GEORGIA INSTITUTE OF TECHNOLOGY
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SPONSORED PROJECT INITIATION

Date: 1/10/81

Project Title: Provide a Paper Illustrating Viable Piloting Concepts for Vessels

Project No: A-2821

Project Director: Mr. E.F. Greneker

Sponsor: U.S. Coast Guard, 2100 Second Street, SW; Washington, D.C. 20593

Agreement Period: From 11/10/80 Until 4/30/81 (Contract Period)

Type Agreement: Contract No. DTCG23-81-C-20016

Amount: $24,967

Reports Required: Final Report

Sponsor Contact Person(s):

Technical Matters

Commandant (G-NSR-1/CGHQ14)
U.S. Coast Guard
Washington, D.C. 20593

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DTCG23-81-C-20016

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Date: 5/28/81

Project Title: Provide a Paper Illustrating Viable Piloting Concepts for Vessels

Project No: A-2821

Project Director: Mr. E.F. Greneker

Sponsor: U.S. Coast Guard, 2100 Second Street, S.W.; Washington, D.C. 20593

Contract No. DTCG23-81-C-20016

Effective Termination Date: 5/31/81

Clearance of Accounting Charges: 5/31/81

Grant/Contract Closeout Actions Remaining:

- Final Invoice and Closing Documents
- Final Fiscal Report
- Final Report of Inventions
- Govt. Property Inventory & Related Certificate
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May 6, 1981

Captain J. T. Montonye, Chief
Short Range Aids To Navigation Branch
Commandant (G-NSR/14)
U. S. Coast Guard
Washington, D. C. 20593

Dear Captain Montonye:

Enclosed are the two preliminary "clean" copies of our position paper entitled "Conceptual Radar Piloting Techniques Using Radar Beacon (RACON) Technology and Other Advanced Marine Radar Technology". The contractually required copies are being forwarded through the established contract channels. Although the enclosed paper represents our final effort, we have followed your directions and included the cover page notation stating that the enclosed material represents a final draft technical report.

We have incorporated the draft Coast Guard review comments that we discussed during my visit April 23rd. Please note that we have edited several of the suggested changes and additions. We took this liberty on the basis of your encouragement to edit the changes that you requested. Specifically we have added some material back to the Introduction Section. We feel this added material is necessary to establish the critical nature of your mission. We have rewritten some of the RACON descriptions in a more straightforward manner consistent with your suggestions; also we have relabeled the figures to show the RACON strobes. We incorporated the remarks of the reviewers where appropriate and have redrawn the frequency allocation chart consistent with the request of the Frequency Management Shop's suggestion.

We appreciate the opportunity of being able to serve the Coast Guard in this high level effort and wish you the greatest success in your new position and in the implementation of the RACON piloting concept program.

If we can be of service in the future, please do not hesitate to let me know.

Yours truly,

Eugene F. Greneker
Associate Chief
Radar Applications Division

cc: E. K. Reedy
    J. L. Eaves
    J. D. Echard

Enclosure

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION
CONCEPTUAL RADAR PILOTING TECHNIQUES
USING RADAR BEACON (RACON) TECHNOLOGY
AND OTHER ADVANCED MARINE RADAR TECHNOLOGY

by
E. F. Greneker and J. E. Matthews

A Final -Draft Technical Report

prepared by the
GEORGIA INSTITUTE OF TECHNOLOGY
Radar and Instrumentation Laboratory,
Radar Applications Division,
Atlanta, Georgia 30332

Prepared for
The Commandant/G-NSR/14
U. S. Coast Guard
Washington, D.C.  20593
Captain J. T. Montonye, Technical Monitor

Contract No. DTCG23-81-C-20016
Georgia Tech Project No. A-2821

16 April 1981
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SECTION 1
INTRODUCTION

Maritime transportation accounts for 99 percent of international movement of raw materials and products between the United States and foreign ports. Domestic marine transportation accounts for 56 percent of the total tonnage of goods moved in domestic commerce. There are over 3,000 collisions and groundings annually as a result of this intense traffic load along the U.S. coast, in our waterways and harbors. These incidents cost the American public, the ship owners and private property owners over 3 billion dollars each year. These expenses do not include indirect costs such as the economic loss to a community. Marine accidents are often the cause of these indirect costs due to the disruption of service along major trade arteries. More importantly, there is no way to measure the value of human lives lost in these accidents.

The United States Coast Guard (USCG) is the United States regulatory agency that is attempting to reduce annual marine accident statistics. Marine accident prevention is foremost among the motives for enhancing the use of radar and radionavigation systems for piloting in convergence zones. The Coast Guard efforts to provide better short range navigation aids should:

* improve piloting safety in channels when environmental conditions suddenly obscure visibility;
* reduce the delays caused by poor visibility or darkness;
* improve the pilot's data and, therefore, his judgment;
* reduce the probability of collision with bridges;
* remove confusing clutter from the radar display, thus allowing instant position fixes and more time for detecting, tracking, and communicating with other vessels;
* allow quick recognition of remaining markers in channels when buoys are submerged by ice;
* improve piloting accuracy, making it possible to accommodate larger vessels in narrower channels;
* improve capacity for ports and waterways;
* improve port and waterway safety;
* lower shipping cost for consumers due to tighter scheduling of vessels under degraded piloting conditions.
This ambitious program employs a mix of electronic navigation aid improvements for vessels, improved systems of aids to navigation on waterways, and refined piloting techniques to achieve program goals. There will be a family of navigation aids for vessels that will meet all basic navigation requirements and offer certain advanced capabilities. These will allow the individual user to determine the level of on-vessel navigation sophistication required for the user's vessel.

This paper is a review of several of the concepts that will be the basic elements of this upgrade being developed by the Office of Navigation, USCG. Also, this paper serves as a forum for the presentation of a few of the exciting system concepts that may be available within this decade to improve coastal, channel, and harbor navigation.

To some extent Radar Beacons (RACONS) alone will allow realization of these objectives; however, the benefits from today's RACON technologies will not be achieved by improving aids to navigation alone. The navigational systems aboard vessels must be modernized too, if those vessels are to perform optimally in ice, poor visibility, and narrow channels. The purpose of this paper is to focus on the development of a set of incremental options for mariners that will afford mariners a range of piloting capabilities consistent with the range of improved aids to navigation services that the United States Coast Guard might expect to provide in the next five years.
Numerous marine radar piloting techniques have been developed. Certain of these techniques may be used by relatively inexperienced radar navigators. Other more complex radar navigation techniques utilize the plotting board and require the navigator to be experienced and able to quickly reduce large amounts of data to useful information. A selected few of the complex radar navigation techniques can be simplified and enhanced if an agency such as the USCG supplies certain supplementary aids. Studies show that one way to improve radar navigation is to develop better radar markers that can be easily recognized on a cluttered radar display.

