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Geodetic Measurements at Sea Floor Spreading Centers

F. N. Spiess
The Marine Physical Laboratory of the Scripps Institution of Oceanography
University of California, San Diego, San Diego, California 92152

Abstract. While space and terrestrial systems can provide the surface motion boundary conditions needed to constrain theories of tectonic driving forces and plate behavior on the large scale and in detail at some transform fault boundaries, the problems of new crust emplacement and its initial deformation as it is incorporated into the steady state plate motion at intermediate and fast spreading centers (5 cm per year full rate or greater) can only be attacked in the deep ocean floor. Advances in three areas of knowledge and experience make it feasible to design, deploy and use acoustic systems in that environment now.

The first area of advance is in our knowledge of the details of spreading center morphology and its implications. We now know that these areas typically consist of a band from a few hundred meters to a km. wide in which there are extensive pillow lava and sheet flows interspersed with occasional small conical peaks all completely devoid of any trace of sediment. Flanking this zone on either side is a region two to four times as wide in which there is extensive fissuring and some faulting with gradual buildup of sediment cover as one goes away from the central strip. Beyond that there is usually little evidence of tectonic activity, except for some additional fault displacement. The clear implication is that the transition from no lateral motion up to full plate speed takes place in a region usually less than 10 km wide and must involve strain rates of 10 microstrain per year or greater. How the strain buildup is distributed within this zone is the major question which sea floor geodetic measurements can answer.

The second area in which knowledge has been built up over the recent past is based on a growing quantity of horizontal temperature and salinity profiles made in these rise crest regions. These show that the small scale random inhomogeneities in sound propagation speed will not introduce errors of more than one or two cm over 10 km except for paths passing within 100 to 200 m. of an active hydrothermal vent. Since such vents are usually at least hundreds of meters apart, any system which is intelligently installed, incorporates sound velocity measurements (or their equivalent) in its survey techniques, and allows for spatial averaging will not be prevented by the environment from achieving cm. accuracy.

Finally, our operational experience with acoustic transponders in the less demanding geological mapping context, plus recently developed precision transponder designs, make it possible to build systems which will yield round trip travel time measurement accuracies of 10 microsec., corresponding to distance uncertainties of less than a cm. Transponder lifetimes of five years are available today, as well as procedures for replacing the units in a given network without loss of precision overall.

A network of 8 or more precision transponder units mounted on the sea floor and interrogated periodically from an instrument package towed near bottom through the area to provide the necessary spatial averaging could thus provide, today, a practical system for observing the pattern of buildup of strain at intermediate and fast spreading centers.

Introduction. Geodetic measurements can make significant contributions to the field of plate tectonics by providing the surface, kinematic boundary conditions which theories of driving forces and plate behaviour must satisfy. Terrestrial methods seem particularly adapted to delineation of strain patterns associated with transform faults as they traverse continental environments, particularly in the San Andreas region, but also in South America and Eurasia. Space techniques can provide larger scale observations of gross motions within and between plates and at present appear to be most applicable across trench zones and for determination of plate deformability, particularly when used in conjunction with detailed data from other sources at plate boundaries. The particular role of undersea methods is for detailed work at the spreading centers, since only short sections of these are available for terrestrial examination and even these are slow spreading and more diffuse than the typical rise crest environments.

As yet only the terrestrial techniques have achieved the centimeter precision which these problems require, and a number of the other papers in this meeting have been devoted to descriptions of land and satellite systems now under development to reach these goals. The purpose of this paper is to display the fact that undersea techniques, well matched to the rise crest strain measurement problem, can be assembled today in such a manner as to meet this challenge.

The advances which make this assertion possible have occurred in three areas over the last decade, primarily in conjunction with fine scale geological studies of the rise and ridge crests using deeply towed instrument systems (Spiess & Mudie, 1970; Spiess et al, 1976; Ballard et al 1975) complemented in some instances by submersible observations (Mid Atlantic Ridge, Galapagos Spreading Center). The three areas of advance are:

1. Delineation of the detailed morphology of a variety of typical spreading centers
2. Extensive observations of the structure of the immediately overlying water at several representative sites.
3. Successful operational use of acoustic techniques in a large number of deep sea sites in a geological mapping context (precisions ~1-2m) and development of equipment designs capable of pushing these

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capabilities to cm. accuracy.

