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Genesis of Loran Augmented Satellite Navigation

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Abstract

The Iotron Corporation was formed specifically to pioneer the development and production of the world's first fully automatic self-plotting radar for merchant ship collision avoidance. Transit satellite navigation was added for worldwide navigation and route planning. Loran C was subsequently added for SatNav augmentation to continuously display the International Maritime Organization (IMO) designated traffic separation lanes accurately on the radar plan position indicator (PPI). Transit required an accurate ship's speed-over-the-ground during the satellite data transmission, and dead reckoning using conventional ship's through-the-water speed logs was not adequate when sailing near land in up to 5-knot currents that exist where the traffic lanes were mandated. Iotron used a super tanker's Doppler docking system's ground speed measurements to obtain the most accurate Transit satellite fixes. Then, in order to maintain this accuracy in between fixes for continuously displaying the charted traffic separation lanes, the integrated concept used the Transit fixes to periodically update Loran C's hyperbolic navigation. Although Loran C's 2drms accuracy alone was only 460m, Iotron's proprietary innovation was the first to utilize Loran C's (18 to 90m) repeatable accuracy to complement Transit satellite navigation's fix updates for maintaining <100m continuous accuracy even in currents. This unpublished maritime Transit augmentation exploited Loran C's continuous repeatable accuracy to provide the nearly 100-meter accuracy that equaled GPS for 20 years until Selective Availability (SA) was removed. Iotron not only pioneered "Hands off" anti-collision Automatic Radar Plotting Aids, later designated by the IMO as an automatic acquisition ARPA, but also accurately superimposed charted sea-lanes and planned route lines on the PPI. The anti-collision equipment was successfully competed against Raytheon, Sperry, IBM and foreign companies by installing DIGIPLOTS on over 500 ships out of the 3000 total that had been sold worldwide. In addition, Transit satellite navigation augmented by Loran C (or Decca Navigator) was fitted on 34 super tankers.

Introduction

Iotron Corporation was co-founded by Herther [i]and four ex-Itek[ii] engineers, who in early 1969 decided to utilize their 12 years of "skunk works" development and satellite/camera production experience [iii]to establish a new company in marine electronics. Because of their involvement in innovative development of digital optical instrumentation using embedded mini-computers, they saw a market opportunity for similar state-of-the-art improvements in ship's bridge operations. The most significant events dictating the requirements for the companies marine equipment designs was the grounding of the Shell tanker ***Torrey Canyon*** on the UK Scilly Islands and the collision of two Chevron tankers in San Francisco Bay. They planned to reduce the workload of bridge officers while adding safety to the ship through collision avoidance and near shore displaying of accurate navigation chart lines on the radar PPI. Clearly, a **single maneuvering display** was needed for prevention of both types of accidents. That could easily be compared with the visual scene to gain faith in the automatic system and use it for more accurate correct "Rules of the road" maneuvering in clear weather. They also envisioned providing fuel saving to ship-owners by developing a fully adaptive digital autopilot: whose potential saving of ½% of fuel costs promised a quick payback, thus helping to offset the cost of the added safety[iv]. The oil companies desire to prevent their companies from being responsible for oil spills was adequate motivation for them buying safety equipment, and it was certain that funds would be made available for buying state-of-the-art navigation equipment that aided bridge operations.

The most pressing need was anti-collision. Their concept was to market as a retrofit a separate "radar-add-on" console with its own embedded mini-computer connected to existing ship's radars, speed log and gyrocompass to provide "hands off" fully automatic radar plotting. This significant development opportunity was initially pursued on the founder's own cash plus a $100k loan as seed money. The potential business opportunity soon attracted a million dollars of venture capital. Almost two years of sea testing was required to perfect the equipment for commercial sale beginning in early 1971. At that time, an additional million-dollar investment was obtained to set up production, to establish worldwide sales and service network and to develop optional navigation and autopilot equipments.

Once funded, the 62-foot ketch motorsailer "Tradewinds," shown in Fig. 1, was purchased and used for developmental sea testing and customer demonstrations on Cape Cod Bay. At one time, the yacht had been owned by Sperry Marine and was used as a demonstrator, so it came outfitted with a complete Sperry equipment suite similar to a large vessel. Its high masts were ideal for mounting the radar scanning antennas to approximate big ship's 3 and 10 cm radar performance. For making design changes, which occurred almost every sea test, the boat's living quarters had been converted to digital hardware and software development labs, which included the evolving prototype automatic radar plotter and integrated radio navigation systems.

"Tradewinds" equipment included:

- Decca X Band and Sperry S Band Stabilized Radars
- Transit and Loran C Receivers
- Sperry Mk 14 North Reference Gyro and accessories:
  - Auto-pilot & Course Recorder
  - Steering Course Repeater
  - RDF with Stabilized Bearing Repeater
  - DIGIPLOT and DIGINAV log/gyro inputs
- Propeller RPM to speed through–the-water converter
- Ship-to shore Radio

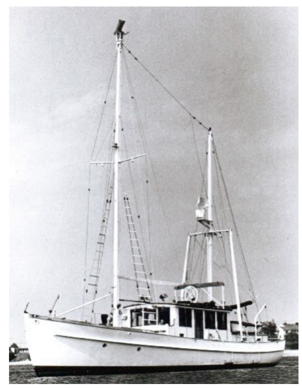

Fig 1. Iotron Test Vessel "Tradewinds"

Radar Plotter Development

An early market investigation showed that many radar plotter developments had been attempted since WWII but none had been successful[v]. One of the simplest was the Phillip's ELPLOT analog auxiliary radar indicator, which consisted of five electronically drawn lines on the PPI that could be manually attached to five echoes. These were tracked with the 5 lines displayed and remaining attached. This concept aided a radar observer by his viewing of the PPI and visually assessing whether or not an echo was moving down a line toward the display center on a constant bearing which would indicate a collision. If the echo moved off to either side of the line, it indicated a close passing ahead or behind. Marconi had also developed a magnetic tape concept called PREDICTOR that recorded all of the echoes on the PPI at one-minute intervals. By replaying successive recordings displayed on the CRT, in effect; this created a "manual-type" relative plot showing collision threats. Kelvin Hughes had PHOTOPLOT, which used a similar technique but actually took pictures of the PPI, developed them in real time and projected them in a similar multiple echo plotted sequence for an anti-collision display. Both Marconi and Kelvin Hughes, in effect had "hands-off" auto acquisition of all echoes, which was only an effective radar anti-collision aid approach in the open ocean. Near land, where it was needed most, the display became cluttered and both equipments had reliability problems.

Other radar plotter manufacturers used military style manual echo acquisition with gated auto tracking of 12 echoes employing analog computation to calculate relative or true predictive vectors projected ahead directly on the radar PPI. The Iotron "add-on" product development was destined to be named DIGIPLOT since its signal processing and computation was to be done digitally, although initially with manual acquisition. After discussing the product's need for adding auto acquisition with Captain Jon Van Leer, Superintendent of US tanker operations for Shell Oil, and a potential customer; we became convinced that to be competitive, the ship's watch officer had to be removed from standing a continuous radar watch[vi]. This meant that manual acquisition was no better than the approach the radar manufacturers were taking and automatic marine radar acquisition had to be invented. This required significantly more funds than the founder's could put up, and they had to be obtained from venture capitalists.

A Telefunken patent was discovered that described radar auto acquisition and tracking of aircraft, involving a pulse-to-pulse correlation technique. Iotron adopted this as its starting concept and had to go on to develop the automatic signal recognition technology for marine surface radars. Their aircraft auto detection theory being that, if after digitizing all the radar pulses in range, at a given range bin, if adjacent bins had a signal, this two pulse correlation both eliminated receiver noise and discriminated that it was a real object's echo that was flying! The Iotron marine surface auto acquisition radar design had to further distinguish the wanted "ship-sized" echoes from receiver noise, as well as land and sea clutter. The resulting patented proprietary video processor design could potentially acquire up to 200 "ship sized echoes" at a signal threshold maintained by automatic gain control to equal the receiver noise level. These potential targets were further software processed and then were all auto-tracked, determined whether closing or not, and range ranked. The closest 40 of these "ship sized echoes" were then separated for subsequent complete calculations of range and bearing, course and speed, Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA) and then display them as vectors inside an outline of the closest radar mapped coastline. The Figure 2 block diagram shows the internal DIGIPLOT and ship equipment connections[vii].

At first, conventional Alpha/Beta filtering was used to calculate very accurate course and speed but course changes didn't show promptly. A collision avoidance display requires constantly showing all of the other vessels present course and speed as shown in Figure 3. The needed nearly instantaneous maneuver response of the other vessel's present course, at an acceptable reduced accuracy, was achieved by developing a patentable four parameter adaptive Alpha/Beta filter with four independent filtering levels.

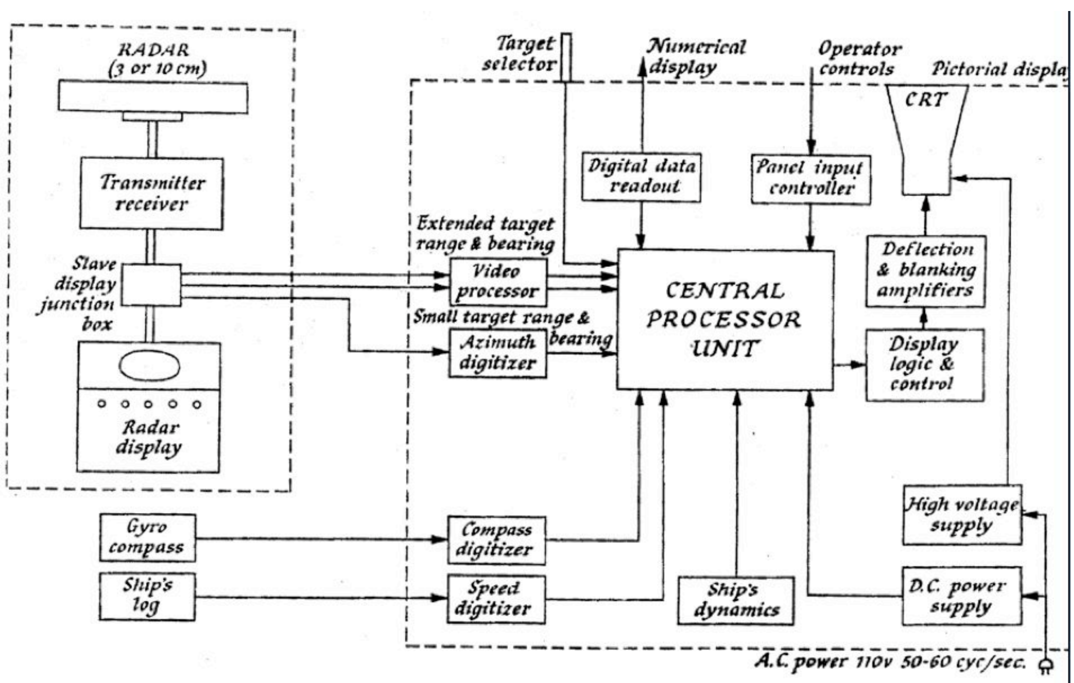

Figure 2 Input and internal DIGIPLOT Operation

Figure 3 DIGIPLOT operator's console

Figure 3 shows a "Head Up" two-color radar PPI display on a 6 nm scale with 6-minute predicted future position vector lengths. Own ship is shown approaching New York harbor entrance with coastlines shown in green. Own ship's vector emanates from the PPI center with up to 40 other "ship-sized echo" moving vessel vectors and/or buoys shown as circles displayed in orange. True vectors show other vessel's present course with only a 15 second delay after a course change, thus providing other vessel's aspect which aids in following the rules-of-the-road in daylight maneuvering. [viii]

Ship "Black Box" Recorder Option

Analogous to aircraft post accident recorders, a MIL-Spec ruggedized waterproof digital disk recorder[1] was selected for implementation. All of the control settings for DIGIPLOT and DIGINAV[2] together with all of the data that an operator could have been viewing were recorded every minute. At the end of the one-hour recording duration, it began a rewrite. In the event of an incident involving own ship (or any other ship involved in an accident which was within radar plotting range), the recording could be stopped and was available for immediate review and/or replay on similar equipment at a 30:1 quick time ratio. One installation of the recorder was used by a Captain, who, when replaced on his bridge watch by a young mate, would replay the entire hour to review the type of maneuvering that was done in his absence. Word got around, and although this was an excellent safety product[3], it was very expensive and was not well received by ship's officers, so the market was limited.