The two devices presently used as radar markers in the marine environment are the radar corner reflector (RAREF) and the RACON. When a RAREF is attached to an object, the radar cross section or reflective area of the object is increased. This increase in effective radar cross section causes small objects such as a buoy to appear as a major target on the radar. The RAREF has the advantage of being a passive device requiring no maintenance.

The RACON generates a "strobe" or "spoke" on the interrogating radar display each time that it is scanned by the radar antenna. The strobe, which extends radially outward from the position of the RAREF on the display, can be coded with a Morse character. This allows specific RAREFS to be identified by their co-located RACONS. The combination creates a reliable reference for piloting that can serve as the basis for relatively accurate channel piloting. This section discusses the RACON enhanced radar piloting techniques that the U.S. Coast Guard conceivably could facilitate through the appropriate placement of such RAREF/RACON combinations.

2.1 RACON APPLICATIONS

2.1.1 LANDFALL AND COASTAL PILOTING

Precise methods to determine a landfall position have been of historical importance to the Mariner. Before the development of electronic systems, landfall navigation errors usually were on the order of tens of miles after an ocean crossing. Lighthouses, lightships, and sea buoys were developed to
allow vessels to find themselves after days of celestial navigation and/or
deck reckoning.

In the last half century, these near-shore traditional aids to navigation have been supplemented by radiobeacons, Loran-C, and other radionavigation services which have decreased the mariner's problems of transition from high seas navigation to coastal piloting. Even though these aids exist, the landfall and coastal piloting phases of navigation remain among the most critical. During the period 1972 through 1977, there were 722 groundings and 525 rammings off the coasts of the United States. Among the major causes of the groundings were: (1) lack of attention to and the misjudgment of the vessel's location and movement relative to the water depth; (2) lack of vigilance by the crew in using all available navigation information; (3) lack of knowledge of the presence of submerged objects and shoals; (4) poor navigation/maneuvering practice; and (5) inoperable or malfunctioning navigation equipment. Two major causes of rammings were identified as: (1) poor navigation practice: failure to use all navigation information available on the vessel to determine the vessel's position; and (2) error in judgment or lack of attention by the conning officer in maneuvering.

These causes of marine accidents in the near-to-shore and channel environment suggest that an improvement in short range navigation aids is required. A leading candidate device to improve short range navigation accuracies is the RACON. There are good reasons why the RACON is an excellent device for the improvement of near coastal and channel navigation.

On the high seas radionavigation systems serve the mariner. Inside harbors, piloting is substantially visual. Along the coasts, however, the radar is used as a primary navigation tool. RACONS located at the entrances to congested harbors can serve coastal piloting safety to a significant extent by giving watch officers less opportunity to misjudge position and destinations and more time to concentrate on traffic and other tasks. RACONS used for close quarter navigation could be configured for several different applications.

Vessels would use parallel index piloting techniques to set up their course to the channel harbor entrance from the known reference point marked by the RACON landfall marker. A course line, "CD", and a Parallel Index Line, "AB", are established as shown in Figure 2.1. Line segment "CD" passes
Figure 2.1. The use of Parallel Index Piloting techniques and the vessel Gyro to pick-up course to next marker.
through the origin of the radar sweep. Line "AB" lies over the RAREF at the origin of the RACON strobe. Should the vessel drift toward shore, line "AB" will move up and over the the RACON strobe. If the vessel drifts seaward, line "AB" moves below the RACON strobe origin.

The process is virtually the same for stabilized and non-stabilized radars. In the stabilized case (head up or north up), line "CD" indicates a true direction which is fixed until the course is changed. The radar picture moves beneath it. On non-stabilized radars, such as aboard barges on the Western Rivers and on carriers on the Great Lakes, the two lines remain at the preset distance but must be rotated manually as the display shifts in response to a change of heading. The heading flasher rotates automatically under line "CD" on stabilized radars, as heading adjustments are made to hold "AB" over the RAREF. While in the non-stabilized situation, "CD" must be rotated manually with respect to the heading flasher by an amount equal to the absolute difference between the course and the heading, which the mariner must compute or estimate.

If the use of a gyro stabilized steering compass is presumed in both cases, the piloting accuracies then are basically a function of the gyro errors involved. Non-stabilized radars introduce the human error element because of mental and manual involvement. However, for landfall positioning, where position checks and heading corrections become much more frequent, the process is more accurate and more practical, even with non-stabilized displays, than with all but the most sophisticated radio positioning techniques.

2.1.2 CHANNEL ENTRANCE MARKING

Sea buoys mark the entrances to all major ports of the U.S. Upon landfall and once inside the headlands, mariners seek to identify and visually align their vessel on sea buoys as quickly as possible. This technique often proves quite difficult because of background lighting, poor visibility, the degrading effect of buoy motion on the availability of their light signals, radar clutter created by other buoys, vessels, islands, and sea returns, and the relatively short radar detection ranges of the sea buoys.

The common application of RACONS for marking channel entrances, therefore, will be aboard channel entrance buoys. As depicted in Figure 2.2, they will serve as bearing marks on radar upon which the central mechanical cursor
Figure 2.2. The radar picture observed when a sea buoy is marked by a RACON.
or an electronic gyro stabilized cursor can be applied as an extension of the parallel indexing technique used to approach the harbor.

2.1.3 CHANNEL MARKERS

RACON leading line markers are being investigated, not only as channel entrance markers on sea buoys, but also as channel centerline markers. Because initial research indicates that the success achievable in using the RACON as a leading line marking technique is sensitive to channel geometry, a "dog leg" channel segment is an ideal situation for RACON use as a center line marker due to the long straight lanes and geometry allowing the RACON to be positioned on land. Channel center line marking could be accomplished with a single RACON when high precision piloting is not required. A RACON pair would be utilized in a "RANGE" type of application when greater navigation precision (than can be achieved with a single RACON) is required.

