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Positioning Systems Used for Canadian Offshore Hydrographic Surveys

by

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Abstract

This report describes the positioning systems that were used to collect bathymetry during hydrographic surveys in Canadian waters. While the emphasis is on electronic positioning systems, some early bathymetry collected prior to World War II was positioned using celestial observations. The characteristics of the positioning systems used during these surveys are described briefly including the types of measurements they provided and the various error sources that contributed to their measurement accuracy. The factors involved in converting these measurements to latitude and longitude are described and final accuracy estimates are given.

Résumé

Ce rapport décrit les systèmes de positionnement qui servaient à recueillir la bathymétrie lors des levés hydrographiques dans les eaux canadiennes. Alors que l'accent est mis sur les systèmes de positionnement électroniques, la bathymétrie recueillie avant la seconde guerre mondiale a été positionnée à partir d'observations célestes. Les caractéristiques des systèmes de positionnement utilisés au cours de ces relevés sont brièvement décrites, y compris les genres des méthodes d'observations des mesures et les différentes sources d'erreurs affectant la précision des observations. Les facteurs contribuant à la conversion de ces mesures en latitude et longitude sont décrits et des estimations de la précision finale sont données.

1 Early Navigation

1.1 Celestial Navigation

Bathymetry off Canada's three coasts has been collected since the first European explorers and fishermen started making regular visits. Prior to the late 18th century, when accurate marine chronometers came into common use at sea, the positional accuracy of the measured depths was several nautical miles (nm) in latitude but many tens of nautical miles in longitude. The uncertainty in longitude determination depended on the accuracy of the dead reckoned (DR) position of the vessel since its last known position, usually several weeks earlier when it left Europe. Latitude was determined from the measurement of the altitude of either the pole star or the sun at meridian passage and the accuracy improved as the almanac data improved and the instrumentation progressed from the back staff and octant to the sextant. The modern sextant can measure to about one minute of arc which is equivalent to about one nautical mile. However, a sextant measurement has many error sources (Bowditch, 1977) ranging from a variety of instrumental errors to personal errors and errors due to atmospheric effects. Some of these errors can be reduced by calibration and error modeling but the bottom line is that the line-of-position (LOP) accuracy due to sextant altitude measurements is typically 2 to 4 nm.

Longitude determination is directly linked to the measurement of time with the error increasing at the rate of 1 nm (at the equator) for every 15 seconds of timing error. Given that survey vessels could have been a few months at sea and unknown clock errors could have been one second per day or more it isn't unreasonable that timing errors could have contributed 2 to 3 nautical miles to the overall uncertainty of a celestial fix. In practice celestial fixes could only be observed at sunrise and sunset when both the stars and the horizon were visible. It was standard practice to observe several stars at different azimuths and altitudes to obtain good angles of cut of the LOPs which tended to cancel out the errors to some extent. Taking all these factors into consideration, celestial fix accuracy prior to radio time signals, was probably about 5 nm improving to perhaps 3 nm when accurate almanacs and radio time signals became available. But that's only half the story because the celestial method only provided two fixes per day at sunrise and sunset. Positions between sights were determined by DR where the positional accuracy could deteriorate considerably with time depending on the sea conditions, the accuracy of the course and speed measurement instrumentation, the helmsman's ability, the ocean currents, etc. However, sun sights during the day helped correct the dead reckoned track. Given all the uncertainty, the final accuracy estimate of a survey based on celestial fixes and DR, even after the introduction of radio time signals, is somewhat subjective but probably about 8 nm 95% of the time. This does not take the weather conditions into account (e.g. cloud cover and rough sea conditions) or the fact that the Grand Banks off the coast of Newfoundland can be shrouded in thick fog for weeks at a time. Celestial navigation began its decline following WW II and today it is not taught at many marine schools.

Celestial positioning was also used to position a number of the Arctic ice islands that collected bathymetry prior to the availability of satellite navigation. Theodolite celestial observations on the relatively stable ice surface gave positions an order of magnitude more accurate than their marine counterparts; about 500 m to 1000 m.

1.2 Horizontal Sextant Fixing

Since the focus of this report is the offshore zone, the use of sextants in the horizontal mode is only mentioned briefly. In this configuration two horizontal angles between two pairs of accurately surveyed shore based beacons are measured – usually the middle beacon is common so that only three shore beacons are needed. The measured angles are set on a 'station pointer' which is used to plot the vessel's position to an accuracy of 10 to 50 m in good geometry with the accuracy decreasing as the geometry degrades and/or the distance from the beacons increases. This technique is typically restricted to 10 to 20 km from shore but, with care, can be extended further. Its primary importance in this report is that it was used to calibrate or initialize the long range offshore radio positioning systems. Many of the soundings collected during the near-shore surveys of Newfoundland and Labrador by Capt. Cook in the 1760s are still on Canadian charts today.

2 Radio Positioning Systems

The development of radio positioning began during WW II and by the early 1950s a number of systems were in common use.

All early radio positioning systems relied on ship and/or shore based transmitters/receivers, the exact configuration depending on the particular system. Radio positioning systems were classified by a number of different characteristics; frequency, type of transmission, range, LOP provided and accuracy as well as other factors such as ease of setup and use, cost, equipment size, etc. In general the lower the frequency, the lower the accuracy, the longer the range, the higher the power needed and the larger the size of the transmitting equipment (and the cost, time and effort to set up).

Except for the satellite systems, the radio positioning systems listed in Appendix A fell into five main frequency bands:

2.1 Line-of-sight Systems

- Extremely High Frequency (EHF) (30 – 300 GHz) – line-of-sight or about 50 km.
    - Motorola Mini-Ranger 3 (MRS 3)
- Super High Frequency (SHF) (3 – 30 GHz) – line-of-sight or about 50 km.
    - Motorola Range Positioning System (R.P.S.)
    - Decca x-band Radar

(Note: EHF and SHF systems were line-of-site systems and were collectively known as microwave systems. They are only mentioned here because they were used to calibrate and/or initialize the longer range MF and LF offshore systems.)

2.2 Offshore Systems

- Medium Frequency (MF) (300 – 3000 kHz) – range to about 150 km.
    - Decca Hi-Fix
    - Decca Mini-Fix
- Low Frequency (LF) (30 – 300 kHz) – range to about 350 to 2000 km.
    - Loran-C
    - Decca Navigator
    - Decca LAMBDA and 2-range Decca

- Very Low Frequency (VLF) (3 – 30 kHz) – range to over 11,000 km.
    - Omega/VLF Communications

(Note: Omega/VLF systems used the Omega navigation system or a combination of Omega signals plus the signals from the dozen or so VLF communications stations around the world. Omega/VLF was only used occasionally during through-the-ice Arctic surveys when no other positioning systems were available. It will be described briefly here.)

