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DIVER NAVIGATION AND SEA-BED SURVEYING EQUIPMENT

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INTRODUCTION

There has been a continuing interest shown in the literature [1,3,5] in diver navigation systems. This present paper describes a real time, self contained, battery operated, personal diver navigation system. In addition to functioning as a ship guidance system for use in difficult waters it also offers modes for shallow water sea bed surveying with consequent applications in mapping archaeological sites, oil rig sites, harbours, sea shores and estuaries. In operation a hand held interrogator unit enables a free swimming diver to obtain precise positional information relative to two transponder base stations deployed on the sea floor. Although the use of only two base stations has consequent operational restrictions it has never the less proved suitable for specific applications. Depth and positional information relative to these fixed base stations are stored at regular intervals in the diver held interrogator unit under micro-computer control for later retrieval. Range is measured conventionaly in terms of the round trip flight time of a short duration sound pulse between the interrogator and the activated transponder. Depth is measured using the pulse echo principle. This allows specified sites on the sea bed to be surveyed enabling depth contour lines to be mapped. If required both battery operated base stations can be left in position, in an automatic shut down mode, for later navigational use. Results obtained with a prototype system in a flooded quarry are presented and confirm the feasibility of the method.

PRINCIPLES OF OPERATION

The main problems envisaged with an acoustic navigation system of this type is in its operation near the water surface and in areas of shallow water. The signal processing involved will have the task of discriminating between sonar pulses and the combined effect of ambient noise, reverberation and, in particular, multi-path effects. A long baseline system (LBL) can be utilised for accurate navigation in areas of shallow water, positional information being determined by multiple range measurements. The accuracy of this LBL system relies upon the estimation of sound speed in water and the accuracy of emplacement of two transponders in line of sight with each other. The advent of intelligent transponders enables transponder baseline distances to be independently established.

In operation one of the base stations, for convenience termed the slave, is deployed on the sea-bed at a desired location. The diver held interrogator unit is switched to mode one which gives the range between the interrogator unit and the slave base station. The diver then deploys the second base station, for convenience termed the master base station, using the interrogators visual display to give an estimate of its range from the slave base station. To obtain precise baseline information the interrogator unit is switched to mode two and plugged into the master base station via an umbilical link (figure 1A). The master base station transmits a frequency, F_0, which the slave base station replies to at its own individual frequency, F_1. The range data thus obtained is transferred to the interrogator unit via an optical data link. The depth of water above the base stations is recorded at the time of transponder deployment and used to compute surface ranges from slant range data. The interrogator unit is then disconnected from the base station and switched to the survey mode, illustrated in figure 1B. The surface swimming diver follows a pre-determined path with the aid of positional information received, and the interrogator unit automatically records and stores at regular intervals transponder range and water depth measurements. These can also be visually displayed. With this information available to the interrogator, the x,y co-ordinates of the diver with respect to the transponders can be computed. If required both base stations can be left in position on the sea-bed and switched to a low-power, shut-down mode ready for reactivation by the interrogator unit.

Applying the sonar equation

The electrical power that must be supplied to produce a specified signal-to-noise ratio can be deduced from the one-way active sonar equation.

The following operational criteria were chosen:-

maximum range = 700 m
nominal operating frequency = 50 kHz

An operating frequency of 50 kHz was chosen due to the availability of transducer elements and from considerations of attenuation and noise. The three signal frequencies have to be contained within the 3 dB bandwidth of the transducer element. A separation of 3 kHz between each frequency results in F_0 being 50 kHz, F_1, 47 kHz and F_2, 53 kHz. The required source level, SL, expressed in dB is then defined:-

$$SL = SNR + TL + (NL - DI) \qquad (1)$$

Where: SNR= signal-to-noise ratio
TL = transmission loss
NL = noise level
DI = directivity index of receiver

Calculation of receiving directivity index.

A cylindrical transducer working at 50 kHz with an outside diameter of 25 mm and a length of 50 mm (see equipment design) will radiate uniformly in the horizontal plane and have a 35 degree, 3 dB, beamwidth in the vertical plane, determined by the finite length of the cylinder. Assuming that the length of the cylinder is much greater than one wavelength (λ) then the directivity index may be approximated by:-

$$DI = 10 \log (2 l/ \lambda) \qquad (2)$$

Where l is the cylinder length. Substituting values gives an approximate DI of 5.2 dB. As a single element will be used for transmission and reception the above directivity index will apply to both.