Early Loran C Potential for Chart Line Referencing on the DIGIPLOT PPI

During DIGIPLOT's developmental sea testing on "Tradewinds," the use of Loran C was discussed with several fishermen who bragged about Loran C's "repeatable accuracy" and the ability to return to the same spot in spite of the fact that its conversion to latitude and longitude for charting was imprecise, only achieving .25 nm 2d rms (<460m)

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1 Used for Polaris submarine instrumentation recording was only 32k (16-bit word) capacity

2 AUTO-MATE'S Navigation complement to DIGIPLOT with its own separate computer

3 Herther was a US Coast Guard technical advisor on ARPA's during the formation of the International Consultative Organization (later became IMO) standards creation during 1979. All of DIGIPLOT's operational functionality has been included, only history dots had to be added to the Iotron product. "Quick calculation response to other vessel's course changes in the Standard (showing aspect) was uniquely Iotron's contribution to the Standard requiring competitors to modify their design. Ironically, the accident event recorder was never considered for a Standard as an ARPA option.

accuracy. Since there are no grid lines on the water, to fisherman the 60 to 300 ft. (18-90m) "repeatable accuracy" was all they needed and they always navigated directly in time differences (TDs). The concept was evaluated for single point Loran C calibration and also potentially for even using accurate Transit fixes for correction. This would overcome "Transit's almost 2 hours in between fixes resulting in a dead reckoning accuracy deficiency when close to shore in the presence of tidal currents. A Loran C receiver was obtained from Internav (Megapulse-Receiver subsidiary) and Iotron engineers analyzed test data taken on "Tradewinds" during radar testing on Cape Cod Bay. Both concepts looked promising and it was observed that indeed they could return to the same TDs at the dock every time they went to sea.

American Steamship had bought a DIGIPLOT for their newly built 1,000-foot ore carrier, which operated only on the Great Lakes. After installation and satisfactory use, the Captain said that he appreciated DIGIPLOT's anti-collision operation, but since congested traffic wasn't his biggest problem, he asked if there was a way to draw north referenced properly positioned chart lines on the PPI to help guide his extremely long vessel into a proper entrance channel into the narrow St. Mary's river in poor visibility. It was recognized that although Loran C's positional accuracy was only .25 nm, its 60 to 300 ft "repeatable accuracy" might enable use of a single point calibration to display sufficiently accurate referenced channel entrance guidelines on the MV St. Clair's radar PPI. A quick implementation of the hyperbolic conversion software was accomplished for line display using the DIGIPLOT. The US Department of Commerce Maritime Administration (MARAD) had funded the subsized ship built equipment purchases for the experiment which was planned to initially utilize the "backside" of the US Coast Guard's "East Coast Loran C chain" and later, their newly built "mini-chain" to provide even better than 0.1 nm accuracy for the navigation approach guidelines to the river entrance.

By comparison with a manual Loran C chart solution, an accuracy of less than 0.1 nm (<600 ft.) was first achieved on the American Steamship's MV St. Clair (a 40k dwt 1000 ft Great Lakes ore carrier) on July 14, 1975, utilizing the "repeatable accuracy" of the "single point calibration. " This accuracy was deemed adequate for successfully referencing a guideline approach to the St. Mary's river entrance on Iotron's DIGIPLOT fully automatic radar plotter PPI.

In unrelated tests later in 1976, the USCG began conducting a series of higher accuracy experiments using their "mini-chain[4]" for actually navigating the entire 60 miles through the extremely narrow St. Mary's River. Their sample data collected in August had a 2d rms (95%) deviation of about 40 feet. The deviation of the nine sample sets collected in October improved to about 25 feet with dynamic results between 30 and 75 ft. Two other companies conducted these experiments and Iotron did not participate in the USCG program. It is not known whether the St. Clair's receiver, when switched from the East Coast chain to the "mini-chain," produced more independently verified better accuracy of the entrance navigation line positioning experiment.

DIGINAV-Omega

Iotron offered DIGINAV for ocean customers by adding a separate computer and a navigation and control display console for the Omega worldwide navigation. Omega being a continuous hyperbolic system like Loran C, its software, was easily changed to make the Lat/Long conversion, which yielded about 2 to 4 nm accuracy. This was modified in order to add propagation corrections reducing the error to about 1 nm. Occasionally the Omega receiver would "lose lock" and have to be manually re-initiated by having the navigator establish his position by other means within a 32 nm lane. Near the coast, this wasn't difficult, but in mid ocean, a daylight sun shot or nightly star fix had to be done which was a nuisance. If loss of lock occurred in a large cloudbank, it could be days before the Omega navigation was working again.

On the last of three ships fitted with DIGINAV Omega, the receiver lost lock frequently. The Captain was so dissatisfied that he told us to take the Omega receiver off the ship, since he could "take a sun shot at noon without Omega with an accuracy of about 5 nm in mid ocean, which was sufficient, whether he needed it or not. Besides, he said he would need much better than 1 nm accuracy near shore and Omega simply wasn't good enough." Iotron credited the ship-owner toward

[4] Olsen, D.L., and Stolz, J.R., *Precision Loran Navigation on the St. Mary's River*, Journal of the Institute of Navigation, Vol. 25, No.# Fall 1978

a Transit replacement and this incident terminated the company's Omega efforts and initiated the Transit development.

Transit

TRANSIT was developed by the Navy to provide an accurate position of a Polaris submarine for initializing its Sperry SINS (Submarine Inertial System). The sub had to expose an antenna for about 15-20 minutes to take the data for a fix while stationary. Magnavox built the receivers and IBM did the submarine software. Once the fix was processed, the position obtained updated the extremely accurate inertial systems (sometimes three SINS that "voted-2 out of 3") for precise inertial dead reckoning to the next Transit update position.

In addition to the radar manufacturers marketing collision avoidance systems, two major system competitors: IBM and Norcontrol, sold not only collision avoidance equipment, but also added Transit navigation. In 1976, Magnavox marketed their first production low cost single channel receiver called the MX 1102, which was purchased by IBM, Norcontrol and Iotron. Magnavox also sold many more stand alone Transit navigation systems direct to the ship owners. Magnavox furnished supporting mini-computer and processing software, which was similar to the "Polaris-submarine type" but with dead reckoning added to account for the ship's motion during receipt of Transit's Doppler fix data by using the ship's gyro and through-the-water speed log for determination of the ship's path over the ground. On seismic or survey vessels, Magnavox sold two channel receivers with Doppler ground speed logs for achieving full Transit accuracy both in terms of determination of a fix and dead reckoning in between. All of the standard single channel commercial vessel's Transit installations only had an alphanumeric controller and output display; and superimposed chart lines on the radar anti-collision PPI wasn't common technology. This position output display indicated to the navigator the Latitude/Longitude at the end of the fix as well as the accumulated errors and actual intervening current's set and drift. Iotron's chart lines display concept for superimposition on the PPI had to be continually referenced accurately in between fixes, not merely shifted to the correct position after the next Transit fix occurred, which was then displayed together with the "after the fact" actual current's set and drift that had occurred.

Transit System Description[ix]

This description was excerpted from [4]. Transit terminated navigation service in 1996 and was decommissioned on 31 December 1999 by the U.S. Government.

> *The Navy Navigation Satellite System, also known as TRANSIT[5], was the world's first operational satellite navigation system. Transit was originally conceived in the early 1960s to support the precise navigation requirements of the Navy's fleet ballistic missile submarines.*
>
> *The satellites broadcast ephemeris information continuously on 150 and 400 MHz. One frequency is required to determine a position. However, by using the two frequencies, higher accuracy can be attained. A receiver measures successive Doppler, or apparent frequency shifts of the signal, as the satellite approaches or passes the user. The receiver then calculates the geographic position of the user based on knowledge of the satellite position that is transmitted from the satellite every two minutes, and knowledge of the Doppler shift of the satellite signal.*
>
> ***Predictable positioning accuracy is 500 meters for a single frequency receiver** and 25 meters for a dual frequency receiver. Repeatable positioning accuracy is 50 meters for a single frequency and 15 meters for a dual frequency receiver. Relative positioning accuracy of less than 10 meters has been measured through translocation techniques. Navigational accuracy is heavily dependent upon the accuracy which vessel knows course, speed, and time. **A one-knot velocity input error can cause up to 0.2 nm fix error**. On Navy and more expensive receivers, two separate frequencies permit correction for ionospheric refraction and for stationary submarines or ocean based oil rigs, 25 passes can be integrated for an*

[5] http://www.fas.org/spp/military/program/nav/transit.htm
Implemented by Charles P. Vick, Sara D. Berman

accuracy of 5 meters.

Availability is better than 99 percent when a Transit satellite is in view. It depends on user latitude, antenna mask angle, user maneuvers during a satellite pass, the number of operational satellites and satellite configuration. The reliability of the Transit satellites is greater than 99 percent. Coverage is worldwide but not continuous due to the relatively low altitude of the Transit satellites and the precession of satellite orbits. Transit satellites provide a two-dimensional fix. Fix rate varies with latitude, theoretically from an average of 110 minutes at the equator to an average of 30 minutes at 80 degrees.

Magnavox[6] Receiver Operation

Transit had five operational Transit satellites in circular, polar orbits, at about 1075 kilometers high, circling the earth every 107 minutes. This constellation of orbits forms a "birdcage" within which the earth rotates, carrying us past each orbit in turn. Whenever a satellite passes above the horizon, we have the opportunity to obtain a position fix. The average time interval between fixes varies from about 35 to 100 minutes depending on latitude. Unlike earth-based radiolocation systems, which determine position by nearly simultaneous measurements on signals from several fixed transmitters, Transit measurements are with respect to sequential positions of the satellite as it passes, as illustrated by Figure 4. This process requires from 10 to 16 minutes, during which time the satellite travels 4400 to 7000 kilometers, providing an excellent baseline.

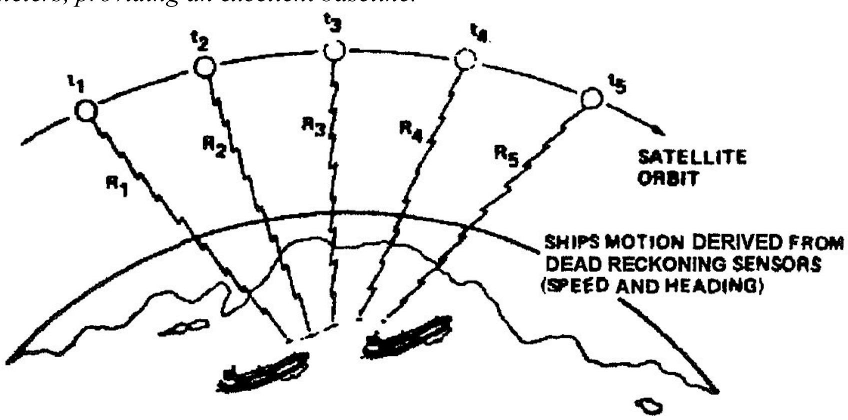

Fig 4 Transit and Ship Tracks During Intermittent Fixes

Because Transit measurements are not instantaneous, motion of the vessel during the satellite pass must be considered in the fix calculations. Also, because the satellites are in constant motion relative to the earth, simple charts with lines of position are impossible to generate. Instead, each satellite transmits a message, which permits its position to be calculated quite accurately as a function of time. By combining the calculated satellite positions, range difference measurements between these positions (Doppler counts), and information regarding motion of the vessel, an accurate position fix can be obtained.

