Bottom Finding with Pinger and Transponder

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ABSTRACT

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The report deals with two approaches to determining the height of an instrument package above the sea floor by acoustic means. Firstly, the time honoured method of placing a free-running pinger on the apparatus and measuring the travel time difference between the direct and bottom reflected signals is reviewed and the problems of record scaling and "cross-overs" are discussed with the objective of producing a tutorial document for field users. Secondly, a new technique of height measurement using an acoustic transponder is outlined and its features are compared with those of the pinger method. An example of an actual graphic record obtained while using the transponder is presented and analyzed.

RÉSUMÉ

Le présent rapport porte sur deux méthodes visant à déterminer acoustiquement la hauteur d'un instrument par rapport au fond de l'océan. La première méthode qui est consacrée par l'usage et qui consiste à placer un générateur de signaux à oscillation libre sur l'instrument et à mesurer la différence de temps entre le déplacement des signaux directs et le déplacement des signaux réfléchis par le fond de l'océan est analysée et les problèmes de mise à l'échelle et de "recouvrement" des enregistrements sont traités de façon à produire un document didactique pour les utilisateurs sur le terrain. La seconde méthode qui est une nouvelle technique de mesure de la hauteur au moyen d'un transpondeur est présentée et ses caractéristiques sont comparées à celles de la première méthode. De plus, un échantillon de données graphiques réelles recueillies par le transpondeur en question est présenté et analysé.

PREFACE

The following description of the operation of an echo sounder is from "A History of Marine Navigation" by Per Collinder (Batsford, London, 1954):

"The echo-sounder is a fine product of man's inventiveness. A ship on her way across the ocean sends from near her keel a sound (sonic signal) down through the water. Its waves dart downwards at a speed fifty times that of a storm wind. After three-hundredths of a second they are past the 50-metre limit, beyond which the human eye cannot see; after a bare quarter of a second they are hurtling past the 400-metre line into the blue-black impenetrable ocean darkness, on and on through the black water where the pressure is from a hundred to a thousand times greater than up above, down past fish and creatures whose size and appearance is unknown to us, till after a few seconds they strike the age-old mud of the ocean floor. Most of the waves' energy is lost in the deep mud, but part, a tiny part of it, is reflected back, hastens upwards as swift as thought through mile after mile of dark water, up to where daylight filters down through the green surface water, and finally, some seconds after being emitted, after a dash of several miles, it reaches back to the ship, avoiding the whirls of the wash and the foaming bow-wave and strikes the bottom as a faint inaudible sound-wave, sensitive apparatus picks it up, multiplies it a hundredfold, registers it on a moving band of paper and so delineates before the captain's eyes the waving line of the billowing landscape of the ocean floor lying beneath the ship as she passes on her way."

1.0 INTRODUCTION

There are many oceanographic experiments which involve an instrument or sampler being lowered close to or onto the sea floor. These require an indicator of instrument height above the bottom. A number of possibilities exist for accomplishing this measurement. One of the most obvious is to measure the amount of wire payed out. Providing the actual water depth is known and due allowance is made for wire angle, an approximation to instrument height above bottom can be made. Unfortunately, the method is prone to error because sub-surface current shears can produce unanticipated wire catenaries.

Another method that goes back to the early days of oceanography (McConnell, 1982) is to detect the change in load which occurs when a weight, composed of the instrument or a subsidiary weight secured beneath it, touches the bottom. This method limits the operator to sensing a single height off the sea floor and the change in load on the wire becomes difficult to detect in deep water. To overcome these limitations, Isaacs and Maxwell (1952) developed a signalling device based on an exploding glass ball to indicate when a corer reached a pre-determined height above the bottom. Pressure sensors are routinely used to sense the depth of the instrument below the surface but don't readily sense height above the sea floor.

A more direct measurement of height above bottom can be made with an acoustic altimeter or self-contained echo sounder attached to the instrument. This works well if the apparatus is being lowered on an electromechanical cable through which the altitude can be telemetered to the observer at the surface. If such a "hard-wire" link is not available, the information must be telemetered by alternate means. While it would be possible to digitize the height then telemeter it acoustically, that approach is unnecessarily complicated. Instead, when there is an acoustic source on the instrument, its height above bottom can be measured directly by correct interpretation of the direct and bottom reflected acoustic signals received aboard the research vessel.

The pinger method of height measurement has been used by at least a generation of oceanographers. In spite of this, the correct interpretation of the record it produces doesn't seem to be well understood, and many are reluctant to take responsibility for using the method to lower an intrument because of fear of running equipment into the bottom. Therefore, this report will extensively review the pinger method and show how to correctly interpret the graphic record it produces. Then a technique using an acoustic transponder will be described. It will be shown that this method eliminates the problems oceanographers encounter in interpreting the pinger records.

2.0 HEIGHT MEASUREMENT WITH A PINGER

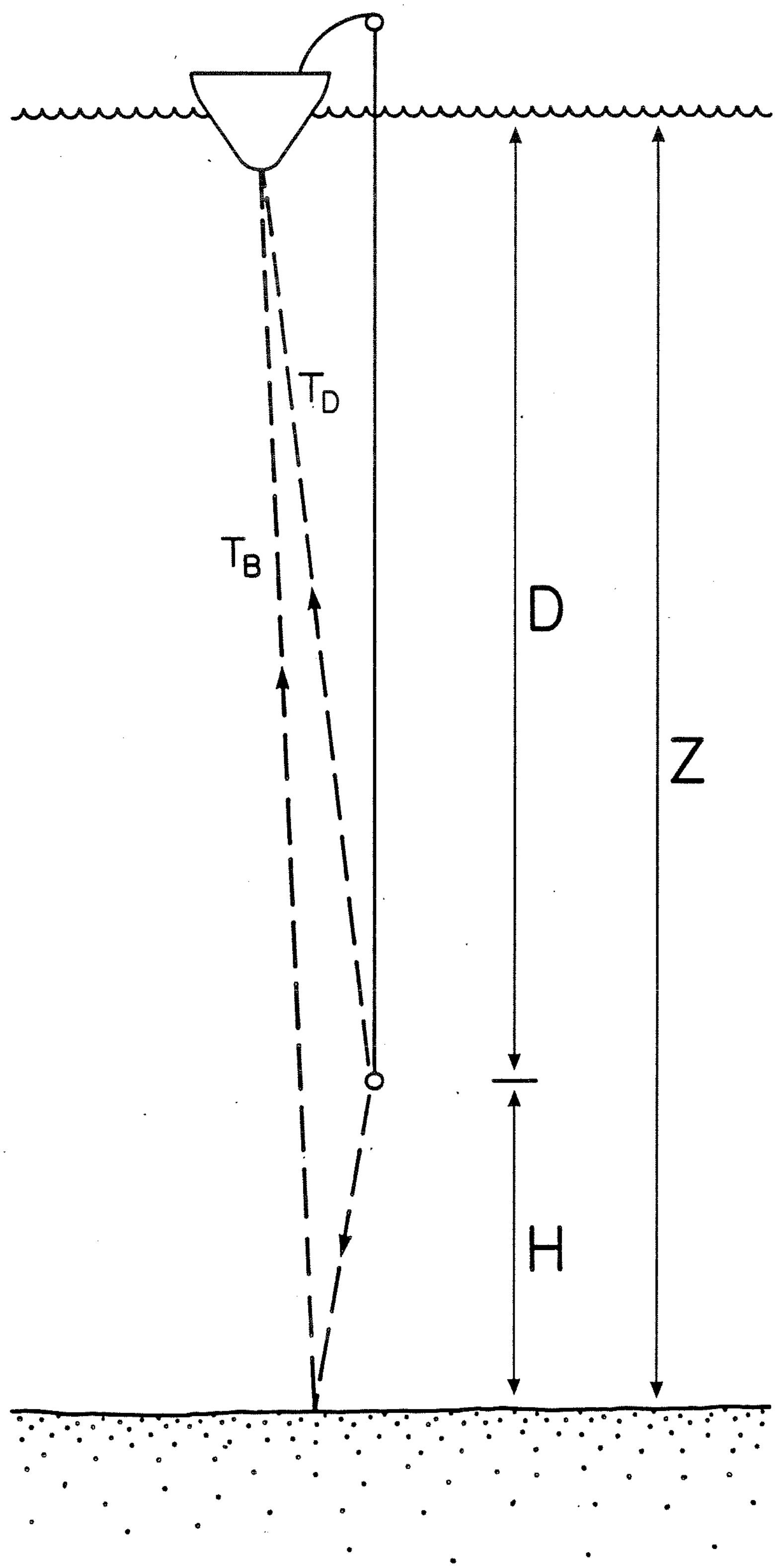
2.1 The Basic Principle

Edgerton and Cousteau (1959) were among the first to describe the concept of using a pinger to measure the height of an instrument package above the sea floor. They placed a 12 kHz acoustic source on an underwater camera then measured the difference in arrival times at the ship between the direct (T_D) and bottom reflected signals (T_B). Hersey (1960) used the same technique for bottom coring. Examination of the geometry of these paths as shown in Figure 1 reveals that this travel time difference is directly related to instrument height above bottom (H) and sound velocity (c) as follows:

$$H = \frac{c\,\Delta T}{2} \qquad (1)$$

where $\Delta T = (T_B - T_D)$.

This relationship is valid only when the source is directly beneath the ship but remains a satisfactory approximation for small deviations from vertical incidence, an assumption that is adopted throughout the following discussions. If there is reason to believe that there is a substantial horizontal displacement between ship and instrument, the work of Weston (1960) and Breslau, *et al.* (1962) should be consulted. They both consider the computation of this horizontal displacement in addition to the vertical one dealt with below.



1. Geometry of source-ship and source-bottom-ship paths for a pinger mounted on an instrument package suspended vertically beneath the ship above a flat, horizontal sea floor.