Each of these three topics will be discussed below, followed by a description of a system configuration appropriate to the problem.

The special questions to which the rise crest data would be relevant can be visualized by anticipating a possible set of results. It seems quite likely that the large scale satellite measurements between points well into the interiors of two separating plates will show a steady drift at a rate comparable to that deduced from magnetic anomaly patters. It is equally likely that detailed measurements of the pattern of buildup of strain very close to the crest will show substantial irregularities with space and time, at least on the scale of meters and years. Anticipating the morphological data to be presented below, it appears likely that the "acceleration" from close to zero strain rate at the rise center to nearly full steady state plate velocity may take place in less than 10 km. If so then we should see relatively steady separation going on at the edge of that zone, while a description of what is happening now within the zone at a variety of sites and over times requiring some patience, may give us direct evidence as to the sequence of events and mechanisms involved in creation & stabilization of new crust; shedding light on the relative importance of the actual insertion of new material, of subsequent fissuring, of hydrothermal activity, of large scale faulting, etc. Determining the pattern of strain buildup across this zone is thus the problem we address.

Spreading Center Morphology

The major consideration which bears on the feasibility and form of a sea floor strain measurement system is the region it must span both across

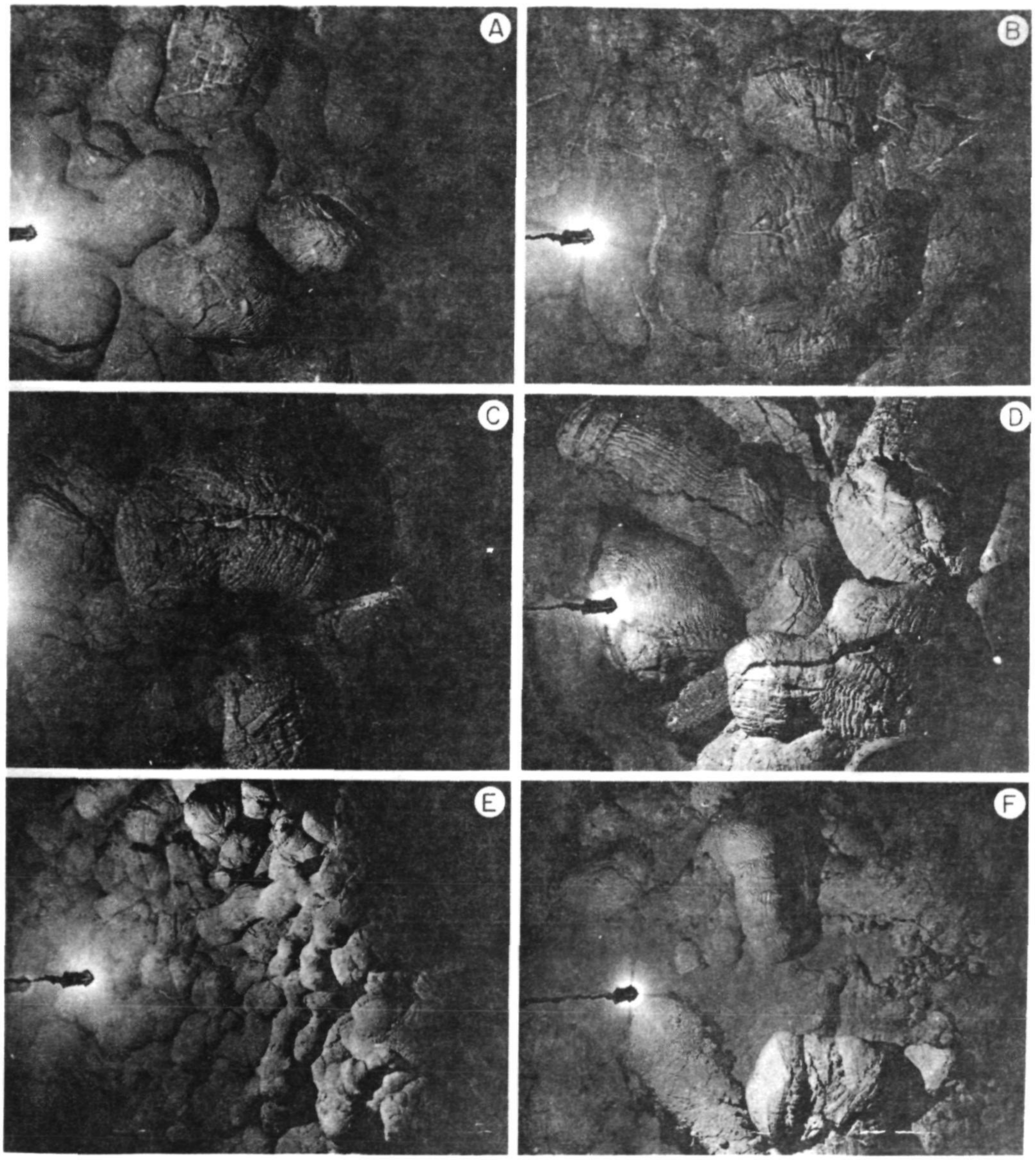

Fig. 1 - Fresh pillow lavas on East Pacific Rise Crest at 9°N.

and along the strike of the central zone. A variety of observations support the notion that the emplacement of new material and the acceleration of that material up to nearly full steady state plate speed takes place in a marginal strip not more than 5 to 10 km wide. The first piece of evidence in that regard has been with us since very early in the development of the field. As the magnetic anomaly patterns were recognized in many