TECHNICAL DEVELOPMENTS IN DEPTH MEASUREMENT TECHNIQUES AND POSITION DETERMINATION FROM 1960 TO 1980

By Dave Wells and Steve Grant

EXECUTIVE SUMMARY

In this paper we describe the evolution during these two decades from simple single-beam echosounders using horizontal sextant fixing (near shore), and celestial sextant positioning interpolated by dead reckoning (offshore) to

(a) (For depth measurement techniques) sidescan sonar, digital echosounders, the first (classified) SASS and Seabeam multibeam systems, and early satellite altimetry, and

(b) (For positioning determination) a plethora of short and long range radio positioning systems, the Transit satellite positioning system, the early designs for GPS, long and short baseline acoustic systems, and

(c) How these developments have since impacted the data available to GEBCO

BIOGRAPHIES

Dave Wells and Steve Grant worked together at the Bedford Institute of Oceanography for several years during the 1970s on some of the developments discussed in this paper, as part of the Canadian Hydrographic Service Navigation Group headed by Mike Eaton. Steve “retired” in 1996 but still works on a variety of hydrographic consulting and teaching projects. Dave “retired” in 1980 and again in 1998, but still teaches at three universities.

INTRODUCTION

During the period from 1960 to 1980, many remarkable advances were made in the technologies applicable to depth measurement and positioning at sea. Some of the initial technological developments dating from those two decades remain the basis for the most modern and effective bathymetric and positioning systems in use today. Others reached productive fruition earlier, and have since been supplanted. In this section we will briefly review the full suite of technical developments between 1960 and 1980. In later sections we will describe the evolution of these technologies into use during bathymetric surveys, by creating two technical “bookend snapshots” for 1960 and 1980.

Underlying all technical developments in position determination and depth measurement over the period of interest is the evolution of the “enabling technology” of sold-state electronics. Some of the milestones in this evolution are:

The transistor: Invented in 1947, by 1960 “digital” computers used transistors for logic, and ferrite cores for memory. During the 1970’s memory chips replaced cores.

Shipboard computers: By 1965 “minicomputers” were small and robust enough to use at sea. One of the first such seagoing computers was the Digital Equipment Corporation PDP-8. One of its initial tasks was navigation computations (Wells, 1969).

The integrated circuit (IC): Invented in 1962 at Intel Corporation, IC logic density followed Moore’s Law until the late 1970s (12 month doubling time). Since then IC logic density has followed the Modified Moore’s Law (18 month doubling time).

Two ironic caveats to Moore’s Law are **Parkinson’s Law of Data** that states, "Data expands to fill the space available for storage", and **Gate’s Law** that states "The speed of software halves every 18 months." (Jargon Dictionary 2003). These Laws were beginning to be felt by most hydrographic data collection agencies around the world by the mid-1980s, as a result of the technical developments described in this paper.

EVOLUTION OF POSITION DETERMINATION

Technical developments in position determination between 1960 and 1980 include the following:

Hyperbolic radiopositioning: Developed during World War II, this concept is based on the measurement of differences in the phase or time of arrival of signals broadcast from (Master – Slave) pairs of transmitters at known locations. Lines of Position (LOPs) created by the differences are hyperbolic curves. The intersection of two hyperbolas (from two pairs of transmitters) determines the navigator's position. The accuracy of hyperbolic radio-positioning systems is spatially variable, depending on three factors: LOP measurement uncertainties, the fanning out (expansion factor) of the hyperbolic LOPs (which depends on distance from the baseline between the master and slave) and the angle of intersection between the LOPs (see Figure 1). Table 1 summarizes the characteristics of hyperbolic systems used in the collection of GEBCO data.

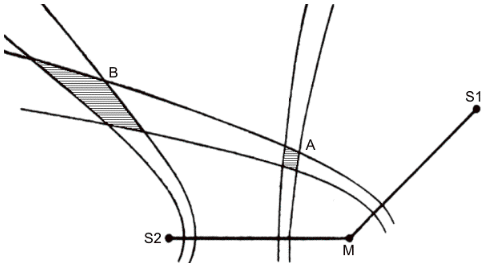


Figure 1. Hyperbolic positioning uncertainty is usually characterized by the longest diagonal in the diamond of uncertainty (the shaded areas). The parallel curves represent LOP uncertainty. At location A, the lane expansion is modest, and the angle of intersection optimal (90°). At location B both the lane expansion and angle of intersection are worse.

*Table 1. Comparison of hyperbolic positioning systems. Hyperbolic systems developed prior to 1960 include **Decca Navigator**, **Loran-A**, and **Loran-C**. Transmitter chains for Decca and Loran-A were well established by 1960.*

System	Principle of Operation	Baseline Length (n.m.)	Frequency Band (kHz)	Range (n.m.)	95% Position Accuracy Good - Bad
Omega	CW phase comparison	5000 - 6000	10 - 14	Global	2 - 6 n.m.
Decca	CW phase comparison	60 - 120	70 - 130	240	30 - 1200 metres
Loran-A	Pulsed Time difference	200 - 400	1850 - 1950	800	1 - 15 n.m.
Loran-C	Pulsed time difference and phase comparison	150 - 800	90 - 110	1200	200 - 600 metres