Noise level.

Very little data is available for shallow water conditions and coastal areas. In such locations the noise is likely to be impulsive and highly variable. Consider an estimated worst case noise spectrum level of:

$$-108 \text{ dB rel. } 1 \text{ Wm}^{-2}\text{Hz}^{-1}$$

The above noise spectrum level is taken from data for noise spectra in coastal locations with a wind speed of 40 knots [4].

The interrogators transducer transmits at F_0 and receives at F_1 and F_2. Let each channel have a bandwidth of 2.5 kHz.
Therefore the noise in a 2.5 kHz band becomes: NL = -74 dB rel. 1 Wm^{-2}

Transmission loss.
The transmission loss is a function of geometrical spreading (assumed to be spherical for worst case conditions but in practice probably less) and absorption. Spherical spreading results in the energy being spread over an area proportional to r^2, where r is the range. For a one-way trip from array to target the transmission loss is given by:

$$TL = 20 \log(r) + \alpha r \qquad (3)$$

Where α is the absorption coefficient in dBm^{-1}.
At a frequency of 50 kHz the absorption coefficient is approximately $0.01 dBm^{-1}$
Therefore TL = 64 dB

Signal-to-noise ratio.
During one survey operation the system can store a maximum of 4000 transponder range measurements. At maximum range the signal-to-noise ratio was chosen such that the system would tolerate one undetected pulse per survey, giving a probability of detection of 99.97 %. It was decided that 1×10^{-6} would be an acceptable probability of false alarm and from the receiver-operating-characteristics this predicts that a signal-to-noise ratio of 16 dB is necessary.

Substituting the above into the sonar equation gives a required source level of 0.77 dB rel. 1 Wm^{-2} at 1 m range. The source level, which is a measure of the intensity of radiated sound, may be defined for a directional array as:-

$$SL = 10 \log (1/4\pi) + 10 \log (W) + 10 \log (DI) \qquad (4)$$

Where W is the acoustic power. Therefore the transmitted acoustic power for a signal-to-noise ratio of 16 dB is approximately 4.5 watts.

Positional accuracy

The range of the diver to each transponder is found by measuring the time interval between transmission and reception of an acoustic pulse, from which range is calculated assuming a knowledge of the sound speed in water. An approximate local sound speed in water is calculated by temperature measurement to better than 1°C. As the water temperature is likely to change during the exercise it will be monitored at regular intervals and used to calculate the speed of sound according to an equation given in reference 4. Figure 2 shows contour lines of equal error for a range resolution of 0.3 m and a sound speed uncertainty as a result of temperature measurement with a 1°C maximum error [2]. Although this plot does give an indication of positional errors in practice the front end amplifier will be driven into saturation resulting in a much reduced range resolution error (see equipment design).

EQUIPMENT DESIGN

The detection circuitry has the task of discriminating between sonar pulses and ambient noise. The ambient noise level is likely to have a steady state content and an impulsive content, which will be considered individually. In order to avoid multi-path signals only the first threshold crossing in a given ranging cycle is considered. At maximum range the signal-to-noise voltage ratio has been estimated at approximately 16 dB, this being significantly improved at closer ranges. It can be seen from figure 3 that the signal-to-noise ratio (SNR) for a given threshold level determines the range resolution as a consequence of the timing error. Thus, a high signal-to-noise ratio results in an improved range resolution.

For a fixed threshold level a low ambient steady state noise level will allow a high amplifier gain to be used thereby improving the range resolution without compromising the systems discrimination. As the steady state noise level is a variable parameter, then the receive amplifier is fitted with an automatic gain control (AGC) which can be varied accordingly. A measure of the ambient noise can be obtained by its progressive amplification up to a pre-set noise threshold level (figure 4). The signal threshold level can now be set relative to the noise threshold level to accommodate the worst case signal-to-noise ratio. It will be assumed that both the transponders and the interrogator unit will detect the same level of ambient steady state noise and therefore apply the same amplifier gain.

