Electronic Navigation Systems

3rd edition

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Routledge
Taylor & Francis Group
LONDON AND NEW YORK

First published as *Electronic Aids to Navigation* 1986
Second edition published as *Electronic Aids to Navigation: Position Fixing* 1991
Third edition 2001
First published by Butterworth-Heinemann
This edition published 2011 by Routledge
2 Park Square, Milton Park, Oxon OX14 4RN
711 Third Avenue, New York, NY 10017, USA

Routledge is an imprint of the Taylor & Francis Group, an informa business

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data
A catalogue record for this book is available from the Library of Congress

ISBN 9780750651387

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Preface

This new edition of *Electronic Navigation Systems* has been extensively rewritten to provide navigators with a detailed manual covering the principles and applications of modern systems.

The past decade has been witness to huge advances in technology and no more so than in maritime navigation and position fixing. As you might expect, spearheading this technological advance has been the computer. It has become as common on board ships as in our normal lives where it now influences virtually everything that we do. A new generation of ship's officer has been trained to use computers, trained to understand how they work and, more importantly, how they can be made to assist in the business of safe and precise navigation. But it would be a serious error to assume that the technology is perfect. All the systems currently used for navigation and position fixing are as near perfect as they can be, but it would be foolhardy to ignore the human link in the electronic chain of action and reaction. In the end, it is a ship's captain who bears the ultimate responsibility and the navigating officer who, with pride, safely brings his ship into port.

Readers will find that this new expanded edition includes many new systems and techniques whereas some older, now obsolete systems have been deleted. The hyperbolic systems, which once formed the backbone of global position fixing, have been decimated by the continuing expansion of the Global Positioning System (GPS).

The hyperbolic systems Decca and Omega have gone, but Loran-C, the one terrestrial network providing extensive coverage, remains as the designated back-up system to the GPS. By Presidential order, on 1 May 2000, Selective Availability, the method by which GPS accuracy was downgraded for civilian users, was set to zero. This significant event means that submetre accuracy position fixing is now available for all users, a factor that will have a major impact on GPS equipment and subsystems over the next decade.

Whilst the GPS is the undisputed king amongst satellite systems, it is by no means the only one. GLONASS, created and maintained by the Russian Federation, also provides users with accurate position fixes and the European Community is actively considering another system to be totally independent of the other two.

Although position fixing by satellite is of paramount importance there are other systems essential to safe navigation. Speed logging, depth sounding, and automatic steering systems are equally as important as they were decades ago and even that most traditional of all systems, the gyrocompass, has been digitized and refined. But essentially, system parameters remain unchanged; it is the collecting, processing and display of data that has been transformed.

Computerization and continuing development of large-scale integration (LSI) technology have been directly responsible for most of the changes. The large-scale manufacture of microchips has enabled the production of low-cost equipment with capabilities that could only have been dreamed about a decade ago. This reduction in size and cost has also brought sophisticated navigation equipment within reach of small-boat owners.

Electronic Navigation Systems has been written to support the training requirements of STCW-95 and consequently the book is an invaluable reference source for maritime navigation students. As with previous editions, each chapter opens with system principles and then continues with their application to modern equipment. Some sections, typically gyrocompass and automatic steering, still contain valid descriptions of analogue equipment but these have been further strengthened with the introduction of new digital technology. Wherever possible we have described the systems and equipment that you, the reader, are likely to meet on board your craft whether it is large or small.

The Global Maritime Distress and Safety System (GMDSS) is a subject which no mariner can ignore and consequently it has been outlined in this book. For extensive details about the principles and applications of this global communications system, see our book *Understanding GMDSS*.

Radar and Automatic Radar Plotting Aids (ARPA) are obviously essential to safe navigation and indeed are now integrated with other navigation systems. They are discussed in depth in the companion volume to this publication, *Electronic Aids to Navigation (RADAR and ARPA)*.

Laurie Tetley and David Calcutt
2000

Acknowledgements

A book of this complexity containing leading edge technology must inevitably owe much to the co-operation of various individuals, equipment manufacturers and organizations. To single out one or more organizations is perhaps invidious. In many cases we have had no personal contact with individuals but despite this they gave freely of their time when information was requested.

We are extremely grateful for the assistance that the following companies and organizations gave during the writing of this book. We are particularly indebted to the organizations that permitted us to reproduce copyright material. Our sincere thanks go to the following.

COSPAS-SARSAT Secretariat
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Furuno Electric Co. Ltd
Garmin Industries
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The INMARSAT Organization
The International Maritime Organization (IMO)
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Litton Marine Systems
The NAVTEX Coordinating Panel
PC Maritime
SAL Jungner Marine
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Trimble Navigation Ltd
UK Hydrographic Office (UKHO)
Warsash Maritime Centre

The following figures are from the IMO publications on GMDSS and *The Navtex Manual*, and are reproduced with the kind permission of the International Maritime Organization, London: Figure 11.1, page 370; Figure 11.3, page 374; Figure 11.4, page 376; Figure 11.7, page 381; Figure 11.8, page 382; Figure 11.10, page 384; Figure 11.11, page 385.

Chapter 1

Radio wave propagation and the frequency spectrum

1.1 Introduction

This chapter outlines the basic principles of signal propagation and the radio frequency spectrum used by the navigation systems likely to be encountered on board merchant ships. The use of radio waves for terrestrial global communications and navigation causes major problems, particularly in the areas of frequency allocation and interference. Consequently, for safe and efficient working practices to be maintained on the restricted radio frequency spectrum, it is essential that this limited resource is carefully policed.

Radio waves cannot and do not respect international boundaries and, consequently, disputes arise between nations over the use of radio frequencies. The international governing body for radio communications services is the International Telecommunications Union (ITU) which, quite rightly, strictly regulates the allocation and use of frequencies. Any dispute that arises is settled by the ITU through various committees and affiliated organizations. All users of radiocommunications systems must be aware that they are licensed to use only specific frequencies and systems in order to achieve information transfer. It would be chaos if this were not so. Essential services, aeronautical, maritime or land based, would not be able to operate otherwise and lives could well be put at risk.

1.2 Maritime navigation systems and their frequencies

Maritime radio navigation requirements have always posed unique problems for the shipboard operator. A ship at sea presents many difficulties to the radio communications design engineer. The ship is constructed of steel which, when floating in salt water, becomes a very effective electromagnetic screen capable of rejecting or reflecting radio waves. In addition, modern ocean-going vessels are streamlined, spelling an end to those sturdy structures, i.e. smoke stacks and masts, that traditionally were used for holding antenna systems. Consequently, shipboard antenna systems tend to be less efficient than was once the case, giving rise to difficulties in both transmission and reception.

Maritime radio navigation and communication systems operate in a number of frequency bands. Listed below is a brief summary.

- Loran-C on the medium frequency 100 kHz.
- Navtex data on 518 kHz.
- Voice, radiotelex and digital selective calling in medium frequency band 1.6–3.4 MHz.
- Voice, radiotelex and DSC in high frequency bands between 3 and 30 MHz
- Voice and DSC in the very high frequency band 30–300 MHz.

- RADAR and SART on the frequency of 9 GHz.
- GPS satellite signals on L-band frequencies.
- INMARSAT communications signals on L-band frequencies.

In each case, the carrier frequency used has been chosen to satisfy two main criteria, those of geographical range and the ability to carry the relevant information. The geographical range of a radio wave is affected by many parameters, but in the context of this book, range may basically be related to the choice of frequency band, which in turn determines the method of radio wave propagation.

1.3 Radio wave radiation

The propagation of radio waves is a highly complex natural phenomenon. It is simplified in the following pages to provide an understanding of the subject with a level of knowledge necessary to comprehend modern navigation systems.

Energy is contained in a transmitted radio wave in two forms, electrostatic energy and electromagnetic energy. The radiation of energy from a simple antenna may be described by considering a centre-fed dipole antenna, which is shown electrically in Figure 1.1.

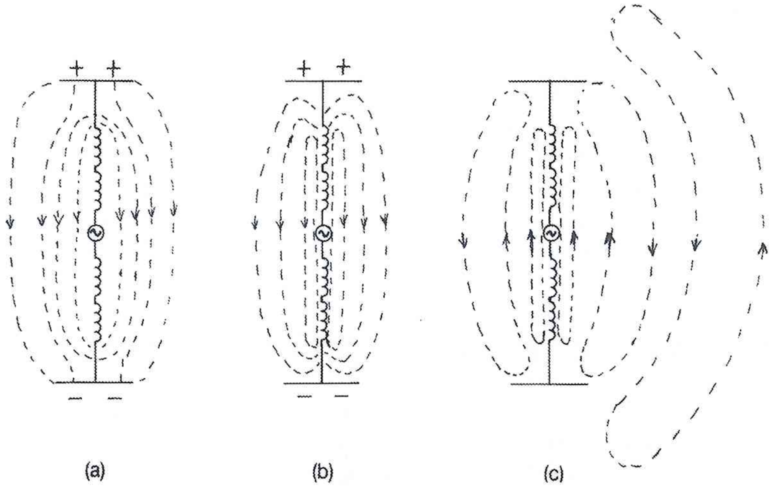


Figure 1.1 Radio wave radiation from a centre-fed dipole antenna.

The antenna shown is formed of two coils, each end of which is at the opposite potential to the other with reference to the centre point. As a complete unit, the antenna forms a tuned circuit that is critically resonant at the carrier frequency to be radiated. The two plates, one at each end of the coil assembly, form a capacitor. Radio frequency current, from the output stage of a suitable transmitter, shown here as a generator, is applied at the centre of the two coils. One of the basic electrical laws of physics states that whenever an electron has its velocity altered by an accelerating force there will be a detachment of energy. In the case of an antenna system this detachment is the energy that is lost from the transmitter and radiated as electrical energy into the atmosphere.

The diagrams clearly show the distribution of the electric field produced around an antenna when an oscillatory radio frequency is applied to it. In Figure 1.1(a) the top plate of the antenna is instantaneously driven positive with respect to the base plate and the current flow in the wire is zero. At this instant the field produced is entirely electric and the electrostatic lines of force are as shown in the diagram.

After the peak of the signal has passed, electrons will begin to flow upwards to produce a current flow in the wire. The electric field will now start to collapse (Figure 1.1(b)) and the ends of the lines of force come together to form loops of electrostatic energy. After the potential difference (positive top plate to negative base plate) across the two plates of the effective capacitor has fallen to zero, current continues to flow and, in so doing, starts to charge the effective capacitor plates in the opposite direction. This charge forms new lines of force in the reverse direction to the previous field, negative to the top plate and positive at its base. The collapse of the initial electrostatic field lags the change in potential that caused it to occur and, consequently, the new electric field starts to expand before the old field has completely disappeared. The electric fields thus created (Figure 1.1(c)) will be caused to form loops of energy, with each new loop forcing the previous loop outwards, away from the antenna. Thus, radio frequency energy is radiated as closed loops of electrostatic energy.

Because a minute current is flowing around each complete loop of energy, a magnetic field will be created around the loop at 90° to it. Thus, the magnetic lines of force produced around the vertical electric field created by a vertical antenna, will be horizontal. Two fields of energy, in space quadrature, have thus been created and will continue in their relative planes as the radio wave moves away from the transmitting antenna.

The electric and magnetic inductive fields are in both time and space quadrature and are 90°out of phase with each other in time, and at right angles to each other in space. The electric field is of greatest importance to the understanding of radio wave propagation, the magnetic field only being present when current flows around the loop as the electric field changes.

Figure 1.2 shows the relative directions of the electric field (*E*), the magnetic field (*H*) and the direction of propagation. The oscillating electric field is represented by the vertical vector OE, the magnetic field by OH, and the direction of propagation by OD. Another electrical law of physics, Fleming's right-hand rule, normally applied to the theory of electrical machines, applies equally to the direction of propagation of the radio wave.

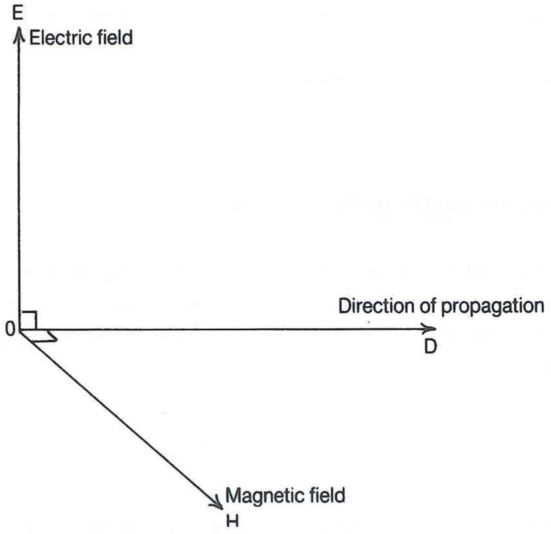


Figure 1.2 The angular relationship of the E and H fields.

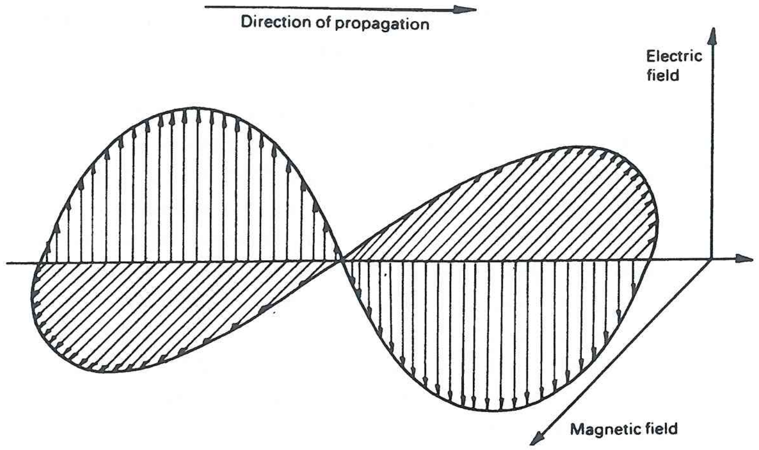


Figure 1.3 Amplitude variations of the E and H fields.

At any instantaneous point along the sinusoidal wave of the electric field it is possible to measure a minute current flow in the loop of energy. The current will be increasing and decreasing as it follows the rate of change of amplitude of the sinusoidal frequency (carrier wave) of the radio wave (see Figure 1.3). It is this instantaneous change of current which, when in contact with a receiving antenna, causes a current to flow at the receiver input and a minute signal voltage, called an electromotive force (e.m.f.), to appear across the antenna input.

The transmitted signal may now be considered to be a succession of concentric loops of ever-increasing radius, each one a wavelength ahead of the next. Radio waves thus produced will be similar in appearance to the waves caused on the surface of a pond when a rock is tossed into it. Similarly, the radio waves radiate outwards from the source and diminish in amplitude with distance travelled from the transmitter. Each loop moves away from the transmitting antenna at the speed of light in free space, usually approximated to be $300 \times 10^6\,\mathrm{ms}^{-1}$, and it is common practice to call the leading edge of each loop a wavefront. The distance between each wavefront depends upon the frequency being radiated and is called the wavelength, λ (lambda).

1.4 Frequency, wavelength and velocity

Although a variable, the velocity of electromagnetic radio waves propagated in the troposphere, close to the earth's surface, is accepted to be $300 \times 10^6\,\mathrm{ms}^{-1}$. This figure is important because it enables the wavelength of a transmitted frequency to be calculated and from that a number of other essential parameters can be determined.

$$\text{Wavelength } \lambda = \frac{300 \times 10^6}{\text{Frequency}} \text{ (in metres)}$$

The actual length of one radio wave during one alternating cycle is a measure of the distance travelled, and the number of alternating cycles per second is a measure of the frequency.

1.5 Radio frequency spectrum

Table 1.1 indicates how the available frequency spectrum has been divided into usable bands. By referring to this table it is possible to gain some initial idea of the approximate range over which radio waves may be received. For instance, if all other parameters remain constant, the anticipated radio range of signals propagated on the VHF band, or those higher, is effectively that of 'line-of-sight'. Consequently, ship-to-ship communications between a life-raft and a surface vessel could expect to have a range of 2–7 nautical miles depending upon the system installation and the relative heights of the antennae. Because of its line-of-sight nature, VHF radio ranges beyond the horizon can only be achieved by using repeater stations or satellites. Maritime mobile satellite systems use much higher frequencies in what is termed the L band and the C band, each providing a line-of-sight link.

Table 1.1 The frequency spectrum

Abbreviation	*Band*	*Frequency range*	*Wavelength*
AF	Audio	0 Hz–20 kHz	∞ to 15 km
RF	Radio	10 kHz–300 GHz	30 km to 0.1 cm
VLF	Very low	10–30 kHz	30 km to 10 km
LF	Low	30–300 kHz	10 km to 1 km
MF	Medium	300–3000 kHz	1 km to 100 m
HF	High	3–30 MHz	100 m to 10 m
VHF	Very high	30–300 MHz	10 m to 1 m
UHF	Ultra high	300–3000 MHz	1 m to 10 cm
SHF	Super high	3–30 GHz	10 cm to 1 cm
EHF	Extreme high	30–300 GHz	1 cm to 0.1 cm

1.5.1 Spectrum management

Radio waves do not respect international boundaries and an international framework has been established in order to control the use of frequencies, the standards of manufacture and the operation of radio equipment in order to limit the likelihood of interference. The forum for reaching international agreements on the use of the radio frequency spectrum is the International Telecommunications Union (ITU). Membership of the ITU is dependent upon acceptance of the strict convention which exists to uphold the regulations laid down by the various conferences and meetings of the ITU.

The radio spectrum management policies agreed among the signatories of the convention are published by the ITU as international radio regulations. One of these is the international Table of Frequency Allocations, which provides the framework for, and the constraints on, national frequency use and planning. The Table of Frequency Allocations and the radio regulations documents are revised at the World Administrative Radio Conferences (WARC) held at periods of 5–10 years.

The administrative structure established by the ITU convention comprises a Secretariat headed by the Secretary General, an Administrative Council, a registration board for radio frequencies, and the consultative committees for radio and telecommunications.

The International Radio Consultative Committee (CCIR) forms study groups to consider and report on the operational and technical issues relating to the use of radio communications. The International Telecommunications Consultative Committee (CCIT) offers the same service for telecommunications. The study groups produce recommendations on all aspects of radio communications. These recommendations are considered by the Plenary Assembly of the CCIR and, if accepted, are incorporated into the radio regulations. Another subgroup of the ITU, the International Frequency Registration Board (IFRB) considers operating frequencies, transmitter sites, and the location of satellites in orbit. Within Europe, a further body, the Conference of European Telecommunications Administrations (CEPT) assists with the implementation of the ITU radio regulations on a national level. Every country appoints an agency to enact the radio regulations thus laid down. In the United Kingdom for instance it is the Radiocommunications Agency and in the USA, civil use of the radio frequency spectrum is controlled by the Federal Communications Commission.

1.6 Radio frequency bands

Radio wave propagation characteristics (see Table 1.2) are dependent upon the frequency used.

Table 1.2 Radio frequency band characteristics

Designation & Frequency	*Propagation Mode*	*Characteristics*
Very low frequency 3–30 kHz	Large surface wave	Very high power transmitters and large antennae needed
Low frequency 30–300 kHz	Surface wave and some sky wave returns	High power transmitters; limited number of channels; subject to fading
Medium frequency 0.3–3 MHz	Surface wave during day. Some sky wave returns at night	Long range at night; subject to fading
High frequency 3–30 MHz	Sky waves returned over long distances	Global ranges using ionospheric returns
Very high frequency 30–300 MHz	Mainly space wave. Line of site	Range depends upon antenna height
Ultra high frequency 0.3–3 GHz	Space wave only	Line of sight; satellite and fixed link
Super high frequency 3–30 GHz	Space wave only	Line of sight; radar and satellite
Extreme high frequency 30–300 GHz	Space wave only	Not used for mobile communications

1.6.1 VLF (very low frequency) band

VLF radio signals propagate using a combination of both ground and space waves. They require vast amounts of power at the transmitter to overcome earth surface attenuation and can be guided over great distances between the lower edge of the ionosphere and the ground. Because VLF possesses a very long wavelength, huge antenna systems are required. As an example, at 10 kHz the wavelength is 30 km. An efficient antenna, often quoted as 'a half-wavelength antenna', needs to be 15 km long and it is only possible to construct one on land, usually slung between mountain peaks.

1.6.2 LF (low frequency) band

Communication is mainly by a ground wave, which suffers increasing attenuation as the frequency increases. Range therefore depends upon the amplitude of the transmitted power and the efficiency of the antenna system. Expected range for a given low frequency and transmitter power is between 1500 and 2000 km. At LF the wavelength is reduced to a point where small-size antennae are practicable. Although the sky wave component of LF propagation is small it can be troublesome at night when it is returned from the ionosphere.

1.6.3 MF (medium frequency) band

Ground wave attenuation rapidly increases with frequency to the point where, at the higher end of the band, its effect becomes insignificant. For a given transmitter power, therefore, ground wave range is inversely proportional to frequency. Range is typically 1500 km to under 50 km for a transmitted signal, with a peak output power of 1 kW correctly matched to an efficient antenna.

In the band below 1500 kHz, sky waves are returned from the ionosphere both during the day and night, although communication using these waves can be unreliable. Above 1500 kHz the returned sky wave has greater reliability but is affected by changes in the ionosphere due to diurnal changes, seasonal changes, and the sun-spot cycle. From experience and by using published propagation figures it is possible for reliable communications to be achieved up to a range of 2000 km.

1.6.4 HF (high frequency) band

This frequency band is widely used for terrestrial global communications. Ground waves continue to be further attenuated as the frequency is increased. At the low end of the band, ground wave ranges of a few hundred kilometres are possible but the predominant mode of propagation is the sky wave.

Because ionization of the upper atmosphere is dependent upon the sun's radiation, the return of sky waves from the ionosphere will be sporadic, although predictable. At the lower end of the band, during the hours of daylight, sky waves are absorbed and do not return to earth. Communication is primarily by ground wave. At night, however, lower frequency band sky waves are returned and communication can be established but generally with some fading. Higher frequency band sky waves pass through the ionized layers and are lost. During the day the opposite occurs. Low frequency band skywaves are absorbed and those at the higher end are returned to earth. For reliable communications to be established using the ionized layers, the choice of frequency is usually a compromise. Many operators ignore the higher and lower band frequencies and use the mid-range for communications.

1.6.5 VHF (very high frequency) band

Both ground waves and sky waves are virtually non-existent and can be ignored. Communication is via the space wave which may be ground reflected. Space waves effectively provide line-of-site communications and consequently the height of both transmitting and receiving antennas becomes important. A VHF antenna may also be directional. Large objects in the path of a space wave create blind spots in which reception is extremely difficult or impossible.

1.6.6 UHF (ultra high frequency) band

Space waves and ground reflected waves are used with highly directional efficient antenna systems. Signal fading is minimal, although wave polarization may be affected when the wave is ground reflected resulting in a loss of signal strength. Blind spots are a major problem.

1.6.7 SHF (super high frequency) band

Frequencies in this band possess very short wavelengths and are known as microwaves. Communication is by space wave only. Because of the minute wavelength, compact and highly directional antennas can be designed. This band is used for maritime radar and satellite communications.

1.6.8 EHF (extreme high frequency) band

Communications is by space wave only. Highly directional antennas are used. Scattering and signal loss is a major problem. The band is not currently used for maritime communications.

1.7 Radio wave propagation

Whilst all transmitting antenna systems produce one or more of the three main modes of propagation (see Figure 1.4), one of the modes will predominate. If all other parameters remain constant, the predominant mode of propagation may be equated to the frequency used. For the purpose of this explanation it is assumed that the mode of propagation is dependent upon frequency because that is the only parameter that may be changed by an operator. The three modes of propagation are:

- surface wave propagation
- space wave propagation
- sky wave propagation.

1.7.1 Surface wave propagation

The surface wave is a radio wave that is modified by the nature of the terrain over which it travels. This can occasionally lead to difficulty in maritime navigation systems where the wave travels from one medium to another, over a coastline for instance. The refraction caused in such cases is likely to induce errors into navigation systems.

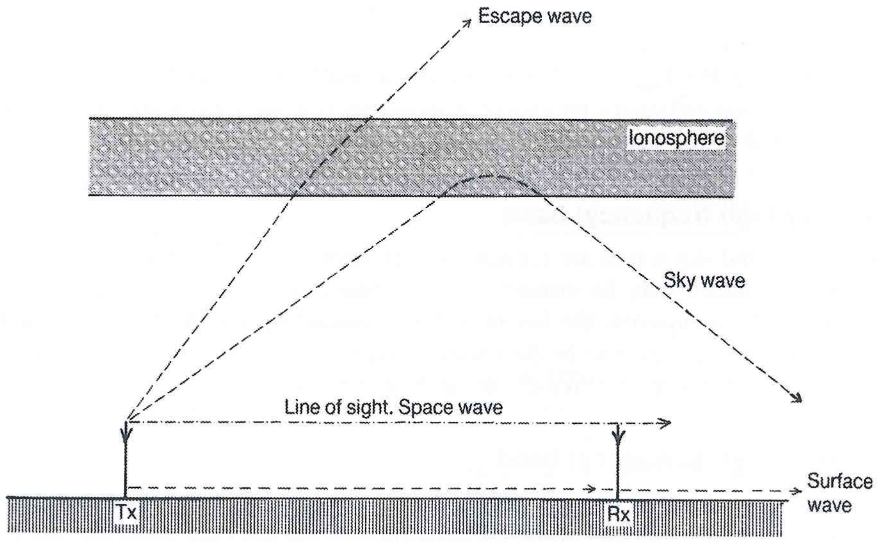


Figure 1.4 Radio wave modes of propagation.

A surface wave will predominate at all radio frequencies up to approximately 3 MHz. There is no clear cut-off point and hence there will be a large transition region between approximately 2 and 3 MHz, where the sky wave slowly begins to have influence.

The surface wave is therefore the predominant propagation mode in the frequency bands VLF, LF and MF. As the term suggests, surface waves travel along the surface of the earth and, as such, propagate within the earth's troposphere, the band of atmosphere which extends upwards from the surface of the earth to approximately 10 km.

Diffraction and the surface wave

An important phenomenon affecting the surface wave is known as diffraction. This term is used to describe a change of direction of the surface wave, due to its velocity, when meeting an obstacle. In fact, the earth's sphere is considered to be a large obstacle to surface waves, and consequently the wave follows the curvature of the earth (Figure 1.5).

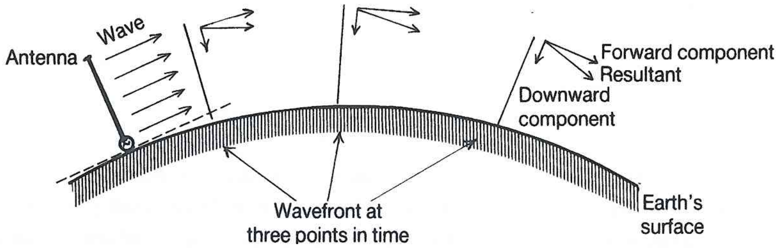


Figure 1.5 Tilting of the surface wavefront caused by diffraction.

The propagated wavefront effectively sits on the earth's surface or partly underground and, as a result, energy is induced into the ground. This has two primary effects on the wave. First, a tilting of the wavefront occurs, and second, energy is lost from the wave. The extent of the diffraction is dependent upon the ratio of the wavelength to the radius of the earth. Diffraction is greatest when the wavelength is long (the lower frequency bands) and signal attenuation increases with frequency. This means that surface waves predominate at the lower end of the frequency spectrum and, for a given transmitter power, decrease in range as frequency increases.

The amount of diffraction and attenuation also depends upon the electrical characteristics of the surface over which the wave travels. A major factor that affects the electrical characteristics of the earth's surface is the amount of water that it holds, which in turn affects the conductivity of the ground. In practice, seawater provides the greatest attenuation of energy and desert conditions the least attenuation.

The propagation range of a surface wave for a given frequency may be increased if the power at the transmitter is increased and all other natural phenomena remain constant. In practice, however, transmitter power is strictly controlled and figures quoting the radio range are often wild approximations. For instance, NAVTEX data is transmitted on 518 kHz from a transmitter designed to produce an effective power output of 1 kW. This gives a usable surface wave range of 400 miles. But, under certain conditions, NAVTEX signals may be received over distances approaching 1000 miles.

Another phenomenon caused by radio-wave diffraction is the ability of a ground-propagated wave to bend around large objects in its path. This effect enables communications to be established when a receiving station is situated on the effective blind side of an island or large building. The effect is greatest at long wavelengths. In practice, the longer the wavelength of the signal in relation to the physical size of the obstruction, the greater will be the diffraction.

1.7.2 Sky wave propagation

Sky waves are severely influenced by the action of free electrons, called ions, in the upper atmosphere and are caused to be attenuated and refracted, possibly being returned to earth.

The prime method of radio wave propagation in the HF band between 3 and 30 MHz is by sky wave. Because under certain conditions, sky waves are refracted from the ionosphere, this band is used extensively for terrestrially-based global communications. Once again, however, there is no clear dividing line between surface and sky waves. In the frequency range between 2 and 3 MHz, surface waves diminish and sky waves begin to predominate.

Sky waves are propagated upwards into the air where they meet ionized bands of atmosphere ranging from approximately 70 to 700 km above the earth's surface. These ionized bands, or layers, have a profound influence on a sky wave and may cause it to return to earth, often over a great distance.

The ionosphere

A number of layers of ionized energy exist above the earth's surface. For the purpose of explaining the effects that the layers have on electromagnetic radiation it is only necessary to consider four of the layers. These are designated, with respect to the earth's surface, by letters of the alphabet; D, E, F_1 and F_2, respectively (Figure 1.6). They exist in the ionosphere, that part of the atmosphere extending from approximately 60 km above the earth's surface to 800 km.

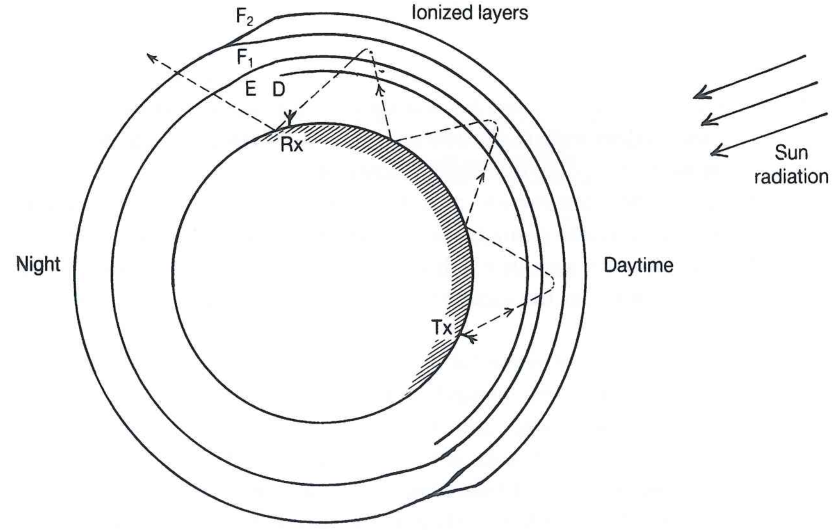


Figure 1.6 Ionized layers and their effect on long-range communications.

Natural ultraviolet radiation from the sun striking the outer edge of the earth's atmosphere produces an endothermic reaction, which in turn, causes an ionization of atmospheric molecules. A physical change occurs producing positive ions and a large number of free electrons. The layers closer to the earth will be less affected than those at the outer edges of the atmosphere and, consequently, the D layer is less ionized than the F_2 layer. Also, the amount of ultraviolet radiation will never be constant. It will vary drastically between night and day, when the layers are in the earth's shadow or in full sunlight. In addition, ultraviolet radiation from the sun is notoriously variable, particularly during solar events and the 11-year sun-spot cycle. During these events, the ionized layers will be turbulent and sky waves are seriously affected.

