Photo 1. Endeavour, pictured on he maiden voyage off Freemantle (Credit, John Lancaster)

Marine NAVIGATION TECHNOLOGY

by Douglas Clarkson

GPS Navigation is the latest aid for ships to find their way around the globe but the prime catalyst for advances in marine navigation technology has been determined by military expediency. Both World Wars and the Cold War, set in train episodes of rapid technological advance which have resulted in today's diverse set of marine navigation aids.

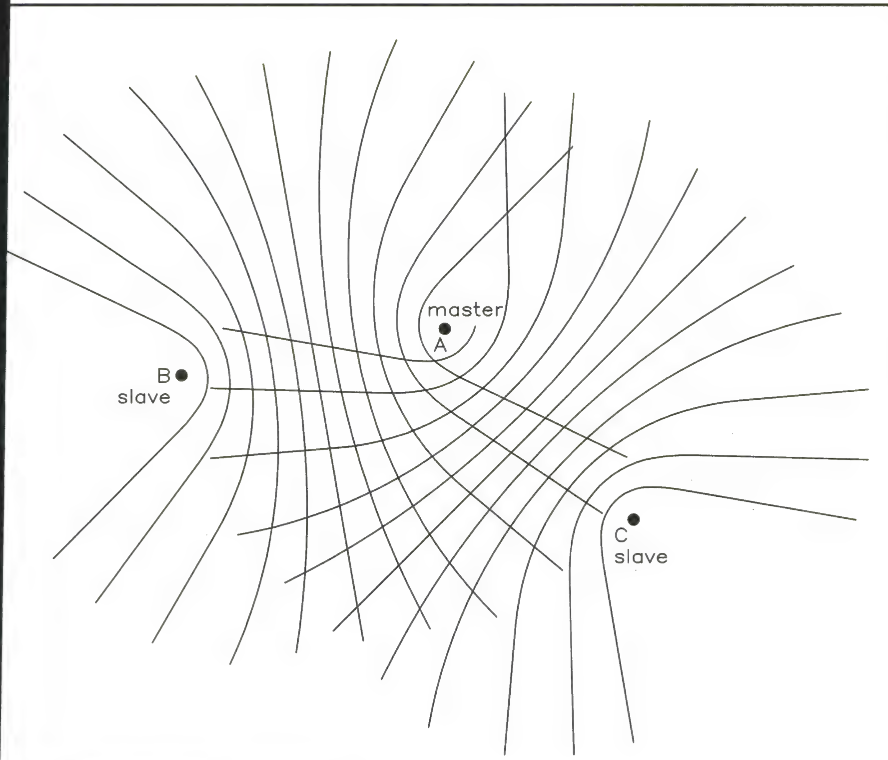
GPS Navigation systems will no doubt make other less accurate forms of marine navigation obsolete. There ar some though that have reservations about being in thrall to essentially a military installation and the accuracy for public use i reduced for reasons of national security. Wh not have a dedicated commercial system wit higher resolution than public access GPS? The answer may be the price tag.

Sea-going vessels, are likely to retain backup systems for navigation using independent technologies such as LORAN C Also, marine navigation on ships tends to be undertaken with an integrated system of connected equipment. Although GPS is taking on a dominant role for positional data other systems such as gyro compass and radar provide key information about ship status and navigation safety.

Also, with increasing technology available, it could be imagined that this would in turn lead towards safer seas. The trend towards use of flags of convenience, and use of inadequately trained and experienced crews is a worrying one. Safety is not totally about technology.

The Return of the Tall Ships

The abiding interest in Tall Ships, is an indication that in an age with ever more complex technology, the attraction of the elements of the sea is itself as strong as ever Modern day replicas such as the *Endeavour*



igure 1. Cartoid signal response of win loop plus vertical aerial element.

wn in Photo 1, are very much kitted out n state-of-the-art marine navigation hnology, though it is discretely hidden to intain an appropriate aura of history.

n the USA, the clipper *Pride of Baltimore,* ially launched in 1977 as a promotion for city namesake, perished in a storm near erto Rico in 1986 with the tragic loss of the otain and three crew. The ship has since en rebuilt as *Pride of Baltimore II* and ed out with advanced navigation hnology. It was launched in 1988.

The fascinating world of the Tall Ship has particular been brought to life by the otographer Max Mudie, based in nington in the UK. Photo 2 shows a ssic image of the ship Nelson with the n behind its sails.

he Magnetic Compass

the time when all manner of exploits re being undertaken to determine the ngitude accurately, the use of magnetic mpasses on ships was generally poorly derstood and with them typically being fective in operation. This was principally cause the nature of magnetic fields was orly understood. Even navigators as pert as Captain Cook were apparently not are of the influence of iron objects on mpass bearing.