*Loran-C transmitter chains began to be established in the early 1960's, continuing to this day. Transmitters for **Omega** were built between the late 1960's and late 1970's. Decca and Omega used continuous wave (CW) signals, and the two Loran systems used radio pulses. CW systems suffer from lane ambiguity and skywave interference.*

Lane ambiguity resolution: CW radiopositioning receivers measure the phase difference within one cycle ("lane" of the comparison frequency) but cannot directly determine the integer lane count. Some method is required to set the correct lane count when the system is first turned on, and whenever the receiver loses lock on the signal (e.g. due to a power failure or noise interference). Decca and Omega use two or more signal frequencies, and form linear combinations that have much lower "beat" frequencies (wider "lanes") that permit unambiguous setting of the proper lane count. Pulsed hyperbolic systems like Loran measure differences in Time-Of-Arrival (TOA) between the Master and Slave signals: there is no pulsed equivalent to lane ambiguity, making multiple frequencies unnecessary.

Skywave elimination: Skywave is the signal reflected from the lower layers in the ionosphere. CW ground wave (accurate) and sky wave (inaccurate) are indistinguishable, limiting the usable range of Decca, and limiting the accuracy (even with special correction tables) of Omega. Loran-A suffered from skywave interference but to a lesser extent (skilled operators could distinguish between ground and skywave on the oscilloscope display). The Loran-C pulse (Figure 2) was specially designed to permit tracking the ground wave (30 microseconds into the pulse) before the earliest skywave contamination could occur. This greatly increased the usable range of Loran-C, in comparison with CW systems in the same frequency band, and led to its widespread adoption during the 1970's and onward.

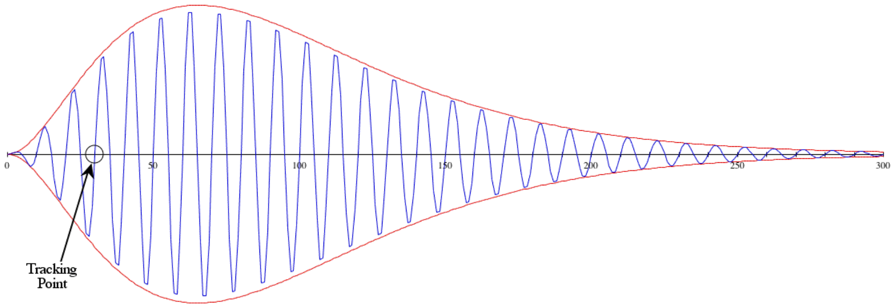


Figure 2. The Loran-C pulse. Unlike Loran-A, Loran-C measurements are made on the zero-crossing following the third cycle of the carrier wave within the pulse. At 100 kHz, the third cycle is 30 microseconds after the pulse leading edge, where the signal strength is fairly strong, but still 10 to 20 microseconds ahead of the arrival of the earliest skywave signal.

Doppler satellite positioning: When Sputnik was launched in 1957, scientists at the Johns Hopkins Applied Physics Laboratory (APL) measured variations in the Doppler shift on Sputnik's radio broadcast, as the satellite passed overhead. Sputnik's along-track and cross-track coordinates (and hence its orbit) were calculated from the time and steepness of the Doppler curve at closest approach (i.e. when the curve is steepest) (Simpson 2000). They designed the Navy Navigation Satellite System, or Transit system by inverting this process (Guier and Weiffenbach 1960). Transit determines receiver cross-track and along-track coordinates (relative to a known satellite orbit), formulated as a least squares solution for receiver latitude and longitude, based on integrated Doppler shift measurements (change in satellite-receiver range during the integration interval). These are hyperbolic measurements. Transit has three limitations: it is a two-dimensional system (receiver height must be known), it provides infrequent fixes (a few dozen per day with 5-6 satellites in orbit), and it requires accurate course and speed information during the 15-minute satellite pass (from another complementary navigation system). Transit provides a navigation framework, rather than being a navigation system. This is in conformance with its primary mission - to update inertial navigator systems used on submarines.

Passive Ranging: With experience tracking TOAs from satellites from Sputnik onward, the US Naval Research Laboratory designed a satellite navigation concept based upon clock synchronization, measuring the TOA of a navigation signal, rather than the (hyperbolic) differences in TOAs. The first TIMe navigATION (TIMATION) satellite was launched in 1967 (Easton 1980). Among the many lessons learned: dual frequency systems can effectively eliminate the effect of ionospheric refraction on signal propagation; multiple range measurement geometry is superior to hybrid range and range-rate measurements; measuring TOAs from four or more satellites simultaneously allows a receiver to solve for three position coordinates and the offset between satellite clock time and the receiver's clock. Alternatively, the minimum number of simultaneous LOPs (satellites) is reduced to three if the navigator maintains clock synchronization by using a very stable atomic clock. This technique (either maintaining or solving for clock synchronization) became known as passive ranging, and later pseudo-ranging. It is the basis for GPS, and for "Rho-Rho Loran-C", a method that uses cesium clocks at the rover to extend coverage by reducing (from three to two) the number of Loran-C transmitters tracked.

Global Positioning System: The TIMATION and Air Force 621B satellite navigation system projects were merged in 1973. 621B had developed the concept of pseudo-random noise coded signals for ranging measurements, which fit well with the TIMATION pseudo-ranging technique. Ten prototype (Block I) GPS satellites were launched between 1978 and 1985. To date 35 operational (Block II) GPS satellites have been launched since 1989. At least 24 GPS satellites have been operational since 1994. Full Operational Capability was declared in April 1995.