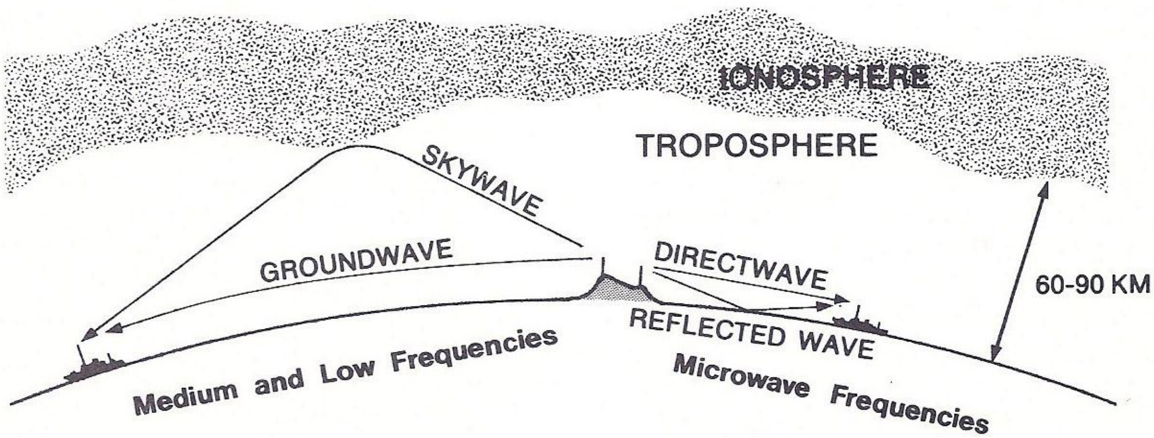


Figure 1 - Radio Wave Propagation
(from Surveying Offshore Canada Lands, 1975)

3 Radio Wave Propagation

Radio wave propagation is a function primarily of frequency but there are many other factors as well. As illustrated in Figure 1, radio waves travel in the troposphere, the zone between the earth and the ionosphere. VLF propagation has several different transmission modes: ground wave, sky wave and wave guided wave. The wave guide effect occurs when a wave passes through a cavity which reflects the wave and confines it to the enclosed space. Near the transmitter, VLF waves propagate as ground waves and sky waves but at long distance VLF waves travel in the troposphere much like wave guided waves. (Bowditch, 1977)

Wave guided signals travel great distances over water due to its low conductivity; over land, and particularly over ice, they attenuate at a greater rate and the ranges are significantly reduced. The earth's waveguide condition is a function of the shape and height of the ionosphere which is in turn a function of the position of the sun and the season of the year. The sun's radiation affects the height and shape of the ionosphere causing *diurnal effect*. During daylight hours the ionization layer drops to about 70 km while at night the layer rises to about 90 km. The result is a diurnal decrease and increase in the measured range to the transmitter. This effect is also seasonal and nonlinear during transition. A long propagation path may be either entirely sunlit (day), entirely dark (night), or experiencing mixed illumination (transition). Propagation tends to be most stable during the day although conditions do vary slowly. At night conditions tend to be constant but less stable than during the day. Transition periods are of intermediate stability and present additional complications in prediction and application.

Propagation correction tables and formulas were needed to correct for these effects. They were based on theoretical models calibrated from worldwide monitor data taken over long periods. A number of permanent monitors were maintained to assess the system accuracy on a long term basis. In most cases the accuracies attained were in the order of 2 to 4 nautical miles (3.7 to 7.4 km). OMEGA system availability was greater than 97% and the system provided independent two or more lines of position (LOP's) position fixes every ten seconds. Omega suffered from the same lane ambiguity problem as Decca (described below) and a wide-lane ambiguity resolution method similar to Decca was also used.

In the LF and MF bands they travel out from the antenna as a wave front with the bottom edge travelling along the earth's surface and the top travelling upward toward the ionosphere. The surface or ground wave is slowed by the atmosphere and the earth's surface effect. The delay due to the atmosphere is called the Primary Phase Lag; it is a linear function of distance and depends primarily on the temperature, pressure and the moisture content of the atmosphere. It is independent of frequency. For MF and LF radio waves there is an additional delay called the Secondary Phase Lag which is a non-linear function of distance and frequency, the conductivity of the earth's surface, the permittivity of the air and earth's surface and the curvature of the wave front. When MF and LF signals travel over land the Secondary Phase Lag is increased by the type of terrain (e.g. rock, wooded, swampy, fresh water, etc.) and the length and location of the land path between the transmitter and the receiver. This additional delay is called the Additional Secondary Factor (ASF). Considerable effort went into studying, testing and modeling these delays during the 1950s, 60s and 70s with the result that quite accurate models were introduced throughout this period.

The usual approach with Decca and Hi-Fix was to set up the transmitters close to the coast thereby eliminating overland phase lag problems and the increased attenuation caused by land path. And, since the maximum useful ranges were 150 to 600 km it was standard procedure to calibrate the systems to find an average propagation velocity that minimized the propagation errors in the survey area. Typical Hi-Fix velocities were in the range 299631 to 299684 km/sec and for Decca the velocity range was between 299572 and 299667 km/sec (Wells, 1970). Loran-C transmitters were positioned to provide the best hyperbolic coverage off the coast which usually meant that there was some land path between the transmitters and receivers. The Loran-C hyperbolic lattices on Canadian Hydrographic Service (CHS) charts incorporated corrections for all three propagation delays mentioned above.

As the waves travel along the earth's surface they are slightly attenuated, MF waves more so than LF waves. Consequently the maximum useful ranges of these systems were 150 km and 2000 km respectively depending on the mode of system operation. The radio waves that travel upward encounter the ionosphere and those arriving at a certain angle are reflected back to earth as sky waves; the remainder travel through or are absorbed by the ionosphere. Sky waves are only slightly attenuated and are often much stronger than the ground wave when they arrive at the receiver, especially at night. However, due to the longer distance they have to travel, sky waves always arrive at the receiver after the ground waves by more than about 30 microseconds, the exact delay depending on the distance between the transmitter and receiver and the height of the reflecting layer of the ionosphere which changes from day to night.

Microwaves travel a direct line-of-sight path to the receiver. However, there may be a ground reflected wave component that sometimes causes interference with the direct wave at the receiver. Because microwave systems were line-of-sight systems they could only be used within about 50 km of the coast. They didn't play a role in offshore positioning except to calibrate the MF and LF systems.

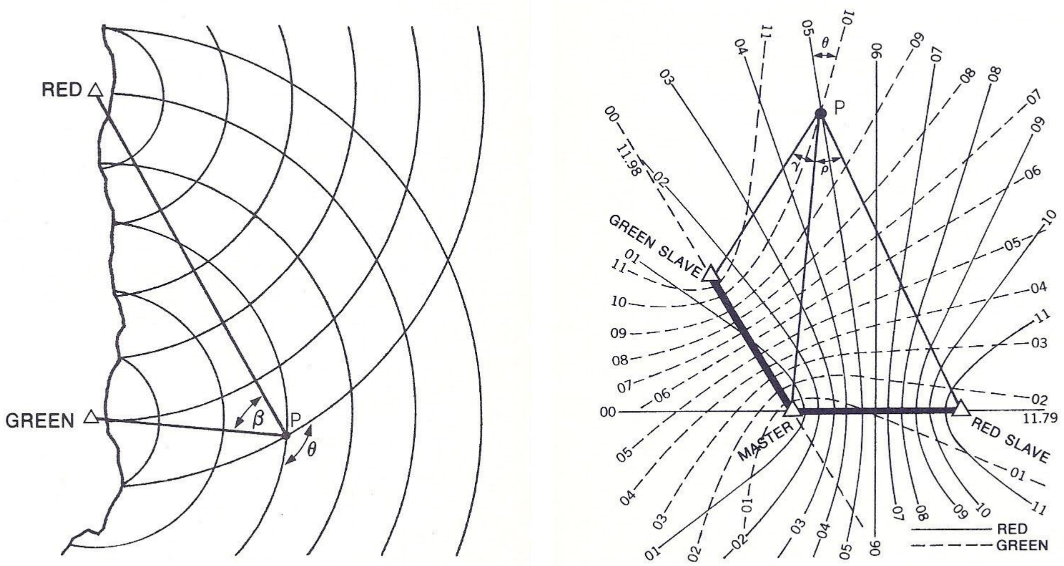
4 Modes of Operation

Radio positioning systems employed two types of measurements: 'phase comparison' by systems that transmitted continuous waves (CW), (e.g. Mini-Fix, Hi-Fix, Decca and Omega/VLF) and 'time difference' measurements by systems that transmitted pulsed signals (e.g. Loran-C, Radar, Motorola R.P.S and M.R.S).