Because the calculations are both complex and extensive, a small digital computer is required. There are two principal components of error in a Transit position fix. First is the inherent system error, and second is error introduced by unknown ship's motion during the satellite pass. The inherent system error can be measured by operating the Transit set at a fixed location and observing the scatter of navigation typically fall in ***the range of 27 to 37 meters rms****. Less expensive single-channel receivers, which do not measure and remove ionospheric refraction errors, typically achieve results in the range of* ***80 to 100 meters rms****. The second source of position fix error is introduced by unknown motion during the satellite pass. The exact error is a complex function of satellite pass geometry and direction of the velocity error, but a* ***reasonable rule is that 0.2 nautical mile (370.4 meters) of position error will result from each knot of unknown ship's velocity****. Predictable positioning accuracy is*

[6] Stansell, T., A., *Many Faces of Transit* Journal of Navigation, Vol. 25, No 1, Spring 1978

500 meters for a single frequency receiver and 25 meters for a dual frequency receiver. Repeatable positioning accuracy is 50 meters for a single frequency and 15 meters for a dual frequency receiver. Relative positioning accuracy of less than 10 meters has been measured through translocation techniques. ***Navigational accuracy is heavily dependent upon the accuracy which vessel knows course, speed, and time.***

Transit Shortcomings Recognized

Transit performed its designed role for over 30 years from 1964 to 1996[x]*, but it had scarcely been in service for 5 years before the Navy wanted to upgrade the system and the Air Force wanted to design their own. The existing Transit system had several shortcomings that the branches of the military wanted to correct in the improved version.* ***The biggest shortcoming was that the user could be without any navigation information at all for up to 100 minutes****, since only a small number of satellites in low orbits were in the constellation. Further, it required continuous tracking of the signal for the entire 10-20 minute pass and only after that time could a position is computed. Further still, the system only worked well for slow moving objects, and the position fix was limited to two dimensions. GPS was developed to overcome these deficiencies.*

Table 1 Gyro and Speed Log Errors

Gyro and Log Speed Errors	Offset	Speed Variation-Normal
Gyro	Cal 0.5 deg	0.36 deg 3 Sigma
Speed Log - Speed Through-the-Water – STW	Cal 0.5 kts	0.20 kts 3 Sigma
Doppler Log-Through-The-Water – TTW	Error > +/- 1% distance run	+/- .025 kts
Doppler Log-Over-The-Ground-OTG depth < 200m	Error > +/- 1% distance run	+/- .05 kts

The Transit fix errors were a function of ground speed errors during Transit's Doppler reception. Table 1 above shows the International Standards[xi] for gyro and through-the-water speed log errors which range between 0.3 to 0.7 knots resulting in Transit Fix rms errors of 160 to 225m as shown in Figure 6. The ground speed error for dead reckoning during the fix using through-the-water speed logs must take into account current, which results in much larger additional errors as shown in Figure 7. Very expensive Doppler docking systems were installed on most Very Large Crude Carrier's (VLCC's), on which DIGINAVs were installed, which were also used as the ship's speed log when underway. Near shore, in shallow waters, they directly measured over-the ground speed **with an overall ground speed error of only +/- 0.05 knots even in the presence of tidal currents.** However, distance run errors, if the Doppler log were to be used exclusively in between fixes, are specified to accumulate errors greater than +/- 1% of distance traveled. For an hour and a half, on a 16 knot vessel this is > 0.24 nm and frequently the intervals are longer, when a missed data pass occurs.

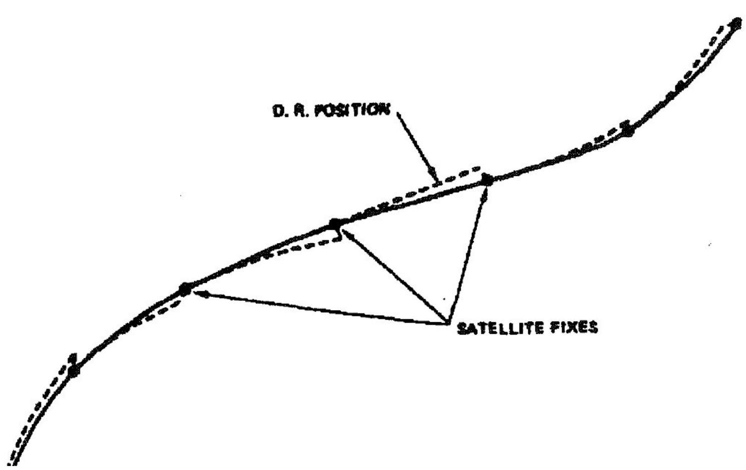

Figure 5 Dead Reckoned Path with Transit Updates

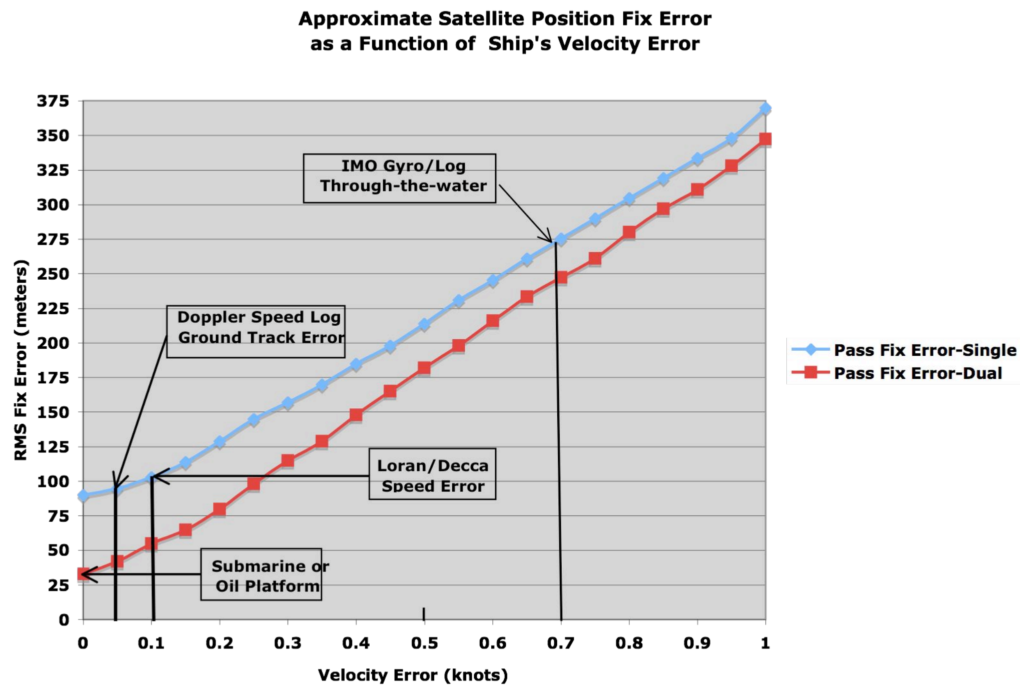

Fig. 6 Plot of approximate position fix error as a function of unknown velocity for Single & Dual channel receivers.

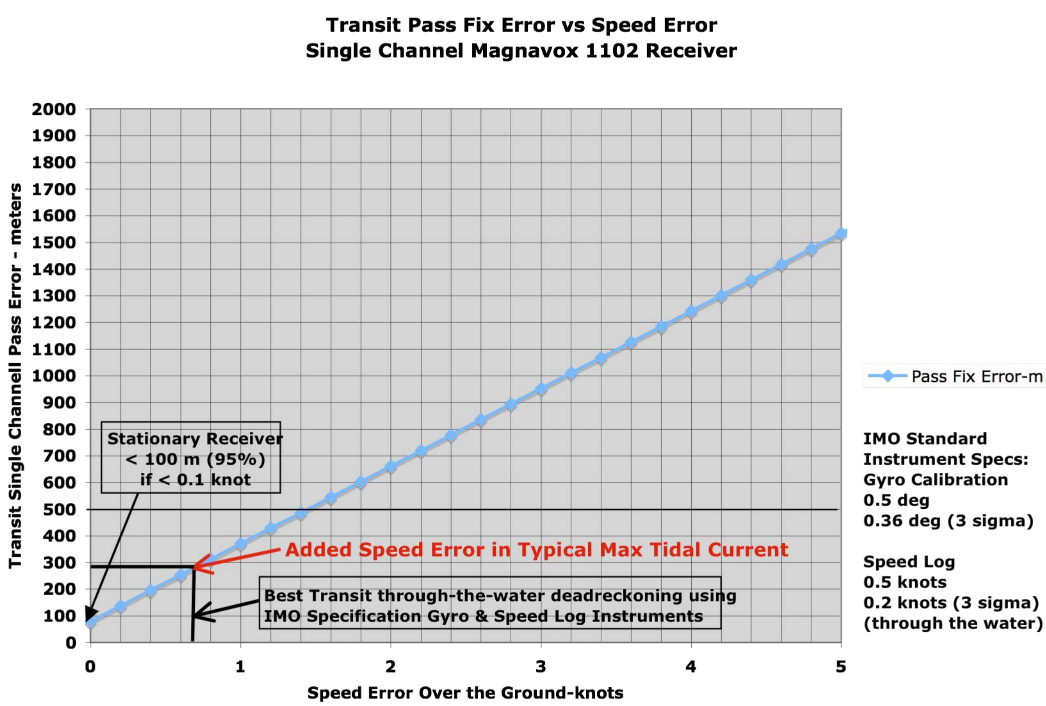

Figure 7 Accuracy comparisons of Transit if dead reckoned in currents

Iotron AUTO-MATE-Transit-1st Space Fleet Management Experiment

When first entering the Transit navigation field, Iotron agreed to purchase the first dozen receivers from Magnavox, and they in turn, furnished their standard processing software. Iotron's

Chief Programmer, Frona Vicksell[7], adapted their code "as is" at first[xii]. This involved dead reckoning with gyro and through-the-water speed logs both during the fix and in between fixes. This standard approach was used in the MormacStar Fleet Tracking Experiment, since this accuracy was adequate for worldwide point-to-point navigation. Iotron considered this navigation/communication program as an opportunity for expanding into new bridge automation products involving vessel tracking and space communication, Iotron proposed using the Marisat space communications network for a two-way data link for transmitting back position for automatic ship tracking and permitting destination redirection from shore.

Since their new fleet of ships was being built with US subsidy of about 50%, it was beneficial and relatively easy for the Moore-McCormack Bulk Transport Inc. to contract with the United States Maritime Administration in 1975 to allow its newest double-hulled tanker, the MormacStar to be outfitted with the Iotron's AUTO-MATE System to participate in a MARAD ship tracking management experiment[8]. The equipment consisted of the DIGIPLOT anti-collision radar plotter and the Transit DIGINAV worldwide radio navigation system as shown in Figure 8. Ship's position was dead reckoned using ship's gyro and speed log to nominally achieve the required 0.25 nm accuracy even in currents of up to one and one half knots. The only extra item to be built and added to the interface to the voice telephone input was a digital-to-tone modem and some software had to be added.

Figure 8 DIGIPLOT and DIGINAV/Magnavox 1102 Transit SatNav

The experiment's objective was to prove that the technology existed for space-based navigation and other data to be sent back and forth via the Comsat Cooperation Satellite communication service, then through a NASA Ground Terminal to a central computer at King's Point for data collection, analysis, and fleet management functions. Marine Management Systems conducted the Maritime Coordination Center's pioneer fleet management experiments supporting the ship-owner. Two-way digital data was sent and received via the Comsat Satellite Communication Link incorporating a commercially available stabilized GEO synchronous antenna for the ship borne terminal. The ship-owner was able to track the ship's movements every hour and also had access to the on board route plan and could even remotely change it to a new destination via new waypoints. A 40-plotted target display on DIGIPLOT was also accomplished but not considered useful.

Although successful as a year long "proof of technology" experiment, afterwards, the ship-owner even had the Comsat terminal removed after the Maritime administration stopped paying the monthly communication charges during the actual experiment duration. This was because it turned out that the high cost per minute for the crew to call home was prohibitive! Shore based micro-management of a single ship or even their small fleet did not appear to be worth the cost of purchase of the equipment and shipyard installation (even at 50%) at that time. The tracking and two way

[7] Coincidentally, before Iotron, Frona worked on SAGE radar at the MIT Lincoln Laboratory under Charlie Zraket during 1954-6

[8] See Appendix A MARAD press release details

communication was shown to definitely have the potential for managing large fleets of similarly outfitted vessels that was used for demonstration on the Mormacstar. Thirteen years later, the US Company GEOTEK[9] began commercial space borne fleet management operations including vehicle tracking and two way messaging. Being under financed and due to other factors, it went bankrupt.[xiii] The Chinese had been negotiating with the company before[10] and later much of their hardware designs were implemented in Bei Duo, which recently started operations.[xiv]

Loran C Augmentation of Transit Satellite Navigation

Later, to improve DIGINAV near shore accuracy, the conventional Transit program was integrated with Loran C and later, Decca Navigator[11]. When installed on VLCC's, which used Doppler ground speed as input in the presence of currents, this obtained the most accurate fix. Hyperbolic navigation was then used for the long duration in between fixes to continuously navigate and accurately position the chart lines. Since IBM and Norcontrol were given the same software, all three companies started with similar performance and they continued with a through-the-water speed log dead reckoned version of the original US Navy Transit navigation software. Magnavox, at that time did not integrate Loran C (or Decca) as Iotron did to improve the "in current" Transit performance. Magnavox stated that *a predictable positioning accuracy was 500 meters for a single frequency receiver* utilizing a conventional gyro and speed log. This accuracy was maintained in slow ocean currents and was essentially the same as Loran C 's worst accuracy achievable on existing chains, which was much better than Omega.

To gain a competitive edge and to overcome Transit's cited deficiencies, Iotron's integrated bridge[xv] needed "hybrid" Transit/Loran C's continuous accuracy in order to provide for the optional display of chart lines. Figure 9 shows English Channel chart lines drawn on the DIGIPLOT PPI. The dots in Figure 9 are a real time outline three successive scans of the closest radar coastline echo.

