation tables which appear in the interferometry results of section 4.4.2 above.
PROGRAM main;

{GLOBAL DECLARATIONS}

CONST
REVISION=0;

{Metrabyte Constants}

(Volts, Input voltage range for Metrabyte board A-D)
VMAX = 2.5;
VMIN = -2.5;

MBBASE=$300; {MetrByte Base Address (hex)}
WINDOW=2000; {Running average window size } 
DELAY=6400; {Delay before sampling }
LONGOFFSET=3.7; {mV, Offset for long cal line (4.0)}
SHORTOFFSET=3.7; {mV, Offset for short cal line (4.5)}

ADLOW=0; {A to D Inputs}
ADHI=1;
STARTAD=0;

SCANREG=2; {Scan Registers}
DIGOUT=3; {Digital Outputs}
DIGIN=4; {Digital Inputs }

DA0LOW=4; {D to A Outputs}
DA0HI=5;
DA1LOW=6;
DA1HI=7;

STATUS=8; {Control}
CONTROL=9;

{Computational Constants}

VLITE=2.997925e8;
CR=$0D; {HEX CARRIAGE RETURN}
TYPE
REGISTER = RECORD
    AX, BX, CX, DX, BP, SI, DI, DS, ES, FLAGS:
    INTEGER;
END;

var
dispmin, dispsec: real;
datafile: text;
samples: real;
lastdiffang: real;

{*******************************************************
*                                                     *
*     RETURN THE TOD CLOCK'S SECONDS COUNT             *
*     IN HUNDREDS OF SECONDS                          *
*                                                     *
}                                                     
FUNCTION SECONDS: INTEGER;

VAR
REGS: REGISTER;

BEGIN

REGS.AX:=$2C00;  {GET TOD FROM DOS FUNCTION 2C)
MSDOS(REGS);
SECONDS:=100*(REGS.DX DIV 256) + (REGS.DX MOD 256)
END;

{*******************************************************
*                                                     *
*                                                     *
*                                                     *
}                                                     
FUNCTION minutes: INTEGER;

VAR
REGS: REGISTER;

BEGIN

REGS.AX:=$2C00;  {GET TOD FROM DOS FUNCTION 2C)

MSDOS(REGS);
minutes:=100*(REGS.CX DIV 256) + (REGS.CX MOD 256)
END;

{ *******************************************************
*  Trig Pack:    24 April 1987   Rev 2
* *******************************************************
*
* Tangent
*    input is in radians
*
}
function tan(x: real): real;
var y: real;
BEGIN
  y:=cos(x);
  if y=0 then
    tan:=9.99999999E30
  else
    tan:=sin(x)/y;
END;

{ *******************************************************
*  Arccos
*    output is in radians
*
}
function arccos(x: real): real;
BEGIN
  if abs(x)>1 then
    if ERRMSG=1 then
      writeln('ERROR: abs(x)>1 in arccos(x)');
  if (x=0) then
    arccos:=PI/2
  else
    if (x<0) then
      arccos:=PI-arctan( sqrt( abs(1/(x*x)-1) ) )
    else
      arccos:= arctan( sqrt( abs(1/(x*x)-1) ) );
function arcsin(x: real): real;
BEGIN
if abs(x)>1 then
  if ERRMSG=1 then
    writeln('ERROR: abs(x)>1 in arcsin(x)');
if (x=0) then
  arcsin:=0
else if (x=1) then
  arcsin:=PI/2
else if (x=-1) then
  arcsin:=-PI/2
else
  if (x<0) then
    arcsin:=-arctan( sqrt(abs( 1/( 1/(x*x)-1 ) )) )
  else
    arcsin:= arctan( sqrt(abs( 1/( 1/(x*x)-1 ) )) )
END;

{ **********************************************
*           Radians to Degrees
* }
function deg(rad: real): real;
BEGIN
deg:=rad*180/PI;
END;

{ **********************************************
*            Degrees to Radians
* }
function rad(deg: real): real;
BEGIN
rad:=deg*PI/180;
END;

{ *******************************************************
* * Common Logs
}
function log(x: real): real;
BEGIN
if x<=0 then
  log := -300
else
  log:=ln(x)/ln(10);
END;

