Primary Navigation 1960–1980

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Scope and Introduction

This article concentrates on primary navigation, the term given to the position fixing system used to constrain a dead-reckoned position. Given the importance of the topic to all spheres of maritime endeavour it is only to be expected that Wormley was mostly a user, albeit an early, well-informed and critical user, of new primary navigation technologies, and not an originator. However, staff at Wormley did make a significant patented advance in dead-reckoning technology that became especially important in the era of Transit satellite navigation, algorithms and software that converted raw Transit data into accurate position fixes were also developed.

Until the end of the 1960s the principal form of primary navigation was based on radio transmissions from stations on land but reverting to celestial using a sextant and astronomical tables when radio navigation aids were unavailable or were unreliable in the region. The 1965-66 Annual Report of the National Institute of Oceanography (NIO) summarised the status as[1], "*Accurate navigation is still one of the most difficult and time-consuming problems in research and map-making in oceanic areas out of range of sufficiently accurate and reliable shore-based aids*". Today's reader might well imagine that the release for commercial use of the US Navy Transit satellite navigation system in July 1967 would have rapidly revolutionised primary navigation at sea, but that was not the case. For several areas of marine science undertaken at Wormley radio navigation remained the preferred approach for over a decade after Transit's introduction.

After brief remarks on the use of celestial navigation we cover the various types of radio navigation systems used by Wormley scientists, concentrating on those used on RRS *Discovery*, before moving to the satellite era with Transit. We also describe the instruments used for dead-reckoning - for speed and heading - that provided the measurements necessary to give estimated locations in the period between position fixes. The article closes with a brief description of how the first computer on RRS *Discovery* was used for collecting and collating navigation data with an example of scientific results arising directly from data provided by the navigation instruments. Throughout we draw on examples from cruise reports to show why particular approaches were used and what accuracy and consistency of position fixes were being achieved. We do not cover GPS as a primary navigation tool as by the time of its introduction on *Discovery* in August 1986 the primary responsibility had long been with the staff of the Research Vessel Services at Barry (formerly, Research Vessel Base).

Celestial Navigation

For the open ocean hydrographic sections and biological stations of the 1950s and 1960s traditional celestial navigation by sextant and astronomical tables, with on-board clocks checked against time signals received by radio, provided sufficient accuracy. For example, the mean positions for hydrographic stations on RRS *Discovery* II International Geophysical Year cruises in 1958 were given to one minute of latitude (one nautical mile, hereafter M, the symbol used by the International Hydrographic Organisation)[2]. The only difference from usual merchant marine practice might be that, if necessary, two officers would take independent

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[1] http://viewer.soton.ac.uk/nol/image/24052/42/

[2] https://darchive.mblwhoilibrary.org/bitstream/handle/1912/2426/WHOI-59-54.pdf

observations[3]. There were times when, in the absence of a celestial fix, the ship's position would be determined by comparing the bathymetry from the echo sounder to that on a chart, as for 29 August 1963 on *Discovery* Cruise 2 near the mid-Carlsberg Ridge in the Indian Ocean[4]:

> *"Owing to overcast weather, there had been no evening star fix and it was therefore with some uncertainty that the position was approached. However the splendid bathymetric and magnetic charts made by H.M.S. Owen earlier in 1963 soon enabled a precise fix to be obtained, these charts were also invaluable in subsequent operations in the area".*

For some of the distinctive new ocean observing methods being developed at Wormley, especially neutrally buoyant Swallow Floats, celestial navigation fixes were of little use due to their limited frequency and accuracy. Instead, for this and other applications, buoys were moored to the seabed and the ship's position relative to the buoy obtained using radar range and bearing, but the story of ship-relative positioning is another topic.

Radio Navigation

Three radio navigation systems were used on RRS *Discovery* at various times: Decca Navigator, LORAN (two variants) and Omega. As with later satellite systems the initial development of these radio navigation aids was for the military, consequently their availability for civilian use was at first either controlled or the apparatus was too costly. Nevertheless, certainly from 1960 onwards, scientists at Wormley and those charged with outfitting *Discovery* were among the earliest adopters of new radio navigation equipment.

Decca Navigator

Decca was a hyperbolic radio system using phase comparisons of low frequency transmissions from 70 to 129kHz (below the UK Long Wave broadcast band). During daylight, ranges of 400M could be obtained, reducing at night to 200M depending on propagation conditions. In 1962 RRS *Discovery* was delivered with a Decca Mk V Navigator, which had been introduced in the early 1950s (Figure 1), together with an associated plotter[5]. Accuracy depended on the width of the lanes, angle of cut of the hyperbolic lines of position, instrument errors and propagation errors. The UK, Scandinavia, and Northern Europe were well catered for when *Discovery* entered service. Later systems (Chains) were established in Japan; Namibia and South Africa; India and Bangladesh; Canada (Newfoundland and Nova Scotia); Northwest Australia; the Persian Gulf and the Bahamas[6].

Laughton's description of using Decca in the Bay of Biscay on *Discovery* Cruise 11 in 1966[7] summarises the typical experience of the time:

> *"In the Bay of Biscay, S.W British, French and Spanish Decca Chains were used for navigation, using two Mk. XII receivers. In the centre of the Bay, night reception was poor, and consequently unusable. On Cantabria Seamount, the Spanish Chain (just installed) gave good daytime fixes but poor night time fixes. Decca navigation was used successfully on Galicia Bank by day but not by night".*

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[3] For this recollection, and numerous others throughout this article, we are indebted to James Crease.

[4] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d2.pdf

[5] Herdman, H.F.P, 1962. A New British Research Ship. International Hydrographic Review. 39 (2):2, 25–28.

[6] See the (incomplete) list at http://www.jproc.ca/hyperbolic/decca_corporate_highlights.html

[7] See https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d11.pdf
Dr. Laughton worked on a collaborative project with the Decca Navigator Company to test its Sea-Fix relative navigation system, with transmitters placed on anchored buoys. Mr. D.J. Phipps and Mr. J.K.V. Lee of Decca sailed on the first leg of this cruise to carry out tests, with the conclusion that it had "*too great an accuracy for the way it was being used*", referring to the fact that the two-metre resolution of Sea-Fix was far too fine for the large watch circle of the buoy in the varying currents.