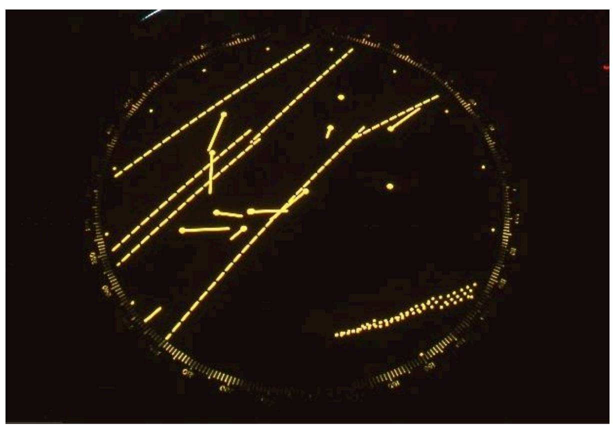

Figure 9 Chart Lines on PPI

on the PPI by taking advantage of hyperbolic navigational measurements of the vessel's position "over the ground." This would be best provided by the ground referenced Loran C than dead reckoning using gyro and through-the-water speed log measurements and almost as good as using a Doppler speed log in a short duration ground tracking mode, near shore, where large currents cause

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[9] (http://www.google.com/search?hl=en&q=rdss&btnG=Google+Search)
1983 GEOSTAR Corporation system called for three geosynchronous satellites would be able to locate an individual $200 transceiver as well as carry short (36-character) messages began commercial operation using Spacenet-3, with the capability of serving upwards of 40,000 users at typical installation costs about $3,300 for transceiver, antenna and keyboard. The Geostar link ran $45 a month for one transmission per hour, 24 hours per day, and a nickel for each additional transmission.

[10] Quote: "China indicates that their RDSS will conform as closely to GEOSTAR as possible in basic design."

[11] Decca Navigator was a UK privately owned short-range hyperbolic navigation system that had been used for D Day navigation during WW II. Decca had widespread acceptance at that time, servicing 23,000 vessels there were 50 Decca-Navigator chains located at heavily traveled narrow waterways and harbors worldwide.

significant additional errors. Currents, prevalent in US Loran C areas, can be more than 50 nm wide with a maximum speed of 5 kts and in the English Channel tidal currents up to 4-knots exist. The Transit/Loran C hyperbolic augmentation navigation technique was also applied to ships using the Decca Navigator.

Integrated Satellite/Loran Navigation Design Compromises Due to CPU Limitations

The AUTO-MATE system had separate embedded Lockheed MAC-16 minicomputers for DIGIPLOT and DIGINAV. The MAC-16 consisted of 12 15 by 15 inch PCBs each with80 IC's together with a large power supply. These central processor units (CPUs) were not floating point nor did they have hardware multiply/divide. The maximum memory capacity was only 64k (16 bit words) each and they ran at a much slower speed than today's processors (estimated at 0.6 MIPS). The DIGINAV CPU had to perform all navigational conversions and for DIGI-PILOT whose calculations had to be done continuously, as well as to control the communication link for displaying the chart lines on DIGIPLOT. The adaptive autopilot software was the most computationally intensive of all of the functions sharing this computer. It was calculating three computationally intensive Kalman filters all the time.

Processing of the Transit fix algorithm required sliding the ship's path over the ground track parallel to itself so as to minimize the difference between the modeled and measured Doppler signal effect. The integration concept was to provide the most accurate continuous hybrid hyperbolic navigation by building on the Loran C program that was operationally proven in the earlier Great Lakes chart line display software. The Mormacstar, in turn, proved out the converted conventional Magnavox Transit program, which wasn't continuous for navigation and was not sufficiently accurate in currents. The integrated Transit SatNav/hyperbolic program that Frona Vicksell[12] wrote was based on saving these positions and applying the geographic offsets to the Loran C fixes, rather than saving and applying the TD offsets and then recalculating the Loran C fix. The latter approach might have been better, but did not easily fit into the existing software design and there were limited computational resources. Saving TD offsets probably also would have made a better hybrid system, because the TD gradients change to a greater or lesser degree as you travel, so the saved geographic offset gradually would become incorrect in both size and direction as the LOP's (lines of position) curved and/or became farther apart or closer together. This, however was definitely a second order effect compared to the hybrid vs. conventional Transit processing using through-the-water speed log based tracks vs. using Doppler log ground-referenced tracks for obtaining the Transit fix sustained by hyperbolic navigation in between fixes.

The unaugmented hyperbolic track without the constant calibration offset would have been just as good, because the Transit fix procedure involved applying a constant offset to slide the track over to its best position. If hyperbolic navigation had been used to determine ship's path for calculating each fix during each Transit pass this would have been even more accurate but was an even bigger software change and would have required even more computer resources. For that reason, the first generation hybrid Loran C or Decca systems needed to use whatever speed estimate was available on the ship for dead reckoning during the fix. Fortunately Doppler over-the-ground speed logs were available on the super tankers (VLCC's), which were the original customers. Subsequent to the fix update, to provide continuity, Loran C (and particularly Decca Navigator) provided a more accurate approach than dead reckoning in between fixes since they both eliminated the current errors that could be up to 5-knots for nearly two hours. A separate Doppler speed log channel was also continuously maintained for a position double-checks and as an alarm, which could be set to call the navigator's attention if there was a discrepancy. The VLCC's Doppler log was used during the fix but could not be used as the primary navigation source for the nearly two hours dead reckoning alone since its position error would be greater than the use of either Loran-C or Decca separately and subject to unknown instrument errors in addition. The Loran C repeatability error was likely to remain nearly constant over the two hours between fixes if the super tanker didn't travel too far. It should be realized that the accuracy of the geographic offset obtained as the result of a Transit

[12] The author is grateful to Frona for the contribution she made by recalling the details of the software that she wrote so long ago, writing the algorithm descriptions and finally proofing the author's rewrite. **After Iotron, Frona, working for Megapulse and Northstar wrote a weighted least-square fix program combining Loran C and GPS pseudoranges in a single fix which had two clock unknowns, reflecting the unknown difference in the front ends of the receivers.**

fix did not necessarily hold up accurately to the full (18 to 90m) Loran C repeatability potential during the interval until the next fix, particularly in those coastal waters where the Additional Secondary Factor (ASF) corrections changed rapidly with position, and in areas with noticeable curvature in the Lines of Position (LOP's,) or if there was a weather or other temporal disturbance affecting the 100 kHz signal propagation. The more sophisticated software augmentations described above would have been implemented in the subsequent production units by incorporating them into more efficient refined software or the next generation more capable CPU. Then the systems would have clearly achieved 100-meter "GPS-like" accuracy more consistently. This implementation could have even allowed the use of the conventional IMO Standard ship's gyro and through-the-water speed logs rather than the very expensive Doppler logs to achieve the 100-meter accuracy instead of the 200 to 300 meters at best when using the through-the-water speed log and gyro.

Auto-mate Integrated Operation

There is an old adage that "in ship operations, the Captain should not rely on any single navigation source." Redundancy and complimentary characteristic synergism of dual bands are beneficial in both in radars and radio navigation systems. Fig 10 shows how the Iotron DIGIPLOT, Recorder and DIGINAV are interconnected through a navigation control console making it easy for bridge officers to make use of all available instruments for "double-checking" and to provide a "hot backup for radars" (and navigation receivers) for collision avoidance particularly when sailing within International sea-lanes in narrow restricted waters[xvi].

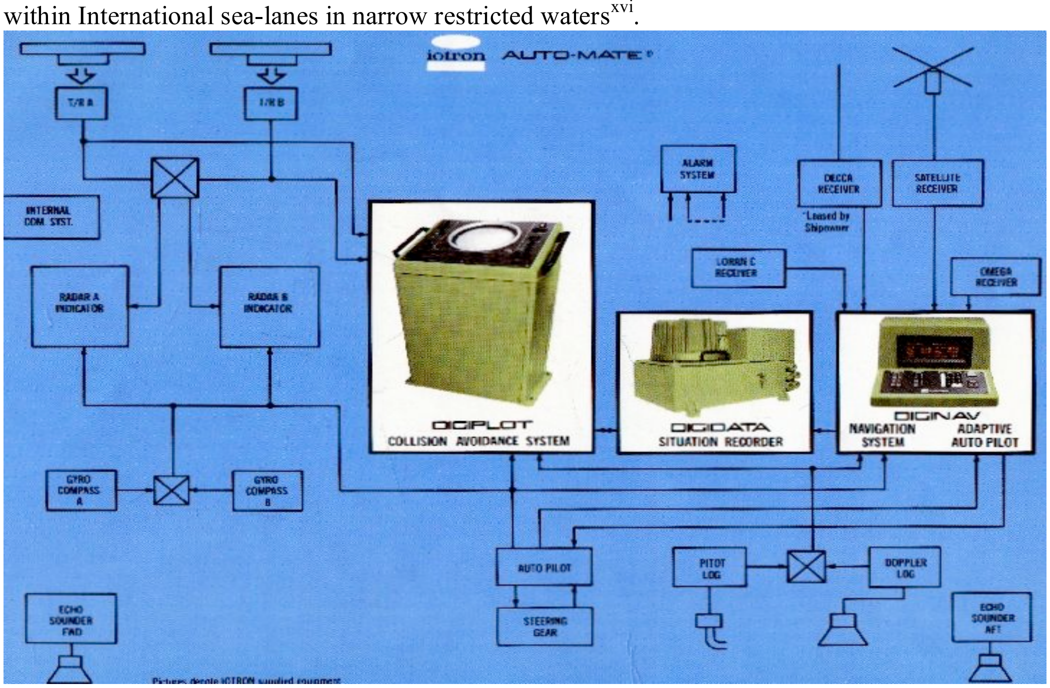


Figure 10 AUTO-MATE Modular Bridge Systems

The diagram shows that the two radars can be operated individually and independently for redundancy, even in the event of failure of either band's transceiver or display units. Both the X and S band radars are shown connected to DIGIPLOT and can be instantly switched from one to the other. The following information explaining the difference between X and S is quoted from a Raytheon radar reference[xvii]

In clear weather, range performance of 3 cm and 10 cm radars are about equal and generally have a range which extends to the horizon, although the 3 cm gives better definition. The lowest lobe, which is important for maximum range target detection, is several times higher for 10 cm. than 3 cm. This proves the detection advantage of 3 cm. by increasing its antenna height, it can be improved. However, in clear visibility a radar is not necessary for navigation, and therefore the better definition is less important. In rain or fog, the 3-cm performance is significantly reduced and the 10 cm is unaltered. The effect of absorption is clearly pointed out in two PPI photographs *contained in the Raytheon manual showing that four ships that are on the 10 cm display have completely vanished from the 3 cm display due to the shorter wavelength radar's microwave energy being absorbed by light rain. Backscatter reflection from rain for 3 cm is 81 times greater than for 10 cm. Small targets in heavy seas that are sometimes completely covered by seawater reducing 3-cm. performances by attenuation and reflection. Sea clutter also affects 3 cm much more at short range than 10 cm and requires more anti-clutter swept gain to be applied causing a further loss of echo signal.*

DIGIPLOT, because it was a fully auto acquisition ARPA, when switched from one radar to the other and back, would quickly show that there were echoes from buoys and vessels that were plotted on 3 cm that were different from the ones plotted from 10 cm. After completion of an installation, when Iotron servicemen trained the ship's officers on DIGIPLOT operation, they often demonstrated this difference to ship's officers. To their dismay, they had never realized this difference existed and they had to double check twice by looking at the different echoes plotted from each band's raw radar display. They didn't believe that it frequently happened that the echoes displayed on the 3 cm and those on 10 cm didn't match seemed strange that neither matched exactly what they saw visually on the water around own ship. The presence of echoes on each band depends on a complex interaction of a number of variables including Radar Cross Section (RCS), antenna height affecting elevation lobe patterns of 3 cm and 10 cm which are different and cause deep null loss of signal,[13] sea state, amount of compensating anti-clutter applied causing the band's sensitivity to be reduced near own ship, etc. At IMO meetings when standards for ARPAs were originally being written, there was much discussion about whether automatic acquisition would work well enough at a high enough probability of detection to consider missed plots having to be manually acquired. There was no discussion of this physical phenomenon of echoes not existing for either band affecting what is acquired whether manually or automatically. Manual acquisition doesn't correct this deficiency if the echoes don't appear on the raw video but if the equipment is automatic acquisition, which could easily be corrected in future developments.