As Edgerton and Cousteau pointed out, the acoustic source should emit a stronger signal downward compared to upward so as to compensate for the strength reduction the reflected signal suffers at the sea floor.

Before proceeding further, a brief word concerning nomenclature and symbols. An attempt has been made to be consistent in both of these throughout the report. The text contains brief definitions of terms and symbols where it is deemed appropriate. More complete definitions may be found in Appendix A.

Further study of Figure 1 reveals that the depth of the acoustic source beneath the surface (D) is:

$$D = c\,T_D \tag{2}$$

Now the same shipboard system can be used in its echo sounder mode to measure the round trip travel time T_s from ship to bottom and back to the ship in order to derive the water depth (Z):

$$Z = c\,\frac{T_s}{2} \tag{3}$$

Providing the bottom is flat and the acoustic paths are nearly vertical, a useful check on the calculations is that:

$$Z = H + D \tag{4}$$

If the round trip travel time of the signal from the ship to the bottom and back to the ship exceeds the time required for the recorder stylus to transit the paper from left to right, T_G, then a more complicated situation prevails. In this case, each of the returning signals marks the paper at some point which is a sum of the elapsed time as measured from Recorder Zero at the left hand edge to the i^{th} trace, ET_i, and one or more complete recorder sweep periods, T_G. If the stylus makes N_i complete sweeps across the paper before making a mark on it corresponding to trace i after a total elapsed time T_i then

$$N_i = Integer[\,\frac{T_i}{T_G}\,] \tag{5}$$

In the case of straight forward echo sounding, it is a simple matter to slow the recorder sweep rate until this overlapping no longer occurs so that the depth Z can be determined unambiguously from equation 3. It is then possible to compute N_s at the higher sweep rate from:

$$N_s = Integer[\frac{2Z}{c\,T_G}] \tag{6}$$

and T_s from:

$$T_s = N_S\,T_G + ET_S \tag{7}$$

In a similar manner, the other round trip travel times become:

$$T_D = N_D\,T_G + ET_D \tag{8}$$

$$T_B = N_B\,T_G + ET_B \tag{9}$$

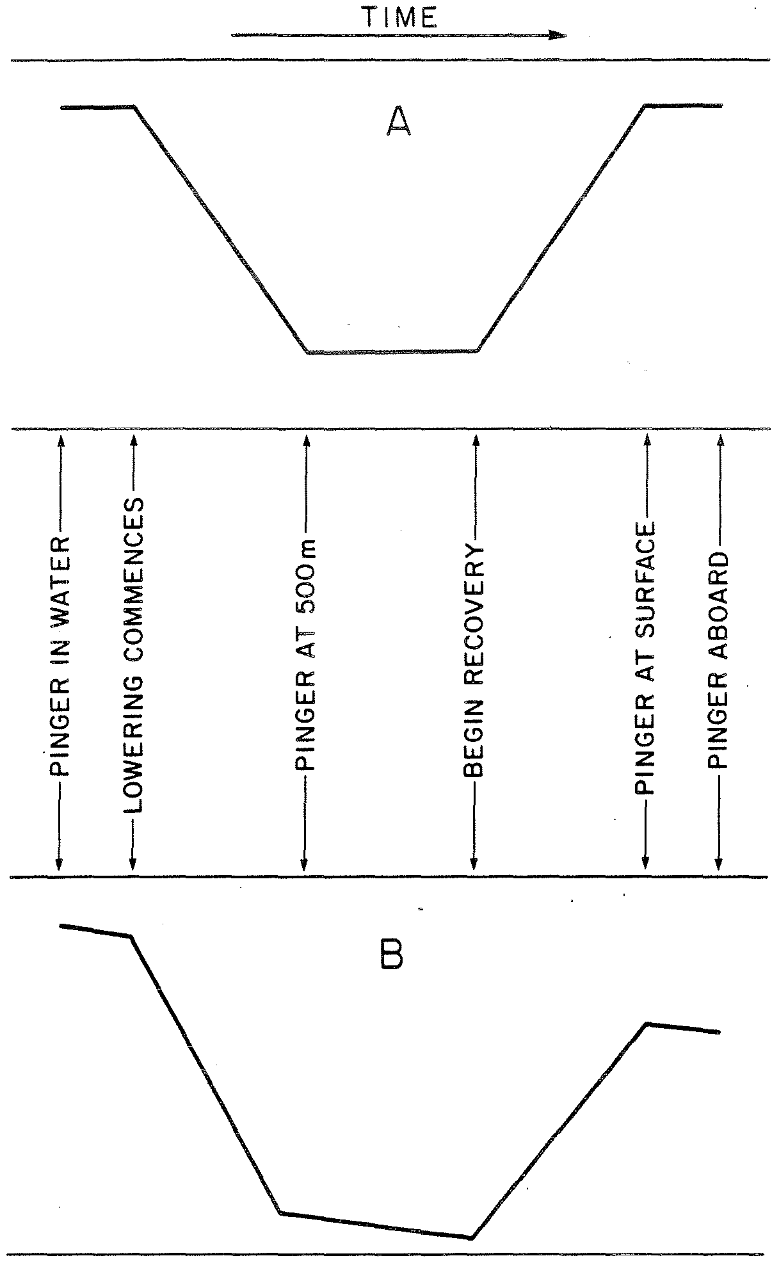
where (T_D, N_D), (T_B, N_B) and (T_s, N_s) are special cases of (T_i, N_i). An example of how to interpret records generated by this overlapping process will be addressed in Section 2.4.

2.2 Other Factors to Consider

2.2.1 Pinger Offset and Drift

When the graphic recorder and pinger are switched on, their internal clocks or time bases start timing from arbitrary and unrelated reference points. Thus, while both may be repeating an action (ping or sweep) once per second when the pinger is placed adjacent to the shipboard transducer, the actual trace of the direct pinger-ship signal may appear any where across the record. The two reference points can be synchronized by "phasing" the recorder, that is, by slowing its sweep rate slightly by depressing an appropriate switch on the recorder so that the pinger direct signal slews across the record to the left hand side near Recorder Zero. Any residual offset between the pinger trace and Recorder Zero then becomes the offset time difference T_O.

Time base drift between the pinger and graphic recorder is another problem which the operator often encounters. Modern pingers and graphic recorders normally have very



2. Simulated lowering and recovery of a pinger: a) in the absence of; and, b) in the presence of relative pinger/graphic recorder time base drift.

accurate crystal controlled time bases. Nevertheless, some drift still occurs but, once its effect is understood, it can be ignored. Figure 2a is a simulated graphic record for a pinger being put over the side and held there for a period, lowered to some depth and again held, recovered to the surface and held, then finally lifted on board. To simplify this discussion, all surface and bottom reflected signals have been deleted from the record. In the case of Figure 2a it is assumed that there is no relative time base drift between the recorder and pinger. Figure 2b illustrates exactly the same deployment cycle but in this case there is some relative time base drift, the magnitude of which is comparable to that normally encountered in practice. This drift may make it awkward to read the record at times.

If the pinger drift rate is PD, the graphic recorder was phased to an offset of T_O at time t_0 and a measurement of instrument depth, D, and height above bottom, H, are required at time t_1 then

$$T_D = (N_D \ T_G + ET_D) - (T_O + PD \ [t_1 - t_0]) \qquad (10)$$

$$T_B = (N_B \ T_G + ET_B) - (T_O + PD \ [t_1 - t_0]) \qquad (11)$$

Obviously pinger drift has no effect on the time difference (T_B - T_D), thus, it only affects determination of instrument depth. In other words, measurement of instrument height above the bottom is independent of pinger drift and "phasing" offset.

2.2.2 Sound Velocity

Graphic recorders enable one to measure travel times. A knowledge of sound velocity is then required to convert this to equivalent distances. Unfortunately, sound velocity is not a constant but varies with salinity, temperature and pressure so that, on the shelf an appropriate value for echo sounding might be 1470 m/sec whereas on the abyssal plain it might be 1510 m/sec. Errors in distance determination are directly proportional to errors in velocity and inversely proportional to the effort required to obtain the correct value.

At one extreme, the most accurate transit time to distance conversion is done through a process of integration using a complete conductivity-temperature-pressure profile which must be measured at the site and converted to sound velocity versus depth. At the other extreme, one can assume a sound velocity of 800 fathoms/sec which makes the scale marks on typical oceanographic recorders (20 marks per sweep) 20 fathoms apart on a one second sweep to simplify interpolation. If a conversion factor of 2 metres per fathom is assumed, transit times on the recorder can be easily converted to approximate distances in metres without the need of a computer or calculator.

2.2.3 Non-Vertical Incidence

The algorithms for the determination of H and D as described in Section 2.1 are only correct if the instrument is directly underneath the ship. If there is any significant wire angle, Θ, with respect to the vertical such as, if the acoustic source where in a towed body, then error begins to accumulate. For example, the instrument depth D becomes

$$D = c\ T_D \cos\Theta \tag{12}$$

and its height above bottom a more complicated function of the two dimensional geometry. Further complicating the problem is the fact that the wire angle at the ship rarely, if ever, correctly defines the true angular relationship between the source and the ship. This matter is dealt with more completely by Breslau *et al.* (1962) and Weston (1960).

2.2.4 Sloping Sea Floor

Another factor which introduces error into the determination of height off bottom, H, with a pinger, is that of a sloping sea floor. If the bottom is sloping and a situation of non-vertical incidence prevails as described in Section 2.2.3 then the geometrical solution for H becomes even more complicated as it will now contain a factor associated with this slope.

