Tool for Planetary Probe Payload Sensor System Integration

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ABSTRACT

Determination of instrumentation for interplanetary science missions is an involved, complex procedure. A final design solution is achieved at the end of this often lengthy process. The analysis methodology presented here investigates mission requirements and generates a mission sensor package using design engineering relations. Given the broad science goals for an interplanetary science mission, the specific scientific measurements required can be determined. From the measurements the required specifications flow down, leading to an overall mission design. The mission design drives the instrumentation requirements and influences the selection of components for the mission. Components are chosen to meet mission requirements, creating an initial sensor package design. Trade studies are performed at component levels. Designs iterate on initial concepts and options are evaluated until a final design is determined. A tool for in-situ measurements is developed using systems engineering design relations to deliver a sensor payload configuration starting from the initial mission concept and the specific measurement objectives.

Design of the sensor payload package for any mission is a combination of different aspects. The final design is a result of individual case studies at the component level and design engineering studies at a system level. Human decision elements are included in the design process, and final selection between competing components is made. The decision to use one flight hardware component over another can arise from many factors – functionality, heritage, Technology Readiness Level (TRL), compatibility, etc. The objective of this work is to combine selection techniques for mission hardware, based on optimization studies with engineering judgment, into a single tool that can be used to generate a preliminary sensor package configuration for planetary missions. A tool for in-situ measurements is developed using systems engineering design relations to deliver a sensor payload configuration starting from the initial mission objectives and the specific measurement types.

The In–Situ Sensor Payload Optimization Tool (ISSPO) consists of a number of individual sensor modules, based on commercially available and space-rated components, and programs to determine the required components. Information on the desired mission location and types of science data to be returned, along with payload limits, are entered into the main program. For each sensor type available within the database, a corresponding module is executed and supplied information on the planetary location and additional sensor requirements. Selection of the final sensor is made based on operational ranges and required performance limits. Logic checks determine whether the sensor package meets or exceeds the mission limits, or if another combination of components would provide a viable solution with some requirement tradeoff. The resulting sensor package represents a preliminary sensor package capable of answering the mission's science requirements.

1.0 Introduction

The driving interest behind the development of this program comes from material presented during a short course on In-Situ Instruments for Planetary Probes and Aerial Platforms hosted as part of the 4th International Planetary Probe Workshop [1]. Attendees were given a mass and power budget for a planetary probe mission that used an aerial platform, and were tasked to develop a sensor package that would meet the mission requirement and fit within the constraints. Long before a mission is launched, during the initial planning stages, a series of studies are conducted to create a sensor package custom tailored to meet the mission requirements. Components are chosen to survive the operating environment and meet mission requirements.

Design of the sensor payload package for any mission addresses several issues. The final optimal payload configuration is a result of individual case studies and design engineering studies. The scope of the tool, is limited to optimization techniques within the sensor payload, however, a higher system level criteria may impact the component level design, resulting in a different component selection. At some point, a human decision is still included in the design process, as final selection between competing elements is made. The decision to use one component over another can arise from many factors – functionality, heritage, Technology Readiness Level (TRL) [2], etc. The objective of this work is to combine all of the selection techniques for mission hardware into a single tool that can be used to generate a preliminary sensor package configuration.

2.0 Methodology

The component selection algorithms implemented in this tool trades sensor component characteristics (operational parameters such as range, performance, weight, accuracy, etc.) to arrive at an optimum component choice, based on a set of mission sensor requirements (e.g., planetary atmospheric data collection). Initial configurations are developed using top level mission requirements. As the solution for each sensor type progresses, the properties of the sensor are evaluated at finer levels of analysis. If a component no longer satisfies a requirement it is eliminated from analysis. If no suitable solution can be determined, a work-around strategy must be made to find a way to modify existing hardware to satisfy the mission requirements, either via a custom built specialized sensor, modifying a commercially available component to allow it to meet the requirement, or by making a modification to the mission requirement. The end result of this design tool for each type of mission science data is a unique commercially available sensor component.

A database of commercially available components is developed for each type of sensor. The down-selection process will employ several methods to eliminate incompatible sensors. Primary selection methods are based on the operational range of the sensor type (e.g., temperature range for Thermocouples, atmospheric gasses for mass spectrometers). Special consideration is given to heritage system components, to further select from multiple sensors that operate over similar operational ranges. Use of heritage materials implies a high level of technological development behind the sensor. The Technology Readiness Level (TRL) employed in a sensor's design, relates the development level and risk associated with the hardware. While technology with a higher TRL is desirable, there are other advantages to a lower TRL device. A given device could be at a high TRL, but be a heavy component or involve a complicated mechanism. A similar device could have a lower TRL, but be significantly lighter. However, the lower TRL device has an increased level of inherent risk in its use, compared to a more mature design. Multi-role components can also be evaluated for their useful properties. These types of units complete the tasks assigned to multiple sensors with the benefit of a single unit capable of recording several data types. The use of these selection factors will allow for the determination of a component that will meet the mission sensor requirements.

As each component is selected for the sensor package, additional interactions between sensors will come into play. Design constraints may limit the use of certain types of sensors. Once a preliminary sensor design package has been completed, interactions between sensors at a system level may determine if any components are incompatible with other sensors. If this condition occurs, individual sensor requirements will have be modified and evaluated via another iteration with all the sensors until the sensors are compatible with each other and a final design solutions exists, or if the program determines that there is no commercially existing solution that meets the mission requirements, a "best solution" option is presented, modified to a custom sensor to meet the mission goal.

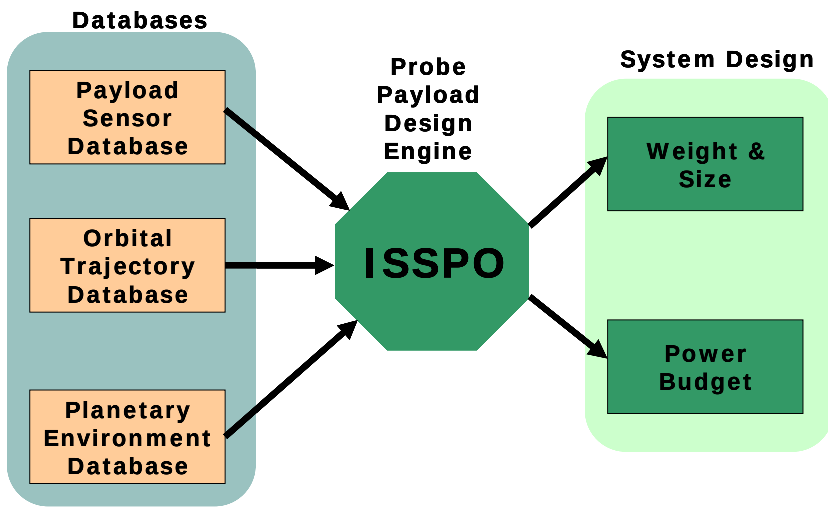

Figure 1 Sensor Payload Tool Design Operation

2.1. N^2 Systems Diagram

The N^2 systems diagram demonstrates the hierarchical nature of the program's operation and the flow of requirements and parameters between the program modules. It visually illustrates the dependent nature of the design selection on all the other sensor component elements within the system. The diagonal flow nature of the chart details the order of operation of the program and illustrates the direction movement of program inputs and outputs between the modules. The program starts with the broadest goals for the final system and uses the top level programs to determine all the inputs needed by the sub-functions and process them in the most efficient manner, as indicated in Figure 2. Arrows in the upper right diagonal portion of the diagram indicate the inputs and outputs of the different modules and how the chosen components provide inputs to other modules. Arrows below the main diagonal indicate a direct relational dependency on a higher level component by another component lower along the diagonal. The organization of the individual components is to reduce the number of "up-flowing" program elements in the illustration.