oceanic regions and as time scales were assembled it became clear that there were some distinct polarity epochs only a few km across and thus only a few hundred thousand years in duration. Quite consistently observed, for example, is the JARAMILLO normal event which occurred about 900,000 years ago with a duration of about 60,000 years. Widespread observation of this strip, which is only 2 km wide in intermediate (3 cm/yr half rate) spreading rate settings, carries a clear implication that the startup process must take place primarily over lateral distances certainly no larger than the width of that zone.

Near bottom magnetometer observations of the boundaries of these zones (summarized by Klitgord, 1975) show that they are quite sharp - complete reversals take place in strips ranging from hundreds of meters to a little over one km wide. A recent near bottom survey carried out at the Brunhes/Matuyama boundary near 21°N on the East Pacific Rise (Macdonald, et al, in prep.) covered a zone about 6 km along (and across) strike and showed undulations in the reversal line with an along strike scale of 0.5 to 1.5 km and across strike amplitude of 200 km. All this clearly indicates a highly localized process.

Moving in to the actual spreading centers it is quite clear from direct visual and photographic evidence that there is a highly localized (usually the order of a km or less) central zone in which most of the new material is being introduced. It is a region characterized by pillow and sheet flow lava forms, with fresh glassy facets and completely lacking any signs of sediment cover (Fig. 1) As one moves away from this zone, at least on the intermediate and fast spreading regions surveyed on the East Pacific Rise and Galapagos spreading centers (Larson & Spiess, 1969; Klitgord & Mudie, 1974; Normark, 1976; Lonsdale, 1977; Larson, 1971), there is an immediate flanking region a few km wide in which there is extensive fissuring and the beginnings of normal faulting. In this region the sediment cover also begins to build up in a fairly steady manner, although local irregularities preclude an assertion that this evidence demonstrates steady state motion on a time scale as short as 1,000 years.