Figure 2.3 shows how the radar display would appear to the pilot using cursor piloting techniques on a single RACON. The RACON would be located in a position such that if the centerline were extended beyond the turn in the channel, the centerline would intercept the RACON'S location. To get the channel centerline using this technique, the following procedures would be followed: the azimuth stabilized display mode would be selected; the electronic or manual cursor would be placed on the true course of the channel centerline; the pilot would then adjust the vessel's course to move the cursor over the RACON origin, and last; the pilot would change course to the desired channel centerline course.

The display cursor would be set to bisect the RAREF in front of the RACON strobe when the vessel was known to be on channel centerline. The pilot would maintain the vessel's course by adjusting the heading so as to keep the central cursor centered on the RAREF.

There is a second center channel marker system that the Office of Navigation is considering implementing where improved center channel line marking is required. Two RACONS would be used to form the equivalent of a "RANGE" type system. Figure 2.4 is an example of how a leading line RACON electronic range would appear to a vessel pilot "eyeballing it" while off the channel centerline.
Figure 2.3. The radar display seen by a pilot using a channel centerline RACON and "CURSOR" piloting techniques.
Figure 2.4. RACON RANGE technique using the alignment of 2 RACONS to indicate center channel alignment of vessel. Vessel not in center of channel in this example.
Figure 2.5 shows how the strobes (without squint*) would appear when the mariner is on the range. Observe the convenience of Morse "A" and Morse "N" codes on the front and rear range structures respectively, yielding a Morse "R" code when on or very near to the channel centerline. The mariner's fundamental objective would be to maintain RACON Morse character overlap and maintain the central cursor over both RACONS. When the overlapping area of the strobes is greater than 50 percent of the strobe width, the mariner can place the course cursor with an accuracy of one half degree, according to field measurements made by Trinity House of Great Britain. When there is no overlap, two degree accuracy is the best that the mariner can expect. In some cases, as shown in Figure 2.6, pairs of lateral RACONS would be just as effective as pairs of leading RACONS. However, it would be necessary to know own ship position accuracy, e.g., midway between two buoys, at the beginning of this parallel cursor piloting process. This is necessary to reduce the mariner's reliance upon the radar's range indicators which are often in error. When two RACONS are used in the methods described above, the course line is not subject to gyro error. A second advantage is that mariners with non-stabilized displays would not be encumbered with the mental arithmetic necessary for adjustment of the parallel lines when indexing off of one lateral mark.

Another channel marking use of RACONS is the marking of essential buoys that are surrounded by a large number of radar reflective targets. Figure 2.7 illustrates an example of this condition, which often occurs when a large number of recreational boaters are passing by the buoy or are fishing adjacent to the channel.

2.1.4 HAZARD MARKING

Hazard marking is an accepted application for RACON technology as shown in Figure 2.8. The wreck identifier is the Morse letter "D". The origin of the strobe marks the actual wreck location. The bearing to the wreck from the vessel is the same as the RACON strobe bearing.

* See Section 2.3.1.1 for explanation of squint angle.
Figure 2.5. Two RACON Range technique showing RACON strobe alignment when vessel is on channel centerline.
Figure 2.6. Parallel Index Piloting using 2 RACONs as Landfall marking devices for non-stabilized radar display utilization.
Figure 2.7. RACON marked channel buoy surrounded by numerous small targets.
Figure 2.8. A RACON marked hazard or wreck.
Uncharted wrecks represent a hazard to all vessels. Therefore, the type of RACON used to mark wrecks must be "visible" on all radars, regardless of potential problems of radar interference to other users in the area not interested in the wreck's location.

2.1.5 MARKING THE APPROACH TO HIGHWAY OR RAILROAD BRIDGES

Another use for RACON technology is marking the approach to highway or railroad bridges. When a harbor or River Pilot approaches a bridge, he must begin lining up on the opening far enough in advance to ensure alignment before the vessel reaches the opening. The rudders of large ocean-going vessels are ineffective at the low speeds required for safe operation in the harbor and channel environment. If the channel current is "running" with the vessel, then rudder effectiveness is reduced even more. For these reasons, it is important, especially during reduced visibility conditions, that the navigator know the precise location of the bridge opening or navigation span as early in the approach as possible.

Figure 2.9 shows how a single RACON can be used to mark the centerline of the navigable channel under a fixed or lift-type bridge. A single RACON can be used for channel marking under the fixed or lift-type bridge because these two types of bridges offer a mounting point that allows the RACON to remain centered over the channel.

Figure 2.10 diagrammatically shows how a pair of RACONS could be used to mark the edge of the channel running under a draw, lift, or fixed bridge. A third technique would utilize the RACON mounting technique shown in Figures 2.11 and 2.12. It would combine both the center channel and edge marking techniques. This third technique would also have an application as a "bridge status" indicator.

The bridge status indicator and marker would alert the pilot should a draw-type bridge not open. The bridge status marker could be implemented with two RACONS. Figure 2.11 shows how one RACON would be mounted at bridge center on the right draw section and the other RACON would be mounted at bridge center on the left draw section. A vessel approaching the closed bridge would see a single strobe as in Figure 2.9. When the bridge was fully opened, as in Figure 2.12, the RACONS would produce the display shown in Figure 2.10. The open bridge would produce two distinct strobes that would also serve to mark
Figure 2.9. A single RACON marking a bridge opening or the center of the navigable channel under the bridge.
Figure 2.10. Bridge channel marker system using two RACONS to mark the edges of the channel.
Figure 2.11. Bridge closed. RACONS are co-located and give the appearance of a single strobe.

Figure 2.12. Bridge open. Individual strobes would be discernable, marking channel boundary under opening.
the channel boundaries. This RACON "bridge status" marker would be of use to alert the navigator, should the bridge not open, and also mark the channel edges. This technique would supplement rather than replace the practice of communicating with the bridge tender via VHF-FM radio.

2.2 BACON TECHNOLOGY

Within the next three years, the Office of Navigation will decide a number of yet to be resolved technical issues that will determine the future of RACON applications in the U.S. The five previously discussed uses for RACONS is not an exhaustive list. There are other RACON-dependent navigation enhancement techniques that can be developed if certain aspects of RACON technology can be improved. International technical forecasts indicate the technology required to develop these advanced RACONS will be available within the decade of the 1980s.