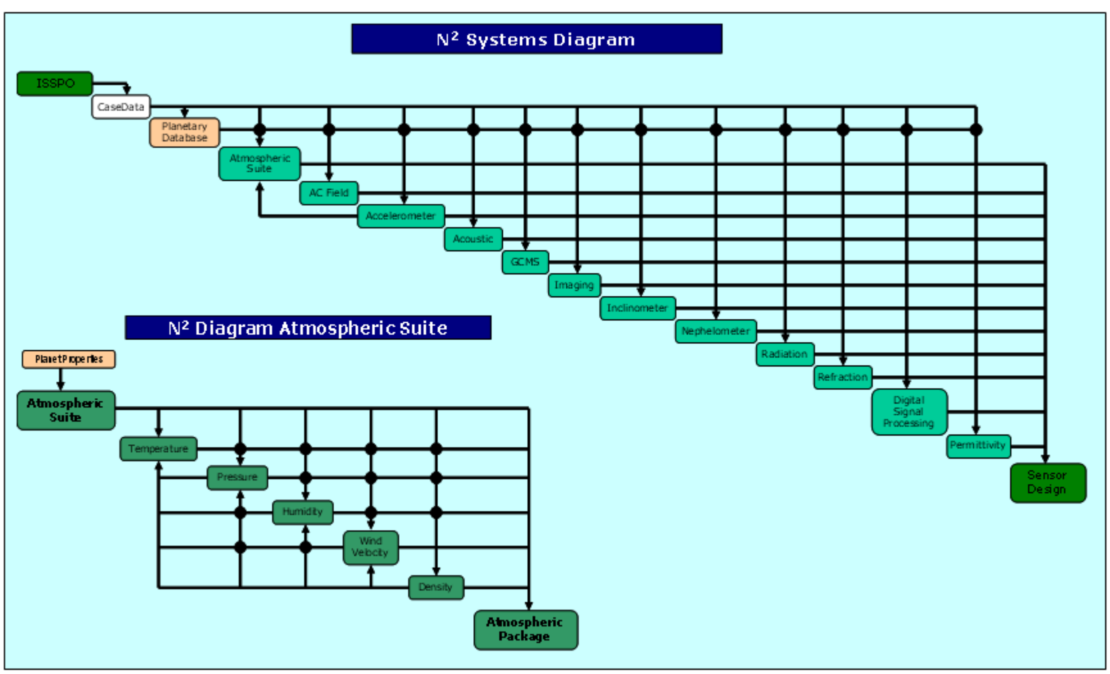

Figure 2 ISSPO Tool Sensor N^2 Diagram

Reduction of up-flowing elements reduces the design cycle process (fewer iterations before a final design). The input file format required by the ISSPO program loads all the required program data and determines which sensor programs to run reducing the number of design cycle iterations. The full system diagram detailing the relationship between all the program modules, and flow down of data is detailed in Figure 2. The atmospheric suite is shown as the single sensor package system as it is called in main program. The individual sensors contained within this module are tightly coupled together, and more dependent on the output of other sensors within this module. The resulting sensor package from the atmospheric suite is then loaded back into the main program and included in the total sensor package. Most of the other specific sensor types record a singular data type and thus the possibility of multi-role sensor use is limited.

3.0 ISSPO Tool Subroutines

The In-Situ Sensor Payload Optimization (ISSPO) Program [3] is comprised of multiple subroutines being called from the main program. Each subroutine is called and returns specific pieces of data back to the main program. Sensor type subroutines are developed as a self contained model only requiring inputs from the main program to select the correct component or, when necessary, obtain data from another module to select the component. The subroutine for each sensor type is only called if a corresponding type of data is requested in the main program (e.g., ACCELERATION for acceleration data, OPTICS for imaging data, GAS ANALYZER for gas properties). This modular development allows for the program to include all sensor types, yet reduce running time to only relevant sensor types. Many planetary science missions feature a basic atmospheric properties sensor pack that monitor temperature, pressure, density, etc. Within the ISSPO tool these atmospheric sensors have been coupled into a single input option selection that calls all the individual sensors automatically. The function and properties of each of the ISSPO Tool subroutines is discussed here. Descriptions here are not meant as an exhaustive description of the design flow through each module, but to detail the key elements of the modules, limitations, design logic and the data used.

3.1. ISSPO Program

The ISSPO routine is the primary program call entered at the MatLAB command prompt. From here, the input data is loaded to the main program and the sensor payload is configured from the sensor modules. Each module contains its own set of variables needed by the program. At the end of each module, the relevant data is written to a '.mat' binary data file. In the main ISSPO program, the data file is loaded into memory and the data is made available for all subroutines to use. A summary program flowchart in Figure 3 outlines the operation of the ISSPO Tool.

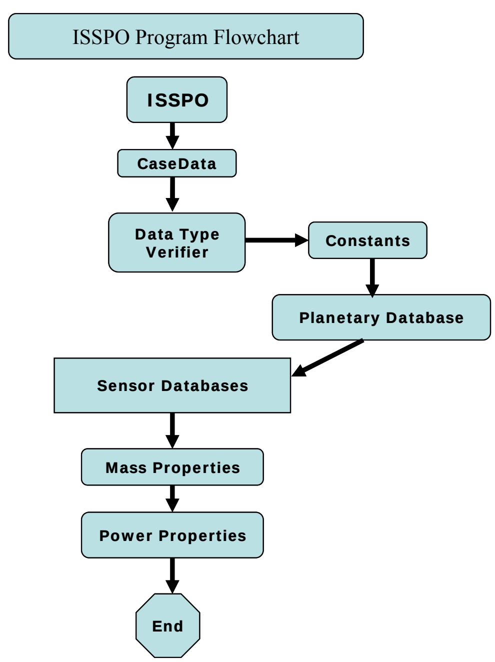

Figure 3 ISSPO Tool Flowchart Diagram

The development and design of the ISSPO program is keyed toward a simple, minimal design. All the program input variables are preloaded into a case data file with the MatLAB '.m' file extension. This allows the file to be evaluated as a program and it loads all the relevant case data. When ISSPO is executed from MatLAB, a brief introduction to the program is displayed and the user is asked to enter the name of the data file that contains the design information for that case. A logic check for the file is made and continues the program. With the file setup correctly, the ISSPO program creates a case directory in a working directory folder. From there a program directory file folder is made and copies of the main program files are copied into the working directory folder. The main program then runs a planetary database program to obtain reference data values for the intended mission location; such as bulk parameters, orbital properties, and atmospheric data. Specific modules are executed for each sensor type depending on the required mission data.

3.2. Input File

The input file is intended to serve as a file to load the basic requirements of the sensor system design into the main program. The benefit here is to quickly load all of the program inputs from a single file, saving the user from having to enter the data from scratch each time the program is executed. Each time a design change is made, only the variable has to be updated in the input file. This setup format allows the ability to evaluate multiple sensor configurations using different technology options for each sensor type. Formatting of the input file follows a free form design. The order of the variables in the file does not matter as long as all the variables are present. Duplication of any variables in the file will override any prior inputs and use the last value entered into the data file.