The ambient noise is likely to have a significant impulsive content during shallow water exercises. Thus by choosing a long pulse length detection period the much shorter impulsive noise signals will be rejected. This will have the effect of reducing further the probability of false alarm.

Amplifier gain

The received signal in the water at the interrogator and the transponder has an intensity, I, given by:

$$I = SL - TL \qquad (5)$$

Which gives: $I = -63.2$ dB rel. 1 $Wm^{-2} = 0.48 \times 10^{-6}\ Wm^{-2}$

$$\text{Also, } I = P^2 \rho^{-1} c^{-1} \qquad (6)$$

Where: P = Acoustic pressure (Pa)
ρ = Density of water (10^3 kgm^{-2})
c = Nominal velocity of sound (1500 ms^{-1})
Therefore the pressure, P, = 0.848 Pa

A typical value for the receive sensitivity, M, of a capped tube = 150 μVPa^{-1}. Therefore the r.m.s. received open-circuit voltage, $V_{o/c\,(rms)}$, for a pressure of 0.484 Pa becomes 127 μV, i.e., the peak value, $V_{o/c\,(peak)}$, = 180 μV. Hence for a 5 V supply rail a receive amplifier gain of approximately 89 dB is required.

Electronic Design

Figure 5 shows, in block form, the complete interrogator unit. Transponder range information is obtained by measuring the time interval between transmission and reception of an acoustic pulse, found by counting 50 kHz cycles using a 16-bit software counter. The transmitted signal is fed into a vmos f.e.t. and then transformed using a step-up voltage transformer, this being matched to the transducer element. The transmitted 50 kHz pulse is received by both transponders who in turn reply on a frequency individual to that transponder. If the interrogator has not received both transponder reply signals before the counter overflows then the operation is aborted. This cycle is repeated every 5 seconds. The received signal is fed into an automatic gain control (AGC) amplifier before being heterodyned up to 455 kHz. The two unwanted frequency components, i.e. F_0 and F_1 or F_2 are filtered out using a narrow band 455 kHz ceramic filter. After rectification the signal is put through a threshold detector which in turn triggers the micro-computer. A decision can then be made as to which of the two transponders is transmitting, i.e. frequency F_1 or F_2. In order to discriminate against impulsive noise that may have tripped the threshold detector, the pulse will be sampled several times before a decision is made as to whether the signal is a valid return or noise. If valid, the micro-computer stores the appropriate count number. This sequence is repeated for each of the transponders. All accumulated data is stored in a 32k byte cmos ram chip, six bytes being allocated to each system operation.

Upon receipt and storage of both transponder reply signals the counter is reset and used to measure the flight time of the depth sounder pulse. The maximum working depth for the echo sounder is not expected to be greater than 30 m. The operating frequency of the depth sounder can be increased resulting in an improved range resolution. An operating frequency of 455 kHz enables the receiver circuit to use 455 kHz ceramic filters without the need for heterodyning. A 15 degree, 3 dB, beamwidth was used to give adequate ground coverage. Figure 6 shows, in block diagram form, the complete depth sounder unit. The depth sounder is packaged with the interrogator unit and is controlled by the interrogators micro-computer but for clarity has been shown in isolation.

Figure 7 shows, in block diagram form, the base station unit. Both transponders receive pulsed signals at 50 kHz and reply on one of two possible frequency channels i.e. 47 kHz or 53kHz. The master base station is also able to transmit at 50 kHz (F_0) and receive at 47 kHz (F_1) for communication with the slave base station in order to obtain the baseline range (see figure 1).

Transducer Design

A thin walled tube was selected for both the transmitting and the receiving elements. The two main modes of resonance in this case are the radial and the length mode. The equation for these modes can be solved for different length/radius ratios. Using this equation and avoiding the critical region where the length resonance approaches the radial resonance, tube dimensions for an operating frequency of 50 kHz were selected. This resulted in a tube of dimensions 25 mm in diameter and 50 mm in length. The tubes were capped and encapsulated in epoxy resin which gave the transducer a final resonant frequency of 49 kHz and a bandwidth of 8 kHz.