As indicated in the AUTO-MATE interconnecting diagram in Figure 10, DIGINAV also had several independent parallel channels of navigation information available at the console for easy verification and comparison depending on whether Loran C or Decca chains were operating including:

- Dead reckoning (DR) with manual fix input
  - Speed Through-the-Water (STW) using ship's gyro and speed log or over-the-Ground (OTG)-Doppler
  - Radar tracking of an operator identified radar reflecting buoy or lightship that was being auto tracked on DIGIPLOT and its Lat/Long was in DIGINAV's database
- Loran C or Decca Navigator converted to Lat/Long as independent navigation channels
- Transit dead reckoned using ship's gyro and speed log STW or OTG
- Hybrid Transit SatNav using Doppler speed OTG log for SatNav fix and updating of either Loran C or Decca Navigator augmentation in between fixes

Maritime Acceptance of Digital Navigation Maneuvering Aids

The wide variety of vessel types and shore-based radars that installed Iotron anti-collision radar systems and options is shown in Figure 11. Most of these smaller vessels were equipped with Decca Navigator or Loran C receivers and used them manually with charts for near shore navigation. On the other hand, VLCCs cost and liability for accidents resulted in their buying the best equipment for the safest operation, which included embedded computer radio navigation with manual backup with charts. In addition to the conventional static vector triangle, a dynamic trial was available that was particularly suitable for VLCCs. The marine architect's turning and stopping characteristics was built in custom for each ship. A 30:1 quick-time trial could be implemented changing course, speed and delay time. The allowed a simulation of picking up a mooring with remarkable precision.

[13] Multipath propagation

The timeline of the table in Figure 12 shows the rate at which anti-collision radar and SatNav was accepted from various manufacturers and the approximate ship set costs. The principle reason for DIGIPLOT acceptance on a variety of vessel types was its ease of use because it was truly automatic, "hands off" reducing workload. During installation, officers were trained that the selected radar should be on and properly tuned and that DIGIPLOT should also always be on and plotting, not only in fog, but also in daylight and nighttime in clear weather. In that way, seeing it operates properly, the crew would get faith in the plotted results by using their binoculars to determine the aspect of the other surrounding vessels and comparing the plotted true vector aspect with the actual aspect. The true plot aspect of the other vessel was accurately calculated and displayed or could be read out numerically within a few degrees of correct if an individual ship vector was tagged by a joy stick controlled symbol. When the crew got consistent agreement this provided confidence for use in poor visibility. Often the aspect was misjudged visually and could be off by 90 degrees and when the plot was seen to be correct, the crew would be impressed. For example, when a vessel off the bow was either coming toward or away from own ship, it's hard to tell aspect particularly when the ship is "hull down." In addition, safety also improved in clear weather, which is when most accidents occur and the ship's officers can properly apply the "rules of the road" enhancing safety within the maritime law and traffic separation lanes as well. Figure 11 shows the variety of vessels and shore installations that used DIGIPLOT, DIGINAV-SatNav, Loran C and Decca as well as Situation recorders and Fuel Saving Adaptive Autopilots. The Navy first bought a unit and thoroughly evaluated it with a shore radar. Afterwards, Admiral Zumwalt had initiated a manpower reduction program and installed units on two destroyers and an AO (need to define AO) to do the evaluation. The results were all positive, since the automatic plotted result on the DIGIPLOT were ALWAYS quicker and more accurate than the CIC (Combat Information Center). The amphibious ships used the auto vector plots to guide landing craft into the beach. The AO new buildings had a special navy console designed and used them to achieve the reduced bridge-manning objective on non-combatants. One was installed in an air transportable shelter with a marine radar for use in third word areas where a traffic control system for a port would have to be in operation quickly. Another one was installed on an island in the submarine test area in Puget sound. The data was remoted to a central control facility where it plotted surface vessel activity. Sonar was used to map the entire area of submarines and thus achieve a three dimensional controlled plot of all moving vessels.

INSTALLATION TYPE	DIGIPLOTS	Sat/NAV	Loran	Decca	DIGI-Pilot	Recorde
VLCC	132	17	3	17	12	16
Tankers	239	3			1	5
Ore/Oil	6					
Bulk Carrier	2		1		1	
Catug/Barge-47k dwt	9					
LNG Carrier	22	2				
LPG Carrier	5					3
Acid Carrier	9					
Hazardous Cargo Vessel Total	424	22	4	17	14	24
Containership	22	3			3	
RO/RO	9	1			1	
Barge Carrier-Seabee	5	1				
Cargo Liner	3					
Cruiseship	9	5	1			2
Passenger	2					
Ferry	1	1		1		
Fishing Trawler	2					
Miscellaneous Vessels						
Amphibious ships-US NAVY	2					
Destroyers-US NAVY	2					
US Navy Oil & Ammunition Supply Ships	6					
US Navy Shore Surveillance	3					
US Navy Total	13					
Shore Surveillance-Traffic Control	2					
Training schools and ships	16	1				2
Shore Based -Traffic Monitoring	18					
TOTAL INSTALLATIONS	508	34	5	18	18	28

Figure 11 AUTO-MATE Equipment by Ship Type from Iotron Ship Installation List

YEAR	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	82 (1/2 YR	Total	% Ships	Av Price	Total
																Fitted	per ship	cumulativ
																	$1000's	$1000's
Iotron																		
DIGIPLOTS		3	4	17	45	69	26	46	55	19	31	83	91	19	508	17%	77	39116
DIGINAV & DIGIPilot						2	3	4	4	6	6	6	1	1	34		45	1530
Total															34		122	40646
Norcontrol/Kelvin Hughes																		
Anti-Collisi		8	11	22	23	28	18	20	20	20	20	20	25	25	260	9%	90	23400
SatNav & Autopilot															200		35	7000
Total															200		125	30400
Sperry																		
Anti-Collision			6	23	41	54	36	50	35	40	90	100	100	75	650	22%	51	33150
SatNav & Autopilot															150		40	6000
Total															150		91	39150
IBM																		
Anti-Collision				2	4	9	10	5	20	13	12	0	0	0	75	3%	135	10125
SatNav & Autopilot																		0
Total																	135	10125
Selenia																		
Anti-Collision				1	10	15	12	12	12	12	15	15	19	13	136	5%	85	11560
Raytheon																		
Anti-Collision									50	90	200	260	350	250	1200	41%	30	36000
Plessey/Decca																		
Anti-Collision											10	15	25	50	100	3%	60	6000
All Other Manufacturers																		
Anti-Collision								10	20	20	50	60	80	60	300	10%	60	18000
ANNUAL RAT		11	21	65	123	175	102	143	212	214	428	553	690	492	3229			
CUMULATIVE		11	32	97	220	395	497	640	852	1066	1494	2047	2737	3229				191881

Figure 12 Anti-Collision, Satnav & Autopilot Data (Iotron Audits & Market Estimates)

The Future of Marine Navigation[xviii]

The following excerpts from the UK General Lighthouse Authority (GLA) recommendation for eLoran augmentation as a GNSS (Global Navigation Satellite System) backup, **which defines the overall functional requirements for merchant ship bridges of the future**.

e-Navigation is expected to be based on a number of structural components:

- *Accurate, comprehensive and up-to-date electronic navigation charts*
- *Accurate and reliable electronic positioning signals*
- *Information on a vessel's route, bearing, maneuvering parameters and other status items, in electronic format*
- *Transmission of positional and navigational information from ship-to-shore, shore to ship and ship-to-ship, using AIS*
- *Clear, integrated displays of the above information on board ship and ashore, using electronic chart display and information system (ECDIS)*
- *Information prioritization and alert capability in risk situations on ship and ashore*

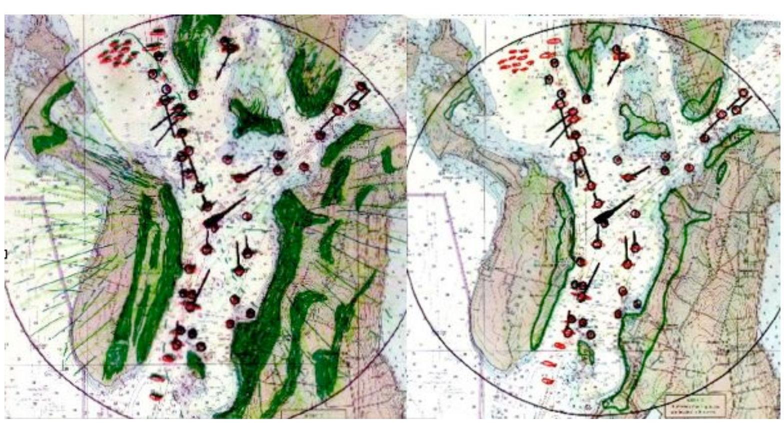
Two Band AUTO-MATE Plus Added Functional Improvement Suggestions:

- *Accurate, comprehensive and up-to-date electronic navigation charts*
- *Accurate and reliable positioning signals* **from GNSS all channel receivers with eLoran augmentation to provide "other band backup and synergism" including GEO "WAAS level" differential corrections via the eLoran Data Channel for overcoming urban and terrain losses, negating temporary blockages and permitting extension of navigation and surveillance into inner harbors and restricted waterways, particularly at high latitudes**

- *Information on a vessel's route, bearing, maneuvering parameters and other status items, in electronic format* ***for a situation display maneuvering aid showing simultaneous superimposed ARPA plot on an eChart as well as an optional quick time dynamic trial maneuver for a 3D prediction showing a true motion display of all surrounding buoys***
- *Transmission of positional and navigational information from ship-to-shore shore to ship and ship-to-ship, using AIS*
- *Clear, integrated displays of the above information on board ship and ashore, using electronic chart display and information system (ECDIS)* ***with ARPA and radar data superimposed on the chart without significant degradation as an integrated aid for both collision avoidance and anti-stranding maneuvering***
- *Information prioritization and alert capability in risk situations on ship and ashore*
- ***Ensure that X and S band interswitched radars are inputs to ARPAs that are operator selectable for plotting X, S or "X and S band correlated" signals***
- ***ECDIS voyage recording including continuous ARPA data at one minute intervals with all operator settings and ARPA data that an observer might have had access to in the previous 12 hour period***

Anti-Collision/Anti-Stranding now 3D Single Maneuvering eChart Display

In the 1970's, anti-collision manual and automatic acquisition radar plotters were invented because that was the most pressing safety need. Acceptance of all of the various manufacturers' functionality later resulted in the creation of the IMO Standard for ARPAs. Anti stranding was defined as Iotron's second priority product need but since electronic charts were not available and using charts was largely a manual task, this was a mismatch of several decades for eCharts compared to a "hands off" fully automatic ARPA. Thus this didn't lend itself to integration, so Iotron innovated another way by combining "chart based guide lines" for providing complete single 2D display maneuvering information, by putting the precision referenced chart lines directly on the DIGIPLOT PPI. At that time, using Transit and coastal hyperbolic systems where available, these were readily combined to provide the continuous accurate reference for positioning the electronic chart guidelines on the radar PPI. The ~100 m accuracy finally achieved by using Loran C enhanced Transit was not sufficient for referencing chart lines for anti-stranding but was deemed adequate for referencing IMO mandated traffic separation lanes in a dozen narrow restricted channels and straits throughout the world. Since then vector electronic charts and the means for their updating have become readily available in accordance with the established IMO ECDIS and ARPA standards and now permit superposition of the ARPA vectors and/or the radar image directly on the 3D depth furnishing eChart, provided they are is clearly distinguishable and they do not degrade the chart data. See Figure 13 showing raw radar vs. the internal processed data from DIGIPLOT that can now be displayed.



Raw Radar and ARPA data on eChart

DIGIPLOT Echo-sketched Radar and ARPA data on eChart

Figure 13 Superposition radar with ARPA inherently compliant in DIGIPLOT

Anti-Stranding Navigation

Electronic navigation of the future requires clear, integrated displays of anti-stranding-navigation and collision avoidance data superimposed on accurate, comprehensive and up-to-date electronic charts. The Loran system has been modernized to enhance its accuracy, integrity, availability and continuity. These improvements known as Enhanced Loran or eLoran for short are to provide a Position Velocity and Time backup for GPS. Today, sixty channel GNSS receivers that are compatible with WAAS/EGNOS already are on the market and presumably can be combined as GNSS/eLoran receivers to include use of Eurofix type Loran Data Channel augmentation. In addition to providing an adequate accuracy GNSS backup, when integrated, provides a more reliable reference for the IMO electronic charts. The USCG Harbor Entrance and Approach repeatable accuracy requirement is 8 to 20 m with ASF's for up to 3 hours, Additionally; LORAN signals can be used to convey differential GPS corrections to 1-3 m accuracy. In Europe, Eurofix differential applied to GPS achieved accuracy of < 5m 95% over a wide area. Recent trials of eLORAN alone, achieved horizontal positioning accuracies better than nine (9) meters with 95% confidence, using modern, miniaturized receivers. This performance level meets the future navigation accuracy requirements stipulated by the International Maritime Organization for port approaches and restricted waters and provides also the needed GNSS backup. A high latitude maritime application in the Kiel Canal requires accuracies better than 30 meters for 10 hours without GPS and EGNOS differential updating since these signals can be blocked by terrain and are not reliable consistently. In high latitude operation of differential GNSS, the maritime urban and terrain losses and blockage are more severe for mariners than aircraft that don't have similar loss of signal for the GNSS and WAAS type GEO correction data because of the altitude. This is where the eLoran low frequency is particularly beneficial and it also provides a completely separate navigation system backup.