The input file is divided into several sections. Inputs on the planetary body under investigation and the desired unit system are loaded. Limits on power, mass, and volume are input to verify final sensor package configuration. A variable array holds all the sensor types needed in the design along with any additional specifications for each sensor type to select the correct hardware. Sensor types are each loaded into a new row in the sensor design matrix with any additional requirements loaded as an additional column with the associated sensor. A sample input file format is shown in Figure 4.

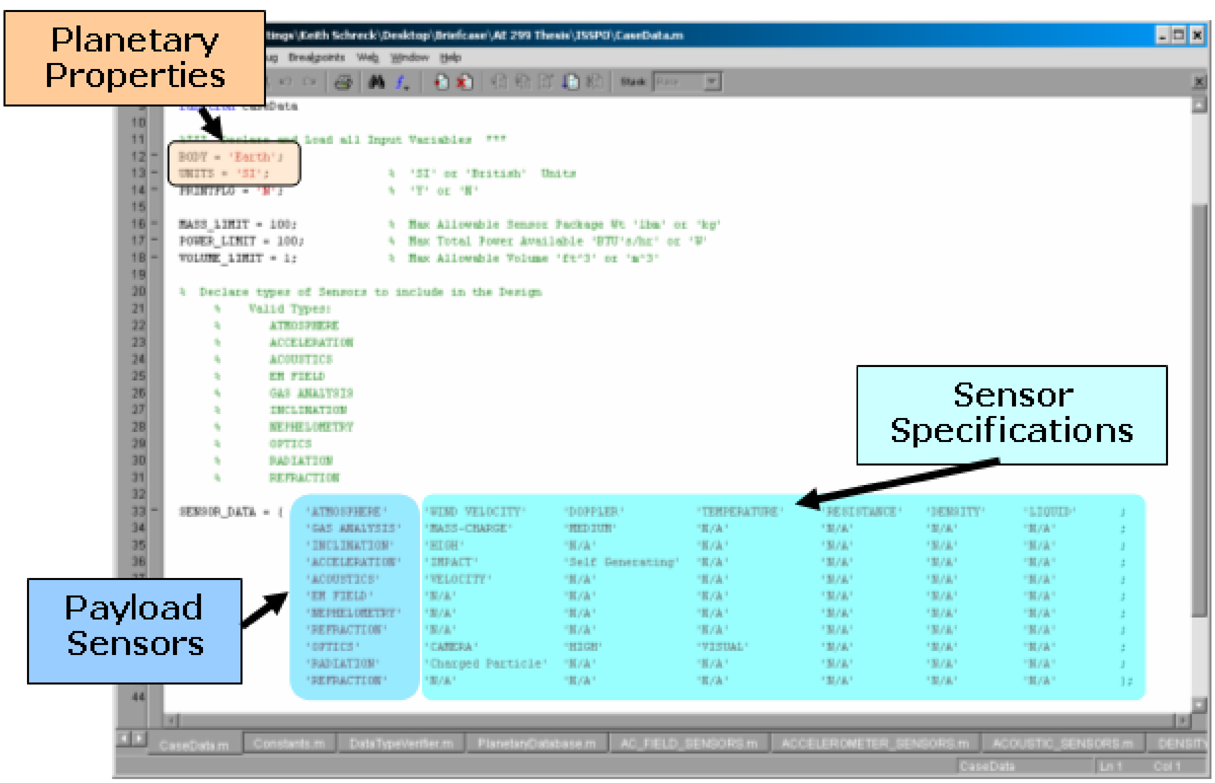

Figure 4 ISSPO Input File Format

3.3. Planetary Database

The primary purpose of this module is to provide data to the main ISSPO program on the planetary environment that the mission would encounter. Planetary data is crucial in the decision process of sensors for the mission. A database of all the planetary values is generated based on the object relevant parameters, and is stored in a data file loaded by the main ISSPO program to be used in selection of the sensor components. From within ISSPO, the planetary database program is called to load the parameters into the main program.

The program consists of a database of planetary bulk parameters (e.g., mass, volume, radius, gravity), orbital parameters (e.g., period, velocity, orbital inclination) and atmospheric properties. Composition of the atmosphere includes major components by percent and trace element composition by particle concentration. These parameters are used to aid further along in the design process in selecting other components.

The planetary database currently contains the full set of properties of 27 celestial objects including the sun, the eight major planets, the moon, the recently reclassified minor planet Pluto, and the eight largest moons of Jupiter and Saturn. A sparse set of data is currently available from NASA's Planetary Database for Jupiter's and Saturn's moons, with currently available data for these objects is included in the database with temporary placeholder values for the unknown properties. Planetary body data is taken only from NASA's Planetary Database [4] to represent a consistent planetary dataset. Planetary values are available from many sources online and in print; however, there are differences in the data that vary from source to source based on the measurements. Additional objects can be added to the database by simply including the additional parameters. Two versions of the database values exist within the planetary database program, one containing SI metric units, the other British Imperial units. All planetary data for the body is not needed to update the database. Placeholder values can be entered into the array based on analytical relationships or estimates until verified data values can be obtained.

While the main planetary data is stored in one database, the atmospheric properties are split into two different data arrays each using a different data structure. The first consists of the major atmospheric components and is stored in pairs of column elements. Data values for the atmospheric compositions are determined from NASA's Planetary Database and represent average values in the atmosphere. Certain planets exhibit large variations in the concentration of compounds in the atmosphere over the course of the year, thus average values are used in the database. Additionally small portions of the atmosphere are comprised of trace elements or due to the uncertainty in the primary composition the total composition of the atmosphere may not equal 100 percent.

For each planet, there are additional trace elements present in the atmosphere, but not in sufficient amounts to be measured as a primary component in the atmosphere. Trace components are stored in a secondary data array requiring three elements to describe its composition. The first column is allotted to a data string containing the name of the gas with the second and third columns holding the number of particles and the concentration, respectively. The Planetary Database program does not actually place any restriction on the concentration unit type in the array. This allows for future corrections to the database to update the concentrations, or if the concentration is updated, to reflect a different unit basis.

3.4. Sensor Databases

Each database was developed in a similar manner. Inputs from the main ISSPO program are loaded into each sensor database file along with any requirements the sensor must be able to meet, based on the planet the mission is going to. Data arrays contain the sensor properties in a two-dimensional array format. Sensors are listed in row format, with each column designated to a property. The number of data arrays in each sensor database varies based on the number of available properties for each sensor type. The elements of each database are unique to the corresponding sensor. Data available from commercial manufactures for each component are included in the database to allow for broad comparison properties for the mission. In selection of the correct sensor requirements placed on the sensors capability are driven form two sources. Environmental conditions the sensor must be able to withstand are driven primarily from the planetary database loaded into the program. Additional requirements on sensor configuration properties are loaded from the input file and specific to that sensor type. The types of sensors available in the database and their additional requirements are shown in Table 1. The final selected sensor properties are recorded to a MatLAB '.mat' data file and saved for use by the main ISSPO program.