4.1 Pulsed Systems

The simplest mode of operation was a ship based system that transmitted a pulsed signal and measured the two-way travel time of the signal to the shore (Radar) or transponder (R.P.S. and M.R. S.) and back to the ship. The distance was calculated by $Dist = v \times t/2$ where v was an appropriate radio wave propagation velocity and t was the two-way travel time. The vessel was located on a range circle with radius $Dist$ and centre at the shore point or transponder. A second measurement to another shore point or transponder gave a second circle with the vessel located at the intersection of the two circles as illustrated in Figure 2-A. Radar positioning accuracy deteriorated more quickly than R.P.S. or M.R.S because of the uncertainty about exactly which land feature was reflecting the signal, unless transponders or passive beacons were being used. Radar positioning by range and gyro bearing was also used but was not as accurate as the range-range mode and was therefore limited to very close in-shore work, if used at all. Ships radars still operate like this today.

A variation of the pulsed mode of operation employed by the Loran-C system was to locate three (or often more) stations on shore, called a Chain, and have the centre station (or Master) transmit at a set interval called the Group Repetition Interval (GRI). When the Master signal arrived at the other stations (called Slaves or Secondaries) they waited a preset unique time interval or Coding Delay and then transmitted as well. The path between the Master and the Slaves was called the Baseline. The Coding Delay spread the transmissions out in time so that the receiver could identify the different slave signals. Onboard the vessel the receiver measured the time differences (TDs) between the arrival times of the Master and Slave signals. Lines of constant TD, when plotted on a chart or plotting sheet described hyperbolas on the earth's surface with the Master and Slave at the foci. The vessel's position was found at the intersection of the two hyperbolas as illustrated in Figure 2-B. For obvious reasons these systems were called 'hyperbolic systems'. The Loran-C receiver used digital signal processing to automatically analyze the shape of the pulse envelope, locate the third cycle of the master and slave pulses (i.e. the 30 microsecond points) and make the TD measurement between the zero crossings following the third cycles. This had two very significant advantages. First of all the sky wave signals always arrived after the third cycle so the measurement point was uncontaminated by sky wave. Since the measurement was made with respect to the carrier signal and not the pulse envelope, it was equivalent in accuracy to the phase measurement mode described in the next paragraph but without the sky-wave problems. Monitor receivers in the coverage area tracked the pattern drift due to oscillator drift and relayed corrections back to the chain controller.



A Intersecting Position Lines from a Range-Range Pair

B Intersecting Position Lines for a Hyperbolic Triad

Figure 2 – Range circles and hyperbolas were the two main radio positioning system configurations. (from Surveying Offshore Canada Lands, 1075)

4.2 Continuous Wave (CW) systems

CW systems like Omega/VLF, Decca and Hi-fix operated by measuring the phase difference between two signals. In the 'range-range' configuration a shipboard transmitter (Decca and Hi-fix only) radiated a CW signal. When the signal was received at a shore station it was retransmitted with the same phase; the shore station was 'slaved' via an electronic phase-locked-loop to the incoming master signal. When the slave signal arrived back at the ship the receiver measured the phase of the incoming signal relative to the phase of the transmitted signal giving a distance between the master and slave of $Dist = n \times \lambda/2 + x \times \lambda/2$ where n was the number of half wavelengths $\lambda/2$ and x was the phase difference converted from 0 to 360 degrees to the range 0 to 1. The distance $\lambda/2$ was called a 'lane' and it was standard terminology to use lanes instead of half wavelengths. The wavelength λ was calculated from the frequency and an appropriate value for radio wave propagation depending on the various factors described earlier. n was determined at the start of the survey by checking in at a known location (i.e. pre-established buoy, R.P.S., horizontal sextant measurements, radar, etc.) where the exact number of lanes to the slave transmitter was known. The ship was located on a range circle with radius $Dist$ and centre at the slave transmitter. A measurement to a second slave provided another range circle and the ship's position was located at the intersection of the two circles as illustrated in Figure 2-A. In the above description it was assumed that the master and slaves transmitted on the same frequency, which was the case for Mini-Fix and Hi-Fix. They used time sharing to separate the master and slave signals. Decca used different frequencies to distinguish the master and slave signals and the phase measurement was made at a comparison frequency, not the transmission frequency. The propagation characteristics and phase lag corrections were therefore determined by the transmitted frequencies but the pattern geometry (lane width) was determined by the comparison frequency.

The range-range mode was limited to a single user and, because of the smaller antenna onboard the ship, its power output and range were limited. Also, there was no way to monitor the signals for oscillator drift because the ship (i.e. master transmitter) was always moving. One of the most serious problems for Decca and Hi-Fix was sky wave interference since, in a CW signal, it is not possible to separate the sky wave and the ground wave as was the case with Loran-C. Not only did this introduce errors into the ground wave phase measurement, but also, great care was needed to make sure that the sky wave didn't cause the Decca or Hi-Fix to 'skip a lane', especially at sunrise and sunset when the ionospheric layers were changing. When a lane skip was suspected it was sometimes unclear how many or in which direction so that the only solution was to return to a known location, typically a buoy anchored to the ocean floor as a reference, to reset the 'lane count'. This was a very time consuming and costly operation because usually the problem occurred far offshore at the limit of ground wave reception. In theory Decca LAMBDA (Low AMbiguity DeccA) was supposed to help resolve this problem by temporarily transmitting at lower frequencies with wider lanes from which course readings could be obtained that were accurate enough to reset the lane count. But this was not always effective in practice. Omega used a similar approach.

Omega, Decca and Hi-Fix could also be operated in the hyperbolic mode similar to the hyperbolic Loran-C described above. This involved placing the master station ashore, usually between the two slaves, with a slightly concave orientation toward the survey area. With this set-up the ship only carried a receiver and measured the phase difference between the master and each of the slave transmissions. The readings were converted to distance differences as described above and the resulting LOPs described hyperbolas on the earth's surface as illustrated in Figure 2-B. This configuration allowed the master to have a much larger antenna and output power, and therefore longer range. The transmissions could be monitored and corrected for oscillator or 'pattern' drift. There could also be an unlimited number of users but the sky wave problem remained.

The Decca company operated many 'Decca Navigator chains' for public use around the world between the mid1950s and late 1980s. Decca Navigator chains differed from Decca survey chains by their transmission frequencies and also by the way their comparison frequencies were derived. Decca Navigator was also called 6f Decca while survey Decca was called 12f Decca as will be made clear in the following example.