As ships began to be constructed in iron d steel, problems in determining agnetic compass bearing became more ute. Ships themselves became, in effect, rmanent magnets whose field dwarfed at of the Earth.

It was only around 1835 that the compass aring of ships at sea began to be mpared against fixed land-based bearings. so, it was understood that compasses on quayside could be influenced by a erthed ship. More to the point, it became apparent that two ships sailing close to each other could cause deviation in each others' magnetic compasses. Contributions from Sir George Airy in 1837 and Archibald Smith during the 1840s further developed models of compass behaviour and corresponding correction. Further significant work was undertaken by William Thompson – later to be known as Lord Kelvin – who patented in 1876 a compass with various adjustments to correct for known errors associated with a ship's own magnetism. Short, powerful magnets were used and mounted on a dry card, which itself was pivoted on knife edges.

Since submarines were totally enclosed metal surfaces, it was impossible to operate a magnetic compass within one. It was possible, however, to implement a magnetic compass on the upper coning of the submarine and in turn, view this through specialist projector optics.

Eventually, a liquid-filled compass would find widest acceptance to cope with more abrupt changes of course. But as the magnetic compass was being perfected, the gyro compass was being developed – initially for military applications.

Waves Around the World

One of the earliest applications of radio in navigation was that of radio direction finding, i.e., the determination of bearing with reference to a fixed transmitter. Where a simple vertical coil is rotated in the reference frame of a horizontally propagated radio wave, a zero of signal occurs when the coil axis is parallel to the incident beam and at a maximum where it is at right angles to it. This gives two possible bearings, 180° apart at null signal. By adding a component of a simple vertical aerial and changing its phase relative to the loop by 90°, a cartoid polar diagram, as indicated in Figure 1, is obtained.

Variations in detecting coil design were developed, based on rotating a crossed loop antennae and decoding the received signal amplitudes of each coil.

In terms of direction finding systems, some effort was directed towards complexity of the transmitter and with utilising a very basic receiver. One trial system developed by Telefunken consisted of an array of 32 receiving antennae – each aligned to a point on the compass. Initially,

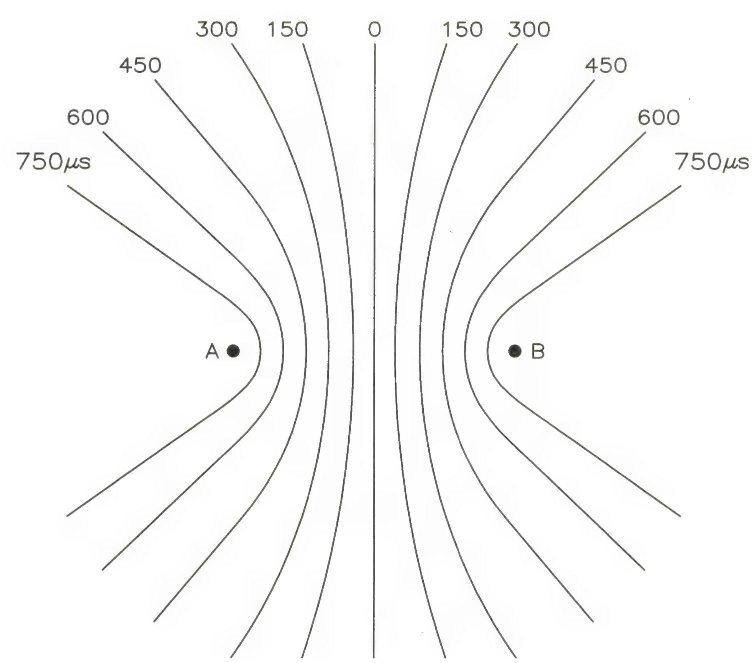


Figure 2. Loci of location of zero time difference in signal reception is also on the centreline and with loci of constant time difference along parabolas.

all antennae were activated, followed at regular intervals by the single antenna at specific compass points. By decoding the line at which the loudest single beam was detected, the direction could be determined to an accuracy of around 10°. Such a system was used in the bombing of London by Zeppelins during the First World War.

A revised system developed by Marconi was a more developed 'wireless lighthouse' – where a revolving paraboloid antennae system rotated one revolution every 2 minutes with a different letter of the alphabet radiated in each sector. By reducing the signal until only the loudest signal remained, the radial could be identified. This system, installed at Inchkeith in 1921, used a 50MHz signal.

While directional signals with individual transmitters could give useful bearing data when used singly and appropriate bearing data when used in pairs, there was a perceived need to determine position when distant from land surfaces and possibly in conditions of darkness or cloud. Considering Figure 2, where transmitters A and B are synchronised to radiate at exactly the same time (pulsed), the locus of zero time difference of receiver stations will be along the centre line. The locus of constant time differences will occur on parabolas passing across the baseline between the two transmitters.