To further complicate matters, the actual acoustic signal paths are not likely to correspond to the idealized situation depicted in Figure 1. This figure and many other diagrams of acoustic rays emanating from a source all have a common problem. They imply that the ray is an infinitely narrow, coherent beam which travels in a straight line. Actually, the pinger is an omni-directional source which emits energy nearly uniformally in a spherical fashion. Also, although the ship's echo sounding transducer may have a beam width of 15° x 30°, in practice it receives energy over a much wider cone. Consequently, in areas of sloping sea floor or mountainous terrain (e.g. the Mid-Atlantic Ridge), there may be multiple "bottom reflected" traces, the first arrival not necessarily being that from a point immediately under the ship.

2.2.5 Acoustic Source Pulse Length

Modern pingers and echo sounders usually emit their signals in the form of a tone burst contained within a rectangular envelope. The width of this envelope can, if necesssary, be adjusted prior to deployment. If the pulse is long, the shipboard receiver filter bandwidth can be narrowed to reduce ambient noise. The shape of a long tone burst is little affected by its passage through the water column so that it is faithfully reproduced on the graphic record. Furthermore, a long pulse makes a more recognizable mark on the graphic record. All of these factors enhance the operator's ability to discerne the acoustic signal on the recorder display.

Unfortunately, a long tone burst has a disadvantage for bottom finding. As the pinger nears the bottom, the tail of the direct signal begins to overlap the front end of the bottom reflected pulse so it becomes difficult to measure the difference in arrival time between the two. The solution is to shorter the tone burst at the expense of graphic record quality. This deterioration in signal quality occurs because receiver bandwidth must be increased which increases the ambient noise level and the envelope of the narrow pulse is substantially altered during its passage through the water column.

2.3 Interpreting a Simple Record

Ever since Edgerton and Cousteau first described their height measuring method, a small group of devotees have ardently embraced the procedure. Unfortunately, there is a much larger group of oceanographic scientists and technicians who approach the responsibility of using a pinger to lower an instrument near or onto the sea floor with considerable trepidation. There seem to be two reasons for this. Firstly, they are uncertain about how to adjust the equipment to display the necessary traces and secondly, they do not know how to scale the graphic recorder trace to derive actual height above bottom. The problem of acoustic receiver and graphic recorder adjustment is a difficult one to address in the format of a report. It is much more an art than a science and is best learned at sea under the tutelage of an experienced operator. The user must try to overcome environmental factors such as attenuation of the acoustic signal over the water path, ambient noise and variations in bottom reflectivity. Under his control are a narrow range of interacting adjustments of receiver and recorder gains, and recorder contrast and thresholds with which he can attempt to optimize displayed signal quality.

However, the novice operator can be better prepared to learn how to deal with these matters if he clearly understands how to identify the source of the various signals which will appear on the record, how to cope with "phasing", pinger drift and "cross-overs" and how to convert the information contained within the displayed traces to actual instrument height above bottom. To show how the principles outlined in Section 2.1 might be employed to interpret and scale a simple graphic record, a hypothetical example will be analyzed.

The following assumptions have been made in constructing the simulated record of Figure 3:

(a) the sea is calm hence there is no heave or vertical ship movement;

(b) the bottom is flat and a good acoustic reflector;

(c) there is no relative pinger/recorder time base drift;

(e) recorder sweep rate is 1 sweep per 4 sec;

(f) water depth is 2550 m;

(g) instrument package lowered to within 150 m of the sea floor.

Looking at Figure 3 in more detail, between time 0 and 3 minutes the ship's echo sounder was turned on. Trace A represents the transmission from the ship and Trace B its reflection from the sea floor which arrives back at the ship 3.4 seconds later, that is, $T_S = 3.4$ sec. At a sound speed through water of c = 1500 m/sec the water depth is

$$Z = \frac{c}{2}\ T_S = \frac{1500}{2}\ 3.4 = 2550\ m$$

At time 5 minutes, the pinger has been placed in the water. Trace C is the direct signal from the pinger to the ship and Trace D its reflection from the sea floor as received back aboard the ship and, at this time, they are analogous to traces A and B respectively. Since the instant of transmission of the pinger signal is unlikely to coincide with the start of the stylus sweep across the recorder paper or Recorder Zero, these traces might initially appear anywhere across the record. For operating convenience, the recorder stylus position is usually adjusted or "Phased" relative to the pinger transmission until Trace C appears near the beginning of the stylus sweep. In Figure 3, as is usually the case, Trace C is not adjusted so that it exactly coincides with Trace A but has an offset (T_O) of 0.1 sec with respect to Recorder Zero. It was shown in Section 2.1 that the differences in travel time between the direct (Trace C) and the bottom reflected (Trace D) travel times, ΔT, is equivalent to the height of the pinger off the bottom. Scaling off Figure 3 it is found that:

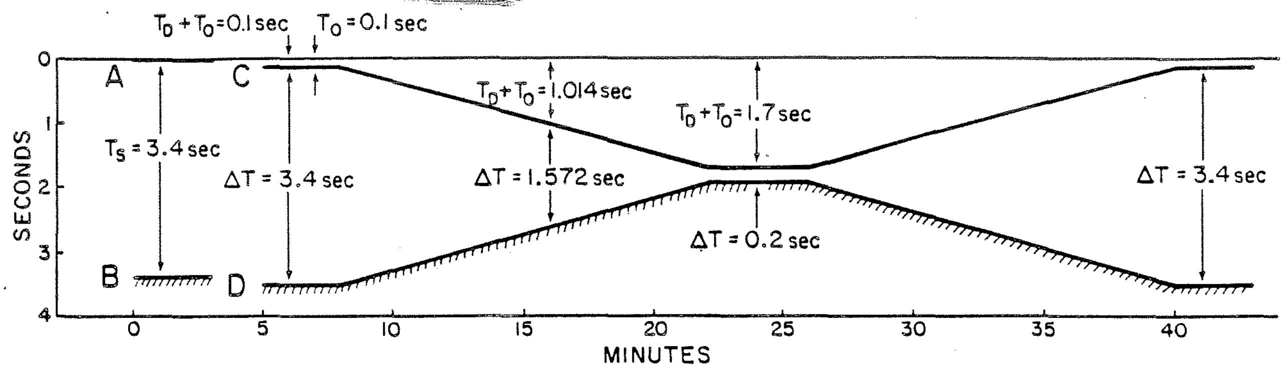
(1) the height of the pinger off the bottom from equation (1) is

$$H = \frac{c}{2}\ \Delta T = \frac{1500\ \ 3.4}{2} = 2550\ m$$

(2) the depth of the pinger below the surface is

$$T_D = (T_D + T_O) - T_O = 0.1 - 0.1 = 0\ sec$$

$$D = c\ T_D = 1500\ \ 0 = 0$$



3. Simulated graphic record of a bottom finding pinger with 4 second repetition rate being lowered to 2400 m. in 2550 m water depth then recovered.

To check the calculations

$$Z = H + D = 2550 + 0 = 2550\ m$$

It should be noted that T_D is derived by scaling off $(T_D + T_O)$ from the Recorder Zero and then correcting it for the offset T_O. This is easier than attempting to scale off T_D directly from the graphic record.

At time 8 minutes, the pinger begins to be lowered toward the sea floor. This is shown by Trace C angling downwards corresponding to the pinger-to-ship travel time, T_D, increasing. At the same time, the bottom reflected pinger signal Trace D angles upward because, although the bottom-ship portion of the path remains constant, the pinger-bottom travel time and therefore T_B steadily decreases as the instrument package approaches the sea floor. The difference in travel time ΔT between the two traces still represents the instrument height H above the bottom as defined by equation (1). For example at time 16 minutes, the difference between the direct and bottom reflected travel times, ΔT, is 1.572 sec. as scaled off the record in Figure 3. This corresponds to an instrument height above bottom of

$$H = \frac{c}{2}\ \Delta T = \frac{1500}{2}\ 1.572 = 1179\ m$$

and a depth below the surface of

$$T_D = (T_D + T_O) - T_O = 1.014 - 0.1 = 0.914\ sec$$

$$D = c\ T_D = 1500\ \ 0.914 = 1371\ m$$

To check the calculations:

$$Z = H + D = 1179 + 1371 = 2550\ m$$

At time 22 minutes, the package reaches a height above the bottom of

$$H = \frac{c}{2}\ \Delta T = \frac{1500}{2}\ 0.2 = 150\ m$$

and a depth below the surface of:

$$T_D = (T_D + T_O) - T_O = 1.7 - 0.1 = 1.6\ sec$$

$$D = c\ T_D = 1500\ \ 1.6 = 2400\ m$$

To check the calculation:

$$Z = H + D = 1500 + 2400 = 2550\ m$$

Figure 4 is a diagramatic representation of the acoustic paths in each of these three cases.