Table 1 ISSPO Tool Sensor Databases and Required Specification Data

Payload Sensors	Sensor Specifications	Planetary Environment
AC Field	N/A	**Planet Properties**
Accelerometer	Acc Level / Power Type	
Acoustic	Sensor Type	
GCMS	Sensor Type / Range	
Imaging	Type / Res / Spectrum	
Inclination	Inclination level	
Nephelometer	N/A	
Radiation	Radiation Type	
Refraction	N/A	
Digital Sig. Processing	Processor Speed / Number of Devices	
Atmosphere	N/A	
Temperature	Sensor Type	
Pressure	N/A	
Humidity	N/A	
Wind Velocity	Sensor Type	
Density	Sensor Type	

4.0 Huygens Probe Benchmark Case

As a test case to validate the methodology developed within the ISSPO program, the interplanetary probe mission to Saturn's Titan moon carried out by the Huygens probe was used. This spacecraft consisted of several complex sensor packages with independent mission objectives. [5, 6, 7] Data on the spacecraft systems and top level packages is obtained from various references to determine which of the hardware components were based on available components, and which were custom designs built to suit a specific science goal for this mission.

Custom designed sensor configurations will always be required when the mission science question is truly unique or the level of fidelity of a commercially developed sensor is not readily available. In this case an available sensor may only need slight modification by the developer to meet the mission objective. The base model design can act as a reference point that can be modified to handle mission requirements that it was not originally designed to meet. In evaluating the component designs for the different sensor packages on the Huygens Lander, there is a combination of commercially available sensors, modified versions, and custom functioning units used.

Each subsystem of the Huygens Planetary Probe was analyzed separately as a stand alone design system. Six primary science packages comprised the science payload for the entire mission. The requirements for each package will be described in turn and evaluated using the mass and power limits for each subsystem. A comparison of the results to the published data available will be made. Despite the large number of instruments contained in the science payload, it represented only a small portion of the total spacecraft mass and volume. The mission profile was for a short lifetime to collect and relay the data thus a number of components has redundant systems or multiple ways to obtain the different data in case a system failed.

4.1 Aerosol Collector and Pyrolyser (ACP)

The Aerosol Collector and Pyrolyser (ACP) Package is one of the science measurements chartered with mapping the properties of Titan's Atmosphere. It samples the atmosphere twice during the entry and descent phase of the mission, in the tropopause (160 – 40 km), and in the cloud layer (23 – 17 km) and prepares the samples for analysis by other components on the probe. Samples are passed to the Gas Chromatograph Mass Spectrometer for analysis. The chemical composition of the samples is analyzed looking for specific combinations of aerosols in the atmosphere. The ACP on its own does not make any direct samples of the atmosphere. Instead, it prepares samples of the atmosphere for the GCMS. The design of the ACP was a collaboration of multiple research institutes and industry. Use of this type of device is not common in planetary probe missions and no broad database of similar devices exists that are commercially available. Calibration of this package type was excluded from the model.

4.2 Descent Imager / Spectral Radiometer (DISR)

The Descent Imager / Spectral Radiometer (DISR) sensor suite onboard the Huygens probe records images as the probe enters the Titan atmosphere. It is responsible for recording both descent imagery to monitor the surrounding terrain during the descent phase to provide background context, and upward looking data to observe the optical properties of the atmosphere. The Huygens probe spun as it entered Titan's atmosphere. With the DISR mounted on the side of the probe, the rotation allowed the probe to record smaller strip and area images that were later compiled into a 360 degree image of the terrain under the craft during descent. As the probe descended towards the surface, the imaging pattern of the spacecraft provided continuously updated terrain images. Upon arrival on the surface, the DISR is also responsible for recording images of the planetary surface and visually determine the landing location of the probe.

To meet all the optical observation requirements commercial grade CCD detectors were coupled to multiple camera lenses, each built to meet a specific observation requirement. This configuration allowed for a higher instrument density focusing multiple devices onto a single CCD array. The custom configuration of the lenses does not represent a commercial viable solution for optical data recording. In this case the ISSPO tool was tasked to select a CCD based on the required types and amount of data to be recorded by the probe during the mission timeframe.

Based on these criteria for a CCD array design, the ISSPO tool determined a similar CCD array configuration to the design flown on the Huygens Probe. A condensed summary of the sensor data is shown in Table 2. Data on the specific CCD array flown on the Huygens probe was not available for a direct comparison of the CCD design. The selected design has a larger CCD area, and offers the same frame transfer and binning capability of the model flown on Huygens. The model 424 CCD array is a flight proven model developed for NASA's Deep Impact Mission. [8]

Table 2 ISSPO System Architecture DISR CCD Array

Sensor Type	CCD 424
Imaging Spectrum:	X-RAY UV VISUAL NIR MICRO
Array Dimensions - Length:	1024 # Pixels
Width:	1024 # Pixels
Sensor Pixel Size:	21.0000 micro-m
Imaging Array Size - Length:	21.500 mm
Width:	21.500 mm
Dimensions - Length:	73.15 mm
Width:	52.83 mm
Height:	6.10 mm

4.3 Doppler Wind Experiment (DWE)

The Doppler Wind Experiment (DWE) carried aboard the Huygens probe is used to determine wind speeds in the atmosphere as the probe descended towards Titan's Surface. The DWE consists of two Ultra-Stable Oscillators, one carried aboard the Huygens Probe, while the other remains aboard the Cassini Orbiter. Measured wind velocity is back calculated from Doppler shifts in the transmitted radio signal frequencies between the two receiver transmitters.

The use of Doppler based velocity detections [9] involves tracking shifts in radio frequencies between two receivers. Based on the different sensor types in the database and the planetary environmental properties that the sensor must cope with the ISSPO determined a sensor package with similar properties to the actual flight unit. The DWE package [10] built by Daimler-Benz Aerospace (DASA), now EADS Germany used a commercially developed space-qualified rubidium oscillator built by Ball Efratom Elektronik GmbH. Detailed information on the specific sensor configuration flown is not available and a similar performing model built by Symmetricom [11] uses a militarized Rubidium Oscillator.

There are slight performance differences between the actual flight unit and the ISSPO design solution. The largest differences is the unit is about half the weight of the Huygens model but consumes more power at max input, but better matches the sensor performance during steady state operation. The model has a significantly shorter warm up period resulting in lower total power consumption. Brief summary results on the DWE sensor package are provided in Table 3.

Table 3 ISSPO DWE Sensor Configuration

ISSPO DWE Sensor System Architecture Result		
Model : Symmetricom 8130A		
Physical Properties:		
Mass (g)	900	
Dimensions (mm)	$102.6 \times 74.1 \times 72.8$	L × W × H
DC power:		
Warm-up power (W)	<35.0	< 10 min
DC consumption (mA)	1094	At 32 V DC input
Energy (Wh)		worst case (minimum temp)
Frequency Parameters:		
Output frequency (MHz)	10	
Frequency long term drift	$<5.0 \times 10^{-11}$	After 1 month
Allen Variation	3×10^{-11}	$\tau = 1$ s
	3×10^{-11}	$\tau = 10$ s

4.4 Gas Chromatograph Mass Spectrometer (GCMS)

Use of Gas Chromatograph Mass Spectrometer (GCMS) in planetary missions is a relatively new option. Typically these units have been custom built and designed specifically for a single mission. As such, a database of flight rated configurations is limited. Numerous laboratory models exist but are not built with the same considerations that are given to flight systems. In aerospace missions mass, power, and volume are all at a premium whereas laboratory models do not have these constraints. Additionally flight rated models must be completely automated as there is no possibility to intervene should a problem arise. The design of such a devise is also a combination of multiple separate instruments. The configuration flown on the Huygens probe is a custom configuration due to the payload constraints but based on commercially available individual products. The completed flight unit now represents a flight proven configuration with enough available performance data that it can represent a stand alone product to be used on other future missions with minimal changes for other planetary atmospheres. The GCMS onboard Huygens was built by NASA's Goddard Space Flight Center (GSFC), [12, 13, 14] and can be made available to reproduce for any future missions needing a similar device. The layout of these components and associated hardware resulted in one of the most complex instruments GSFC has ever built.