Integrated navigation systems: During the 1970s (and 1980s), no single complete navigational solution (as we now enjoy with GPS) was available for deep-sea surveys. Transit was available everywhere, but required a complementary system to (a) provide accurate velocity during a Transit pass, and (b) provide positioning between Transit fixes. Several complementary systems were used: inertial navigation on military vessels; hyperbolic or Rho-Rho Loran-C when within coverage; long baseline acoustic positioning for limited-area detailed surveys (such as ridge crests); Doppler sonar when the water depth permitted (the deepest capability was 1000 m); and speed and heading sensors when all else failed. In order to manage and merge the measurements made by various combinations of these systems, a number of integrated navigation systems were designed (e.g. Grant and Wells, 1983). The purpose of such systems was to use the strengths of each measurement type to overcome the weaknesses of the others.

Figure 3 summarizes the evolution and coverage provided by several of the systems used for offshore positioning over the past 60 years. The number of land and satellite-based transmitters doesn't equate to available coverage, because some systems have limited range. No attempt is made here to address the global distribution, accuracy or intermittent nature of some systems (e.g. Transit). In particular, virtually no coverage was available in the southern hemisphere until Transit and Omega became operational in the late 1960's.

EVOLUTION OF DEPTH MEASUREMENT

Technical developments in depth measurement between 1960 and 1980 include the following:

Single-beam echosounders: Invented in the 1920's (Langevin 1924), the echosounder came into widespread use for depth measurements during the 1930's and especially during World War II (Klein 1968). By 1960, all hydrographic surveys used echosounders as the principle depth measurement device. In 1960, a single depth measurement was a line burned into specially-prepared paper by a stylus moving across that paper. The speed of the stylus represented the speed of sound. The stylus motion was synchronized with the transmission of depth sounding acoustic pulses. For each sweep of the stylus across the paper, the voltage applied by the stylus to the paper was controlled by the return signal waveform from the corresponding acoustic pulse.

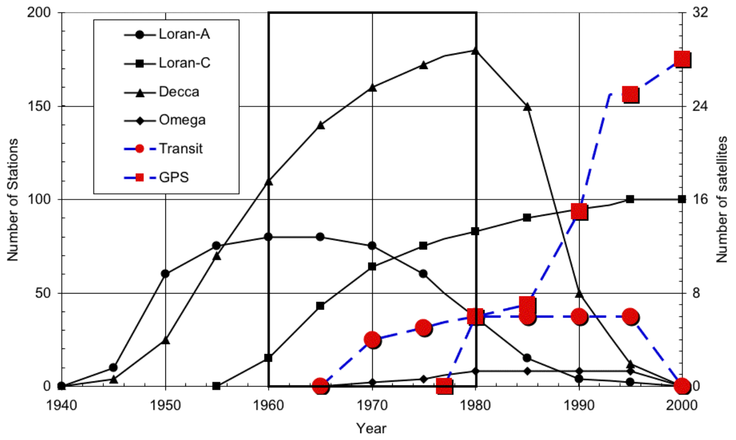
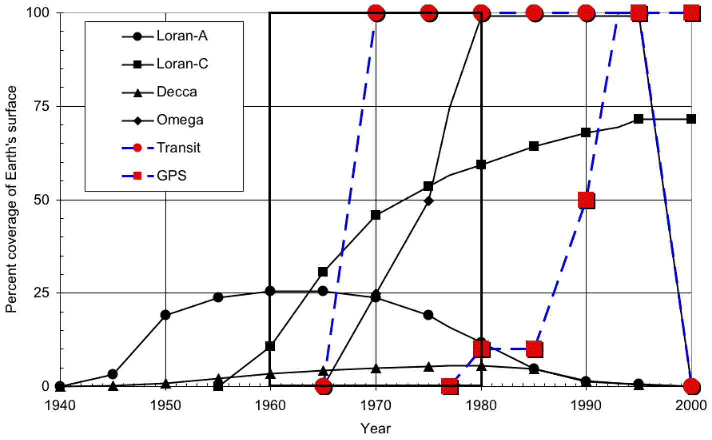


Figure 3(a). Timeline of approximate number of operational shore-based transmitters / satellites for of several systems.

Figure 3(b). Approximate global coverage for the systems included in 3(a). This does not address several issues:
i) intermittent nature of Transit satellite fixes
ii) spatially-variable hyperbolic system accuracy
iii) limited range from shore of systems like Decca (maximum 250 n.m.)



Digital echosounders: During the 1960's two methods of converting traditional analog echounding records into digital form were developed, both as add-ons to existing echosounders: chart scalers and signal digitizers. **Chart scalers** read echosounder records (paper rolls), first manually, and later automatically, following the bottom trace, converting it into digital records for processing, storage and management by computers. **Signal digitizers** were added to the echosounder itself, converting the returned signal waveforms, rather than paper records produced from them, into digital detections of the seabed (e.g. Wells 1968). This was the first attempt at what is now referred to as "bottom detection". The first attempts often produced unreliable results (losing bottom lock). Reliability improved as better "bottom tracking" algorithms were developed.