Nevertheless Decca had its strengths, especially when the ship was well within the system's daytime coverage areas, such that in 1971 with *Discovery* operating off the Hebrides on Cruise 41 Decca was preferred to the Transit satellite system[8]:

> *"Satellite fixes were coming in regularly at roughly hourly intervals during this leg and, after a difficult starting period, during leg 1, but they were not particularly useful in this good Decca region".*

LORAN

LORAN (LOng RAnge Navigation) was also a hyperbolic radio navigation system but operated with pulsed signals. Two variants were used over the years on *Discovery*, LORAN-A (operating between 1.75–1.95MHz, useful to about 200M during daytime) and LORAN-C (operating at 100kHz to provide improved range up to 1,500M). Traditional LORAN receivers displayed the time difference between each pairing of the primary and one of the selected secondary stations, which was then used to find the appropriate Time Difference line on specially prepared charts. Later LORAN receivers displayed latitude and longitude coordinates instead of time differences.

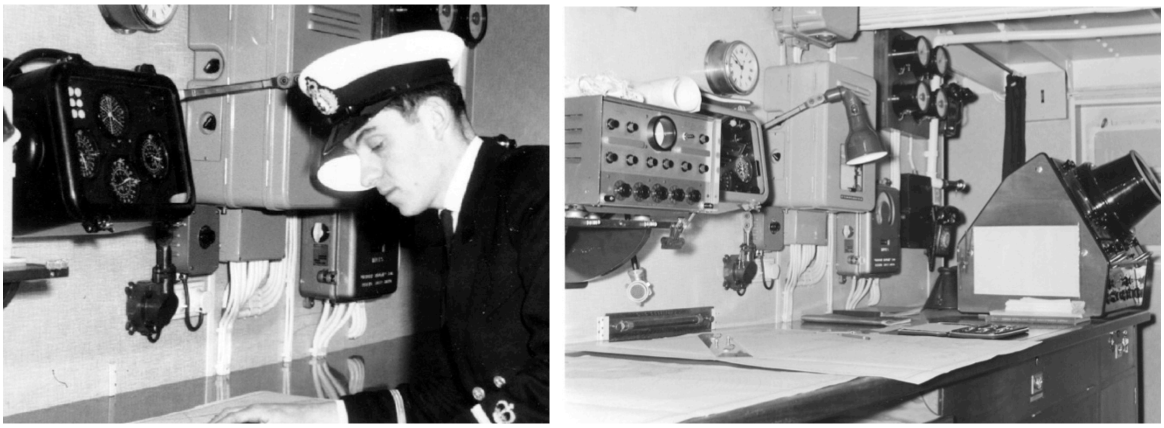

Figure 1. Chart Room of RRS *Discovery*. Left: in 1963 with a Decca Mk V decometer indicator dial. Right: in 1971 with, on the left above the chart table, an Enac Triton DX Navigator combined LORAN-A and LORAN-C receiver. Everett Sarratt, the designer of this equipment, had been presented with the inaugural Product Award of the US National Marine Electronics Association (NMEA) in 1964. Partially visible to the right of the LORAN receiver is a Decca Mk XII decometer readout unit. Courtesy National Oceanographic Library/NOC, NOL image 3197.

NIO scientists Crease and Swallow made early use of LORAN-C during the *Aries* expedition off Bermuda in 1960. This well known early use of Swallow floats was a collaborative project with Stommel of the Woods Hole Oceanographic Institution (WHOI), and WHOI engineer Robert Walden built the LORAN-C receiver[9]. While there were five manufacturers of LORAN-C receivers in 1960, four were for military contracts and the typical price was $45,000[10]. Crease recalls preparing large-scale time difference charts at NIO ahead of the expedition and that position variations were typically 0.2M. This was in keeping with the generally accepted performance, an absolute accuracy of 0.10–0.25M (185–463 m), although repeatability was better, typically 0.01–0.05M (18–91 m).

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[8] See https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d41.pdf

[9] http://www.argo.ucsd.edu/Gould_Float_history.pdf

[10] See http://www.loran-history.info/Loran-C/Jansky%20_%20Bailey%201962.pdf page 103

RRS *Discovery*'s Indian Ocean cruises were outside the coverage of LORAN and so it was not until Cruise 10 in early 1966 that Swallow wrote[11], "*Navigation in the 50-mile square was greatly assisted by the new Azores-Madeira-Cape St. Vincent Loran A chain*". Figure 1 shows a view of *Discovery*'s chart room in 1971 with an Enac Triton DX-Navigator LORAN set on the left.

The care needed in verifying LORAN-A fixes, affected by vagaries of radio propagation and errors in the early published charts, is clear from Laughton's summary of LORAN-A performance on the following *Discovery* cruise[7], as is their foresight in preparing lattice charts at NIO before sailing:

> *"On passage and at Peake-Freen Deeps, Loran A gave good signals but errors on the charts made them unreliable. A lattice (computed at N.I.O. based on assumed station positions) was made self consistent by adjusting 1S5 by 20μ sec; checked against topography, the lattice appeared to shift day by day up to 5 miles, and was therefore only useful for relative fixing".* (1S5 was the code for the station pair Sagres, Cape St. Vincent, Portugal and Porto Santo, Madeira. The time difference adjustment of 20μ sec is equivalent to a shift of 6km in distance between the two stations.)

RRS *Discovery* was fitted with a Decca DL21 LORAN set in 1970, an early installation of a solid-state receiver, the first having been built for the Royal Navy in 1967[12]. It provided a valuable backup for the Magnavox 702CA Transit satellite navigation receiver that had been installed in 1969. Importantly, the DL21 provided direct digital outputs that could be logged by the IBM 1800 computer, readings from the DX-Navigator had to be entered into the computer manually[13]. Whitmarsh, in the report[14] for RRS *Discovery* Cruise 43 (Oct–Nov 1971), tells of LORAN-A being used following an irreparable failure of the satellite navigator's power supply:

> *"Subsequent navigation was by Loran A, which was usable only between about 1000 and 1700 hours, giving an accuracy of about 1 mile, and by celestial observations whenever available. However, it was found possible to continue the survey linking consecutive legs by the comparison of targets seen by GLORIA on both legs. This method turned out to be accurate to a few cables [1 cable length being ⅒M, or* 185.2 m.*], although rather tedious. Some navigational ties were made by bathymetric comparisons at cross-over points.*

While the use of celestial, radio and satellite primary navigation on this one cruise is notable, so too is the use of terrain-matching relative navigation, a technique that was to be adopted three decades later by the Autosub autonomous underwater vehicle[15].