The science objectives for the GCMS are defined relatively broad [15], and include the following goals: to determine the noble gas abundance, isotopic ratios, and identify the high molecular weight trace organic compounds. Sufficient data from these sources provided enough design information to add the sensor configuration to the GCMS database. The flight unit is comprised of commercially available products including five ion sources attached to the mass spectrometer. The different components were machined to fit and assembled together to create the final flight unit. The final assembled version houses all the sensor components and associated electrical hardware to sample the Titan atmosphere and analyze the data. The data in Table 4 corresponds to the final published data for this component. It is not clear, from the reports whether this range is the maximum sensing range of unit or merely the range of chemical compounds expected to be found within the Titan atmosphere. Designs within the ISSPO tool can be set to lower or higher ranges, if the chemical contents of the planetary atmosphere are unknown; however with a better understanding of the compounds under investigation the required sensing range can be reduced.

Table 4 ISSPO GCMS Sensor Configuration

ISSPO GCMS System Architecture Design Result		
Model : GCMS - Huygens		
Physical Properties:		
Mass (kg)	17.30	
Dimensions (mm)	470 × 198 × 198	L × W × H
DC power:		
Typical Power (W)	28	After 36 min warm-up period
Average Power (W)	41	At 28 V DC input
Peak Power (W)	71	
Sensing Parameters:		
Mass – Charge Range	2-141	amu
Number of Ion Sources	5	units
Ion Source Charge Field Range	1.00	W degas
	16.00	W degas

4.5 Huygens Atmosphere Structure Instrument (HASI)

The Huygens Atmosphere Structure Instrument (HASI) is a key multi-sensor component to mapping the Titan atmosphere. In incorporated multiple atmospheric sensor elements into an overall package that would monitor most atmospheric properties during the planetary entry. Sensors within this package have been categorized into the type of environmental data that is returned. These categories include: acceleration, pressure, temperature, and Permittivity, Wave, and Altimetry. Mission science objectives for the HASI sensor suite are to determine the density, temperature, and pressure through the descent profile to the surface, determine the nature of the surface contact, whether solid or liquid, determine atmospheric electrical conductivity, electric fields and atmospheric lightning, and surface topography by monitoring surface dielectric fields. Within the design of this sensor package a certain amount of redundancy is included; in case a single element failed the secondary unit would continue to provide information.

A summary of the different science data to be returned, and sensor system components, is detailed in Table 5. The sensors in the PWA subsystem or mounted external to the spacecraft, and shielded from the electric field generated within the probe body by all the electronic components.

Table 5 Huygens HASI Science Package Objectives

HASI Sensor Packages		
Sensor Package	**Sensor Type**	**Measured Parameter**
Accelerometers (ACC)	3-Axis Acc	Atmospheric deceleration, Descent Monitoring, Impact Response
Pressure Profile Instrument (PPI)	Kiel probe, capacitive gauges	Atmospheric Pressure
Temperature Sensor	2-Dual Element Platinum Thermometers	Atmospheric Temperature
Permittivity, Wave & Altimetry (PWA)	Mutual impedance	Atmospheric electric conductivity
	AC field measurement	Wave electric fields & Lightning
	Relaxation probe	Ion conductivity and DC electric field
	Acoustic sensor	Acoustic noise due to turbulence of storms
	Radar signal processing (FFT)	Radar echoes below 60 km altitude

Performance data on the sensitivity of the PWA sensor components is available in several documents [16, 17] however, no data on the physical specification (dimensions, weight, materials, etc.) of the sensors is available. The scope of the ISSPO tool is determine the necessary sensor components based on mission requirements from databases of existing commercially available components. The mutual impedance sensors and relaxation probe design used do not represent a broad enough spectrum of uses to develop a database of configuration for interplanetary missions. These components are excluded from the rest of the sensor design analysis.

Information on sensors in this package based on commercially available sensors was incorporated into the sensor databases and analyzed to determine the selection reasoning for each component in this sensor package. For each of the separate science requirements the appropriate sensor configuration is selected by the ISSPO tool out of the databases based on the information required by the program for each different sensor type. A comparison of the ISSPO tool results to the known flight units for each component of the HASI sensor package is shown in Table 6.

Table 6 HASI Sensor Package Summary Results

HASI Sensor Package Components		
Sensor Package	**Flight Unit**	**ISSPO Results**
Accelerometer – 3 axis servo	Sundstrand QA-2000-030	QA2000-030
Accelerometer - piezo-resistive	Endevco 7264A-2000T	Endevco 7264A-2000T
Pressure Profile Instrument	Vaisala - Barocap	Series 48-0025
Temperature Sensor	dual element platinum resistance thermometers Rosemount Aerospace Inc.	Goodrich Model 0146MD
PWA – Acoustic Sensor	Kulite CT-190M	Kulite CT-190M
PWA – Digital Signal Processor(FFT)	Analog Devices ADSP-2100A	ADSP-2100A

4.5.1 Accelerometers

Two different configurations of accelerometers are carried aboard the HASI sensor package. The selected sensors feature single axis calibration, one featuring a high sensitivity used along the probe primary x-axis to precisely measure the deceleration profile of the probe through the entry phase, the other configuration three single-axis sensors to measure acceleration loads along all three primary axis at reduced resolution. Sundstrand, makers of the three-axis servo accelerometer [18], was acquired by Allied Signal in 1994, and operated for 5 years before being acquired by Honeywell sensors in 1999 [19]. Since, the launch of the Huygens probe additional versions of the sensors have been developed based on the same sensor platform and sensor performance data varies in sources. Due to the nature of the designs of these elements the maximum operational range of these components is shown on datasheets, however, through signal conditioning the maximum range of the models can be reduced with a corresponding increase in sensor resolution. For the piezoresistive accelerometer the design comes from the Endevco 7264 accelerometer line [20], the optional "T" configuration of the design reduces the transverse sensitivity to one percent from the default three percent calibration.

4.5.2 Pressure Profile Instrument

The Pressure Profile Instrument's objective is to map Titan's atmosphere pressure profile during the descent phase of the mission. Available data [17] on the configuration of the PPI sensor indicates that the silicon capacitive absolute pressure sensor flown is a variant of the Barocap design manufactured by Vaisala Co., in Helsinki Finland. Two types of silicon diaphragm were used, constructed based on different thicknesses to yield different sensitivities to the pressures in different regions of the atmosphere. Searches for specific information on the configuration flown aboard Huygens yielded no successful results. Available configurations on the Vaisala website, do not represent the flight rated model, or cover the same operational range. Without the specific flight configuration data to incorporate into the database, the planetary environmental data is used to determine an alternate sensor with similar performance capabilities.