Potential ARPA Performance Improvements

The major improvement needed to improve the DIGIPLOT technology is for operation not only in Harbor entrances and approaches but also to operate fully automatically within harbors and on inland waterways. DIGIPLOT was tested against the IMO ARPA standard and the design was fully compliant. That design could now be hardware and software updated to meet the newly defined appropriate functionality of harbor approach and inner harbor operation functions as described in the above suggestions. For both radar and navigation receivers, there are many reasons for state-of-the-art equipment designs to utilize different radio frequency bands synergistically. This includes basic redundant backup as well as many other operational benefits. Large ships have both S and X band radars, whose primary justification for being installed is that when sailing with both radars on, this provides a "hot spare" backup. In addition, they are normally interswitched for complete flexibility in the event of a subsystem failure at a critical time. With digital techniques of today, both bands can be processed in parallel and their echo positions correlated, which would insure that ALL (or at least a much larger percentage) of the surrounding vessels and buoys whose echoes are above a noise threshold can be auto acquired and tracked in a fully automatic ARPA. This band correlation would improve integrity by overcoming one of the major deficiencies of marine radar and in particular for manual acquisition ARPA's.[14].

This simple modification would improve "Hands Off" ARPA operation, by increasing the probability of overcoming each band's shortcoming of "missed echoes" being plotted for collision avoidance. The ARPA standard for automatic detection mandates that the performance should not be inferior to that which would be obtained using manual radar observation. With 1970's technology, and severe CPU and memory limitations, each band's auto acquisition was of equal performance and it was up to the observer to choose by switching to plot on either X or S band for plotting. Improving the radar X and S band echo inconsistency should also result in a significant safety improvement, if a DIGIPLOT type auto acquisition ARPA were to be chosen as opposed to manual acquisition ARPA's. Charting and precision navigation would then not only be equal to past ARPA "Hands Off" effortless operation for a single 2D display maneuvering aid on the bridge. This single aid could easily be directly compared with clear weather aspect through the bridge window observations of the

[14] Both Japanese and Russian radars have been built with the X and S antennas operating back-to-back, but apparently this concept in analogue form has not yet been accepted commercially

other surrounding vessels. Tracked buoys overlaying actual buoys marking channels can show an out of place buoy by comparison with the underlying chart.

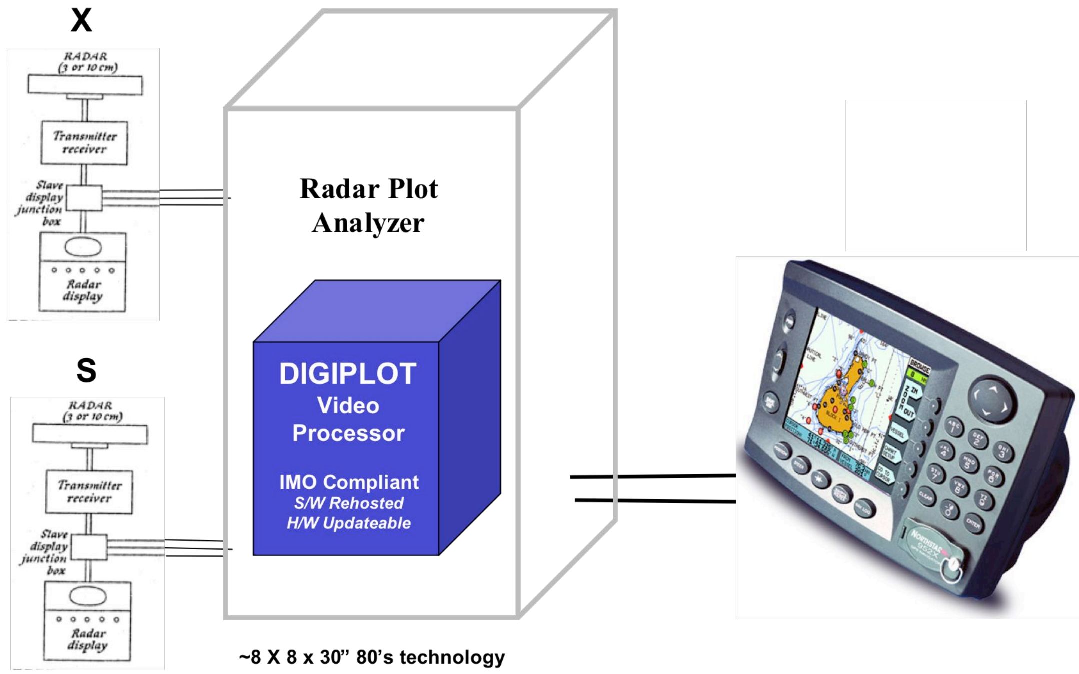


Figure 14 Notional DIGIPLOT Subsystem Using COTs Chart Nav Display

Figure 14 shows a chartplotter and AutoPlot Radar Analyzer (ARA) module, which is a compliant IMO ARPA add-on as a marine anti-collision/anti-stranding aid when connected to any manufacturer's radar. This equipment can also be shore based for harbor or serve coastal surveillance or other self-plotting radar needs providing a 3D maneuvering aid when displayed on an ECDIS vector electronic navigational chart. A repackaged ARA version would only be somewhat larger than a brick.

Processing power and memory of CPU's were limited and expensive in the 1970's. For example, the Lockheed MAC 16 computer had 13-15 x 15 inch PCBs with 89 IC's on each PCB and cost $10,000 with its core memory costing $1 for each16 bit word! At today's PC and memory prices, an embedded system shown in Figure 14 can now be manufactured and sold for one-tenth the cost of earlier integrated AUTO-MATE systems. The much reduced price for the Radar Plot Analyzer for civil use with chart plotter, not only allows the > 10,000 large vessels that could afford the higher IMO mandated equipment prices as in the past, but also the more than 100,000 smaller commercial vessels can have the same self plotting radar display. These vessels have radars but are not obligated to carry IMO Standard ARPAs. Vessel owners of all types in the future would now be able afford to have IMO compliant equipment such as a modernized AUTO-MATE at a much more affordable price. For situational awareness, many military applications utilizing the GPS Precise Positioning Service instead of the civil GNSS signals could be fitted for use on carriers and most smaller vessels. Coastal radars and oilrigs at sea could also use unattended radars for monitoring, alarms and data logging of all moving vessels in and out of an area as a coastal radar monitor for unattended, monitoring of moving traffic.

CONCLUSION

A single point calibration utilizing Loran C's repeatable accuracy characteristic successfully achieved 0.1 nm (~200m) accuracy in 1975 to display geographically positioned north referenced chart lines on the radar's plan position indicator (PPI). as an approach aid for entering a narrow river channel.

When the International Maritime Organization (IMO) mandated traffic separation lanes in the world's narrow straits and channels, since there were no electronic charts available, it was decided to equivalently display chart lines directly on the DIGIPLOT radar PPI for aiding in maneuvering of supertankers. Iotron innovated a synergistic concept for significantly improving the Transit SatNav dead reckoned accuracy in between fixes, when sailing in currents near land, where the mandated separation zones existed. Loran C was used to augment Transit SatNav to continuously display the designated charted lanes accurately on the radar's PPI. This unpublished maritime Transit augmentation exploited Loran C's continuous repeatable accuracy to provide the nearly 100-meter accuracy that equaled GPS for 20 years until Selective Availability (SA) was removed. Iotron not only pioneered "Hands off" Automatic Radar Plotting Aids, later designated by the IMO as an automatic acquisition ARPA, but also accurately superimposed charted sea-lanes and planned route lines on the PPI. The anti-collision equipment was successfully competed against Raytheon, Sperry, IBM and foreign companies by installing DIGIPLOTS on over 500 ships out of the 3000 total that had been sold worldwide. In addition, Transit satellite navigation augmented by Loran C (or Decca Navigator) was fitted on 34 super tankers.

The technology exists today to integrate the display of "Hands Off' fully automatic radar plotter (ARPA) data with the synergistic combination of two-band radio navigation positioning of an electronic vector chart by integrating GNSS/eLoran. Iotron's AUTO-MATE bridge navigation system incorporated most of the "on ship" bridge functionality that has recently been defined as required for meeting the "navigation needs of the future." DIGIPLOT's design, done in the 1980's, is fully compliant with the IMO ARPA standards. The equipment's separate video processor and software is amenable to reverse engineering to utilize today's processor and memory improvements and other cost reducing manufacturing technologies. The recommended operational improvement upgrades in ARPA performance could also be readily added during repackaging including simultaneous X and S band ship's radar's as correlated echo inputs to improve band integrity in anti-collision plotting as well as permitting "self plotting radar's" ability to operate in more confined waters such as inside inner harbors and larger rivers.

Installed radars, could be retrofitted by the addition of a Radar Plot Analyzer and eChartplotter for unattended radar watch as was done previously on the ships and shore installations. This could be accomplished on any existing radars on civilian or USCG, Navy or other government vessels or shore sites. As an unattended adjunct to existing radars, this could make an inexpensive add-on as a labor saving watch station for homeland security of the US coastline for narcotics, illegal immigrants, terrorist vessels, etc. As in the past-unattended operation, the observation position and vector data could be relayed via telephone line or appropriate communication link. Unfortunately, self-plotting radar was 30 years ahead of its time.

During Desert Shield preparations, fielding receivers implemented Loran C in about 6 months to be used during the Desert Storm invasion to overcome GPS Availability limitations. The Loran C chain had already been installed by Megapulse for the Saudi Arabian government and was operating for maritime navigation. By plotting accurate GPS fixes on Loran C charts to "calibrate" Loran's inherent lack of absolute accuracy, while using its accurate repeatability to enable "continuous" navigation at night in the off road featureless desert terrain. This DoD concept is a manual version using exactly the same principle as the embedded computer integrated LorSat approach that was developed in the late 1970's and installed on 34 merchant ships as described in this paper. Transit passes were every 100 minutes with data taken for 10 minutes to determine a <100 m fix at the end. Thus, this accuracy was only available <1% of the time, but when combined with Loran C inertial in between, the result was continuous at the 50 - 90m level. Synergistically < 90 m was maintained and quite adequate for the "end around through the desert" surprise mission.

See details in Appendix C describing DoD's field commander's recognition of the problem and the two receivers per vehicle synergistic solution. Similar to the renaissance in software development, eLoran since then has been dramatically improved by using GPS techniques and technology to navigate at <10 m repeatability which can be approached as almost the same absolute accuracy by differential corrections similar to the point calibration in 1975 to meet the stringent harbor entrance accuracy of 8 to 20 m together with availability, integrity (believability) and other improvements for meeting all Civil FAA and USCG mission requirements. These are also the minimum for DoD military mission use, since a tenfold improvement in targeting is necessary and requires the eLoran compass quickness to first fix and factor of nearly 20 improvement in True North sensing. Underwater broadcast

and potentially even duplex communication offer potential military mission advantages.

Lessons learned: Two concepts, considered competitive often offer a better solution if combined synergistically, SatNav Loran is certainly the poster child example!!