Thus, in Figure 2, for transmitters A and B, a series of patterns is developed. An observation of a delay, for example, of 450μs, limits position to lie on two separate parabolas on opposite sides of the baseline. When this is combined with another baseline series involving another slave transmitter, a more exact determination of position is possible. Also, in practical terms, the navigation position is probably known to within a few tens of miles in any case.

One of the most widely used hyperbolic systems, LORAN C, is now discussed.

LORAN C

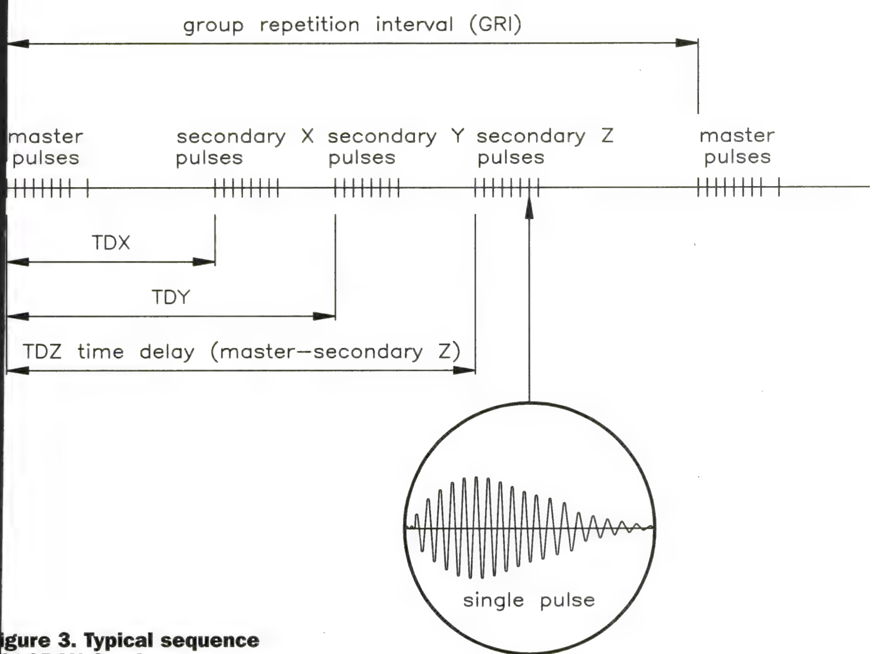
LORAN C, which developed out of LORAN A during World War II, was first implemented in 1957 and now covers major shipping routes, particularly around North America, the Atlantic and Europe along the Mediterranean. Although being replaced by GPS as the prime reference system for navigation, it is still being retained as a backup system for the foreseeable future.

Figure 3 indicates a typical display of pulses. In a given chain, the order of master, slave pulses is constant for anywhere in a receiving chain. This simplifies decoding techniques. These different chains are identified by the Pulse Repetition Frequency (PRF) of the chain master. In the North Atlantic, the 7930 chain has a PRF corresponding to a cycle period of 79,300μs.

The initial LORAN A consisted of a single series of pulses from a master and slave. LORAN C provides relative phase differences between alternate pulses.

Errors associated with this technique include variability of speed of propagation over different surfaces such as land, sea or ice. Also, signals can be modified within the

Photo 2. Image of the Tall Ship Nelson with the sun behind its sails. (Copyright Max Mudie).



igure 3. Typical sequence f LORAN C pulses.

hour daily cycle of propagation changes he ionosphere.

ORAN C lattice tables are published for as of coverage with included erposition values of chain coverage. ors are least on the baseline and increase y from it. Signals are typically broadcast 00kHz. Usually, detectors detect the 3rd le tracking point in the sharply rising se shape. Accuracies of between 50 to 0ft. are routinely achieved in areas with od signal coverage. Hyperbolic systems h as LORAN C, however, have good eatability.

onne and Consol

e Consol system was developed from the nne system used by Germany during rld War II – in particular, being used to e bearings to U boat commanders. hough Consol is more of historical interest w as a means of navigation, it is relevant to scribe the techniques used. As a word of rning, however, an understanding of nsol is not easy to obtain.

Consol was an example of a collapsed abola system. Rather than having a master d two slave transmitters separated by ndreds of kilometres, a series of transmitters , A0 and A2, are separated approximately 3 velengths apart. At an operational frequency 300kHz, this corresponds to the transmitters ing 3km apart.

The transmitters A1 and A2 alternately liate for 0·5s with the phase of the outer nsmitters maintained at +90° and -90° to e central transmitter and with this phase versed for 0·125s. Along hyperbolae lines, e phases of A1 and A2 will always cancel d an equisignal tone is heard. Where the nals of A1 and A2 are received in phase ring the 0·5s cycle, this will give rise to a ro signal and during the corresponding 125s antiphase cycle, no signal will be tected. The signal will be heard as a quence of dashes. Where the signals of A1 d A2 are received in anti-phase during the 0·5s cycle, this will give rise to a zero signal and during the corresponding 0·125s antiphase cycle, a brief signal will be detected. This will be heard as a sequence of dots.