Contrary data [21] on the performance of the pressure sensing range proposes an upper limit on the sensing range of 1600 mbar. Onboard the spacecraft the pressure profile instrument was not exposed directly to the atmosphere, but atmospheric samples were funneled through a Kiel Probe into the instrument. The performance data for the flight model is compared to the ISSPO sensor configuration in Table 7.

Table 7 ISSPO HASI Pressure Profile Instrument Sensor Configuration

ISSPO HASI PPI Sensor Package Comparison		
Model :	Barocap – Flight Unit	ASCO 48-0025
Physical Properties:		
Dimensions (mm)	70.00 × 50.0 × 17.00	48.56 × 22.23 × 22.23
Sensing Parameters:		
Pressure Range (g's)	0 – 2000 mbar	0 – 1724 mbar
Accuracy	1.0 %	0.5 %

4.5.3 Temperature Sensors

The flight unit temperature sensors carried as part of the HASI sensor package features a coarse and fine sensor design. The designs features a platinum resistance thermometer mounted onto a platinum-rhodium truss frame that is mounted on a small STUB boom that extends past the spacecraft boundary layer, shown in Figure 15, during entry to measure free stream temperatures. The original flight units were produced by Rosemount Aerospace, Inc. based in Minnesota, U.S.A. Since the qualification effort and launch of the Cassini- Huygens mission, they were acquired by Goodrich Sensor Systems [22], and data on the specific model is no longer available. A number of similar capable platinum resistance thermocouples are available within the known performance specifications of the original model. The performance properties of the selected sensor are shown in Table 8.

Table 8 ISSPO HASI Temperature Sensor Configuration

ISSPO HASI Temperature Sensor Package Results		
Model : M-0146MD		
Physical Properties:		
Mass (g)	0.35	
Dimensions (mm)	45.72 × 1.524 × 1.524	L × W × H
Sensing Parameters:		
Temperature Range	-269 – 400	deg C
Stability	0.03	%
Repeatability	≤ 0.1	deg C

4.5.4 PWA Acoustic Sensor

The Acoustic sensor flight unit carried aboard the Huygens probe HASI experiment package [23] is tasked to measure the acoustic noise due to the turbulence of storms. However the environmental conditions on Titan placed additional constraints on the selection of the sensor. Due to the cold thermal environment, the reasoning [24] was made to use a pressure sensor capable of surviving the harsh environment, and sacrificing the ability to detect low level noise environments. This reduced ability to detect sounds prevents the pressure sensor from monitoring quiet sounds but allowed it sufficient resolution to detect strong winds and thunder as specified in the mission requirement. A summary of the relevant performance parameters is listed in Table 9.

Table 9 ISSPO HASI Acoustic Sensor Configuration

ISSPO HASI Acoustic Sensor Package Results		
Model : Kulite CT-190M		
Physical Properties:		
Mass (g)	4.0	
Dimensions (mm)	34.3 × 9.5 × 9.5	L × W × H
Sensing Parameters:		
Acoustic Range	56.8 – 135	dB_{SPL}
Resonance	500	kHz
Temperature Range	-195.5 – 37.0	deg C

4.5.5 PWA Digital Signal Processing

Data collected from the various sensors in the PWA package that required real time processing to trigger events, or interpret the data was processed via a Digital Signal Processor. For time critical events, the data must be sampled, analyzed, and results output quickly or else a critical time event may be missed. Additional crucial selection consideration is the type of tasks the processor is required to complete. Special processor versions are available, tailored with specific computational processing abilities, or algorithms to be able to perform specific types of calculations. Selection of the DSP unit flown on the Huygens Probe is based on the required computation speed of the processor and the attached components. Sensor data from the mutual impedance, relaxation probes, acoustic sensor, and radar altimeter unit is passed to the DSP unit and undergoes Fast Fourier Transform analysis before transmitting the data to the Huygens orbiter back to Earth. A summary of properties of the ISSPO resulting selection is in Table 10.

Table 10 ISSPO HASI DSP Component Configuration

ISSPO HASI DSP Sensor Package Results		
Model : Analog Devices ADSP-2100		
Physical Properties:		
Output Power (mW)	790.0	
Dimensions (mm)	33.83 × 33.83 × 9.12	L × W × H
Operating Parameters:		
CPU Operating Speed	8.192	MHz
Data Memory	16 K-Words	16 Bins
Program Memory	32 K-Words	24 Bins
Temperature Range	-55.0 – 125.0	deg C

4.6 Surface Science Package (SSP)

The Surface Science Package (SSP) carried aboard the Huygens Titan probe is comprised of nine different sensors monitoring seven different types of planetary science data. The charge of the SSP is to measure and determine the nature of Titan's surface properties. A summary of the SSP's scientific objectives is shown in Table 11.

Table 11 Huygens Surface Science Package Scientific Objectives

Surface Science Package (SSP) Scientific Objectives
Determine the physical nature and condition of Titan's surface at the landing site
Determine the abundances of the major constituents, placing bounds on atmospheric and ocean evolution
Measure the thermal, optical, acoustic and electrical properties and density of any ocean, providing data to validate physical and chemical models
Determine wave properties and ocean/atmosphere interaction
Provide ground truth for interpreting the large-scale Orbiter Radar Mapper and other experimental data

Based on the summary of mission requirements input into the ISSPO program, a summary sensor design package is detailed in Table 12. The inputs and summary comparison for each sensor design is discussed in the following sections. Information on commercial components used in the SSP is scarce and several of the sensors are approximated in the final ISSPO design solution by similar components. Several of the components utilized in the SSP represented custom design solutions for the specific application they were tasked for on the Huygens probe.

Table 12 ISSPO - Huygens SSP Sensor Component Comparison

SSP Sensor Components		
Sensor	**Flight Unit**	**ISSPO Results**
Accelerometer – Impact penetrometer ACC-E	Piezoelectric Ceramic PZT-5A	N/A
Accelerometer - Impact accelerometer ACC-I	Endevco 2271AM20 0 – 100 g's	Endevco 2271AM20
Tilt Sensor TIL	Spectron L-211U +/- 60°	Spectron L-211U
Temperature Sensor THP	Hot Wire 65 – 100 K	M-0146MD
Velocity of Sound API-V	Piezoelectric Transducers – 2 150 – 2000 m/s	Physical Acoustics R80 Alpha
Acoustic Sounder API-S	Piezoelectric Transducers Array	N/A
Fluid Permittivity PER	Capacitance Sensor	N/A
Density of Fluid DEN	Archimedes Sensor 400 – 700 kg/m^3	N/A
Refractive Index REF	Critical Angle Refractometer 1.25 – 1.45	Huygens Design

4.6.1 Accelerometers ACC

To determine the impact acceleration loads on the vehicle during the final phase of the atmospheric descent, two different types of units are used. One unit (ACC-I) measured the landing acceleration loads dependent on the surface material composition. The other probe was based on a penetrometer design and extends forward of the outer skin of the vehicle and is designed to measure the surface resistance force on the penetrometer tip as the probe lands on the surface. The ACC-I unit flown is an Endevco 2271AM20 piezoelectric accelerometer [25].

4.6.2 Tilt Sensor TIL

The tilt sensor [26] carried aboard the Huygens probe primary purpose was to return orientation data about the spacecraft if it were to land in an ocean. Combined with data from the onboard accelerometer, the position and movement of the probe could be obtained. The unit was also designed to operate during the entry phase, and provide orientation data that would improve the fidelity of data collected in the DWE by adding probe orientation data to determine atmospheric wind speeds. The sensor component flown aboard Huygens consists of two single axis tilt sensors mounted in a dual axis configuration on a small mounting block [27]. Sensors used on the SSP were chosen for their quality, performance and high reliability.

