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1. Introduction

Modeling the effects of tectonic and volcanic processes on land relies heavily on careful measurements of deformation of the crust - changes of elevation, tilt and horizontal dimensions (strain) (e. g. Denlinger and Okubo, 1995; Dragert and Lisowski 1990; Hyndman and Wang, 1995). Data of similar type are not yet available for the deep sea floor, although the results of developments started many years ago should emerge in the near future.

Our group has been concerned with developing the technology for making relevant measurements of the horizontal component of crustal deformation on the sea floor (Spiess, 1978; Spiess, 1985a). Our approach has been to develop means for improving the accuracy and resolution of conventional long baseline acoustic transponder navigation systems (Spiess, et al, 1966). In order to be relevant to seafloor spreading processes this means improving from individual measurement accuracies of a few meters to a few centimeters for individual observations over ranges of five to ten km (Spiess, 1985b).

In this approach, no attempt is made to have the transponders communicate with one another directly. The upward refraction, characteristic of the nearly isothermal conditions near the floor of the deep ocean, produces a near bottom shadow zone such that sources and receivers close to the sea floor are acoustically isolated from one another. Direct connecting paths may exist through exploitation of occasional favorable topography, or if towers are used. In the latter case in order to achieve centimeter accuracy it is essential that provision be made for measuring any tower tilt that may occur during the life of the installation.

As has been done in the case of conventional long baseline transponder systems, many sets of round trip travel time observations between a roving towed vehicle or ship and multiple transponders are combined to adjust the relative coordinates of the transponders to minimize the residual differences between the observed and calculated ranges (Lowenstein, 1966). This is compatible with an additional operational requirement, that of carrying out a local sound velocity survey, which is done with the same towed vehicle simultaneously with collection of the travel time data.

Our first step, and the principal object of this report, has been to develop means for improving the transponder system itself to reach a capability of measuring round trip travel times to better than 10 microseconds (which would correspond to 7.5 mm based on round trip travel time measurement at normal underwater sound speeds of about 1500 m/sec) over distances approaching 10 km. A concept for achieving this was conceived in 1978 (Spiess, et al, 1980.) and development and evaluation of embodiments of that approach have been underway since.

At-sea test applications were made in waters just off San Diego in 1987 and 88 (McIntyre, 1989). These have been followed by further development and testing and operational installations at two deep ocean sites - one on the Juan de Fuca Plate to implement a combined GPS and acoustic approach (Spiess, 1985a) to study convergence across the Cascadia Subduction Zone between that plate and North America (predicted to be closing at 4 cm per year), and a second installation that now spans the crest of the Juan de Fuca Ridge at its Cleft segment (44° 40° N, 130° 22° W, geological spreading rate 6 cm per year). This paper is intended to provide a description of the range-measuring system as evaluated in calibration facilities and actually used at sea through the summer of 1996.

2. Transponder System: Basic Concept

Conventional acoustic transponders typically are built to listen for, and recognize, a particular interrogation, and, immediately after recognition, to transmit their own characteristic signal which is in turn recognized at the receiver. The elapsed time between transmission and recognition of the returning signal is measured and then used in conjunction with some sort of sound velocity model to calculate an estimate of the distance between the interrogating vehicle and the transponder. Since the travel times are generally not much greater than 10 seconds, there is no time base problem in measuring the intervals involved with accuracy of a microsecond - corresponding, at normal oceanic sound speeds of 1500 m/sec, to range uncertainties of the order of a millimeter.

Unfortunately there are system problems other than provision of an adequate clock that limit the ability of conventional transponders to make travel time measurements to 10 microsecond accuracy for a system having range capabilities of over 5 km. The primary problem is that of recognition of the instant of arrival of the measurement signal at either the transponder or the receiving vehicle. Typical interrogation signals are of the order of 10 msec in duration in systems having range capabilities of 5 to 10 km, although some use signals as short as 3 msec. The resulting turnaround times between arrival of the interrogation at the transponder and the time at which the reply is transmitted are generally uncertain to as much as a millisecond, depending principally on signal to noise ratio.