There are eight types of existing and conceptual RACONS that could be employed. There are: (1) Frequency Agile RACONS (FARS); (2) Offset Frequency Agile RACONS (OFARS); (3) Stepped Swept; (4) Fixed Frequency; (5) Interrogated Fixed Frequency; (6) Slow Swept Frequency; (7) Fast Swept Frequency; and (8) the Random Swept Frequency RACON. Each of these eight types of RACONS has at least one characteristic that makes it unique from all other available RACONS. The first four are considered primary candidates for utilization by the U.S. Coast Guard.

2.2.1 FREQUENCY AGILE (REFLEXIVE) RACONS

The Frequency Agile Reflexive RACON (FARS) determines the frequency of each incoming radar pulse and responds on that frequency alone. Its code appears on the radar, wanted or not, upon each revolution of the radar antenna during preset intervals; for example, for ten seconds out of every thirty seconds.

The potential for interference to other radars is reduced because the RACON is transmitting only on the frequency of the triggering radar. FARS introduces no squint angle errors.* The RACON response always appears on the interrogating radar display whether desired or not, unless the RACON is operating in a limited duty cycle mode.

* See Section 2.3.1.1 for explanation of squint angle.
2.2.2 OFFSET FREQUENCY AGILE (REFLEXIVE) RACONS (OFARS)

The Offset Frequency Agile (Reflexive) RACON (OFARS) responds on a frequency that is offset by a fixed magnitude and direction from the radar's transmitting frequency. The OFARS transmission frequency will be offset from the triggering radar frequency by an increment that will allow the interrogating radar to display of the RACON returns independently of normal returns. The radars interrogating OFARS must be specially modified to receive their signals. Because the response is at a fixed offset in frequency from the interrogating radar the response will not be masked by clutter. The magnitude and direction of the offset will be determined by international agreement. Use of OFARS introduces a small calibrated fixed squint angle for radars with slotted antennas.

2.2.3 STEP-SWEPT

The Step-Swept RACON utilizes a transmitter that steps between four sub-bands of the radar band, while slowly sweeping in frequency within the sub-bands. Each time the RACON receives an interrogating radar's pulse, it responds on whatever frequency the RACON's transmitter is tuned to, and steps to the next sub-band.

Because of the stepping, the frequency transmitted by the RACON matches the frequency of an interrogating radar about once each minute, rather than once each two minutes, which means that the RACON code will be displayed on each transmitting radar about once each minute. Close aboard, however, (e.g., within 2 miles), the effective bandwidth of the radar receiver increases sufficiently to make the RACON visible upon each revolution of the radar antenna.

2.2.4 FIXED FREQUENCY

This type of RACON utilizes a broadband receiver, but is triggered like a Swept or Step-Swept RACON. It responds on a fixed preset frequency. The response will not be visible on a marine radar unless the radar receiver is tuned to the fixed RACON transmitter frequency (9.31 GHz). The fixed response frequency should be located near the center of the marine radar band so that
the tuning range of the local oscillator and the squint angle* effects are minimized. This type of RACON has the advantage that its response is not masked by clutter surrounding the RACON. It is available on demand in response to every interrogation. The RACON is therefore visible at a glance.

2.2.5 INTERROGATED FIXED FREQUENCY

Interrogated Fixed Frequency RACONS are functionally the same design as the Fixed Frequency, except with greater accessibility to vessel radars. This type of RACON is triggered by an encoded or special length pulse from a ship's radar on the radar's regular operating frequency. The RACON responds on a fixed preset frequency, located ideally in the center of the radar band. The RACON information is available only on demand. Like the Fixed Frequency, this type of RACON response is not masked by clutter.

2.2.6 SWEPT FREQUENCY RACON (SLOW)

The interrogating radar causes this type of RACON to respond while slowly sweeping across the radar band over a typical period of 90 seconds. The pulse length of the RACON is on the order of 18-24 microseconds, producing a usable return on the display of the triggering radar for about five seconds out of every 90 seconds.

2.2.7 SWEPT FREQUENCY RACON (FAST)

The interrogating Radar causes the RACON to respond while rapidly sweeping across the radar band, typically once every 12 microseconds, several times per interrogation. This produces a series of dots on the interrogating radar's display. The response from this type of RACON cannot be encoded.

2.2.8 RANDOM SWEPT FREQUENCY RACON

The Random Swept Frequency RACON functions as both a Slow and Fast Sweep RACON. The time required to sweep across the radar band is varied or switched from slow to fast. Slow sweep provides time for an operator to identify the RACON. Rapid sweep times provide frequent display update. Current testing draws mixed review. Typical sweep times vary randomly from 10 to 120 seconds.

* See Section 2.3.1.1 for explanation of "squint angle"
Table 2.1 has been included as a source for comparative review of some of the advantages and disadvantages of these eight types of RACONS.

2.3. ISSUES TO BE CONSIDERED AND RESOLVED

Over 5,000 vessels serve the U.S. economy annually. Only 500 of this total number fly the U.S. flag. This statistic strongly suggests that 90 percent of users of RACON systems in U.S. waters may be occasional users. If "exotic" radar modifications are required to allow a vessel to utilize these advanced services, the cost benefit ratio may be too low to induce foreign vessels to voluntarily participate. The USCG's Office of Navigation will work with the member nations of the Inter-governmental Maritime Consultative Organization (IMCO) to resolve many of the RACON issues.

The nations participating in the 1979 World Administrative Radio Conference (WARC) have already attached a certain importance to RACON utilization by allocating dedicated spectrum space for Fixed Frequency RACON operation. In addition, an expansion of the X-band portion of the marine radar spectrum has been proposed. Figure 2.13 shows the spectrum allocations as proposed in the 1979 WARC. Many issues must be solved before this allocation will be adopted worldwide. After RACON technical issues are resolved, the legal issues relating to spectrum allocation can be solved.

The Office of Navigation will, within the next three years, decide a number of technical issues that could determine the future of RACON technology developed in the U.S. The five previously discussed uses for RACONS is not an exhaustive list. There are other RACON-dependent navigation enhancement techniques that can be implemented as other aspects of RACON technology are developed. Technical forecasts indicate the technology required to develop advanced RACONS will be available within the decade of the 1980s.