{ *******************************************************
{ *******************************************************

{ *******************************************************
* * Analog Inputs
* *
*       Input: channel numbers 0-15
*       Output: 0-((2^12)-1 = 4095)
* *
*   Errors: Returns -1 if channel number not in range [0,15]
*          Returns -2 if hardward acknowledgement timeout
* *
*  function getanalog(channel: integer): integer;
var
  timer: integer;
BEGIN
  if (channel>15) then getanalog:=-1 else
    if (channel<0) then getanalog:=-1 else
      begin
        port[MBBASE+SCANREG]:=channel + $100*channel;
        {point to analog channel}
        port[MBBASE+STARTAD]:=channel;

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timer:=10;  // (start conversion)
while (port[MBBASE+STATUS]>127) and (timer>0) do
    timer:=timer-1;  // (check for timeout)
if timer=0 then
    begin
        getanalog:=-2;
        writeln('getanalog: timeout on A/D completion');
    end
else
    getanalog := (port[MBBASE+ADLOW] div 16)
    + (port[MBBASE+ADHI] * 16);
end;
samples:=samples+1;
END;

{ *******************************************************
  *                                               *
  *                         Digital Outputs           *
  *                                               *
  *    Output:                                      *
  *    15 >= (one nybble to OP3-OP0) >= 0           *
  *                                               *
  * }                                            *
procedure putdigital(data: integer);
BEGIN
    data := abs(data) mod 16;
    // (Guarentee that output nybble is in range)
    port[MBBASE+DIGOUT]:=data;  // Output the data
END;

{ *******************************************************
  *                                               *
  *                     Screen Output Metrabyte      *
  *                     status register             *
  * }                                            *
procedure showstatus;

var
    i, j: integer;

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BEGIN

i:=port[MBBASE+STATUS];
write(' status = ', i:5);
write(' status upper nybble = ', ((i div 16) ):2 );
writeln(' status lower nybble = ', ( i - (i div 16)*16):2 );
END;

{ *******************************************************
* Repeat voltage samples from A/D converter
* Average WINDOW samples from the requested channel mod 16
* Return the averaged voltage
* }
function getamp(channel: integer): real;
var
i, analog: integer;
tempk, tempc, tempf, volts: real;
BEGIN
if samples>9999 then samples:=0;
channel := channel mod 16;
vols:=0; { Low pass filter by averaging }
{ over a window of length WINDOW }
for i:=1 to WINDOW do
  volts := volts + getanalog(channel);
getamp := volts*(VMAX-VMIN)/4096/WINDOW + VMIN;
{writeln('from getamp - volts = ', volts:5:3, ' [volts]');}
samples := samples + WINDOW;
end;

{ ******************************************
* Iteratively solve for amplitude and phase

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procedure phase;

var
  manual: boolean;
  i, j: integer;

freq, (Hz, frequency of measurement)
length, (meters, length of diff phase transmission line)
vf, (fraction of c, velocity factor of transmission line)
anglen, (angle induced by transmission line length)
bracket, (intermediate iterative limits)
vshort, (short line measured DC voltage)
vlong, (long line measured DC voltage)
amp, (resulting amplitude)
diffang, (resulting angle = f(amp))
diffang0 (storage for first diffang)
:real;

testchar: char;

  (nonlinear function to evaluate)

function itterate(diffang: real): real;
begin
  itterate := vshort*cos( diffang + anglen )
             - vlong*cos( diffang );
end;

BEGIN

(editor)

(freqs=135;             (frequency in MHz)
length:=0.263;
    {specific to differential phase module number 2 about }
    { 45 deg at 70 MHz, physical length of cal line in meters}
vf:=66;              (cal line velocity factor in percent)
vshort:=300.0;       (initialize in mV)
vlong:=-519.6;

testchar:='a';       (anything other than ESC)
manual:=FALSE;       (Manual versus automatic acquisition mode)
while 1>0 begin  {loop forever}