As a static system, Consol would not be very useful. In any position, all that would be heard would be either dots, dashes or the equisignal. The usefulness of Consol, however, lay in the sweeping of phase during part of the transmitter output sequence so that equisignal lines were swept round the transmitter focus. By altering phase difference by equal and opposite amounts around the central A0 transmitter, the equisignal lines were typically swept clockwise in the upper half and counterclockwise in the lower half of an installation. The operator counted the corrected number of dots and dashes until an equisignal line was detected from the start of the phase sweep cycle. This gave a subdivision of 60 parts within a sector of the Consol system. A Consol system installed at one time at Stavanger in Norway had around 12 working sectors. At best, the system gave an angular error of 0·3° during the day and 0·7° at night.

The system could also broadcast a continuous tone for conventional direction finding (DF) bearing, in order to resolve sector ambiguity. The advantage of the system was to subdivide the sectors into at best 60 sub-units of angle.

Decca Navigator

While hyperbolic systems can provide location finding systems from relative time differences of signal between master and slave transmitters, use can also be made of relative phase differences. The Decca Navigator system can be traced to a system devised by W. J. O'Brien while working in the USA in 1937. This system was extensively developed for the Normandy landings in 1944.

Figure 4 shows the parabolic pattern of zero phase differences arising from two stations radiating in phase. A typical baseline pair separation would be 120km. A lane can be considered to exist between lines of zero phase difference. Within a lane, the system can further resolve phase into centi-lanes – corresponding to phase differences of 3·6°. While it is simple enough to determine the relative phase within a lane, the basic system does not resolve the lane corresponding to the parabolic phase difference.

To provide lane identification, master and slave transmitters will broadcast on a set of related frequencies, as outlined in Table 1.

In this example, the decoding system multiplies the master frequency by four and the red slave by three to derive a 340kHz signal for phase comparison with an associated lane width of 440m.

A key issue with such a system is lane identification. One option is, of course, to identify a lane by comparison with known landmarks and for the system to maintain a lane count as lanes are crossed. The system,

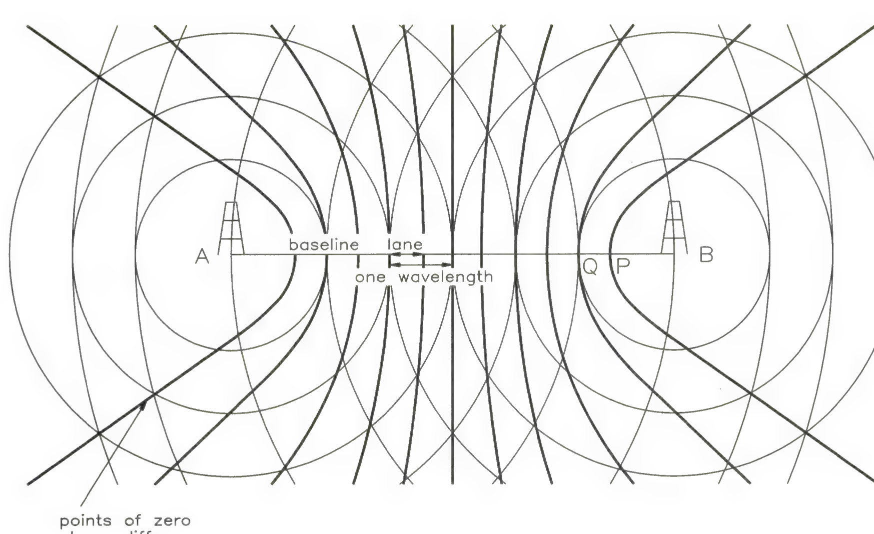


Figure 4. Hyperbolic pattern of zero phase differences arising from two stations operating the Decca navigator system.