Discovery's Decca DL21 was replaced with the Mk2 version in July 1978 in time for the multi-ship JASIN campaign off Rockall. A major part of the scientific programme required tracking floats and a drifting current meter string beneath a spar buoy relative to the ship. It was found that the best approach used the EM log and gyrocompass to interpolate between half-hourly LORAN-C fixes. In reaching this decision Pollard, Saunders and Burnham[16] noted:

> *"(a) The Decca line always lay to the north of the LORAN fix, the mean difference between the Decca/SL3Y fix and the LORAN fix being about 300 m.*
> *(b) The LORAN fix lay, in the mean, north-east of the satellite fix, the mean difference being 400-500 m, depending on how stringent were the conditions for rejecting satellite fixes."*

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[11] See https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d10.pdf

[12] https://www.bodc.ac.uk/data/documents/nodb/pdf/DeccaNavigator_13jul2011.pdf

[13] Fasham, M.J.R., 1970. The use of a shipborne computer for navigation. Proc. IERE Conference on *Electronic engineering in ocean technology*.

[14] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d43.pdf

[15] https://tinyurl.com/gv2p3f7

[16] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d94.pdf

A method of quality assurance was adopted by which LORAN fixes were rejected should the calculated current exceed 1 knot, thereby screening out poor fixes due to sky-wave or loss of lock, leading to the conclusion, "*Thus our impression that LORAN is a better navaid than satellites in the JASIN area is confirmed".* Figure 2 shows the comparison Pollard et al. made between Decca, LORAN and Transit fixes, clearly showing the offset of the satellite fixes.

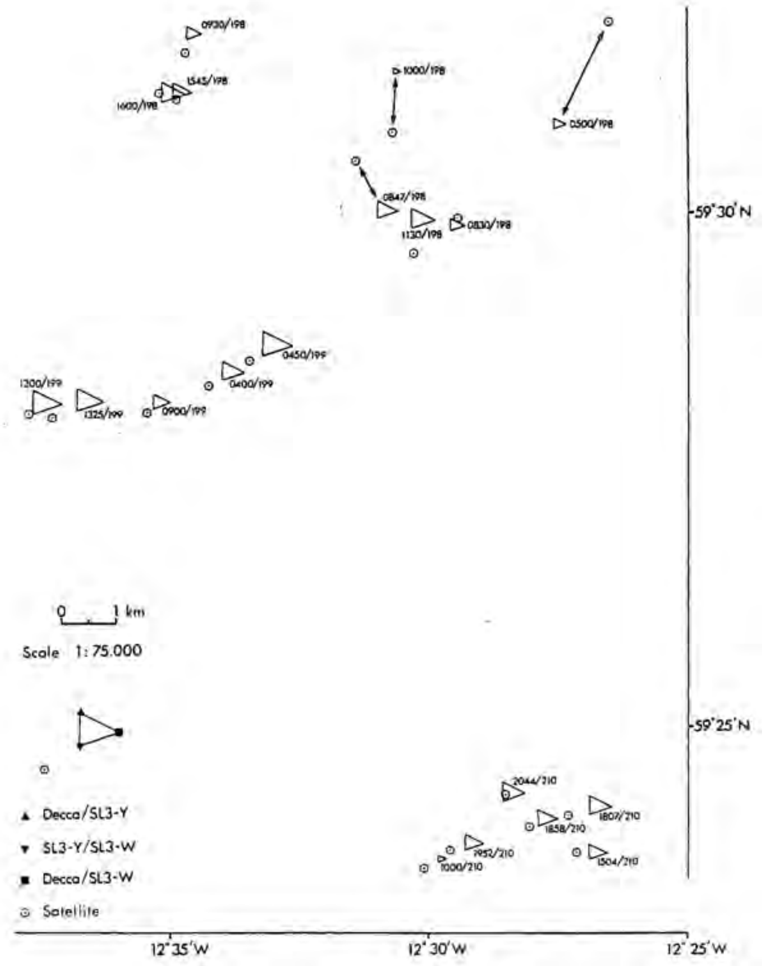

Figure 2. Comparison of LORAN/Decca, LORAN and Transit satellite fixes on RRS *Discovery* Cruise 94 in 1978[16]. For the triangles, the upper point is Decca/SL3-Y, the lower point SL3-Y/SL3-W, and the right point Decca/SL3-W. Each comparison is labelled with time and Julian Day.

Throughout the era of Transit satellite navigation LORAN-C remained widely used with coverage of the entire Atlantic and Pacific albeit with different accuracies depending on distance from the transmitters and day or night reception of either a ground-wave or a sky-wave fix.

Omega

Omega was a global-range radio navigation system that became operational in 1971, reached its final eight-station configuration in 1982 and was shut down in 1997 due to the availability of the Global Positioning Satellite (GPS) System[17]. It enabled ships and aircraft to determine position by receiving very low frequency (VLF) radio signals in the range 10 to 14kHz transmitted by a network of fixed terrestrial radio beacons. At best Omega could be used to determine a position to a precision of +/- 1.4M (2200 m). The development of Omega was

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[17] http://www.dtic.mil/dtic/tr/fulltext/u2/a285948.pdf

linked to the Transit satellite navigation system to determine the correct location between two possible locations for any given measurements on a global scale.

In late 1965 M.J. Tucker was on sabbatical from NIO as a Visiting Scientist at the Massachusetts Institute of Technology, during which, on a voyage from Panama to Woods Hole on the RV *Atlantis* II he witnessed experiments in VLF navigation by J. Stanbrough[18]. Tucker[19], writing at a time when the US Navy's Transit satellite navigation system was in development, "*but for security reasons it is not available at the present time, and in any case there is no guarantee that it will be maintained*" provided a report on the potential for VLF radio navigation, including the use of existing low frequency transmitters such as the Post Office's GBR station at Rugby.

As it turned out seven years elapsed before an Omega receiver was installed on *Discovery*. Redifon had launched the NV1 in early 1972, the first Omega receiver to be designed and built in the UK[20], at a price of under £2000. A set should have been delivered to *Discovery* for use on Cruise 51 in November–December 1972 but the company failed to deliver[21]. A set was installed for Cruise 53 - the three-leg Mid-Ocean Dynamics Experiment off Bermuda - but it proved faulty, requiring repairs by Redifon engineers at Southampton in June 1973.

The first successful use of the Omega receiver on RRS *Discovery* was on Cruise 54 (June–August 1973) with tests undertaken to assess its accuracy and usefulness against Transit satellite fixes[22]:

> *"Omega readings were recorded during three days in port in Ponta Delgada and after propagation corrections had been applied, positions calculated by computer. Errors of 3 - 4 miles occurred during the night but day positions agreed to within 2 miles. An analysis of Omega fixes taken during the FAMOUS survey compared to satellite derived positions showed that errors seldom exceeded 3 miles and are mostly less than 1 mile. The reason for a higher accuracy in the survey area than in Ponta Delgada is not known. It was concluded that Omega is a valuable navigational aid in the absence of a satellite navigator."*

There follows a note that for several periods of between twelve hours and several days adequate signals were not received, believed to be due to inadequate transmission.