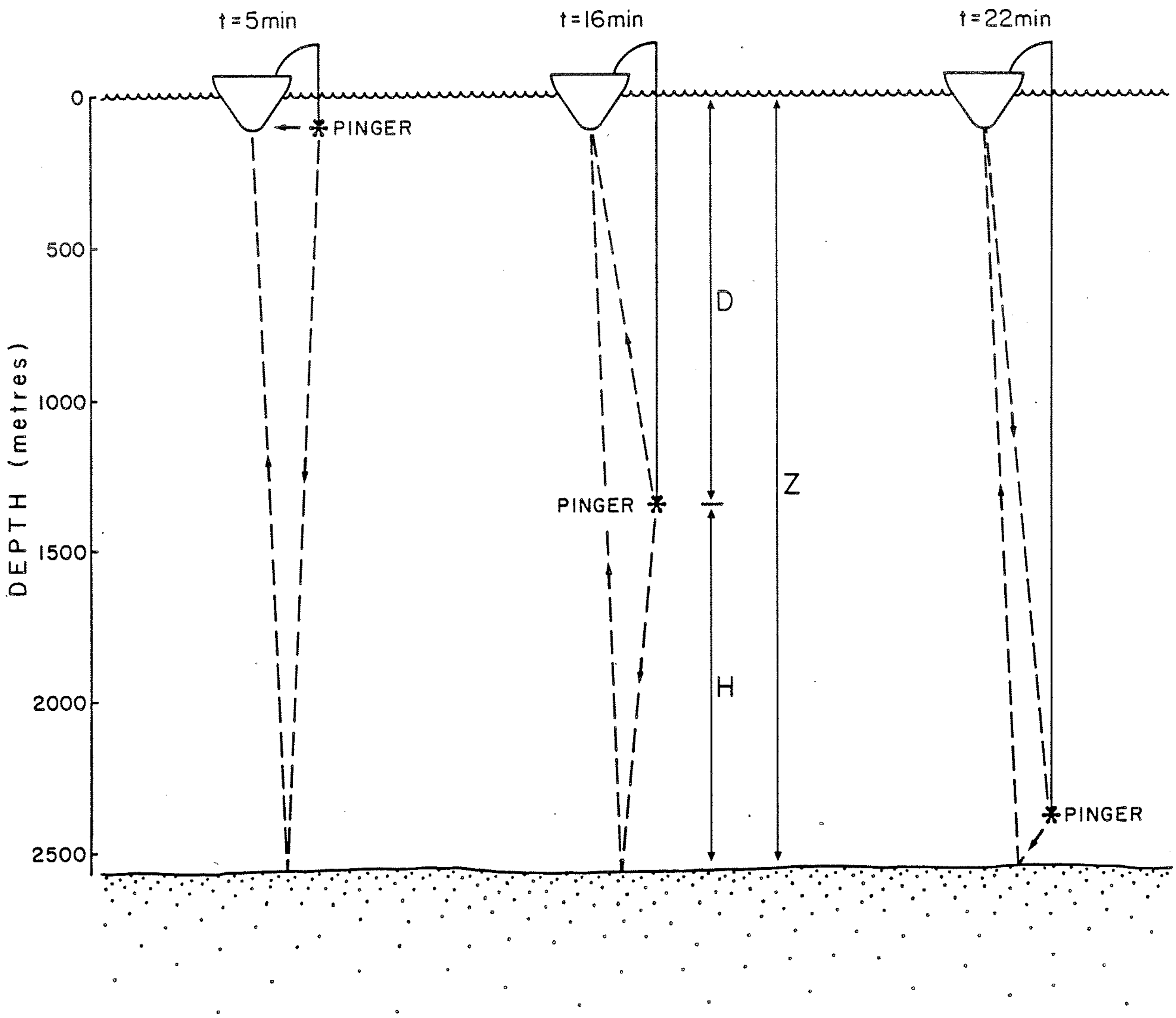
It is held at this depth until time 26 minutes, whereupon recovery commences. As the pinger is hauled up, the direct pinger-ship distance decrease so Trace C angles upward toward the Recorder Zero while the pinger-bottom-ship distance begins to increase causing Trace D to move away from the zero axis. Finally, as the pinger reaches the surface at time 40 minutes, its height above bottom again becomes:

$$H = \frac{c}{2}\ \Delta T = \frac{1500}{2}\ 3.4 = 2550\ m$$

2.4 Interpreting a More Realistic Record

The above approach is satisfactory if the operator does not wish to approach too close to the bottom. However, there is often a need to place the instrument package on or within a few metres of the bottom. Therefore, it is necessary to increase the depth display resolution of the record compared to that of Figure 3. One simple way of doing this would be to increase the span of the graphic record. Figure 5 is an example of what happens to the first half of Figure 3 if the recorder width were to be increased by a factor 4 while maintaining the pinger repetition rate at 1 pulse per 4 seconds. Obviously, the operator can now determine the height off the sea floor with much greater resolution. Unfortunately, it is not practical to increase the graphic recorder span by constructing a 56" wide recorder.

An equivalent increase in resolution can be achieved by increasing the recorder sweep speed by a factor of four relative to that of Figure 3. This has the effect of "folding" the record of Figure 5 at the 1 second marks corresponding to the points on the traces labelled 'a', 'b', 'c', 'd' to produce the equivalent record shown in Figure 6. The pinger repetition rate would normally be increased to 1 pulse per second so that the graphic record would be marked every time the stylus traversed the paper instead of once in four sweeps at the 1 pulse per 4 sec rate. This change in pinger rate has two positive effects namely, it improves the coherence of the visual record and it generates updated information on instrument height more



4. Representation of pinger-ship acoustic paths for cases of: a) pinger at the surface; b) pinger 1179 m above the bottom; and, c) pinger 150 m above the bottom.

frequently. The disadvantage is that the record can no longer be "unfolded" by reverting to the slower sweep speed. A record of the type depicted in Figure 6 is the type normally encountered when using a pinger for bottom finding in deep water.

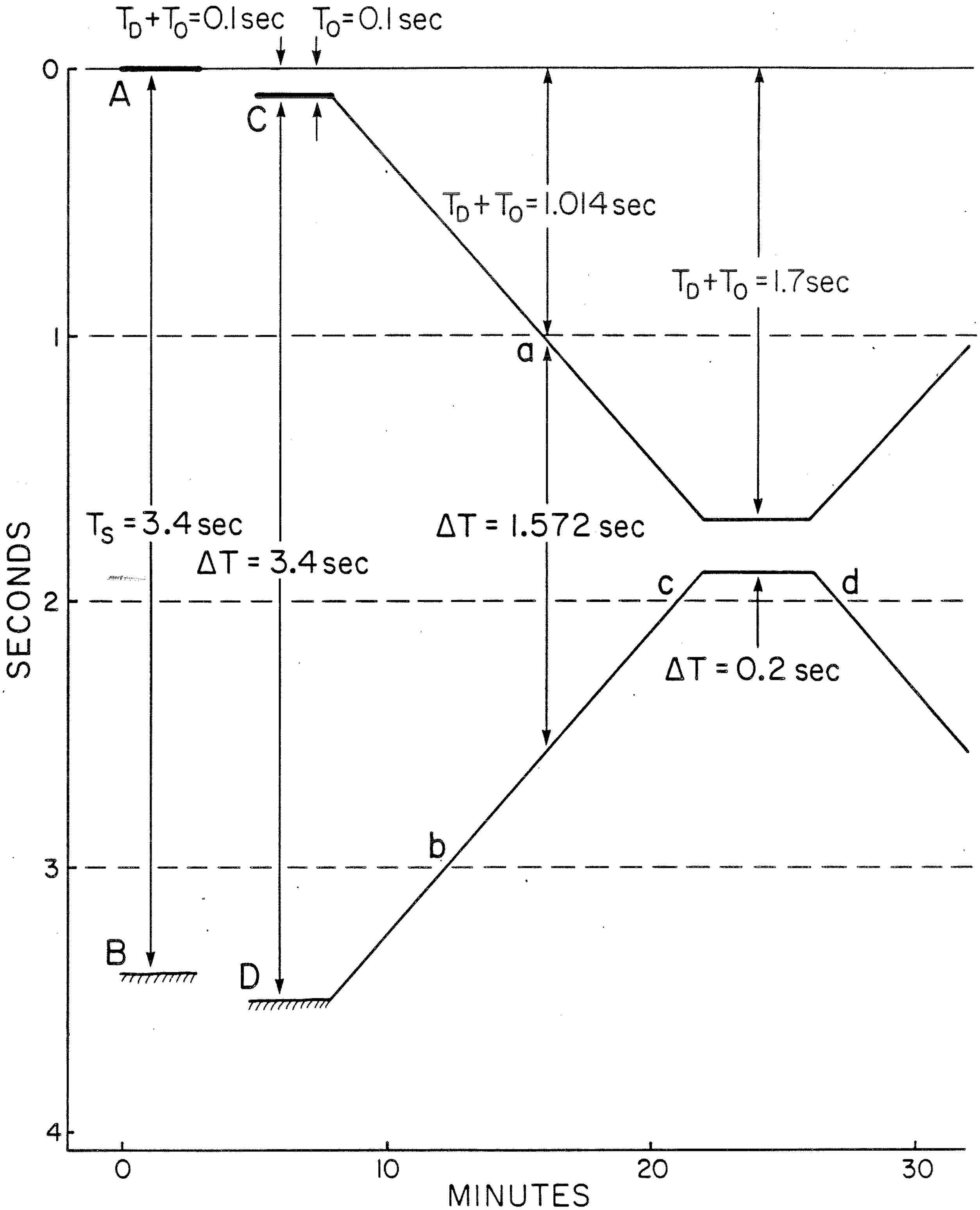
Consider first the Traces A and B produced by the ship's echo sounder. They are now apparently 0.4 seconds apart instead of 3.4 seconds. The 3 seconds has "disappeared" as a consequence of folding the record at 1 second intervals

The stylus now produces a mark on Trace A, then, sweeps across the record 3 times plus 0.4 seconds before making a mark on Trace B. We can confirm that the water depth is 2550 metres by switching to a slower sweep rate such as 5 seconds. The number of complete stylus sweeps between transmission and reception of the signal at a one second sweep rate in 2550 m water depth can be determined from equation (6) as