Biography

John C. (Jack) Herther graduated from North Carolina State in 1953 with a Bachelor of Science degree in Mechanical Engineering. Under Charles Stark "Doc" Draper's tutelage he graduated from Massachusetts Institute of Technology (MIT) in 1955 with a master's degree in Aeronautical and Electrical Engineering. His thesis proposed a satellite guidance and stabilization system that he was later able to implement on subsequent Air Force engineering assignments. Over the years, hundreds of USAF, NASA, and other satellites would orbit successfully using the Herther three-axis active stabilization. He became an Air Force Space Pioneer[15] and was inducted into the Space Hall of Fame in 2003[16]. During 13 years at Itek he lead the development of several generations of satellite and aircraft reconnaissance cameras, including the original design of the lens and prototypes for the CIA A-12 (later USAF SR-71 "Blackbird") camera and for the Large Format Camera (LFC)[17] a high altitude aerial mapping camera, was operated from the NASA Space Shuttle Challenger Mission STS-4-G on October 5-13, 1984. It achieved a ground resolution of 14 to 25 meters in Earth-orbital altitude of 180 nautical miles, continuing post-CORONA space mapping for the WGS84 Geoid. Original development of the lens and prototype camera was done in Herther's Research and Development Directorate during his time at Itek. Previously CORONA panoramic photography had been the sole source of space mapping photography used for the WGS-84 Geoid which became the basis for Transit and GPS satellite navigation systems[18]. Aerospace historian Dwayne Day has called Jack Herther "one of the unsung pioneers of the early space age." In 1969, Herther founded Iotron Corporation, served as its first president and acted as system architect for its products. In 1983, Herther joined MITRE Corporation in Bedford, MA and was involved in Air Force, Army, Navy and NSA communications and electronic systems engineering programs, including GPS III and Navwar. Still an entrepreneur, he sails, water skis, and is still working and innovating full time.

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15 http://www.peterson.af.mil/hqafspc/history/pioneers.htm
16 https://www.peterson.af.mil/hqafspc/history/herther.htm
17 http://academic.emporia.edu/aberjame/geospat/space/space.htm
18 http://www.fas.org/spp/military/program/imint/at_950525.htm

Appendix A

U.S. Maritime Administration (MARAD) Press Release **July 1975**

Shipborn Navigation/Communication

First Space Computer-to-Computer Experiment

MORMACSTAR

"This ship is so advanced it is a step into the 21st Century"

– MARAD

The MORMACSTAR was the ship being discussed when the above statement was made. What makes this ship so unique?

The MORMACSTAR is the first commercially owned ship in history to have –

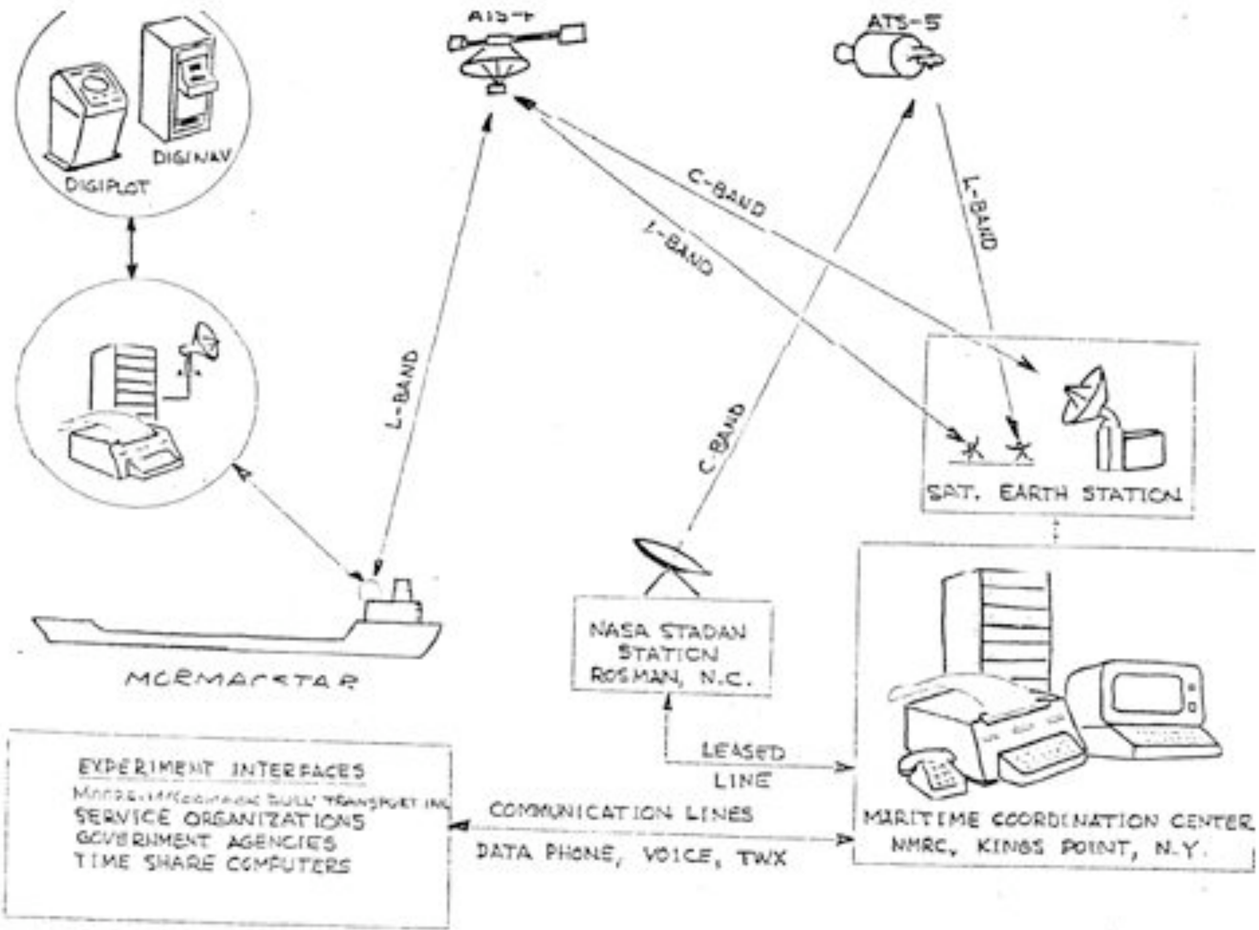
- A Ship-to-shore satellite communication system which allows world-wide reliable and confidential transmission of information between the owner and his ship.
- A fully automatic third generation, integrated navigation system.
- Ship's navigation computer-to-shore computer MARISAT communication.

The Experiment

The Maritime Administration sponsored 'Computer-to-Computer" MARISAT two-way communication experiment will investigate the value of transmitting "on-board" processed navigational data for "on-shore" analysis and its usefulness to fleet managers. Specifically, data from the Internavy... Specifically, data from the Iotron DIGINAV system, including the ship's present position, course and speed, as well as the navigator's route plan, will be automatically transmitted via MARISAT to the Maritime Coordination Center (MCC). These transmissions can be accomplished at regular intervals or on demand of the Maritime Coordination Center. Recommended changes in the routing of the ship, based on the received data, can, in turn, be transmitted to the ship from the Maritime Coordination Center.

After the implementation of the initial navigation experiments, a variety of other experiments using the automatic ship-to-shore transmission will be performed, e.g., information on weather routing, logistic and administrative functions, and sensing and monitoring of shipboard performance parameters.

The following block diagram graphically represents all elements and the flow of experimental information through the system.



EXPERIMENTAL DATA TRANSMISSION SYSTEM

Appendix B

US Navy Military and Shore Based "Self Plotting" Radar Applications

DIGIIPLOT INSTALLATION-LOCATION	Country	Ship Name or Organization	
Destroyer (Development Group)	U.S. NAVY	USS Glover-AGDE-1 (Newport,RI)	1973
Destroyer (Operational Tests)	U.S. NAVY	USS Roark-DE 1053 (San Diego)	1973
USN Fleet Oiler, Support & Command	U.S. NAVY	USS Detroit-AOE-4 (Mediterranean)	1973
USN Amphibious Tranport -landing craft to beach	U.S. NAVY	USS Ponce de Leon-command/control	1976
USN Amphibious Tranport -landing craft to beach	U.S. NAVY	USS Nashville-command/control	1976
USN Fleet Oiler-Reduced bridge manning	U.S. NAVY	AO-177 USS Cimmarron	1980
USN Fleet Oiler-Reduced bridge manning	U.S. NAVY	AO-178 USS Monongahela	1980
USN Fleet Oiler-Reduced bridge manning	U.S. NAVY	Avondale NB AO-180	1982
USN Fleet Oiler-Reduced bridge manning	U.S. NAVY	Avondale NB AO-186	1982
USN Military Sealift Command	U.S. NAVY	USN Sirius (T-AFS-8-Civilian Manned)	1982
Naval Vessels-All Types	10		
USN Shore Based Laboratory Annapolis	U.S. NAVY	Laboratory-Performance evaluation	1976
USN Shore Surveillance Panama City FL	U.S. NAVY	Shelterized Harbor Control	1975
USN Shore Surveillance-Undersea Warfare-Seattle WA	U.S. NAVY	Torpedo Range Safety	1979
Naval Shor Based Installations-All Types	3		
Shore Based -Shanghai Harbor	China	C9ivil Harbor Control	1980
Surveillance-Marine Area Traffic Observation System-MATROS	Neth	M.V.Small Agt- Rotterdam	1982
Shore Surveillance-Situation Awareness	2		
Training AmsterdamHarbor & Simulator	Neth	Amsterdam College	1974
Training Pireaus-Harbor & Simulator	Greece	Merchant Marine	1977
Training New York City-Harbor & Simulator	US	American Radio Assoc.	1977
Training Seattle-Harbor & Simulator	US	Maritime Administration	1980
Training Calif Maritime-Harbor & Simulator& Ship	US	Golden Bear	1979
Training La Guardia-Harbor & Simulator	US	Marine Safety Inter.	1979
Training King's Point NY-Harbor & Simulator	US	Merchant Marine Academy	1979
Training New York-Harbor & Simulator	US	Maritime Administration	1980
Training New Orleans-Harbor & Simulator	US	Maritime Administration	1980
Training AmsterdamHarbor & Simulator	Neth	TNO Nautical Institute	1981
Training Wageningen-Harbor & Simulator	Neth	Nautical Institute	1981
Training Ship Tokyo-Harbor & Simulator	Japan	T/S Shinyo Maru	1981
Training London-Harbor & Simulator	UK	Wabash Nautical College	1981
Training Hong Kong-Harbor & Simulator	Hong Kong	China Polytechnic Nautical	1981
Training Delft-Harbor & Simulator	Neth	Nautical Institute	1981
Training Harbor & Simulator	Unknown	Training Institute	1982
Training schools harbor & and ship radar plotting	16		
Total US Navy and Shore Installations	31		

Figure 14 US Navy and Shore Based "Self Plotting" Radar Surveillance Installations

In 1970, Shell Laboratory bought the first production DIGIPLOT and tested it for Collision Avoidance functionality, particularly automatic acquisition functions for two years on the Methane Princess, a UK Liquid Gas Carrier. Afterward, it was installed at the Mas radar station at the Hook of Holland to act as a 24/7-auto detector and plotter of all ships entering and leaving the Port of Rotterdam, the busiest Port in the world. Traffic was monitored continuously for 100 hours and recorded every 15 seconds at a rate of up to 40 targets within 12 nm range at a time including their positions and speed vectors using a standard DIGIPLOT. The ships were identified when possible. Based on this highly satisfactory experiment, The Shell Lab, Dutch government and their contractor worked for 5 years to design an on-line marine traffic monitoring system by adding a computer to a special DIGIPLOT. They specified an increase to 60-target capacity with the ability to size each vessel's echo into ten categories for display and recording. The system was installed on the 56m motor vessel named **"Small AGT"** and called **MATROS (Marine Area Traffic Observation System). MATROS, which operated for 10 years in the North Sea.** (The USN already had a special packaging and control panel and MATROS was a modification as shown in Figure 15)

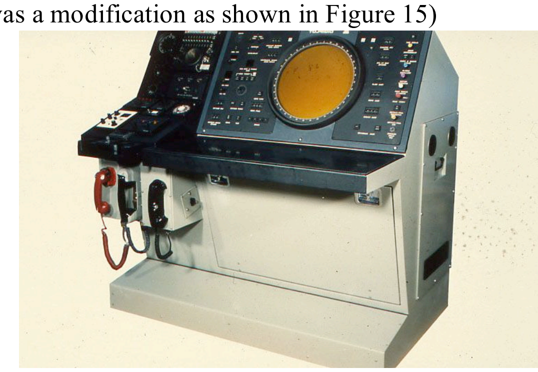
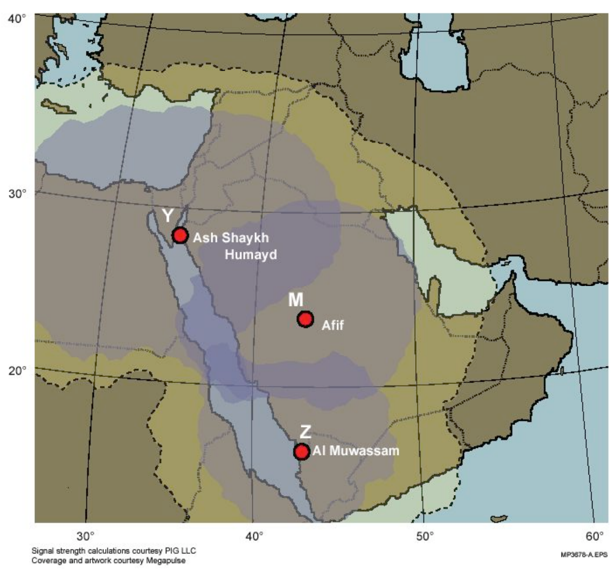


Figure 15 US Navy Tactical Mission and MATROS Shore Surveillance Model DIGIPLOT

Appendix C
Transit (then GPS)/Loran Military and Civilian Events

- 1940s: Development begins (military use through 1960s)
- 1970s: Established for civilian use (maritime & timing applications)
- 1975: Sing Point Calibration achieved <200 m entering St. Mary's River (Iotron-Vicksell
- 1979: Transit/Loran C continuous ship navigation @ 100 m accuracy (Iotron-Vicksell)
- 1980s: MOA-1 (CG/FAA): Mid-CONUS expansion for civilian aviation users
- 1981: RTCM SC 75 Minimum Standards Loran Coordinate Converter (iotron Herther)

General Schwarzkopf used the Saudi Arabian Civil Loran C Chain for the successful Desert Storm End-around Maneuver as GPS Backup



During Desert Shield, since Transit was not continuous and GPS satellite navigation constellation wasn't fully populated, 10,000 marine Loran C receivers and whip antennas @ $4000 ea were bought or the convoy "end run" transit through the desert in heavy sand and dust off road conditions. Loran's 300m absolute accuracy wasn't adequate, but due to its 50 to 90 m repeatable accuracy 50 to 90 m so when GPS @ 16 to 30m was intermittently available, it could update Loran C charted tracked positions to 90 m absolute accuracy, worst case for CONTINUOUS navigation!