Side-scan sonar: Obliquely-transmitted acoustic signals had been used for submarine detection for decades (Klein 1968), before the first sidescan mapping system, the "Shadowgraph" was developed for the U.S. Navy in the early 1950s (Kozak 2003). The simple sidescan indicates variations in acoustic backscatter over a wide swath to each side of a survey vessel. However, except under flat seabed conditions, a simple sidescan is incapable of unambiguously distinguishing between depth anomalies and variations in seabed texture and composition, nor in accurately positioning the cross-track anomaly location.

Two-row sidescan interferometry: First proposed by Chesterman et al (1958), this was developed into the deep-sea, shallow-tow Geological Long Range Inclined Asdic (GLORIA) system, starting in 1965 (Laughton, 1981). It is based on observing interferometry fringes formed by the differences in the phase of the return waveform, as observed by two parallel acoustic sensors. The two-row scheme was later increased to

multiple rows (Cook and Mackay 1971), permitting better resolution of the phase wraps (full cycle phase differences) that limit two-row systems. Deep water, deep tow systems (e.g. SeaMarc) were developed in the early 1980’s, as were shallow water systems such as the Bathyscan system.

Electronic beam steering: Initially suggested by Tucker et al (1958), this technology uses a discrete array of acoustic elements, rather than a single continuous acoustic transducer, to permit forming several different linear combinations of the signals coming from individual array elements (Figure 4, courtesy of Christian de Moustier). Tucker (1960) proposed an optimal two-array geometry (Mills cross), one to transmit and the other to receiving returns. Beam forming / steering is very computation-intensive, and has become more sophisticated as Moore’s Law has allowed. Early applications were four systems built by the Harris Division of General Instrument Corporation (later Seabeam Corporation): **Narrow Beam Echo Sounder** (NBES) first used on NOAA ship Surveyor in 1964 (Tyce et al 1987); **Sonar Array Sounding System** (SASS), the first multibeam echosounder (Figure 5), installed on several US Naval Oceanographic Office ships by 1970 (Glenn, 1970); **Seabeam** multibeam system installed on the Australian HMAS Cook in 1976, and the French Jean Charcot in 1977 (Renard and Allenou 1979); and **BO’SUN** medium depth multibeam system (White 1971).

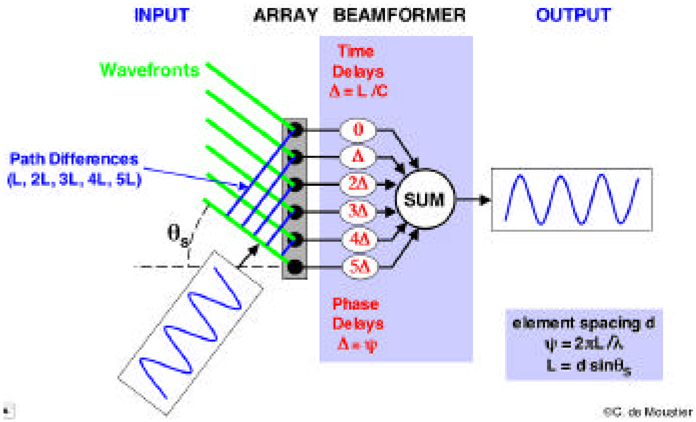
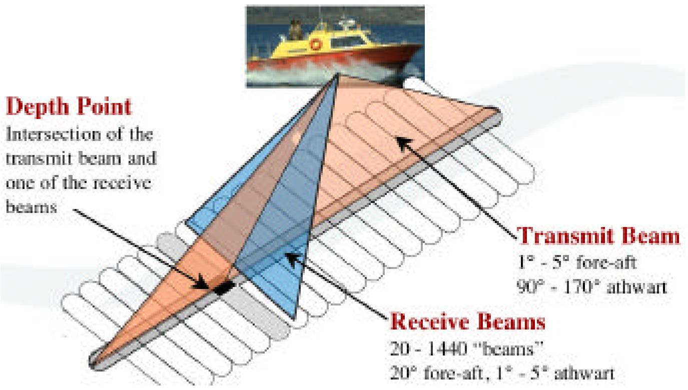


Figure 4. Electronic beam steering. Phase or time delays applied to signals arriving at discrete acoustic array elements result in a linear combination that is sensitive (amplifies) signals coming from a unique direction, determined by the delay values.

Figure 5. Multibeam sounding concept. A transmit array long in the along-track direction creates an ensonification beam that is narrow fore-aft and broad athwartships. Using beam steering array processing, and a receive array long athwartships, many receive beams are formed simultaneously at different elevation angles. Depth datapoints are transmit / receive beam intersections.



Airborne Laser Bathymetry (ALB): Although the first operational systems did not appear until the mid-1980s (Casey et al, 1985, Penny et al 1986), the laser bathymetry concept was first conceived, and systems proposed in the 1960’s (Sorenson, 1966, Hickman and Hogg 1969).

Satellite altimetry: This technology is the subject of another contribution to this workshop. Here we note only that the concept of radar altimetry from space was first tested onboard Skylab in 1973 (NASA, 2003).

1960 SNAPSHOT

In 1960, the vertical single-beam echosounder was in universal use for depth determination in offshore surveys, while offshore positioning was still mainly based on celestial positioning and Radio Direction Finding (RDF) (see for example Hobbs 1981; and Bowditch 1977).

During the 1960's, sidescan was adopted by many hydrographic offices as an important complement to vertical-beam echosounders, providing the possibility of complete insonification / investigation of the seabed for the first time. By the end of the 1960's many survey-quality vertical-beam echosounders were dual-frequency, and digital.