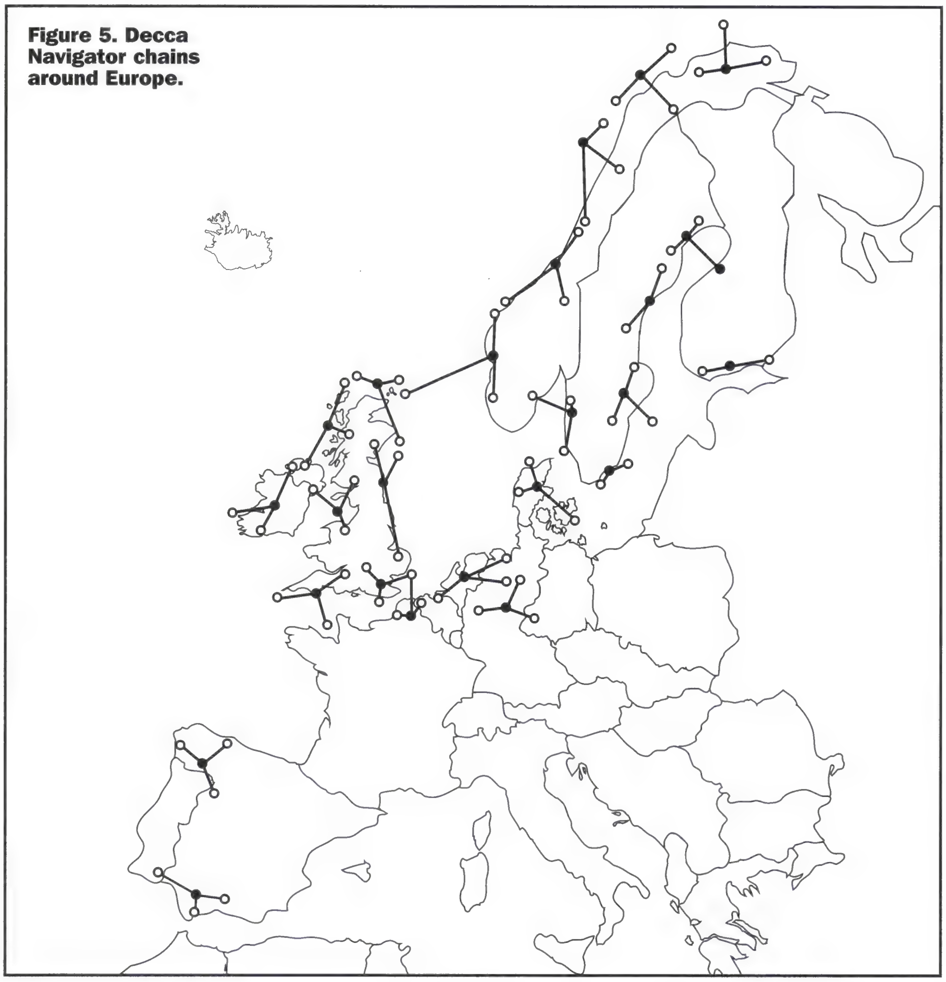


Figure 5. Decca Navigator chains around Europe.

however, allows each transmitter in turn to broadcast all the frequencies of the chain at the same time. This allows the relative phase of a signal at fundamental frequency f to be derived – in the case of the red chain, identifying lanes of width 10·5km wide. This in turn allows lane count to be re-established if lost. Figure 5 indicates the Decca Navigator chains around Europe.

Radar

In increasingly congested waters, the use of radar provides invaluable assistance in navigation. Historically, the great impetus to radar came with the advent of the Second World War. The development of the Magnetron in 1940 by a British team was a critical breakthrough in this field. Also, by rapidly communicating these details to the USA and utilising its extensive manufacturing capability, aircraft systems rapidly became available to hunt and destroy U boats in the North Atlantic and hence tip the balance of the war.

The principle of radar is simple – pulses are radiated and their echoes are detected. The frequency of the radar tends to be in the GHz range. A typical magnetron resonating at 10GHz will produce a wavelength of 3cm. The pulse duration is usually adjusted automatically with selected range.

Depending on range, the pulse duration of radars tends to be automatically selected. Thus, pulse lengths can be varied through 0·08, 0·25, 0·5 to 1·0μs to optimise clarity of image in varying range from around one nautical mile to 50 nautical miles. Options exist also to interface to a navigation system to indicate North Up display rather than the conventional 'heading up' display. The typical beam profile is indicated in Figure 6.

The shorter the pulse length, the higher the chance of resolving objects that are close together. As pulses are made shorter, however, less energy is radiated back and the system loses sensitivity. At the extremes of range, however, pulse lengths require to be longer to ensure sufficient energy is reflected back.

In the immediate vicinity of the transmitter, echoes from waves will tend to give the appearance of 'sea clutter'. This effect can be minimised by reducing the transmitter gain corresponding to the time associated with such 'sea clutter' echoes.

Rain can degrade radar performance by returning numerous reflections from raindrops. By taking effectively only the leading edge of signals for display purposes, such 'rain clutter' signals can typically be suppressed.

Specialised navigation buoys called racons retransmit the radar wavelength to draw attention to the buoy location. They appear as a point from which a fan like signal spreads out.

The conventional radar is always imagined as the rotating V antennae where microwa energy is focused in a narrow beam. In sm marine radars, however, use can be made small waveguide designs with accurately milled slots on one side. Increasingly, use i also being made of phased array technolog where an array of small copper pads is selectively energised to 'sweep' a beam in space in real time. The waveguide and pha array techniques provides effectively a rotating beam but without any moving par

The horizontal and vertical beam width also affect the quality of the display obtained. A typical horizontal beam width around 4° and that of the vertical around 25°. The greater vertical beam width ensu that as the boat rolls, the beam is not lost the sky or directed down into the sea – there will normally always be a portion of the radar beam propagating horizontally. terms of horizontal beam width, the narrower the beam, the better objects ca be separated.