The concept underlying the MPL precision transponders is to arrange that the necessary timing signal turnaround delay should be held to a particular value, within an uncertainty of only a few microseconds (Spiess, et al, 1980). This is accomplished by using a two part interrogation signal, and a storage delay line of carefully determined length. One element of the interrogation signal is similar to a conventional transponder-triggering signal, while the other is used as the actual timing portion.

As indicated in Figure 1, the transmitting unit sends out a broad band timing signal, with an associated triggering tag. It simultaneously sends a replica of the timing signal to be stored in the shipboard correlator. The transponder recognizes the transmission and sends back the timing signal, which is loaded into the correlator and compared with the outgoing signal to determine the time between transmission and reception.

The receive portion of the transponder embodies two functions (fig. 2). First, it includes conventional circuitry designed to carry out its function of recognition of the trigger signal. The second, parallel, element is a precisely timed delay line buffer that is continually loaded with successive samples of the output of the receiving hydrophone, with the oldest sample being destroyed as each new sample is entered. The buffer total delay is chosen to be somewhat greater than the length of entire transmitted signal, plus an allowance for recognition time.

Upon recognition of the triggering signal, the transponder shifts from listening to transmitting, sending, immediately, the samples in the buffer at the same rate as they were originally sampled. Each sample of the sound field as it existed at the transponder at an earlier time is thus sent on its way with a delay exactly equal to the carefully controlled length of the buffer. At the time at which the triggering portion of the signal would be retransmitted it is overwritten by a new tag that identifies the particular transponder involved.

Finally, at the ship, the received signal triggers loading of the timing portion into a second buffer in the processing correlator. The cross correlation process is then carried out between the originally stored replica and the newly stored return from which the delay time to the principal peak of the correlogram is determined. The total travel time is thus the time between transmit and shipboard recognition plus the fine scale delay time determined from the correlation process minus the length of the transponder delay line.

There are two obvious ways of arranging the sequence of trigger and timing signal. First, the trigger signal would immediately precede the timing portion, with the recognition circuit listening at the far end of the buffer. The second approach would be to have the trigger follow the timing portion. Our choice was to use the latter configuration, since we were concerned that if the trigger signal preceded the timing signal, the former's local reverberation might overlay the timing signal and distort the results.

In the overall process it is essential that, as nearly as possible, the timing portion of the signal be treated the same in both the propagated and the stored replica paths. For example, the number and characteristics of the required band pass filters are the same for both branches of the system.

The practical problems of carrying this out with adequate fidelity, with low power consumption and at high enough signal to noise ratio to assure a good measurement over a path length of 5 to 10 km will be described in the subsequent sections - characteristics of the transponder, the nature of the signal used, correlator design, short range calibration tests and at-sea experience.

3. The Precision Transponder

In principle the transponder could be quite a general device to repeat any of a wide variety of signals. In practice some generality is sacrificed for aspects of reliable performance - particularly the needs to drive the transducer efficiently, to identify individual members of an array and to minimize false triggering. The first selection to be made was of the operating center frequency and bandwidth. Here there is the inevitable tradeoff between high frequency and broad bandwidth for good timing against the range-limiting sound absorption, to maximize the useful range, given some assumed background noise characteristics. The desired ranges are about the same as for the conventional long baseline transponder systems (5 to 10 km). The reason for not pursuing greater ranges was that it was estimated that the sound velocity, at the most optimistic, would not be knowable to better than a part in a million, with the result that the desired centimeter accuracy could not be achieved over greater ranges. The tradeoff considerations led to choice of a frequency band comparable to that used for conventional deep ocean long baseline systems, with emphasis on the higher end in order to favor the time measurement. The optimization calculations assumed that the useful bandwidth would be about one fourth of the center frequency. Since the early phases of system design visualized use between a deeply towed, quiet vehicle and the seafloor transponder, the calculations used a background noise corresponding to sea state three (Urick, 1983).