Available hyperbolic radiopositioning systems were Loran-A and Decca Navigator (see Figure 3a). Loran-C coverage was growing, but it was a military system until the late 1960's. The first civilian Loran-C receivers weren't available until the mid 1970's (Roland, 2003). In 1960 the Decca Navigator system was available in European and North Atlantic waters as well as Atlantic Canada and the Persian Gulf. Loran-A transmitters were providing coverage for much of the North Atlantic, North and Central Pacific, Bay of Bengal and Northern Australia since World War II. The Korean War stimulated expansion in Japan and the East China Sea. In 1965 chains were established in Portugal and the Azores and soon after, chains became available in the Bay of Biscay and Gulf of Mexico. Loran-A provided the largest percentage of global coverage in 1960 at over 20%. Figure 6 shows the extent of that coverage. Note that there was no coverage south of the equator.

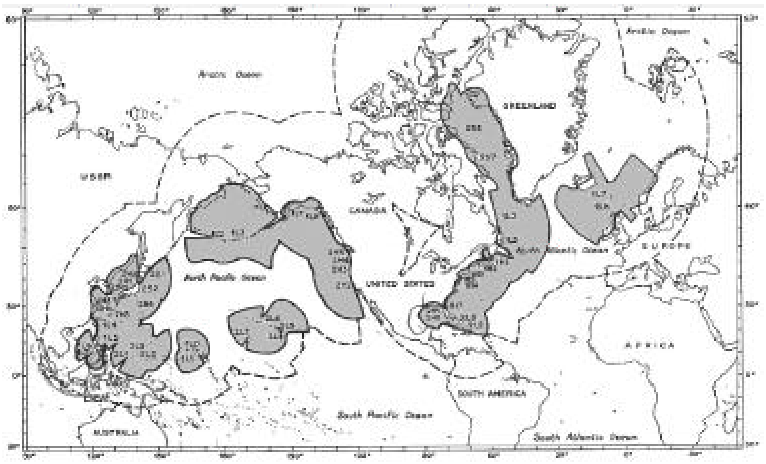


Figure 6. LORAN-A coverage in early 1960s (IHB 1965). Shaded areas are ground wave coverage (day and night operations). Pecked line is limit of skywave coverage (night only).

1980 SNAPSHOT

By 1980 multibeam data began to contribute to the GEODAS database followed by GLORIA two-row sidescan data during the 1980s. Dramatic changes in radiopositioning technology and policy were looming. The first edition of the U.S. Federal Radionavigation Plan was published in 1978, and new editions have since appeared regularly, nominally at two-year intervals. This policy document attempts to strike balances between cost, security and economic benefits of the many sea, air and land radionavigation systems supported by the U.S. government. The default position from 1978 on is that GPS will eventually replace everything else. In the main, this has come true, the main survivor being Loran-C.

The first Transit satellite was launched in 1961; the system declared operational in 1964; and released for civilian use in 1967, due in part to demand generated by a paper by Talwani et al (1965). Transit, together with dead-reckoning, was probably the mainstay of offshore GEBCO positioning during the 1970s and 1980s. It was shut down in 1998.

Eight Omega stations in Argentina, Norway, Liberia, France, Japan, Australia and the U.S.A., providing global hyperbolic coverage, were contructed between the late 1960s and late 1970s. Omega was declared operational in 1983 (Proc 2003; Hobbs 1981). However, Omega's 2 – 4 n.m. accuracy and operating costs ensured that Omega's lifespan was limited. It was shut down in 1997.

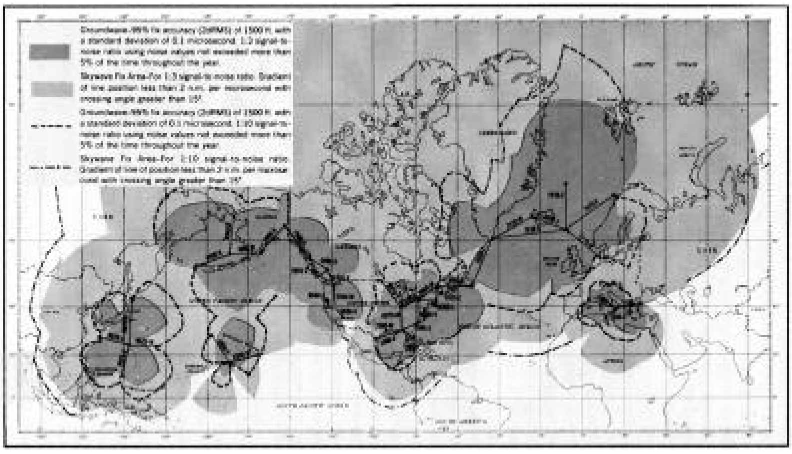
Decca coverage was at its peak in 1980. Loran-A coverage had declined to about half its peak. The advantages of Loran-C over Decca and Loran-A would reduce their use dramatically over the next decade. The last Loran-A and Decca transmitters (both in Japan) were shut down, respectively, in 1997, and early in the new century.

Loran-C was fully operational by 1980, providing coverage for most of the waters of the northern hemisphere (Figure 7). Relatively inexpensive, easy to use, automatic, civilian receivers exploded onto the market starting in the mid 1970's and by the 1980's Loran-C was the most widely used navigation systems in the history of navigation (since supplanted many fold by GPS of course).