4.6.3 Temperature Sensor THP

The Temperature sensor carried aboard the Huygens probe as part of the SSP is a dual operation hot wire thermometer to measure surface thermal conductivity. The sensor configuration consists of a redundant pair of cylinders housing a platinum wire resistor. Since the final landing environment was unknown, and the possibility existed that the probe could land on either solid ground or in an ocean environment, each cylinder is designed for a liquid measurement or gaseous atmospheric sample. Each cylinder contains a platinum wire resistor configured to operate as a four wire resistance thermometer, and operates via a transient hot wire method. [28] The material construction of this sensor is the same platinum as the thermal sensor carried in the HASI sensor package. The configuration of the components here is custom but the same basic configuration can be converted to suite the purpose of the experiment.

4.6.4 Acoustic Sensor API

The Acoustic Properties Instrument (API) is comprised of two separate instruments. A pair of piezoelectric ceramic transducers [29] comprising the API-V element are mounted facing each other. The two units transmit and receive ultrasonic pulses [30] over the unobstructed path. The other component to the API sensor is an array of 10 resonant piezoelectric plates and uses an acoustic beam transmitted to the surface to detect from the signal scattering the number of particles in the atmosphere. The use of an acoustic array in this manner is not widely flown on planetary missions, thus a database of commercially available components featuring this ability is limited and was excluded from direct comparison in this analysis. The API components were designed and built under research collaborations between academia and industry. Data on the configuration of the flight unit version of the components for the sound velocity sensor was unavailable. However, a wide enough database of acoustic transducers, allow the ISSPO tool to determine a similarly capable option that could measure the speed of sound. The performance properties of the resultant ISSPO design configuration are shown in Table 13.

Table 13 ISSPO SSP Acoustic Sensor Configuration

ISSPO SSP Acoustic Sensor Package Results		
Model : Physical Acoustics R80 Alpha		
Physical Properties:		
Mass (g)	32	
Dimensions (mm)	19.0 × 19.0 × 21.4	L × W × H
Operating Parameters:		
Frequency Range	200 – 1000	kHz
Temperature Range	-54.0 – 124.0	deg C

4.6.5 Permittivity PER
The task of the permittivity sensor flown aboard Huygens is to measure the static permittivity of any fluid samples found on the surface. In part this was to aide in the determination of the mixing ratio of ethane to methane in any surface liquids. The Huygens design consists of 22 stacked open plate capacitors. [29, 31] The design would be custom built for each application and be based on any number of mission constraints or tuned specifically to determine a number of fluid or gaseous properties can be determined. These units serve a variety of functions that serve other industries and uses, such that no standard design configurations exist. Capacitance units for this application can be configured via many different parameters and are best suited being designed for each application.

4.6.6 Density DEN
The density sensor flown aboard the Huygens probe employs Archimedes' principle in its operation. A buoyant float is suspended off the Top Hat inner wall by a thin flexible beam [31] and the resulting forces on the beam are measured by strain gauges. The unit was configured as a Wheatstone bridge circuit, and the unit was designed to operate in the region of 400 – 700 kg/m^3 with a science mission requirement of a resolution of ± 2 kg/m^3 at a density of 550 kg/m^3. The design of the electronic circuit can be based on any circuit configuration and no data on the cylindrical float unit incorporated into the design is available. Only a constant voltage source is required and the resulting deflection of the float alters the Wheatstone bridge circuit resistance, and changes the output voltage. Density sensor configurations like this are simple common components, but usually custom configured to the exact system use. Sensor configurations currently within the ISSPO database are based on larger scale Archimedes buoyancy float designs for measuring density in pipe flows or other large liquid systems.

4.6.7 Refractive Index REF
The Refractive Index (REF) sensor carried aboard the Huygens probe measured the refractive index of the Titan atmosphere to determine the abundance of methane and ethane in any liquid samples on the surface. The flight model is a linear critical angle refractometer [31], which uses a sapphire prism to aid in determining the refractive index range. The flight unit also incorporates a detector array which incorporates a self-scanning linear photodiode array.

The final flight configuration is a combination of commercial components which was designed for laboratory use and custom elements to aid in detection and operation. The component was built as a collaboration between the University of Manchester Institute of Science and Technology (UMIST) and Rutherford Appleton Laboratory. Data on the original laboratory model was not available to include in the ISSPO database, however enough data is available on the performance and configuration of the flight unit to add it to the database for refractometer sensors and is the resulting design from the ISSPO tool. The resulting design is chosen by the refraction index range and data based on the planetary bodies environment. The summary of the resulting sensor data is then shown in Table 14. The photodiode array [32, 33] is a commercially available unit mounted to the refractometer to record the data sampled during the mission.

Table 14 ISSPO SSP Refractometer Summary Configuration

ISSPO SSP Refractometer Sensor Package Results		
Model : Huygens - Ref		
Physical Properties:		
Dimensions (cm)	10.0 × 10.0 × 11.61	L × W × H
Power (mW)	10	Photodiode array requirement
Operating Parameters:		
Refractive Index Range	1.25 – 1.45	Refractive Index Units
Accuracy	0.001	Refractive Index Units

4.7 ISSPO Huygens Summary

The results of the ISSPO tool comparison with the Huygens mission requirements shows a high correlation of the ISSPO tool results with the flown sensors. Given the mission requirements for science data and the sensor package power and mass limits, the ISSPO tool was able to assemble a sensor configuration capable of meeting the requirements. Data on sensor configurations is based on product specified data sheets available from commercial suppliers. Variations in reported data amongst different vendors make for difficult product comparisons. Data not available for all sensor configurations amongst suppliers is zeroed out within the sensor databases.

For each sensor package the payload totals were used for ISSPO program inputs. Often power or mass properties of the individual components were not available for the individual components to compare against the total sensor package weight. Total sensor package weights used in the input files also includes mounting hardware for the components, electrical wiring components, and miscellaneous elements which in many cases were not available.

Custom configured sensors for some of the sensor packages carried aboard the Huygens probe were not included since they represent a single point design, or use of the sensor has not been extensive enough to develop a database of sensor configurations. Additional space missions with similar science objectives are required to develop additional sensor databases.

5.0 Venus Atmospheric Properties Mission

With the development of the ISSPO tool, a study for an interplanetary mission can be made. Of the inner planets, Venus with one of the most extreme planetary environments poses many interesting questions, which have yet to be answered.

Venus's atmosphere [1] with a surface pressure about 90 times that of earth, planetary surface temperature of 730 K, and a carbon dioxide (CO_2) atmosphere with cloud layers compromised of sulfuric acid, poses a challenging problem to a sensor designer. The nature of the harsh environment on Venus, and the observed differential atmospheric flows, makes long term observation of atmospheric properties difficult, and the underlying operation of some of the atmospheric properties are likely to remain a mystery until new methods can be found to survive the environment.