A frequency band of 13.5 to 17.5 kHz was chosen for the timing signal, with a tag at 16 kHz for the transmitted signal and frequencies in the 10 to 12.5 kHz range (in 0.5 kHz steps) for the identifying tags from the individual transponders. The latter were chosen so that, if desired, the transponders could be used in a conventional long baseline system mode, ignoring (or omitting) the timing portion of the signal.

In the course of transponder development a variety of signal waveforms were used, including pseudorandom sequences with both frequency shift and phase shift modulation, and chirp frequency modulation. The first order goal was to achieve maximum transducer output while maintaining a band width approaching one quarter of the center frequency for the timing portion of the signal. An important second condition, however, was minimization of distortion of the signal due to the phase shift characteristics of the combination of the transducer, its mounting environment and the necessary matching network between the transducer and its associated power amplifier. The system was particularly sensitive to these effects since, in order to achieve the best possible time resolution, the processing was carried out to generate and use the correlation function retaining its high frequency components, rather than relying solely on its envelope. These considerations led to the conclusion that a signal configuration that emphasized the use of the available bandwidth at its two extreme ends, rather than having a uniform utilization across the entire band, provided the best combination of output power and low distortion. It was thus determined that the timing signal would be configured as two frequencies - 17.5 kHz and 13.5 kHz, stepping abruptly between them at mid-pulse.

While one might anticipate that the phase distortion in the transducer/ amplifier combination could be compensated, and thus a more complex signal used, a major finding of our calibration tests was that some of the distortion is dependent on the azimuth and elevation of the arriving or departing signal. This characteristic is not usually specified in transducer design, and relevant measurements can only be made in calibration facilities large enough that one is in the far field of the transducer and free of multiple reflections from the boundaries (at least for the duration of the transmitted pulse). Operating in the Navy's Transdec facilitywe were able to observe the effect on our signals as evidenced by changes in shape of the cross-correlation function between the transmitted signal and the signal at the transponder hydrophone output as the transducer was rotated, while maintaining the relative separation of the calibration hydrophone and the transponder transducer otherwise constant. These effects were effectively minimized by adjustments of the matching network for each transponder based on calibration facility data, but remain a subject for further investigation.

The signal duration was chosen initially as 4 msec, but was increased to 8 msec during one of the redesign steps to help achieve the goal of 6 km useful range. The ultimate limit of useful signal length is related to the fact that the shipboard or towed transmitter/receiver would be subject to significant motion at periods of a few seconds, with resultant Doppler distortion. While the search for a correlation peak could be carried out in platform velocity space as well as time, we were not willing to undertake that complexity, particularly in view of the quasi-periodic nature of the motion and the magnitudes of the related accelerations. Emphasis on phase retention and low power consumption led to a decision to load the delay line with simple closely spaced polarity samples (hard-clipped digital representation). A one megaHerz sampling rate was selected as being clearly sufficient to achieve the desired 10 microsec resolution goal.

As construction and testing at sea and in the calibration facility proceeded, it became clear that further measures would be needed to reduce power consumption. A powering pattern of three operating levels was thus adopted. The lowest drain mode is a conventional long term resting condition in which the unit listens for a complex signal that will activate, for an 18 hour period, the next higher level of processing. At the second level the normal recognition capability is activated, but not the buffer delay line components or the power amplifier. Upon recognition of a short initial part of the leading 17.5 kHz portion of the timing signal, the delay line and power amplifier elements are powered and the transponder is in full action, awaiting the 16 kHz tag to trigger it to go into the transmit mode. If no tag is received within a time somewhat longer than the total length of the original signal (12 msec.) after the 17.5 kHz recognition, the unit reverts to its intermediate recognition status.