Whilst it may appear that radio communication via these layers is unreliable it should be remembered that most of the environmental parameters affecting the intensity of an individual layer are predictable. The external natural parameters that affect a layer, and thus the communication range, are:

- the global diurnal cycle
- the seasonal cycle
- the 11-year sun-spot cycle.

Radio wave ionospheric refraction

An electromagnetic radio wave possesses a wavelength, the velocity of which is affected when it passes from one medium to another of a different refractive index, causing a change of direction to occur. This change of direction is called refraction.

As previously stated, the atmosphere is ionized by the sun's radiation. It is convenient to view the ionized region produced by this action as ionized layers. The outermost layer, closest to the sun's radiation, will be intensely ionized, whereas the layer closest to the earth's surface is less ionized (Figure 1.7). Due to the collision of free electrons, an electromagnetic radio wave entering a layer will have its velocity changed causing the upper end of the wavefront to speed up. If, before the wave reaches the outer edge of an ionized layer, the angle of incidence has reached the point where the wavefront is at right angles to the earth's surface, the radio wave will be returned to earth where it will strike the ground and be reflected back into the ionosphere.

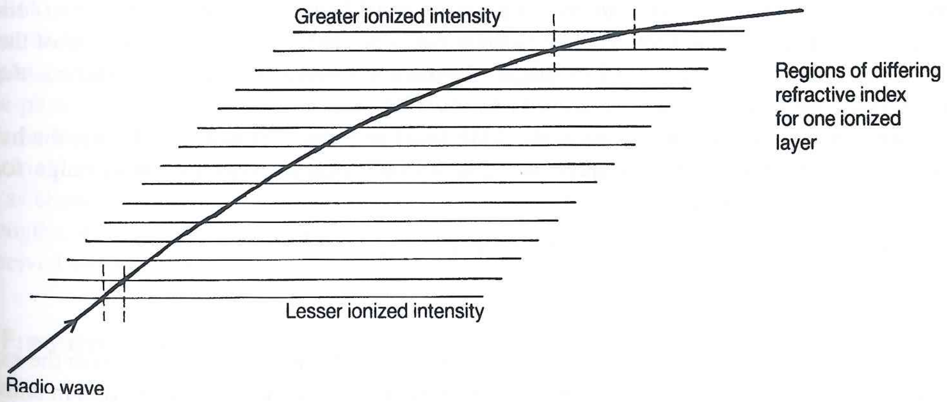


Figure 1.7 Radio wave refraction due to progressively higher ionization intensity.

The extent of refraction, and thus whether a radio wave is returned to earth, can be controlled and is dependent upon three main parameters:

- the density of the ionosphere
- the frequency of propagation
- the angle of incidence of the radio wave with a layer.

Obviously it is not possible to control the density of the ionosphere, but other parameters may be changed by a shore-based radio station which has control over antenna systems. For a maritime mobile system, however, it is only the frequency that can be changed.

Despite its complexity, it is the phenomenon of refraction that enables terrestrial global communications to be achieved. Radio waves make several excursions between being refracted by the ionosphere and reflected from the earth's surface, with each journey being known as one hop.

1.7.3 Space wave propagation

The space wave, when propagated into the troposphere by an earth surface station, is subject to deflection by variations in the refractive index structure of the air through which it passes. This causes the radio wave to follow the earth's curvature for a short distance beyond the horizon making the radio horizon somewhat longer than the visible horizon. Ship's navigators will know the effect whereby the surface radar range extends slightly beyond the horizon. Space waves propagated upwards away from the troposphere may be termed free space waves and are primarily used for satellite communications.

Space waves are rarely returned from the ionosphere because the wavelength of the carrier frequency is reduced to the point where refraction becomes insignificant. Such a wave, when propagated upwards, passes through the ionized layers and is lost unless it is returned by an artificial or natural earth satellite.

If a space wave is propagated along the surface of the earth or at a short height above it, the wave will move in a straight line from transmitting antenna to receiving antenna and is often called a line-of-sight wave. In practice, however, a slight bending does occur making the radio horizon somewhat longer than the visual horizon.

The troposphere extends upwards from the earth's surface to a height of about 10 km where it meets the stratosphere. At the boundary between the two there is a region called the tropopause which possesses a different refractive index to each neighbouring layer. The effect exhibited by the tropopause on a radio space wave is to produce a downward bending action, causing it to follow the earth's curvature. The bending radius of the radio wave is not as severe as the curvature of the earth, but nevertheless the space wave will propagate beyond the visual horizon. In practice, the radio horizon exceeds the visual horizon by approximately 15%.

The actual range for communications in the VHF band and above is dependent upon the height of both the transmitting and receiving antennae. The formula below gives the radio range for VHF communications in nautical miles:

$$R = 2.5\sqrt{h_T + h_R}$$

where h_T and h_R are in metres.

Given a ship's antenna height of 4 m and a coastal radio station antenna height of 50 m the expected radio range is approximately 23 nmiles. This rises to 100 nmiles for antenna heights of 4 m and 100 m, respectively. Ship-to-ship communications with each ship having a 4-m high antenna gives a range of 10 nmiles. Search and rescue (SAR) communications between a life-raft and another surface vessel may have a range of only 4 nmiles.

It should be noted that VHF space waves cannot pass through, or be diffracted around, large objects, such as buildings or islands, in their path. This gives rise to extensive radio shadow areas behind large structures.

1.8 Signal fading

One of the major difficulties encountered when radio waves are propagated via the earth's atmosphere is that of signal fading. Fading is a continual variation of signal amplitude experienced at the antenna input to a receiving system. In practice, fading may be random or periodic but in each case the result will be the same. If the signal input to a receiver falls below the quoted sensitivity figure there may be no output from the demodulator and hence the communications link is broken. If the signal amplitude at the antenna doubles, a large increase in audible output will be produced either causing possible overloading of an automatic system or discomfort for an operator. Steps are taken at the receiver to overcome the problem of signal fading, which may be classified as one of three main types:

- general signal fading
- selective fading
- frequency selective fading.

1.8.1 General signal fading

In a global system, fading may occur because of the continually changing attenuation factor of an ionospheric layer. Ultraviolet radiation from the sun is never constant, and consequently, the intensity of the ionization of a layer will continually change. The signal attenuation of a specific layer may cause complete signal fade-out as the intensity of the sun's radiation changes. With the exception of this extreme case, the use of automatic gain control (AGC) circuits in a receiver effectively combats this phenomenon.

1.8.2 Selective fading

Selective fading occurs for a number of reasons. Radio waves arriving at an antenna may have travelled over two or more different paths between transmitter and receiver. Each path-length is different and the signals arriving at the receiving antenna produce a combined signal amplitude, which is the phasor sum of the two. The two signals, of the same frequency and the same origin, will be out of time-phase with each other and will therefore produce a resultant signal that is either larger or smaller in amplitude than the original. In most cases the signal path-lengths are unpredictable and often variable, leading again to the need for a good quality AGC circuit in the receiver. This effect can occur, as shown in Figure 1.8, when two sky waves are refracted from the ionosphere over different path-lengths, when a sky wave and a ground wave are received together, or when two ground waves are received over different paths.

1.8.3 Frequency selective fading

This occurs where one component of a transmitted radio wave is attenuated to a greater extent than other components. In any wideband communications link a large number of frequencies are contained

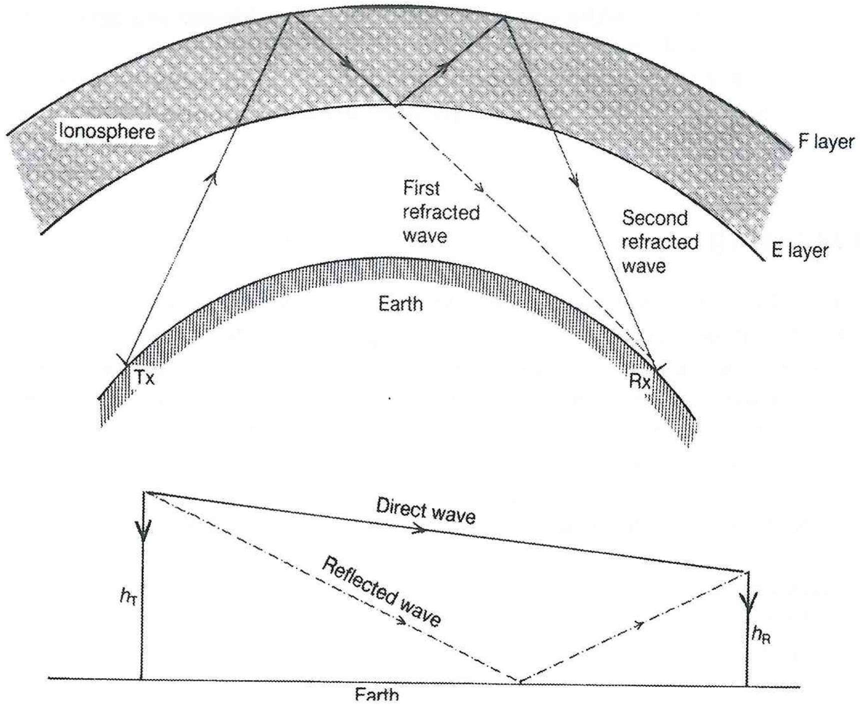


Figure 1.8 Signal fading caused by multipath propagation.

within the bandwidth of the transmitted signal. The individual frequencies contained in the transmission are those of the fundamental carrier frequency plus the RF frequencies generated by the method of modulation employed. To produce an error-free or distortion-free communications link, all modulation baseband frequencies at the transmitter must be faithfully reproduced at the receiver output. If any of the modulated frequencies are lost in the transmission medium, which may happen when frequency selective fading is present, they cannot be reproduced by the receiver.

More importantly, however, if the carrier frequency is lost in the transmission medium it will be impossible to demodulate the audio intelligence at the receiver, unless specific circuitry is available and the carrier loss is predictable.

Frequency selective fading cannot be cured by the use of AGC circuits in a receiver. Its effects can, however, be limited by using:

- a transmission which radiates one mode only – a carrier frequency or narrow band signal
- single sideband (SSB J3E) fully suppressed carrier transmission telephony
- frequency modulation.

1.9 Basic antenna theory

An antenna is arguably the single most critical part of any radio communications system and those used by radio navigation systems are no exception. Unfortunately, however, it is often the part of a radio installation that is less than efficient, not because of deficiencies in antenna design but because

of the major problems of antenna siting and installation. As ships become more streamlined, the available antenna space reduces, often to the point where multiple antenna systems simply cannot be fitted.

Radio navigation systems use a variety of antennae, each one designed with individual characteristics to suit operational needs, but whatever the construction, they all operate on similar principles.

Antenna design and construction is a complex area of radio communications theory and the following description is limited to that needed to understand radio navigation systems. Whilst some basic antenna theory is considered, it should be noted that it is only necessary for the reader to understand antennae from an operational and maintenance viewpoint.

An antenna is essentially a piece of wire that may or may not be open at one end. The shortest length of wire that will resonate at a single frequency is one that is critically long enough to permit an electric charge to travel along its length and return in the period of one cycle of the applied radio frequency. This period of one cycle is called the wavelength. The velocity of a propagated RF is that of light waves, i.e. 299 793 077 ms^{-1}, which is usually approximated to 300×10^6 ms^{-1} for convenience. The wavelength in metres of any RF wave is therefore:

$$\lambda = \frac{300 \times 10^6}{f}$$

Because the RF charge will travel the length of the wire and return, it follows that the shortest resonant wire is one half of a wavelength long. In fact many antenna systems are called half-wave or $\lambda/2$. If, as an analogy, the resonant length is assumed to be a trough with obstructions at each end and a ball is pushed from one end, it will strike the far end and return, having lost energy. If, at the instant the ball hits the near end obstruction, more energy is given to the ball it will continue on its way indefinitely. However, it is critically important that the new energy is applied to the ball at just the right time in order to maintain the action. In practice, if the timing is in error the length of the resonant trough may be changed to produce the optimum transfer of energy along the wire. Antennae, therefore, must be constructed to be a critical length to satisfy the frequency of the applied RF energy.

Antennae, exhibit the 'reciprocity principle', which means that they are equally as efficient when working as a transmitting antenna or as a receiving antenna. The main difference is that a transmitting antenna needs to handle high power and is usually more substantially built and better insulated than a corresponding receiving antenna. For efficient radio communications, both the transmitting and receiving antennae should possess the same angle of polarization with respect to the earth. Polarization refers to the angle of the transmitted electric field (E) and, consequently, if the E-field is vertical, both transmitting and receiving antennae must be vertical. The efficiency of the system will reduce progressively as the error angle between transmitting and receiving antennae increases up to a maximum error of 90°.

1.9.1 Half-wavelength antenna

An antenna operating at precisely half a wavelength is traditionally called a Hertz antenna. Many antennae do not operate at $\lambda/2$ because they would be excessively long. A $\lambda/2$ antenna is effectively a $\lambda/4$ transmission line with a signal generator, the transmitter, at one end and an open circuit at the other, as shown in Figure 1.9.

Ohm's Law states that when an open circuit exists the current will be zero and the potential difference (p.d.) across the open circuit will be maximum. Figure 1.10 shows voltage (E) and current (I) standing waves which indicate this fact.

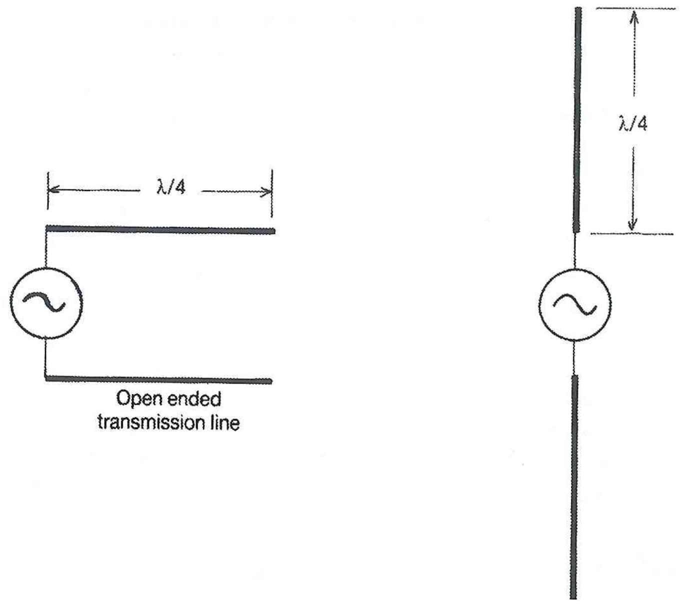


Figure 1.9 Half-wavelength antenna derived from a quarter-wavelength transmission line.

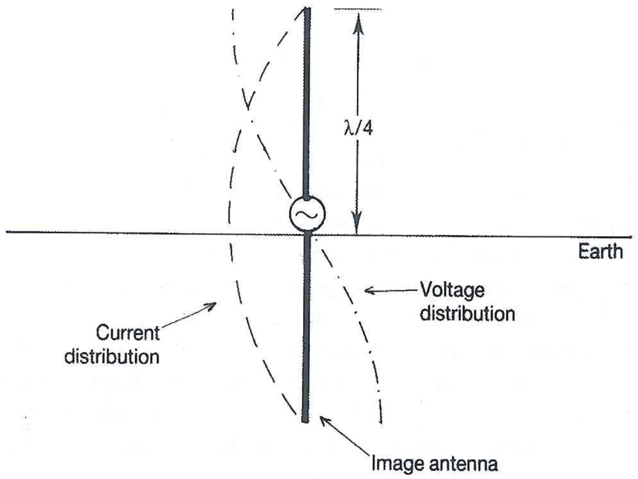


Figure 1.10 A grounded quarter-wavelength antenna showing the voltage and current distribution curves.

E and *I* distribution curves are standard features of antenna diagrams. If the generator (signal source) is λ/4 back from the open circuit, the *E* and *I* curves show minimum voltage and maximum current at the antenna feed point. In most cases this is the desirable *E* and *I* condition for feeding an antenna. If the two arms of the transmission line are now bent through 90°, a λ/2 efficient antenna has been produced.

Ohm's Law also states that the resistance of a circuit is related to the voltage and the current. In this case the impedance of the antenna will be maximum at the ends and minimum at the centre feed point. Again this is desirable because the centre impedance is approximately 73 Ω, which ideally matches the 75 Ω (or in some cases 50 Ω) impedance coaxial cable used to carry the output of the transmitter or the input to a receiver.

1.9.2 Physical and electrical antenna lengths

Ideally, an antenna isolated in free space would follow the rules previously quoted, whereby the actual and electrical lengths were the same. Both are calculated to be λ/2 of the transmission frequency. However, because the velocity of the radio wave along the wire antenna is affected by the antenna supporting system and is slightly less than that in free space, it is normal to reduce the physical length of the antenna by approximately 5%. In practice, the corrected physical length of an antenna is therefore 95% of the electrical length.

Antennae and feeders are effectively 'matched transmission lines', which, when a radio frequency is applied, exhibit standing waves, the length of which are determined by a number of factors outside the scope of this book. However, the waves are basically produced by a combination of forward and reflected power in the system. A measurement of the ratio between forward and reflected power, called the standing wave ratio (SWR), provides a good indication of the quality of the feeder and the antenna. Measurement of the SWR is made using voltage and becomes voltage standing wave ratio (VSWR).

1.9.3 Antenna radiation patterns

A graph showing the actual intensity of a propagated radio wave at a fixed distance, as a function of the transmitting antenna system, is called a radiation pattern or 'polar diagram'. Most antenna radiation patterns are compared with that of a theoretical reference antenna called an isotropic radiator. Radiation patterns may be shown as the *H*-plane or the *E*-plane of transmission or reception. Figure 1.11 shows the *E*-plane radiation patterns of an isotropic radiator and a λ/2 dipole antenna.

It should be noted that this is a two-dimensional diagram whereas the actual radiation pattern is three-dimensional. The maximum field strength for the λ/2 dipole occurs at right angles to the antenna and there is very little radiation at its ends. In the horizontal plane, therefore, this type of antenna is directional, whereas an isotropic radiator is omnidirectional. However, a λ/2 antenna can be made omnidirectional when it is vertically polarized.

A second important principle of an antenna is its beamwidth. The radiation pattern is able to illustrate the antenna beamwidth. It is calculated at the 'half-power points' or –3 dB down from the

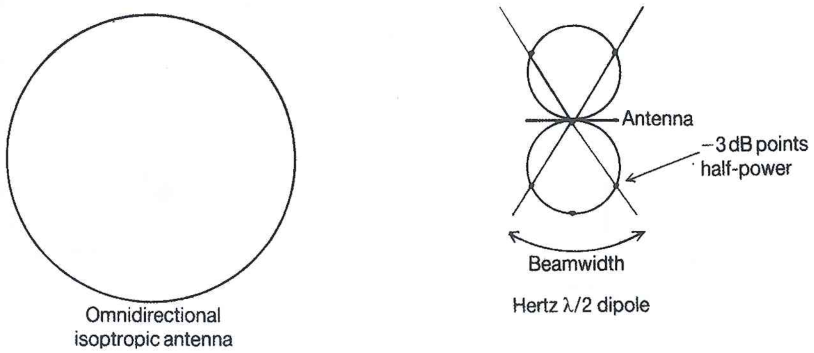


Figure 1.11 Two-dimensional radiation patterns for an omnidirectional antenna and a λ/2 antenna.

peak point. If the receiving antenna is located within the beamwidth of the transmitting antenna good communications will be made.

Antenna gain patterns for receiving antennas are again called polar diagrams or azimuth gain plots (AGP).

1.9.4 Antenna gain and directivity

Antenna gain and directivity are very closely linked. The greater the directivity an antenna exhibits, the greater it will appear to increase the transmitted signal in a specific direction. The $\lambda/2$ dipole, for instance, possesses a gain of typically 2.2 dB, on those planes at right angles to the antenna, when compared with an isotropic radiator. As a consequence, zero signals will be propagated along the other two planes in line with the dipole.

Both properties of gain and directivity are reciprocal and apply equally to both transmitting and receiving antennae. In practice it is important to consider the effect of both the transmitter and receiver antenna gains in a complete radio communications system. The formula below provides a simple method of calculating the signal strength at a receiver input.

$$P_r = \frac{P_t G_t G_r \lambda/2}{16\pi^2 d^2}$$

where P_r = power received in watts, P_t = power output of transmitter in watts, G_t = the ratio gain of the transmitting antenna, G_r = the ratio gain of the receiving antenna, λ = wavelength of the signal in metres, and d = the distance between antennae in metres.

1.9.5 Ground effects

The overall performance of an antenna system is extensively changed by the presence of the earth beneath it. The earth acts as a reflector and, as with light waves, the reflected radio wave leaves the earth at the same angle with which it struck the surface. Figure 1.12 shows the direct and reflected radio waves at a receiving antenna.

Because the surface of the earth is rarely flat and featureless, there will be some directions in which the two waves are in phase, and thus are additive, and some where the two are out of phase, and thus subtractive.

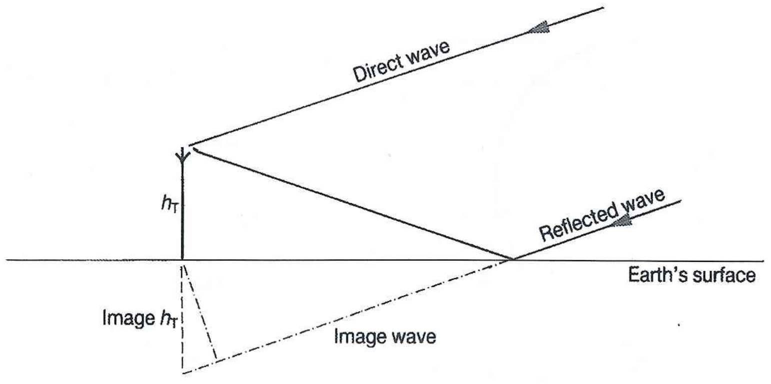


Figure 1.12 Direct and earth reflected radio waves received by an antenna.

Because the effects of ground wave reflected waves are unpredictable, some antenna arrays are constructed with a ground plane. Reflections from the ground plane are, to some extent, predictable and may be compensated for in the receiving system. Satellite navigation antennas and VHF RDF fixed antennae often use a ground plane to improve sensitivity and limit signal reflections.

1.9.6 Antenna efficiency

Antenna efficiency is of particular importance in all communications systems. If the efficiency of an antenna drops to 50%, the maximum radiated signal also drops resulting in a consequent loss of range. It would be rare indeed to find any system that is 100% efficient and antennae are no exception. However, antenna losses are well documented and, consequently, the effective isotropic radiated power (EIRP) figure for a system is usually calculated with reference to known efficiency figures.

The losses leading to inefficiency in an antenna system may generally be classed as dielectric losses affecting the transmission properties of the antenna. Such losses in a transmitting antenna may be produced by arcing effects and corona discharge, and in a receiving antenna they may be produced by bad connections or damaged wiring. Most of these losses can be controlled by careful installation, good positioning of the antenna, and diligent maintenance.

1.9.7. Antenna feed lines

Whilst the connection between the transmitter output and the antenna input appears to be made by a simple wire it is, in fact, made by a balanced transmission line that possesses impedance. Usually, the feed line is a correctly terminated coaxial cable specifically designed for the purpose. For most transmitting and receiving antenna systems the feed line possesses an impedance of 50 or 75 Ω. Because of its need to handle more power, a transmitter coaxial cable will be physically larger than a corresponding receiver coaxial line, unless of course both use the same line. The inner copper conductor forms the live feed wire with the screen sheath providing the ground line. The outer sheath should be bonded to ground to prevent inductive pick-up in the centre conductor wire, which would generate interference in the communications link.

Coaxial cables used in a marine environment are double sheathed and occasionally armour plated. They are fully waterproofed and should remain so throughout their life. Moisture ingress into the cable insulation material will cause considerable losses as energy is absorbed and not radiated.

1.10 Glossary

The following lists abbreviations, acronyms and definitions of specific terms used in this chapter.

Antenna	A carefully constructed device for the reception or transmission of radio energy into the air.
Antenna gain pattern (AGP)	Occasionally also referred to as polar diagrams. These are a graphical representation of the transmitting or receiving properties of an antenna.
CEPT	Conference of European Telecommunications Administrations. A group that assists with the implementation of ITU radio regulations on a national level.
CCIR	International Radio Consultative Committee. The body that considers and reports on issues affecting the use of radio communications.
CCIT	International Telecommunications Consultative Committee.

Diffraction	The term describing the 'bending' of a surface radio wave ground large obstacles in its path.
E field	Radio wave electrostatic energy field.
EHF	Extreme high frequency, the 30–300 GHz band. Still experimental.
Fading	The loss of power in a radio wave caused by environmental effects.
FCC	Federal Communications Commission. The body which polices the civilian use of radio communications in the USA.
Feed line	The wire connecting an antenna to the communications system.
H field	Radio wave electromagnetic energy field.
HF	High frequency, the 3–30 MHz band. Traditionally provides terrestrial global communications using medium power and acceptable antenna lengths.
ITU	International Telecommunications Union, the radio frequency watchdog.
LF	Low frequency, the 30–300 kHz band. Requires long antenna and large power input to be useful. Generally ground wave mode only.
MF	Medium frequency, the 300 kHz to 3 MHz band. Traditionally provides short-range communications using medium power and acceptable antenna lengths.
Refraction	The 'bending' of a sky wave by the effect of the ionosphere causing it to return to earth.
RF spectrum	The usable section of the extensive natural frequency spectrum.
SHF	Super high frequency, the 3–30 GHz band; microwaves. Line of sight communications. Generally used for satellite communications and RADAR.
Sky wave	A propagated radio wave that travels to the ionosphere from where it may or may not be returned to earth.
Space wave	A propagated radio wave that travels in a straight line. Used for point-to-point communications
Surface wave	A propagated radio wave that predominantly travels along the surface of the earth.
UHF	Ultra high frequency, the 300 MHz to 3 GHz band; microwaves. Line-of-sight transmission. Generally used for satellite communications.
VHF	Very high frequency. The 30–300 MHz band. Line-of-sight transmission from short antenna using low power. Maritime short-range communications band.
VLF	Very low frequency, the 10–30 kHz band. Requires huge antenna and great power for long-range communication.
WARC	World Administrative Radio Conference. The body that produces radio regulations and a Table of Frequency Allocations.
Wavelength	The physical length in metres between one cycle of the transmitted frequency. A parameter used in the calculation of antenna lengths.

1.11 Summary

- Radio waves travel through free space at approximately $300 \times 10^6\,\mathrm{ms}^{-1}$.
- The frequency, wavelength and velocity of the radiowave are interrelated.
- The radio frequency spectrum is regulated by the International Telecommunications Union (ITU).
- The Table of Frequency Allocations and radio regulatory documents are revised at the World Administrative Conference (WARC).

- The radio frequency spectrum is divided into several bands: they are VLF, LF, MF, HF, VHF, UHF, SHF and EHF.
- A propagated radio wave contains both electromagnetic and electrostatic energy called the magnetic field and the electric field.
- A radio wave propagates from an antenna in one or more of three modes; surface wave, sky wave and space wave.
- Surface waves travel along the ground and consequently the transmitted power is attenuated, thus limiting communication range.
- Sky waves travel to the ionosphere from where they may or may not be returned to the earth. Sky waves provide terrestrial global communications.
- Space waves offer line-of-sight communications. Range is limited by the curvature of the earth, and large objects in the path of the wave will block the signal creating shadow areas.
- Amplitude and/or frequency fading of the signal are a major problem in communication systems.
- Antennae are critically constructed to satisfy frequency, power and environmental requirements.
- Transmitting antenna need to handle large power outputs and are more robust than receiving antenna, although a single antenna may be employed for both purposes.
- Antennas may be directional or not depending upon requirements.
- Antenna feed lines are often called coaxial cables and consist of an inner (signal) wire surrounded by a mesh of copper called the earth (ground) connection.

1.12 Revision questions

1. Why does it appear that the radiocommunications range on MF/HF is greater at night than during the day at your location?
2. How is it possible to receive LF radio waves in regions that are radio-shadow areas to VHF radio waves?
3. Unwanted sky wave reception gives rise to errors in some navigation systems, typically Loran-C. Why is the effect more prevalent at night?
4. How may frequency selective fading be minimized in a receiver system?
5. How are the receptive properties and an antenna's physical length related?
6. What is an antenna azimuth gain plot?
7. If a VHF antenna is remounted higher on the mast of a vessel, radio communications range is increased. Why is this?
8. If a vertical antenna is remounted horizontally at the same height above sea level, radio communications range is severely reduced. Why is this?
9. How are an antenna's directivity and gain related?
10. By carefully locating some antennas, problems of signal fading, and in the case of GPS, errors in the range calculation can be reduced. Why is this?

Chapter 2

Depth sounding systems

2.1 Introduction

Sonar (*so*und *n*avigation *a*nd *r*anging) is the acronym identifying those systems that rely for their operation on the transmission and reception of acoustic energy in water. The term is widely used to identify all modern systems that propagate acoustic or electromagnetic energy into seawater to determine a vessel's speed or the depth of water under the keel. This book is not concerned with those specialized sonar techniques that are used for locating submerged objects, either fish or submarines. A navigator in the Merchant Navy is interested only in the depth of the water beneath the vessel, an indication of the speed of his ship and the distance run. See Chapter 3 for a description of speed logging equipment.

The first section of this chapter deals with the characteristics and problems that arise from the need to propagate energy in seawater.

2.2 The characteristics of sound in seawater

Before considering the problems of transmitting and receiving acoustic energy in seawater, the effects of the environment must be understood. Sonar systems rely on the accurate measurement of reflected frequency or, in the case of depth sounders, a precise measurement of time and both these parameters are affected by the often unpredictable ocean environment. These effects can be summarized as follows.

- Attenuation. A variable factor related to the transmitted power, the frequency of transmission, salinity of the seawater and the reflective consistency of the ocean floor.
- Salinity of seawater. A variable factor affecting both the velocity of the acoustic wave and its attenuation.
- Velocity of sound in salt water. This is another variable parameter. Acoustic wave velocity is precisely 1505 ms^{-1} at 15°C and atmospheric pressure, but most echo-sounding equipment is calibrated at 1500 ms^{-1}.
- Reflective surface of the seabed. The amplitude of the reflected energy varies with the consistency of the ocean floor.
- Noise. Either inherent noise or that produced by one's own transmission causes the signal-to-noise ratio to degrade, and thus weak echo signals may be lost in noise.

Two additional factors should be considered.

- Frequency of transmission. This will vary with the system, i.e. depth sounding or Doppler speed log.
- Angle of incidence of the propagated beam. The closer the angle to vertical the greater will be the energy reflected by the seabed.

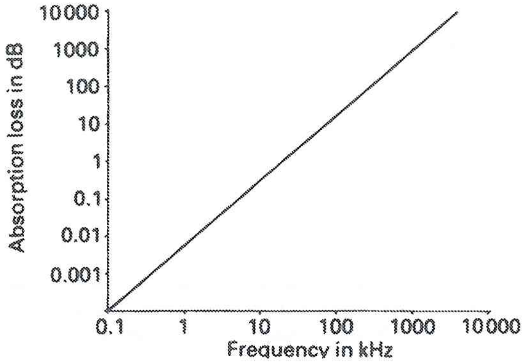


Figure 2.1 A linear graph produced by plotting absorption loss against frequency. Salinity of the seawater is 3.4% at 15°C.

2.2.1 Attenuation and choice of frequency

The frequency of the acoustic energy transmitted in a sonar system is of prime importance. To achieve a narrow directive beam of energy, the radiating transducer is normally large in relation to the wavelength of the signal. Therefore, in order to produce a reasonably sized transducer emitting a narrow beam, a high transmission frequency needs to be used. The high frequency will also improve the signal-to-noise ratio in the system because ambient noise occurs at the lower end of the frequency spectrum. Unfortunately the higher the frequency used the greater will be the attenuation as shown in Figure 2.1.