RESULTS OF FIELD TRIALS

A prototype of the equipment described was used for a preliminary survey of an area of a flooded quarry at Dosthill, Tamworth. The survey was carried out by towing the interrogator unit behind an inflatable boat. The base stations were deployed on floating platforms securely anchored at fixed positions. During the survey the boat was rowed along the track shown in figure 8c and data collected at 360 points. It can be observed in figure 8c that there was one sharp deviation from an otherwise smooth track, marked by the letter X, this was attributed to a false alarm.

The data collected by the interrogator unit was later downloaded onto a Honeywell main-frame computer and analysed to produce a three dimensional and depth contour plot of the area. These are presented in figures 8a and 8b. Although this quarry has not been previously mapped in detail the survey would seem to have produced a plot which is consistent with what is known about the area.

CONCLUSION

This paper describes a portable system for personal diver navigation and sea-bed surveying in prescribed areas of water. The hand-held, mobile, interrogator unit collects, stores and displays depth readings and precise positional information, obtained from two fixed transponder base stations, for later computation. Data is presented from a trial with a prototype of the equipment at a flooded quarry. Processing of the data has allowed evaluation of the equipments performance in underwater surveying and confirmation of its design. This divers aid has important applications in underwater archaeology, marine biology and geology, as well as uses in guiding and searching operations.

ACKNOWLEDGEMENT

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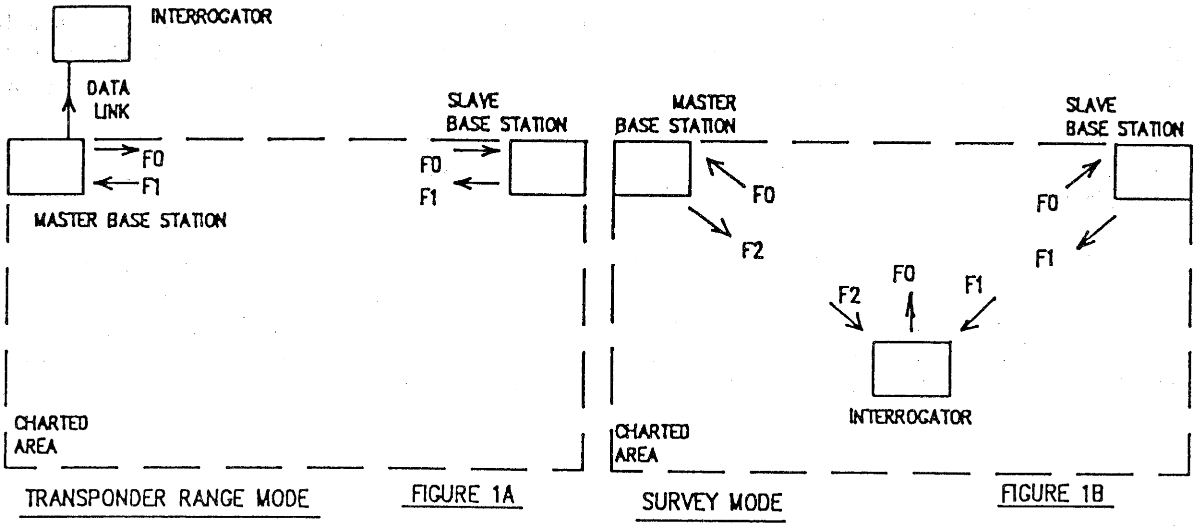