In addition to the normal transponder functions, later models include channels to carry out various ancillary system functions on command from the ship above.These allow the transponder to accept up to seven special acoustic signals. Each command is individually addressable, that is each command is sent to only one transponder at a time determined by one of sixteen unique addresses. The commands are sent as short bursts of three frequencies in a sequence that make up a binary word. A burst starts with the address word and is immediately followed by the command word. There are two status commands: One that requests a report of how many times the transponder has been turned on and one on how many valid interrogations it has received. The first was implemented primarily to determine if the unit had been inadvertently been turned on by acoustic activity other than ours. The second status command was implemented to determine approximate remaining battery life based on our knowledge of how much energy each ping cycle requires. The transponder reports its status count by sending out a series of eight double pulses for eight consecutive seconds with the leading pulse being 5 ms long and the trailing pulse 8 msec long. The reason for eight pulses is so that when viewed on a graphic chart recorder the pulses will show up as short dark lines in the background noise field. The time between the two pulses is proportional to the count with full scale being a 1 second separation between pulses.

A command is also included to activate a recall circuit (which was used early on in development for testing) so that, if the necessary additional equipment is installed, the transponders can be recalled acoustically. There are also two commands implemented to modify the recognition criteria to adapt to changing bottom reflectivity etc. (as was witnessed when going from the Santa Cruz basin to the Juan de Fuca plate). The seventh command is reserved for future use.

The battery pack and all electronics are, in the current design, housed in a glass sphere pressure case approximately 45 cm. in diameter, with the ceramic transducer mounted on the upper surface of the sphere itself. The sphere is held in an iron frame whose weight is sufficient to insure that the unit will be well connected to the sea floor. The resulting height of the transducer off the bottom is about 1 meter, and the bulk of the sphere is sufficient to shield the transducer from nearby bottom reflected acoustic transmission paths. The battery pack chosen is composed of Lithium cells (Electrochem series CSC93, Lithium Sulfuryl Chloride), sufficient in a conservative analysis to provide five years of listening and six survey visits each involving 120k transmissions. Figure 3 is a detailed block diagram of the transponder and Figure 4 is a photograph of the most recent version as it appears just prior to launch.

4. Signal generation and transmission

The signal to be transmitted is generated in the towed vehicle or adjacent to the shipboard transducer in simple binary digital form upon command from the primary system clock. This pulse sequence - 5 msec at 17.5 kHz, 4 msec at 13.5, a 2 msec gap followed by the tag of 3 msec at 16 kHz - is then fed to the power amplifier which puts the wave train into the water at a source level of about 194 dB re. 1 μPa at 1m. During transmission of the outgoing pulse the T/R (transmit/receive) switch channels a part of the signal through the receiver amplifier and filter circuits thus enabling a copy of the outgoing pulse to be stored in a digital memory topside for eventual cross correlation with the received signal. Since this signal takes the same electrical path to the correlator as the reply will take a few seconds later, any time delays or distortion will be common to both the reference and received signals.

Care is taken to minimize multipath possibilities in the vicinity of the transmit/receive transducer. In the case of towed vehicle interrogation, the transducer has a beam pattern emphasizing the horizontal direction, and it is suspended 7 to 8 m below the vehicle to avoid superposition of echoes from the vehicle itself. In the hull mounted case the transducer is designed with a beam pattern emphasizing the direction about 45° from the downward vertical, the direction in which most GPS/Acoustic work is carried out.

5. Receive and analysis functions

The same transducers are used for receive as for transmission. The T/R switch delivers the low level returning signal, which is amplified, band limited (9-18 kHz) and transmitted either directly in the case of the hull mounted system, or through the vehicle telemetry system and tow cable to the analysis portion of the system.

The analysis portion consists of 6 identical channels, one to accommodate each of up to 6 transponders in the field being surveyed. Each channel consists of an analog recognition board similar to those in the transponders, a correlator, and a timer. The timer for each channel is started at the time of transmission, and the reference memory board in the correlator is loaded with the hard clipped digitized version of the outgoing signal as received through the same electrical path as the eventual received signal. The recognition circuits are each tuned for a particular tag frequency. Upon sensing its assigned tag, its timer is stopped, and the signal in that channel is hard clipped, digitized, and loaded into the second memory of its particular correlator.