From reading the navigation sections of cruise reports over the next few years it appears that the Omega receiver was little used, most likely because there were few instances with no satellite navigation or acceptable LORAN-C.

Transit Satellite Navigation

System characteristics

The Transit satellite navigation system was developed in the USA in the 1950s and 1960s out of the need to have accurate position updates for inertial navigation equipment aboard Polaris submarines[23]. Until the advent of GPS Transit was the only navigation aid with global operation, unaffected by ionospheric weather conditions, capable of position fixing accuracy competitive with short-range radiolocation systems.

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[18] https://darchive.mblwhoilibrary.org/bitstream/handle/1912/6137/WHOI-66-61.pdf

[19] Tucker, M.J., 1966. Navigation using VLF radio transmissions: an assessment of its potentialities. NIO Int. Rep. A24. Available at http://eprints.soton.ac.uk/392098/1/00525816.pdf

[20] https://books.google.co.uk/books?id=GYCSW7LZn3sC&pg=PA332

[21] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d51.pdf

[22] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d54.pdf

[23] https://www.ion.org/museum/files/TransitBooklet.pdf

Transit became operational in January 1964 and was released to commercial users in July 1967. The satellites had circular polar orbits at an altitude of approximately 1,075 kilometres, circling the earth every 107 minutes. The full constellation of five satellites formed what is frequently referred to as a "birdcage" within which the earth rotated, putting the earth underneath each orbit in turn. Each satellite was updated about every 12 hours with a navigation message based on orbit calculations uploaded from a ground station (the ephemeris information). The minimum interval between satellite passes depended on latitude, from about 35 minutes at 70° to about 100 minutes at 30°.

To obtain a position fix required 10–18 minutes of visibility above the horizon during which time the satellite travelled 4,400 to 7,000 km. The satellite transmitted a message that permitted a position to be calculated as a function of time. By combining the calculated satellite positions, range difference measurements between positions (Doppler counts) and information regarding the motion of the vessel, a position fix could be obtained. This required the use of a computer in addition to the satellite receiver.

There were two principal components of error in a Transit position fix, first was the inherent system error over which the user had no influence. The second error was introduced by motion of the ship during the satellite pass. A figure generally used to illustrate this error (velocity, altitude, ship's pitch and roll) gave a 0.2M (370 m) position error for each knot of unknown ship's velocity. The computer associated with the receiver was interfaced to the gyrocompass and speed log to provide the velocity information during a pass. Users could download the satellite ephemeris information, including predictions for the times of future passes. If necessary, ship manoeuvres could then be avoided during passes to give a better chance of a good fix, or an east or west course at slow speed would be called for to minimise the Doppler error. Positions were defined to a reference datum WGS-72 although this was not perfect everywhere and local datums could be implemented

Tests of a Magnavox 702CA Transit receiver at Wormley, 1968

A substantial capital investment by the Natural Environment Research Council at NIO in 1968 enabled the purchase of two IBM 1800 computers, one for *Discovery* and one at Wormley. The acquisition of a Magnavox 702CA Transit satellite receiver (Serial No. 10, Figure 3) was associated with this major capital investment[24]. Stansell's 1968 review article gave the cost of a stand-alone Transit satellite receiver of the time as about $30,000[25].

NIO's first acquaintance with Transit had come three years earlier. Tucker, on RV *Atlantis* in late 1965, had seen in operation one of 23 prototype AN/SRN-9 Transit receivers that had been built at Johns Hopkins University. His comment that there was no guarantee that Transit would be maintained[19] was perhaps coloured by the fact that in January 1965, when *Atlantis* began her around the world cruise three Transit satellites were in operation but only one was still working in November 1965 when he was aboard[18].

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[24] James Crease, personal communication, 9 September 2017.

[25] https://journals.lib.unb.ca/index.php/ihr/article/download/23923/27708

Figure 3. Magnavox 702CA, the first Transit satellite navigation receiver used by NIO in 1968. Courtesy National Oceanographic Library/NOC, NOL archive 2820/1.

The inherent error of a Transit fix could be measured by operating the receiver at a fixed location and observing the scatter of fixes. This measurement was the first experiment to be performed in November 1968 at NIO with the Magnavox 702CA receiver. Gulliver's report[26], which drew on contributions by Crease, Fasham and others, details the analysis of 29 satellite passes between 9–29 November 1968 and arrived at "*an accuracy of better than 0.05M*". From Figure 4, rather than accuracy, the conclusion today would be that the circular error probable was about 0.05M. Gulliver did note that his analysis was, "*more concerned with relative rather than absolute accuracy of fixes*", an aim confirmed by Crease recalling that there was no thought of taking the equipment to a precisely known location, e.g. Greenwich Observatory. Consistent relative accuracy was more important than absolute accuracy in some key applications, such as tracking neutrally buoyant Swallow floats.

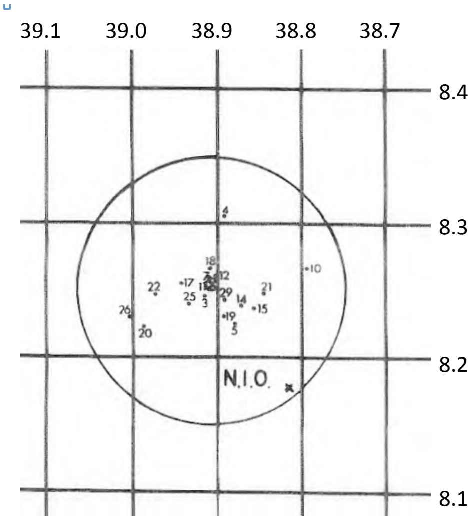

Figure 4. An expanded version of Appendix IX from Gulliver[26], the scales are in minutes, add 52˚ to the latitude scale. The NIO position 'X' was taken from a 6" to 1 mile Ordnance Survey map, with the mean of the Transit fixes being offset nearly 0.1M at 324˚. A January 1970 revised position for NIO, noted in a corrigenda to the report, reduced this mean offset to 0.03M at 0˚.