The objective goals of the mission would be to provide additional information on the structure, and other atmospheric mechanisms of Venus's atmosphere. Along with the atmospheric suite, additional sensors can provide additional contextual information during the mission timeframe. Unfortunately due to the extremely hot and corrosive nature of Venus's atmosphere, a long term mission (weeks or months) is not possible. The mission window would be limited to several hours Earth time (including the atmospheric entry). The sensor elements required during this planetary mission are shown in Table 15, along with information on the nature of the observation and its benefit to the planned mission concept. With the relative closeness of Venus, the mission timeframe is reduced, and the transmission time delay is significantly shorter than missions to the outer planets.

Table 15 Venus Atmospheric Mission Objectives

Venus Atmospheric Mission Objectives	
Mission Data	**Objective Reasoning**
ATMOSPHERE - Temperature	Provide Atmospheric Temperature for mission trajectory, temperature calibration data for other sensors onboard
ATMOSPHERE - Pressure	Provide Atmospheric Pressure for mission trajectory, pressure calibration data for other sensors onboard
ATMOSPHERE – Wind Velocities	Measure Wind Velocity profiles throughout the atmospheric descent, providing data to validate physical models
INCLINATION	Provides spacecraft orientation information to determine relative wind flows around spacecraft
ACCELERATION	Provide descent deceleration profile information and use for event sequence timings
EM FIELD	Map planetary magnetic field to determine if it accounts for observed wind flows
RADIATION	Detect charged particle occurrences in the atmosphere looking for energetic reactions in the atmosphere
OPTICS	Provide visual observations of wind flows in visual, ultraviolet, and infrared wavelengths to track cloud motion patterns

These sensor data types are then loaded into an ISSPO input file to investigate the destination planet Venus, and use the "SI" unit system. In this case the mission is being planned and there are no fixed limits to apply to the sensor design for a preliminary configuration. Values are still required by the program, but can be set to any values. If the resulting package is less than the input values, the mission design will "appear" to "succeed", and if the input limits the tool will "appear" to "fail". However, since there is no driving goal to meet for this mission concept, a failure case merely means that the input limits are too low. This can be resolved by finding ways to reduce the weight, volume, or power consumption, through a custom designed configuration, or find ways to increase the payload budget limits. Either of these two methods usually means additional development time and additional budgetary costs. Sensor operating requirements and types loaded in the input file are shown in Table 16.

Table 16 Venus Atmosphere Concept Mission ISSPO Input Data

1st Column	2nd Column	3rd Column	4th Column	5th Column	6th Column
"ATMOSPHERE"	"WIND VELOCITY"	"ANEMOMETER"	"TEMPERATURE"	"VOLTAGE"	
"INCLINATION"	"MEDIUM"				
"ACCELERATION"	"MEDIUM"	"Voltage"			
"EM FIELD"					
"RADIATION"	"Charged Particle"				
"OPTICS"	"ARRAY"	"MEDIUM"	"VISUAL"	"UV"	"NIR"

Resulting sensor design is shown in Table 17. It includes a minimum design for each sensor, and the quality of the data returned would be improved by incorporating all spacecraft axis and some redundancy into the sensor design. Sensors that record one-dimensional data, i.e. wind velocity, inclination, and acceleration would require at least one sensor along each primary spacecraft axis to provide a complete description of the data being recorded. With the primary data interest in wind velocity, use of a redundant design would be beneficial to the returned science data.

Table 17 ISSPO Venus Atmosphere Mission Sensor Package Summary Results

ISSPO Venus Atmosphere Sensor Package Results					
SENSOR	**NAME**	**RANGE**	**MASS**	**VOLUME**	**POWER**
ATMOSPHERE – Temperature	K	- 200 – 1250 deg C	0	0	0
ATMOSPHERE - Pressure	13(C,U)2000P	0 – 13789.5 kPa	0	29.41 cm^3	0.030 W
ATMOSPHERE – Wind Velocities	FT 702	0 – 70 m/s	0.500 kg	0.0004 m^3	0
INCLINATION	L-212T	-45 – 45 deg	0	12.00 cm^3	0
ACCELERATION	MA15	-50 - 50 g's	0.1417 kg	47.72 cm^3	0.64 W
EM FIELD	TAM-1	0 – 1000 mG	1.080 kg	0.0016 m^3	0
RADIATION	LPD	0 – 250 MeV	7.00	0.0067 m^3	15 W
OPTICS	CCD 3041	UV VISUAL NIR	0	3.384 cm^3	0
SUMMARY			**8.7217 kg**	**0.00871 m^3**	**15.77 W**

Data for some of the components is not available, and the results might vary with additional sensor data.

6.0 Summary

The ISSPO Tool is developed as a preliminary tool to determine the sensors required to answer planetary science mission questions. Given a planetary body and a description of planetary science objectives to be accomplished, the tool will determine the sensors needed to return the results. ISSPO selects the correct sensor components based on the input criteria and the planetary environmental properties. Selection of the final sensor components are then based on additional operational parameters that vary for each different sensor component. Databases for each type of sensor are based on commercially available sensors. The goal of this is to reduce the amount of time spent performing trades studies to determine the correct sensor to use. The use of commercially developed products and flight rated hardware reduces the time and cost of new space missions by having to develop new custom hardware components for each mission.

A benchmark case proving the sensor design algorithms was performed on the Huygens probe mission to Titan. Science objectives for each sensor package were broken down into the different types of sensor data that was to be provided. The requirements for the different sensors were input into the ISSPO input file along with the sensor package weight and power limits. Evaluating each sensor package resulted in selection of the Huygens hardware for known flight components. For sensors where the commercial component was unknown, similar performing sensors were chosen based on operational range, environmental properties and the other sensor requirements input into the ISSPO program file. The resulting design configurations agree within a reasonable margin to the sensor package mass and power requirements.

A sensor payload configuration was developed for a conceptual mission design to Venus to answer additional question on the mechanisms that drive the intense atmospheric winds. The sensor package was designed to monitor atmospheric winds, probe orientation, acceleration, planetary magnetic fields, charged particle radiation, and optical imaging to provide a visual record of atmospheric cloud movements. At this conceptual level no restrictions on payload mass, volume, or power constraints are applied to the mission design. In this manner the ISSPO tool can provide preliminary budgets, for mission requirements, to determine the minimum sensor configuration needed to obtain the mission science data.

The summary package comprises commercially available design components, and could be modified further by the use of custom designed sensors to provide higher fidelity data or modified to reduce mass or power requirements. The use of custom mission components, adds complexity, time, and cost into the development time fame for any mission, as the unit must be fully qualified and tested before being certified for flight use.

The ISSPO tool also aids in mission design. Based on the knowledge of the planetary science mission a preliminary payload mass budget can be determined. With this knowledge the associated spacecraft hardware can be determined required to support the mission. The size of the spacecraft will determine the required size of the launch vehicle and the operating capabilities it will need to have to send the probe to its target. This information then can be used to determine the operating timeline for the mission.

7.0 Future Work

The framework has been established here for a tool to determine the optimal sensor configuration based on the mission science requirements. Refinements can be made to each available sensor database, update existing database values, add additional performance values, incorporate sensors based on different governing equations, new sensor types, etc. As each new planetary mission is executed, sensor components within the database can be updated, and the selection algorithms refined. Additional refinements can be made to the tool at system level parameters and account for interactions between the sensors and the spacecraft systems.

With each new planetary mission the databases of flight proven equipment will grow, and new methods will be evaluated to obtain science data. Development of custom configurations today will lead to common components in the future. The science and technology for these new sensor designs can be built into the ISSPO Program and expanded as new methods are found to determine answers to new scientific questions.

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