Assuming a base frequency of 14 kHz, a Decca Navigator, or 6f Decca Chain used the following frequencies:

	Transmitted Frequency	Comparison Frequency
Master	6f = 84 kHz	
Red Slave	8f = 112 kHz	24f = 336 kHz
Green Slave	9f = 126 kHz	18f = 252 kHz
Purple Slave	5f = 70 kHz	30f = 420 kHz

For a 12f or Survey Decca Chain:

	Transmitted Frequency	Comparison Frequency
Master	12f = 168 kHz	
Red Slave	8f = 112 kHz	24f = 336 kHz
Green Slave	9f = 126 kHz	36f = 504 kHz

A third mode of operation was the 'rho-rho' mode that used atomic clocks/atomic frequency standards at the transmitter to control the transmission times and phases. At the receiver a second atomic clock/frequency standard predicted the transmission times and phases and was used to measure the radio wave travel time or phase change at the receiver.

Rho-rho Decca operation was similar to its range-range sibling except that only the shore station transmitted. Onboard the ship the receiver, with input from an atomic frequency standard, measured the phase change of the incoming signal caused by the movement of the vessel. The distance to the transmitter was found from $Dist = n \times \lambda + x \times \lambda$ where the parameters in the equation are the same as for the range-range mode. However, note that the 'lane width' is now a full wavelength λ. n was found the same way as for the range-range mode. An additional problem with rho-rho Decca was monitoring and correcting for the relative drift between the two atomic clocks/frequency standards. This was accomplished by recording the Decca range at a fixed location for a day or two and noting its rate of change.

Omega operated primarily as a hyperbolic navigation system as just described for Decca except that the coverage was global in extent. With the introduction of atomic clocks at all the Omega and VLF stations, receivers, also equipped with atomic clocks, were able to operate in rho-rho mode and ranges could simultaneously be measured to all the Omega and VLF stations plotted in Figure 3 with strong enough signals. This improved both the coverage and accuracy of Omega/VLF navigation.

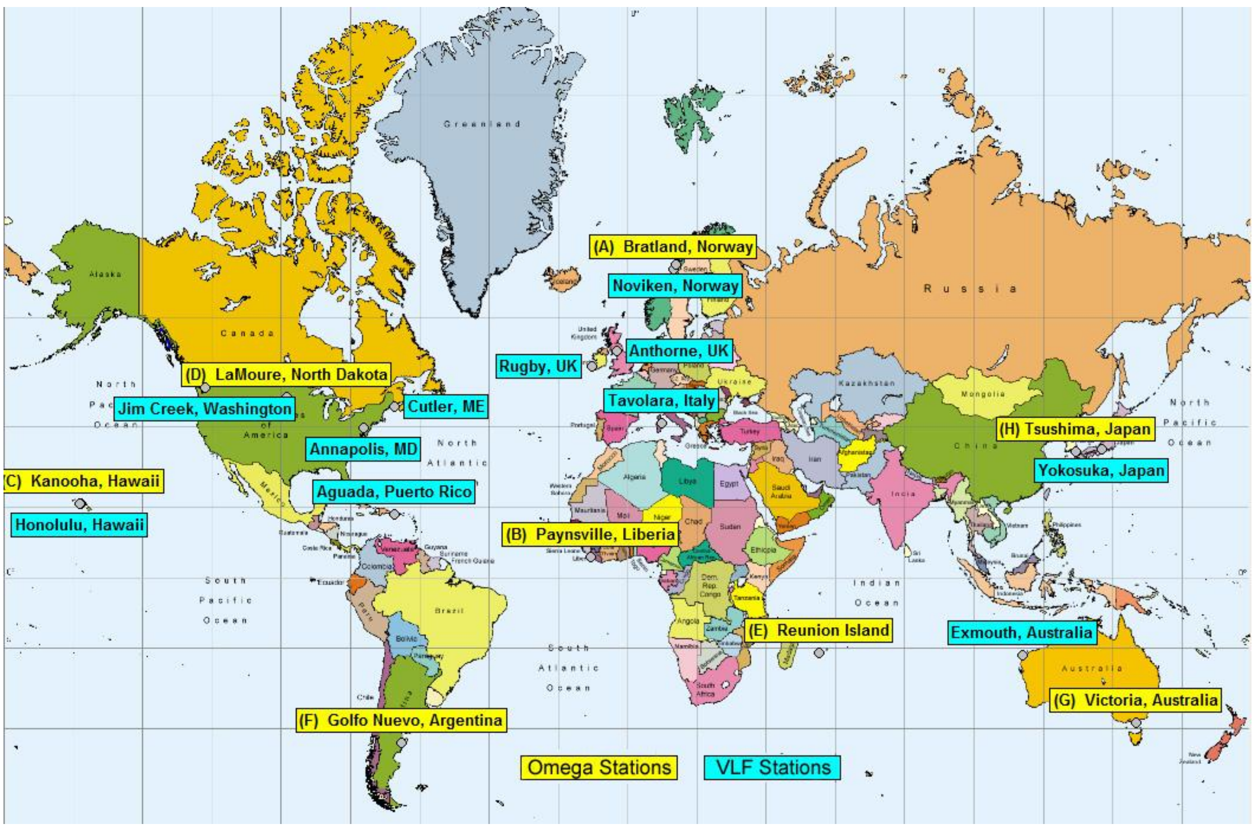


Figure 3 - Omega/VLS Transmitter locations

Rho-rho Loran-C was made possible with the installation of atomic clocks at all Loran-C transmitters in the early 1970s (Grant, 1973). Before rho-rho operation could begin the receiver atomic clock was synchronized with the chain GRI by calculating the travel time to at least one of the chain transmitters, taking into account phase lag and ASF. Because all Loran-C transmitters in a chain were accurately synchronized via monitors throughout the coverage area, once the rho-rho receiver was synchronized to one transmitter the synchronization could be extended to all stations in the chain. To compute a position, the travel times were converted to distances using a propagation velocity corrected for phase lag and ASF and, as above, two such ranges are sufficient to define the receiver's position. This mode of operation had the advantage over hyperbolic Loran-C that it gave strong position line geometry over a larger area using only two transmitters compared with the three transmitters needed for a hyperbolic fix. Also, in much of the coverage area, three or more ranges could be observed giving redundant information that improved the quality of the positioning. In addition to the phase lag corrections, an additional correction was needed with rho-rho operation to account for the relative drift between the chain and receiver atomic clocks amounting to a few tens of metres per day.

5 Accuracy and Coverage

In practice it was important to know a system's coverage, or where it could provide adequate accuracy and signal strength. There are three types of accuracy (Bowditch, 1995): 'Predictable accuracy' (also known as Geographic or Absolute accuracy) is the positioning accuracy with respect to geographical coordinates; 'repeatable accuracy' is a measure of the system's ability to return to a position whose coordinates were measured previously with the same system; and 'relative accuracy' is a measure of the system's ability to determine a position relative to another user of the same navigation system, at the same time. The main factors that separated Geographic accuracy from the other two were time dependent errors (i.e. atomic clock or oscillator drifts) and location dependent errors (i.e. propagation errors). Considerable effort was devoted to modeling and eliminating both these error sources, but undoubtedly some errors remained with the result that geographic accuracy was always worse than repeatable and relative accuracies. It was generally assumed that the remaining errors of all types were random and normally distributed.

Geographic accuracy depended on three factors: instrumental accuracy, noise (i.e. radio noise plus residual time and location dependent modeling errors) and pattern geometry. Furthermore, pattern geometry contributed to the overall accuracy based on the angle of cut of the LOPs and, for the hyperbolic systems, by the fanning out of the LOPs – often referred to as 'lane expansion'. The expression 'LOP accuracy' will include the instrumental accuracy, noise and lane expansion contributions and 'geographic accuracy' will combine the LOP accuracy with the angles of cut of the LOPs.