The correlator operates by comparing each memory location in the reference sequence with the corresponding location in the data memory and summing the number of matches. The memories are then shifted relative to one another by one address location and the comparison is made again until the reference memory is completely cycled around. The address location where the best match occurred provides an offset or "fine time" adjustment to the gross time so that a total time from transmit to receive is measured with resolution of about ± 1.5 ms. The results are logged for each cycle with a transmit time stamp, the gross and fine times for each correlator and a quality number which is the magnitude of the best match peak. The shape of the correlogram in the vicinity of the highest peak is also recorded for future analyses of data quality.

An external frequency source produces a once per second timing pulse to synchronize transponder operation with that of other elements of the survey activity. This once per second pulse is further divided down to provide a keying repetition interval such that replies from all transponders will have returned before the next interrogation signal is transmitted. This usually leads to a transmit repetition period of 6 to 8 seconds. At the end of an interrogation cycle all the counters and memories are cleared.

6. At-sea results

Initial at-sea test operations were carried out in 1987 and 88 in the Santa Cruz Basin, a valley in the continental borderland off San Diego, with a smooth flat bottom at a depth of about 2 km. While these tests provided useful information (McIntyre, 1989), they also revealed that the first generation system did not achieve the ranges desired. After some significant alterations to power amplifiers and signal duration, the second generation units were tested at sea in 1990.

In the 1990 at-sea operations, signals transmitted from, and received at the hull mounted transducer on R/V New Horizon produced well defined correlograms at ranges of up to 7 km. One such correlogram is shown in Figure 5. The correlogram peak is clearly defined and supports travel time resolution of a few microseconds.

Following this success we were supported by NASA to install, in 1991, a first geophysics-oriented seafloor installation on the Juan de Fuca Plate (at Lat. 48.17 N , Long. 127.17 W) off the northwest coast of North America to begin a study of convergence across the Cascadia Subduction Zone. This approach used a combined GPS/Acoustic system (Spiess, 1985a) and included assistance in GPS data collection and processing by Caltech Jet Propulsion Laboratory personnel, ship support from the Canadian Institute of Oceanographic Science, and both at-sea support and shoreside reference station operation by the Pacific Geoscience Centre.

During the 1991 operation a number of changes were made at sea, particularly alterations in the recognition criteria as implemented in the transponders. Also at that time there was not a capability to make a precise near-bottom survey that would help determine the uncertainties in range measurement from some kind of internal consistency approach.

Near bottom surveys were subsequently carried out, however, with NSF and NASA support.

At this site the mild topography and relative simplicity of the sound velocity field (due to absence of hydrothermal activity) make it possible to evaluate the performance of the transponders fairly. After making the appropriate adjustments of the transponder array geometry, the residual differences between the calculated and observed ranges is shown in the histogram of figure 6 (Chadwell, et al, 1996). This shows an RMS spread of approximately $\mp$ 5 cm, well within the limits needed for the purpose of determining transponder positions with cm accuracy from a few thousand observations.

7. Conclusions

While it is clear that the approach embodied in the MPL precision transponder is capable of supporting relevant geodetic studies on the deep sea floor, further improvements in implementing the concept should be made. These should focus on two areas in particular - greater range capability and elimination of phase distortion. The former will be essential to the use of GPS/Acoustic techniques in the vicinity of major trenches, and the latter is particularly important in carrying out near-bottom surveys with greater accuracy than is at present available.

Improvements in range are essential in the context of GPS/Acoustic applications. In this context it should be feasible to transmit adequate acoustic power from the ship to insure that there will be good signal to noise ratio at the transponder in its quiet sea floor environment. This may require additional investment in the hull mounted transducer to handle increased driving voltages. Similarly, increased output from the transponders will be essential.

Design for the necessary 10 km range for a ship mounted system implies that the question of the optimum frequency band should be revisited. The original choice of operating frequency was predicated on use in the near bottom survey mode. As a result the limiting background noise spectrum assumed was ambient noise generated by weather at the sea surface, and the design operating range of 6 km was chosen because of assumptions as to our lack of ability to know the sound velocity adequately beyond ranges of that order. In the ship mounted case the shape of the background noise spectrum will be different, and in the GPS/Acoustic approach, knowledge of the sound velocity is not as important. These considerations may well dictate lower operating frequencies.