The choice of transmission frequency is therefore a compromise between transducer size, freedom from noise, and minimal attenuation. Frequencies between 15 and 60 kHz are typical for depth sounders fitted in large vessels. A high power is transmitted from a large magnetostrictive transducer to indicate great depths with low attenuation. Small light craft use depth sounders that transmit in the band 200–400 kHz. This enables compact electrostrictive or ceramic transducers to be used on a boat where space is limited. Speed logs use frequencies in the range 300 kHz to 1 MHz depending upon their design and are not strictly sonar devices in the true definition of the sense.

Beam spreading

Transmission beam diverging or spreading is independent of fixed parameters, such as frequency, but depends upon distance between the transducer and the seabed. The greater the depth, the more the beam spreads, resulting in a drop in returned energy.

Temperature

Water temperature also affects absorption. As temperature decreases, attenuation decreases. The effect of temperature change is small and in most cases can be ignored, although modern sonar equipment is usually fitted with a temperature sensor to provide corrective data to the processor.

Consistency of the seabed

The reflective property of the seabed changes with its consistency. The main types of seabed and the attenuation which they cause are listed in Table 2.1. The measurements were made with an echo sounder transmitting 24 kHz from a magnetostrictive transducer.

Table 2.1 Sea bed consistency and attenuation

Consistency	*Attenuation (dB)*
Soft mud	15
Mud/sand	9
Sand/mud	6
Sand	3
Stone/rock	1

These figures are typical and are quoted as a guideline only. In practice sufficient transmitted power will overcome these losses.

2.2.2 Salinity, pressure and the velocity of the acoustic wave

Since a depth sounder operates by precisely calculating the time taken for a pulse of energy to travel to the ocean floor and return, any variation in the velocity of the acoustic wave from the accepted calibrated speed of 1500 ms^{-1} will produce an error in the indicated depth. The speed of acoustic waves in seawater varies with temperature, pressure and salinity. Figure 2.2 illustrates the speed variation caused by changes in the salinity of seawater.

Ocean water salinity is approximately 3.4% but it does vary extensively throughout the world. As salinity increases, sonar wave velocity increases producing a shallower depth indication, although in practice errors due to salinity changes would not be greater than 0.5%. The error can be ignored except when the vessel transfers from seawater to fresh water, when the indicated depth will be approximately 3% greater than the actual depth. The variation of speed with pressure or depth is indicated by the graph in Figure 2.3.

It can readily be seen that the change is slight, and is normally only compensated for in apparatus fitted on survey vessels. Seasonal changes affect the level of the thermocline and thus there is a small annual velocity variation. However, this can usually be ignored.

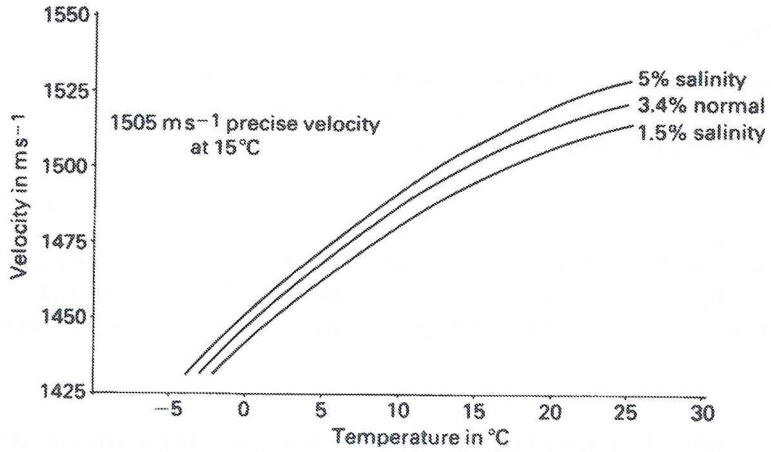


Figure 2.2 Graph showing that the velocity of acoustic energy is affected by both the temperature and the salinity of seawater.

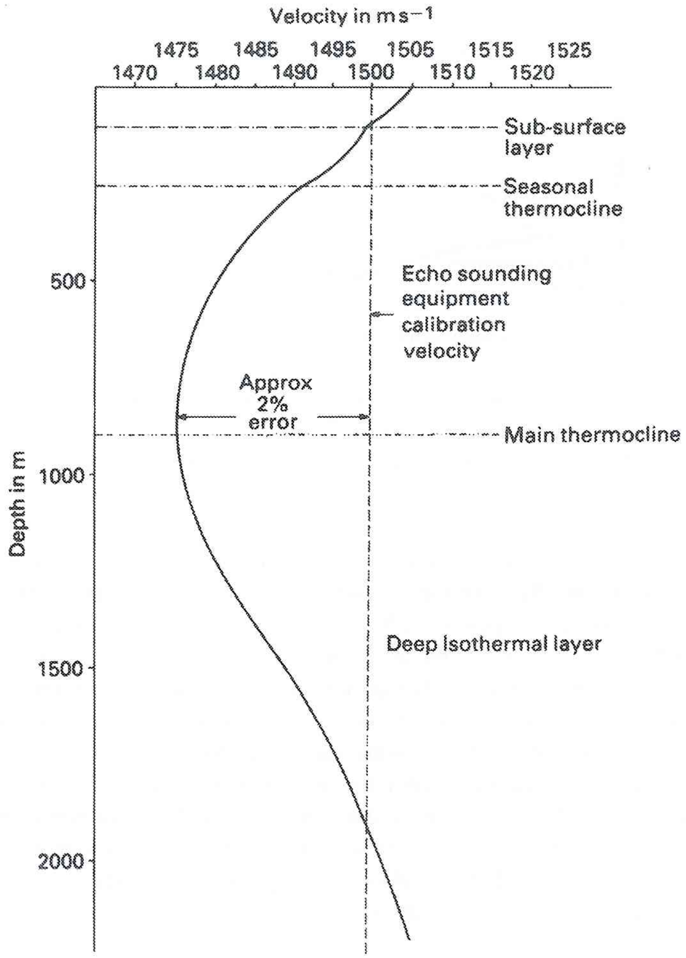


Figure 2.3 Variation of the velocity of acoustic waves with pressure.

2.2.3 Noise

Noise present in the ocean adversely affects the performance of sonar equipment. Water noise has two main causes.

- The steady ambient noise caused by natural phenomena.
- Variable noise caused by the movement of shipping and the scattering of one's own transmitted signal (reverberation).

Ambient noise

Figure 2.4 shows that the amplitude of the ambient noise remains constant as range increases, whereas both the echo amplitude and the level of reverberation noise decrease linearly with range. Because of beam spreading, scattering of the signal increases and reverberation noise amplitude falls more slowly than the echo signal amplitude.

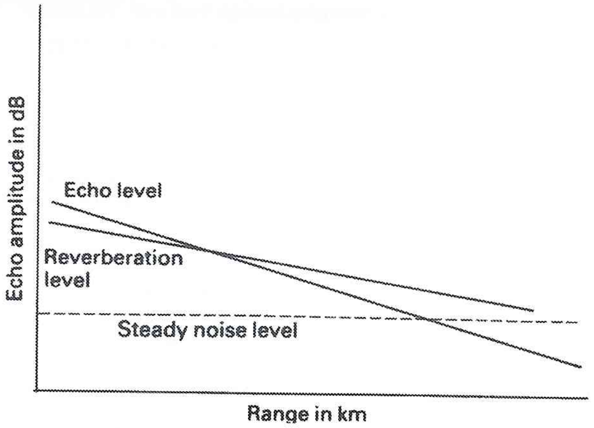


Figure 2.4 Comparison of steady-state noise, reverberation noise and signal amplitude.

Ambient noise possesses different characteristics at different frequencies and varies with natural conditions such as rainstorms. Rain hitting the surface of the sea can cause a 10-fold increase in the noise level at the low frequency (approx. 10 kHz) end of the spectrum. Low frequency noise is also increased, particularly in shallow water, by storms or heavy surf. Biological sounds produced by some forms of aquatic life are also detectable, but only by the more sensitive types of equipment.

The steady amplitude of ambient noise produced by these and other factors affects the signal-to-noise ratio of the received signal and can in some cases lead to a loss of the returned echo. Signal-to-noise ratio can be improved by transmitting more power. This may be done by increasing the pulse repetition rate or increasing the amplitude or duration of the pulse. Unfortunately such an increase, which improves signal-to-noise ratio, leads to an increase in the amplitude of reverberation noise. Ambient noise is produced in the lower end of the frequency spectrum. By using a slightly higher transmitter frequency and a limited bandwidth receiver it is possible to reduce significantly the effects of ambient noise.

Reverberation noise

Reverberation noise is the term used to describe noise created and affected by one's own transmission. The noise is caused by a 'back scattering' of the transmitted signal. It differs from ambient noise in the following ways.

- Its amplitude is directly proportional to the transmitted signal.
- Its amplitude is inversely proportional to the distance from the target.
- Its frequency is the same as that of the transmitted signal.

The signal-to-noise ratio cannot be improved by increasing transmitter power because reverberation noise is directly proportional to the power in the transmitted wave. Also it cannot be attenuated by improving receiver selectivity because the noise is at the same frequency as the transmitted wave. Furthermore reverberation noise increases with range because of increasing beamwidth. The area covered by the wavefront progressively increases, causing a larger area from which back scattering will occur. This means that reverberation noise does not decrease in amplitude as rapidly as the transmitted signal. Ultimately, therefore, reverberation noise amplitude will exceed the signal noise amplitude, as shown in Figure 2.4, and the echo will be lost. The amplitude of both the echo and reverberation noise decreases linearly with range. However, because of beam spreading, back scattering increases and reverberation noise amplitude falls more slowly than the echo signal amplitude. Three totally different 'scattering' sources produce reverberation noise.

- Surface reverberation. As the name suggests, this is caused by the surface of the ocean and is particularly troublesome during rough weather conditions when the surface is turbulent.
- Volume reverberation. This is the interference caused by beam scattering due to suspended matter in the ocean. Marine life, prevalent at depths between 200 and 750 m, is the main cause of this type of interference.
- Bottom reverberation. This depends upon the nature of the seabed. Solid seabeds, such as hard rock, will produce greater scattering of the beam than silt or sandy seabeds. Beam scattering caused by a solid seabed is particularly troublesome in fish finding systems because targets close to the seabed can be lost in the scatter.

2.3 Transducers

A transducer is a converter of energy. RF energy, when applied to a transducer assembly, will cause the unit to oscillate at its natural resonant frequency. If the transmitting face of the unit is placed in contact with, or close to, seawater the oscillations will cause acoustic waves to be transmitted in the water. Any reflected acoustic energy will cause a reciprocal action at the transducer. If the reflected energy comes into contact with the transducer face natural resonant oscillations will again be produced. These oscillations will in turn cause a minute electromotive force (e.m.f.) to be created which is then processed by the receiver to produce the necessary data for display.

Three types of transducer construction are available; electrostrictive, piezoelectric resonator, and magnetostrictive. Both the electrostrictive and the piezoelectric resonator types are constructed from piezoelectric ceramic materials and the two should not be confused.

2.3.1 Electrostrictive transducers

Certain materials, such as Rochelle salt and quartz, exhibit pressure electric effects when they are subjected to mechanical stress. This phenomenon is particularly outstanding in the element lead zirconate titanate, a material widely used for the construction of the sensitive element in modern electrostrictive transducers. Such a material is termed ferro-electric because of its similarity to ferro-magnetic materials.

The ceramic material contains random electric domains which when subjected to mechanical stress will line up to produce a potential difference (p.d.) across the two plate ends of the material section. Alternatively, if a voltage is applied across the plate ends of the ceramic crystal section its length will be varied. Figure 2.5 illustrates these phenomena.

The natural resonant frequency of the crystal slice is inversely proportional to its thickness. At high frequencies therefore the crystal slice becomes brittle, making its use in areas subjected to great stress forces impossible. This is a problem if the transducer is to be mounted in the forward section of a large merchant vessel where pressure stress can be intolerable. The fragility of the crystal also imposes limits on the transmitter power that may be applied because mechanical stress is directly related to power. The power restraints thus established make the electrostrictive transducer unsuitable for use in depth sounding apparatus where great depths need to be indicated. In addition, the low transmission frequency requirement of an echo sounder means that such a transducer crystal slice would be

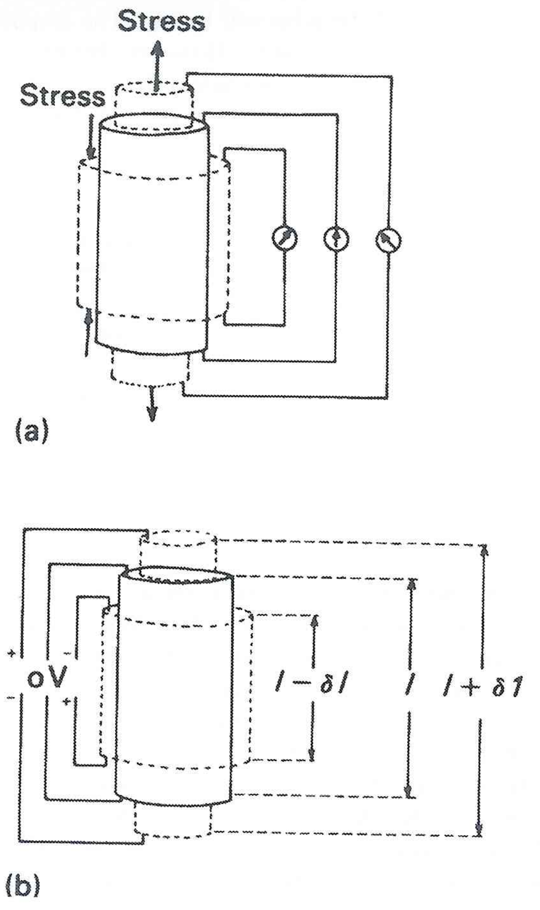


Figure 2.5 (a) An output is produced when a piezoelectric ceramic cylinder is subjected to stress. (b) A change of length occurs if a voltage is applied across the ends of a piezoelectric ceramic cylinder.

excessively thick and require massive transmitter peak power to cause it to oscillate. The crystal slice is stressed by a voltage applied across its ends, thus the thicker the crystal slice, the greater is the power needed to stress it.

The electrostrictive transducer is only fitted on large merchant vessels when the power transmitted is low and the frequency is high, a combination of factors present in Doppler speed logging systems. Such a transducer is manufactured by mounting two crystal slices in a sandwich of two stainless steel cylinders. The whole unit is pre-stressed by inserting a stainless steel bolt through the centre of the active unit as shown in Figure 2.6.

If a voltage is applied across the ends of the unit, it will be made to vary in length. The bolt is insulated from the crystal slices by means of a PVC collar and the whole cylindrical section is made waterproof by means of a flexible seal. The bolt tightens against a compression spring permitting the crystal slices to vary in length, under the influence of the RF energy, whilst still remaining mechanically stressed. This method of construction is widely found on the electrostrictive transducers used in the Merchant Navy. For smaller vessels, where the external stresses are not so severe, the simpler piezoelectric resonator is used.

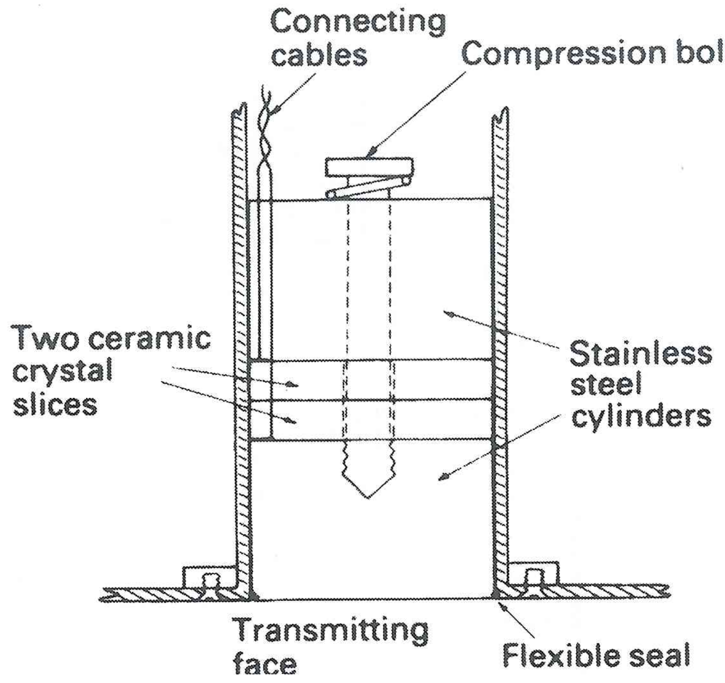


Figure 2.6 Construction details of a ceramic electrostrictive transducer.

2.3.2 Piezoelectric resonator

This type of transducer makes use of the flexible qualities of a crystal slice. If the ceramic crystal slice is mounted so that it is able to flex at its natural resonant frequency, acoustic oscillations can be produced. The action is again reciprocal. If the ceramic crystal slice is mounted at its corners only, and is caused to flex by an external force, a small p.d. will be developed across the ends of the element. This phenomenon is widely used in industry for producing such things as electronic cigarette lighters and fundamental crystal oscillator units for digital watches. However, a ceramic crystal slice used in this way is subject to the same mechanical laws as have previously been stated. The higher the frequency of oscillation, the thinner the slice needs to be and the greater the risk of fracture due to external stress or overdriving. For these reasons, piezoelectric resonators are rarely used at sea.

2.3.3 Magnetostrictive transducers

Figure 2.7 shows a bar of ferromagnetic material around which is wound a coil. If the bar is held rigid and a large current is passed through the coil, the resulting magnetic field produced will cause the bar to change in length. This slight change may be an increase or a decrease depending upon the material used for construction. For maximum change of length for a given input signal, annealed nickel has been found to be the optimum material and consequently this is used extensively in the construction of marine transducers.

As the a.c. through the coil increases to a maximum in one direction, the annealed nickel bar will reach its maximum construction length ($l+\delta l$). With the a.c. at zero the bar returns to normal (l). The current now increases in the opposite direction and the bar once again constricts ($l-\delta l$). The frequency

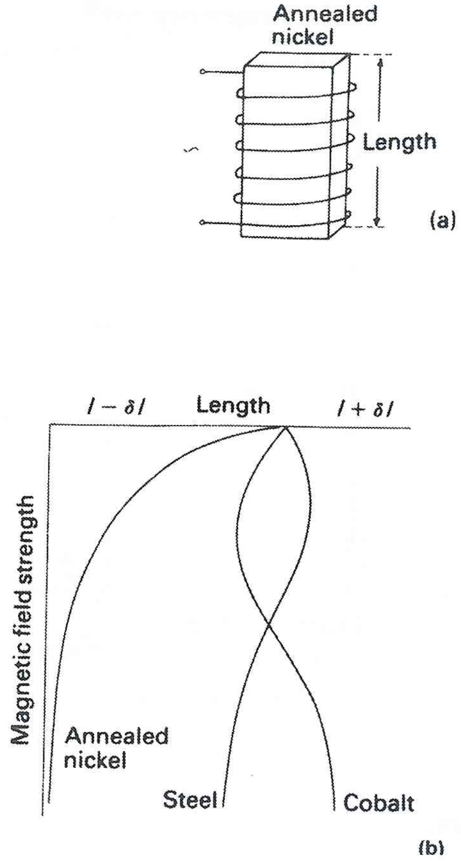


Figure 2.7 (a) A bar of ferromagnetic material around which is wound a coil. (b) Relationship between magnetic field strength and change of length.

of resonance is therefore twice that of the applied a.c. This frequency doubling action is counteracted by applying a permanent magnet bias field produced by an in-built permanent magnet.

The phenomenon that causes the bar to change in length under the influence of a magnetic field is called 'magnetostriction', and in common with most mechanical laws possesses the reciprocal quality. When acoustic vibrations cause the bar to constrict, at its natural resonant frequency, an alternating magnetic field is produced around the coil. A minute alternating current is caused to flow in the coil and a small e.m.f. is generated. This is then amplified and processed by the receiver as the returned echo.

To limit the effects of magnetic hysteresis and eddy current losses common in low frequency transformer construction, the annealed nickel bar is made of laminated strips bonded together with an insulating material. Figure 2.8 illustrates the construction of a typical magnetostrictive transducer unit. The transmitting face is at the base of the diagram.

Magnetostrictive transducers are extremely robust which makes them ideal for use in large vessels where heavy sea pounding could destroy an unprotected electrostrictive type. They are extensively used with depth sounding apparatus because at the low frequencies used they can be constructed to an acceptable size and will handle the large power requirement of a deep sounding system. However, magnetic losses increase with frequency, and above 100 kHz the efficiency of magnetostrictive transducers falls to below the normal 40%. Above this frequency electrostrictive transducers are normally used.

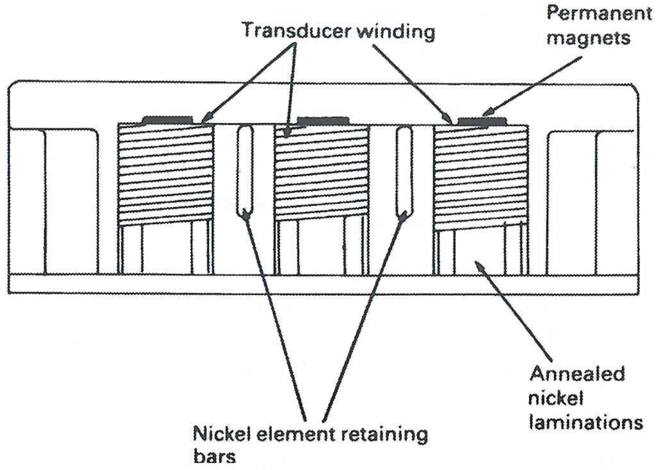


Figure 2.8 Cross-section of a magnetostrictive transducer. (Reproduced courtesy of Marconi Marine.)

2.3.4 Transducer siting

The decision of where to mount the transducer must not be made in haste. It is vital that the active face of the transducer is in contact with the water. The unit should also be mounted well away from areas close to turbulence that will cause noise. Areas close to propellers or water outlets must be avoided.

Aeration is undoubtedly the biggest problem encountered when transducers are wrongly installed. Air bubbles in the water, for whatever reason, will pass close to the transducer face and act as a reflector of the acoustic energy.

As a vessel cuts through the water, severe turbulence is created. Water containing huge quantities of air bubbles is forced under and along the hull. The bow wave is aerated as it is forced above the surface of the sea, along the hull. The wave falls back into the sea at approximately one-third the distance along the length of the vessel from the bow. A transducer mounted aft of the position where the bow wave re-enters the sea, would suffer badly from the problems of aeration. Mounting the transducer ahead of this point, even in the bulbous bow, would be ideal. It should be remembered, however, that at some stage maintenance may be required and a position in the bulbous bow may be inaccessible.

A second source of aeration is that of cavitation. The hull of a vessel is seldom smooth and any indentations or irregularities in it will cause air bubbles to be produced leading to aeration of the transducer face. Hull irregularities are impossible to predict as they are not a feature of the vessel's design.

2.4 Depth sounding principles

In its simplest form, the depth sounder is purely a timing and display system that makes use of a transmitter and a receiver to measure the depth of water beneath a vessel. Acoustic energy is transmitted perpendicularly from the transducer to the seabed. Some of the transmitted energy is reflected and will be received by the transducer as an echo. It has been previously stated that the velocity of sound waves in seawater is accepted to be $1500\,\text{ms}^{-1}$. Knowledge of this fact and the ability to measure precisely the time delay between transmission and reception, provides an accurate indication of the water depth.

$$\text{Distance travelled} = \frac{\text{velocity} \times \text{time}}{2}$$

where velocity = $1500\,\text{ms}^{-1}$ in salt water; time = time taken for the return journey in seconds; and distance = depth beneath the transducer in metres. Thus if the time taken for the return journey is 1 s, the depth of water beneath the transducer is 750 m. If the time is 0.1 s the depth is 75 m, and so on.

The transmitter and transducer, must be capable of delivering sufficient power and the receiver must possess adequate sensitivity to overcome all of the losses in the transmission medium (seawater and seabed). It is the likely attenuation of the signal, due to the losses described in the first part of this chapter, which determines the specifications of the equipment to be fitted on a merchant vessel.

2.4.1 Continuous wave/pulse system

The transmission of acoustic energy for depth sounding, may take one of two forms.

- A continuous wave system, where the acoustic energy is continuously transmitted from one transducer. The returned echo signal is received by a second transducer and a phase difference between the two is used to calculate the depth.
- The pulse system, in which rapid short, high intensity pulses are transmitted and received by a single transducer. The depth is calculated by measuring the time delay between transmission and reception.

The latter system is preferred in the majority of applications. Both the pulse length (duration) and the pulse repetition frequency (PRF) are important when considering the function of the echo sounding apparatus.

Continuous wave system

This system is rarely used in commercial echo sounding applications. Because it requires independent transmitters and receivers, and two transducer assemblies it is expensive. Also because the transmitter is firing continually, noise is a particular problem. Civilian maritime echo sounders therefore use a pulsed system.

Pulsed system

In this system the transmitter fires for a defined period of time and is then switched off. The pulse travels to the ocean floor and is reflected back to be received by the same transducer which is now switched to a receive mode. The duration of the transmitter pulse and the pulse repetition frequency (PRF) are particularly important parameters in this system

The pulse duration effectively determines the resolution quality of the equipment. This, along with the display method used, enables objects close together in the water, or close to the seabed, to be recorded separately. It is called target or echo discrimination. This factor is particularly important in fish finding apparatus where very short duration pulses (typically 0.25 or 0.5 ms) are used.

Echo discrimination *(D)* is:

$$D = V \times l \text{ (in metres)}$$

where V = the velocity of acoustic waves, and l = pulse length.

For a 0.5 ms pulse length:

$$D = 1500 \times 0.5 \times 10^{-3} = 0.75\,\text{m}$$

For a 2 ms pulse length:

$$D = 1500 \times 2 \times 10^{-3} = 3\,\text{m}$$

Obviously a short pulse length is superior where objects to be displayed are close together in the water. Short pulse lengths tend to be used in fish finding systems.

A short pulse length also improves the quality of the returned echo because reverberation noise will be less. Reverberation noise is directly proportional to the signal strength, therefore reducing the pulse length reduces signal strength which in turn reduces noise. Unfortunately, reducing the signal strength in this way reduces the total energy transmitted, thereby limiting the maximum depth from which satisfactory echoes can be received. Obviously, a compromise has to be made. Most depth sounders are fitted with a means whereby the pulse length can be varied with range. For shallow ranges, and for better definition, a short pulse length is used. On those occasions where great depths are to be recorded a longer pulse is transmitted.

For a given pulse length, the PRF effectively determines the maximum range that can be indicated. It is a measure of the time interval between pulses when transmission has ceased and the receiver is awaiting the returned echo.

The maximum indicated range may be determined by using the following formula:

$$\text{Maximum range indication } (r) = \frac{v \times t}{2} \text{ (in metres)}$$

where v = velocity of sound in seawater ($1500\,\text{ms}^{-1}$) and t = time between pulses in seconds. If the PRF is one per second (PRF = 60), the maximum depth recorded is 750 m. If the PRF is two per second (PRF = 120) the maximum depth recorded is 375 m.

The maximum display range should not be confused with the maximum depth. For instance, if the PRF is one per second the maximum display range is 750 m. If the water depth is 850 m, an echo will be returned after a second pulse has been transmitted and the range display has been returned to zero. The indicated depth would now be 100 m. A system of 'phased' ranges, where the display initiation is delayed for a pre-determined period after transmission overcomes the problem of over-range indication.

2.4.2 Transmission beamwidth

Acoustic energy is radiated vertically downwards from the transducer in the form of a beam of energy. As Figure 2.9 shows the main beam is central to the transducer face and shorter sidelobes are also produced. The beamwidth must not be excessively narrow otherwise echoes may be missed, particularly in heavy weather when the vessel is rolling. A low PRF combined with a fast ship speed

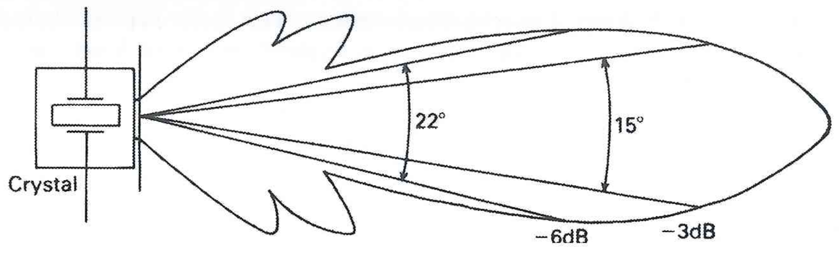


Figure 2.9 Transmission beam showing the sidelobes.

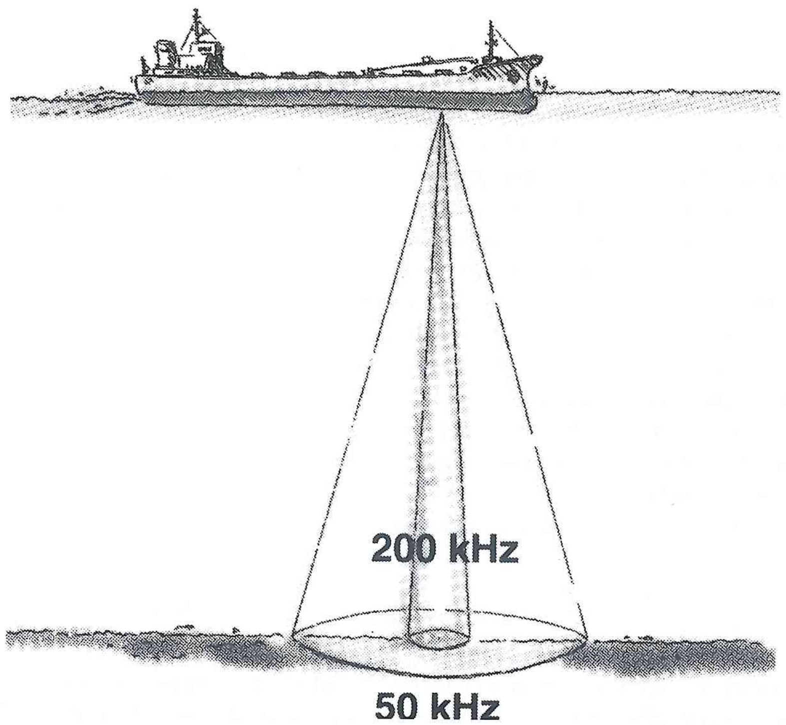


Figure 2.10 Typical beamwidths for echo sounders transmitting low and high frequencies. (Reproduced courtesy Furuno Electric Co. Ltd.)

can in some cases lead to the vessel 'running away' from an echo that could well be missed. In general, beamwidths measured at the half-power points (–3 dB), used for depth sounding apparatus are between 15° and 25°. To obtain this relatively narrow beamwidth, the transducer needs to be constructed with a size equal to many wavelengths of the frequency in use. This fact dictates that the transducer will be physically large for the lower acoustic frequencies used in depth sounding.

In order to reduce the transducer size, and keep a narrow beamwidth, it is possible to increase the transmission frequency. However, the resulting signal attenuation negates this change and in practice a compromise must once again be reached between frequency, transducer size and beamwidth. Figure 2.10 shows typical beamwidths for a low frequency (50 kHz) sounder and that of a frequency four times greater.

2.5 A generic echo sounding system

Compared with other systems, echo sounder circuitry is relatively simple. Most manufacturers of deep sounding systems now opt for microprocessor control and digital displays, but it was not always so. Many mariners preferred the paper-recording echo sounder because the display was clear, easy to read and provided a history of soundings.