The eight types of RACONS that could be used by the U.S. Coast Guard have been presented. From this group there emerges two classes of RACONS. The Class I type RACONS are those that share the frequency spectrum where the radars operate. The Class II RACONS will operate in a Fixed Frequency mode. They will use a small portion of dedicated spectrum set aside for their operation. The Class II device, known as a Fixed Frequency RACON is the most controversial type of RACON, because the shipboard radar must have a capability of tuning to the RACON's Fixed Frequency of operation.
TABLE 2.1
TYPES OF RACONS AND COMPARATIVE ASPECTS OF EACH

<table>
<thead>
<tr>
<th>TYPES OF RACON</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
<th>IMPACT ON FUTURE MARINE RADAR DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Frequency Agile Reflexive (FARS)</td>
<td>Encoded response available to all users. High RACON response rate, constant over range from the RACON. Minimal interference to other vessel radars operating in the area.</td>
<td>RACON response cannot be shut off, except by time multiplexing the RACON. RACON response may be masked by ground clutter.</td>
<td>No modifications to user's radar required.</td>
</tr>
<tr>
<td>2. Offset Frequency Agile Reflexive (OFARS)</td>
<td>Encoded RACON response available on demand at a high response rate. Response not masked by ground clutter. RACON response causes minimal interference to other vessel radars operating in the area.</td>
<td>Modifications to radar receiver required. Small fixed squint angle is introduced.</td>
<td>Receiver local oscillator must be detuned to allow reception of RACON response.</td>
</tr>
<tr>
<td>3. Stepped Swept</td>
<td>Encoded response available to all users without modification to vessel's radar.</td>
<td>Rate of RACON response varies with range. Response can be masked by ground clutter. RACON response can not be shut off and causes a moderate amount of interference to other vessel radars operating in the area.</td>
<td>No modifications to user's radar required.</td>
</tr>
<tr>
<td>4. Fixed Frequency</td>
<td>Encoded RACON response available on demand and not masked by ground clutter. High response rate with no interference to other vessel radars operating in the area.</td>
<td>Noticeable squint angle effect. Modifications to radar receiver required. Possible response saturation and radar operating frequency 'grouping' near the RACON response frequency.</td>
<td>Receiver local oscillator must be detuned to allow reception of RACON response. Some compensation for squint angle effects may be necessary.</td>
</tr>
<tr>
<td>5. Interrogated Fixed Frequency</td>
<td>Same as Fixed Frequency.</td>
<td>Same as Fixed Frequency, except saturation problem is minimal.</td>
<td>Same as Fixed Frequency, plus a modification to the pulse forming network to provide the RACON triggering signal.</td>
</tr>
<tr>
<td>TYPES OF RACON</td>
<td>ADVANTAGES</td>
<td>DISADVANTAGES</td>
<td>IMPACT ON FUTURE MARINE RADAR DESIGN</td>
</tr>
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<tr>
<td>6. Slow Swept</td>
<td>Encoded RACON response available to all users without modifications to vessel radar.</td>
<td>Very low response rate. RACON response may be masked by ground clutter and can not be shut off. RACON can cause interference to other vessel radars operating in the area. Early design type.</td>
<td>No modifications to user's radar required.</td>
</tr>
<tr>
<td>7. Fast Swept</td>
<td>Non-encoded response available to all users at a high response rate.</td>
<td>Response not encodeable and easily masked by ground clutter. Response can not be shut off and causes a moderate amount of interference to other vessel radars operating in the area. Early design type.</td>
<td>No modifications to user's radar required.</td>
</tr>
<tr>
<td>8. Random Swept</td>
<td>Semi-encoded response available to all users with a widely varying response rate.</td>
<td>RACON response can be masked by ground clutter and can not be shut off. Moderate amount of interference to other vessel radars operating in the area. Experimental design type.</td>
<td>No modifications to user's radar required.</td>
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<tr>
<td>ALLOCATIONS</td>
<td>FREQUENCY (GHz)</td>
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<td>-----------------------------</td>
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<tr>
<td>MARITIME (EQL) RADIONAV.</td>
<td>9.300</td>
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<td></td>
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<tr>
<td>NAVIGATION</td>
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<tr>
<td>RADIOLOCATION</td>
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<tr>
<td>NAVIGATION pri.</td>
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<tr>
<td>NAVIGATION sec.</td>
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<tr>
<td>MARITIME RADIONAV.</td>
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<tr>
<td>(SHORE BASED RADARS)</td>
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<tr>
<td>MARITIME RADIONAV.</td>
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<tr>
<td>(SHIP RADARS)</td>
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<tr>
<td>SWEPT FREQUENCY RACONS</td>
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<td>SHIP TRANSPONDERS</td>
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<tr>
<td>FIXED FREQUENCY RACONS</td>
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</table>

The use of the band 9.300-9.500 GHz by the aeronautical radionavigation service is limited to airborne weather radars and ground-based radars. In addition, ground-based radar beacons in the aeronautical radionavigation service are permitted in the band 9.300-9.320 GHz on the condition that harmful interference is not caused to the maritime radionavigation service. In the band 9.300-9.500 GHz, ground-based radars used for meteorological purposes have priority over other radio-location devices.

Figure 2.13. Frequency allocations in the Marine Radar Band.
2.3.1 PROBLEMS WITH FIXED FREQUENCY RACON UTILIZATION

The problems relating to Fixed Frequency utilization involve technical, legal, and economic aspects. The Office of Navigation takes the position that for many RACON applications the pilot should be provided with a radar marker displayed at a glance and free of any other data such as radar clutter or interference. The Fixed Frequency RACON and the OFARS RACON are leading candidates to meet all of these requirements.

Figure 2.14 shows the type of obscuration that can occur when a RACON is displayed simultaneously with the returns from an active radar. This photograph was taken from a vessel approaching a highway bridge marked with two RACONS. The origin of the RACON strobes are completely masked by the active radar returns (clutter). This particular test used RACONS encoded with the morse letter "T". Little imagination is required to decode the "T" strobe marker. However, if this marking scheme was applied to several bridges along a channel, then different characters would be required to mark each bridge. "Dits" could very easily be lost in the very heavy clutter present when a RACON return is displayed simultaneously with the return of an active radar. Given the possible severity of the "clutter" problem at various locations, the Fixed Frequency RACON is a very attractive device to alleviate the clutter problem.

The Office of Navigation also recognizes that it is the inherent problems of Fixed Frequency RACON operation that is of concern to the world user community. The solution of problems associated with Fixed Frequency operation are not trivial.