FIGURE 1A FIGURE 1B

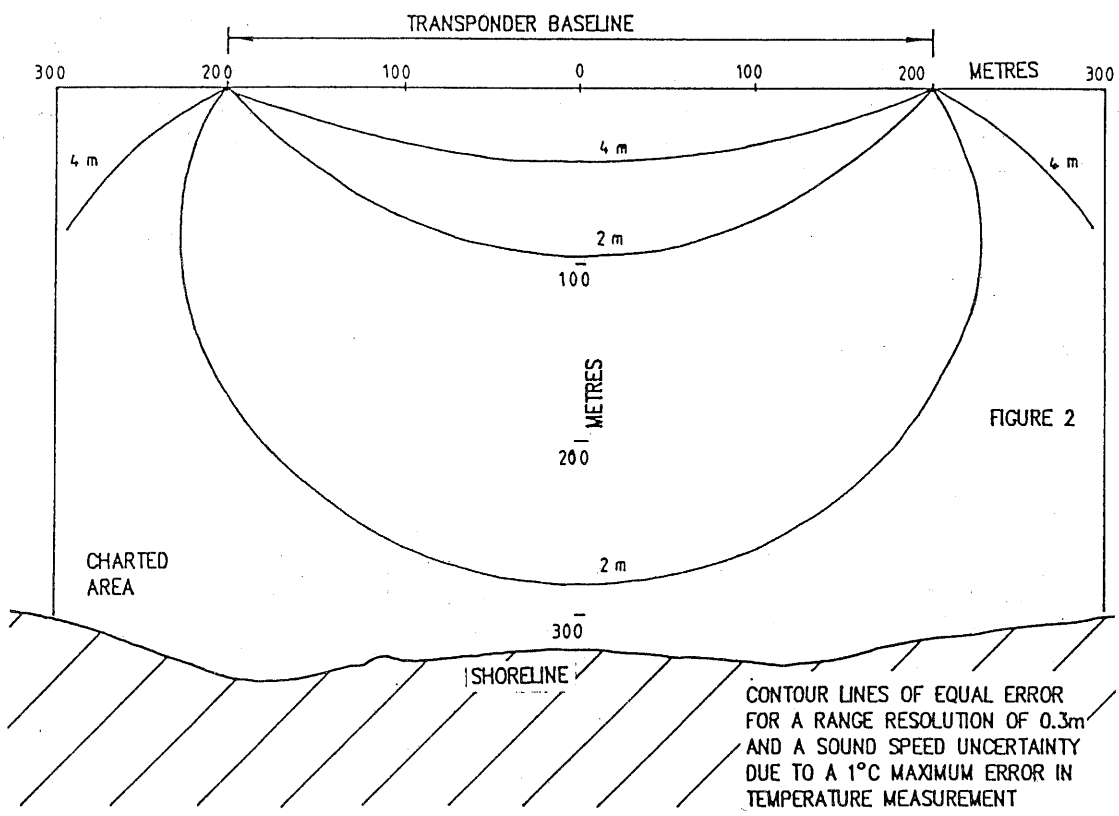


FIGURE 2

CONTOUR LINES OF EQUAL ERROR FOR A RANGE RESOLUTION OF 0.3m AND A SOUND SPEED UNCERTAINTY DUE TO A 1°C MAXIMUM ERROR IN TEMPERATURE MEASUREMENT