The problem of phase distortion is a more subtle thing. A first step is to establish a technique for measuring the distortion in some manner that is independent of the nature of the particular signal being used (e. g. some function of frequency from which the effect on any given signal could be predicted). Since part of the effect that has been observed is dependent on the azimuth and elevation of the incoming or outgoing sound, at least a part of the measurement process must be carried out in a calibration facility.

Once a measurement method has been established then the effects of varying the manner in which the hydrophone is mounted to the pressure case can be investigated systematically, and separated from the effects of the transponder electronics (e. g. matching network). With this level of understanding, means can then be developed to assure that we are in fact achieving the goal of having the transponder be a simple, non-distorting, repeater, with an accurately known internal delay for the timing portion of the signal.

These aspects of potential improvement will be pursued as appropriate funding becomes available. Until that time, however, the present design appears to be adequate for initial seafloor geodetic studies requiring precise travel time measurements over distances up to about 7 km.

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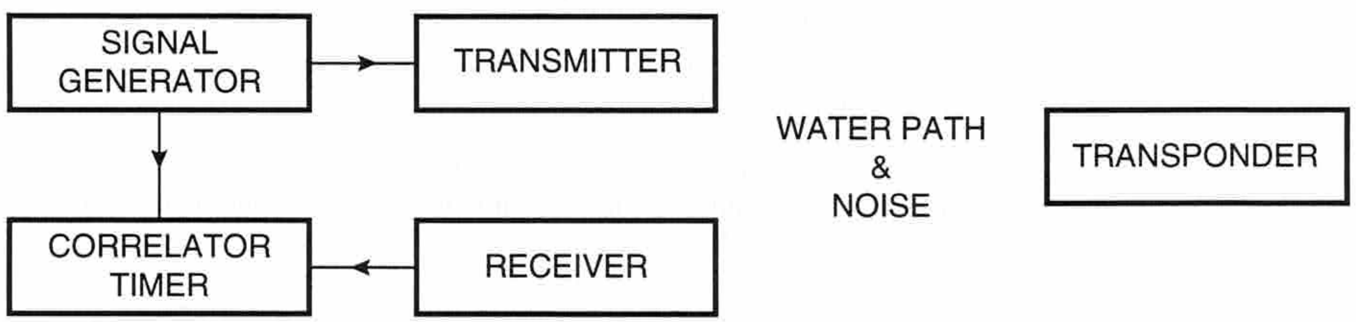

Fig. 1 - Overall system block diagram - signal generation and transmission component with outputs to the sea and to the memory of the correlator; the intervening ocean, with its signal spreading and absorption and addition of noise; the transponder/repeater; back through the ocean to the receiver/ correlator for determination of total time delay from transmit to receive.