Marconi Marine's 'Seahorse' echo sounder (Figure 2.11) was typical of the standard paper-recording echo sounder. Built in the period before microprocessor control, it is used here to describe the relatively simply circuitry needed to produce an accurate read-out of depth beneath the keel. From the description it is easy to see that an echo sounding system is simply a timing device.

The system used a transmission frequency of 24 kHz and two ranges, either manually or automatically selected, to allow depths down to 1000 m to be recorded. The shallow range was 100 m and operated with a short pulse length of 200 μs, whereas the 1000 m range uses a pulse length of 2 ms. Display accuracy for the chart recorder is typically 0.5% producing indications with an accuracy of ±0.5 m on the 100 m range and ±5 m on the deepest range.

2.5.1 Description

Receiver and chart recorder

When chart recording has been selected, transmission is initiated by a pulse from a proximity detector which triggers the chart pulse generator circuit introducing a slight delay, pre-set on each range, to ensure that transmission occurs at the instant the stylus marks zero on the recording paper. This system trigger pulse or that from the trigger pulse generator circuit when the chart is switched off, has three functions:

- to initiate the pulse timing circuit
- to operate the blanking pulse generator
- to synchronize the digital and processing circuits.

The transmit timing circuit sets the pulse length to trigger the 24 kHz oscillator (transmission frequency). Pulse length is increased, when the deep range is changed, by a range switch (not shown). Power contained in the transmitted signal is produced by the power amplifier stage, the output of which is coupled to the magnetostrictive transducer with the neon indicating transmission.

When the transmitter fires, the receiver input is blanked to prevent the high-energy pulse from causing damage to the input tuned circuits. The blanking pulse generator also initiates the swept gain circuit and inhibits the data pulse generator. During transmission, the swept gain control circuit holds the gain of the input tuned amplifier low. At cessation of transmission, the hold is removed permitting the receiver gain to gradually increase at a rate governed by an inverse fourth power law. This type of inverse gain control is necessary because echoes that are returned soon after transmission ceases are of large amplitude and are likely to overload the receiver.

The echo amplitude gradually decreases as the returned echo delay period increases. Thus the swept gain control circuit causes the average amplitude of the echoes displayed to be the same over the whole period between transmission pulses. However, high intensity echoes returned from large reflective objects will produce a rapid change in signal amplitude and will cause a larger signal to be coupled to the logarithmic amplifier causing a more substantial indication to be made on the paper. The logarithmic amplifier and detector stages produce a d.c. output, the amplitude of which is logarithmically proportional to the strength of the echo signal.

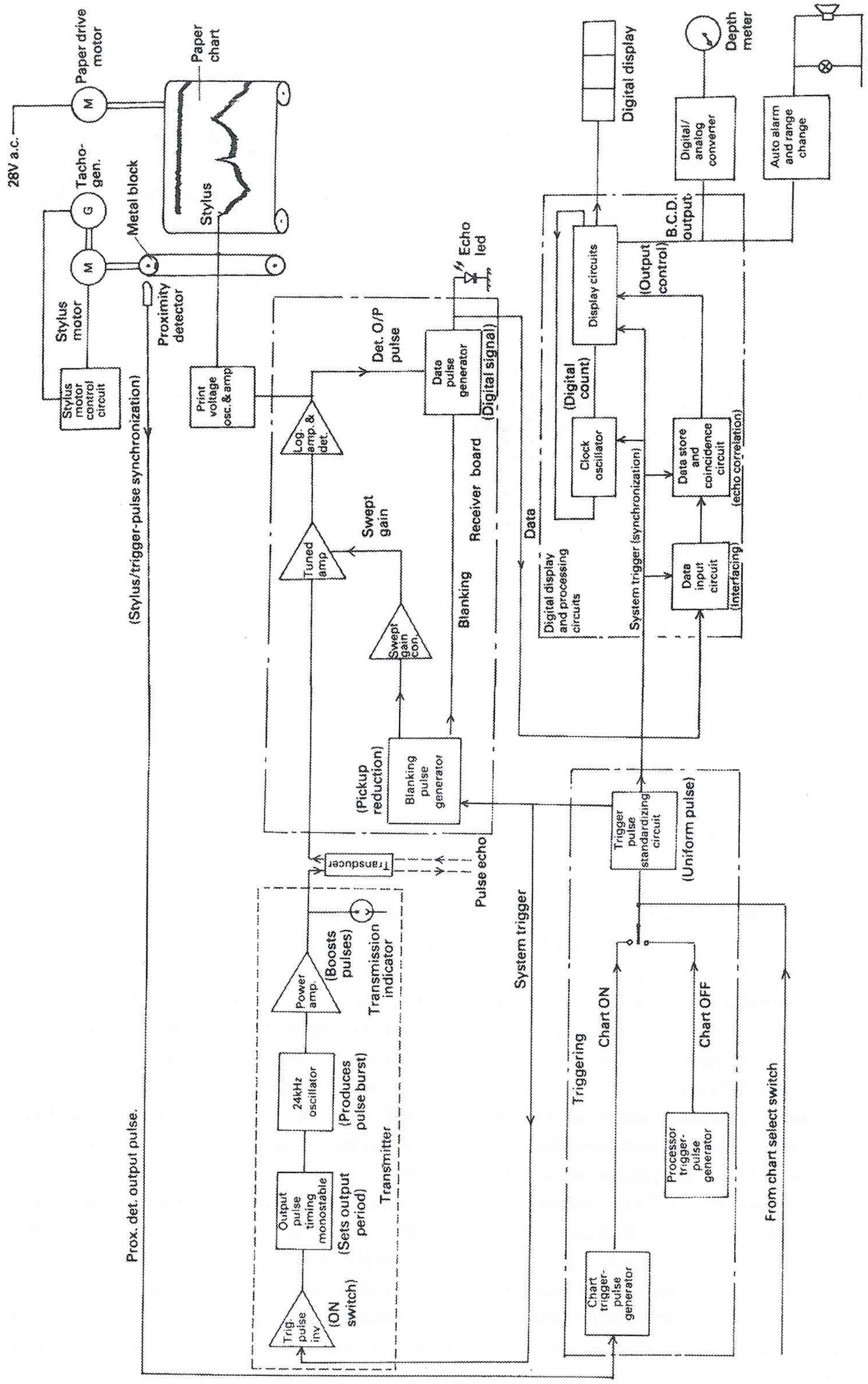


Figure 2.11 A block schematic diagram of the Seahorse echo sounder. (Reproduced courtesy of Marconi Marine.)

In the chart recorder display, electrosensitive paper is drawn horizontally beneath a sharp stylus. The paper is tightly drawn over the grounded roller guides by a constant speed paper-drive motor. Paper marking is achieved by applying a high voltage a.c. signal to the stylus which is drawn at 90° to the paper movement, across the surface of the paper on top of the left-hand roller. The paper is marked by burning the surface with a high voltage charge produced through the paper between the stylus and ground. Depending upon the size of the returned echo, the marking voltage is between 440 and 1100 V and is produced from a print voltage oscillator running at 2 kHz. Oscillator amplifier output is a constant amplitude signal, the threshold level of which is raised by the d.c. produced by a detected echo signal. Thus a high-intensity echo signal causes the marking voltage to be raised above the threshold level by a greater amount than would be caused by a detected small echo signal.

For accurate depth marking it is essential that the stylus tracking speed is absolutely precise. The stylus is moved along the paper by a belt controlled by the stylus d.c. motor. Speed accuracy is maintained by a complex feedback loop and tacho-generator circuit.

Digital circuits

The digital display section contains the necessary logic to drive the integral three-digit depth display, the alarm circuit, and the remote indicators. Pulse repetition frequency (PRF) of the clock oscillator is pre-set so that the time taken for the three-digit counter to count from 000 to 999 is exactly the same as that taken by the paper stylus to travel from zero to the maximum reading for the range in use. The counter output is therefore directly related to depth.

When the chart recorder is switched off, the digital processing section and the transmitter are triggered from the processor trigger pulse generator circuit. Both the transmit and receive sections work in the same way as previously described. A low logic pulse from the trigger pulse standardizing circuit synchronizes the logic functions. The d.c. output from the receiver detector is coupled via a data pulse generator circuit to the interface system. Unfortunately in any echo sounder it is likely that unwanted echoes will be received due to ship noise, aeration or other factors.

False echoes would be displayed as false depth indications on the chart and would be easily recognized. However, such echoes would produce instantaneous erroneous readings on the digital counter display that would not be so easily recognized. To prevent this happening echoes are stored in a data store on the processing board and only valid echoes will produce a reading on the display. Valid echoes are those that have indicated the same depth for two consecutive sounding cycles. The data store, therefore, consists of a two-stage counter which holds each echo for one sounding cycle and compares it with the next echo before the depth is displayed on the digital display.

The display circuit consists of three digital counters that are clocked from the clock oscillator circuit. Oscillator clock pulses are initiated by the system trigger at the instant of transmission. The first nine pulses are counted by the lowest order decade counter which registers 1–9 on the display least significant figure (LSF) element. The next clock pulse produces a 0 on the LSF display and clocks the second decade counter by one, producing a 1 in the centre of the display. This action continues, and if no echo is received, the full count of 999 is recorded when an output pulse from the counting circuit is fed back to stop the clock.

Each time transmission takes place the counters are reset to zero before being enabled. This is not evident on the display because the data output from the counters is taken via a latch that has to be enabled before data transfer can take place. Thus the counters are continually changing but the display data will only change when the latches have been enabled (when the depth changes). If an echo is received during the counting process, the output is stopped, and the output latches enabled by a pulse from the data store. The new depth is now displayed on the indicator and the counters are reset at the start of the next transmission pulse.

With any echo sounder, it is necessary that the clock pulse rate be directly related to depth. Whe the shallow (100 m) range is selected a high frequency is used which is reduced by a factor of 10 whe the deep range (1000 m) is selected.

Modern echo sounders rely for their operation on the ubiquitous microprocessor and digita circuitry, but the system principles remain the same. It is the display of information that is the outwar sign of the advance in technology.

2.6 A digitized echo sounding system

The Furuno Electric Co. Ltd, one of the world's big manufacturers of marine equipment, produces a echo sounder, the FE606, in which many of the functions have been digitized. Transmission frequenc is either 50 or 200 kHz depending upon navigation requirements. A choice of 50 kHz provides greate depth indication and a wider beamwidth reducing the chance that the vessel may 'run away' from a echo (see Figure 2.10).

The pulse length increases with depth range from 0.4 ms, on the shallow ranges, to 2.0 ms on th maximum range. This enables better target discrimination on the lower ranges and ensures tha sufficient pulse power is available on the higher ranges. Pulse repetition rate (sounding rate) is reduce as range increases to ensure adequate time between pulses for echoes to be returned from greate depths.

The system shown in Figure 2.12 is essentially a paper recorder and two LCD displays showin start depth and seabed depth. As before, transmission is initiated at the instant the stylus marks the zer line on the sensitive paper by a trigger sensor coupled to the control integrated circuits. Dependin upon the range selected, the pulse length modulates the output from the transmit oscillator, which i power amplified and then coupled via a transmit/receive switch to the transducer.

A returned echo is processed in the receiver and applied to the logic circuitry. Here it is processe to determine that it is a valid echo and then it is latched through to a digital-to-analogue converter t produce the analogue voltage to drive the print oscillator. Thus the depth is marked on the sensitiv paper at some point determined by the time delay between transmission and reception, and th distance the stylus has travelled over the paper.

2.7 A microcomputer echo sounding system

As you would expect, the use of computing technology has eliminated much of the basic circuitry and in most cases the mechanical paper display system of modern echo sounders. Current systems are much more versatile than their predecessors. The use of a computer enables precise control and processing of the echo sounding signal. Circuitry has now reached the point where it is virtually all contained on a few chips. However, the most obvious changes that users will be aware of in moder systems are the display and user interface.

Once again there are many manufacturers and suppliers of echo sounders or, as they are often no called, fish finders. The Furuno navigational echo sounder FE-700 is typical of many. Depending upo requirements the system is able to operate with a 200 kHz transmission frequency giving high resolution shallow depth performance, or 50 kHz for deep-water sounding.

Seabed and echo data is displayed on a 6.5 inch high-brightness TFT colour LCD display which provides the navigator with a history of soundings over a period of 15 min, much as the older pape recording systems did (see Figure 2.13).

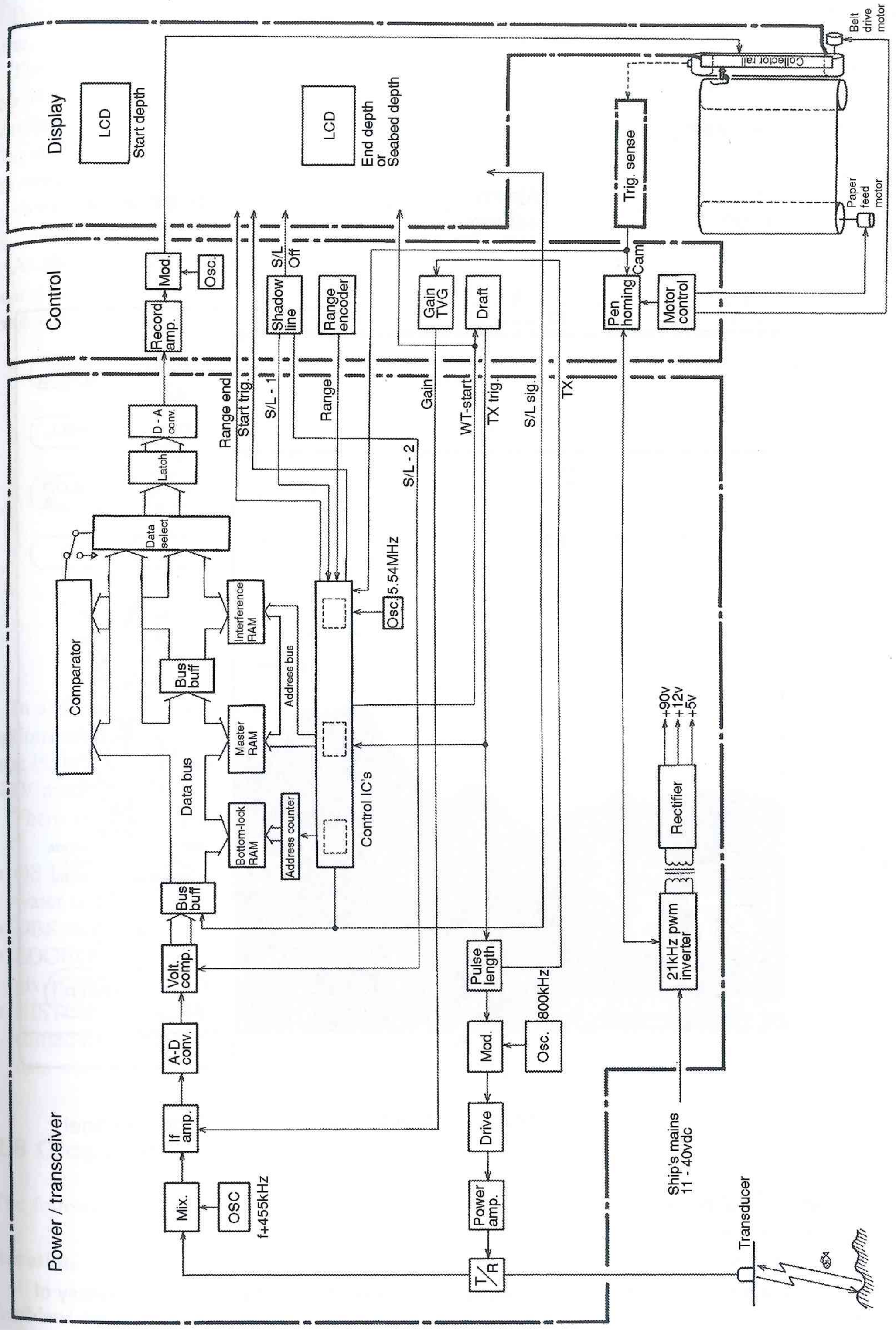


Figure 2.12 Furuno FE-606 echo sounding system. (Reproduced courtesy of Furuno Electric Co.)

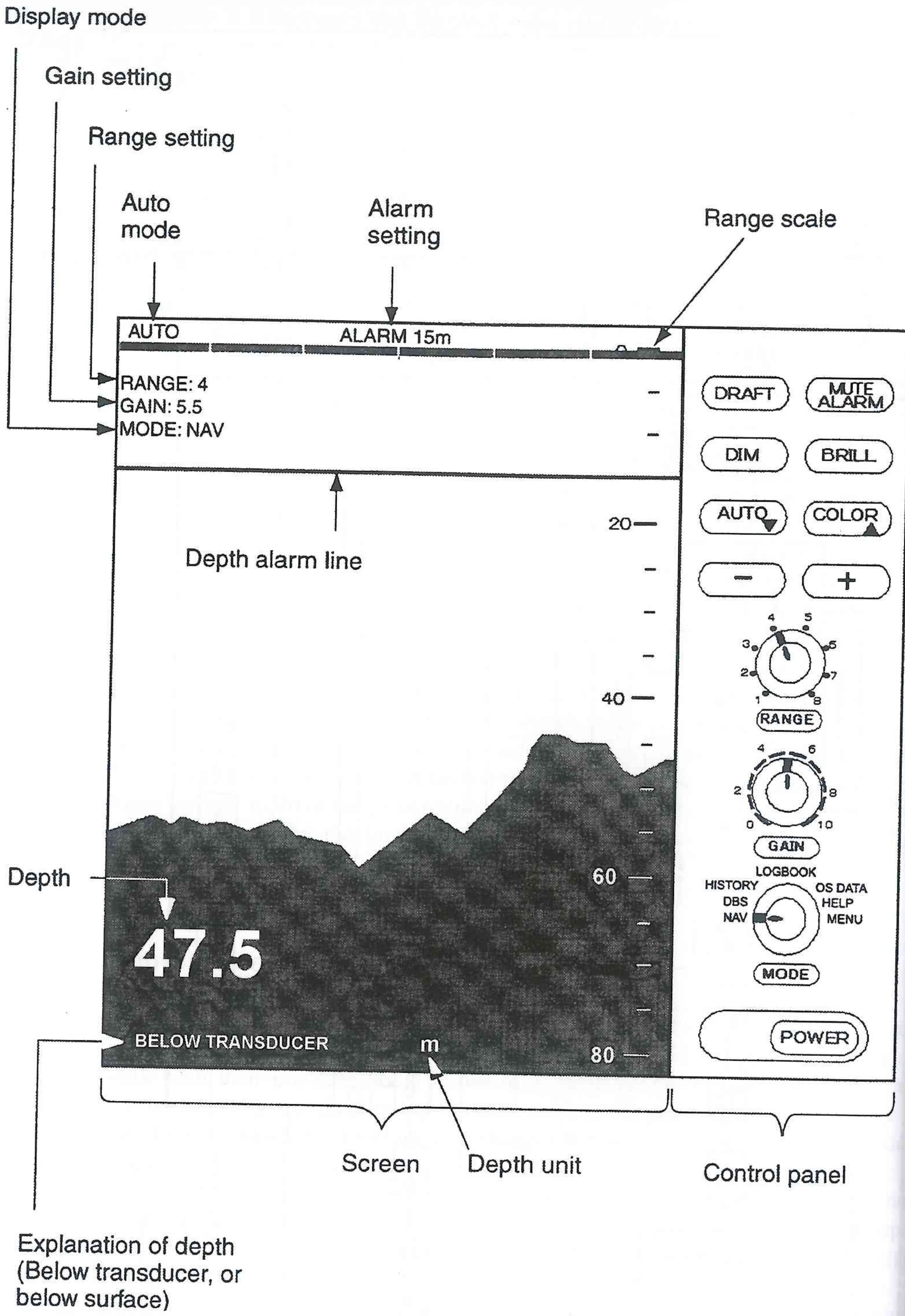


Figure 2.13 Furuno FE-700 LCD TFT data display (Navigation Mode.) (Reproduced courtesy of Furuno Electric Co.)

Depths, associated time, and position are all stored in 24-h memory and can be played back at any time. This is a useful function if there is any dispute following an accident.

The main depth display emulates a cross-sectional profile of the ocean over the past 15 min. At the top of the display in Figure 2.13, the solid zero line marks the ocean surface or transducer level whichever is selected. At 15 m down, a second line marks the depth at which the alarm has been set. The undulating line showing the ocean floor depth is shown varying over 15 min from 58 to 44 m and the instantaneous depth, also shown as a large numerical display, is 47.5 m. Other operation detail is as shown in the diagram. What is not indicated on the display is the change of pulse length and period as selected by range.

As shown in Table 2.2, the pulse length is increased with the depth range to effectively allow more power to be contained in the transmitted pulse, whilst the pulse period frequency is reduced to permit longer gaps in the transmission period allowing greater depths to be indicated

Table 2.2 Echo sounder range vs pulse length vs PRF

Depth (metres)	*Pulse length (ms)*	*PRF (pulses per minute)*
5, 10 and 20	0.25	750
40	0.38	375
100	1.00	150
200	2.00	75
400 and 800	3.60	42

In addition to the standard navigation mode, Furuno FE-700 users are provided with a number of options adequately demonstrating the capability of a modern echo sounder using a TFT LCD display (see Figure 2.14). All the selected modes display data as a window insert on top of the echo sounder NAV mode display.

There are four display-mode areas.

- OS DATA mode. Indicates own ship position, GPS derived course, time and a digital display of water depth.
- DBS mode. Provides a draft-adjusted depth mode for referencing with maritime charts.
- LOGBOOK mode. As the name suggests, provides a facility for manually logging depths over a given period.
- HISTORY mode. Provides a mixture of contour and strata displays. The contour display can be shifted back over the past 24 h whilst the strata display (right-hand side of display) shows sounding data over the last 5 min.

2.8 Glossary

The following lists abbreviations, acronyms and definitions of specific terms used in this chapter.

Aeration	Aerated water bubbles clinging to the transducer face cause errors in the system.
Ambient noise	Noise that remains constant as range increases.

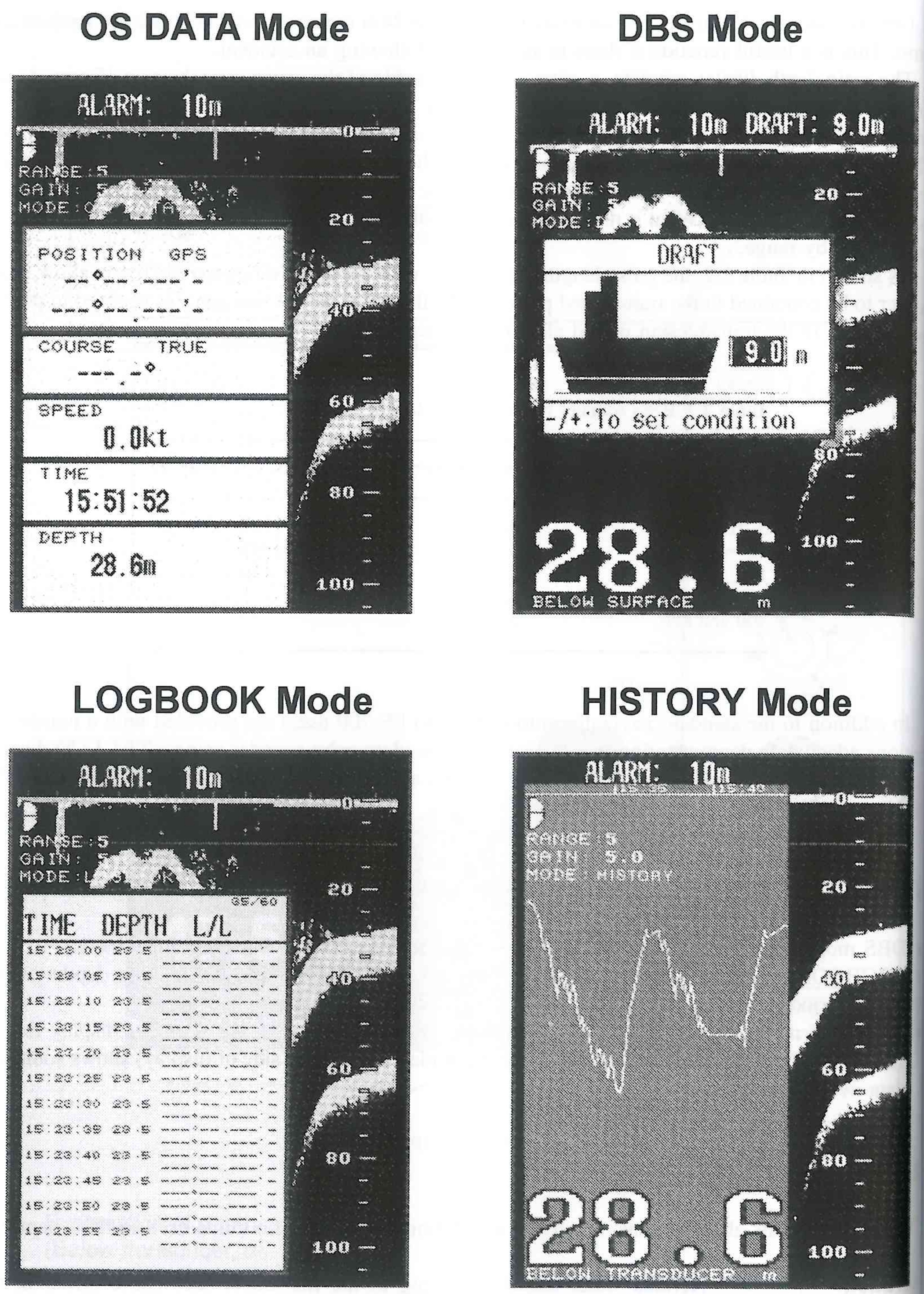


Figure 2.14 Different display modes demonstrating the flexibility of a microcomputer-controlled echo sounder. (Reproduced courtesy of Furuno Electric Co.)

Beam spreading	The transmitted pulse of energy spreads as it travels away from the transducer. The use of a wide beam will cause noise problems in the receiver and a narrow beam may lead to an echo being missed as the vessel steams away from the area.
Chart recorder	A sensitive paper recording system which, when the surface is scratched by a stylus, marks the contour of the ocean floor.
Continuous wave system	An echo sounding system that uses two transducers and transmits and receives energy at the same time.
Electrostrictive transducer	A transducer design based on piezoelectric technology. It is used when a higher transmission frequency is needed such as in speed logging equipment or fish-finding sounders.
Magnetostrictive transducer	A design based on magnetic induction. A large heavy transducer capable of transmitting high power. Used in deep sounding systems.
Pulse duration (length)	The period of the transmitted pulse when the transmitter is active.
Pulse repetition frequency (PRF)	The number of pulses transmitted per minute by the system. Similar to RADAR
Pulse wave system	A system that, like RADAR, transmits pulses of energy from a transducer which is then switched off. The received energy returns to the same transducer.
Reverberation noise	Noise that decreases as range increases.
Sonar	*So*und *n*avigation *a*nd *r*anging.
Velocity	Speed of acoustic waves in seawater; 1505 ms^{-1} or approximated to1500 ms^{-1}.

2.9 Summary

- Sonar stands for *so*und *n*avigation *a*nd *r*anging.
- Sound travels relatively slowly in seawater at 1505 ms^{-1}. This is approximated to 1500 ms^{-1} for convenience.
- The velocity is not a constant, it varies with the salinity of seawater. Ocean salinity is approximately 3.4%.
- Transmitted signal amplitude is attenuated by saltwater and the ocean floor from which it is reflected.
- Noise caused by sea creatures and ocean activity is a major problem affecting sonar equipment.
- The temperature of the seawater affects the velocity of the acoustic wave and consequently affects the accuracy of the displayed data. Temperature sensors are contained in the transducer housing to produce corrective data.
- Transducers are effectively the antennas of sonar systems. They transmit and receive the acoustic energy.
- There are two main types of transducer in use; magnetostrictive and electrostrictive. Magnetostrictive transducers are large and heavy and tend to be used only on large vessels. Electrostrictive transducers are lighter and often used in speed logging systems and on smaller craft.
- Low frequencies are often used in deep sounding systems typically in the range 10–100 kHz.
- The depth below the keel is related to the time taken for the acoustic wave to travel to the ocean floor and return. Put simply if the delay is 1 s and the wave travels at 1500 ms^{-1} then the depth is $0.5 \times 1500 = 750$ m.

- Pulsed systems, like those used in maritime RADAR, are used in an echo sounder. The pulse lengt or duration determines the resolution of the equipment. A short pulse length will identify objec close together in the water. If all other parameters remain constant, the pulse repetition frequenc (PRF), the number of pulses per minute, determines the maximum range that can be indicated.
- The width of the transmitted beam becomes wider as it travels away from the transducer. It shoul not be excessively narrow or the vessel may 'run away' from, or miss, the returned echo.
- Modern echo sounding equipment is computer controlled and therefore is able to produce a host o other data besides a depth indication.

2.10 Revision questions

1 Why do deep sounding echo sounders operate with a low transmission frequency?
2 For a given ocean depth, how is it possible for returned echoes to vary in strength?
3 If a vessel sails from salt water into fresh water the depth indicated by an echo sounder will be i error. Why is this and what is the magnitude of the error?
4 Noise can degrade an echo sounder display. How does narrowing the transmitted beamwidt reduce system noise and at what cost?
5 Why are electrostrictive transducers used in maritime applications in preference to piezoelectri resonators?
6 Why do marine echo sounding systems use pulsed transmission and not a continuous wave mod of operation?
7 Many echo sounders offer the ability to vary the transmission pulse duration. Why is this?
8 How are the pulse repetition frequency (PRF) and the maximum depth, indicated by an ech sounding system, related?
9 Why is the siting of an echo sounder transducer important?
10 What do you understand by the term target discrimination?
11 What effect may a narrow transmission beamwidth have on returned echoes if a ship is rolling i heavy seas?

Chapter 3

Speed measurement

3.1 Introduction

Speed measurement has always been of the utmost importance to the navigator. The accuracy of a dead reckoning position plotted after a long passage without star sights being taken, is dependent upon a sound knowledge of the vessel's heading and speed.

To be of value, the speed of any object must be measured relative to some other point. At sea, speed may be measured relative to either the seabed (ground reference speed) or to the water flowing past the hull (water reference speed). Both of these types of speed measurement are possible and both have their place in modern navigation systems.

This chapter deals with the methods of speed logging that are in general use on board modern vessels. One of these, the pressure tube log, is old but it still gives a satisfactory performance. Another, the electromagnetic log, is often used on smaller vessels and the popular Doppler speed log is to be found everywhere.

3.2 Speed measurement using water pressure

When a tube, with an opening at its base, is vertically submerged in water, a pressure, proportional to the depth to which the tube is submerged, will be developed in the tube. If the tube is held stationary the pressure remains constant and is termed 'static' pressure. If the tube is now moved through the water, whilst keeping the depth to which it is submerged constant, a second pressure called 'dynamic' pressure is developed. The total pressure in the tube, called a Pitot tube, is therefore the sum of both the static and dynamic pressures.

To ensure that the dynamic pressure reading, and thus speed, is accurate, the effect of static pressure must be eliminated. This is achieved by installing a second tube close to the first in such a way that the static pressure produced in it is identical to that created in the Pitot tube but without the pressure increase due to movement through the water (see Figure 3.1).