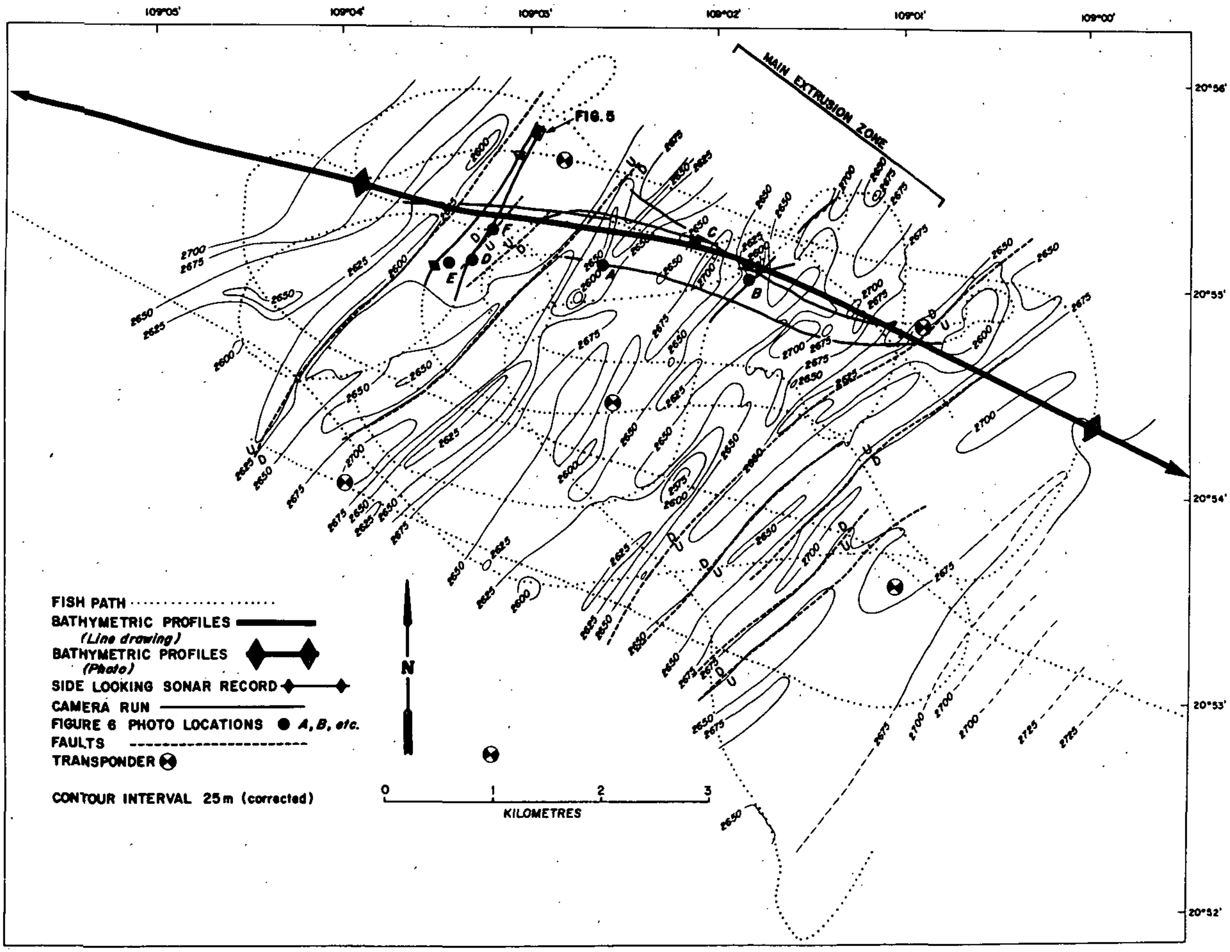

Fig. 2 - Fine scale topographic chart of East Pacific Rise Crest at 21°N. Full spreading rate 6 cm/yr.

Using data (Fig. 2) from the East Pacific Rise crest at 21°N (Normark, 1976) where the full spreading rate is 6 cm/yr, the total separation appears to be generated in a 6 km wide strip for an overall predicted strain rate of 10 microstrain per year. It seems likely that this will not build up in a spatially uniform manner, thus there should be intervals within this band which will show 2 or 3 times this value over distances of the order of a km or so. In a faster spreading environment (12 cm/yr full rate) at 9°N the region in which activity appears to be concentrated is somewhat more diffuse (Fig. 3), but still is less than 10 km for an overall rate of 1.2 microstrain per year and again an implication of local rates within the zone which must exceed this.