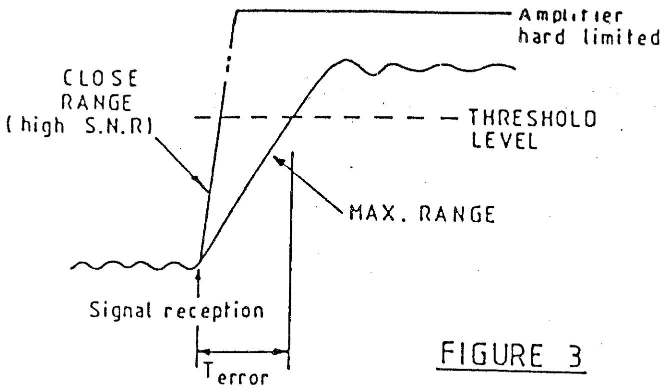


FIGURE 3

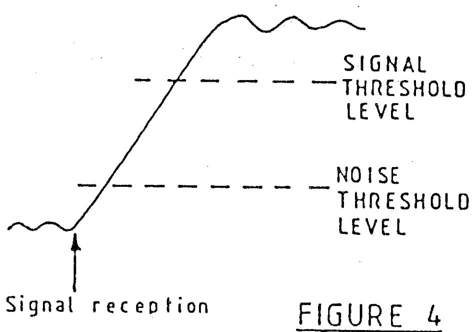


FIGURE 4

BLOCK DIAGRAM OF INTERROGATOR UNIT

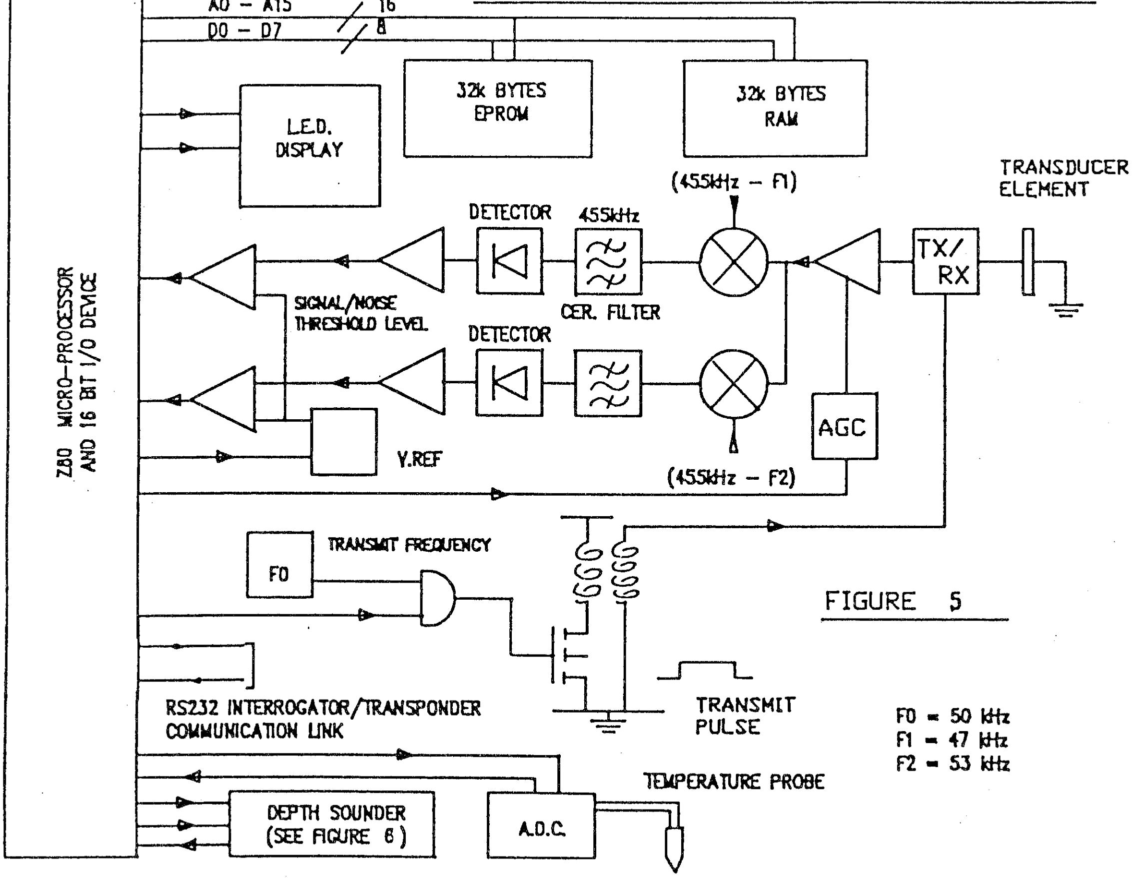
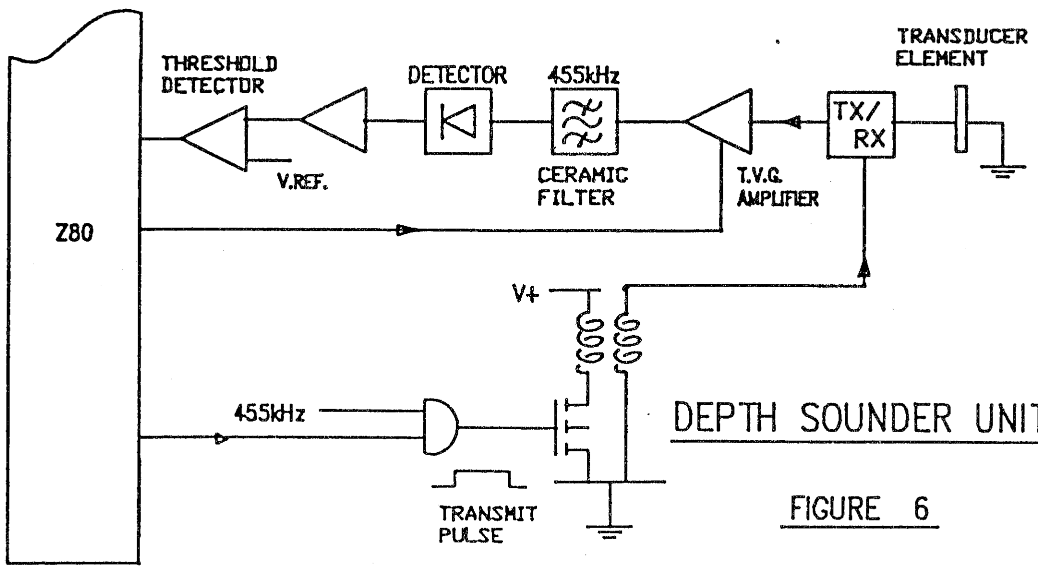