2.3.1.1 Squint Angle

The "squint angle" effect is a major problem facing the international user community in relation to spectrum assignment for Fixed Frequency RACONS. In simple terms the "squint angle" effect causes the RACON strobe to appear at a false azimuth on the radar display. The angular difference between the actual strobe azimuth angle and the displayed azimuth averages 0.8 degrees of azimuthal error for each 100 MHz the RACON operates away from the radar antenna center design frequency, when radar operation is at X-band frequencies. This effect, due to antenna design, is only present on radars having slotted array antennas.
Figure 2.14. An actual photograph of obscuration that can occur when ground clutter saturates display and RACON strobes.
Referring back to Figure 2.13, the WARC spectrum allocation assigned Fixed Frequency RACONS to the 9.30 to 9.32 GHz portion of the X-band marine microwave spectrum. This same WARC action also expanded the spectrum available for use by marine radars to 9.8 GHz, but the U.S. will continue to oppose any maritime use of the expanded spectrum space, as will a number of other administrations.

There is a secondary effect that occurs with slotted waveguide antennas tuned to frequencies other than their design frequency. Their center frequency gain diminishes in direct proportion to the spread between their design frequency and the "forced" operating frequency. Because of "squint angle" effects, the Office of Navigation will conduct a "sensitivity" analysis to first determine the effect of "squint angle" on the accuracy of these advanced techniques and then determine the effect that reduced gain will have on the range at which these techniques will be useful.

2.3.1.2 Modifications and Retro-Fits to Existing Radars

The user of Fixed Frequency RACON techniques must have the capability of tuning the radar receiver to 9.31 GHz to receive the RACON reply, which the present generation marine radars do not have. Thus, the manufacturers of marine radars must: (1) provide modification kits and installation personnel to upgrade the existing marine radars to receive Fixed Frequency RACONS; and (2) begin the design for a Fixed Frequency RACON receiver that can be factory installed and be included as a standard option on all new radars.

There is controversy on an international level concerning the modifications that will be required to existing radars to allow them to receive Fixed Frequency RACONS. The range of options start with a simple modification to the receiver local oscillator (with an inherent set of accompanying problems) and increase in complexity. The most complex option proposed involves the development of a separate receiver channel, antenna and receiving system. The price range of the options vary from $500 for the simplest modifications to $15,000 for the most complex "fix."

2.3.1.3 Spectrum Utilization

The Radar and RACON transmitters emit pulsed signals. The power product of a pulsed signal spreads across the spectrum as an inverse function of the
pulse width. Basically, the shorter the pulse width, the broader the spread of the power over the available spectrum. For example, when a marine radar employs a transmitter pulse width of 1 microsecond (1/1,000,000 second), 98 percent of the power is spread over 1 MHz of spectrum space. Most marine radars have a "short pulse" mode of 0.1 microseconds duration. When a pulse of 0.1 microsecond is transmitted, the power is distributed 5 MHz each side of the transmit center frequency. The radar receiver must have an Intermediate Frequency (IF) bandwidth of 10 MHz to capture 98 percent of the echo power returned from a target illuminated by a 0.1 microsecond transmitted pulse. Thus, most receivers will have an effective bandwidth of 10 MHz and several may feature IF bandwidths of 30 MHz. The wide IF bandwidth requirement, coupled with a low "Q" response curve for receiver selectivity, may allow the receiver IF amplifier to pass high amplitude ground clutter echoes even though the receiver may be removed by as much as 50 MHz from the radar receiver center frequency. This fact of physics may induce the radar and magnetron manufacturer to under utilize spectrum space near the Fixed Frequency RACON Band if future techniques require the radar to display RACON returns without displaying radar returns.

Assuming the broad IF to be a problem, 100 MHz ±50 MHz of marine band spectrum space adjacent to the Fixed Frequency RACON frequency may be lost for future use, due to the potential interference caused by the RACON transmission.

2.3.2 PROBLEMS WITH ALTERNATIVE RACONS

The basic advantages and disadvantages outlined above exist for any RACON whose response frequency is different from the interrogating radar's operating frequency. However, a new type of RACON still in the developmental stages has all of the favorable characteristics of the Fixed Frequency RACON without some of its disadvantages. This RACON is the Offset Frequency Agile (Reflexive) RACON (OFARS), which responds on a set frequency offset from the operating frequency of the interrogating radar. Because the magnitude of this frequency offset is relatively small and always constant, the squint angle effect is minimal. Unlike Fixed Frequency RACONS, there is no disadvantage to the interrogating radar from transmitting from any portion of the radar band. There is a low probability of frequency grouping in any one portion of the radar band.
The USCG's Office of Navigation is conducting empirical tests, technical analyses, and formulating policy to determine the impact and solve the technical problems of "squint" versus achievable accuracies, vessel radar modification cost, and other issues involved in the implementation of the RACON techniques. The Office of Navigation is sensitive to the objections concerning certain aspects of these techniques that may be raised by other agencies within the Federal Government, user groups, and the foreign regulatory and user communities.

2.4 REQUIREMENTS FOR RACON CONCEPT IMPLEMENTATION

There are certain specifications relating to RACON performance that manufacturers must begin to appreciate. The success of these techniques is dependent on state-of-the-art technology being applied to meet requirements as they are specified.

For example, the candidate RACONS used in the previously mentioned applications must maintain precise strobe lengths under the temperature and voltage extremes likely to be encountered. The RACON trigger circuitry must be improved to prevent the triggering of the RACON from radar antenna sidelobe "spillover" when the vessel is close to the RACON. Logic circuits must be included to reduce sidelobe triggering and produce constant width strobes. Recall the "two RACON leading line" technique that was presented. The utility of this technique will suffer if the lead RACON of a two RACON leading line system should be broader than the second RACON and cover the trailing strobe, making alignment determination impossible.

The RACON manufacturers must also solve the problem of RACONS triggering each other when they are operated in close proximity. The bridge status marking technique may not be practical due to the present tendency of two closely spaced conventional RACONS to trigger each other in a "ring-a-round" situation. The problem of clutter obscuring RACON strobes on the radar display must be solved if the navigator is expected to utilize non-Fixed Frequency RACON strobes for precision navigation.

One answer to displaying clear strobes (on non-Fixed Frequency RACONS) during moderate clutter problems may be to increase the RACON output power. RACON manufacturers may be requested to develop systems with higher output power. Then, battery and solar power systems would become part of the solution.
Cost effectiveness of the RACON concepts discussed are being considered. The USCG recognizes that if certain RACON standards are set, the Office of Navigation must be prepared to pay a higher purchase price for RACONS and assume a greater operational cost due to more frequent maintenance. Vessel owners must also be prepared to participate financially. Radar upgrades will be required. Radar display options will be required if more than the most basic navigation option is utilized.