In a practical installation, tube B, the Pitot tube, extends below the vessel's hull to a depth *d*, whereas tube A, the static pressure intake tube, is flush with the hull. With the vessel stationary, the static pressures from tube A to the top of the diaphragm and tube B to its underside almost cancel. The unequal pressures, which cause a small indication of speed to be displayed when the vessel is stationary, are compensated for in the log electromechanical system and the erroneous indication is cancelled. As the vessel moves through the water, in the direction shown, water is forced into tube B producing a combined pressure in the lower half of the chamber equal to both the static and dynamic pressures. The difference in pressure, between upper and lower chambers, now forces the diaphragm upwards thus operating the mechanical linkage. Obviously the greater the speed of the vessel through the water, the more the diaphragm will move and the greater will be the speed indicated.

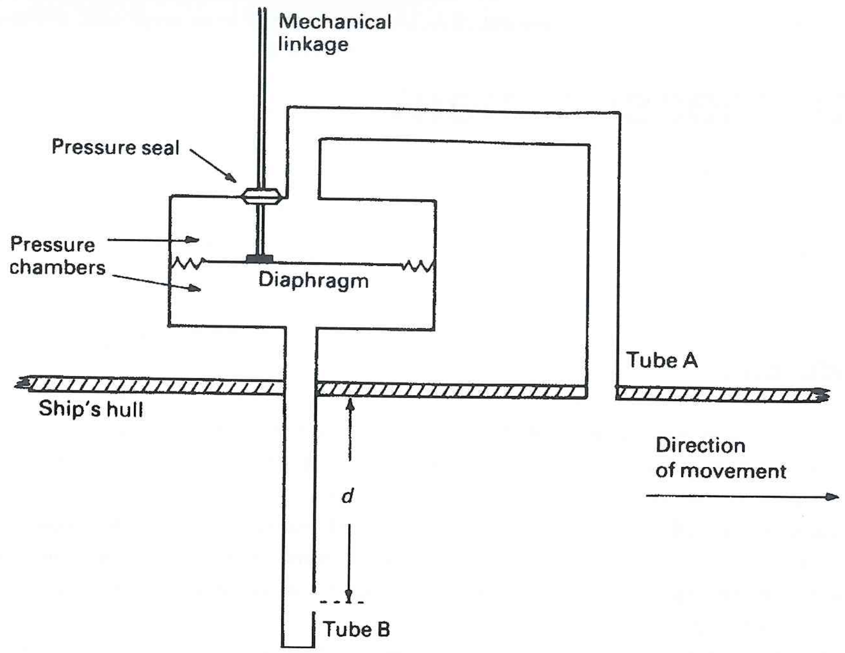


Figure 3.1 The pressure tank and tube intakes of a pressure tube speed logging system.

Unfortunately, the dynamic pressure developed in tube B, by the relative movement through the water, is proportional to the square of the vessel's speed. Pitot's Law states that this pressure p i proportional to the square of the ship's speed v multiplied by the coefficient K.

$$p = K \times v^2$$

where the constant K is derived from the vessel's tonnage, shape of hull, speed of the ship, and the length of the protruding part of the Pitot tube (distance d).

As shown in Figure 3.2, the speed indication produced is not linear. It is necessary therefore t eliminate the non-linear characteristics of the system and produce a linear speed indication. This i achieved mechanically, by the use of precisely engineered cones or electronically using CR (capacitive/resistive) time constant circuitry.

3.2.1 A pressure tube speed logging system

Figure 3.3 shows a typical installation of the Pitot system on board a vessel with a double bottom. The Pitot tube is encased in a sea-cock arrangement with valve control, to enable the tube to be withdrawn without shipping water, when the vessel goes alongside. The static pressure opening is controlled by the use of a valve. Both dynamic and static pressures are transferred via air collectors and strainer valves to the pressure chamber. The strainer valves are designed to prevent water oscillations in the interconnecting pipes during operation. Such oscillations would cause the diaphragm to oscillate producing an erratic speed indication.

Figure 3.4 shows the basic speed and distance translating system of a Pitot tube log. The diagram includes two repeating systems for speed and distance data transmission to remote indicators on the ship's bridge. This system was superseded by the SAL24E which replaced some of the mechanical apparatus with electronics. The original log has been included here because it is still in use on many vessels and is a fine example of a pressure type speed logging system.

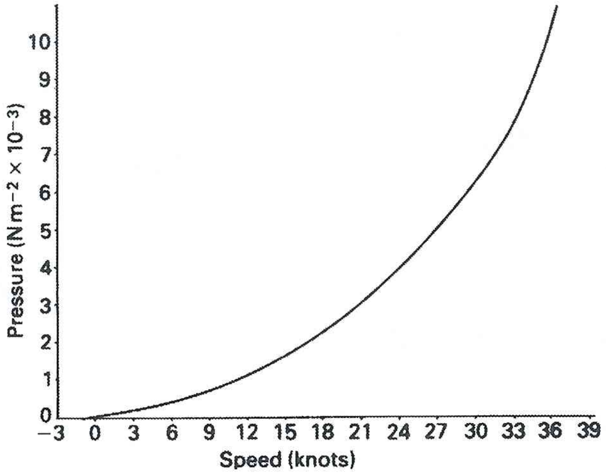


Figure 3.2 Graph indicating the non-linear increase in pressure due to speed.

Description of operation

An increase in the vessel's speed will cause an increase in the dynamic pressure beneath the diaphragm in the pressure chamber (1). This causes the diaphragm to move upwards, pushing the pressure rod (2) and moving the lever (3) to the right on pivot (4). The upper end of the lever (3) moves the electric start contact (5) to the right to connect power to a reversible motor (6). The motor now turns causing the main shaft (7) to move a spiral cam (8) clockwise. This action tilts the lever (9), also pivoted on (4), to the left. The deflection stretches the main spring, producing a downward pressure on the diaphragm, via lever (3), causing it to cease rising at an intermediate position. This is achieved when equilibrium has been established between the dynamic pressure, acting on the lower side of the diaphragm, and the counter pressure from the spring on the upper side. At this point the motor (6) stops and thus holds the spiral cam (8) in a fixed position indicating speed.

This method of pressure compensation provides accurate indications of speed independent of alterations of the diaphragm caused by ageing. The shape of the spiral cam (8) has been carefully calculated to produce a linear indication of speed from the non-linear characteristics of the system. Also attached to the spiral cam is a second gearing mechanism (19) that transfers the movement of the speed indicator to the three-phase speed transmission system (20). An identical servo-receiver (22) is fitted in the remote speed repeater unit fitted on the ship's bridge and thus remote speed indication has been achieved.

Distance recording is achieved by using a constant speed motor (10) which drives the distance counter (11), via friction gearing. The constant speed motor has been used in order that a distance indication may be produced that is independent of the non-linear characteristic of the system. The motor is started by contact (5) as previously described. The main shaft (7), whose angle of rotation is directly proportional to the speed of the ship, is fitted with a screw spindle (12). The rotation of the shaft causes a lateral displacement of the friction wheel (13). At zero speed, the friction wheel rests against the apex of the distance cone (14), whilst at maximum speed the wheel has been displaced

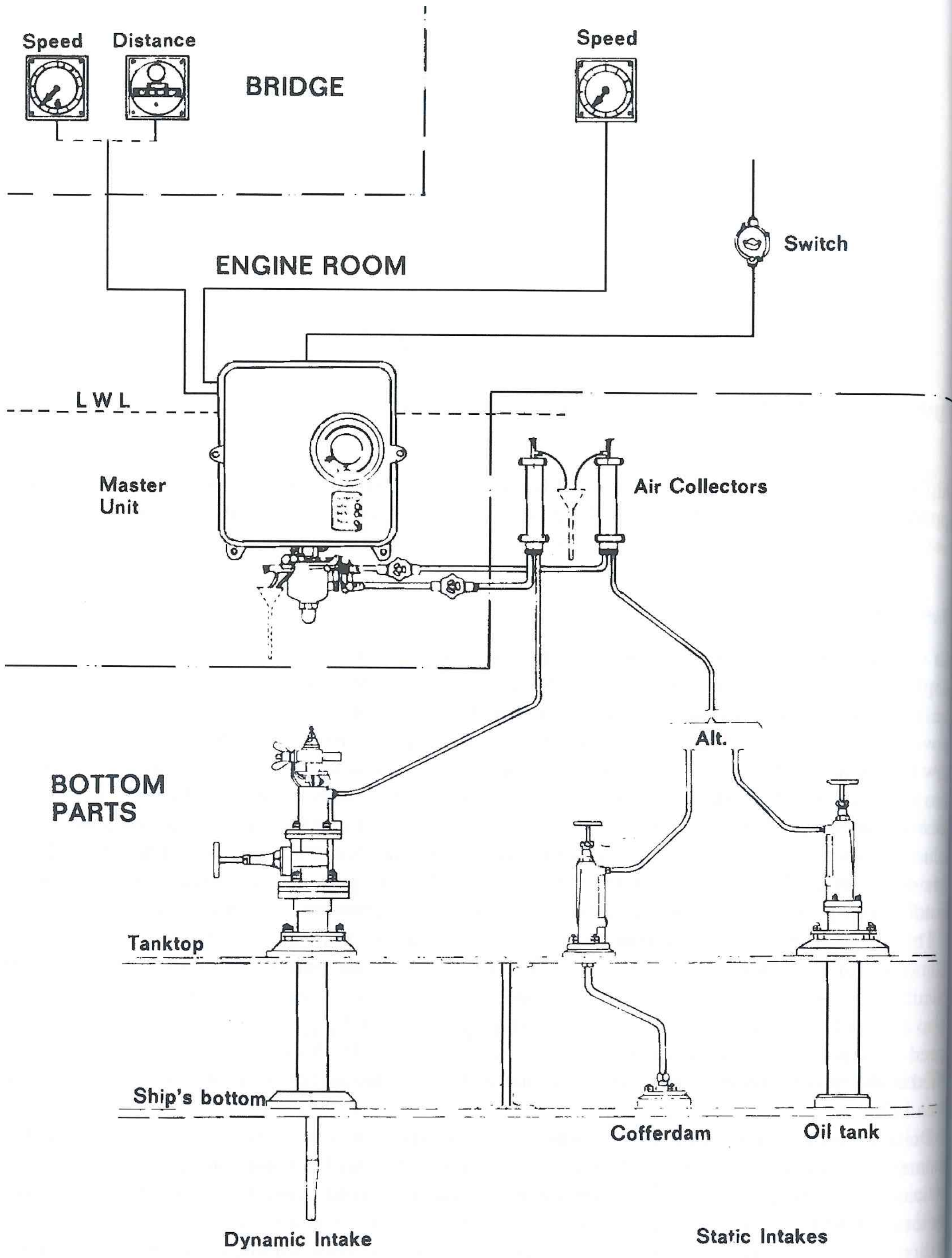
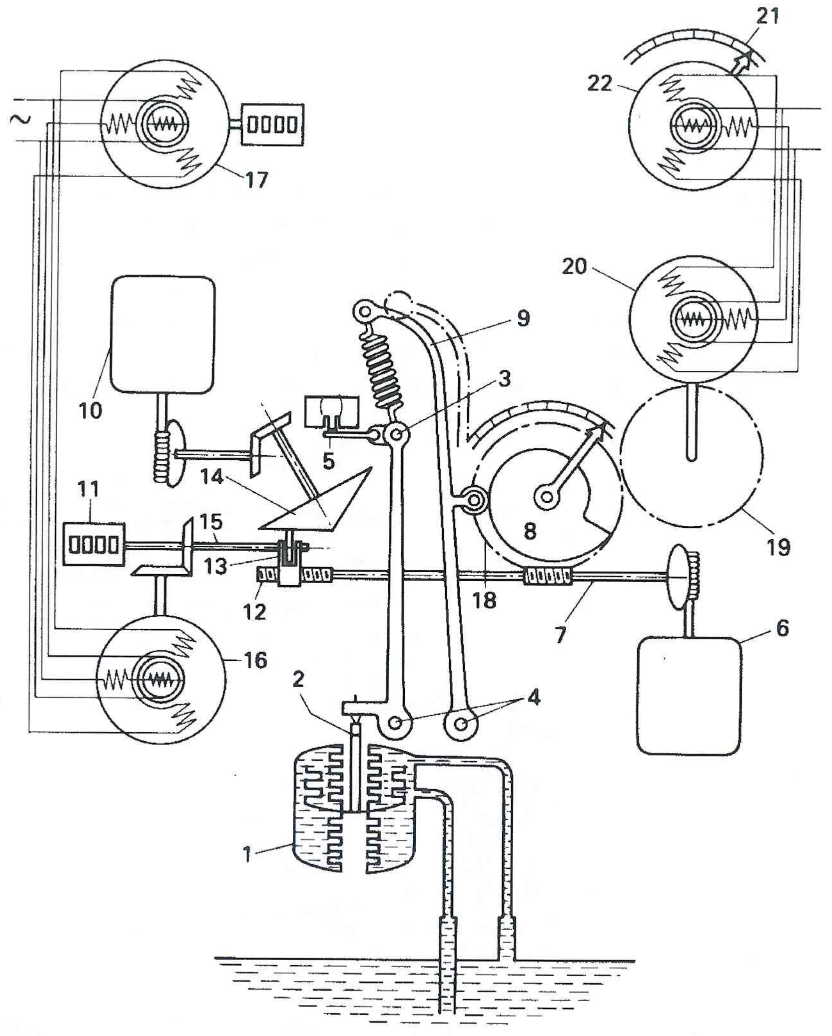


Figure 3.3 A shipboard installation. (Reproduced courtesy of SAL Jungner Marine.)



1. pressure chamber
2. pressure rod
3. lever
4. pivot
5. electric start contact
6. reversible motor
7. main shaft
8. spiral cam
9. lever
10. constant speed motor
11. distance counter
12. screw spindle
13. friction wheel
14. distance cone
15. distance shaft
16. servo transmission system
17. servo transmission system
18. gear wheels
19. gear wheels
20. speed servo transmitter
21. remote speed indicator
22. servo receiver

Figure 3.4 The mechanical speed translating system of the SAL 24 pressure tube log. (Reproduced courtesy of SAL Jungner Marine.)

along the cone to the rim. The distance indicator (11) is driven from the constant speed motor (10) v the cone. The nearer to the rim of the cone the friction wheel rides, the greater will be the distanc indication. Revolutions of the distance shaft (15) are transmitted to the remote distance indicator v the servo transmission system (16 and 17).

Operation of the SAL 24E

The SAL 24E utilizes the same system of tubes, pressure tank and diaphragm to convert pressu variations due to speed, to electrical pulses suitable to drive the electronic circuits that replace muc of the mechanical arrangement of the SAL 24 log. The distance integration mechanism with serv cone and counter has been fully replaced with electronic circuitry.

As previously described, when the vessel moves forwards, the dynamic pressure acting on th underside of the diaphragm causes it to move upwards forcing the pushrod upwards. As shown i Figure 3.5, this causes the pushrod arm assembly to move to the right on the pivot, increasing th

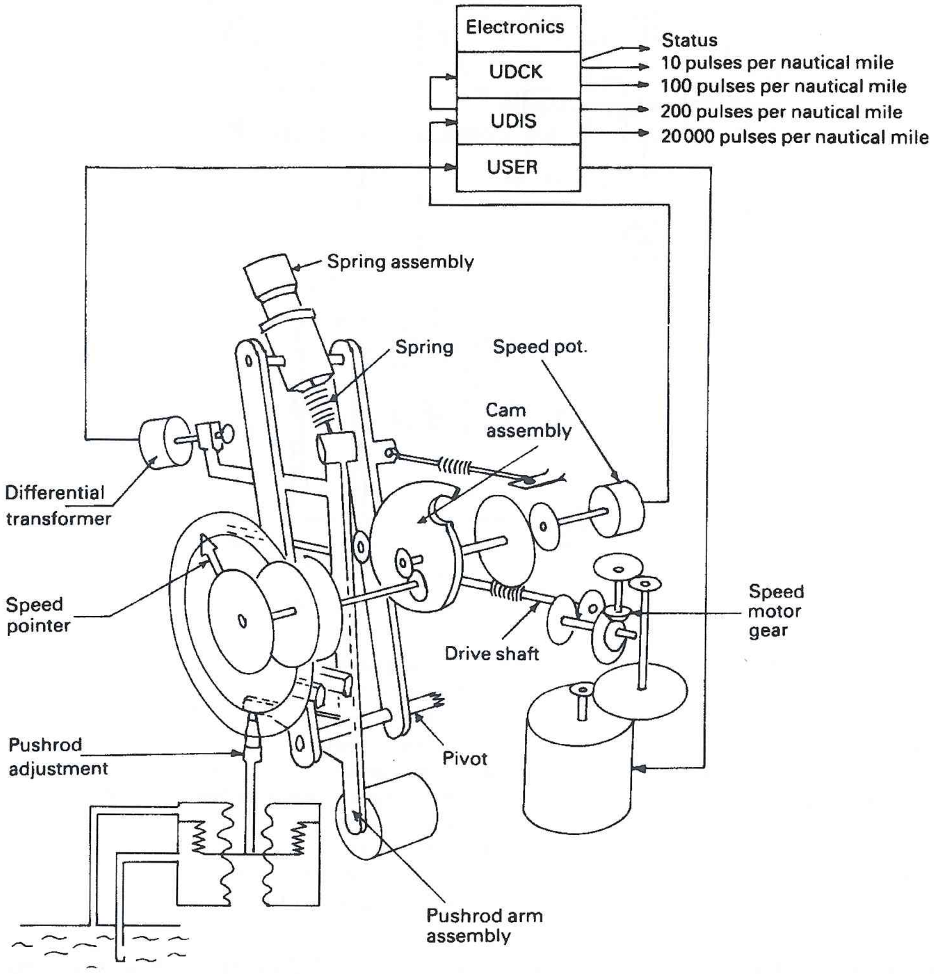


Figure 3.5 Pressure/mechanical assembly of the SAL 24E electronic pressure speed log. (Reproduced courtesy of SAL Jungner Marine.)

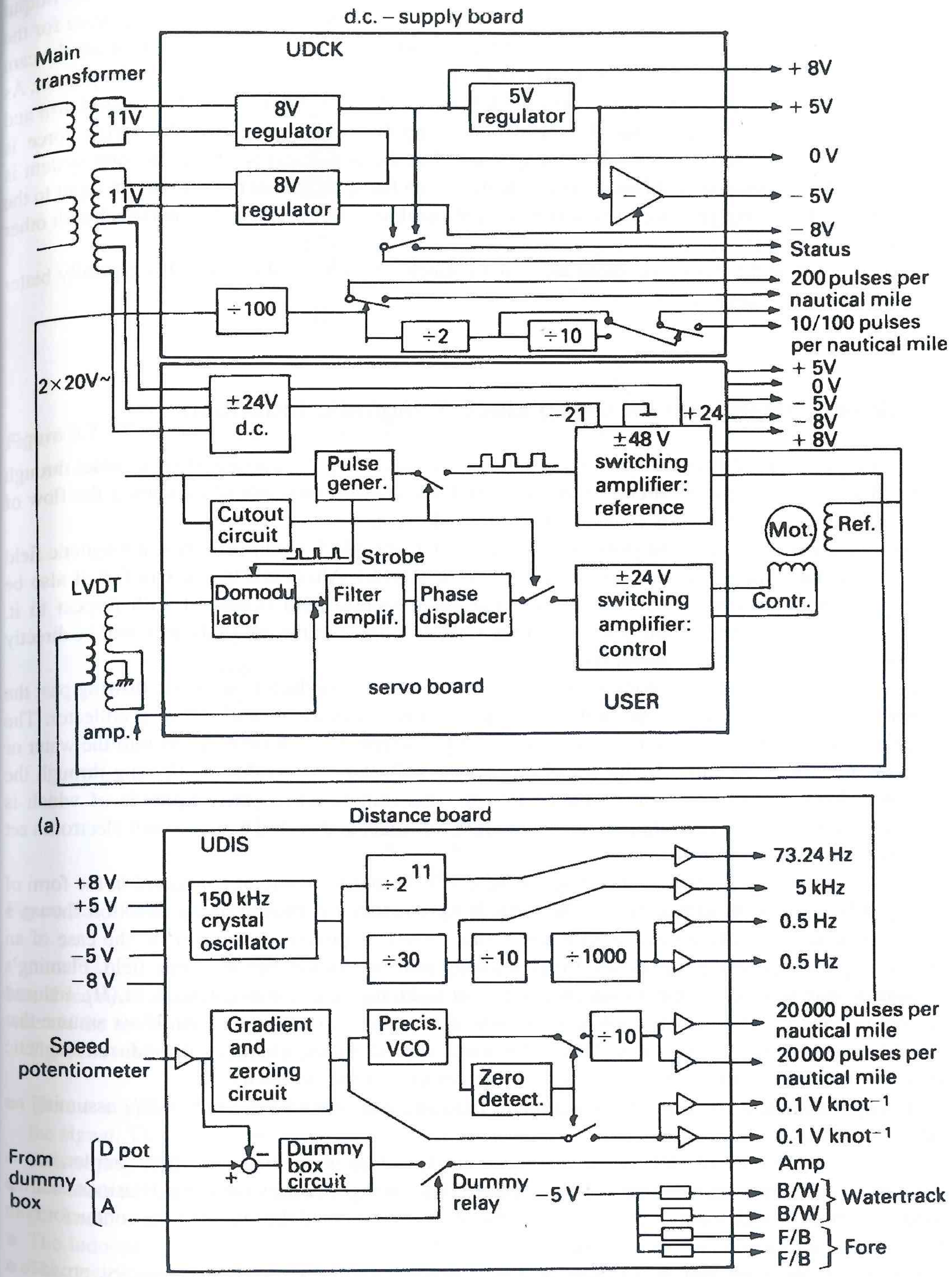


Figure 3.6 The electronics unit. (Reproduced courtesy of SAL Jungner Marine.)

tension on the spring assembly and producing an output from the differential transformer. This outp is applied to the USER board, shown in Figure 3.6, where it is processed to provide the drive for th speed servo-control winding via a ± 24 V switching amplifier. The servo now turns and rotates the ca assembly via gearing and the drive shaft. An increase in speed is now shown on the speed pointer. A the cam rotates it forces the balance arm to the left and tightens the spring until the pushrod arm an the diaphragm bellows are balanced. The cam is carefully designed so that the spring force i proportional to the square of the rotation angle and thus the non-linearity of the pressure system i counteracted. The speed potentiometer turns together with the speed pointer to provide an input to th UDIS board. This input produces a variety of outputs enabling the system to be interfaced with othe electronic equipment.

The accuracy of the Pitot type speed log when correctly installed and calibrated is typically bett than 0.75% of the range in use.

3.3 Speed measurement using electromagnetic induction

Electromagnetic speed logs continue to be popular for measuring the movement of a vessel throug water. This type of log uses Michael Faraday's well-documented principle of measuring the flow o a fluid past a sensor by means of electromagnetic induction.

The operation relies upon the principle that any conductor which is moved across a magnetic fiel will have induced into it a small electromotive force (e.m.f.). Alternatively, the e.m.f. will also b induced if the conductor remains stationary and the magnetic field is moved with respect to i Assuming that the magnetic field remains constant, the amplitude of the induced e.m.f. will be directl proportional to the speed of movement.

In a practical installation, a constant e.m.f. is developed in a conductor (seawater flowing past th sensor) and a minute current, proportional to the relative velocity, is induced in a collector. Th magnetic field created in the seawater is produced by a solenoid which may extend into the water o be fitted flush with the hull. As the vessel moves, the seawater (the conductor) flowing through th magnetic field has a small e.m.f. induced into it. This minute e.m.f., the amplitude of which i dependent upon the rate of cutting the magnetic lines of force, is detected by two small electrodes se into the outer casing of the sensor.

Figure 3.7 shows a solenoid generating a magnetic field and a conductor connected in the form o a loop able to move at right angles to the field. If the conductor is moved in the direction shown, tiny current will be induced in the wire and a small e.m.f. is produced across it. In the case of a electromagnetic speed log, the conductor is seawater passing through the magnetic field. Fleming' right-hand rule shows that the generated e.m.f. is at right angles to the magnetic field (H). Induce current flowing in the conductor produces an indication of the e.m.f. on the meter. If we assume th the energizing current for the solenoid is d.c. the induced e.m.f. is βlv, where β = the induced magneti field, l = the length of the conductor, and v = the velocity of the conductor.

β is approximately equal to H, the magnetic field strength. Therefore, e.m.f. = Hlv assuming n circuit losses.

To reduce the effects of electrolysis and make amplification of the induced e.m.f. simpler, a.c. i used to generate the magnetic field. The magnetic field strength H now becomes $H\text{m}\sin\omega t$ and th induced e.m.f. is: $H\text{m}lv\sin\omega t$. If the strength of the magnetic field and the length of the conductor bot remain constant then, e.m.f. $\simeq$ velocity.

Figure 3.8 illustrates that the changes of e.m.f., brought about by changes in velocity, produce linear graph and thus a linear indication of the vessel's speed. The e.m.f. thus produced is very smal

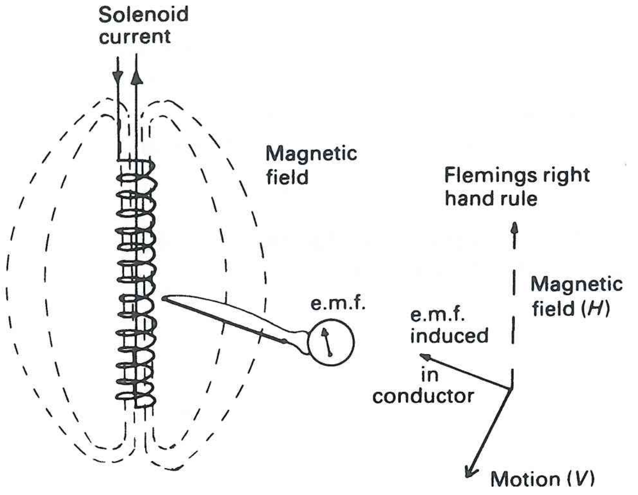


Figure 3.7 Effect of moving a conductor through a magnetic field.

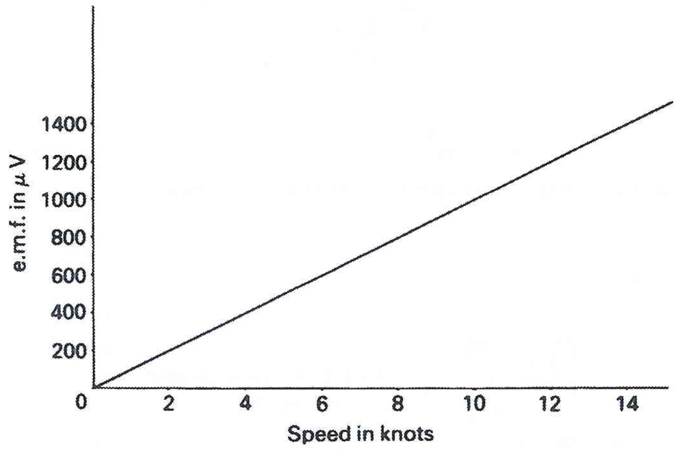


Figure 3.8 Relationship between the vessel's speed and the output from the sensors.

but, if required, may be made larger by increasing the energizing current, or the number of turns of wire on the solenoid.

The following points should be noted.

- The a.c. supply to the solenoid produces inductive pick-up between the coil and the wires that carry the signal. This in turn produces a 'zero' error that must be compensated for by 'backing off' the zero setting of the indicator on calibration.
- The induced e.m.f. is very small (for reasonable amplitudes of energizing current), typically 100 µV per knot.
- The induced e.m.f. and hence the speed indication will vary with the conductivity of the water.
- The device measures the speed of the water flowing past the hull of the ship. This flow can vary due to the non-linearity of a hull design.

- Ocean currents may introduce errors.
- Pitching and rolling will affect the relationship between the water speed and the hull. Error due this effect may be compensated for by reducing the sensitivity of the receiver. This is achiev using a CR timing circuit with a long time constant to damp out the oscillatory effect.
- Accuracy is typically 0.1% of the range in use, in a fore and aft direction, and approximately 2 thwartships.

Figure 3.9 shows a typical sensor cutaway revealing the solenoid and the pick-up electrodes. A spee translating system is illustrated in Figure 3.10.

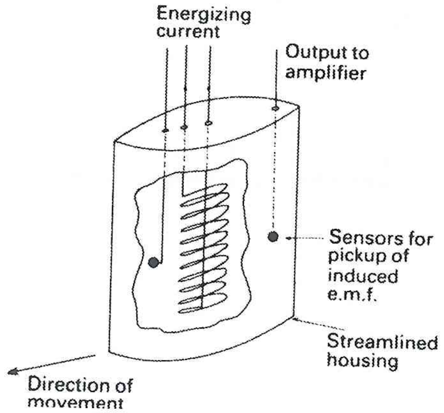


Figure 3.9 Constructional details of an electromagnetic log sensor.

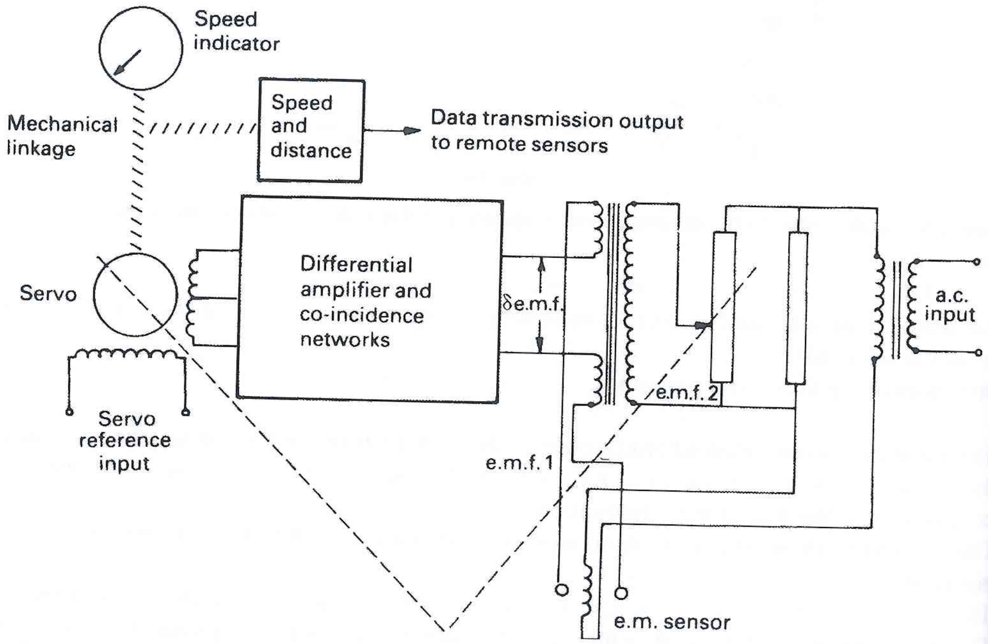


Figure 3.10 An e.m. speed log translating system.

Description of the speed translating system

The small signal speed voltage from the sensor, e.m.f.1, is applied to a differential transformer where it is compared to a reference voltage, e.m.f.2, produced from a potentiometer across the input a.c. supply. The potential difference produced across the reference resistor provides the energizing current for the solenoid in the sensor.

If the signal voltage e.m.f.1. differs from the reference voltage e.m.f.2. an error signal voltage δ e.m.f. is produced. This error voltage is applied to the speed signal amplifier where it is amplified to produce sufficient power to drive the servo motor. The servo will in turn produce a speed reading, via a mechanical linkage, on the indicator. Also coupled to the servo shaft is the slider of the speed potentiometer that turns in the direction to reduce the error voltage δ e.m.f. When this error voltage drops to zero the servo ceases to turn. The speed indicator is stationary until the next error voltage δ e.m.f. is produced. Each time an error voltage is created the servo turns to cancel the error and thus balances the system.

3.3.1 A practical electromagnetic speed logging system

The potential developed across the transducer electrodes is proportional to magnetic field strength (and consequently the energizing current) and the flow velocity in the volume of water influenced by the field. The magnetic field strength is in no way stabilized against any changes in the ship's main voltage, temperature, etc, but by effectively comparing the energizing current with the voltage at the electrodes, their ratio provides a measure of the ship's speed.