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[26] https://eprints.soton.ac.uk/392321/1/1189186-1001.pdf

Transit navigation on RRS **Discovery**

After this experiment at Wormley the system was installed on RRS *Discovery* in advance of Cruise 25 (MEDOC – a joint UK, French and US physics experiment) that commenced on 25 January 1969. The installation took place in Aberdeen but was not without incident as the ship moved back and forth whilst a shore-side crane with a suspended man bucket provided the platform from which the antenna was fitted to the foremast. The instrument rack of equipment was placed in the Chart Room aft of the Wheelhouse with the Teletype on the Wheelhouse chart table. At sea all went well[27]:

> *"Satellite navigator – no problems arose with this interface. Reliable fixes were obtained and errors that arose were due to the need for manual intervention through lack of a complete program set".*

By November 1972 a second antenna was installed above the Wheelhouse and a second receiver, a Magnavox 702A-3, had been bought to provide redundancy. On *Discovery* Cruise 51, "*The new receiver was not run routinely but towards the end of the second leg we were able to sample its data*"[21].

R.C. Searle and M. Beney, when implementing the Eötvos correction to underway gravity data (a correction dependent on the east-west speed of the ship over ground) on *Discovery* Cruise 84 in 1977, concluded that, "*The problem* [of steps in the Free Air Anomaly] *could be overcome if more sophisticated navigation software were available to make a "best fit" of track to fixes, rather than forcing the track to pass through every fix*". Their interim solution was to use their gravity data to assess the quality of the Transit fixes, in so doing they rejected up to 40% of daily fixes[28].

In late 1979, in advance of *Discovery* Cruise 106, Research Vessel Base (RVB) staff installed a Magnavox MX1107 new generation receiver, Figure 5, whilst the vessel was in refit at South Shields[29]. The microcomputer technology in the MX1107 gave more functionality over the 702CA, including a self-test that ran automatically every two hours. The MX1107 gave the Officer of the Watch a continuous display of latitude, longitude and time (GMT) and continuous DR between satellite fixes with automatic speed and heading inputs. In addition to the basic navigation functions, the system determined and compensated for unknown set and drift, provided great circle and rhumb line range and bearing to any selected waypoint and determined the heading to steer to these waypoints. Size was also a big difference, with the 702CA taking an instrument rack whilst the MX1107 was freestanding within a yoke approximately 35cm x 30cm x 30cm.

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[27] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d25.pdf

[28] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d84.pdf

[29] Positions from the MX1107 on *Discovery* were still being logged at least as late as August 1995.

Figure 5. Magnavox MX1107 receiver, courtesy Colin Beatty.

J. Sherwood and C. Paulson of RVB compared the positions from the MX1107 and the 702A-3 on Cruise 107, finding that,[30] "*the two systems usually agreed to within 1/6 mile and rarely differed by more than 1/3 mile*". Specific sections on navigation became less common in subsequent cruise reports, often being subsumed into the computing section and covered by RVB rather than Wormley staff.

Dead-Reckoning

Dead-reckoning (DR) is the age-old method of estimating present position given a previous position fix from a primary navigation aid and the vector distance travelled, resolved to latitude and longitude. A more refined version recalulates the DR position between a previous and a current primary navigation position fix using a best-fit algorithm. On research ships during this era the vector distance travelled was usually determined via a log to measure speed through the water and a gyrocompass for heading.

Speed

The measurement of a ship's speed through the water is just one instance of the more general problem of flow measurement. In the early 1950s T.R. Barber and M.J. Tucker at NIO had been working to develop and use electromagnetic (EM) flow meters to measure currents at sea. Refinements and a reduction in size led to the seminal work by K.F. Bowden (NIO then Liverpool University) and colleagues on turbulent fluctuations in a tidal current[31].

However, it was not until ten years later that N.D. Smith at Wormley adapted a Bowden flow meter (borrowed from Liverpool) for use as an experimental two-component speed log on RRS *Discovery* Cruise 10 in 1966. This EM log was on the end of a 50cm spar fitted through a gland on the plate at the bottom of *Discovery*'s ASDIC trunk. The two analogue voltage outputs were recorded on a Leeds and Northrup chart recorder together with a trace for the ship's heading for further analysis by hand. Importantly, the two components - fore/aft and athwartships - enabled J.C. Swallow to study the dependence of *Discovery*'s leeward motion on wind and ship's

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[30] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d107.pdf

[31] Bowden, K.F. and Fairbairn, L.A., 1956. Measurements of turbulent fluctuations and Reynolds stresses in a tidal current. *Proc. Roy. Soc. A: Math. Phys. & Eng. Sci.*, 237: 422-438.

speed thereby improving the quality of DR navigation between position fixes[32]. Smith's experiments identified several weaknesses in the experimental EM log, including drift in the measurements of up to a knot after some weeks in the water[11]. Characteristically, Swallow used the opportunity of the ship being stopped just outside Funchal, Madeira on 18 March 1966, with no wind, to investigate:

> *"Electrical zero has drifted on Channel A in particular. This due to imbalance of double triode output from phase-sensitive rectifier. ... We really need to build in a shorting contact to put a check zero on every hour or so"*[33].

However, the results showed sufficient promise to pursue further developments.

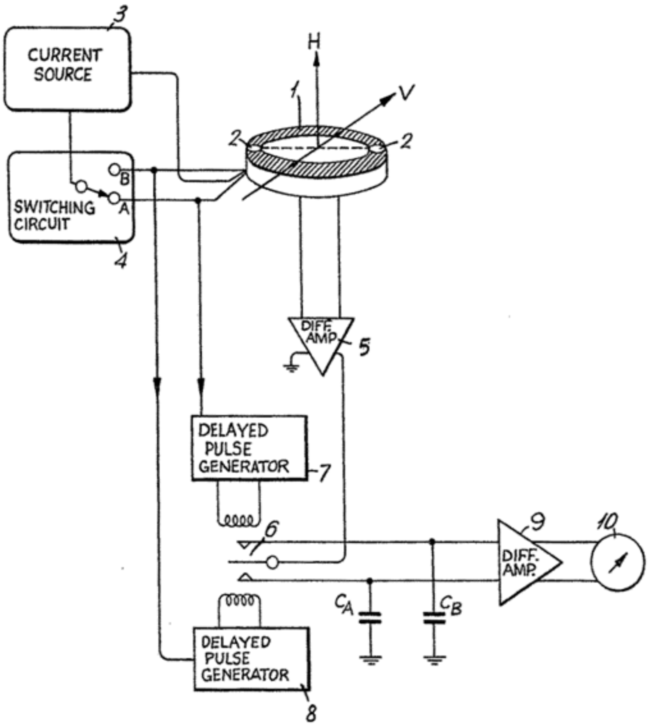

Figure 6. Diagram of the patented 1968 EM log as developed at NIO by Tucker and colleagues (from patent GB1235482).

