Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Seafloor Geodetic Networks for monitoring tectonic plate motion and deformation

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This paper argues that seafloor geodetic networks, monitoring tectonic plate motion and deformation, supplementing terrestrial geodetic networks, can provide important information for the understanding of crustal processes, globally. The proposed monitoring system consists of 3 main components: real-time kinematic-differential GPS ship positioning, precise acoustic ranging between ship and seafloor transponders -which establish the network nodes- and near bottom direct acoustic measurements of the network baselines. The coordinates of the transponders in a geodetic reference system can be determined from these observations and a sound-speed structure model. The motion and deformation of the tectonic plate can be traced as a change of coordinates and/or the internal geometry of the network. Stochastic and mathematical models, algorithms and data analysis are crucial for achieving the necessary accuracy in such a demanding process regarding seafloor position estimation.

1 Introduction

In recent years, with the development of space-based geodesy and mainly Global Positioning System (GPS) techniques, global terrestrial networks have been established for the study of tectonic plate motion and deformation. However, due to the fact that 70% of the Earth is covered with water, there are large gaps in global coverage. Islands are good indicators of the motion of the underlying plates, but often they will not be found in large ocean areas. Furthermore, islands are typically absent in the vicinity of underwater plate boundaries, which are some of the tectonically most active areas of the Earth [1].

Direct ocean bottom monitoring seems to be the answer, but in this case techniques that use electromagnetic energy that is attenuated quickly into sea water are unsuitable. On the other hand, acoustic energy can travel long distances into the sea water, and the development of the relevant equipment has been intense over the last decades. Combined GPS/Acoustic systems have made possible the establishment of seafloor geodetic networks linked to the global reference datum to monitor underwater plate dynamics. Ocean bottom data can supplement terrestrial observations to provide global coverage.

2 System Description

The proposed system consists of 3 main components: dGPS surface positioning, precise acoustic ranging between the ship and seafloor transponders which represent the network nodes, and near-bottom direct acoustic baseline measurements of the network (Fig.1).

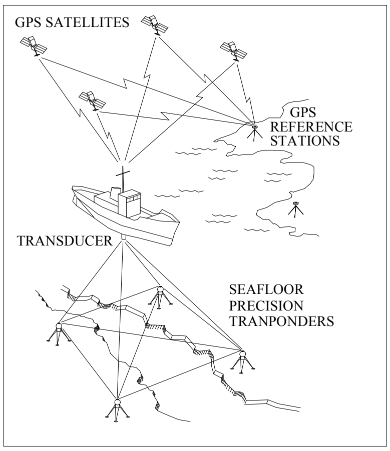

Figure 1. Combined dGPS /Acoustic System

The coordinates of the network nodes can be determined from all the above data through a stochastic solution. Tectonic plate motion and deformation can be traced as a change of coordinates and/or of the internal geometry of the network [2]. Although crust deformation during violent geological events, such as earthquakes and volcano eruptions can reach many meters, the typical long-term rate of plate motion is 5-10cm/year [1, 3]. That implies that the coordinates of the network nodes must be estimated with an accuracy of a few centimetres. Repeated network surveys once or twice a year should reveal the long term rate of plate motion after a few years.

2.1 Long-BaseLine (LBL) acoustic positioning system

The proposed system is based on a LBL underwater acoustic positioning system. An LBL system has two segments. The first segment comprises a number of acoustic transponders moored on the sea floor with known coordinates in a local or global datum. The distances between them form the ‘baselines’ used by the system. The second segment comprises an acoustic transducer which is normally installed on the hull of a ship.

The distance from the transducer to a transponder can be measured by transmitting an acoustic signal from the ship, which the transponder detects and after a known delay-time transmits an acoustic signal in response that is received by the ship. The two-way travel time is measured and is converted to slant range multiplied by the sound speed. In this application geodetic precision transponders are used, that have the ability to interrogate each other when triggered by a signal from the ship, so as to perform direct measurements of baselines. The collected data are stored and transmitted to the ship.

2.2 GPS equipment

Collected data on board should include single and double frequency pseudo-range and carrier-phase measurements. In addition shore reference stations provide the necessary corrections to effectively eliminate common errors such as satellite clock bias, ionospheric and tropospheric delay. The ship is equipped with a set of GPS antennas (ideally at least 4 antennas are used to provide redundancy). Data from the main antenna are used for determining ship position and velocity at 1sec intervals.

The achieved positioning accuracy depends on the distance from the shore reference stations. For distances of 30-50km an accuracy of 1-2cm can be expected, reduced to 10cm for a distance of 100km [4, 5, 6]. The combined data from all antennas are used to determine the ship's 3-D attitude at 1sec intervals.