The cost of atomic clocks had dropped in price by the mid 1970's (most Loran-C stations used four). Also available by 1980 were passive ranging (rho-rho) Loran-C receivers, using cesium clocks to predict the Loran-C transmission times and measure TOAs. Transit fixes were used to keep track of the atomic clock drift. Rho-rho Loran / Transit systems provided improved accuracy over larger areas than conventional hyperbolic Loran-C.

The first four GPS satellites were launched in 1978. While it was not until 1995 that GPS was declared an operational system, many navigators used the incomplete GPS system, employing "clock aiding" (cesium clocks) and "height aiding" (assuming the height is known) to reduce the minimum number of required GPS satellites from four to only two.

Figure 7. Loran-C coverage (Hobbs 1981). Positioning uncertainty is better than 460 m (95%) within the dark shaded areas, which are the limits of ground wave coverage.



GEBCO IMPACT

Clearly, any technical developments affecting the measurements of depths, and positions associated with those depths, will have an impact on the quality of data products such as the General Bathymetric Chart of the Oceans (GEBCO). GEBCO is a cumulative product, depending upon data accumulated over a period of several decades (or longer). As the performance of depth and position sensors has improved, so has the quality of more recently collected data. However the ocean is vast, and as yet incompletely mapped, so legacy data from earlier decades are not frivolously discarded. Hence the relationship between evolving depth and positioning technologies, and the overall quality of products like GEBCO is complex.

In order to delineate this relationship in some approximate way, we have chosen to consider the bathymetric soundings contained in the GEOphysical DAta System (GEODAS) Marine Trackline Geophysics database (NGDC 2003), maintained by NOAA's National Geophysical Data Center, as a proxy for the data underlying GEBCO products. We realize that contours have played a major role in GEBCO in the past, and that the GEODAS database contains bathymetric point values rather than contours. However, GEODAS is easily accessible for spatial and temporal analysis, and it is our belief that as gridded datasets join charts as GEBCO products, the role of point data will become more important.

The timeline of the data currently contained in the GEODAS database is shown in Figure 8. Less than 2% of the data were collected prior to 1960. By 1970 about 14%, and by 1980 almost 40% of the data had been collected. Hence 1960 is a comparison baseline for improvements in depth and position measurement technologies used to populate the GEODAS bathymetric database.

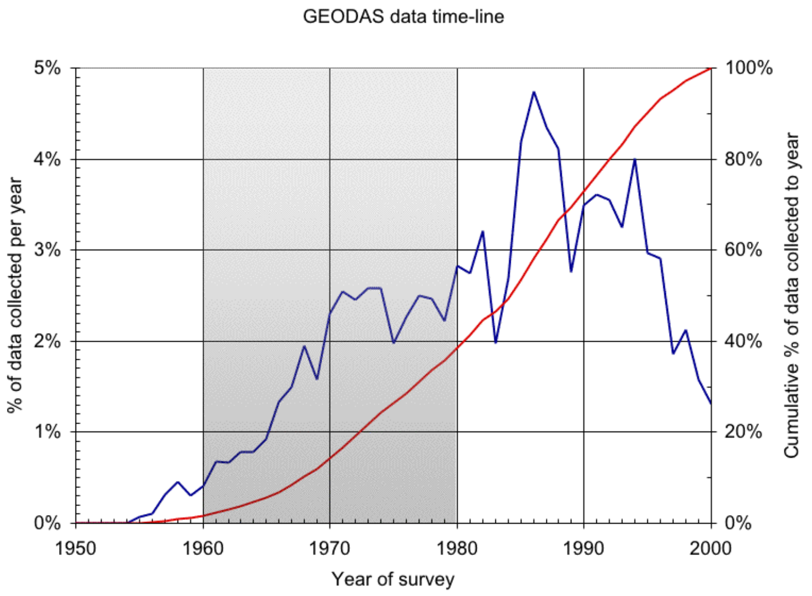


Figure 8. Temporal distribution of bathymetric data currently held in the GEODAS database, expressed as percentage of the total holdings per year of survey. Both yearly contributions, and cumulative totals up to each year are shown. The two decades under consideration in this paper are outlined.

Figure 9 (courtesy of Martin Jakobsson) depicts the navigation methods used for each trackline in the GEODAS Marine Trackline Geophysics Database. The 14 categories shown in the figure are a generalization of the 563 categories of entries in the "Navigation Instrumentation" field of the header record in the Marine Geophysical Data Exchange Format (MGD77) that is the basis for GEODAS. Appendix G in Mayer et al (2002) contains a complete list of the relationships between the original 563 categories, and these 14 generalized categories, and assigns nominal accuracies associated with each of the generalized categories, reproduced below as Table 2. Note: One of us (SG) was the Hydrographer-In-Charge for the survey of Davis Strait and the Southeast Baffin Island coast in 1983. Although shown as "unknown" in Figure 9, the positioning method used was Rho-Rho Loran-C and Transit, with an estimated positional accuracy (95%) of 250 m.

SUMMARY

Most of the technical developments in depth measurement techniques were first proposed and realized during the two decades from 1960 to 1980. While many technical developments in position determination were also initiated and realized during this period, including the gestation of the Global Positioning System, reliable inexpensive offshore positioning did not become available until the 1990s, when GPS became operational. During this period about 40% of the current GEODAS database was collected.