Those further developments by Tucker, Smith and E.P. Collins at NIO were sufficiently fundamental that a patent application was filed in 1968 and published[34] in 1971. The fundamental innovation was to change from a sinusoidal drive to the coil to a periodically reversing direct current (DC) and measuring the difference in induced potentials for the two polarities only after transient effects due to electrode effects, stray capacity and inductance had died down (20 milliseconds), Figure 6. This arrangement resulted in a stability of about 0.1 knot in still water. Further details were published in Nature[35] and the Journal of Navigation[36].

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[32] NIO Annual Report for 1965/66.

[33] From J.C. Swallow notebook May 1960-June 1967. Archives of the National Oceanographic Library, Vol. 2, p. 296. Available at http://viewer.soton.ac.uk/nol/image/24222/296/

[34] Patent available at https://tinyurl.com/y8adthgz

[35] Tucker, M.J., Smith, N.D. and Collins, E.P., 1968. Two-component electromagnetic ship's log, *Nature*, 217: 1244

[36] Tucker, M.J., Smith, N.D., Pierce, F.E. and Collins, E.P., 1970. A two-component electromagnetic ship's log. *J. Nav.*, *23*: 302-316.

Analogue outputs from this EM log were logged by the IBM 1800 computer towards the end of the first cruise with the IBM 1800 onboard in January-March 1969. At that time the log was still installed as a temporary fixing in the ASDIC trunk. By August 1969 the log was in a permanant position on the starboard side of the cofferdam, with a second unit later placed symmetrically on the port side, Figure 7. It was on this cruise (*Discovery* Cruise 29) that the two-component EM log data was first used with Transit satellite fixes in the automatic generation by the IBM 1800 of position estimates between satellite fixes and "*closure error between dead reckoning and fixes attributed to surface currents*" were listed on demand every 200 minutes[37] following the work of M.J. Fasham, J. Crease, J. Berry, J. Sherwood and R. Howarth.

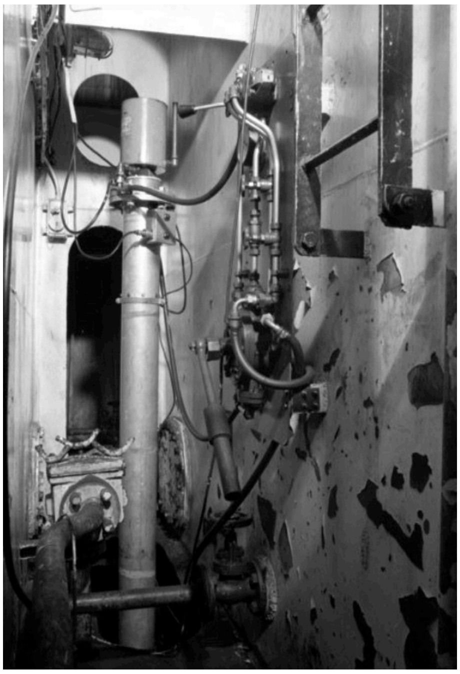

Figure 7. The Colnbrook EM Log spar (vertical tube just left of centre) on RRS *Discovery* was deployed and retracted using a hand pumped hydraulic system (large lever in the middle, with the small lever above to select up or down). Courtesy National Oceanographic Library/NOC, NOL archive 4619/2.

This practical success of the EM log led to a licence to manufacture the sensing head and the associated electronics being granted to Colnbrook Instrument Development Ltd.[38]. A 1971 booklet on *Discovery* noted that the log was being produced commerically, but there were still teething issues with temperature dependent zero drift with the Mk1 commercial electronics reported in 1973[39]. After "*a simple circuit modification*" six pre-production units were constructed for evaluation.

The Colnbook EM Logs on *Discovery* came with a default calibration of 4 knots per volt and the fore/aft component was assumed to be perfectly aligned with the centreline of the ship's hull. A more accurate calibration could be achieved by deriving the ship's speed through the water from measuring the rate of change of range to an acoustic transponder fitted beneath a surface buoy. As an example, the calibration of the port EM Log on *Discovery* Cruise 162 in September

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[37] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d29.pdf

[38] A productive relationship developed with Colnbook, and other technologies developed at Wormley were licensed to the company. The Colnbook factory had closed by 1994.

[39] See the entry in the IOS 1973/74 Annual Report at http://viewer.soton.ac.uk/nol/image/24081/35/#head

1986 by Swallow and Pollard took three hours for four runs at 2, 4, 6 and 8 knots for the fore/aft component[40]. A "*very satisfactory*" calibration (in knots) was obtained:

Vfore/aft(true) = 0.93145 * Vfore/aft(nominal)+0.1955

This was followed by lying to for 15 minutes with the light wind on the port and starboard beams to calibrate the athwartships component:

Vathwartships(true) = 0.962 * Vathwarthships(nominal) -0.015

The misalignment angle was estimated as 1.7° (clockwise) but as the results varied by about 2° over the speed range the covariance approach of Fasham[41] did not produce a sensible result. As was often the case, this calibration was carried over to subsequent cruises.

Heading

Throughout the period covered by this article the gyrocompass was the standard instrument used to determine heading from true north to combine with speed for DR. Being essential navigation instruments access to their outputs for science was on the basis of not interrupting marine operations – an area of great trepidation for those connecting a new instrument. Few get to see the actual gyrocompasses (two instruments were invariably installed to provide resilient redundancy) since they are usually mounted in a small room close to the ship's centre of gravity. On RRS *Discovery* at build there was a Sperry Mk20 and an Arma Mk10 in the Gravimeter Room on the Upper Deck. A switchable distribution system fed signals (three-phase synchro or stepper) to multiple repeaters located around the ship (the bridge, port and starboard bridge wings, a number of laboratories and in the steering flat). As part of *Discovery*'s 1991/92 extension and refit two S.G. Brown 1000 gyrocompass systems were installed.

Over the years logging heading from the gyrocompass has taken several forms, initially by pencil and paper, then, with the introduction of the IBM 1800 computer in 1969, by fitting a shaft encoder with a grey-code optically-read disk to the bearing repeater in the computer room (Figure 8), there followed an electronic synchro-to-digital converter and, for the S.G. Brown 1000 gyrocompasses, serial data signals in an NMEA format.