5.1 Line-Of-Position (LOP) Accuracy

For LF and MF systems it was technically difficult to measure phase to better than about 1/100th of a wavelength. The wavelength of Loran-C, at 100 kHz, was 3 km. In the hyperbolic mode the comparison wavelength was half this or 1.5 km, giving a theoretical instrumental accuracy of about 15 m (one standard deviation). But this was only along the baselines between the master and slaves. Hyperbolic lane expansion increased the comparison wavelength to a factor of about 4 depending on what part of the coverage area the vessel was in and range (distance) from the baselines. Due to land along the propagation paths, the final LOP accuracy for a hyperbolic pattern was about 10 times the instrumental accuracy along the baseline. The final hyperbolic Loran-C LOP accuracy ranged from about 30 m in prime coverage to about 150 m at the outer limits of coverage.

The comparison wavelengths of hyperbolic 12f Decca were 450 m (Red) and 298 m (Green) giving LOP accuracies of between 14 to 45 m (Red) and 9 to 30 m (Green) in the coverage area. The Decca Navigator lanes were approximately 450 m (Red), 590 m (Green) and 350 m (Purple) giving instrumental accuracies along the baselines of about 4.5 m, 5.9 m and 3.5 m or, using the same lane expansion factors as for Loran-C, 14 to 45 m, 18 to 60 m and 10 to 35 m respectively in the coverage area. Mini-Fix and Hi-Fix, at about 2 MHz, had a theoretical instrumental accuracy of less than a metre or about 10 m in the coverage area.

Range-range system measurement accuracies (i.e. Decca) were about the same but, since it didn't have the hyperbolic lane expansion problem, the LOP accuracy only degraded slightly with range due to radio noise, modeling errors, etc. Once the effective propagation velocity was known, Decca range LOP accuracies of 50 m at 500 km were typical (Wells, 1970). Rho-rho Decca LOP accuracy was worse than range-range Decca by a factor of two because the lane width was a full wavelength at the comparison frequency while range-range Decca lane width was λ/2. Rho-rho Loran-C theoretical instrumental accuracy was 30 m and the LOP accuracy deteriorated with range. Grant (1973) analyzed the various contributions to the accuracy of a rho-rho Loran-C range measurement and found that under good conditions (i.e. strong signal less than 1000 km from the transmitter, no land path, only 5 days of relative atomic clock drift, good initial synchronization, etc.) the ranging accuracy was 135 m and that this deteriorated to 185 m under poor conditions such as at the maximum range of about 2000 km and with land along the propagation path. When Transit Satellite fixes were used to monitor and correct the relative atomic clock drift and adjust the over land phase lag corrections these numbers dropped to 90 m and 135 m respectively, independent of the length of time at sea (i.e. atomic clock drift), all figures at the one standard deviation level.

5.2 Geographic Accuracy

Given estimates of the LOP accuracy it was necessary to look at the angles of cut of the LOPs to determine the Geographic Accuracy. A simple approach that was in common use for many years was the 'diamond of error'. This involved plotting the LOPs at their angle of cut at the fix location and then plotting the LOP accuracy limits around them as depicted in Figure 3. This quick and intuitive approach was very useful for determining the maximum and minimum error directions. In Figure 3 the same accuracy limits are shown for each LOP. This was seldom the case; it was normal to see quite different accuracy limits on each of the two LOPs depending on the vessel's location in the coverage area. This approach was also consistent with the manual fix plotting technique used until about the mid1970s. An extension to this approach was to plot accuracy contours of equal value of the long axis of the error diamond or error ellipse to show regions of good and poor accuracy. Figure 4 is an example of these types of contours.

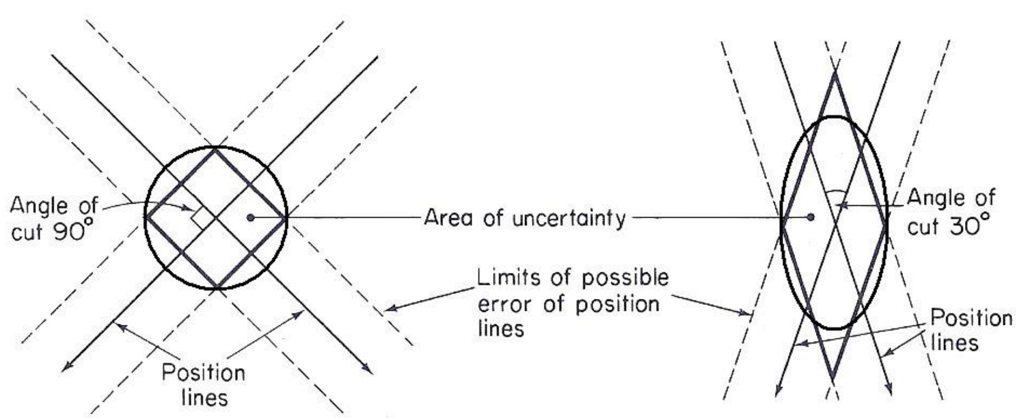


Figure 4 – The effect of LOP accuracy and angle of cut on fix accuracy.
(from Ingham (1975) with additions)

The diamond-of-error approach couldn't be used with more than two LOPs and it was cumbersome when different combinations of LOPs were used (e.g. rho-rho Decca and hyperbolic Loran-C), nor was it statistically rigorous. The answer was the 'standard error ellipse' that used the standard deviations in the maximum and minimum directions as the semi-major and semi-minor axes. The standard error ellipse described an area that included the true position with a 39% probability. To obtain the 95% probability region the axes were multiplied by 2.45. The standard error ellipse parameters were easily computed as part of the least squares fix calculation routines of digital positioning systems. These digital systems could also easily accommodate multiple LOPs, different LOP types, etc.

It is not possible to derive simple equations to obtain accurate geographic accuracy figures given the LOP accuracies and angles of cut and the distances to the transmitters. However, in some cases it is possible to come up with reasonable approximations. For ranging systems like Decca LAMBDA and rho-rho Loran-C a fair estimate of the 95% probability error ellipse semi-major axis can be found using the equation $a = 2.45 \operatorname{cosec} \beta \sqrt{(\sigma_1^2 + \sigma_2^2)}$ where σ_1 and σ_2 are the standard deviations of the two ranges and β is their angle of intersection (Surveying Offshore Canada Lands, 1975). For example, for rho-rho Loran-C ranges at the tail of the Grant Banks using Cape Race, NL with σ_1 =50 m and Caribou (Presque Isle), ME with σ_2 = 90 m and an angle of cut of 50°, the semi-major axis of the 95% probability error ellipse is about 330 m. The problem is more difficult for hyperbolic systems but if the LOP accuracy, adjusted for lane expansion as was done above is used, the above equation gives reasonable results. For example, using the maximum LOP accuracies for 12f Decca derived above (i.e. 45 and 30 m) and an angle of cut of 45°, a = 187 m.

The following figures show the coverage diagrams of the various systems that have been discussed.