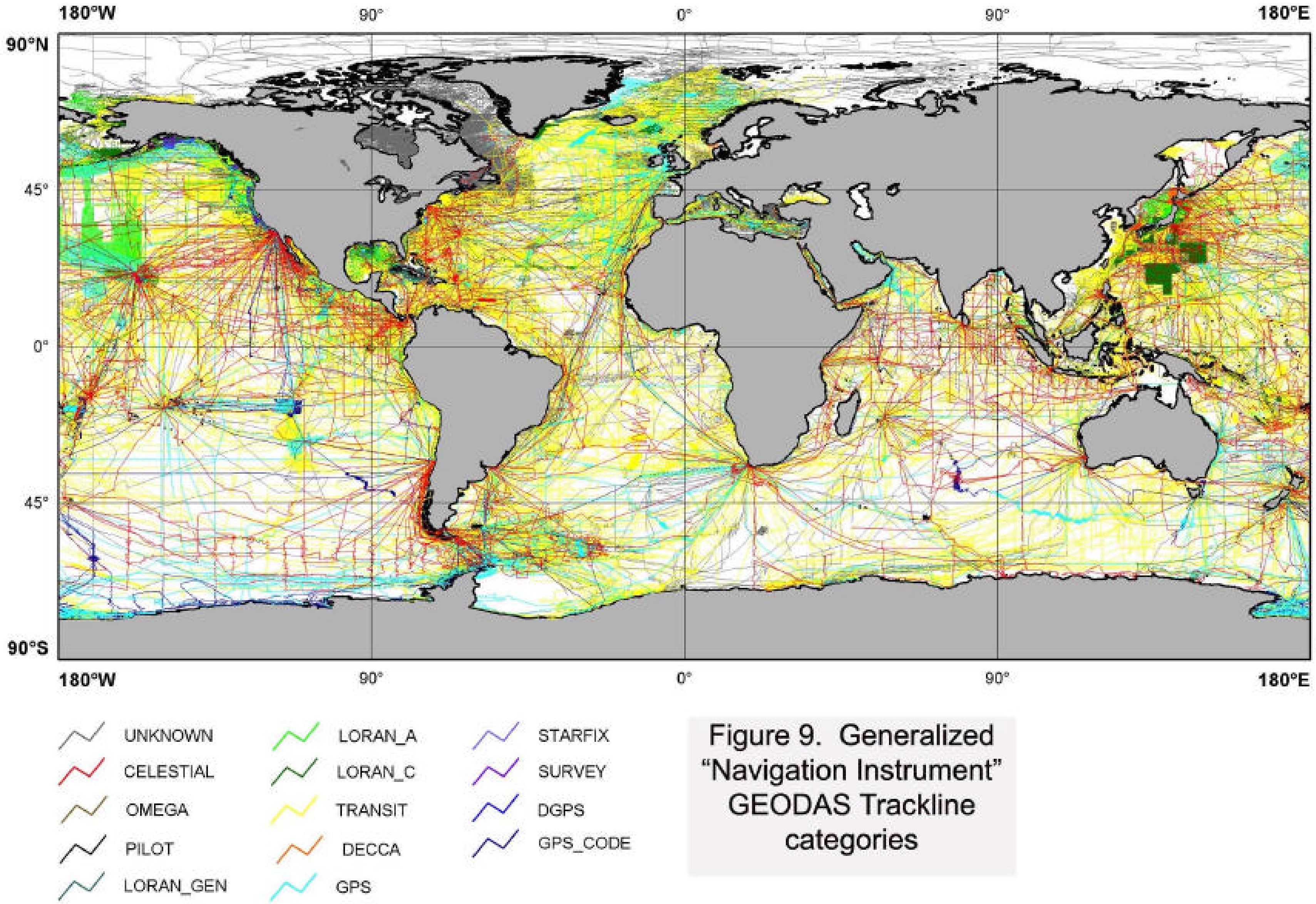


Figure 9. Generalized “Navigation Instrument” GEODAS Trackline categories

Generalized Navigation Category	Navigational Fix Accuracy (m) [Mayer et al 2002]
Unknown	10000
Celestial	10000
OMEGA	7300
Pilot	2000
LORAN A	1200
LORAN	1200
TRANSIT	500
LORAN C	500
DECCA	500
GPS	100
Survey	50
STARFIX	50
GPS P-CODE	20
DGPS	20

Table 2. Generalized navigation categories, representing 563 different entry classes found in the MGD77 "Navigation Instrument" field in the GEODAS database, and assigned positioning accuracies (95%) from Mayer et al (2002) Appendix G. "Pilot" refers to radar, horizontal sextant and other visual navigation observations. LORAN (unspecified) was assumed to be LORAN A. "Survey" refers to line-of-sight microwave positioning systems (e.g. Miniranger, Trisponder) and limited-range medium frequency systems (e.g. HiFix, Raydist, Argo). "Starfix" was a proprietary satellite-transponder-based positioning system operated by John E. Chance and associates, widely used in the Gulf of Mexico prior to the operational availability of GPS (and not the "Starfix" DGPS service provided by the same company after GPS became operational).

REFERENCES

Bowditch (1977) The American Practical Navigator. National Imagery and Mapping Agency.

Casey, M.J., R.A. O'Neil, and P. Conrad (1985). The advent of LARSEN, Proceedings of the Canadian Hydrographic Conference, Halifax, pp. 7-12.