The range of radar tends to be limited b the curvature of the Earth. For a height above the sea Ha in metres and a target height Ht in metres, the range R in nautic miles is given by:

$$R = 2{\cdot}2\,(Ha^{0\cdot5} + Ht^{0\cdot5})$$

Thus, for a height above sea of 3m, a bo some 10m high will be able to be detecte at around 11 nautical miles range. Thus, small boats have an inherent problem wit

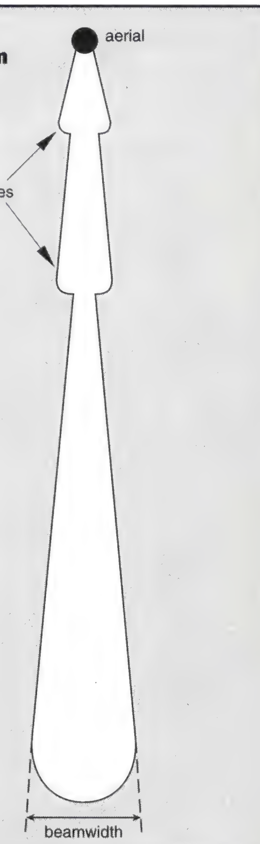


Figure 6. Typical beam profile of radar beam.

Location (kHz)	Harmonic (kHz)	Frequency width (m)	Harmonic	Frequency	Lane
Master	6f	85·00			
Purple	5f	70·83	30f	425	352
Red	8f	113·33	24f	340	440
Green	9f	127·5	18f	255	586

Table 1. Relationship of master transmitter to purple, red and green chains in English Channel (code 5B).

ge. It would be pointless, therefore, to all a 100 nautical mile range radar on a ll vessel.

n terms of radar technology, increasingly histicated systems are being produced smaller boats. Using slotted waveguide nnology, for example, the Navico R1000 vides peak pulse power of 1·5kW output n a continuous power consumption of than 30W. Target capture is offered from m to 16 nautical miles. The radone losed aerial is less than 30cm in diameter.

PS Technology

he 24 satellite GPS system, each satellite adcasts on two radio frequencies – L1 is typically at 1·57452GHz and L2 at 272GHz. These frequencies are selected multiples of a base atomic clock quency of 10·23MHz.

he L1 signal is in turn modulated with a h frequency P-code for precision ranging l a lower frequency coarse acquisition le – the CA-code. The L2 signal is dulated with a different P code. Subtle ativistic corrections have to be applied to atomic clocks onboard the satellites to ount for the different values of vitational field present between orbital sition and the notional surface of the th and also for the different values of bital velocity relative to the velocity at the rth's surface.

The P codes basically contain more ormation than the CA-code and fferential P code measurements can rrect for propagation errors through the mosphere.

A series of tracking stations with the adquarters at Colorado Springs in the SA compute the exact orbital path of each tellite. Is there any significance here that is was also the site chosen by Nicola Tesla r his famous set of experiments? emember, also, it was one of Tesla's goals use a transmitting site to communicate me to the entire world. Variations to rrect in the satellite trajectories include inute orbital drag, gravity anomalies on e surface of the Earth and variations in avity arising from the sun and the moon.

Measurements undertaken by typical GPS ceivers utilise pseudo range calculations, here the receiver locks onto a pseudo ndom signal from a satellite and performs erative calculations to determine the istance from the satellite. With each tellite radiating its 'absolute' positional formation relative to the surface of the arth, a GPS observer is able to fix an bsolute location – latitude, longitude and ltitude from four satellites. On the ocean urface – assumed to be on the zero of ltitude – readings from three satellites are ufficient to determine position.

Utilising GPS Technology

he use of GPS technology has introduced vholly new concepts into marine avigation. There is, however, more than ver the requirement to interface GPS echnology to other navigation equipment. This is achieved by means of the National Maritime Electronic Association (NMEA) interface language developed in the USA. Most low cost commercially available GPS systems exist as stand-alone units with no requirement for interfacing to other systems.

Not surprisingly in marine use, there is invariably added to GPS function various 'nautical' features. Thus, in addition to standard latitude, longitude, course over ground (COG), speed over ground (SOG), features present could include a position mark/man overboard function, anchor watch alarm, route planning and way point identification.

An array of systems now interface to maps of the world's waterways, with the software package identifying features such as channels, coastlines, listed navigation buoys, shallows, etc. By clicking on destination points on the display, automatic details of course setting to each point can be calculated. The set of Navionics Microchart codes are widely acknowledged as the best in their class. A useful feature also, is the Track History, where the logged position is tracked on the GPS display. In competitive sailing, the use of Speed over Ground (SOG) is ideal for optimising a boat's performance. This technology has, therefore, allowed boat performance – whether sail or power – to be monitored with a high level of accuracy and precision.