if manual then
    begin  {get from keyboard, ask only once}
        clrscr;
        gotoxy(1, 10);
        write('short length voltage V(short) [', vshort:6:1, ' mV] = ');
        readln(vshort);
        write(' long length voltage V(long) [', vlong:6:1, ' mV] = ');
        readln(vlong);
        writeln;
        writeln;
        write(' measurement frequency freq [', freq:5:2, ' MHz] = ');
        readln(freq);
        write(' differential cable length length [', length:5:3, ' meters] = ');
        readln(length);
        write(' cable velocity factor vf [', vf:4:1, ' %] = ');
        readln(vf);
        end;

    if vshort>=9999 then
        manual:=FALSE;

    if not manual then
        begin  {get from Metrabyte board}
            putdigital(0);  {Turn off calibrate relay}
            write(' turn off relay ');
            for i:= -DELAY to DELAY do
                for j:=1 to 5 do;
                vshort:= getamp(9)*1000;  {convert to millivolts}
                vshort:= vshort + SHORTOFFSET;  {correction for metrabyte hardware offset}
            putdigital(15);  {Turn on calibrate relay}
            write(' turn on relay ');
            for i:= -DELAY to DELAY do
                for j:=1 to 5 do;
                vlong := getamp(9)*1000;  {convert to millivolts}
                vlong := vlong + LONGOFFSET;  {correction for metrabyte hardware offset}
            putdigital(0);  {Turn off calibrate relay}
write(' turn off relay ');
(readln;)
end;

freq:=freq*1e6;            (convert MHz to Hz)
vshort:=vshort/1000;      (convert mV to V)
vlong:=vlong/1000;        (convert mV to V)
vf:=vf/100;               (convert percent to unitless)

(deduce cal cable angle from cable length, freq, and vf)
anglen:=(freq/VLITE/vf)*length*360);

clearscr;

writeln(' MEASURED VOLTAGES'); writeln;
writeln(' short length voltage V(short) = ', vshort*1000:6:1, ' mV');
writeln(' long length voltage V(long) = ', vlong*1000:6:1, ' mV');

dispsec:=seconds/100;
dispmin:=minutes/100;
WRITE(datafile, dispmin:2:2, ',', dispsec:2:2 ); (SAVE DATA)
write((datafile, vshort, ',', vlong);

writeln; writeln;

writeln(' HARDWARE DEPENDENT PARAMETERS');
writeln;
writeln(' measurement frequency freq = ', freq/1e6:5:2, ' MHz');
writeln(' switched cable length length = ', length:5:3, ' meters');
writeln(' switched cable angle cable angle = ', anglen:4:1, ' deg');
writeln(' cable velocity factor vf = ', (vf*100):4:1, ' %');

anglen:=rad(anglen);
{convert cable length to radians from degrees}

****** Iterrate
*     *  
*     *  
  
{initial conditions}
diffang:=-PI;

{iterative solution 1}

bracket:=1;
while ( (diffang<PI) and (bracket>0.00001) )
begin
bracket:=bracket/10;
{ writeln('bracket = ', bracket:8:6);
}
while
( (diffang<PI) and
  ( itterate(diffang)*itterate(diffang+bracket) > 0 )
)
begin
diffang:=diffang+bracket;
end;
end;
if diffang>PI then
begin
writeln('CRASH1: diffang = ', deg(diffang):6:2);
end;
diffang0:=diffang+bracket;
amp:=vshort/cos(diffang);
writeln; writeln;
writeln(' RESULTS'); writeln;

if amp<0 then
begin

----------

{iterative solution 2}

diffang:=diffang0;

{iterative solution 2}

bracket:=1;
while ( (diffang<PI) and (bracket>0.00001) )
begin
bracket:=bracket/10;
{ writeln('bracket = ', bracket:8:6);
}
while
( (diffang<PI) and

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( iterate(diffang)*iterate(diffang+bracket) > 0 )

begin
  diffang:=diffang+bracket;
end;

write('2nd Solution: 	 ');
end  (end of amp<0)
else
write('1st Solution: 	 ');

if diffang>PI then
begin
  writeln('CRASH: diffang = 	 deg(diffang):6:2);
end;

amp:=vshort/cos(diffang);

if amp<0 then
begin
  writeln('CRASH: 0>amp = ', amp:6:3);
end;

write(' Power = 	 (1000*amp*amp/50):6:3, ' mW = ');
writeln( (10*log(amp*amp/50)+30):5:1, ' dBm');
writeln(' Amplitude = 	 amp:6:3, ' volts');
writeln(' ang = 	 deg(diffang):5:1, ' degrees');
writeln;
write(' diffang = ');
writeln(' degrees');