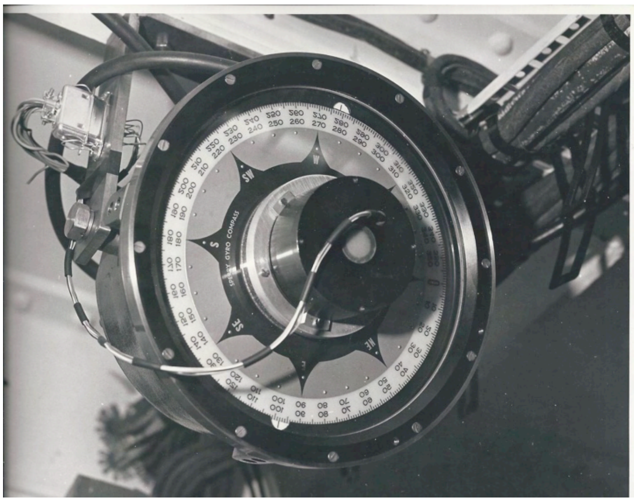

Figure 8. A shaft encoder (black cylinder) fitted to the gyrocompass bearing repeater in the RRS *Discovery* computer room in late 1969 to provide data to the IBM 1800. Courtesy National Oceanographic Library/NOC, NOL Archive 2818/13.

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[40] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/d162.pdf

[41] Fasham, M.J.R., 1976. Misalignment angle and calibration of a two-component electromagnetic log. *J. Nav. 29*: 76-81.

The effects of gravity and the earth's rotation on a spinning gyroscope are used in survey grade gyrocompasses to reduce errors. However, errors can still occur for short periods arising from rapid changes in speed or direction (Schuler oscillations). The ship's speed and latitude also lead to heading errors; manufacturers provide means to compensate for these errors using settings on the gyrocompass itself. While ship's officers would periodically check the heading taken from either the port or starboard bridge wing repeater against the known heading of a celestial object, scientific parties rarely took notice. It was only in the late 1980s, following installation of acoustic Doppler current profilers (ADCP) to the research ships, that gyrocompass heading errors were seen to be the cause of spurious cross-track currents on ADCPs. While the report[42] for RRS *Charles Darwin* Cruise 58/59 in 1991 shows that ship's officers were asked to take celestial checks of the gyrocompass at least twice a day, if conditions allowed, the fact that Table 5 in the report does not include notes of ship's speed and heading shows that the problem was not yet fully understood.

Research into alternatives to mechanical gyrocompasses in the 1970s and 80s examined several alternatives. One project at the Admiralty Compass Observatory (ACO) at Slough (which became the Navigation Department of the Admiralty Surface Weapons Establishment) investigated the possibility of "communicating with" spinning atomic nuclei using Nuclear Magnetic Resonance[43]. Tim Crocker recalls that he "was dispatched by Brian McCartney" to the ACO for a briefing on what could have been a breakthrough technology. Unfortunately, it turned out that the method measured earth-relative rather than absolute-in-space angles - resulting in a gyroscope and not a north-seeking gyrocompass.

It was only with the advent of specialised GPS-derived heading measurements that the errors and uncompensated variations in research ship gyrocompasses were fully established. In August 1992 B.A. King working with E.B. Cooper of RVS installed on the *Discovery* a four-antenna Ashtech GPS 3DF set for determining attitude, including heading, to an accuracy of better than 0.1° [44,]. Their measurements showed heading-dependent gyrocompass errors of up to 3°, subsequent work led to a post-processing method to correct the gyrocompass for those data sets where it mattered.

Collating navigation data: RRS *Discovery*'s IBM 1800 computer

One of the factors that led to the installation in January 1969 of an IBM 1800 process control computer on RRS *Discovery* was that the growing requirements of science programmes meant that[45], "*Navigational demands on the deck officers were becoming heavy*". Fasham[13] provided an overview of the IBM 1800 system over its first year of operation, describing the digital interface to the shaft encoder for the gyrocompass, the analogue interface for the EM log and the digital interface to the 702CA Transit receiver. Direct input of LORAN fixes awaited the delivery of the new Decca DL21 receiver, and for Decca a "*four pattern sine/cosine converter has been ordered, that can be connected to the existing Decca (or a HI-FIX) receiver to give BCD (Binary Coded Decimal) output of the lane number*". Clearly 1969 and 1970 were years of transition.

Data acquisition and reduction for the 702CA Transit satellite navigation receiver

The Magnavox 702 series of Transit receivers installed on *Discovery* did not output position fixes; that was a capability not seen until a decade later with the MX1107 in 1979. In summary,

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[42] https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/cd58_59.pdf

[43] Potts, S.P. and Preston, J., 1981. A cryogenic nuclear magnetic resonance gyroscope. *Journal of Navigation*, *34*(1), pp.19-37.

[44] King, B.A. and Cooper, E.B., 1993. Comparison of ship's heading determined from an array of GPS antennas with heading from conventional gyrocompass measurements. *Deep Sea Research Part I*. *40*: 2207-2216.

[45] Crease, J., 1971. Experience with a Computer in Oceanographic Research at Sea. *J. Nav. 24*: 294-299.

here is what Wormley staff had to program for the IBM 1800 to arrive at position fixes, the details are in Crease[46]:

- Calculate the satellite position at exact even minute boundaries. This required an IBM 1800 assembler program to parse the 6103 binary bits of data transmitted by Transit satellites every two minutes that included the orbital parameters from which the satellite position could be calculated[23]. This input program was, "*a direct adaption of one by E. Caughran of IBM at Scripps",* this was for the IBM 1800 that had been installed on the RV *Thomas Washington* in June 1967.
- Given the inevitability of dropouts and or data corruption there was redundancy in the transmitted message and the fixed orbital parameters were the same in other messages. It was for the programmer to select and code a method to arrive at error-free orbit parameters.
- An estimate of the current position was needed, followed by a computation of the slant range from that estimated position to each satellite position at a two minute boundary during a pass. The estimated ship's position at each two minute boundary would be updated from the estimated position shift from the EM log and gyro information.
- The receiver provided counts of the Doppler frequency shift, accumulated over two minutes, between the satellite's transmission frequencies of 150 and 400MHz and its own internal high stability oscillator. The IBM 1800 program had to calculate changes in slant range from the Doppler, compare with those calculated from the estimated ship's position, form residual differences for latitude and longitude, and then by adjusting the ship's assumed position minimise the root mean square residuals over the set of two minute intervals forming a pass.
- In the real world, not all of the two minute intervals contained full sets of Doppler counts. For example, of the 29 satellite passes during the 1968 tests at NIO 17 had some missing Doppler information. Gulliver[26] describes a simple ratio and manual curve-fitting technique to estimate the missing Doppler values to use in the position fix calculations, with an example of a fix using estimated missing Dopplers giving a, "*radial distance of 0.056M from the accepted position*".
- Subsequent extensions to the programming led to fully automatic position fixes without operator intervention, with Crease[45] noting in 1971 that, "*it is only recently that we are beginning to recover the quality of fix achieved in those early stages*" as their automated rejection criteria improved and with reduced uncertainty in the ship's velocity.