FIGURE 5



DEPTH SOUNDER UNIT

FIGURE 6

BLOCK DIAGRAM OF TRANSPONDER UNIT

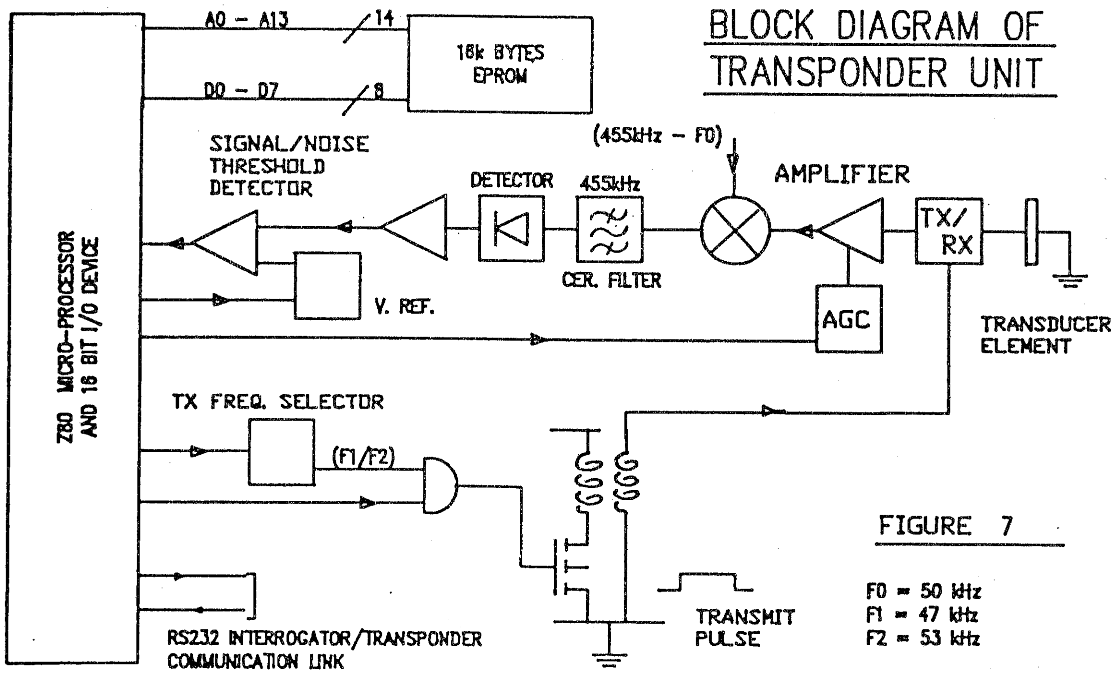


FIGURE 7

F0 = 50 kHz
F1 = 47 kHz
F2 = 53 kHz