{-----------
{readln; ***}
if manual then
  read(kbd, testchar)
else
  writeln;

{writeln('char = ', ord(testchar) );
readln;}

if ord(testchar)=ESC then (terminal condition)
begin
  clrscr;
  halt;
end;
freq:=freq/le6;
vf:=vf*100;
vshort:=vshort*1000;
vlong:=vlong*1000;
lastdiffang:=diffang;
end;
END;

{ ***********************************************
* *
* *
procedure init;
*
*
var i, j: integer;

BEGIN

clrscr;
port[MBBASE+CONTROL]:=0;  (Initialize Metrabyte board)
putdigital(0);          (Turn off calibrate relay  )
lastdiffang:=0;

ASSIGN(datafile,'pdoa.dat');  (OPEN THE TOTE STACKER
STATE FILE)

  (TEST FOR THE EXISTENCE OF FILE)
  {$I-}
RESET(datafile);
  {$I+}

IF (IORESULT<>0) THEN
  BEGIN  (FILE IS EMPTY)
  CLOSE(datafile);
  ASSIGN(datafile,'pdoa.dat');  (OPEN FILE)
  REWRITE(datafile);  (CLEAR FILE TO WRITE NEW STATE)
  WRITE(datafile, dispmin:2:2, dispsec:2:2 );  (SAVE DATA)
  CLOSE(datafile);
  WRITE('PDOA data file was empty or nonexistant')
  END
ELSE
  BEGIN  (ELSE READ IN AND INITIALIZE THE LOCAL VARIABLES)
  WRITE('PDOA file exists');
  RESET(datafile);
  CLOSE(datafile)
  END;

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ASSIGN(datafile,'pdoa.dat');  (OPEN FILE)
REWRITE(datafile);  (CLEAR FILE TO WRITE NEW STATE)
END;

{ ********************
*  MAIN LINE PROCEDURE
*  *
} BEGIN
  init;
  (header;)
  phase;
END.
F. Interferometric Hardware and Schematics

Figures 4.13 and 4.15 include in block diagram form the RF signal processing hardware which was assembled to perform the interferometric measurements at the SILS site. All custom electronics were designed to operate from a 12 VDC supply with the exception of the operational amplifier circuit in the PLLs which use +/- 12 VDC. The following text describes the schematics found in the associated Figures.

Phase Locked Loops. The phase locked loops were built to facilitate a 60 to 80 MHz tuning and lock range with appropriate output power to facilitate the RF power levels required in other portions of the circuit. Their loop filters employ the "perfect integrator" operational amplifier circuit to guarantee that the output phase equals that of the input signal. This should be compared to other filter topologies which do not guarantee phase equality between input and output signals during a locked condition. The extra pole at the complex Laplacian origin provided by this integrator facilitates this requirement.

The design methods presented in Manassewitsch [20] and Gardner [21] were used to choose the components with a narrow loop bandwidth being a design goal to facilitate the exclusion of received noise. The originally computed
component values did not produce satisfactory operation of the loops. Lock was easily broken upon the hardware experiencing mechanical or electrical transients. However, after "tweaking" the component values to widen the loop bandwidth and overcoming a few faulty components and pieces of laboratory equipment, satisfactory PLL operation was attained.

The phase locked loop electrical schematic of Figure F.1 shows manually adjustable offsets to compensate for current offsets into the operational amplifier inputs and DC offsets from the phase detector output. After incorporation of the "bleeder" resistor across the integration capacitor, neither of these compensation circuits should be necessary. However, the variable offset were left in place. The integrator does just that with whatever small input offset occurs until the operational amplifier hits its supply rails without the "bleeder" resistors.