This all implies a requirement to determine distances between reference points a km apart to within about a cm in order to obtain useful data from an annual re-survey cycle. It also implies that, unless there is substantial deformation taking place within the plate, one should in fact see a very continuous displacement generated between the extreme edges of this zone.

A number of possible models can be postulated based on the evidence in hand, ranging from a primarily tensional picture across the entire zone with lava flows filling gaps in the center, to the other extreme in which local dike intrusions produce compression in their immediate vicinity and tension in adjacent along-strike zones. A network of measurement sites with one to three km spacing, extending across the entire zone and along

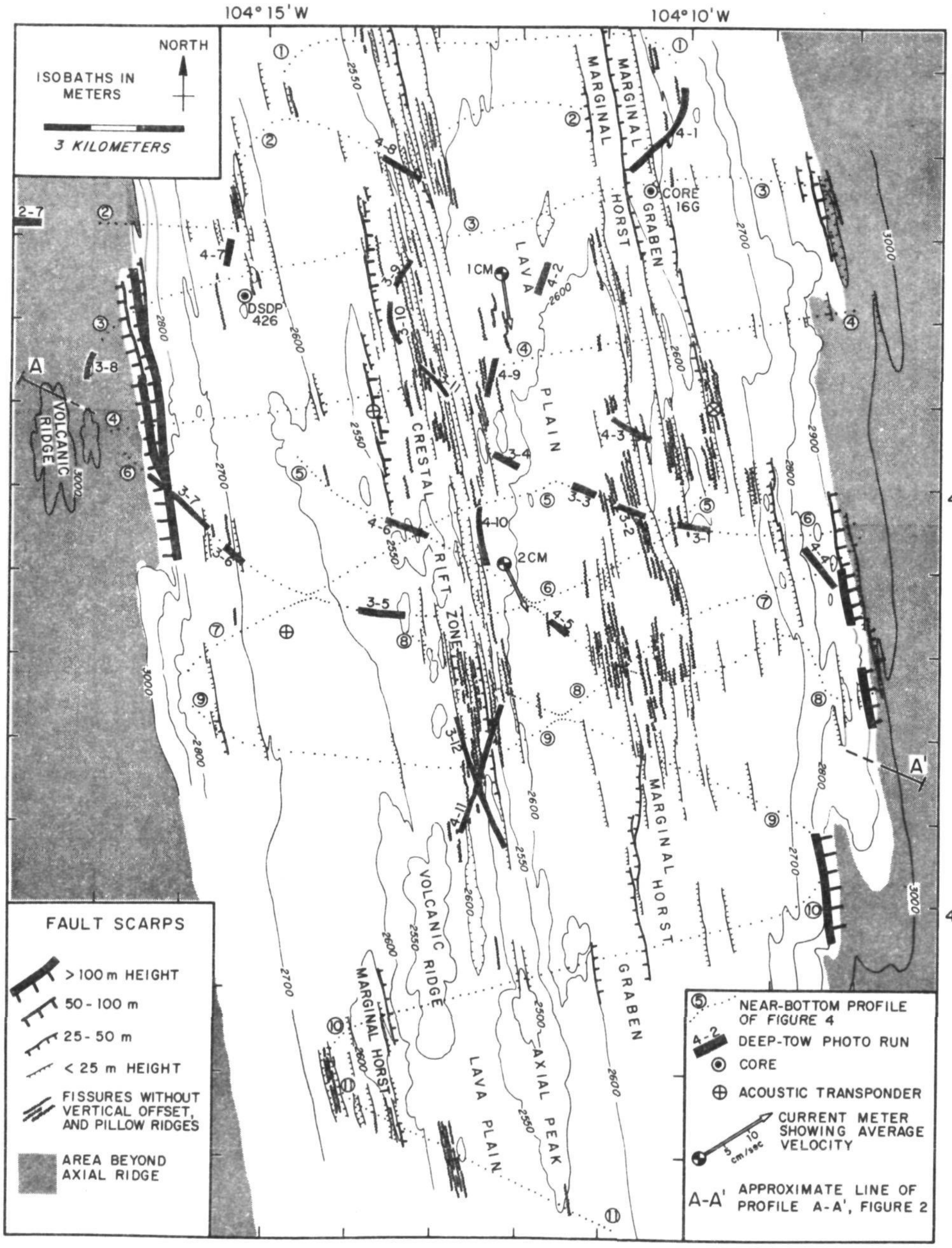

Fig. 3 - Fine scale topography at 9°N on East Pacific Rise Crest. Full spreading rate 12 cm/yr.

strike for several km would provide the necessary information to distinguish among the alternatives and place strong boundary conditions on the development of models for plate structure and driving forces.

Water Column Considerations

The two major concerns in the overlying water column are first, the attenuation of whatever radiation might be used for measurement of distance or angle and second, the nature of the index of refraction or energy propagation speed variations with time and space. In sea water the attenuation lengths for electromagnetic radiation are very short, generally only a few wavelengths, except as one approaches the optical regime. Even here, however, in the clearest water one can expect 1/e in 20 meters, making the km dimensions across the highly irregular central zone very difficult to achieve even with lasers or other optical systems. Acoustic energy is attenuated as well, with absorption increasing with frequency. The values are such, however, that a useful regime for km transmission with adequate bandwidth exists from a few tens of kiloherz to hundreds, with an optimum in the 20 to 100 kHz range strongly controlled by the nature of the background noise spectrum. The acoustic approach thus seems to be the most practical manner in which to attack the geodetic problem (Spiess, 1966).

Given a sound propagation speed of about 1500 m/sec this implies wavelengths of the order of a few cm. In turn this means that devices for accurate angle measurement must be quite large and confirms one's intuitive impression that distance rather than angle measurements are more appropriate to this situation.