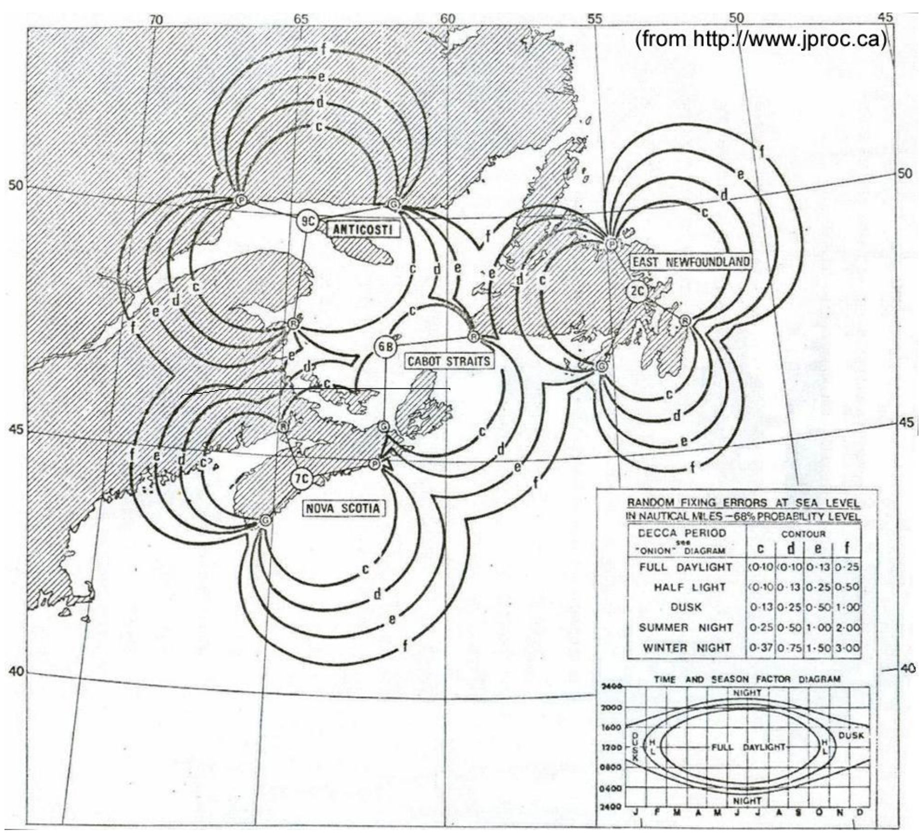


Figure 5 - Eastern Canada Decca Navigator Coverage 1964

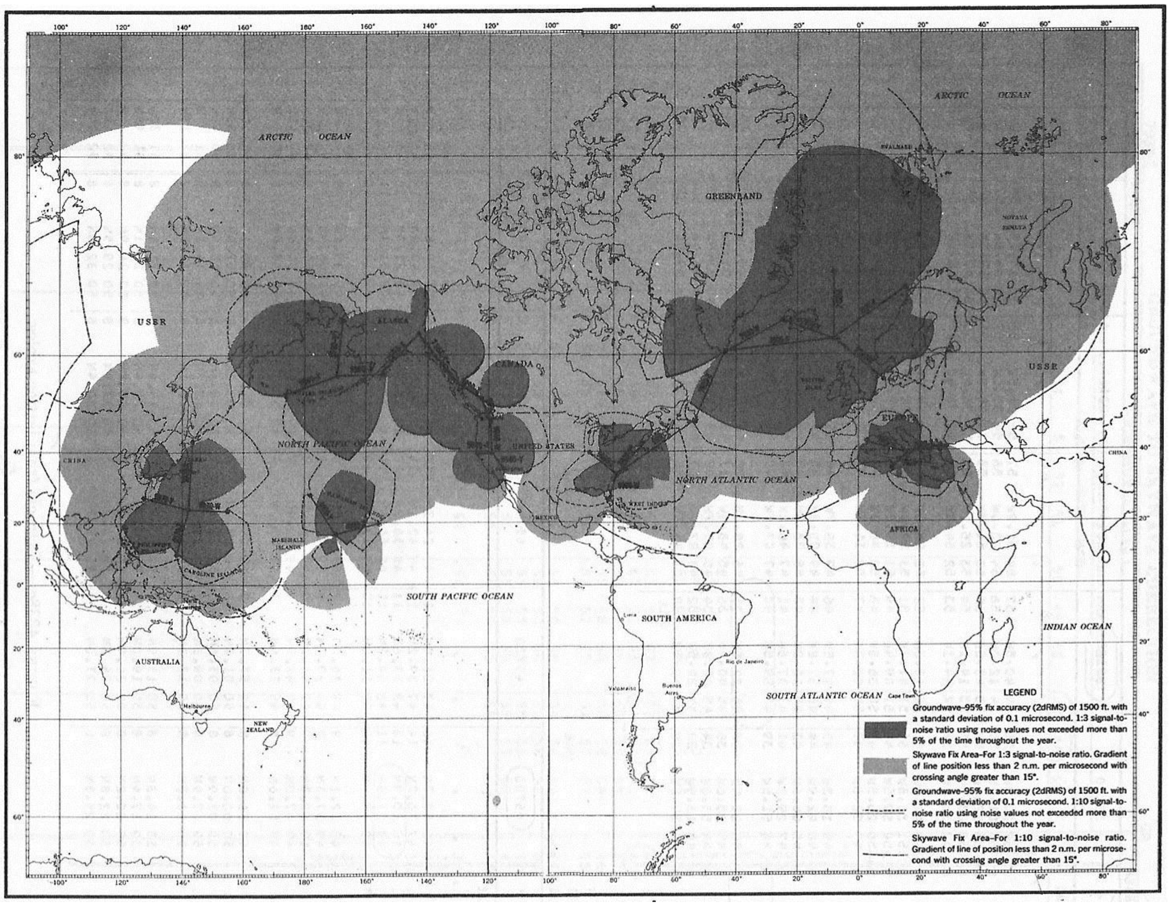


Figure 6 – Hyperbolic Loran-C Coverage Diagram (from Bowditch, Vol. 1, 1977)

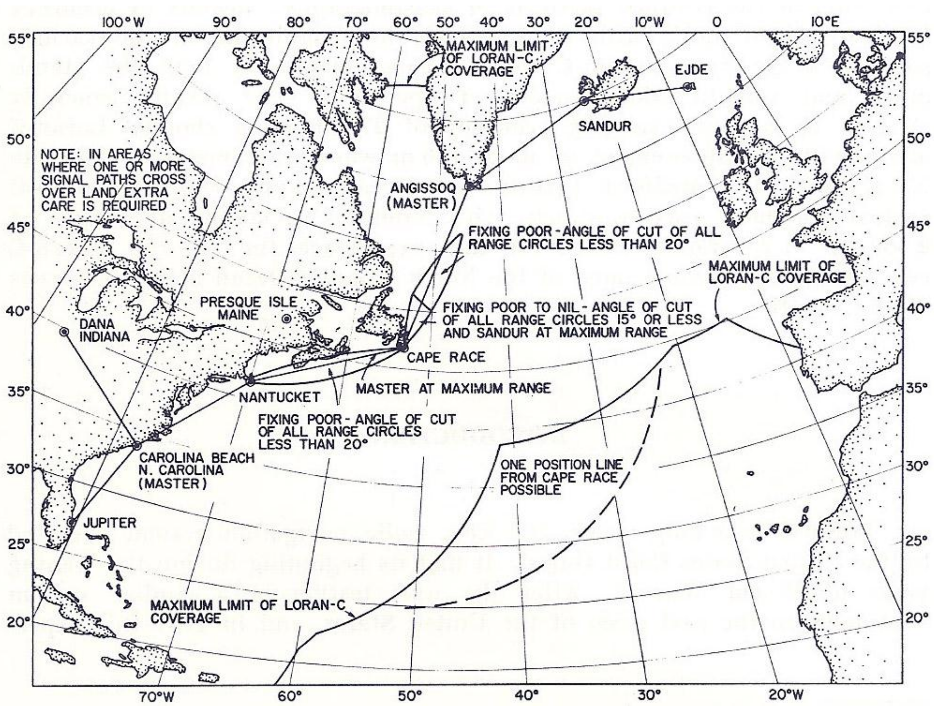


Figure 7 – Rho-rho Loran-C Coverage, North Atlantic Ocean 1973 (from Grant, 1973)