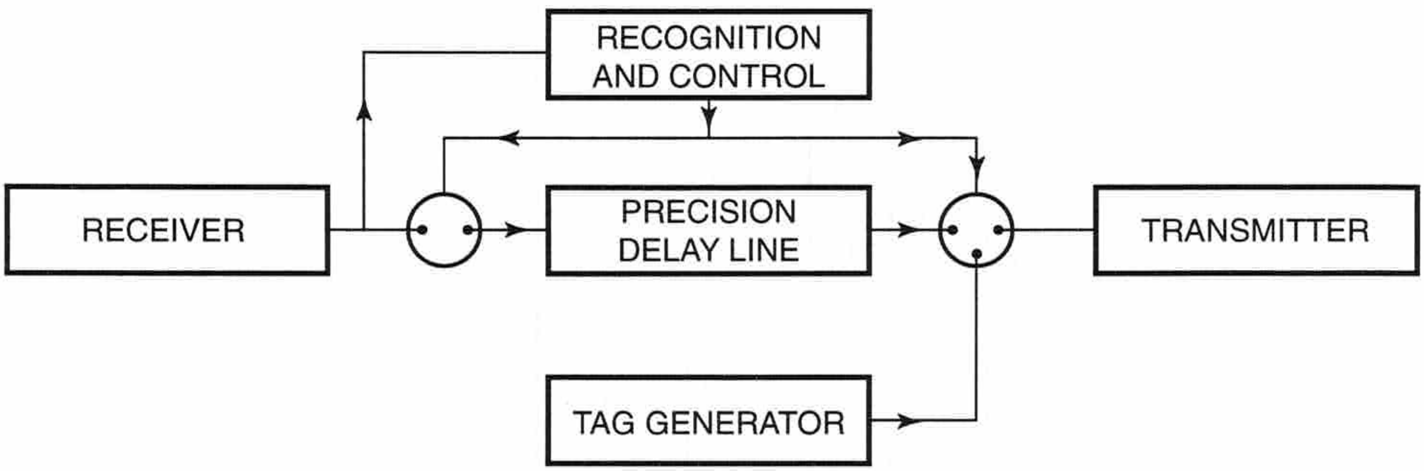

Fig. 2 - Simplified block diagram of the MPL Precision Transponder - receive section, split to 2 channels - one for recognition and tag generation and the other through the delay line, combining at the output to drive the hydrophone.

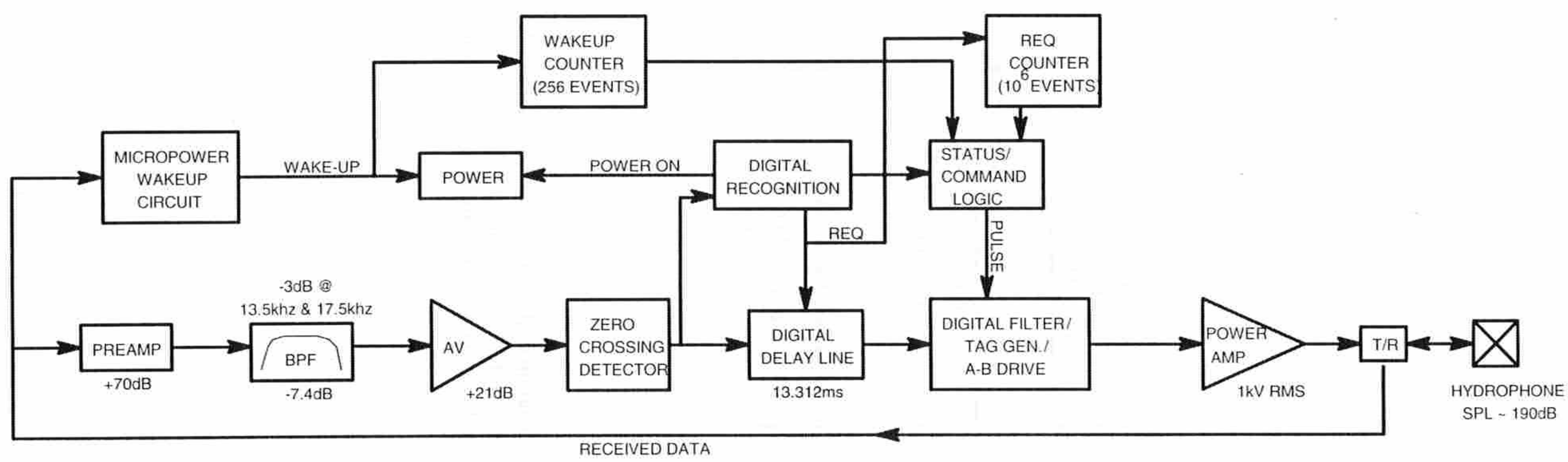

Fig. 3 - Detailed block diagram of the precision transponder.

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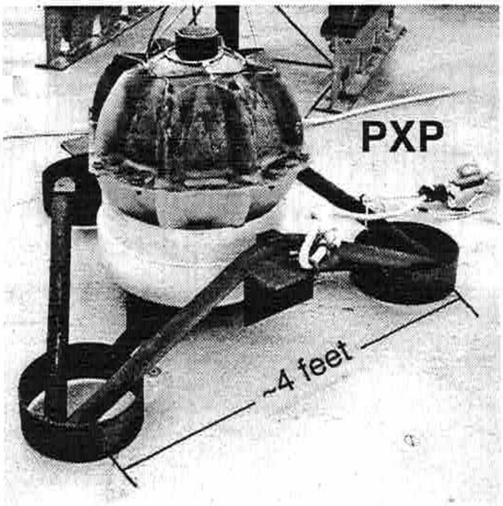

Fig. 4 - Photograph of the most recent configuration of the MPL Precision Transponder.