Radar transmitter tube (magnetron) manufacturers must undertake the development of a family of magnetrons to operate over the entire proposed X-band marine radar spectrum. Any "bunching" of magnetron frequencies anywhere in the radar band would be undesirable due to problems of mutual interference between radars operating with "advantageously" tuned magnetrons. The solution to ensure planned spectrum utilization may be a formal channelizing approach to magnetron frequency selection.

2.5 CONCLUSIONS CONCERNING FIXED FREQUENCY RACONS

Initial results of tests conducted by the USCG's Office of Navigation indicate that the advantages of using an out-of-band (Fixed Frequency) RACON for many purposes has technical merit. The implementation of Fixed Frequency RACONS on a practical basis is uncertain due to the problems relating to vessel radar modifications and spectrum utilization. The Office of Navigation will monitor international developments in Fixed Frequency RACON utilization and will continue to conduct tests of Fixed Frequency RACON concepts. The Office of Navigation will pursue the development of OFARS and other RACON techniques that offer the potential benefits, but not the implementation problems, of the Fixed Frequency RACONS.

2.6 CONCLUSIONS AND RECOMMENDATIONS REGARDING RACONS IN GENERAL

The RACON is a useful tool that will be used by the Office of Navigation. New techniques can be developed to use RACONS only if: (1) there is cooperation from manufacturers in the development of more sophisticated RACON receiver signal processing techniques; (2) "squint angle" problems can be solved through a well-thought out approach to spectrum allocation; (3) ship owners will make the modifications necessary to receive off frequency RACON replies; and (4) the U.S. Coast Guard will continue to support the development
of RACON technology to the point that RACONS can be used for more purposes than simple position markers.
The U.S. Coast Guard's Office of Navigation has assumed the responsibility to evaluate any techniques that may offer improvements in the way radar data is displayed to the mariner. This section describes one incremental option that may be offered to the mariner. This option can provide a map-type outline of areas of safe passage superimposed upon the radar display. This type of system is known as the Path Display Radar and it is intended to supplement, rather than replace, the conventional shipboard radar system. A Path Display Radar would be extremely useful during periods of reduced visibility. The system would provide the mariner with the type of information that would enable a pilot to better assess the ship's position in reference to the channel boundary, bridges, and other nearby vessels. In fact, the Path Display Radar was developed to provide "at a glance" knowledge of a vessel's own position within a charted channel, in relation to other features of the channel such as bridges, obstructions, and other applications such as approaches to locks. This option should enhance all weather piloting capability in channels and harbors by providing more data than is presently available from conventional radars.

3.1 DESCRIPTION

The Path Display Radar concept will be tested by the Office of Navigation. It will have a presentation similar to that shown in Figure 3.1. Data superimposed on the normal radar plan position indicator (PPI) display could include the channel outline, the traffic separation scheme employed in the waterway, or bridge and lock approach outlines, all in relation to own ship. Gyro stabilized electronic bearing and cursor lines will also be presented on the PPI display.

The Path Display Radar could also present the mariner with depth contours for a given harbor or river, thus providing the vessel operator with an outline of the vessel's safe operating area. The amplifying information to be displayed would be unique for a given harbor, channel, or waterway. This data would be digitized and stored on a cassette tape or in a microcircuit storage
Figure 3.1. Display observed on Path Display Radar with superimposed graphics.
medium. Users would purchase the digitized data in its storage medium from a central distribution point in a manner similar to the way navigation charts are presently purchased.

The Path Display Radar will probably be offered with either manual-adjust or automatic lock-on options. The manual system would require the navigator to initially orient the system by matching reference points on the synthetic map to prominent reference echoes detected by the radar. The automatic lock option would use Loran-C or another precision navigation system to initially determine when the vessel is in a zone covered by a stored map. Given that the vessel's location is known to the accuracy of a Loran-C fix, the proper map would be displayed. Automatic pattern recognition circuitry would rotate and translate the coordinates of the map until the radar derived reference points were matched to the map reference.

Manual "tweaking" of the map position would be required to ensure that all designated radar echo reference points were the intended reference points, and that the map overlay was properly oriented. This feature would be necessary to compensate for situations when radar echo reference points were missing or could not be detected.

3.2 TECHNICAL CONSIDERATIONS

There are several issues to be resolved during the development of the Path Display Radar concept. They include the type of display, the resolution required to accurately display the map information, and the expected minimum performance requirements under anomalous propagation conditions. The most versatile external reference navigation system (Loran-C or other system) used to "call" the proper map must also be evaluated. Other technical considerations must also be considered in the implementation of the path display system.

3.2.1 DISPLAY PRESENTATION TYPES

Two types of PPI displays are possible with Path Display Radar: true motion and relative motion. Each of these types of presently available display schemes has advantages and disadvantages in a Path Display Radar system.

For example, a true motion display presentation offers the mariner a chance to observe the other vessel's true motion, as well as the mariner's own
vessel's motion by stabilizing all stationary targets. The superimposed map outline would be shifted in relation to the vessel's course (as determined by the gyro) and the vessel's speed (as determined by the speed log or manual input). The primary drawback to using a true motion scheme would be that the map position can become significantly misaligned if the data from the gyro, or the speed log (or manual speed), setting are erroneous. Some radar systems feature compensation for current flow. If any of this amplifying data is rapidly changing or erroneous, then the system will require constant monitoring by the vessel radar operator to ensure that the map does not become significantly displaced from its correct position. This constant monitoring required of the vessel radar operator will significantly reduce the amount of time that he has available to perform other duties required to ensure safe operation of the vessel.

Relative motion is the conventional type of radar PPI display. Superimposed map information would be referenced to several selected radar targets. As the vessel position changes in relation to these targets, the map would be shifted accordingly. This type of display may prove to be more desirable for use in Path Display Radars because of the minimal possibility of errors in map positioning and the reduced amount of attention required from the operator, once the system is initialized.

3.2.2 MAP RESOLUTION AND ACCURACY

It is essential that the graphic information superimposed upon the PPI display be positioned and oriented correctly. It is equally important that the information be presented in such a manner that the line widths of the map and graphics are sufficient to be observed, yet not so large as to obscure targets of interest.