6 Satellite Positioning

6.1 Navy Navigation Satellite System / Transit

The first generation of satellite positioning systems was the U.S. Navy Navigation Satellite System (NNSS) or Transit. Development took place between 1958 and 1963 at the Applied Physics Laboratory of Johns Hopkins University and the first civilian receivers were generally available in mid1967. The system used near polar orbiting satellites (4 in 1969) at altitudes of about 1075 km, circling the earth every 107 minutes. At 45° north latitude there was a pass about every hour but, since only satellites with maximum elevations between about 15° and 75° were usable, the time interval between usable passes was more like 1½ hours. At the equator the interval increased to 2½ hours while at 70° the interval was more like 30 minutes. Also, the passes sometimes tended to be like city busses, several in quick succession followed by long gaps. The satellite signals also could interfere with each other so that sometimes neither of two nearly simultaneous good passes could be used.

The Transit/NNSS operated by observing the Doppler shift of the satellite signals over a series of two minute periods. Each observation generated a hyperboloid in space and the intersection of two hyperboloids and the surface of the earth determined the receiver's position. However, the satellite and receiver oscillators drifted relative to each other at an unknown rate so that another two minute observation was needed to solve for this offset. Acceptable satellite passes lasted 10 to 18 minutes giving 5 to 9 two-minute Doppler counts or observations. The satellite ephemeris data was superimposed on the satellite signal and was decoded by the receiver and used to compute the satellite positions in space.

In general high elevation passes gave good latitude determinations and low passes gave good longitudes. The satellite signals were refracted as they passed through the troposphere, but since refraction was a function of the signal frequency the errors were minimized by the use of two frequencies of 150 and 400 MHz. The accuracy of individual Transit/NNSS fixes from a stationary receiver were about 100 m. By averaging over a period of time, accuracies better than 10 m were possible. The accuracy of averaged distance measurements between two receivers using the same satellite signals was often better than 1 m. Also, if one of the receivers was located at a known point, it was possible to measure the offset of a fix from the known position and use this offset to correct the position of the other receiver. This 'differential' mode of operation achieved accuracies better than one meter as well. However, since Doppler measurements are a measure of relative velocity, for offshore applications it was necessary to know the vessel's velocity very accurately during the satellite pass. Using Stansell's (1969) rule of thumb that the accuracy of a Transit fix degraded 0.25 nm for every knot of velocity error, Grant (1973) estimated that Transit fixes accurate to about 180 m (one standard deviation) were possible using Loran-C velocities. Transit/NNSS was shut down in 1996, replaced by GPS.

6.2 Global Positioning System (GPS)

The second generation satellite positioning system is the Global Positioning System (GPS). GPS design started in 1973 and the first satellites were launched in 1978. Over the following 16 years first the Block I and then the Block II and Block IIA 'operational' satellites were placed in six equally spaced orbital planes inclined at an angle of 55° to the equator. The satellites orbit at an altitude of 20,200 km above the earth giving an orbital period of 11 hr. 58 min. They transmit on two L-band frequencies of L1 (1575.42 MHz) and L2 (1227.60 MHz). The system was approved for civilian use in 1993 and was declared fully operational in 1995; Transit/NNSS was shut down the following year. GPS was fully operational and available for civilian use in 1995 and GPS receivers were readily available at decreasingly smaller sizes and cheaper prices.

Unfortunately, the accuracy was limited by deliberate degradation of the satellite ephemeris data and dithering of the signal timing to 100 m; this deliberate degradation was called Selective Availability (SA). However, innovative civilian differential GPS (DGPS) developments during the late 1990s made SA less and less relevant and it was recognized that considerable economic benefits would result from its removal; it was finally turned off in 2000. This immediately improved the accuracy to about 10 m. DGPS techniques had progressed to the point where accuracies at the cm level were being achieved routinely with the accuracy degrading with distance from the differential monitor. A wide area satellite based differential correction system was being developed and deployed during this period, called the Wide Area Augmentation System (WAAS); it became available in 2003. WAAS uses a network of ground-based reference stations, in North America and Hawaii, to measure small variations in the GPS satellites' signals. These variations are processed into corrections that are sent via special geostationary satellites back to earth where WAAS-enabled GPS receivers use the corrections while computing their positions to achieve accuracies at the 3 m level.

7 The Bedford Institute of Oceanography Integrated Navigation System (BIONAV)

Around the mid1970s it was recognized that improved positioning accuracy and reliability was potentially possible by combining the systems in Figure 1 in a computer based system. The development of BIONAV began in March, 1977 and it was first used operationally in late 1978. The symbiotic relationships among the basic components are shown in Figure 7. The improvement in positioning and velocity accuracy was achieved by using the strengths of one system to compensate for weaknesses of the other systems as follows:

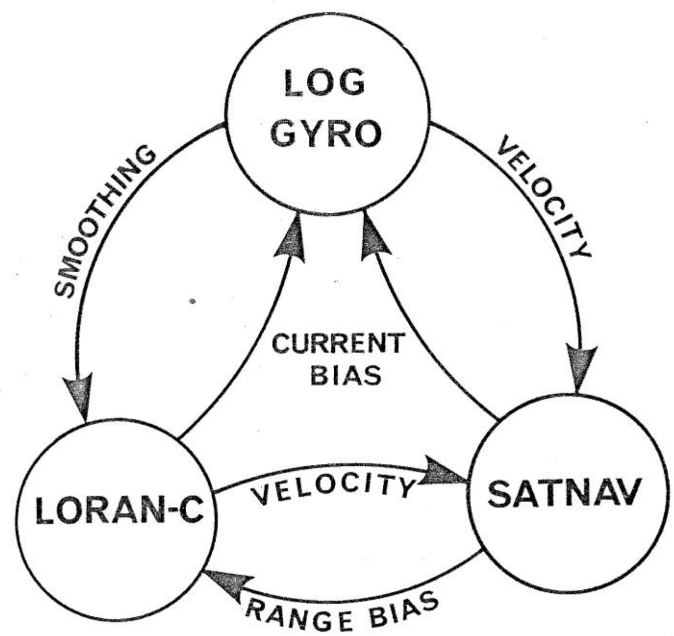


Figure 8 – Schematic Representation of the Basic BIONAV System

a) the Transit fix accuracy was improved by inputting accurate, smooth, real-time water based ship's course and speed from log and gyro;
b) which, in turn, were corrected for instrumental biases and ocean currents by comparison with the noisier but earth based rho-rho Loran-C velocities,
c) and the Loran-C atomic clock drift and phase lag corrections were improved by comparing the observed ranges with ranges computed from the increased number of more accurate Transit fixes.

The three main contributions of BIONAV were (a) improved positioning and velocity accuracy, (b) automation of the tedious, manual, error prone correction process for rho-rho Loran-C atomic clock drift and phase lags and re-computations of Transit fixes and (c) the creation of a platform and structure for incorporating and testing new navigation inputs and providing new unique navigation related outputs (e.g. Eötvös corrections, creation of near real-time ocean current vector fields, etc.). During the decade and a half that BIONAV was operational, four systems were constructed, one on the Pacific coast and three on the Atlantic coast and it was even used during Project LOREX'79 at the North Pole (Weber, 1979). Over the years numerous devices were interfaced to BIONAV: Decca, Hi-Fix, Mini-ranger, Omega, propeller rpm, rudder angle and GPS. BIONAV was finally replaced by GPS in the late 1990s.