Systems also have a waypoint arrival alarm, which sounds when the boat comes within a certain preset range of a target waypoint. The anchor watch alarm function provides warning if the boat moves more than a set distance from a notionally stationery position. The use of GPS equipment in the marine environment requires additional levels of weatherproofing to be implemented.

Tiller Pilots

In large sailing vessels, the control of the tiller is typically augmented by a mechanical drive system. Tiller pilots are hand-held control units which allow rapid control of rudder function. Having typically port and starboard steerage changes of 1° or 10° steps, an 'auto tack' control will turn a sailing vessel directly when making a 90° course change. When tiller pilots are interfaced to other navigation aids, options such as steer to compass bearing, steer to wind setting and steer to GPS bearing can be implemented at the touch of a button. Thus, modern sea-going yacht races are very much undertaken using state-of-the-art high technology navigation tools.

Sonar Systems

The use of sonar systems in marine technology ranges over the need for a simple indication of depth of water beneath a boat to the detection of shoals of fish by trawler fleets. The velocity of sound in water is affected both by temperature and salinity. A velocity value of 1,500m/s is typically taken for water at 13° C and 35 part per thousand salinity. Variations of these values can cause errors of several percent to develop. There is also an effect of change of velocity with water depth, though in most typical applications, this error is not significant. Most low cost units (under £500) provide values of depth under the transducer with a resolution of 0·1m.

Sidney George Brown and the Gyro Compass

S. G. Brown was to patent over a thousand inventions in diverse fields, including those of submarine cables, signal repeater systems, the 'loud speaker', bone conduction systems for the deaf and radio direction finding systems. Born in Chicago in 1873 of English parents, the family returned to England in 1879. After distinguishing himself in many fields where his great practical and intuitive skills in science and technology become apparent, it was in the improvement of the gyroscope necessitated by the outbreak of war in 1914 for which he is principally remembered.

When S. G. Brown undertook the task of improving the gyro compass, the principle error of such systems was that any significant rolling motion of the ship caused the gyroscope to wander from its true indication. Brown solved this problem by detecting such motion and damping it before system accuracy could be degraded.

At one time, he was able to demonstrate a gyro compass which outperformed both the Sperry system from the USA and Anschultz design from Germany. Much to S. G. Brown's dismay, however, the Admiralty sold his patent to Sperry. Today, the company S. G. Brown still continues to make high quality gyroscopes and inertial guidance systems, principally for marine navigation. Photo 4 shows a model SGB 1000S – the 'offshore survey gyro standard' manufactured by S. G. Brown.

Basics of the Gyro Compass

Gyro compass technology is very complex. At the heart of a mechanical gyroscope is a wheel spinning at around 15,000rpm. This is associated with a vector of angular momentum which is considered to be invariant – unchanging if no forces act to degrade its value. If a gyroscope was set spinning with a fixed direction of angular

Photo 3. The model SGB 1000S – the 'offshore survey gyro standard' manufactured by S. G. Brown. (Courtesy, S. G. Brown).

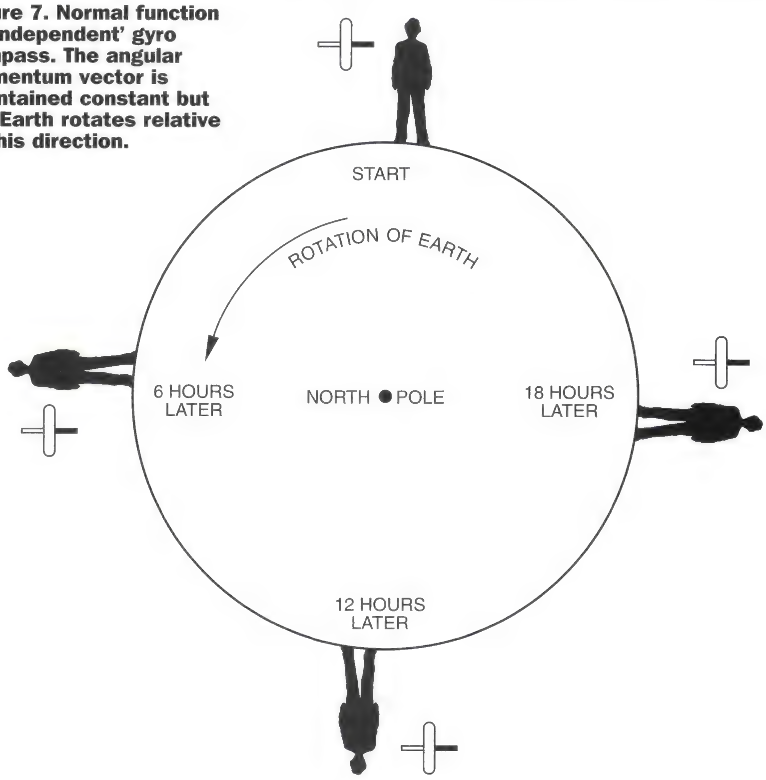


Figure 7. Normal function of 'independent' gyro compass. The angular momentum vector is maintained constant but the Earth rotates relative to this direction.

momentum then to an observer, the vector would appear to change – with the rotation of the Earth, as indicated in Figure 7.