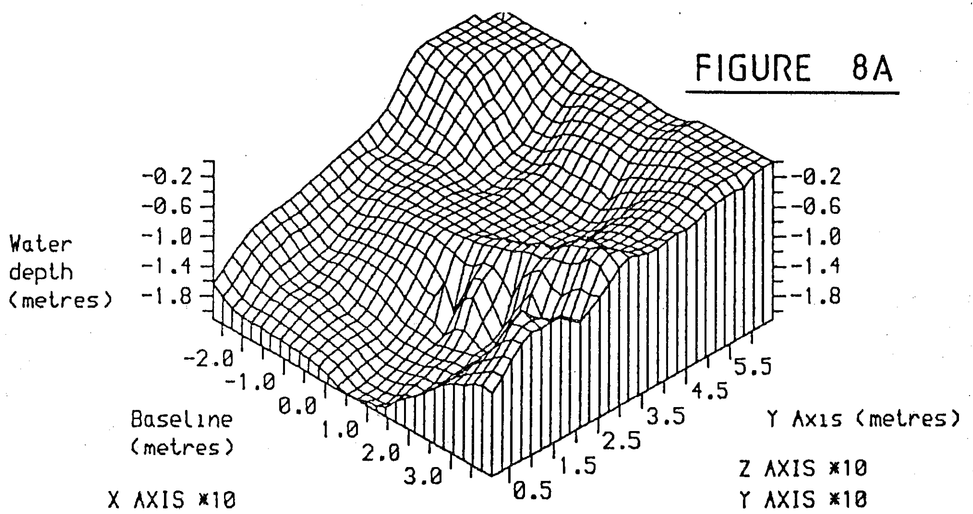


FIGURE 8A

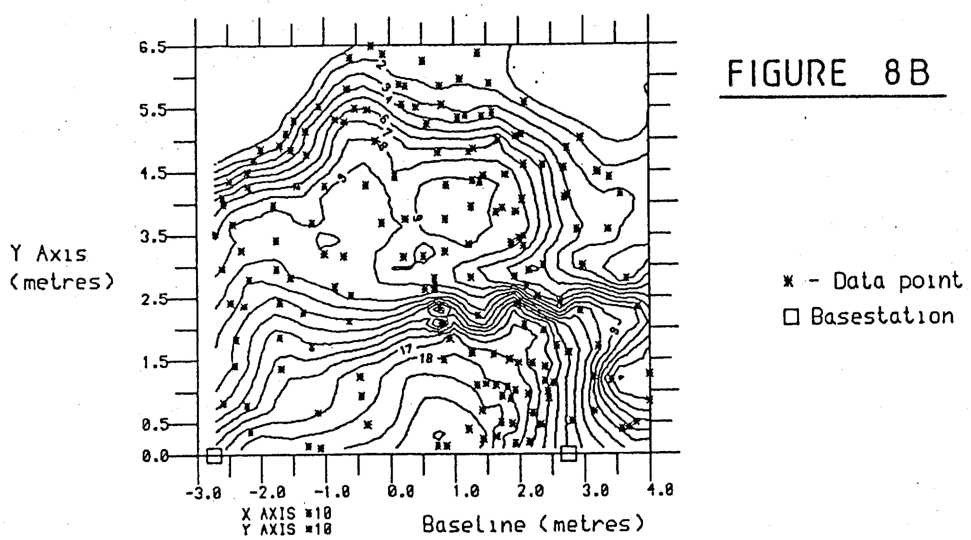


FIGURE 8B

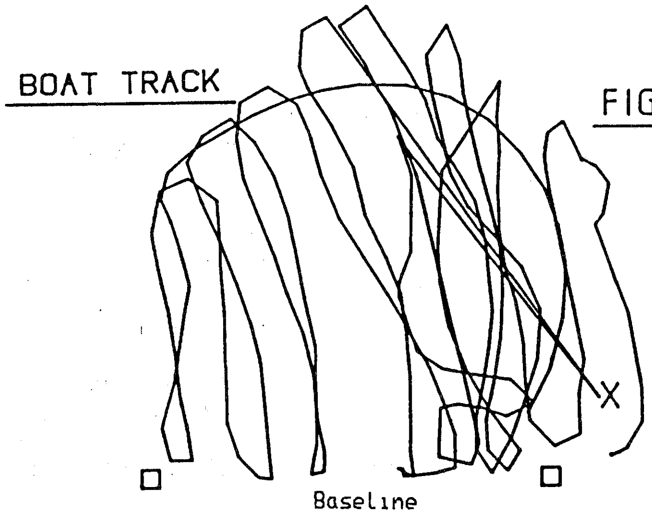


FIGURE 8C