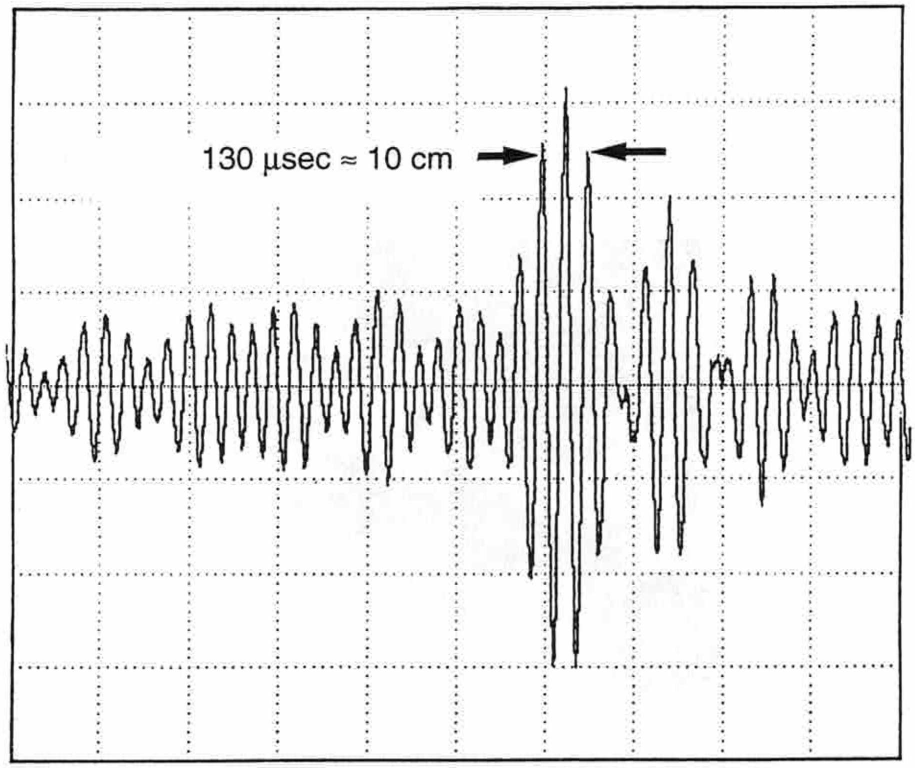

Fig. 5 - Correlogram at 7 km range between R/V New Horizon's hull mounted transducer and a precision transponder on the sea floor at a depth of 2 km.

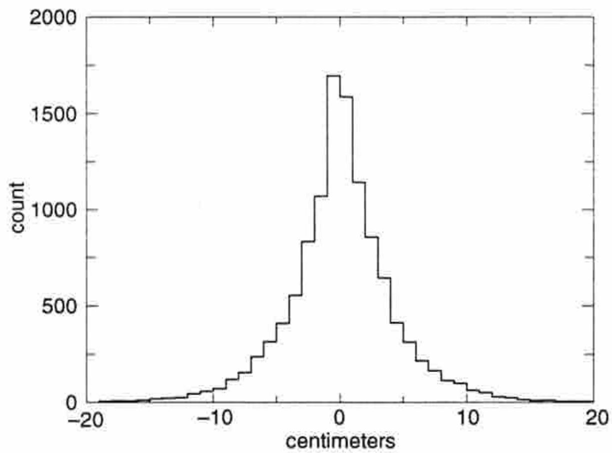

Fig. 6 - Histogram of acoustic slant range residuals from the 1995 near bottom survey at the Juan de Fuca Plate Cascadia Subduction Zone site (Chadwell, et al, 1996).