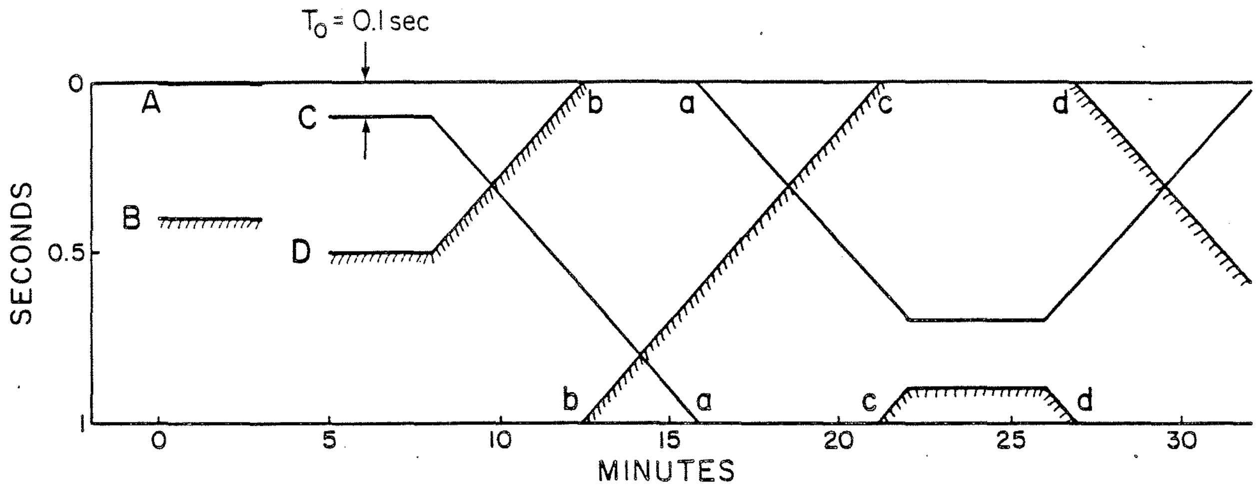
$$N_s = Integer[\frac{2\ Z}{c\ T_G}] = Integer[\frac{2\ 2550}{1500\ 1}] = 3$$

Traces C and D of Figure 6 produced by the pinger at time 5 to 8 minutes before it is lowered are exactly equivalent to Traces A and B respectively. It is apparent that $T_O = 0.1$ seconds. Starting at time 8 minutes, the pinger is lowered and the two traces begin to converge as the pinger height above bottom decreases. For the moment, consider only Trace C, that is, the direct pinger-ship signal. At approximately time 15.9 minutes (point "a") the trace disappears off the lower edge of the record but simultaneously reappears at the upper edge. This event corresponds to the first "fold" at 1 second sweep time. Let N_D be the number of times the direct pinger-ship trace crosses Recorder Zero, incrementing it if the pinger is being lowered and decrementing it when the pinger is being raised. Thus, at 15.9 minutes $N_D = 1$. The trace continues on toward the lower edge of the record until, at 22 minutes, lowering is stopped.

Returning now to the 9 minute point on the graphic record of Figure 6 and examining both Traces C and D simultaneously, the traces converge as they did for the case depicted in Figure 3. At about time 9.8 minutes they "cross-over". Referring back to Figure 5,



5. Width of simulated graphic record of Figure 3 expanded by a factor of 4.



6. Graphic record of Figure 5 "folded" at 1 second intervals.

it is apparent that this is not the consequence of any particular physical characteristic of the water column but is simply an artifact of the "folding" process at 1 second intervals. If N_c is the number of "cross-overs" from the time lowering commences, and is incremented during lowering and decremented during recovery, then, at this point $N_c = 1$. At about 14.1 minutes a second "cross-over" occurs so $N_c = 2$ and a third occurs at 18.5 minutes so $N_c = 3$. During recovery, a cross-over occurs at 29.5 minutes decrementing N_c to 2 and so on down to zero back at the surface. In more general terms the maximum number of cross-overs that will occur when lowering a pinger to the sea floor is:

$$(N_c)_{MAX} = Integer[\frac{2\ Z}{c\ T_G}] \qquad (14)$$

As the instrument is lowered, the bottom reflected trace D runs off one edge of the graphic record at point "b" and immediately reappears at the other edge. This is similar to point "a" of trace C. We will count these in the same fashion so that $N_B = 1$. Another such "fold" occurs at point "c" so that, at time 21.1 minutes, $N_B = 2$ and so on. Another generalization can now be stated. When an instrument reaches the sea floor

$$N_D + N_B = (N_c)_{MAX} \qquad (15)$$

Also, a little algebraic manipulation of equations (1), (10), (11) and (15) reveals that

$$H = \frac{c}{2}\ [((N_c)_{MAX} - N_c)\ T_G + (ET_B - ET_D)] \qquad (16)$$

This is an especially useful relationship because it relates instrument height off bottom to parameters N_c and $(ET_B - ET_D)$ which are easily read off the graphic record and $(N_c)_{MAX}$ which is readily pre-computed from equation (14).

Now to illustrate how this descriptive information and the algorithms of Section 2.1 can be applied to the solution of instrument height off bottom, H, and depth beneath the surface, D, for a realistic graphic record such as that of Figure 6, three different times during the lowering will be examined. The cases chosen correspond to those chosen in section 2.3 for Figure 3.

<u>Case 1: t = 5 minutes</u>

$ET_D = 0.100$ sec

$N_D = 0$

$ET_B = 0.500$ sec

$N_c = 0$

$T_O = 0.100$ sec

$PD = 0$ sec/minute

$t_o = 0$ minutes

$T_G = 1$ second/sweep

$c = 1500$ m/sec

$Z = 2550$ m

$$(N_c)_{MAX} = Integer[\frac{2\ Z}{c\ T_G}]$$

$$= Integer[\frac{2\ 2550}{1500\ 1}]$$

$$= 3$$

$$H = \frac{c}{2}\ [((N_c)_{MAX} - N_c)\ T_G + (ET_B - ET_D)]$$

$$= \frac{1500}{2}\ [(3-0)\ 1 + (0.500 - 0.100)]$$

$$= 2550\ m$$

$$T_D = (N_D\ T_G + ET_D) - (T_O + PD\ [t - t_o])$$

$$= (0\ 1 + 0.100) - (0.100 + 0\ [5 - 0])$$

$$= 0\ seconds$$

$$D = c\ T_D$$

$$= 1500\ 0$$

$$= 0\ m$$

To verify the computations

$$H + D = 2550 + 0$$

$$= 2550\ m$$

that is, the water depth Z.

<u>Case 2: t = 16 minutes</u>

$ET_D = 0.014$ sec

$N_D = 1$

$ET_B = 0.586$ sec

$N_c = 2$

$T_O = 0.1$ sec

PD = 0 sec/minute

$t_o = 0$ minutes

$T_G = 1$ second/sweep

c = 1500 m/sec

Z = 2550 m

$$(N_c)_{MAX} = Integer[\frac{2\ \ Z}{c\ \ T_G}]$$

$$= Integer[\frac{2\ \ 2550}{1500\ \ 1}]$$

$$= 3$$

$$H = \frac{c}{2}\ \ [((N_c)_{MAX} - N_c)\ \ T_G + (ET_B - ET_D)]$$

$$= \frac{1500}{2}\ \ [(3-2)\ \ 1 + (0.586 - 0.014)]$$

$$= 1179\ m$$

$$T_D = (N_D\ \ T_G + ET_D) - (T_O + PD\ \ [t - t_o])$$

$$= (1\ \ 1 + 0.014) - (0.100 + 0\ \ [16 - 0])$$

$$= 0.914\ seconds$$

$$D = c\ \ T_D$$

$$= 1500\ \ 0.914$$

$$= 1371\ m$$

To verify the computations

$$H + D = 1179 + 1371$$

$$= 2550\ m$$

that is, the water depth Z.

Case 3: t = 22 minutes

$ET_D = 0.70$ sec

$N_D = 1$

$ET_B = 0.900$ sec

$N_c = 3$

$T_O = 0.1$ sec

$PD = 0$ sec/minute

$t_o = 0$ minutes

$T_G = 1$ second/sweep

$c = 1500$ m/sec

$Z = 2550$ m

$$(N_c)_{MAX} = Integer[\frac{2\ Z}{c\ T_G}]$$

$$= Integer[\frac{2\ 2550}{1500\ 1}]$$

$$= 3$$

$$H = \frac{c}{2} * [((N_c)_{MAX} - N_c)\ T_G + (ET_B - ET_D)]$$

$$= \frac{1500}{2}\ [(3-3)\ 1 + (0.900 - 0.700)]$$

$$= 150\ m$$

$$T_D = (N_D\ T_G + ET_D) - (T_O + PD\ [t - t_o])$$

$$= (1\ \ 1 + 0.70) - (0.100 + 0\ [22 - 0])$$

$$= 1.600\ sec$$

$$D = c\ T_D$$

$$= 1500\ 1.600$$

$$= 2400\ m$$

To verify the computations

$$H + D = 150 + 2400$$

$$= 2550\ m$$

that is, the water depth Z.

So far it has been assumed that the bottom is a good acoustic reflector, thus, the bottom reflected signal appears on the graphic record as soon as the pinger is placed in the water. In practice, this may not be true and no amount of receiver gain adjustment will solve the problem. Usually it is possible to lower the pinger at a constant rate until the bottom echo appears then stop and sort out the situation. At this time, the traces can be extrapolated back to the starting point to identify cross-overs and to check that scaled and computed pinger depth below surface and above bottom agree with measured wire out and water depth.