For example, commanders had to keep both a Loran and a GPS receiver in the lead vehicle for navigation purposes, because the time window from about 2300 hours to 0200 hours (local time) was a bad window for NAVSTAR satellite tracking and there were 7 periods each day of up to 40 minutes duration when fewer than four satellites were in view, so no GPS fix was possible and Loran C had to be relied upon.

Commander's prophetic quote: ***Although these two systems appear to provide some of the needed capability, neither system completely fills the requirements!***

GPS/Loran Military History

The following is quoted from a GAO Report to the Chairman, Subcommittee on Regulation, Business Opportunities, and Energy, Committee on Small Business, House of Representatives, **OPERATION DESERT STORM**-Early Performance Assessment of Bradley and Abrams, January 1992, GAO/NSIAD-92-94-appendix III:

Crews Would Like a Navigation System in Every Vehicle

Navigation systems enabled the Bradley and Abrams crews to determine their vehicles' location in the vast desert, but crews believed there were not enough systems available. ***Combat units generally had one or two navigation systems per company, or roughly one for every 6 to 12 vehicles. Two types of navigation systems were used in the Persian Gulf War: the Loran-C and GPS.***

The Loran-C determines position based on radio transmissions from ground-based radio transmitters. ***When U.S. forces deployed to Saudi Arabia, they found a series of Loran radio transmitters already in place. To take advantage of the existing navigation infrastructure, the Army purchased 6,000 Loran-C receivers. During use in the Persian Gulf War, Loran-C enabled vehicle commanders to determine their location within 300 meters.***

GPS is a space-based navigation system utilizing signals from satellites. The device used by Bradley and Abrams crews in the Persian Gulf War to receive the satellite signals was the Small Lightweight GPS Receiver (SLGR). The SLGRS used in the Persian Gulf War were hand-held units purchased from commercial vendors and slightly modified for military use. SLGRS enabled vehicle commanders to determine their location within 16 to 30 meters. The Army purchased ***about 8,000 SLGRS****, of which* ***roughly 3,500 were shipped to Army forces in time to be used during the ground war****. Crews experienced in the use of both systems generally preferred the SLGR because it was more accurate.*

According to crews, commanders, and other Army officials, U.S. forces would not have been able to navigate the nearly featureless desert without navigation systems. Navigation systems helped U.S. armored forces quickly traverse the lightly defended desert in eastern Iraq and cut off the bulk of the Iraqi force in Kuwait. A captured Iraqi general cited the SLGR as an example of being "beaten by American technology again." Support units also used navigation systems. For example, maintenance and logistics personnel used SLGRS to locate combat units. Engineers with the 24th Infantry Division used SLGRS to mark newly created combat trails inside Iraq.

Because SLGR relied on satellite information, the system was inoperative during certain times of the day when satellites were out of range. *Despite this, soldiers we interviewed believed that navigation systems should be installed in as many vehicles as possible. A TACOM report on armored systems' performance in the Persian Gulf War noted, "Without exception every person...wanted a GPS in both the Abrams and Bradley." Armor and Infantry Center reports on the Bradley's and Abrams' performance in the Persian Gulf War also recommended installing GFS receivers in both systems.*
The Army, in conjunction with the other services, is developing military specifications and requirements for the next generation of GPS receivers—the Precision Lightweight GPS Receiver (PLGR). ……………………………………….

P.74-If the DSP and communications satellites were applied successfully in tactical operations, by far the most important automated space system employed in Desert Storm was the Navstar Global Positioning System. Like DSP, it too proved vital to military success. Before the Iraqi invasion of Kuwait, the Army had purchased only about 1,000 military GPS receivers (called Small Lightweight GPS Receivers, SLGRs or "sluggers.").
As the Desert Shield deployment continued and the demand for sluggers in the field soared, the GPS Program ***Office made emergency purchases of some 13,000 civilian GPS receivers for use on military vehicles. Moreover, many soldiers, desperate for the navigational advantage that GPS offered, bought their own from civilian electronics stores or received them as gifts rushed from home. The soldiers were able to have them working within a half hour of opening the box.***

Because most of the GPS receivers employed in Desert Storm were civilian models and unable to use encrypted signals, for the greater navigational accuracy the Air Force

and Defense Department chose to leave GPS signals unencrypted and risk Iraqi forces also using the same GPS signals. *That risk was judged acceptable because Coalition forces were lighting a war of movement in unfamiliar territory,* ***while the Iraqis were tied down in fixed positions, and lacked precision guided weapons that could use the GPS data.*** *But the usefulness of the GPS data also was limited to Coalition forces because the complete satellite network had not yet been established in orbit. GPS provided accurate data when four satellites were in view of a receiver* ***but in 1991 there were seven periods each day up to 40 minutes in duration when fewer than four were in view. During these GPS "sad times" as they were called. Coalition forces had to revert to LORAN or dead reckoning.***

GlobalSecurity.Org-1992 ***The Need For Improved Helicopter Navigation Systems***
http://www.globalsecurity.org/military/library/report/1992/DCW.htm

Long Range Navigation (LORAN) systems have also been installed on a limited number of aircraft. This system, which is capable of self-initialization, uses low-frequency (LF) radio signals from a series of master and slave stations (called chains) divided into geographical regions, to triangulate the aircraft's position, often with accuracy within a couple hundred feet.

Fortunately for the U.S., there is a LORAN chain centered in Saudi Arabia, which provided coverage for the Iraq/Kuwait battle areas of Desert Shield/Desert Storm. Unfortunately, with the exception of extensive coverage of the North American continent, global coverage is limited.

Although these two systems appear to provide some of the needed capability, neither system completely fills the requirements.

Hoskinson's Gulf War Photo Gallery ***"First To Defend"***
We practiced three artillery raids, this time at the battalion level. These were full-scale rehearsals. All three were conducted at night, of course. We learned many valuable lessons.

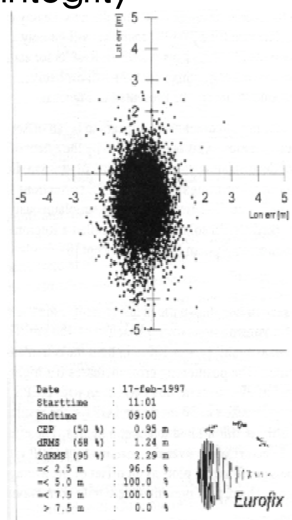
For example, commanders had to keep both a LORAN and a GPS receiver in the lead vehicle for navigation purposes, because the time window from about 2300 hours to 0200 hours (local time) was a bad window for NAVSTAR satellite tracking.

- **1990s: GPS reached IOC/FOC – DoD moves out of Loran**
- **1993: Megapulse (Vicksell) using Loran C pseudoranges improved GPS for Availability**[xix]
- **1994: DOT announces plan to shut Loran down in 2000**
- **1996: Congress begins funding improvements**

- **1998 Locus (Roth) *The Case for Loran*-Improving Availability**

eLORAN stations as Ground Pseudolites effectively significantly increasing the number of GPS SV s for Availability and Integrity

- Use of Loran Stations as GPS Pseudolites The US Loran system could easily be synchronized to GPS UTC, and this simple upgrade would **provide a major performance advantage to combined GPS/Loran receivers. In such receivers, Loran transmitters would essentially act as GPS pseudolites. There are 29 Loran transmitters in the US and Canada, and since 20 of them are dual-rated, there would be 49 present. Given new all-in-view Loran receivers and the plethora of Loran transmitters, the number of available GPS GPS unavailability concerns would virtually disappear over North America**. The Figure of Eurofix corrections from Sylt transmitter. Data recorded at Delft University of Technology
- **Similar conclusions in Europe and the Middle East, but not as many stations!**
- **Reference: *The Case for Loran* by G. Linn Roth Locus Inc, Madison, WI (Google for a copy)**



- **1998: PDD-63 directs DOT to study GPS vulnerabilities**

- **2003: MOA-3 (CG/FAA/DOT):**
  - **—Parties recognize Loran as best theoretical multimodal GPS backup**
  - **—Parties recognize necessity of managing Loran as a national asset**
  - **—Parties will provide recap, modernization & continued operation**
- **2003: Task Force Report released by DOT**
- **2004: Cost Benefit Analysis delivered to DOT – currently under agency review**
- **2004: Technical Feasibility Study released by DOT**
- **2005: No announcement on long-term need but no notice of Loran closure**
- **2005 CDD Analysis of Alternatives had eLoran all Green except Orientation was red**

  Newly discovered world most accurate. quickest acting compass technology
- **2008 DHS Announces eLoran as GPS Civil Backup**
- **2008 DHS Reverses Decision**

- **2008 NAS Enterprise Architecture Board Summary Charts for eLoran Augmentation**

Loran- C vs. *eLoran* Metrics
FAA 2002 *Murder Board* Requirements

	Accuracy	Availability	Integrity	Continuity
Loran-C Definition of Capability* (US FRP)	0.25 nm (463 m)	0.997	10 second alarm/ 25 m error	0.997
FAA NPA (RNP 0.3)** Requirements	0.16 nm (307 m)	0.999 – 0.9999	0.9999999 (1 x 10-7)	0.999 - 0.9999 over 150 sec
US Coast Guard HEA Requirements	0.004 - 0.01 nm (8 – 20 m)	0.997 - 0.999	10 second alarm/ 25 m error (3×10^{-5})	0.9985 – 0.9997 over 3 hours

* Includes Stratum 1 timing and frequency capability
** Non-Precision Approach Required Navigation Performance

Information Presented to IAT: Backup Alternatives to GPS

GPS needs dissimilar, complementary, multi-modal, and independent source of GPtS & PNT

Service	PNT	Multi-Modal	Independent of GPS		
			System	Signal	User
Galileo	✓	✓	✓	×	×
eLoran	✓ (no 3D)	✓	✓	✓	✓
DGPS	×	✓	×	✓	×
SBAS	× ✓	✓	× ✓	×	×
Radar	×	×	✓	✓	✓

eLoran is frequency and signal diverse as well as much more powerful (virtually unjammable)

Enterprise Architecture Board
13 June 2008

Note: Deficiency of 3D in eLoran can be inexpensively accomplished in the hybrid eLoran/GPS receiver by adding an IMU or if magnetic compass and tilt sensor already incorporated, just add an "ADS-B type height sensor" to furnish accurate height to 6 m up to 20k ft. for 3D/6 axis (even underwater). True North is uniquely sensed by eLoran receivers to 1 mr 95% which is insensitive to latitude errors and unlike any other technology, even performs at full accuracy at the North Pole. DoD's best magnetic compass in the Common Vector 21 Laser Range Finder requires field calibration and at best is only ~20 mr 95%. Magnetic nor inertial technology does not work at all at the poles.

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[xviii] *The Case for eLoran*, Research and Radionavigation, General Lighthouse Authority, United Kingdom and Ireland, 8th May 2006

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