It was discovered that the "perfect integrator" operational amplifier circuit employed in the PLLs works best when it's output is less than a few millivolts. Operation was poor when the integrator had been allowed to ramp up to the almost 5 volts required to tune the VCOs to the desired 70 MHz range. The final circuit provided tuning by the summing of a manually controlled DC voltage with the integrator's output. The PLLs were tested for phase lock by
locking each loop to a low phase noise CW source then mixing the PLL output with a copy of the CW input and detecting a DC output. This DC voltage varied appropriately with a phase change induced by varying the cable lengths to the phase detector.

**Phase Detector.** As is discussed in the earlier text, the phase detector is realized as an enhanced mixer with pre-amplification and a switchable length of transmission line to facilitate the removal of amplitude ambiguities. The DC output is low pass filtered with a RC network. Were a high impedance voltage sensor not used then a voltage follower circuit would be required to facilitate a low impedance output and buffering. Schematics for the phase detector module are shown in Figure F.2.

**Amplifiers.** The gain blocks are purchased Mini-Circuits ZHL-1A amplifiers [19] and modules constructed from various Mini-Circuits MMIC amplifiers.

**Filters.** Because CW or 100 kHz wide signals were used as the interfering signal during live satellite tests, 250 kHz wide SAW bandpass filters centered at 70 MHz were used following helical resonator filters to limit the extraneous channel noise power into the phase comparator. Figure F.3 shows the schematics incorporating these purchased SAW filters surrounded by the required impedance transformation networks and MMIC amplifiers needed to recover the insertion
loss of the filters. The helical resonators were 6 MHz wide bandpass filters designed to isolate one television signal at a 70 MHz IF. Without the 6 MHz filters, the preamplifiers preceding the SAW filters were overwhelmed by the satellite channel noise power.
Unless otherwise noted:
All capacitors are ceramic disc
All resistors are 1/4W 5%
MMIC, Splitters, and Phase Detector
are Mini-Circuits parts

**80-80 MHz Phase Locked Loop**
for an Interferometric SLS System

Wednesday 18 April 1990 Rev 5
Whit Smith
Unless otherwise noted:
- All resistors are 1/4W 5%
- MMICs are Mini-Circuits parts
- L1, L2 are 5 turns of 22 gauge wire on a 4mm diameter air core tuned for best upper harmonic rejection

Phase Detector Module for the Interferometric SLS System
Monday 23 April 1990 Rev 2
Whit Smith

Figure F.2

[Diagram of the Phase Detector Module for the Interferometric SLS System]
70 MHz SAW Bandpass Filter for an Interferometric SLS System

Wednesday 18 April 1990 Rev 2
Whit Smith

Cast Aluminum Enclosure

Sawtek 851541 Bandpass Filter
Center Frequency = 76.00 MHz
-3dB Bandwidth = 250 kHz
Typical Loss = 17.5 dB

Unless otherwise noted:
All resistors are 1/4W 5%
MMICs are Mini-Circuits parts

\[
\begin{align*}
\text{RF In} & : 50 \text{ Ohm} \\
\text{RF Out} & : 50 \text{ Ohm} \\
\text{Gain} & = 30 \text{ dB} \\
\text{Saturation} & = 11 \text{ dBm} \\
\end{align*}
\]
RF Amplifier Module for an Interferometric SILS System

Wednesday 18 April 1990 Rev 1
Whit Smith

Unless otherwise noted:
All resistors are 1/4W 5%
MMIC is a Mini-Circuits part

Cast Aluminum Enclosure

+12V
1000pF

RF In
50 Ohm

RG-174

0.1uF Chip

MAR-6 MMIC Amp
Gain=28dB
Saturation=0dBm

RFC (10uH)

RG-174

RF Out
50 Ohm

0.1uF Chip
Bibliography


Vita

William Whitfield Smith, Jr. (Whit) was born in Goldsboro, North Carolina, on August 17th, 1959. He received the B.E.E and M.S.E.E. degrees in 1982 and 1986 from the Georgia Institute of Technology, Atlanta, from which he plans to graduate with his Ph.D. in Electrical Engineering in June 1990.

During his undergraduate career, he designed, built, and installed industrial computer controls for a variety of firms. From 1982 until 1984, he was employed by the Broadcast Products Division of the Harris Corporation where he designed and developed high power commercial broadcast transmitters and their control equipment. He has also pursued various Graduate Research Assistantships and consulting activities during his graduate student career which have resulted in at least one patent.