The input transformer T1 (shown in Figure 3.11) possesses a very high inductance and a step-down ratio of 5:1. This results in an input impedance, as seen by the pick-up electrodes, approaching 20 MΩ which when compared with the impedance presented by salt water can be considered an open circuit. Hence changes in salinity have no effect on the measured voltage and the resulting speed indication. A switched resistor chain (R1/R5) sets the gain of the overall amplifier in conjunction with resistor chain (R6/R10) which controls the amplitude of the feedback signal.

The output of IC1 is coupled, via IC2, which because of capacitive feedback (not shown), ensures that the circuit has a zero phase shift from T1 through T2, to the demodulator. Demodulation is carried out by TR1/TR2 that are switched in turn from an a.c. reference voltage derived from a toroidal transformer monitoring the energizing current of the transducer. By driving TR1/TR2 synchronously, the phase relationship of the voltage detected by the electrodes determines the polarity of the demodulated signal. 0° and 180° phasing produce a positive or negative component; 90° and 270° produce no output and hence a complete rejection of such phase-quadrature signals. The demodulated signal is applied to the Miller Integrator IC3 which in turn drives the current generator. Speed repeaters are current-driven from this source.

Operation of the loop

With no vessel movement, there will be a zero signal at the input to IC1 and consequently there will be no signal at the multiplier chip input. No feedback signal is developed at the input to IC1. As the vessel moves ahead, the small signal applied to IC1 is processed in the electronic unit to produce a current flow through the speed repeaters and the multiplier. There now exists an output from the multiplier, proportional to the speed repeater current and the reference voltage produced by the toroidal transformer monitoring the transducer energizing current. The a.c. from the multiplier is fed back to IC1 in series with, and 180° out of phase with, the small signal secondary of T1. This a.c. signal rises slowly and eventually, with the time constant of the demodulator, is equal to the signal p.d.

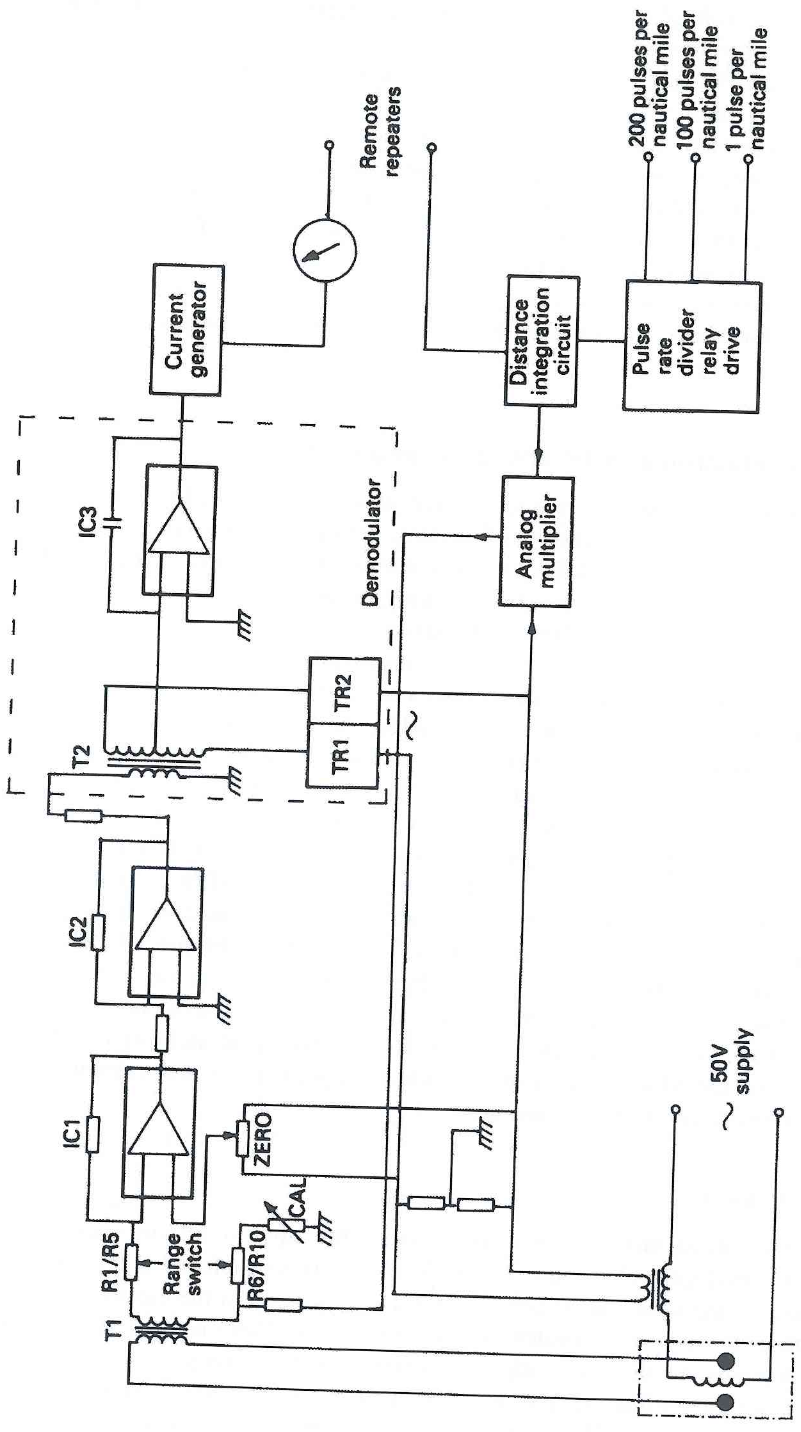


Figure 3.11 Simplified diagram of an e.m. log. (Reproduced courtesy of Thomas Walker and Son Ltd.)

developed across T1. At this time the resultant signal applied to IC1 falls to zero and therefore the demodulator output remains at a constant figure. Any further change in speed results in an imbalance in the secondary of T1 producing a resultant a.c. signal to IC1. As a result, the demodulator output increases or decreases (faster or slower ship's speed) until the balance condition is restored. The speed repeaters will indicate the appropriate change of speed.

Distance integration

The speed current is passed through a resistive network on the distance integration board, in order that a proportional voltage may be produced for integration. The output of this board is a pulse train, the rate of which is proportional to the indicated speed. The 10 ms pulses are coupled to the relay drive board which holds the necessary logic to give the following outputs: 200 pulses per nautical mile, 100 pulses per nautical mile, and 1 pulse per nautical mile.

3.4 Speed measurement using acoustic correlation techniques

Unlike the previously described speed log, which measure the vessel's speed with respect to water only, the SAL-ICCOR log measures the speed with respect to the seabed or to a suspended water mass. The log derives the vessel's speed by the use of signal acoustic correlation. Simply, this is a way of combining the properties of sonic waves in seawater with a correlation technique. Speed measurement is achieved by bottom-tracking to a maximum depth of 200 m. If the bottom echo becomes weak or

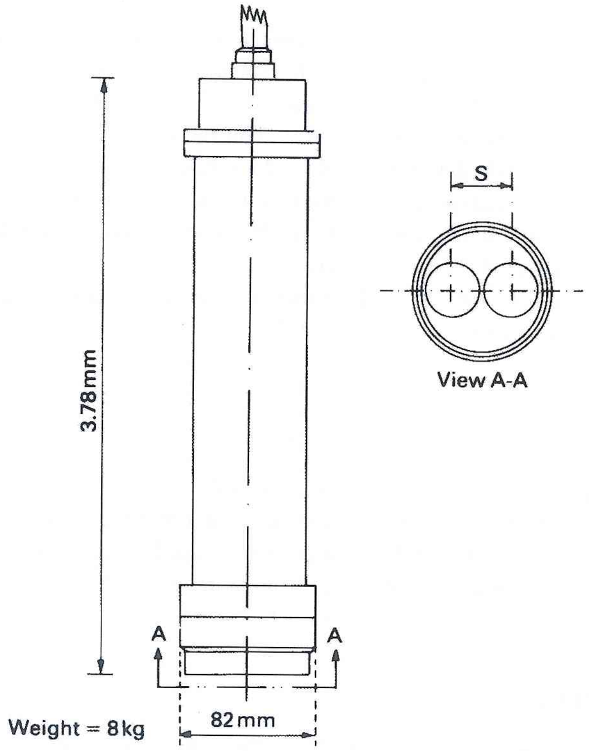


Figure 3.12 Piezoelectric ceramic transducer for the SAL acoustic correlation speed log.

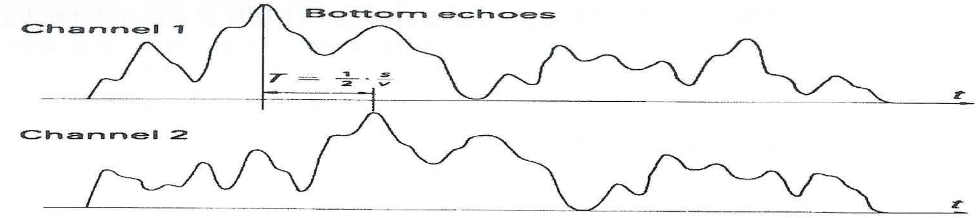


Figure 3.13 Illustration of the time delay (*T*) between each channel echo signal.

the depth exceeds 200 m, the system automatically switches to water-mass tracking and will record the vessel's speed with respect to a water mass approximately 12 m below the keel.

The transducer transmits pulses of energy at a frequency of 150 kHz from two active piezoceramic elements that are arranged in the fore and aft line of the vessel (see Figure 3.12). Each element transmits in a wide lobe perpendicular to the seabed. As with an echo sounder, the transducer elements are switched to the receive mode after transmission has taken place.

The seabed, or water mass, reflected signals possess a time delay (*T*) dependent upon the contour of the seabed, as shown in Figure 3.13. Thus the received echo is, uniquely, a function of the instantaneous position of each sensor element plus the ship's speed. The echo signal, therefore, in one channel will be identical to that in the other channel, but will possess a time delay as shown.

The time delay (*T*), in seconds, can be presented as:

$$T = 0.5 \times s\ v$$

where s = the distance between the receiving elements and v = the ship's velocity.

In the SAL-ACCOR log (see Figure 3.14), the speed is accurately estimated by a correlation technique. The distance between the transducer elements (s) is precisely fixed, therefore when the time (T) has been determined, the speed of the vessel (v) can be accurately calculated.

It should be noted that the calculated time delay (T) is that between the two transducer echoes and not that between transmission and reception. Temperature and salinity, the variables of sound velocity in seawater, will not affect the calculation. Each variable has the same influence on each received echo channel. Consequently the variables will cancel.

It is also possible to use the time delay (T) between transmission and reception to calculate depth. In this case the depth (d),in metres, is:

$$d = \frac{T}{2} \times C$$

where C = the velocity of sonic energy in seawater (1500 ms^{-1}).

Dimensions of the transducer active elements are kept to a minimum by the use of a high frequency and a wide lobe angle. A wide lobe angle (beamwidth) is used because echo target discrimination is not important in the speed log operation and has the advantage that the vessel is unlikely to 'run away' from the returned echo.

3.4.1 System description

Initiating the sequence, the power amplifier produces the transmitted power, at the carrier frequency of 150 kHz, under the command of a pulse chain from the clock unit. Returned echoes are received by two

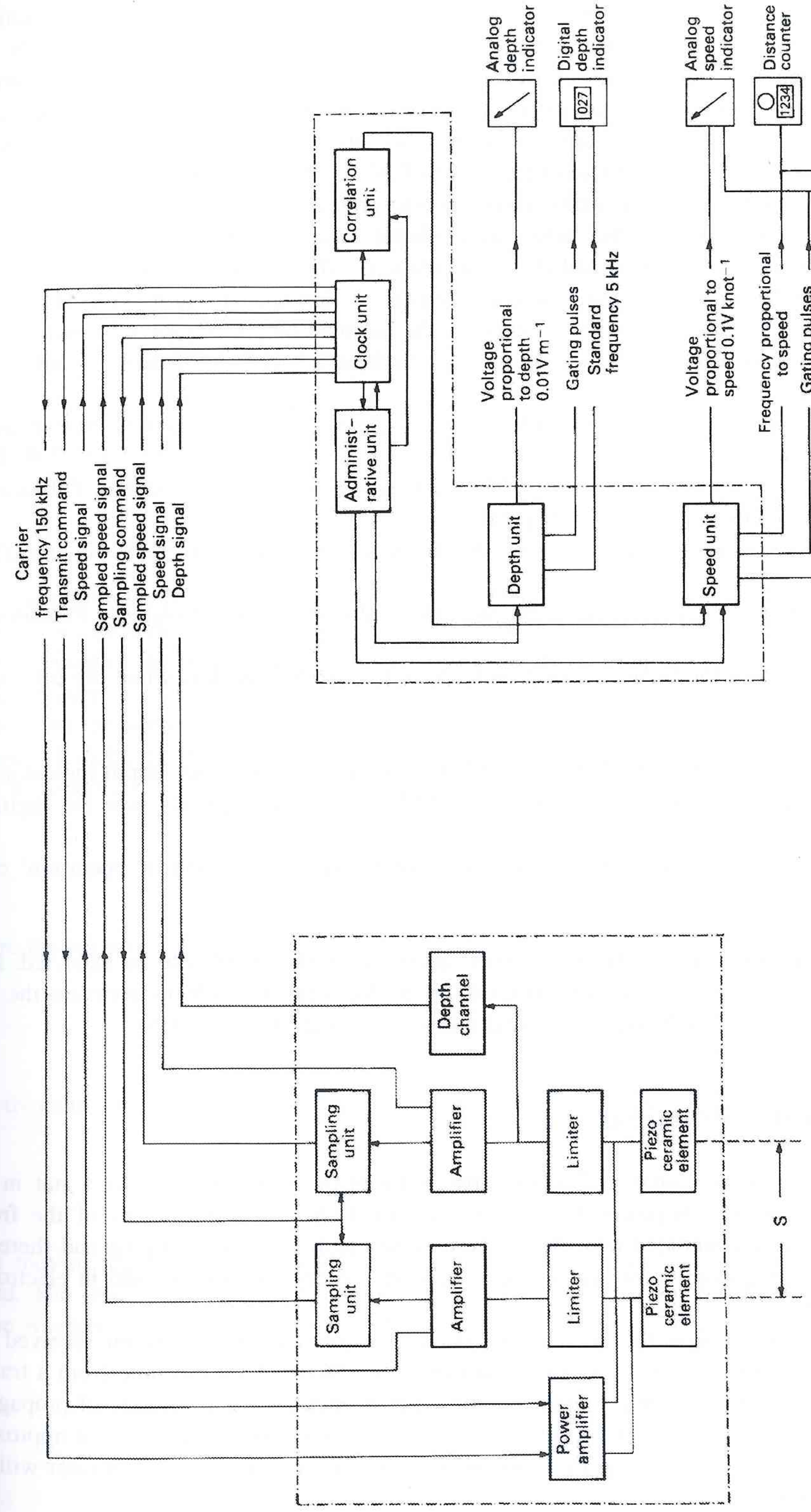


Figure 3.14 System diagram of the SAL-ACCOR acoustic correlation speed log. (Reproduced courtesy of SAL Junger Marine.)

independent identical channels and are pre-amplified before being applied to sampling units. Each sampling unit effectively simplifies the echo signal to enable interconnection to be made between transducer and main unit without the risk of signal deterioration. As with other functions, sampling is commanded by a clock unit, which also provides a highly stable 150 kHz for the carrier frequency. This frequency is also used as a standard frequency for the other functions on the electronics board, where it is divided to produce the 5 kHz needed to operate some of the speed indicators.

As the name suggests, the administration block controls most of the electronic functions. This block initiates the transmit/receive cycle, determines whether the system selects B-track or W-track operation and supervises the speed and depth calculations. The unit is effectively a microprocessor operating to a pre-determined program. Actual speed calculation takes place in the correlation block. The process extracts the time delay by correlating the sampled output of each channel.

The speed unit provides the following outputs to drive both speed and distance counters.

- An analogue voltage, the gradient of which is 0.1 V/knot, to drive the potentiometer servo-type speed indicators.
- A pulse frequency proportional to speed. The frequency is 200/36 pulses/s/knot. Pulses are gated into the digital counter by a 1.8-s gate pulse.
- A positive/negative voltage level to set the ahead/astern indication or the B track/W track indication.
- 2000 pulses per nautical mile to drive the stepping motor in the digital distance indicator.

The depth unit provides the following outputs to drive the depth indicators when the echo sounding facility is used.

- An analogue voltage with a gradient of 0.01 $\mathrm{Vm^{-1}}$, to drive the analogue depth indicator.
- Pulses of 2 $\mathrm{ms\,m^{-1}}$, which are used to gate a 5 kHz standard frequency into the digital depth indicator.
- A positive/negative voltage level to cause the indicator to display 'normal operation' or 'over-range'.

When correctly installed and calibrated, a speed accuracy of ±0.1 knot is to be expected. Distance accuracy is quoted as 0.2%. The SAL-ICCOR speed log can be made to measure the vessel's transverse speed with the addition of a second transducer set at 90° to the first.

3.5 The Doppler Principle

In the early 19th century, Christian Doppler observed that the colour emitted by a star in relative movement across the sky appeared to change. Because light waves form part of the frequency spectrum, it was later concluded that the received wavelength must be changing and therefore the apparent received frequency must also change. This phenomenon is widely used in electronics for measuring velocity.

Figure 3.15(b) shows that the wavelength (λ) is compressed in time when received from a transmitter moving towards a receiver (λ_1) and expanded (Figure 3.15c) in time from a transmitter moving away (λ_2). Consider a transmitter radiating a frequency (f_1). The velocity of propagation of radiowaves in free space (c) is $300 \times 10^6\,\mathrm{ms^{-1}}$ and in seawater it is much slower at approximately $1500\,\mathrm{ms^{-1}}$. After a period of 1 s, one cycle of the transmitted acoustic wave in seawater will occupy a distance of 1500 m.

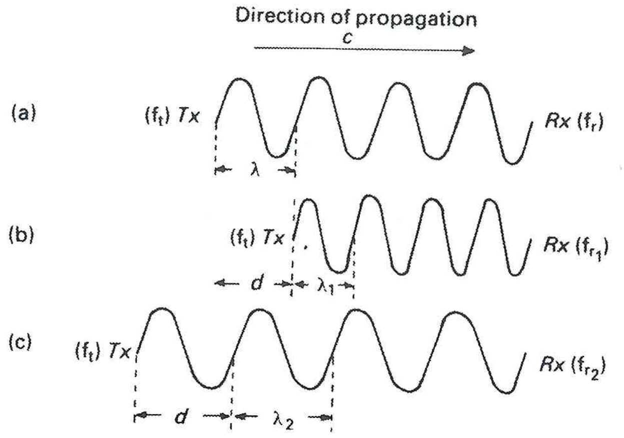


Figure 3.15 Expansion and compression of wavelength.

If the transmitter moves towards an observer at speed (v) it will, at the end of 1 s, have travelled a distance (d) towards the receiver. Each transmitter wave has now been shortened because of the distance travelled by the transmitter towards the observer. By definition, a shorter wavelength defines a higher frequency (f_r). The shortened wavelength, or higher frequency, received is directly proportional to the speed of movement of the transmitter.

In Figure 3.15(b), the transmitter has moved towards an observer by a distance (d). This is the distance travelled during the time of generating one cycle (T).

$$T = \frac{1}{ft} \quad \text{and} \quad d = v \times T = \frac{v}{ft}$$

Therefore the apparent wavelength is

$$\lambda_1 = \lambda - \frac{v}{ft}$$

and the frequency is

$$fr_1 = \frac{c}{\lambda_1} = \frac{c}{\lambda - v/ft} = \frac{cft}{\lambda ft - v} = f_t\,\frac{c}{c - v}$$

For a moving transmitter that is approaching a receiver, the received frequency is apparently increased. The reverse is true of a transmission from a transmitter moving away from an observer, when the wavelength will be stretched and the frequency decreased.

$$\lambda_2 = \lambda + v/ft$$

$$f_r = f_t\,\frac{c}{c + v}$$

If an observer moves at velocity (v) towards a stationary sound source, the number of cycles reachin the receiver per second is increased, thus the apparent received frequency is increased. The receive frequency is

$$f_r = f_r + v/\lambda$$

and

$$1/\lambda = f/c$$

therefore

$$f_t + f_v/c = f_t(1 + v/c) = f_t \frac{c + v}{c}$$

If the observer now moves away from the stationary transmitter the apparent received frequency is;

$$f_r = f_t \frac{c - v}{c}$$

If, as in the Doppler speed log, both the observer and the sound source (transmitter and receiver) ar moving towards a reflecting surface, the received frequency is;

$$f_r = f_t \frac{c}{c - v} x \frac{c + v}{c} = f_t \frac{c + v}{c - v}$$

The Doppler frequency shift is

$$f_d = f_r - f_t \text{ (or } f_t - f_r)$$

$$f_d = f_t x \frac{c + v}{c - v} - f_t$$

$$= \frac{cf_t + vf_t - cf_t + vf_t}{c - v}$$

$$= \frac{2vf_t}{c - v}$$

The velocity of radio waves (c) is always far in excess of v and therefore the expression abov can be simplified to;

$$f_d = \frac{2vf_t}{c}$$

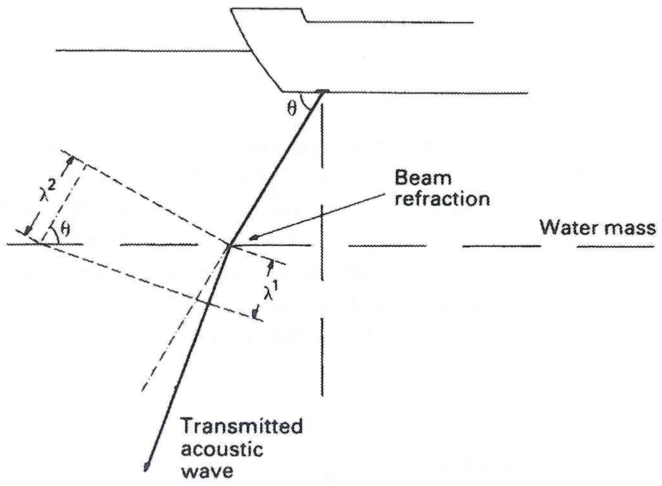
where f_d = Doppler frequency shift in cycles per second, v = relative speed in the direction of th transmitted wave, f_t = transmitted frequency, and c = velocity of propagation of the radio wave.

3.6 Principles of speed measurement using the Doppler effect

The phenomenon of Doppler frequency shift is often used to measure the speed of a moving object carrying a transmitter. Modern speed logs use this principle to measure the vessel's speed, with respect to the seabed, with an accuracy approaching 0.1%.

If a sonar beam is transmitted ahead of a vessel, the reflected energy wave will have suffered a frequency shift (see Figure 3.16), the amount of which depends upon:

- the transmitted frequency
- the velocity of the sonar energy wave
- the velocity of the transmitter (the ship).



λ^1 = Wavelength after refraction

λ^2 = Wavelength before refraction

Figure 3.16 Illustration of the change of wavelength that occurs when an acoustic wave crosses a water mass.

The frequency shift, in hertz, of the returned wave is:

$$fd = ft - fr$$

where ft = the transmitted wave frequency, and fr = the received wave frequency.

The Doppler shift formula, for a reflected wave, is given as:

$$fd = \frac{2vft}{c}$$

where v = the velocity of the ship, and c = the velocity of the sonar wave (1500 ms^{-1} in seawater).

Obviously there can be no objects directly ahead of a vessel from which the acoustic wave may be reflected. The wave is therefore transmitted towards the seabed, not vertically as with echo sounding, but ahead at an angle of 60° to the horizontal. This angle has been found to be the optimum angle o incidence with the seabed, which will reflect a signal of sufficient strength to be received by th transducer. The shape of the seabed has no effect on the frequency shift. Provided that the seabed i not perfectly smooth, some energy will be reflected.

The angle between the horizontal plane and the transmission must now be applied to the basi Doppler formula:

$$fd = \frac{2vft\cos\theta}{C} \text{ (in hertz)}$$

Figure 3.17(a) shows this angle. Using trigonometry, cosθ = Adjacent/Hypotenuse. Therefor Adjacent = C cosθ.

Given a propagation angle of 60°, cosθ = 0.5

$$fd = \frac{2vft\cos\theta}{C} = \frac{vft}{C}$$

It follows that if the angle changes, the speed calculated will be in error because the angle o propagation has been applied to the speed calculation formula in this way. If the vessel is not in correc trim (or pitching in heavy weather) the longitudinal parameters will change and the speed indicate will be in error. To counteract this effect to some extent, two acoustic beams are transmitted, one ahea and one astern. The transducer assembly used for this type of transmission is called a 'Janus configuration after the Roman god who reputedly possessed two faces and was able to see into bot the future and the past. Figure 3.17(b) shows the Janus assembly.

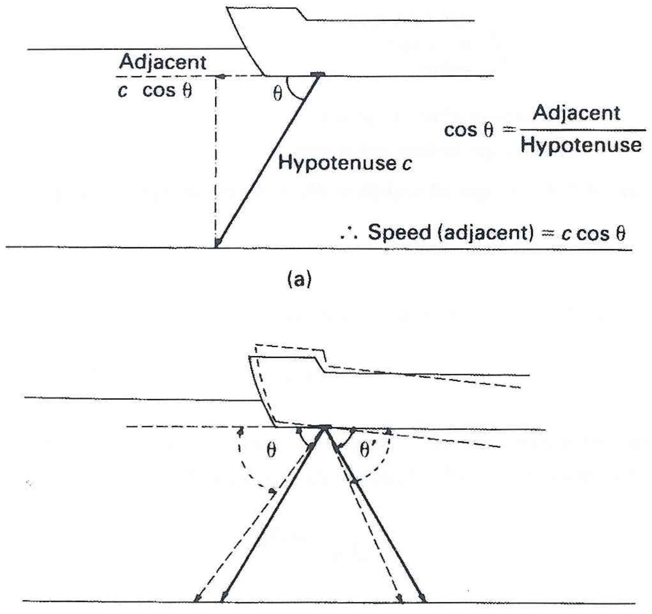


Figure 3.17 (a) Derivation of longitudinal speed using trigonometry. (b) The effect of pitching on a Janus transducer configuration.

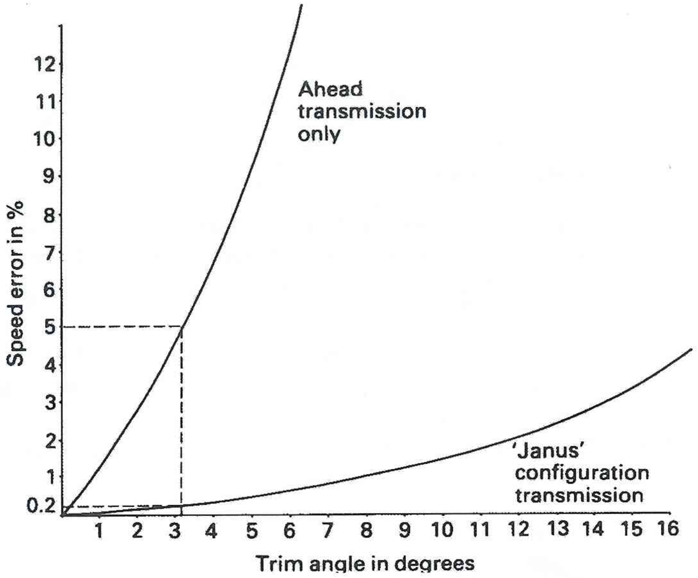


Figure 3.18 Graphs of speed error caused by variations of the vessel's trim.

The Doppler frequency shift formula now becomes:

$$fd = \frac{2vft}{C}(+\cos\theta + \cos\theta')$$

(+ cos 60° + cos 60°′ = 1) therefore the transmission angle can effectively be ignored.

As Figure 3.17(b) shows, in heavy weather one angle increases as the other decreases effectively cancelling the effects of pitching on the speed indication.

Figure 3.18 shows the advantage of having a Janus configuration over a single transducer arrangement. It can be seen that a 3° change of trim on a vessel in a forward pointing Doppler system will produce a 5% velocity error. With a Janus configuration transducer system, the error is reduced to 0.2% but is not fully eliminated.

The addition of a second transducer assembly set at right angles to the first one, enables dual axis speed to be indicated (Figure 3.19).

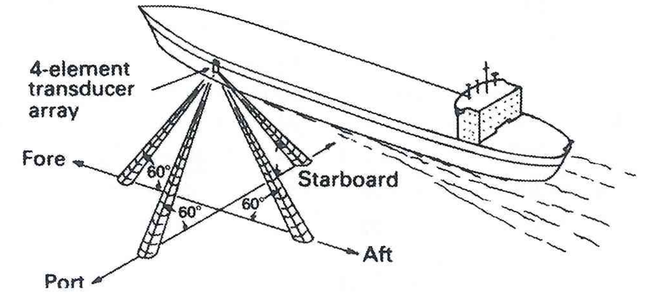


Figure 3.19 Dual axis speed is measured by transmitting sonar pulses in four narrow beams towards the sea bed.

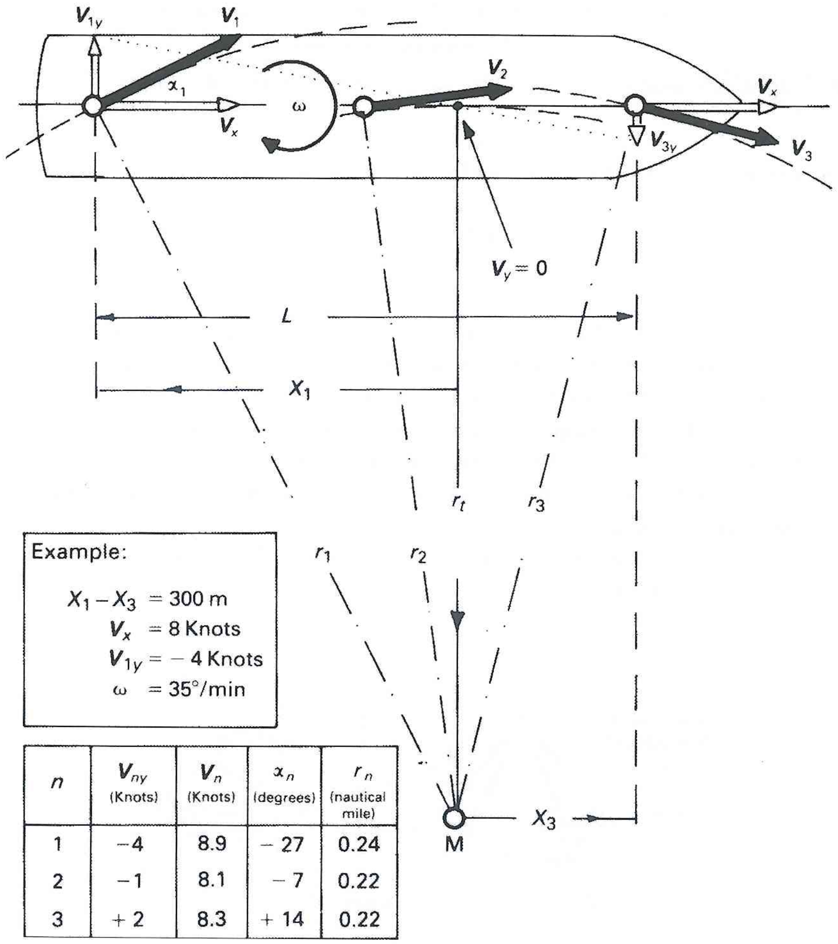
3.6.1 Vessel motion during turn manoeuvres

A precise indication of athwartships speed is particularly important on large vessels where the bo and stern sections may be drifting at different rates during docking or turning manoeuvres.