The environmental factors that enter are thus the motion of the water and the irregularities in the sound velocity field. Currents of the order of 15 cm/sec are occasionally observed at rise crests, varying with tidal periods. While such velocitiies would produce appreciable effects on one way paths (a part in 10^{4}), when two way paths are used their influence drops to $\sim 10^{-8}$ which is far below the required 10^{5}.

The major limitation is the variability of sound velocity in the water due to temperature variations and, to a lesser extent, chemical effects. 0.003 C over the entire path length will give a change in sound speed of a part in 10^{5}. Such changes can occur over long times and large areas at many places near the deep sea floor. In addition there are hydrothermal effects at intermediate and fast spreading centers which can locally produce larger anomalies. It will thus be essential to couple into any acoustic measurement program of geodetic type a capability to determine the sound speed locally to the desired accuracy at the time of each survey. Laboratory measurements of sound speed to 10^{-6} have been made (Greenspan 1972) and, although today's oceanic sound velocity meters are usually good only to 10^{-4}, it appears that 10^{-5} is an achievable goal and such an instrument is under construction in the Marine Physical Laboratory at the present time (F.H. Fisher & E.D. Squier, private communic.).

With an in situ measurement capability of this type, one is still left with residual small scale variations in space and time which must be treated statistically. During several recent rise crest surveys (Galapagos spreading center, East Pacific Rise at 21°N and 9°N) we have made continuous near bottom temperature records over the central 10 km of the terrain (Crane, 1977; Crane and Normark, 1977). Typically, except within a hundred meters of the few active hydrothermal vents in the Galapagos area, the fluctuations are less than 5 mdeg, with scales of the order of 100 m. A number of authors have treated the problem of fluctuations in travel times as related to spatial variations of propagation velocity. One form is given (Chernov, 1960) roughly by:

$$\Delta t = \frac{\sqrt{2AR}}{C_o} \sqrt{\mu^2} \tag{1}$$

Here R is the one way path length, C_o the average sound speed, A the characteristic length scale of the fluctuations and $\mu = \frac{C_o}{C} - 1$. Converting this to a length error, E, recalling that we are using round trip travel times, gives

$$E = \sqrt{\tfrac{1}{2}}\,AR\,\sqrt{\mu^2} \tag{2}$$

The error thus grows as $\sqrt{R}$. Using A = 100 m and $\sqrt{\mu^2} = 10^{-5}$, the uncertainty ranges from a little over 2 mm at 1 km to 7 mm at 10 km, all well below the desired cm. precision. An additional safety factor can be introduced, as will be described in the section below, by arranging the system layout to provide substantial averaging over both space and time.