The form of the navigation fix printout on 4 April 1970 during *Discovery* Cruise 32 is shown in Figure 9. This suggests that the fix put the ship at 1512 hours 1.05' south and 26.13' east (1.05M south and 16.6M east) of the DR position at 1520. Unfortunately we cannot say how long the ship had been running under DR before this fix, or indeed whether the fix was sensible. As the EM log measured speed through the water the difference between the DR and satellite-inferred position could be ascribed to a surface current; if that current was not sensible, the satellite fix might be of doubtful accuracy.

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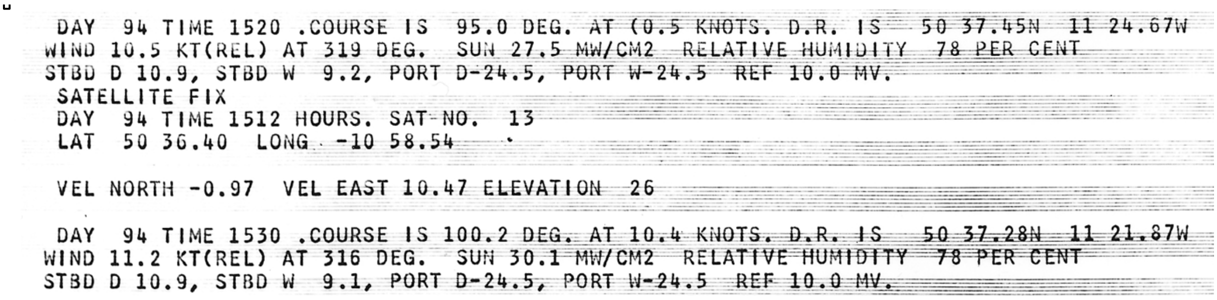
[46] https://eprints.soton.ac.uk/392401/1/1194197-1001.pdf



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 DAY  94 TIME 1520 .COURSE IS  95.0 DEG. AT (0.5 KNOTS. D.R. IS   50 37.45N  11 24.67W
WIND 10.5 KT(REL) AT 319 DEG.  SUN 27.5 MW/CM2  RELATIVE HUMIDITY  78 PER CENT
STBD D 10.9, STBD W  9.2, PORT D-24.5, PORT W-24.5  REF 10.0 MV.
 SATELLITE FIX
 DAY  94 TIME 1512 HOURS. SAT-NO.  13
 LAT  50 36.40  LONG  -10 58.54

 VEL NORTH -0.97  VEL EAST 10.47 ELEVATION  26

 DAY  94 TIME 1530 .COURSE IS 100.2 DEG. AT 10.4 KNOTS. D.R. IS   50 37.28N  11 21.87W
WIND 11.2 KT(REL) AT 316 DEG.  SUN 30.1 MW/CM2  RELATIVE HUMIDITY  78 PER CENT
STBD D 10.9, STBD W  9.1, PORT D-24.5, PORT W-24.5  REF 10.0 MV.
```

Figure 9. Example printout of a navigation fix from the IBM 1800 program on 4 April 1970. Courtesy National Oceanographic Library/NOC, NOL image 2905-5.

Example of scientific use: EM Log and satellite fixes to derive surface currents

While rarely documented in cruise reports there was collaboration between deck officers and scientists to try and get the navigation right, especially in the pre-GPS era covered in this article. As has already been mentioned, arriving at sensible surface current estimates is a good test of accurate navigation fixes and DR. J. Gould[47] recalls that Geoff Howe (Chief Officer then Master of RRS *Discovery*), "*was a great ally in this regard and collected surface current estimates off his own bat*".

An example of the scientific usefulness of surface currents derived from the difference between satellite position fixes and dead reckoning using *Discovery*'s two-component EM Log is in Quadfasel and Schott (1979)[48]. In their paper, the combined surface currents (Figure 10) determined from *Discovery* and the US research vessels *Columbus Iselin* and *Researcher* off the coasts of Kenya and Somalia clearly showed two surface gyres with their associated regions of upwelling.

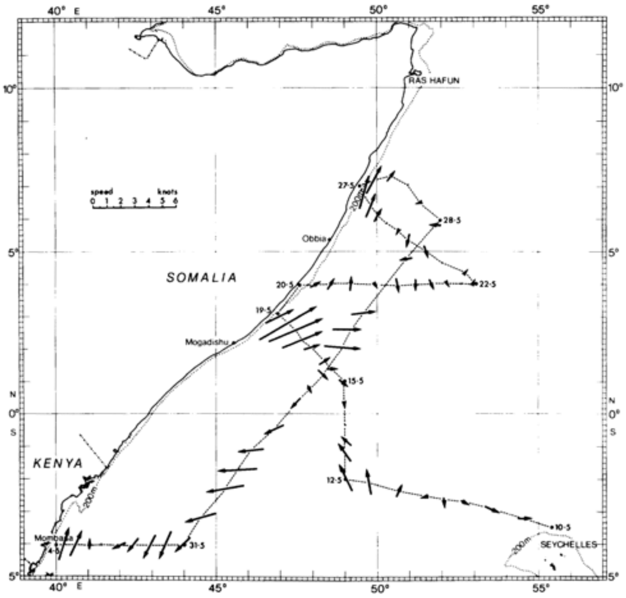

Figure 10. Surface currents in the North West Indian Ocean on *Discovery* in May-June 1979 obtained from difference between EM Log dead-reckoning and Transit satellite fixes[49].

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[47] Personal communication, June 2017.

[48] Quadfasel, D.R. and Schott, F., 1982. Water-mass distributions at intermediate layers off the Somali Coast during the onset of the southwest monsoon, 1979. *J. Phys. Oceanog.*, *12*: 1358-1372.

[49] Swallow, J.C., 1979. RRS *Discovery* Cruise 102, 10 May - 6 July 1979. Physical oceanography studies in the western Equatorial Indian Ocean: a contribution to the FGGE oceanographic programme, IOS Report 83 available at https://eprints.soton.ac.uk/14104/