Chesterman, W.D., P.R. Clynick and A.H. Stride (1958) An acoustic aid to sea-bed survey. Acustica, Vol. 8 pp. 285-290

Cook, J.C., and J.M. Mackay (1971) A precise sonar for hydrographic surveying. National Electronics Review, Vol. 7, No. 1, pp. 5-11.

Easton, (1980) The navigation technology program. in Global Positioning System, Volume 1. Papers published in Navigation. ISBN 0-936406-00-3. pp. 15-20.

Glenn, M. F. (1970). Introducing an operational multi-beam array sonar. International Hydrographic Review, Vol. 47, No. 1, pp. 35-39.

Guier, W.H. and G.C. Weiffenbach (1960). A satellite Doppler navigation system. Proceedings of the Institute of Radio Engineers, Vol. 48, pp. 507-516.

Grant, S.T. and D. E. Wells (1983) Interactions among integrated navigation system components. Marine Geodesy, Vol. 7, No. 1-4, pp. 153-170.

Hickman, G.D. and J.E. Hogg, (1969). Application of an airborne pulsed laser for near-shore bathymetric measurements, Remote Sensing of the Environment, Vol. 1, pp. 47-58. Elsevier, New York

Hobbs, R.R. (1981). Marine Navigation 2: Celestial and Electronic, Naval Institute Press, Annapolis, MD, USA

International Hydrographic Bureau (1965). Radio Aids to Maritime Navigation and Hydrography. 2nd ed., International Hydrographic Bureau, Monaco, Special Publication No. 39

The Jargon Dictionary(accessed 14 March 2003) <http://info.astrian.net/jargon/terms/m/Moore_s_Law.html>

Klein, E. (1968). Underwater sound and naval acoustic research and applications before 1939. Journal of the Acoustical Society of America, Vol. 43, No. 5, pp. 931-947.

Kozak, G. (2003). Personal Communication.

Langevin, P. (1924) Sounding with the aid of sound. International Hydrographic Review, Vol 2, pp. 51-121 (also IHB SP-14, 1926).

Laughton, A. S. (1981). The first decade of GLORIA. Journal of Geophysical Research 86, 11511-11534.

Mayer, Larry, Martin Jakobsson, and Andrew Armstrong (2002). The Compilation and Analysis of Data Relevant to a U.S. Claim Under United Nations Law of the Sea Article 76. Center for Coastal and Ocean Mapping/Joint Hydrographic Center University of New Hampshire Durham, N.H. <http://www.ccom-jhc.unh.edu/unclos/index.htm>

National Aeronautics and Space Administration (2003) Skylab Experiment S193, Microwave radiometer, scatterometer, and altimeter. (accessed 14 March 2003). <http://history.nasa.gov/EP-107/ch5.htm#n2c>

National Geophysical Data Center (accessed 14 March 2003). <http://www.ngdc.noaa.gov/mgg/geodas/geodas.html>

Penny, M.F., R.H. Abbot, D.M. Phillips, B. Billard, D. Rees, D.W. Faulkner, D.G. Cartwright, B. Woodcock, G.J. Perry, P.J. Wilsen, T.R. Adams and J. Richards (1986). Airborne laser hydrography in Australia, Applied Optics, Vol. 25, No. 13, pp. 2046-2058.

Proc, G. (accessed 14 March 2003). Hyperbolic Navigation Systems at <http://webhome.idirect.com/~jproc/hyperbolic/index.html>

Renard, V., and J. P. Allenou (1979). Sea Beam, multi-beam echo-sounding in Jean Charcot. Description, evaluation and first results. International Hydrographic Review, Vol. LVI, No. 1, pp. 35-67.

Roland, W. (2003). Personal Communication

Simpson, J.C. (2000) Pioneers of Discovery: Guiding Satellites. Johns Hopkins Magazine, April. Available online at <http://www.jhu.edu/~jhumag/0400web/04.html>

Sorenson, G.P. (1966). 13 June 1966 Letter to Commander, US Amphibious Forces, Pacific, proposing the use of airborne lasers for near-shore bathymetric mapping.

Talwani, Manik, James H. Dorman, J. Lamar Worzel, and George M. Bryan (1966). Navigation at sea by satellite, J. Geophys. Res., 71(24), 5891-5902.

Tucker, D.G., V.G. Welsby, and R. Kendell (1958) Electronic sector scanning. Journal British Institute of Radio Engineers, Vol 18. pp. 465-

Tucker, D. G. (1960). Directional echo-sounding. International Hydrographic Review, Vol. 37, No. 1, pp. 43-53.

Tyce, R., S. Ferguson, and P. Lemmond (1987). NECOR Sea Beam data collection and processing development. Marine Technology Society Journal, Vol. 21, No. 2, pp. 80-92.

Wells, D.E. (1968) Report on the demonstration of the ATLAS digital survey sounder and the DECCA digital logger. 7th Annual Canadian Hydrographic Conference, Ottawa.

Wells, D.E. (1969) The automatic plotting of ship's tracks. Transactions of Applications of Sea Going Computers Symposium, Marine Technology Society, pp. 131-141.

White, D. J. (1971). BO'SUN, a multibeam sonar for search and survey. Proceedings of the Third Annual Offshore Technology Conference, Houston, Tx, 19-21 April, Vol. 2, pp. 393-406. Paper OTC 1457.