2.5 Lowering an Instrument to the Sea Floor

The foregoing has been a detailed description of how the height of a pinger above the bottom or depth below the surface can be computed at any time. Operationally, the problem often reduces to the special case of lowering an instrument package such as a corer onto the sea floor. In this case, the procedure can be greatly simplified. Before the instrument plus pinger are placed in the water, depth to the sea floor (Z) is measured with the ship's echo sounder. Usually the recorder sweep speed is 1 second/sweep so the number of cross-overs betwen the surface and bottom can be predicted from:

$$N_c = Integer[\frac{Z}{750}] \tag{17}$$

The operator then deploys the pinger and counts the number of 'cross-overs". When this increments to N_c, the pinger is less than 750 m above the bottom. The operator then monitors the direct and bottom reflected traces until they merge. At this point, the instrument package with its pinger has just reached the sea floor. Between the last cross-over and touch-down, the height of the pinger off the bottom is:

$$H = 750 \quad \Delta T \; metres \tag{18}$$

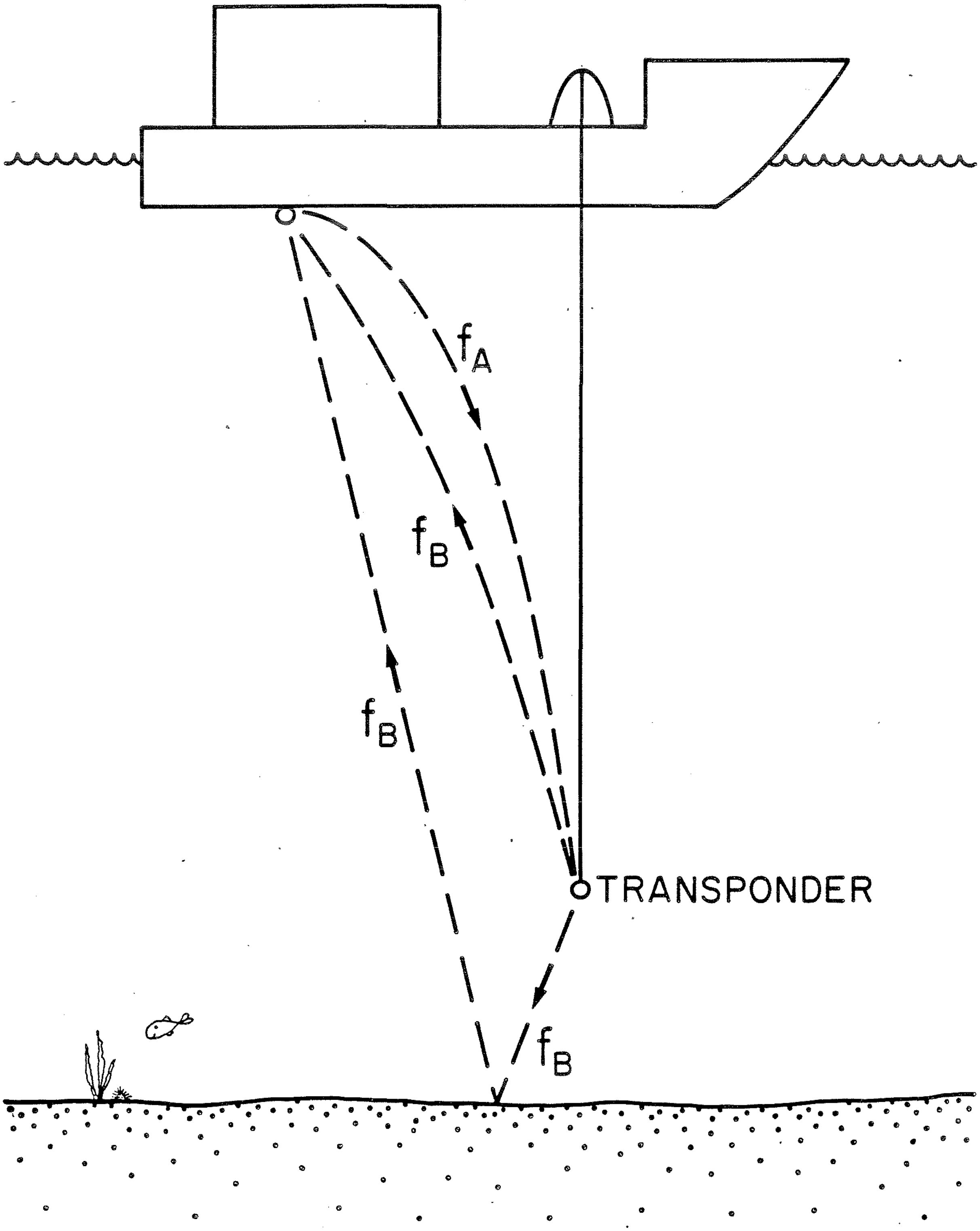
3.0 HEIGHT MEASUREMENT WITH A TRANSPONDER

3.1 The Basic Principle

In Section 2, it was shown that the resolution of height measurement with a pinger can be improved if its repetition rate and the recorder sweep speed are both increased. Unfortunately, there is a price which must be paid in that, if the ship-bottom-ship travel time exceeds one recorder sweep period then "cross-overs" occur. Their presence complicates record interpretation and, in situations where bottom reflectivity is poor, it may prove extremely difficult to correctly count all "cross-overs". In such cases, if a pinger is being used, the only hope of correctly calculating pinger height above bottom is to deduce it from known water depth and amount of wire paid out until such time as a clearly identifiable bottom echo appears. This problem can be solved by replacing the pinger with an acoustic transponder, a unit which transmits an acoustic pulse in response to a transmission it receives from the ship.

Figure 7 illustrates the basic elements of this system. The ship transmits an acoustic tone burst at a frequency f_A each time the recorder stylus begins its sweep across the graphic record. When this pulse reaches the transponder, it replies with an acoustic pulse at a different frequency, f_B. This signal travels directly back to the ship to create a mark on the graphic record, analogous to Trace C of Figure 3. At the same time, the signal travels to the ship via a sea floor reflection to produce on the graphic record a mark analogous to Trace D of Figure 3. Two important practical points must be noted here. The level of the outgoing signal from the ship should be kept low so that its bottom reflected component does not trigger a second transponder response. Also, the reply frequency f_B must be different than the interrogate frequency f_A so that its reflections do not retrigger the transponder and so that multiple reflections of transmission at frequency f_A can be filtered out by the shipboard receiver so as not to complicate the graphic record by being marked on it.

The main difference between the transponder and pinger method of bottom finding lies in the fact that the response of the former is at all times under the control of the operator aboard the ship. Its repetition rate can be altered by varying the recorder sweep rate or one



7. Geometry of the acoustic paths when a transpodner is used for height above bottom measurement.

can even stop it transmitting by ceasing to send interrogations from the ship. This is a very powerful element of control because it allows the operator to run the recorder at a slow sweep rate until the unit nears the sea floor (equivalent to Figure 3) then step up the resolution as much as desired near the sea floor (equivalent to Figure 6) by speeding up the recorder sweep rate. The height above bottom is still defined by equation (1) but depth below the surface of the instrument package now becomes

$$D = \frac{c}{2} \ (T_T - TAT) \tag{18}$$

where T_T is the round trip-transponder-ship travel time and TAT is the transponder turn-around-time.

Figure 8 is a simulated graphic record of the same hypothetical case as was used in Sections 2.3 (Figure 3) and 2.4 (Figure 6) but this time an acoustic transponder has been used instead of a free-running pinger. The same method has been used to label traces in Figures 3, 6 and 8, that is:

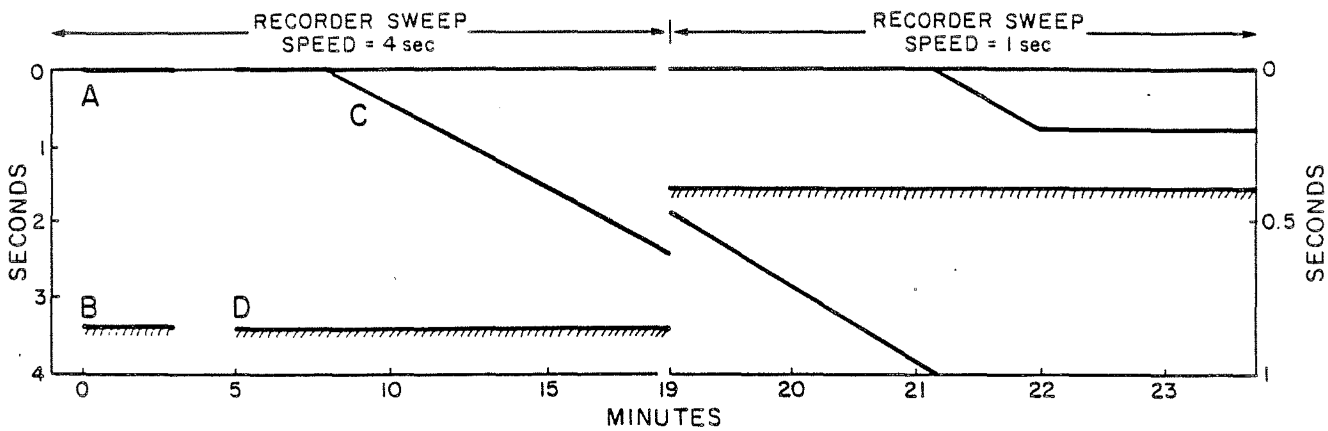
A = transmission by ship's echo sounder

B = bottom reflection of ship's echo sounder signal

C = direct signal from acoustic source on instrument

D = bottom reflected signal from acoustic source on instrument

When comparing Figure 8 with Figures 3 and 6, two things are immediately obvious. First, in terms of height measuring resolution it equates to Figure 3 before time 19 minutes and Figure 6 after although in neither case are there any "cross-overs" to cause confusion. This change in resolution was accomplished by the operator simply increasing the recorder sweep rate on board the ship. Second, Trace D does not move up toward the reference axis but remains at a constant offset with respect to Recorder Zero. This aspect of the record makes its representation of the physical situation immediately apparent to even the most inexperienced operator because, intuitively, he expects to see the bottom stay in one place on the record as the instrument is lowered towards it.