Speed vectors during a starboard turn

A dual axis Doppler speed log measures longitudinal and transverse speed, at the location of th transducers. If transducers are mounted in the bow and stern of a vessel, the rate of turn can b computed and displayed. This facility is obviously invaluable to the navigator during difficu manoeuvres.

Figure 3.20 shows the speed vectors plotted from bow and stern transducer data when a ship i turning to starboard without the effect of water current. When the rudder is put hard over, th transverse speed indication vector (**Vy**) can point either to the side to which the rudder has been move or to the other side. This will depend upon the longitudinal speed, the angular speed (rate of turn) an

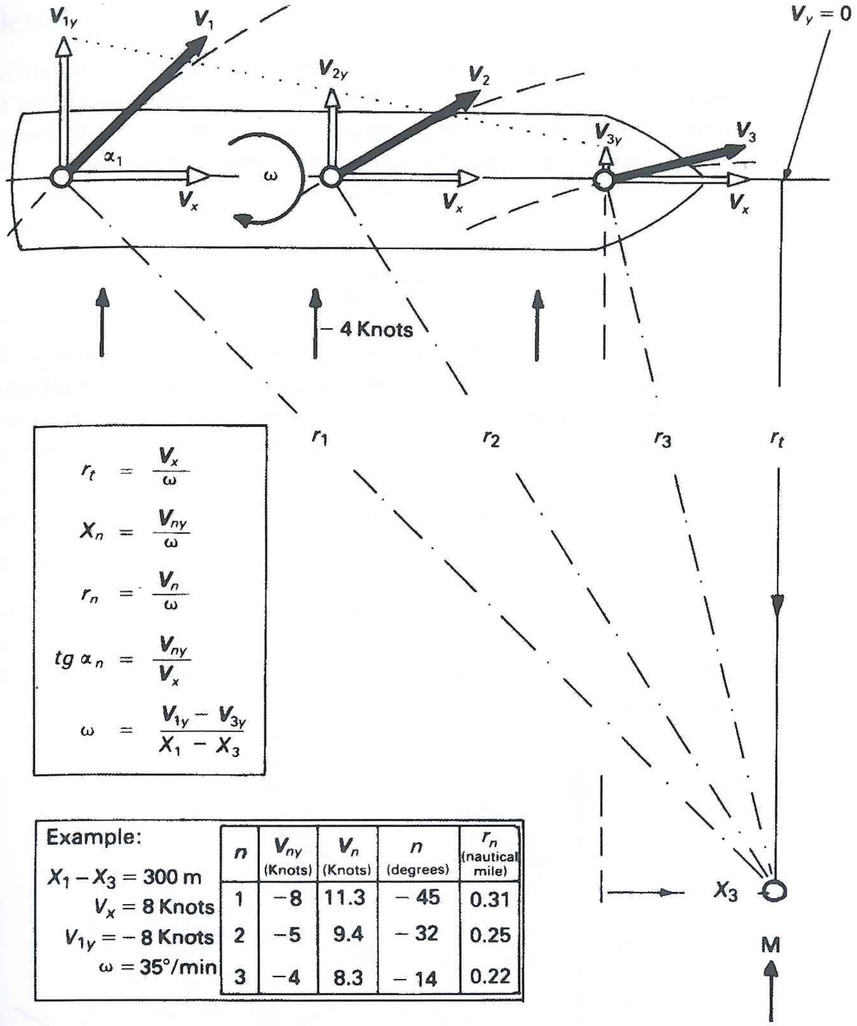


Example:

$X_1 - X_3 = 300$ m
$V_x = 8$ Knots
$V_{1y} = -4$ Knots
$\omega = 35°$/min

n	V_{ny} (Knots)	V_n (Knots)	α_n (degrees)	r_n (nautical mile)
1	−4	8.9	−27	0.24
2	−1	8.1	−7	0.22
3	+2	8.3	+14	0.22

Figure 3.20 Speed vectors during a starboard turn with no current. (Reproduced courtesy of Krupp Atlas Elektronik.)



$$r_t = \frac{V_x}{\omega}$$

$$X_n = \frac{V_{ny}}{\omega}$$

$$r_n = \frac{V_n}{\omega}$$

$$tg\ \alpha_n = \frac{V_{ny}}{V_x}$$

$$\omega = \frac{V_{1y} - V_{3y}}{X_1 - X_3}$$

Example:

$X_1 - X_3 = 300$ m
$V_x = 8$ Knots
$V_{1y} = -8$ Knots
$\omega = 35°$/min

n	V_{ny} (Knots)	V_n (Knots)	n (degrees)	r_n (nautical mile)
1	−8	11.3	−45	0.31
2	−5	9.4	−32	0.25
3	−4	8.3	−14	0.22

Figure 3.21 Speed vectors for a starboard turn under the influence of a four knot current . (Reproduced courtesy of Krupp Atlas Elektronik.)

weather/tide conditions. If the longitudinal speed and transverse speeds at two points of the vessel are known, the ship's movement is completely determinable. The bow transverse speed vector ($\mathbf{V}_{3y}$) points to starboard, the direction of the ship's turning circle.

Under the influence of the 4-knot current, shown in Figure 3.21, however, V_{3y} points to port. The transverse speed development along the ship's length is represented by a dotted line (between $\mathbf{V}_{1y}$ and $\mathbf{V}_{3y}$). The intersection of this line with the longitudinal axis produces a point at which the ship has longitudinal speed but no transverse speed. This point ($V_y = 0$) is normally positioned, approximately, in the fore third of the vessel (see Figure 3.20) if the ship is to turn along a circle about point M (the instantaneous centre of rotation). The effect of current from the starboard side causes point $V_y = 0$ to be ahead of the vessel and the ship to turn around point M in Figure 3.21, which is shifted forward relative to that shown in Figure 3.20. It is obvious therefore that an accurate indication of transverse speeds at various points along the vessel enables the navigator to predict the movement of his ship.

Speed components with the rudder amidships

Dual axis Doppler logs are able to measure accurately the ship's speed in a longitudinal direction (V and a transverse direction (V_y). The data derived from these measurements enables the navigator predict the course to steer in order to optimize the performance of the vessel. By measuring both spe components (i.e. the velocity vector) it is possible to optimize the vessel's course by computing th drift angle:

$$\propto \; = \text{arc tan} \frac{V_y}{V_x}$$

In the water-tracking mode this is the leeward angle (caused by wind) which is the angle between th true course (heading) and the course-made-good (CMG) through the water. In the bottom-trackin mode, it is the angle due to wind and tidestream between the heading and the CMG over the groun With the help of a two-component log the ship can be navigated so that heading steered plus drift angl measured by the log, results exactly in the intended chart course (see Figure 3.22).

The transverse speed at the stern is computed from the transverse speed of the bow, the ship's ra of turn and the ship's length as follows:

$$V_{q2} = V_{ql} - \omega L$$

where V_{q2} = stern transverse speed, V_{ql} = bow transverse speed, ω = rate of turn (angular velocity and L = distance between bow and stern points of measurement.

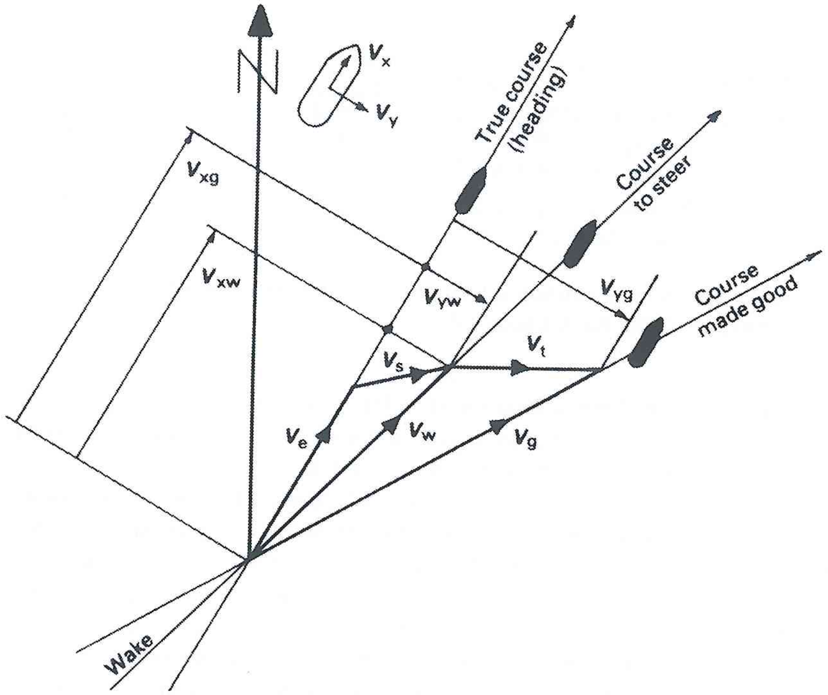


Figure 3.22 External environmental effects of a vessel's track. (Reproduced courtesy of Krupp Atlas Elektronik.)

3.6.2 Choice of frequency/transducer

As with depth sounding, the size of the transducer can be kept within reasonable limits by using a high frequency. This is particularly important in the situation where many elements are to be mounted in the same assembly. Unfortunately, as has already been discussed, attenuation losses increase exponentially with the transmission frequency. The choice of frequency is therefore a compromise between acceptable transducer size and the power requirements of the acoustic wave in order to overcome the signal losses due to the transmission media. Frequencies used in speed logging systems vary widely and are usually in the range 100 kHz to 1 MHz.

The factor with the greatest effect on speed accuracy is the velocity of the acoustic wave in seawater. Propagation velocity is affected by both the salinity and the temperature of the seawater through which the wave travels. However, velocity error due to these two factors can be virtually eliminated by mounting salinity and temperature sensors in the transducer array. Data from both sensors are processed to provide corrective information for the system. Alternatively, the Krupp Atlas Alpha transducer system effectively counteracts the effects of salinity and temperature by the use of a phased beam.

ALPHA transducer array

The necessity of a tilted beam normally dictates that the transducer protrudes below the keel and therefore may suffer damage. It is possible to produce the required angle of propagation by the use of

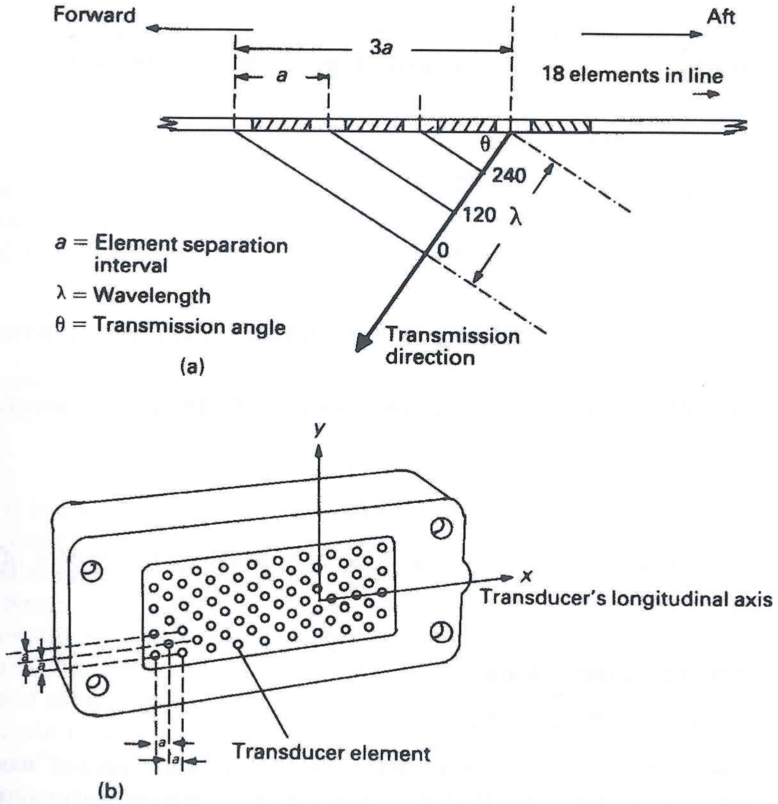


Figure 3.23 (a) Principle of the alpha transducer array. (b) A 72-element alpha transducer array.

a number of flush fitting transducers. The Krupp Atlas Alpha (Atlas Low Frequency Phased Arra multiple transducer 'Janus' assembly uses (4 × 18 = 72) flush fitting elements in each of the fore an aft positions. In theory any number of elements may be used, but the spacing of the elements must n exceed certain limits in order to keep unwanted side lobes down to an acceptable level.

Figure 3.23(a) is a cut-away bow section of a vessel fitted with an Alpha transducer array. F clarity, only a three-element assembly is shown. If the three elements are fed with in-phase sign voltages the beam formed would be perpendicular. However, if the signal voltages to each element ar phase delayed, in this case by 120°, the main lobe is propagated at an angle (which under the conditions is about 50°). In this case the elements are fed with three sine waves each shifted clockwi by 120°. For the Janus configuration the same elements are fed alternately clockwise and count clockwise. The Alpha system also overcomes the external factors that influence the velocity acoustic waves in salt water and is thus able to counteract the unwanted effects of salinity an temperature change.

The standard Doppler formula, from which velocity is calculated, comprises a number parameters, two of which are variable. Ideally the vessel's speed (v) should be the only unknow factor in the formula, but unfortunately the velocity of acoustic waves (C) is also a variable. Sinc speed accuracy depends upon the accuracy of acoustic wave velocity in salt water it is advantageou to eliminate (C) from the formula.

$$fd = \frac{2vft}{C}\cos\theta$$

With the Alpha system, the angle of propagation (θ) is a function of the velocity of acoustic wave because of the geometry and mode of activating the multiple elements (see Figure 3.23(a)). The angl of propagation is:

$$\cos\theta = \frac{\lambda}{3a} = \frac{C}{3a\,ft}$$

where a = the transducer element spacing and is therefore a fixed parameter.

$$\lambda = \frac{C}{ft} = \text{one acoustic wavelength in salt water}$$

If the two earlier equations in this section are now combined, the Doppler frequency shift is:

$$fd = \frac{2v}{3a}$$

$3a$ is a fixed parameter and therefore v is now the only variable. Two modes of operation ar possible.

3.6.3 Choice of transmission mode

Continuous wave mode (CW) transmission

Two transducers are used in each of the Janus positions. A continuous wave of acoustic energy i transmitted by one element and received by the second element. Received energy will have bee reflected either from the seabed, or, if the depth exceeds a predetermined figure (20 m is typical), fro

a water mass below the keel. Problems can arise with CW operation particularly in deep water when the transmitted beam is caused to scatter by an increasing number of particles in the water. Energy due to scattering will be returned to the transducer in addition to the energy returned from the water mass. The receiver is likely to become confused as the returned energy from the water mass becomes weaker due to the increasing effects of scattering. The speed indication is now very erratic and may fall to zero. CW systems are rarely used for this reason.

Pulse mode operation

To overcome the problems of the CW system, a pulse mode operation is used. This is virtually identical to that described previously for depth sounding where a high energy pulse is transmitted with the receiver off. The returned acoustic energy is received by the same transducer element that has been switched to the receive mode. In addition to overcoming the signal loss problem, caused by scattering in the CW system, the pulse mode system has the big advantage that only half the number of transducers is required.

Comparison of the pulse and the CW systems

- Pulse systems are able to operate in the ground reference mode at depths up to 300 m (depending upon the carrier frequency used) and in the water track mode in any depth of water, whereas the CW systems are limited to depths of less than 60 m. However, CW systems are superior in very shallow water, where the pulse system is limited by the pulse repetition frequency (PRF) of the operating cycle.
- The pulse system requires only one transducer (two for the Janus configuration) whereas separate elements are needed for CW operation.
- CW systems are limited by noise due to air bubbles from the vessel's own propeller, particularly when going astern.
- Pulse system accuracy, although slightly inferior to the CW system, is constant for all operating depths of water, whereas the accuracy of the CW system is better in shallow water but rapidly reduces as depth increases.

3.6.4 Environmental factors affecting the accuracy of speed logs

Unfortunately environmental factors can introduce errors and/or produce sporadic indications in any system that relies for its operation on the transmission and reception of acoustic waves in salt water.

- *Water clarity.* In exceptional cases the purity of the seawater may lead to insufficient scattering of the acoustic energy and prevent an adequate signal return. It is not likely to be a significant factor because most seawater holds the suspended particles and micro-organisms that adequately scatter an acoustic beam.
- *Aeration.* Aerated water bubbles beneath the transducer face may reflect acoustic energy of sufficient strength to be interpreted erroneously as sea bottom returns producing inaccurate depth indications and reduced speed accuracy. Proper siting of the transducer, away from bow thrusters, for instance, will reduce this error factor.
- *Vessel trim and list.* A change in the vessel's trim from the calibrated normal will affect fore/aft speed indication and an excessive list will affect athwartship speed. A Janus configuration transducer reduces this error.

- *Ocean current profile.* This effect is prevalent in areas with strong tides or ocean currents. In t water track mode, a speed log measures velocity relative to multiple thermocline layers several fe down in the water. If these layers are moving in opposite directions to the surface water, an err may be introduced.
- *Ocean eddy currents.* Whilst most ocean currents produce eddies their effect is minimal. Th problem is more likely to be found in restricted waters with big tidal changes or in riv mouths.
- *Sea state.* Following seas may result in a change in the speed indication in the fore/aft and/or po starboard line depending upon the vector sum of the approaching sea relative to the ship's axis
- *Temperature profile.* The temperature of the seawater affects the velocity of the propagated acoust wave (see Figure 2.2 in Chapter 2). Temperature sensors are included in the transducer to produ corrective data that is interfaced with the electronics unit.

3.7 Doppler speed logging systems

There are many maritime Doppler speed logging systems available, ranging from simple an inexpensive units designed for the leisure market to the complex rugged units fitted on moder merchant vessels, and they all rely for the operation on the first principles described in this chapte The difference between the cheaper leisure Doppler logs and those designed for a more demandin environment, lies in their construction, their reliability under pressure, the facilities they offer, and th fact that they are type-approved for use on ocean trading vessels.

3.7.1 The Sperry SRD-500 Dual Axis Doppler Speed Log System

One of the traditional manufacturers Sperry Marine Inc., now a part of Litton Marine Systems produces and markets a dual axis log, the SRD-500 (see Figure 3.24), which is a fine example of ho microtechnology may be used in signal processing and data presentation in a modern Doppler spee log.

The SRD 500 is a dual axis speed log capable of indicating speed along the fore and aft axis, in th range -20 to 50 knots, and along the port and starboard axis, range ± 10 knots, using a four-elemen electrostrictive transducer assembly. Additional electronic signal processing circuitry enables an ech sounding function, when bottom tracking speed mode is available.

The transmission frequency is 307.2 kHz and the radiated power is 15–20 W.

Display unit

The SRD-500 main navigation display is shown in Figure 3.25. Whilst many of the unit controls wi be familiar to navigators, a few are listed below to show how the company has used electroni processing to get the most out of the system. For ease of viewing, the equipment uses illuminate liquid crystal displays.

- *Speed display.* This shows the vessel's fore/aft speed in knots, m/s (metres per second) or ft/s (fee per second). The speed range is 0–20 knots astern and 0–50 knots ahead. Bottom-tracking spee accuracy is ± 0.1 knots below 2 knots speed and ± 0.05 knots above 2 knots. Accuracy when wate tracking is ± 0.1 knots below 10 knots, ± 0.025 knots in the range 10–25 knots, and ± 0.1 kno above 25 knots.

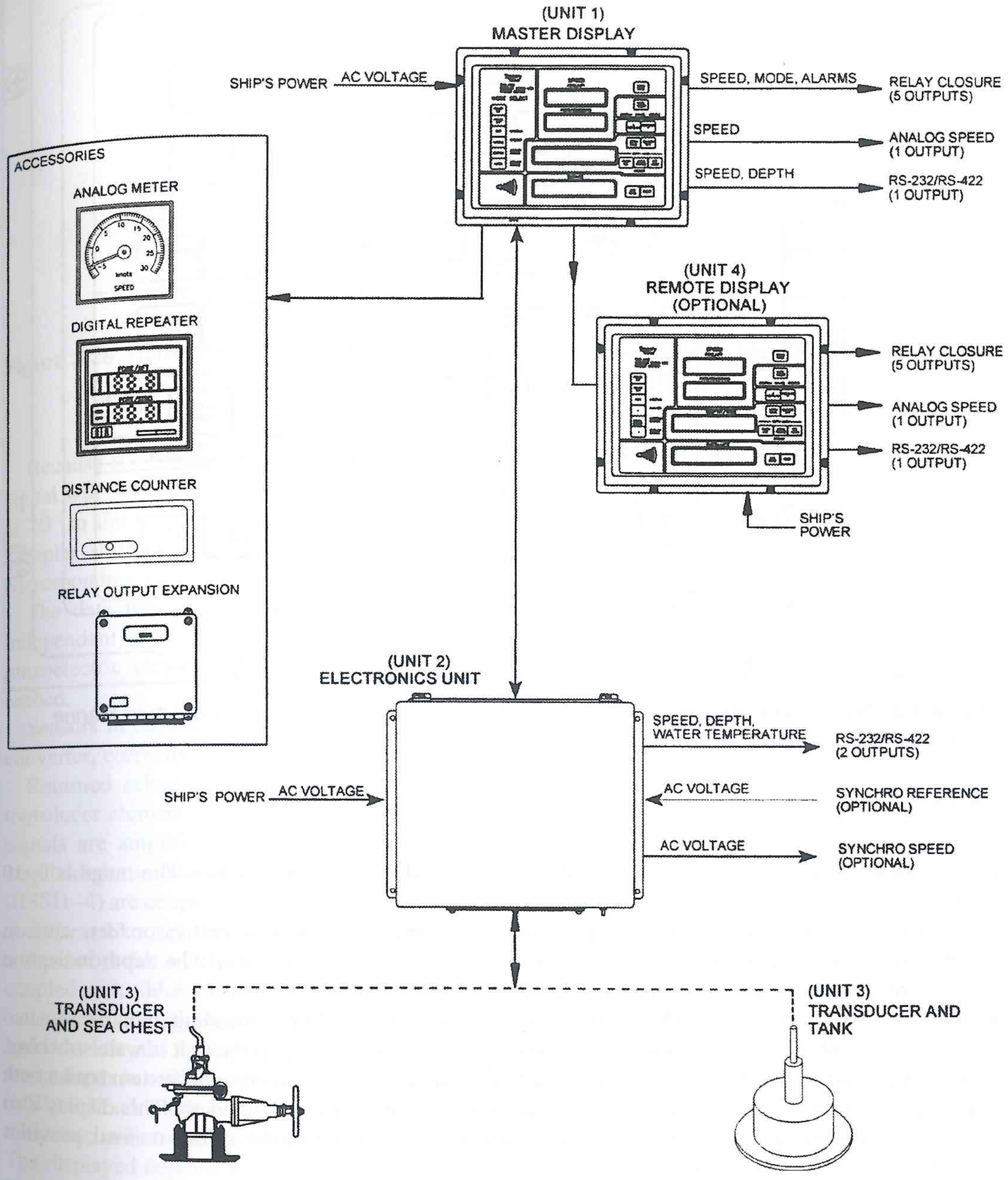


Figure 3.24 Sperry SRD-500 dual axis Doppler speed log system. (Reproduced courtesy Litton Marine Systems.)

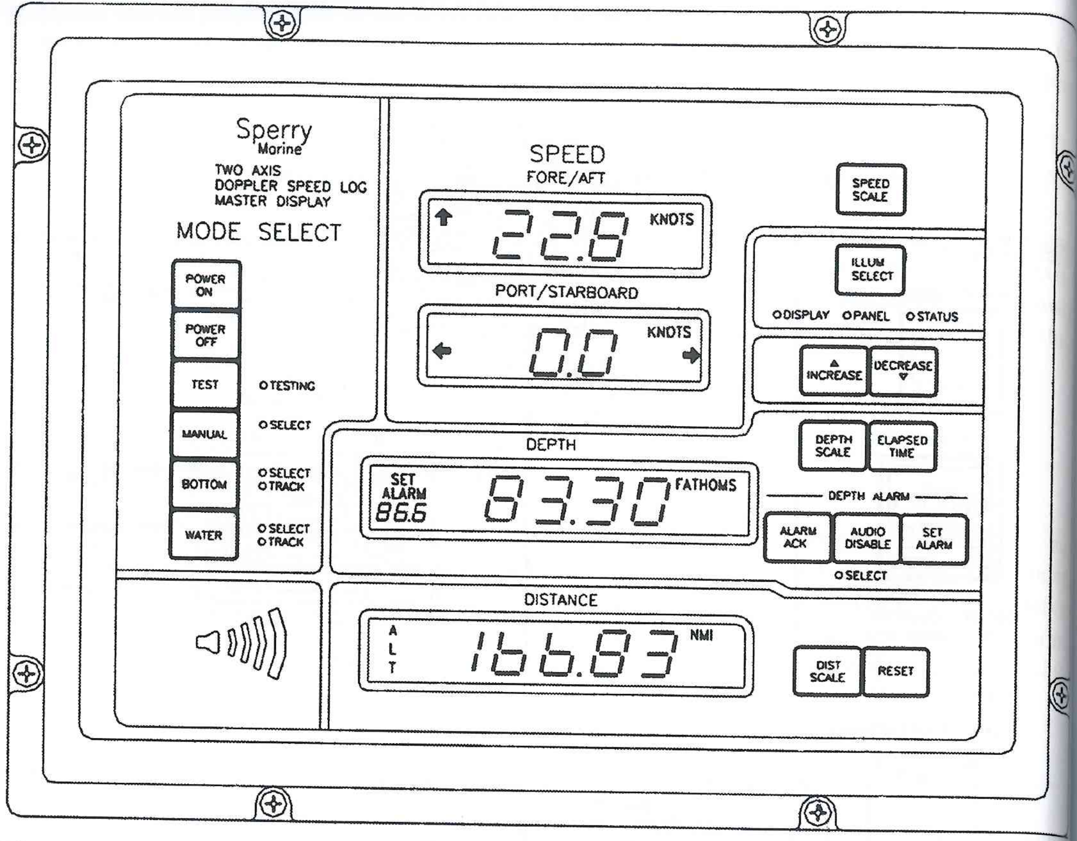


Figure 3.25 Master display unit, controls and indicators. (Reproduced courtesy of Litton Marine Systems.)

- *Port/starboard display.* This indicates athwartship speed in knots, m/s or ft/s. The range is 0–10 knots.
- *Depth/time display.* This indicates water depth to the seabed, in fathoms, metres or feet, when in either water or bottom-tracking mode, providing the depth is within 200 m. The depth indication circuitry also includes a depth alarm.
- *Distance display.* This shows the distance run in nautical miles or km. Depending upon the selected mode and depth, the display indicates over-the-bottom distance or, when the unit is water tracking, the distance travelled through the water. If the ALT characters are showing, the system tracks both bottom and water simultaneously and provides both outputs to external devices. This display also provides a numerical indication which, when used in conjunction with the system manual, provides clues to any system malfunction.

System description

The Sperry SRD-500 uses a four-element piezoelectric and prism transducer assembly with the four heads aligned as shown in Figure 3.26.

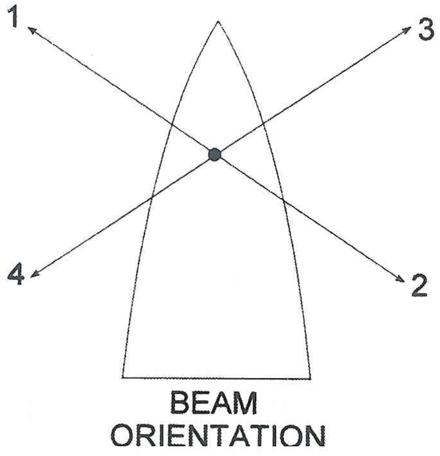


Figure 3.26 Transducer beam orientation. (Reproduced courtesy of Litton Marine Systems.)

Because the beams are aligned at 45° to the ship's fore/aft and port/starboard axes, each returned signal will hold data about the fore/aft and port/starboard speed of the vessel. Each beam is inclined at 20° to the vertical axis. When the ship is moving ahead, beams 1 and 3 will contain a positive Doppler shift (a compression of the transmitted wavelength) whereas beams 2 and 4 will hold corresponding data.

The data line XMIT from the Processor Board initiates transmission (see Figure 3.27). Four independent transmit amplifiers are pulsed to generate 15–20 W of power causing the four piezoelectric elements to oscillate at 307.2 kHz and transmit acoustic energy pulses towards the seabed.

Sensors in the transducer assembly monitor the seawater temperature and provide, via an A to D converter, corrective data for the central processor.

Returned echoes from either the seabed or scattered from water particles, are received by the transducer elements and coupled to the Receive Amplifier and Frequency Comparison Board. The signals are amplified, gain controlled and then fed to a limiter circuit where the received signal amplitude is monitored and a receive signal strength indicator (RSSI) level is produced. The four levels (RSSI1–4) are coupled back to the processor, which uses the data to determine bottom detection, signal quality and to set the receiver gain. The four-channel signal data is then coupled to frequency comparators that are clocked by the frequency correlation and processing circuitry. From here the data is coupled with address information to the parallel interface and serial I/O boards for distribution.

The RSSI signals generated by the receive circuitry are used to determine the range to the seabed. Individual depths are computed for each beam. The minimum (shallowest) is used to determine if the water depth is sufficient for the log to operate in Water Track mode. The ability of the log to operate in Water Track mode requires a minimum of 3 m depth below the transducer. In deep water the ability to operate in Bottom Track mode is based on obtaining bottom-returned pulses on at least three beams. The displayed depth is an average of the individual depths indicated by the beams. System operation is commanded at start up by the Navigation Display Unit (see Figure 3.28)

These routines are performed when the system is switched on or the manual button is pressed. This includes initializing all program variables, the setting-up of peripheral components and communication controllers and the recall of display configuration data stored in NVRAM (non-volatile random access memory).