Technological Advances

Over the last ten years there has been a major step forward in ability to determine positions of devices in the deep sea through the introduction of acoustic transponders. Systems for this purpose are now in use on a regular basis by several research and operational groups. Most of the transponders are of the general type described some years ago by McGehee and Boegeman (1966), receiving a signal at one frequency in the 7 to 15 kHz range, recognizing it with some threshold device and replying at a second frequency. Power supplies giving a capability of 5 years in the ready receiving mode and 10^{6} output pulses are now in existence.

With a set of these units moored to the sea floor one can measure the acoustic travel times corresponding to the ranges between the vehicle or instrument package and several of the transponders and make a determination of its coordinates relative to that array. In our system the vertical coordinate of the vehicle is determined either by echo sounding on the sea surface or by a precision measurement of hydrostatic pressure.

While a number of operational computational approaches have been used the most sophisticated to be implemented to date is an adaptation of a method well known in geodesy. In this we start the survey using a set of rough approximate coordinates for the transponders and compute successive vehicle positions relative to these. In cases for which more than two simultaneous ranges are

..ailable a least squares criterion is used to determine the position and an error measure is calculated at the same time. The raw range data are stored and after the vehicle has traversed the area a number of times 50 or more well placed multi-transponder positions are selected and used in iterative fashion to determine an improved set of transponder and vehicle coordinates.

A carefully made survey for geological purposes result is in position uncertainties of the order of a couple of meters. This is quite adequate for the navigational need but obviously differs by a factor of 100 from the cm. uncertainties which represent both the required geodetic accuracy and one which is attainable relative to environmental limitations. The necessary improvements can be achieved by including more detail in the computational methods and using a more sophisticated type of transponder.

Current transponder designs involve a delay of a millisec or more in the recognition circuitry and lack of control of this parameter results in a contribution of the order of a meter to the timing uncertainty. We have designed and made in-water tests of a new approach which provides a very accurately controlled time delay (a few microsec) in the pulse retransmission process (Spiess, et al, 1978). Using this approach and pulses in the 30 to 40 kHz range, with signal to noise ratios in excess of 15 db, one can easily achieve resolution to 10 μsec, or less than 1 cm, on each transmission.

On the computational side the principal complications are that one must compensate for motion of the survey package while the sound pulse is in transit for several seconds and take into account the substantial variation of sound speed with water depth. These are aspects which merely dictate that care is exercised in developing the detailed computer programs to be used.

With these improved transponders and computational methods one can begin to gather the data necessary to determine strain change distributions at rise crests over prolonged periods. The most logical approach is to install a network of 10 or more units in the area, with spacings along and across the crest ranging from one to three km with the exact layout dictated by the detailed morphology of the particular site. Each resurvey operation (done on a time scale of months to one or two years, depending on the spreading rate) would be carried out by towing the survey package close to the sea floor through the area, ranging on the transponders and measuring the sound velocity. By using many multiple transponder fixes and calculating the network geometry from the moving vehicle one provides means for spatial averaging over the sound speed inhomogeneities as well as smoothing other random errors. The network elements can be replaced without precision sea floor operations by installing the new units close to the old prior to a survey operation and removing the old ones for refurbishing after the entire augmented network geometry has been determined.

It thus appears feasible, given the narrow zones of activity and the rapid spreading rates, to match underwater acoustic techniques to the problem of determining the strain buildup patterns in these areas on time scales ranging from months to decades.

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