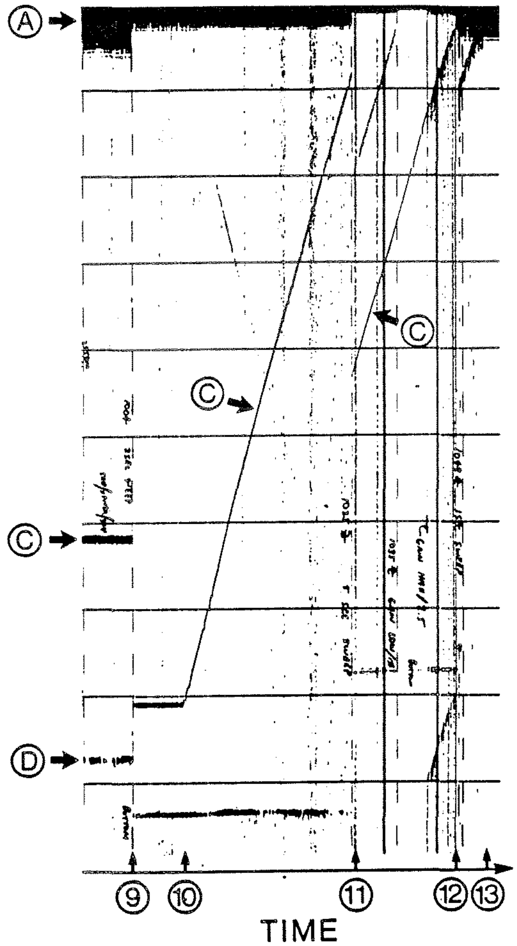
8. Simulated graphic record illustrating the use of an acoustic transponder for height above bottom measurement. At time 19 minutes, the sweep speed of the recorder has been increased by a factor of 4.

3.2 A Practical Realization of the Technique

There are different ways in which the transponder measurement of height above bottom could be implemented. At the Bedford Institute of Oceanography, a particular choice has been made based on the acoustic equipment installed aboard its vessels. The Institute was fortunate to have purchased deep sea echo sounders with dual frequency capability a few years ago. Normally, these are set up to transmit and receive at 12.0 kHz on one channel and 10.0 kHz on the other. The former is used for echo sounding and receiving signals from pingers. The latter is used to receive signals from acoustic releases on current meter moorings. Since the units are not required to transmit in this latter mode, their normal use is not impaired if the second channel is changed to transmit at 12.0 kHz and receive at 10.0 kHz. These frequencies are close enough together that the same ship's transducer can be used for both but far enough apart that the bottom echo from the 12.0 kHz transmission is not marked on the graphic record.

To complement this shipboard equipment, a Datasonics model UAT-371 acoustic transponder was purchased. This unit, when interrogated with a 5 msec long 12.0 kHz tone burst, replies at 10.0 kHz. It has a turn-around-time of 4.5 msec, a re-transmit or lock-out time of 0.86 sec and a transmission pulse width of 7.0 msec.

Figure 9 is an example of an actual graphic record produced with this sytem. It differs from the simulated record of Figure 8 mainly in that it represents the recovery from rather than the lowering to the sea floor. The water depth was 2890 metres. Prior to time T = 9, the sweep speed of the recorder is 1 second and both the direct ship/transponder/ship (trace C) and the bottom reflected ship/transponder/bottom/ship (trace D) signals are present. By scaling the time difference between traces C and D, it can be determined that the transponder is 180 metres above the bottom. At time T = 9, the recorder sweep rate was changed to 2 seconds. The height measuring resolution is immediately halved. At time T = 10, recovery of the transponder commences. Trace C begins to move upwards towards the transmission signal (trace A) or apparently toward the ship while the bottom (trace D)



9. Actual graphic record of an acoustic transponder being recovered from a depth of 2710 metres in a water depth of 2890 metres.

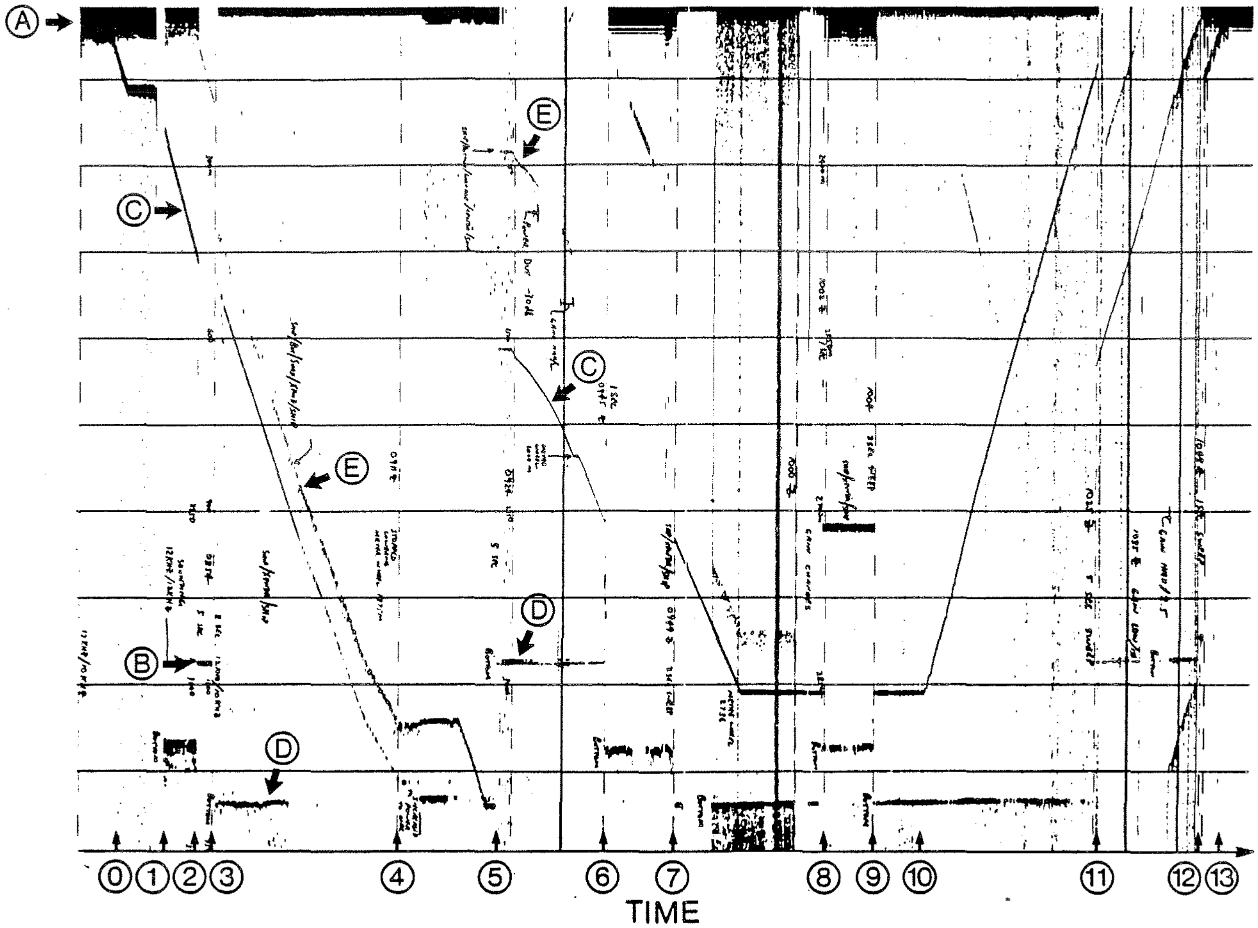
remains horizontal, in agreement with the natural expectation of the observer. In contrast, if a pinger were being used, the bottom would appear to move away from the ship at the same time as the pinger started upward. At time T = 11, the recorder sweep rate was changed to 5 seconds and at T = 12 it was changed to 1 second. This latter change was made to bring the ship/transponder/ship signal out of the transmission signal (trace A) where it had disappeared on the 5 second sweep rate. Such changes in sweep speed when using a pinger would have no effect other than to confuse the graphic record. Finally at T = 13 the transponder reached the surface.

Figure 9 is actually the right hand portion of Figure 10 which illustrates the complete deployment and recovery cycle of the transponder. Table 1 lists some of the more significant events in the record. There is one extra signal in this figure, trace E. If one

Table 1. Events Depicted in Figure 10.

Time	Description
0	Transponder placed in water, 1 sec. sweep
1	Gain adjusted to reveal bottom reflection
2	Echo sounder turned on, depth 2890 metres
3	Interrogating transponder on 2 sec. sweep
4	Stopped lowering transponder briefly
5	Sweep rate change to 5 sec.
6	Sweep rate changed to 1 sec.
7	Sweep rate changed to 2 sec.
8	Near bottom, sweep rate changed to 1 sec.
9	Sweep rate changed to 2 sec.
10	Commenced recovery
11	Sweep rate changed to 5 sec.
12	Sweep rate changed to 1 sec.
13	Transponder out of water

examines trace E at time T = 5, then its elapsed time from Recorder Zero is 0.915 sec. and the corresponding actual travel time will be 0.915 sec. plus one or more 5 sec. recorder sweeps. At time 4, the measured length of wire paid out was 1375 m and approximately 150 m more wire



10. Deployment and recovery of an acoustic transponder to 2710 metres in water 2890 metres deep.

has been paid out since then. Therefore, trace E must correspond to a distance of at least 1525 m. Additional information about the situation at time T = 5 includes the following:

1. trace E moves toward full scale as the source is lowered;

2. at time 5, trace C indicates that the round trip transit time ship-transponder-ship including TAT (4.5 msec.) is 2.065 seconds so that, in the terminology of Appendix B,

$$T_1 = \frac{(2.065 - 0.0045)}{2} = 1.030\ sec$$

3. the water depth is 2890 m so that, in the terminology of Appendix B,

$$T_2 = \frac{(2890)}{1500} = 1.927\ sec$$

Now, exploring the possible acoustic paths identified in Table B.2 of Appendix B;

Path I + IV	$2T_1 = 2.060$ seconds
Path I + VI	$2T_2 + 2T_1 = 5.914$ seconds
Path III + IV	$2T_2 + 2T_1 = 5.914$ seconds
Path III + VI	$4T_2 + 2T_1 = 9.768$ seconds

Since the total transit time of trace E is either 0.915, or 5.915, or 10.915, etc. seconds, the acoustic path it represents is either Path I + IV (ship-transponder-surface-bottom-ship) or Path III + IV (ship-bottom-surface-transponder-ship). Shortly after time T = 5, the shipboard echo sounder output was reduced by 30 db and trace E promptly disappeared. This strongly suggests that it is the ship-bottom-surface-transponder-ship path which means that the transponder is detecting the ship's transmission at ranges of at least 7300 m in spite of losses in signal strength at both the bottom and surface reflection points. A similar analysis of a different multiple reflection path during another lowering at the same site, indicated that the shipboard receiver could detect the transponder over distances in excess of 5200 m including one reflection at the sea floor. Therefore, the system is useable in all water depths of interest to BIO.