The map and target information can only be positioned as accurately as the resolution achievable by the radar. The limiting factor is usually the pulse width of the radar. Any attempts to position the graphic (map) information with greater accuracy than achievable given the radar's resolution will be wasted effort, due to the uncertainty that will exist in the detected versus actual positions of the radar targets. In summary, the map position accuracy should not exceed the capability of the radar to locate targets in azimuth and range.
3.2.3 REFERENCE TARGETS

The radar targets selected as map references will be chosen by their prominence. If several of the radar reference targets picked as map position references are out of place, the displayed positional accuracy of the superimposed map can be adversely affected. For example, if a reference radar target has a positional uncertainty, such as a buoy on a long chain, the map orientation may be affected. For this reason, it is critical that radar targets used for map reference positioning be selected carefully. Ideal reference targets are those which are fixed geographically, readily identifiable to the radar observer, and "visible" to a radar over most or all of the harbor or river operation areas. Targets marked by RACONS would be an optimum choice, because the RACon return is relatively immune to anomalous propagation problems, and the encoded strobe provides unmistakable recognition features. It may be necessary to survey the harbor or channel using a radar equipped vessel and associated digitization system to ensure that the radar references are properly selected. The selected references must not be in a position to be obscured by transient phenomena such as blockage from temporarily anchored vessels. The careful selection of references is also necessary to ensure high radar signal-to-noise ratios during degraded propagation conditions.

3.2.4 EFFECTS OF ADVERSE OPERATING CONDITIONS

Optimal selection of radar reference targets is necessary for reasons other than ease of identification and the maintenance of high signal-to-noise ratios. Targets in areas where vehicles or vessels pass nearby may, under certain conditions, cause the target tracking gate to jump tracks from the fixed target to a nearby moving target. This condition would cause a reorientation of the superimposed map information. These types of problems can be minimized by selecting reference targets that are not near highways, railroad tracks, or temporary vessel mooring areas.

A reference target must not only be visible to a radar over wide areas, but also return a signal sufficiently above the radar noise level to provide an adequate radar target for the Path Display tracking system. During periods of rain or snow, the radar's signal will be attenuated. This requires that fade margins be considered. The problem of large amplitude weather returns
masking the radar targets must also be considered and compensated for in some manner. Otherwise, the function of the Path Display Radar option may not be reliable during periods of adverse weather conditions when the Path Display system should be most useful. The Office of Navigation will test the system to ensure that sea clutter due to heavy seas during high wind conditions does not render the Path Display Radar useless to the mariner.

3.2.5 EXTERNAL REFERENCES

As previously mentioned, Loran-C could be used as an optional external reference, to provide initial positioning of the superimposed map data. Other global positioning systems such as OMEGA, the family of satellite navigation systems, or even a local positioning system such as RAYDIST may be used as independent positional reference sources. Regardless of the system chosen, the mariner must be aware that each of the external global navigation systems has limitations in the form of absolute positional accuracy. The positional error can vary from 50 feet to several miles, depending upon the vessel's position and the type navigation system used. It should be noted that local systems (such as RAYDIST) must be used to achieve positional accuracies of 10 feet. RAYDIST reference transmitters are not presently located along a majority of the rivers, channels, and waterways that could be served by Path Display Radars.

3.3 ADVANTAGES OF SYSTEM IMPLEMENTATION

The Path Display Radar would provide the mariner with very useful supplemental data. The cost benefit of adding Path Display equipment may be reasonable when weighed against the price of vessel and cargo loss. The cost benefit trade-offs of Path Display radar will be investigated by the Office of Navigation.

The Path Display Radar is a device that requires the integration of existing technology, not a totally new technology. Figure 3.2 shows a block diagram of a possible Path Display Radar configuration. No external position references would be required with this system. The radars presently on board most commercial vessels would be adequate for use by a Path Display Radar of this design, given that pending regulations require that a large number of vessels have a collision avoidance radar system on board. Most types of
automated radar collision avoidance systems will already contain many of the components shown in Figure 3.2. The only new components required for the Path Display option would be the operator interface controls for adjusting the position of the superimposed information and the input/storage device for the local graphics information.

3.4 SYSTEM STANDARDIZATION

The Office of Navigation is presently examining the options available to the USCG concerning the generation of the digitized map data and radar markers necessary for use with the Path Display system. There is an advantage to the standardization of the data used to generate the fixed path map display. If worldwide data format standards were adopted, local harbor pilots would not be required to maintain extensive map libraries of cassettes or other storage devices to use with each type of commercially available system; instead, a single library could be produced, maintained and used with any manufacturer's brand of Path Display system.

This same argument for standardization applies to the map generation effort. If a non-standardized approach to map software development is allowed, each manufacturer will be required to develop proprietary software to use with their particular display system. It must also be noted that the Office of Navigation recognizes the benefit of certain map presentation formats that would be developed for competitive reasons if the non-standard map generation process were allowed. The issues relating to proprietary data formats and map generation are complex and tied to the market place. The Office of Navigation reserves the right to develop an official position on these matters at some point in time. The opinions of the manufacturers and future users of Path Display systems are solicited on these and other issues in order that the Coast Guard may have the benefit of input from all parties with interest in these issues.

There is a final problem to be resolved: Do the manufacturers, or does the USCG, take the responsibility for the siting, erection, and maintenance of the radar reference markers that may be required for Path Display use in certain harbors? Precedents have already been set that will support either the manufacturers of Path Display systems supplying their own radar references or the USCG installing and maintaining the radar reference markers. RAYDIST installations are an example of how a manufacturer may be involved in the
Figure 3.2. A block diagram of the Path Display Radar components.
furnishing of a navigation marker system to private industry. The planned
RACON upgrade is an example of how the USCG can supply a basic aid that, when
utilized with user supplied equipment, can improve navigation accuracy.
Policy will be established on this issue by the Office of Navigation in the
near future.

3.5 TRENDS IN THE MARKETPLACE

Manufacturers of marine radar systems are showing interest in the Path
Display concept. Already one manufacturer has developed a Path Display system
that will be demonstrated to the USCG within the next six months. Another
manufacturer has advertised a Path Display system that will allow the user to
generate graphics of the user's choice and display the composite radar/
graphics data on the system display. Another manufacturer is advertising a
non-radar Path Display that uses Loran-C as the reference system. The Office
of Navigation feels that these embryonic efforts to develop Path Display
systems should be encouraged due to the perceived improvement in safety that
such a system can offer.