If a weight is hung on a support bar under the spinning wheel, this acts to turn the gyroscope axis to a north south direction. This is the direction to which the gyro compass will remain aligned, as indicated in Figure 8.

In addition to determining heading, the gyro compass will also indicate pitch and roll. Conventional gyro compasses also have a finite settle time to take up a correct heading. This is typically around 10 minutes at dockside and 20 minutes at sea. Ships sailing under IMO rules must have an operational gyroscope system before sailing.

Corrections required to be supplied to typical gimballed mechanical gyro compasses include latitude and craft speed for which NEMEA 0183 interface connection is typically used. Most conventional gyro compasses are designed to operate between 80° north latitude and 80° south latitude. Also, gimbal limits of ±45° of roll are typically specified.

Specialist 'gyropilot' systems interface using NMEA 0183 to gyro compasses for automatic control of rudder steering systems. Such systems give indication of heading and rudder angle and in particula provide essential data for rudder control for the steering of large vessels. Photo 5 shows the NT 925G Universal Autopilot, manufactured by Navitron Systems Ltd., which control other ship systems based o signals from a master gyroscope.

Gyro compass technology, however, is rapidly developing. Recently developed systems use solid-state accelerometer type devices, either singly or in association with ring laser technology.

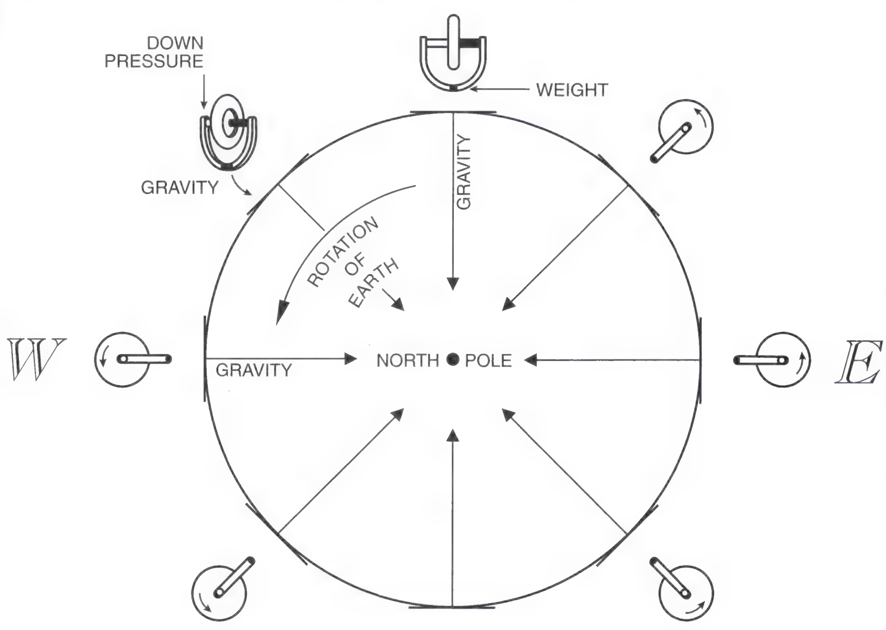


Figure 8. The addition of a weight to the support axle acts to align the gyro compass true north-south.

Summary

A wide range of navigational systems are used in marine navigation technology. The trend is towards integrating as many discrete systems together and utilising GPS as the prime system for determining position and derived qualities such as speed over ground (SOG) and course over ground (COG). The existing positional accuracy of GPS is entirely adequate for maritime navigation purposes. A study of this field, however, reveals the great ingenuity directed towards navigation, in particular, with diverse methods of surface-based radio location systems.

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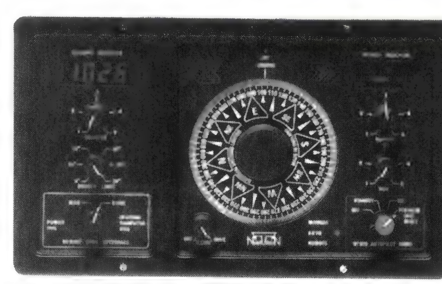

Photo 4. The NT 925G Universal Autopilot, manufactured by Navitron Systems Ltd. (Courtesy, Navitron Systems).

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