Of practical note are two points. First, multiple reflection signals such as trace E can usually be eliminated by decreasing shipboard transmitter power output and/or receiver gain. Second, the direct signal, trace C, is usually easily identified relative to such multiple path signals because it is generally darker, of shorter duration and more continuous. On the other hand the latter often are lighter grey on the record, tend to make a longer, more diffuse mark and are often discontinuous.

4.0 SUMMARY

Two different acoustic methods of monitoring the altitude of an instrument package have been described. The first utilizes a pinger as the acoustic source on the package and the second an acoustic transponder. The transponder is the simplest to use because the operator can, at will, alter its repetition rate remotely to improve height measuring resolution or resolve measurement ambiguities. Unfortunately, it is a more complex type of acoustic source than the pinger and the shipboard transceiver must be capable of simultaneously transmitting and receiving at different frequencies.

The pinger system uses simpler equipment but record interpretation is more difficult. The operator must understand how the acoustic trace is "folded", usually at one second intervals, and how to predict and keep track of "cross-overs" so that he can correctly compute instrument height off bottom at any time.

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APPENDIX A: SYMBOLS AND NOMENCLATURE

A.1 Symbols

c	sound velocity
D	depth of source below surface
ET_i	elapsed time from Recorder Zero to trace i on the graphic record
H	height of source above bottom
N_c	number of "cross-overs" or times the direct and bottom reflected pinger traces intersect on the graphic record
N_i	number of complete recorder sweeps between transmision and reception of signal depicted by trace i
PD	drift rate of a pinger timebase with respect to the graphic recorder timebase
t_o	time when recorder was "phased"
t_i	time relative to t_o when meaurement of instrument depth or height above bottom is required
TAT	transponder turn-around-time or delay between arrival of signal at transpsonder and consequent transmission
T_B	travel time of signal from source via bottom to ship
T_D	travel time of direct signal from source to ship
T_G	recorder sweep period or time required for stylus of graphic recorder to traverse paper from left to right
T_i	general expression for travel time
T_O	offset or delay of pinger transmission instant with respect to Recorder Zero
T_s	round trip ship-bottom-ship travel time
T_T	round trip ship-transponder-ship travel time
Z	water depth
ΔT	travel time difference between direct and bottom reflected acoustic signals from source to ship
Θ	angular offset from vertical of acoustic source with respect to ship

A.2 Nomenclature

Cross-over - The apparent intersection of two acoustic travel time traces on a graphic record as the ship-source-bottom geometry changes.

Phasing - The process of changing the instant at which the recorder begins its sweep so that it coincides approximately with some other reference time such as the instant of transmission of a pinger.

Recorder Zero - The left hand edge of the recorder where the stylus begins its sweep across the paper.

APPENDIX B: A COMPENDIUM OF LIKELY ACOUSTIC PATHS

In addition to the direct paths between acoustic source and receiver, there are a multitude of others which exist as a consequence of the acoustic signals being reflected off the sea floor, sea surface and other reflectors in the vicinity. In the context of instrument height measurement with a pinger or transponder, it can be presumed that the only reflectors present are the sea floor and sea surface and, furthermore, there is significant signal loss at each reflection so the total number of likely paths is severely restricted.

Figure B.1 illustrates all possible ship-instrument and instrument-ship paths which exist on the assumption that, if the signal undergoes more than two reflections it will not be detected. Table B-1 summarizes the travel times which result from each in the case of a pinger at a depth D where

$$T_1 = \frac{D}{c}$$

$$T_2 = \frac{Z}{c}$$

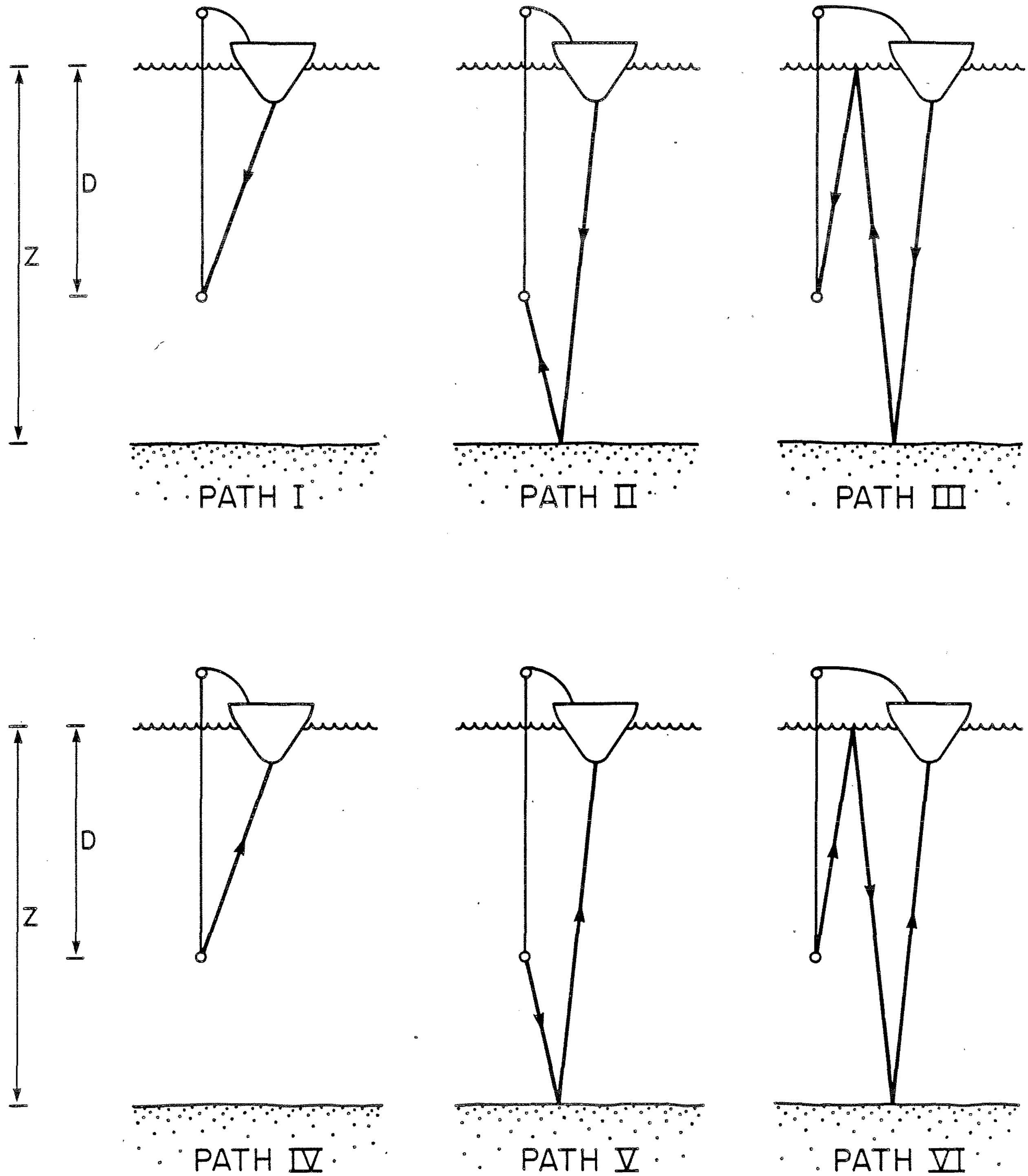
Also listed are qualitative statements describing the appearance of the trace produced by each on the graphic recorder as the pinger is lowered. In practice, the graphic record for the pinger is likely folded at one second intervals so measured elaped times from the reference axis to the trace may not equate to the absolute travel time given in Table B.1. Nevertheless, it should be possible to identify the source of each trace. Table B.2 provides the same information in the event that a transponder rather than a pinger is attached to the end of the cable. In this case it is assumed that reflections produced by the ship transmission at frequency f_A are filtered out by the receiver which is tuned to the transponder frequency, f_B.

Table B.1. Total travel Times, Pinger on End of Cable

Path	Total Travel Time	Appearance of Trace Graphic Record as Instrument Lowered
IV	T_1	moves toward full scale
V	$2T_2 - T_1$	moves toward zero
VI	$2T_2 + T_1$	moves toward full scale

Table B.2. Total Travel Times, Transponder on End of Cable

Path	Total Travel Time	Appearance of Trace Graphic Record as Instrument Lowered
I + IV	$2T_1$	moves toward full scale
I + V	$2T_2$	remains constant
I + VI	$2T_2 + 2T_1$	moves toward full scale
II + IV	$2T_2$	remains constant
II + V	$4T_2 - 2T_1$	moves toward zero
II + VI	$4T_2$	remains constant
III + IV	$2T_2 + 2T_1$	moves toward full scale
III + V	$4T_2$	remains constant
III + VI	$4T_2 + 2T_1$	moves toward full scale



B.1 Several possible acoustic paths which might exist between a ship and an acoustic source suspended beneath it.