8 Geodetic Datums and Related Considerations

Horizontal geodetic datums which incorporate the size, shape, orientation and placement of a reference ellipsoid with respect to the physical earth were originally established by observations only on the surface of the earth. Such a datum was the North American Datum 1927 (NAD27). All horizontal control on the North American continent was referenced to this datum and, by extension, all bathymetry collected using positioning systems tied to this datum was referenced to this geodetic datum. As satellites were launched it was noticed that they responded to the gravity fields of the earth as a whole and this led to the definition of a number of progressively more accurate geocentric geodetic datums, the most relevant one for this discussion at the moment being the World Geodetic System 1984 (WGS84), which for practical purposes, is equivalent to the North American Datum 1983 (NAD83). The difference between the NAD27 and NAD83 coordinates of a point can be as much as several hundreds of metres in some areas although the transformations between these datums have improved to the point where the errors are now less than 10 metres.

A more important consideration from the point of view of combining bathymetry from different surveys from different time epochs is the fact that many of the early surveys were not tied to any geodetic datum. Differences between recent surveyed positions and early surveys of a few kilometers were not uncommon. Indeed, as recently as the 1980s in the Canadian Arctic it was not unusual to have a vessel's track pass over a charted island that was clearly visible a few nm away. The development of techniques of map matching shorelines from the early surveys with shorelines from modern surveys and satellite and aerial photographs has been very productive in recent years in incorporating this early data into modern data sets (Regular, D. et. al. 2003).

9 Conclusions

The period from about 1960, when Loran-C and Transit were coming on stream, until 2000 when GPS had become fully operational and SA was removed, was a very dynamic period in offshore positioning. At the start of this period Decca was the primary offshore positioning system but was suffering from sky wave interference problems with the CW signal at the outer limits of the Grand Banks. Loran-C receivers were purchased initially to help check and re-initialize the Decca lane count. However, with the introduction of rho-rho Loran-C and its marriage with Transit/NNSS to monitor and correct for the atomic clock drift, phase lag and ASF, it was found that it was providing similar accuracies to Decca over much larger coverage areas at a fraction of the cost and with considerably less effort than Decca. The last Decca controlled offshore survey was conducted about 1975. Over the next decade the rho-rho Loran-C/Transit combination was further developed within BIONAV by adding inputs from the ship's log and gyro to give more accurate velocities during the satellite passes, thereby giving more accurate satellite fixes which, in turn, gave more accurate values for the rho-rho Loran-C atomic clock and phase lag corrections. BIONAV was the primary offshore survey positioning system for the area of Canada's Atlantic offshore from about 50° north to Davis Strait, between Greenland and Baffin Island, at 67° north. During this period GPS signals were available for short periods from the limited number of satellites in orbit. BIONAV was modified to include them as well. As the surveys moved northward the signal from Cape Race, NL became weaker and finally private seasonal Loran-C transmitters were established in northern Labrador and Baffin Island. GPS continued to improve and in the mid to late 1990s BIONAV was eventually replaced by GPS.

Positioning System Characteristics

System	Frequency	Approx. LOP Accuracy (m)	Approx. Positioning Accuracy (m)***	Approx. Maximum Range**	Line-of-Position*	Signal Type
Motorola RPS	9,000 MHz	2	3 - 15	LOS	R	Pulse
Decca Radar	8,000 - 12,000 MHz	20 - 100	70 - 700	LOS	R	Pulse
Motorola Mini-Ranger 3	5,400 - 5,900 MHz	2	3 - 15	LOS	R	Pulse
Decca Hi-Fix & Mini-Fix	1,700 - 2,000 kHz	2 - 10	7 - 70	150 km	R, H	CW
Decca Navigator	70 - 130 kHz	15 - 100	75 - 10,000	550 km	H	CW
Decca Lambda	100 - 200 kHz	10 - 45	35 - 325	600 km	H, R, O	CW
Loran-C	100 kHz	30 - 200	100 - 700	2000 km	H, O	Pulse/CW
Omega/VLF	10 – 17 kHz	2,000	3,000 – 8,000	World Wide - continuous	H, O	CW
Sextant - Navigational		5,000	5,000 - 10,000	World Wide - Intermittent		
Sextant - Horizontal		5 - 10	8 – 100	LOS		
Transit/NNSS	150/400 MHz		75 - 500	World Wide - Intermittent		
GPS	1,575.42 / 1,227.60 MHz		3 - 10	World Wide - Continuous		
DGPS	1,575.42 / 1,227.60 MHz		0.03 - 3	Variable		

*R = Range-Range, H = Hyperbolic, O = Rho-rho
LOS = Line-of-sight * 95% probability

References/Bibliography

Admiralty Manual of Hydrographic Surveying, Vol. 1, 1965. Hydrographic Department, Ministry of Defense, Taunton, United Kingdom.

Admiralty Manual of Navigation, Vol. 3, 1955. Hydrographic Department, Ministry of Defense, Taunton, United Kingdom.

Bigelow, H.W., 1965, "Electronic Surveying: Accuracy of Electronic Positioning Systems", Journal of Surveying, Mapping Division Proc. Am. Soc. Civil Engineers, Oct. 1963. (Reprinted: Supplement to the International Hydrographic Review, Vol. 6, 1965 pp77-112, International Hydrographic Bureau, Monaco)

Bowditch, N., 1995 & 1977, "The American Practical Navigator", U.S. Defense Mapping Agency, Maryland, U.S.A.

Cook, P.J. and C.M. Carleton (editors), 2000, "Continental Shelf Limits – The Scientific and Legal Interface", Oxford University Press, Oxford.

Eaton, R.M., 1968, "Sounding Accuracy", Bedford Institute of Oceanography Internal Note 1968-18-I, Bedford Institute of Oceanography, Dartmouth, NS, Canada.

Grant, S.T., 1973. Rho-rho Loran-C Combined with Satellite Navigation for Offshore Surveys. International Hydrographic Review, Vol. L, No. 2, July 1973, International Hydrographic Bureau, Monaco.

Ingham, A.E., 1975, "Sea Surveying", John Wiley and Sons, Toronto.

Laurila, S., 1976, "Electronic Surveying and Navigation", John Wiley and Sons, Toronto.

Regular, D. , C. Zeller, S. Grant and N. Stuifbergen, 2003 "The On Datum Project", Proceedings of the US Hydrographic Conference, Biloxi, MS.

Surveys and Mapping Branch, Department of Energy, Mines and Resources, 1975, "Surveying Offshore Canada Lands for Mineral Resources Development", October 1975.

Weber, J.R. 1979, "The Lomonosov Ridge Experiment: LOREX 79", EOS Transactions of the American Geophysical Union, 60: 715-720.

Wells, D.E., 1970, "Navigation Lecture Notes", Technical Report, Canadian Hydrographic Service, February 1970, Canadian Hydrographic Service, Bedford Institute of Oceanography, Dartmouth, NS, Canada.

Wells, D.E., S.T. Grant and D. McKeown, 1980, "Accuracy of the Bedford Institute of Navigation Integrated Navigation System (BIONAV)", Proceedings, 19th Canadian Hydrographic Conference, Halifax, NS, Canada.