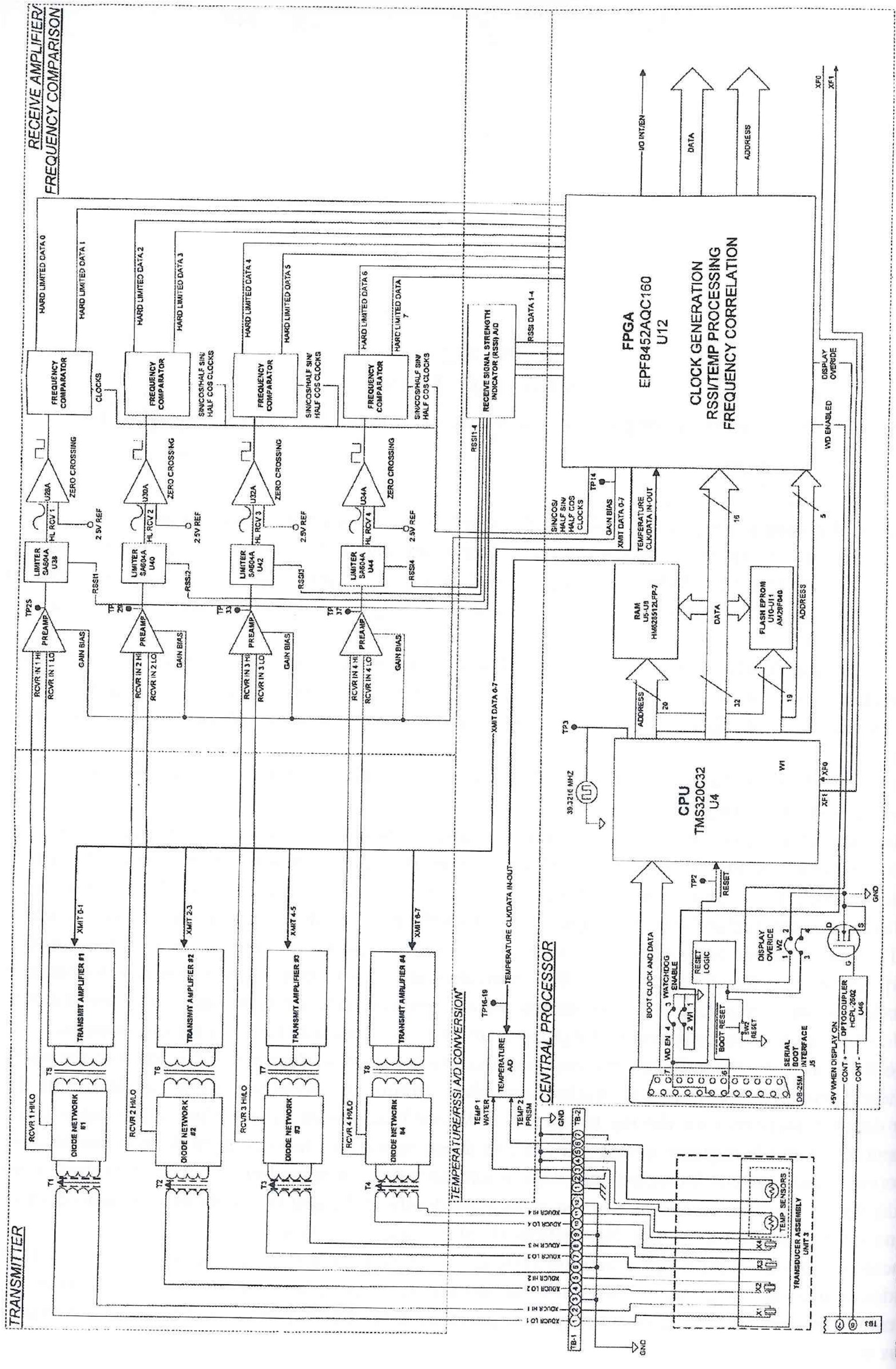


Figure 3.27 Electronics unit functional block diagram. (Reproduced courtesy of Litton Marine Systems.)

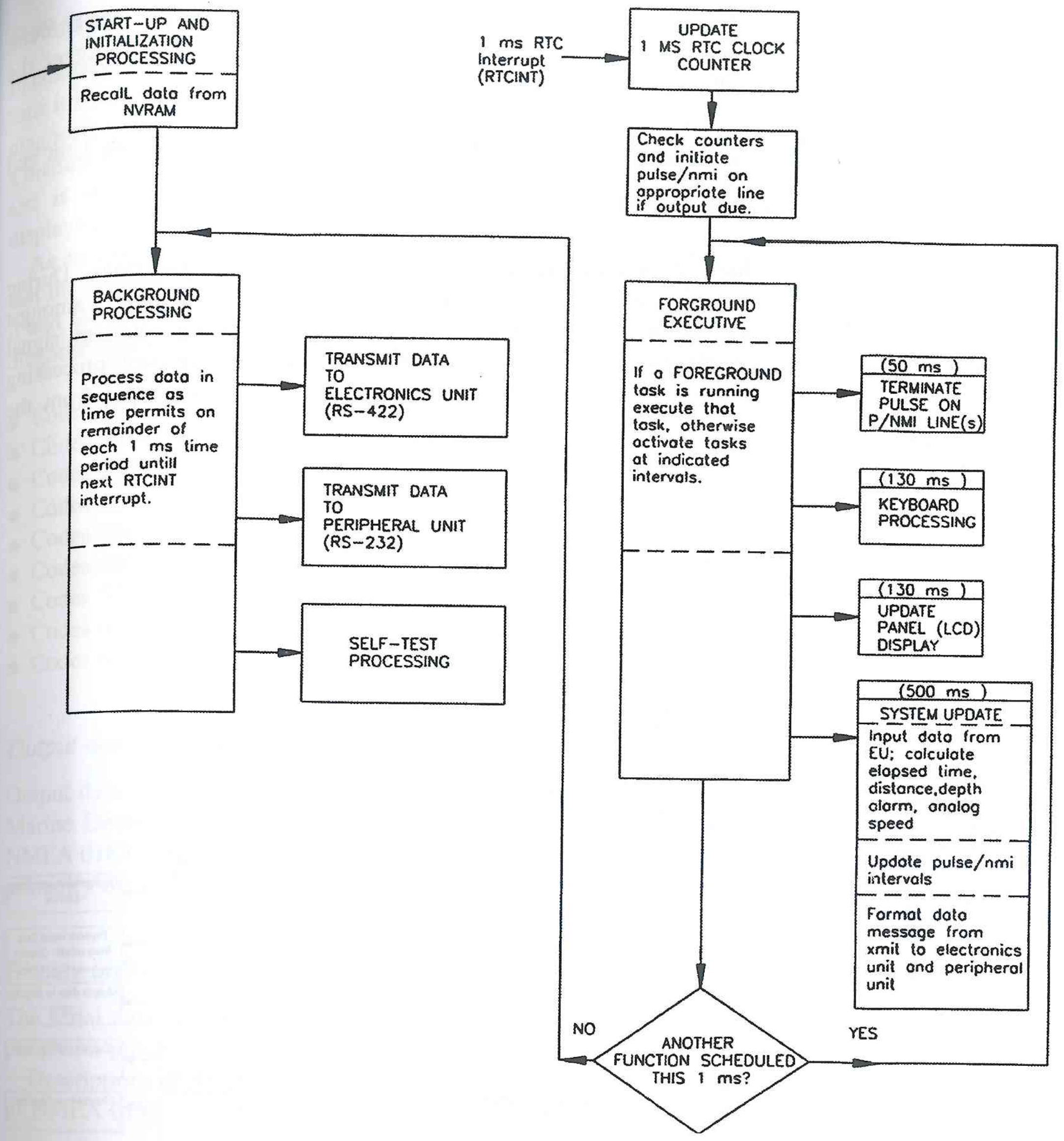


Figure 3.28 Display unit start-up flow chart. (Reproduced courtesy of Litton Marine Systems.)

The foreground executive processing routines are initiated by a 1-ms real-time interrupt line (RTCINT), which instructs the circuitry to perform the following.

- Keyboard Data Processing: reads and processes any input from the keypad.
- Panel Processing: updates the LCD displays with the latest stored variables.
- System Update: incorporates the latest data from the Electronics Unit into the system variables for processing. Also formats data messages for transmission to the Electronics Unit and to peripheral equipment.

When the Foreground Executive processing routine has completed its tasks, the Backgrou Processing Routine is initiated. This runs until the next RTCINT pulse arrives to retrigger t sequence. Background Processing enables the following actions.

- Data Message Output: enables the outputting of formatted data to both the Electronic Unit a Peripheral Units.
- Self-Test Processing: initializes the self-test program.

The system control flow chart, shown in Figure 3.29, illustrates the main functions. Duri operation, the foreground processing unit commands all system functions: determining, among other things, whether the log is in water or bottom-track mode, processing returned sign information, and operating the self-testing procedure. At 10-ms intervals the background processi subroutine commands data outputs to external navigation equipment and reads input from t master display.

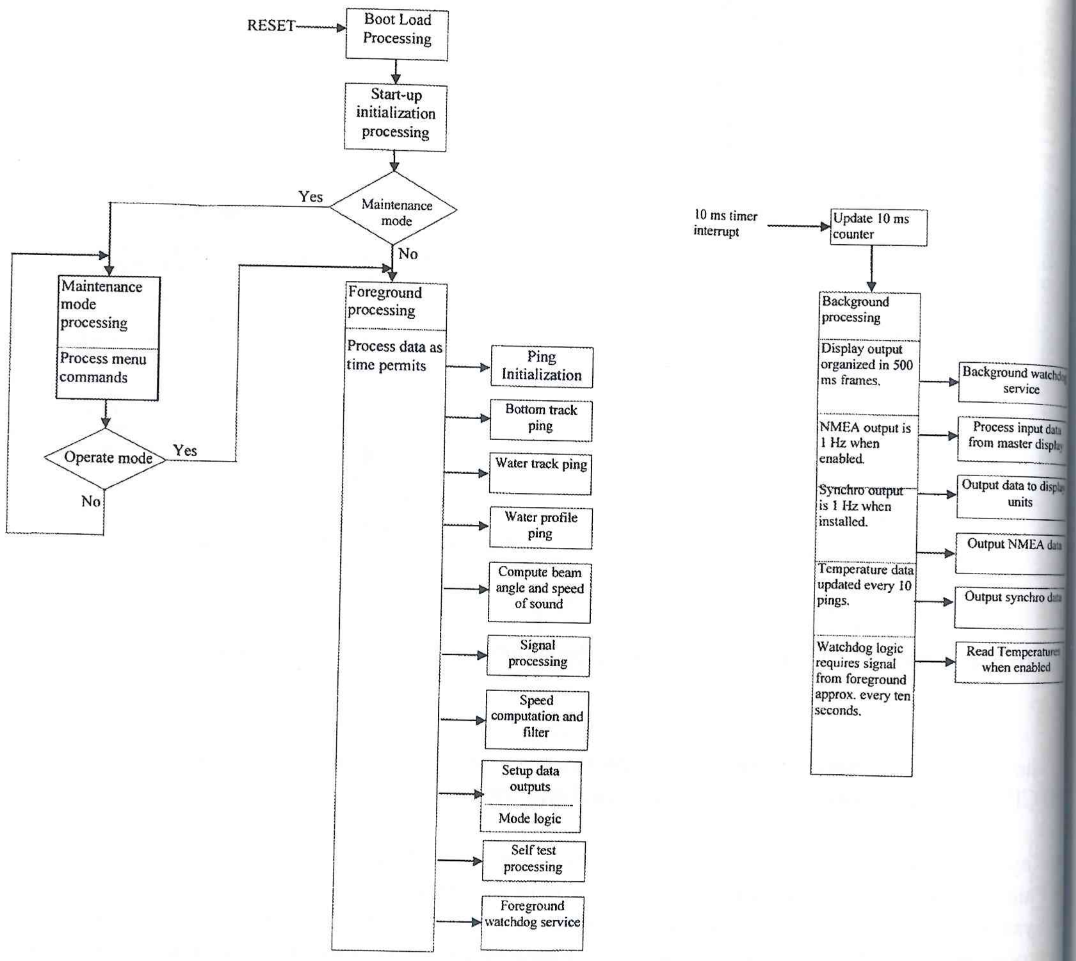


Figure 3.29 System control flow chart. (Reproduced courtesy of Litton Marine Systems.)

Built-in test circuitry

In common with most computer-controlled equipment, the system operates a self-test procedure every time it is switched on and performs a fault detection routine at regular intervals during operation. Fault diagnosis routine and testing can be performed manually via the Master Display Unit keypad. During a manual test sequence all LEDs are illuminated and the LCD digits are sequentially displayed. If the test is successful, PASS is displayed in the Distance display. If not, a fault code number is displayed.

As an example of this, the number 402 indicates that the Water Temperature reading is faulty and that the probable faulty component is the temperature sensor in the transducer or the wiring between it and the processing card 2A1. As a further indication of the depth to which the system is able to diagnose faults, the other codes are listed below.

- Codes 101 or 102: keypad faults in the Master Display Unit.
- Codes 201–208: communication faults between the Display Unit and the Main Electronics Unit.
- Codes 255 and 265: RS-232/422 outputs faulty from the Display Unit.
- Codes 301–308 and 355–365: refer to faults in the Main Electronics Unit.
- Codes 401–403: temperature measurement faults.
- Codes 490 and 491: memory test faults.
- Codes 520–524: transmit/receive ping faults.
- Codes 600–604 and 610–614: noise level and sensitivity faults.
- Codes 620–630: receive/transmit signal faults.

Output data formats

Output data sent to remote navigation systems is formatted in the standard protocol for Interfacing Marine Electronics Navigation Devices developed by the National Marine Electronics Association NMEA 0183 (see Appendix 3 for full details). A second output, in Sperry Marine Format, is intended primarily for the direct printout of speed data.

Display unit – serial data output format

The serial data output port of each display is configured so that the data can be communicated to peripheral processing devices. Data can be interfaced using RS-232 or RS-422 protocols.

Descriptions of the Sperry SRD-500 communications data format are given in Table 3.1. Examples of NMEA 0183 format messages sent by the RS 422 interface at 4800 bauds are as follows.

Speed message format:	$VDVBW,sww.ww,sxx.xx,A,syy.yy,szz.zz,A*cc<CR><LF>
Depth message format:	$VDDRU,ddd.dd,A,,V,*cc<CR><LF>
Water Track format:	$VDVBW,16.24,-0.62,A,,,V*25
	$VDDRU,,V,,V,*7D

The Sperry Marine Format, intended primarily for the direct printout of speed data, is shown in Table 3.2.

Data output is transmitted in ASCII coded format and is structured to be displayed or printed in six-headed columns on a standard page with a width of 80 characters and a length of 56 lines. The serial data interface is set up with 8 data and 2 stop bits and no parity. No handshaking lines are used. Messages are never repeated. A new set of data is formatted for transmission every 0.5 s.

Table 3.1 Sperry SRD-500 communications data format – NMEA 0183. (Reproduced courtesy of Litton Marine Systems)

Data field	*Description*
$	Message header character
VD	Talker ID
VBW	Message type (speed bottom/water)
DPT	Message type (depth with keel offset)
DRU	Message type (depth)
MTW	Message type (water temperature)
XDR	Message type (transducer measurements)
G	Generic
eee.ee	Percentage good; first, second, and last 'e' omitted if not used
PCB1	Beam one ID for bottom speed
PCW1	Beam one ID for water speed
S	Sign – for aft/port speeds, omitted for fore/stbd speeds
ww.ww	Fore/Aft water speed (knots); first and last 'w' omitted if not used
xx.xx	Port/Stbd water speed (knots); first and last 'y' omitted if not used
zz.zz	Port/Stbd bottom speed (knots); first and last 'z' omitted if not used
ddd.dd	Depth (meters); first, second and last 'd' omitted if not used
oo.oo	Keel offset (decimeters); first and last 'o' omitted if not used
ttt.tt	Temperature (C°); first, second and last 't' omitted if not used
A	Data status (A = valid, V = invalid)
*	Message data trailer
cc	Checksum; 8 bit running XOR of character between $ and*
<CR>	Carriage return
<LF>	Line feed

Electronics Unit – serial data output

There are two bi-directional auxiliary ports (Aux 1 and Aux 2) in the Electronics Unit, each of whic can be selected to output NMEA 0183 format data directly to peripheral devices.

The baud rate can be selected between 1200 and 115200 and defaults to 4800. Message words ar 8 data bits long with selectable parity, a single Start bit and selectable Stop bits (one or two). Th default communication setting for Aux 2 complies with NMEA 0183 version 2.1 recommendation one Start bit, eight data bits, one Stop bit, no parity and a 4800 baud rate.

Both output serial ports send NMEA messages at a 1-s (1 Hz) data rate for speed, depth and wate temperature; and at a 10-s rate (0.1 Hz) data rate for 'percent good pings for Bottom Speed' an 'percent good pings for Water Speed'.

Examples of output data formats

Speed message format:
$VDVBW,sww.ww,sxx.xx,A,syy.yy,szz.zz,A*cc<CR><LF>

Depth message format:
$VDDPT,ddd.dd,oo.oo(keel offset)*cc<CR><LF>

Water temperature message format:
$VDMTW.ttt.tt,C*cc<CR><LF>

Table 3.2 Sperry SRD-500 display unit – serial output data format (Sperry ASCII) (Reproduced courtesy of Litton Marine Systems)

Data	*Format*	*Comments*
Operating mode	EUTEST^ OPTEST^ BOTTOM^ WATER^ WATBOT^ MANUAL^	7 character field
Fault code	FFF^^^ ^*^^^^	6 character field FFF = 3 digit fault code ^*^ = no fault
F/A bottom speed	svv.vv^m/s^^^	13 character field s = sign bit (-blank) vv.vv = speed value, zero fill if necessary m/s = unit indicator
	^^^*****^^^^^	speed undefined
F/A water speed	same as F/A bottom	
P/S bottom speed	same as F/A bottom	
P/S water speed	same as F/A bottom	
Depth (altitude)	^ddd.d^m^m^cle	13 character field ^^^d.d if altitude < 10 m ^^dd.d if altitude < 100 m ^ddd.d if altitude > = 100 m m = unit indicator c = carriage return l = line feed e = end of text character
	^^*****^^^cle	Depth defined

Note: a '^' character represents a blank character

Percent good pings for Bottom Speed message format:
$VDXDR,G,eee.ee, ,PCB1,G,eee.ee, ,PCB2,G, . . . ,PCB3,G, . . . ,PCB4*cc<CR><LF>

Percent good pings for Water Speed message format:
$VDXDR,G,eee.ee, ,PCW1,G,eee.ee, ,PCW2,G, . . . ,PCW3,G, . . . ,PCW4*cc<CR><LF>

To decode the above symbols, see Table 3.1.

Message example for Water Track Speed

```
$VDVBW, 2.0,-0.25,A,,,V*
$VDDPT,2.5,-1.0,*79
$VDMTW,18.4,C*0C
$VDXDR,G,000,PCB1,G,000,PCB2,G,000,,PCB3,G,000,,PCB4*58
$VDXDR,G,100,,PCW1,G,100,PCW2,G,100,,PCW3,G,100,,PCW4*58
```

As an example, the first line of this message may be simply decoded as follows.

$ (header) VD (talker ID) VBW (speed bottom/water) s (aft/port speeds) 2.0 (aft speed in kts) s (a port speeds) 0.25 (port speed in kts) A (data status).

The above description is only a simple outline of how the NMEA 0183 protocol is used to interfa data from this speed log with other electronic systems. Refer to Appendix 3 for a more detail description of the protocol.

3.7.2 The Furono Doppler Sonar DS-50 System

Another respected manufacturer of marine equipment, Furuno, produces a Doppler sonar system, t DS-30, based on the principles of Doppler speed measurement. Whilst the system principles are t same as with other speed logs in this category, Furuno have made good use of the data processi circuitry and a full colour 10-inch wide LCD display to present a considerable amount of informati to a navigator. The display modes or shown in Figure 3.30.

The system uses a triple beam, 440 kHz pulsed transmission and from the received Doppler shift signal calculates longitudinal, thwartship speeds and depth beneath the keel at the bow.

In addition, a Laser Gyro may be fitted on the stern to provide a further data input of transver speed and rate of turn information (see Figures 3.21 and 3.31). Position data from a GPS receiver ma also be input to the CPU.

There are three principle modes of data display.

- The Speed Mode showing all the normal speed/depth/distance indications.
- The Berthing Mode which, with the additional inputs from a laser gyro at the stern, shows a vessel movements during low speed manoeuvres (see Figure 3.31).
- The Nav Data Mode with a display reminiscent of an integrated navigation system.

Berthing Mode display

The display diagram key shows the following.

A	Intersection of perpendicular from ship's ref. point to marker line.
B	Yellow arrowhead showing wind direction.
C	Blue arrowhead showing current direction.
D	Echo monitor.
E	Tracking mode.
F	Heading (input from gyro).
G	Rate of turn (measured by laser gyro).
H	Readout of speed and direction of water current.
I	Readout of wind speed and direction (input from wind sensors).
J	Under-keel clearance measured by an external echo sounder.
K	Range and bearing (true) to marker line.
L	Marker line.
M	Ship's speed: transverse, longitudinal and transverse at stern with laser gyro.
N	Grid scale and presentation mode.
O	Ship's predicted motion.

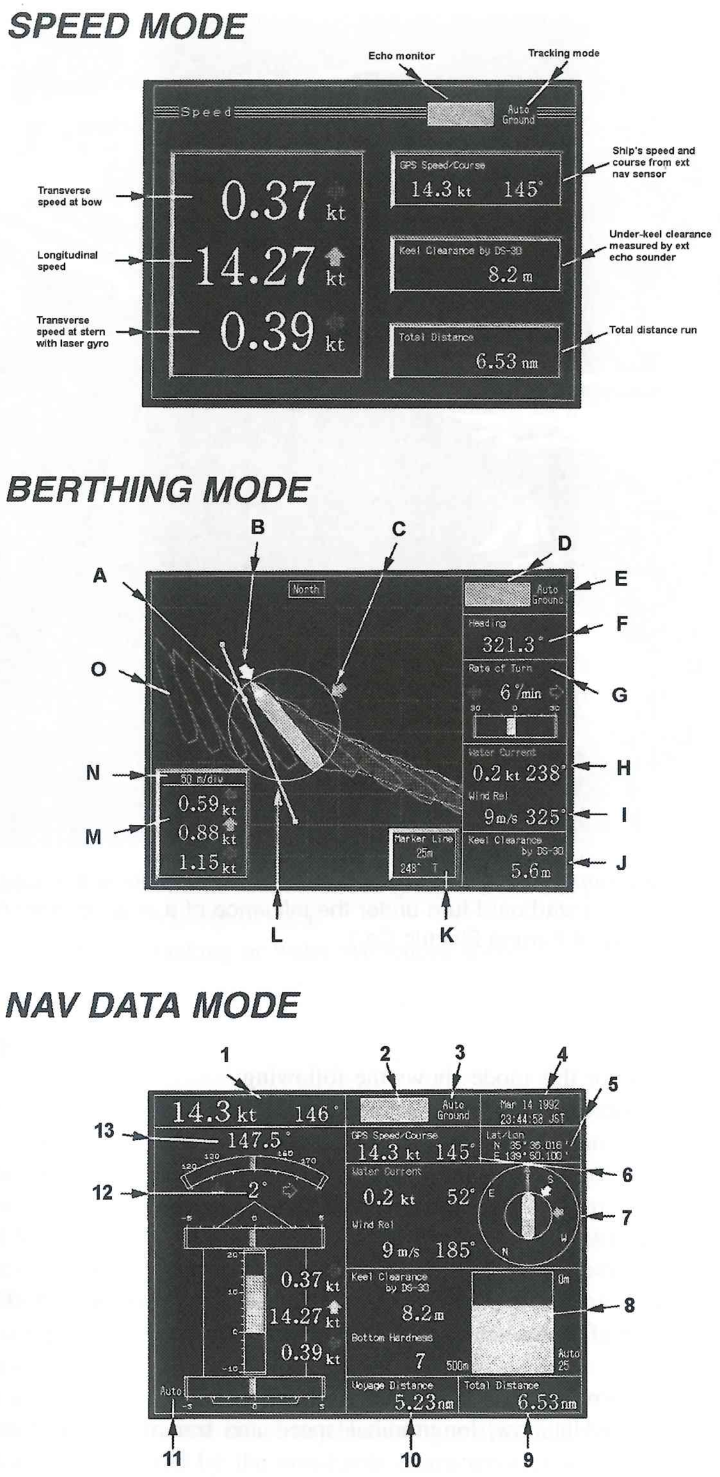


Figure 3.30 Furuno Doppler Sonar DS-30 display modes. (Reproduced courtesy of Furuno Electric Co.)

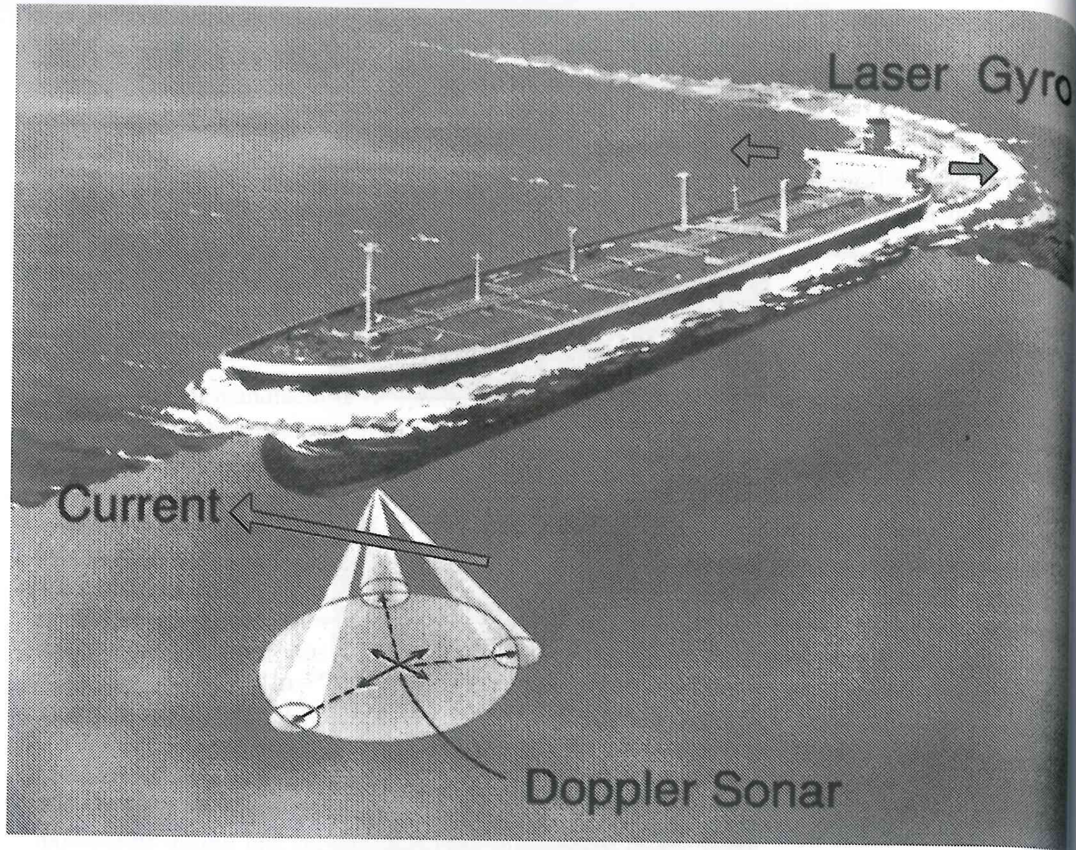


Figure 3.31 Triple beam transducer configuration of the Furuno Doppler Sonar Log. Note the forces acting on the vessel during a starboard turn under the influence of a cross-current from the port side. (Reproduced courtesy of Furuno Electric Co.)

Nav Data Mode display

The display diagram key for this mode shows the following.

1 Ship's speed and course.
2 Echo monitor.
3 Tracking mode and echo level indicator.
4 Date and time.
5 Position (input from external sensors).
6 Ship's speed and course (input from external sensors).
7 Current speed and direction (app.088°) and wind speed and direction (app. 038°).
8 Graphic presentation of under-keel clearance.
9 Total distance run.
10 Voyage distance from reset.
11 Ship's transverse speed at bow, longitudinal speed and transverse speed at stern with lase gyro.
12 Drift angle (deviation of course over ground from ship's course).
13 Course heading.

3.8 Glossary

Aeration	The formation of bubbles on the transducer face causing errors in the system.
ALPHA (Atlas Low Frequency Phased Array) transducer	A flush fitting transducer using multiple elements to create the transmitted beam.
Beamwidth	The width of the transmitted acoustic pulsed wave. The beam spreads the further it travels away from a transducer.
BITE	Built-in test circuitry. A self-test or manually operated diagnostic system.
CW mode	Continuous wave transmission. Both the transmitter and receiver are active the whole time. Requires two transducers.
Distance integrator	The section of a speed log that produces an indication of distance travelled from speed and time data.
Doppler principle	A well-documented natural phenomenon enabling velocity to be calculated from a frequency shift detected between transmission and reception of a radio signal.
E.M. log	An electronic logging system relying on the induction of electromagnetic energy in seawater to produce an indication of velocity.
G/T	Ground-tracking or ground referenced speed.
NMEA	National Marine Electronic Association. Interfacing standards.
Pitot log	An electromechanical speed logging system using changing water pressure to indicate velocity.
Pulse mode	Acoustic energy is transmitted in the form of pulses similar to an echo sounding device or RADAR
Transducer	The transmitter/receiver part of a logging system that is in contact with the water. Similar to an antenna in a communications system.
Translating system	The electronic section of a logging system that produces the speed indication from a variety of data.
W/T	Water-tracking or water referenced speed.

3.9 Summary

- To be accurate, speed must be calculated with reference to a known datum.
- At sea, speed is measured with reference to the ocean floor (ground-tracking (G/T)) or water flowing past the hull (water-tracking (W/T)).
- Traditionally, maritime speed logging devices use water pressure, electromagnetic induction, or the transmission of low frequency radio waves as mediums for indicating velocity.
- A water pressure speed log, occasionally called a Pitot log:
  (a) measures W/T speed only;
  (b) requires a complex arrangement of pressure tubes and chambers mounted in the engine room of a ship and a Pitot tube protruding through the hull;
  (c) produces a non-linear indication of speed which must be converted to a linear indication to be of any value. This is achieved either mechanically or electrically in the system;
  (d) speed indication is affected by the non-linear characteristics of the vessel's hull and by the vessel pitching and rolling;
  (e) possesses mechanical sections that require regular maintenance.

- An electromagnetic speed log:
  - (a) measures W/T speed only;
  - (b) produces a linear speed indication;
  - (c) operates by inducing a magnetic field in the salt water flowing past the hull and detecting minute change in the field;
  - (d) produces a varying speed indication as the conductivity of the seawater changes.
  - (e) Indication may be affected by the vessel pitching and rolling in heavy weather.
- Speed logs that use a frequency or phase shift between a transmitted and the received radio wa generally use a frequency in the range 100–500 kHz. They also use a pulsed transmissio format.
- A log using the acoustic correlation technique for speed calculation:
  - (a) can operate in either W/T or G/T mode. G/T speed is also measured with respect to a wat mass;
  - (b) measures a time delay between transmitted and received pulses;
  - (c) produces a speed indication, the accuracy of which is subject to all the environmental problem affecting the propagation of an acoustic wave into salt water. See Chapter 2.
- Doppler frequency shift is a natural phenomenon that has been used for many years to measu velocity. If a transmitter (TX) and receiver (RX) are both stationary, the received signal will be th same frequency as that transmitted. However, if either the TX or the RX move during transmission then the received frequency will be shifted. If the TX and/or RX move to reduce the distanc between them, the wavelength is compressed and the received frequency is increased. The opposi effect occurs if the TX and/or RX move apart.
- A Doppler speed logging system:
  - (a) transmits a frequency (typically 100 kHz) towards the ocean floor and calculates the vessel' speed from the frequency shift detected;
  - (b) measures both W/T and G/T speed;
  - (c) produces a speed indication, the accuracy of which is subject to all the environmental problem affecting the propagation of an acoustic wave in salt water;
  - (d) uses a Janus transducer arrangement to virtually eliminate the effects of the vessel pitching i heavy weather;
  - (e) may use more than one transducer arrangement. One at the bow and another at the stern to sho vessel movement during turn manoeuvres.

3.10 Revision questions

1 A speed indication is only of value if measured against another parameter. What is the spee indication, produced by a pressure tube speed log, referenced to?
2 What is the approximate velocity of propagated acoustic energy in seawater?
3 In a pressure tube speed logging system, why is the complex system of cones required in th mechanical linkage?
4 What is the speed indication produced by an electromagnetic log referenced to?
5 How does the non-linearity of a ship's hull affect the speed indication produced by a electromagnetic speed log?
6 Does the amount of salinity in the water affect the speed indication produced by an acousti correlation speed log?
7 Why do all Doppler speed logs use a Janus configuration transducer assembly?
8 How does aeration cause errors in the speed indicated by a Doppler log?

9 Using the V_x and V_y speed components produced by a Doppler speed log, how is it possible to predict a vessel's drift rate?
10 Why are pulsed transmission systems used in preference to a continuous wave mode of operation?
11 Why are water temperature sensors included in the transducer assembly of a Doppler speed logging system?
12 How may the distance run be calculated in a speed logging system?