2.3 Estimation of the ship's transducer position

Since the geodetic position of the ship's transducer at the times of transmissions and receptions of acoustic signals represent the reference points of the acoustic measurements, they have to be determined with the highest possible accuracy. GPS positioning refers to the main antenna on the ship's mast, while the transducer is located on the ship's hull several meters below. Precise measurement of their relative position will provide a vector between them with an accuracy of a few mm [7].

The problem is reduced to determining the instantaneous orientation of the vector at the times of transmissions and receptions of acoustic signals from the GPS data, since the ship should be considered to be in a constant motion. The acoustic positioning system is synchronised to the GPS system so that the time of transmission coincides with a GPS position determination, thus the vector orientation is known. At the time of reception the vector orientation is determined by linear interpolation between the two adjacent GPS position determinations.

2.4 Direct measurements of seafloor network baselines

These measurements have a distinct advantage. Since all seafloor transponders are located at more or less the same depth, acoustic signals follow paths close to the sea bottom where temperature and salinity are almost constant and sound speed variation is due to pressure change with depth only. Taking readings of the temperature and pressure sensors at each transponder is all that is necessary to accurately estimate the baseline lengths.

On the other hand, in order to ensure that direct acoustic paths between transponders exist, sea bottom bases (tripods) have to be used that place the transponders a few meters above the sea bottom. For a smooth sea bottom a height of 3m should ensure direct acoustic paths over distances up to 1500m. Because much higher bases are prone to get displaced by currents, the network will be designed around this baseline length.

3 The basic problems of acoustic measurements

3.1 Estimation of Sound Speed

The seawater medium is strongly stratified and exhibits large spatial and temporal changes of its acoustic properties. Estimation of sound speed is complicated as it is affected by temperature, salinity and pressure. Before an acoustic measurement can be made, a sound speed profile of the area is needed. Traditionally this is accomplished from CTD measurements by using an empirical formula. The Del Grosso formula, which is considered to be the most suitable for deep water applications and long distances, at best provides an accuracy of 0.05m/sec, when temperature, salinity and pressure are measured with an accuracy of 0.003^{o}C, 0.001mS/cm, and 1dbar (1m) respectively [3]. In practise errors up to 2m/sec are not unusual [8].

In addition CTD measurements only provide information at specific points of the water medium and at specific times. The created sound speed structure lacks fine detailing and refers to a certain time. Regarding precise acoustic measurements the accuracy and spatial and temporal density of CTD measurements are insufficient, especially for dynamic environments where temperature and salinity change quickly with time.

Underwater positioning poses one unique difficulty not to be found in ordinary terrestrial positioning. The basic observable is a measured travel time of an acoustic signal between a source and a target, and the slant range between them is to be estimated. However, the travel time is related to the refracted acoustic path, not to the slant range. In addition the sound speed constantly changes in the various layers of the water medium.

Equations that convert a measured time to slant range require a constant 'mean' sound speed that is related to the slant range. This 'mean' sound speed depends on the positions of source and target and the sound speed profile, and has to be estimated for each measurement. Under some assumptions ray-tracing methods address this problem.

From the above it should be clear that the construction of a sound speed profile and the subsequent estimation of a 'mean' sound speed are far from ideal and, although acceptable for ordinary field work, can result in a significant a priori error in high accuracy applications.

3.2 Estimation of Time – Of –Arrival (TOA) of an acoustic signal

Every acoustic positioning system has to address two problems at the same time: identification of a valid acoustic signal in a noisy environment and accurate estimation of its time of arrival. The first problem requires a high Signal to Noise Ratio (SNR) which means long signal duration and/or high Source Level (SL). Due to the constructional limitations of transducers and the increased energy requirements that severely limit the battery life of underwater transponders, the logical choice is to use signals of relatively long duration that provide sufficient SNR. The variance of the TOA is given by the following equation:

$$\sigma_{TOA}^2 = \frac{1}{\overline{B}^2 \cdot SNR} \quad (3.1)$$

Where: B² the mean square bandwidth of the signal. From Eq.(3.1) it is evident that to achieve higher accuracy in TOA estimation (i.e. to reduce the variance) SNR and/or B have to be increased. These two requirements are contradictory for conventional sinusoidal signal with B = 1/T, where T is the duration of the signal, because decreasing T will increase B but it will also decrease SNR.

The key to improving the accuracy of acoustic measurements is the use of digitally modulated signals which are based on a pseudo-random sequence of digits 0 and 1 that may look like random, but in reality follows a mathematical algorithm (M-sequence). Such digitally modulated signals, even with relatively long duration for a good SNR, exhibit a high value of B and excellent autocorrelation properties that allow very accurate TOA estimation [9]. Phase modulation, where the digits 0 and 1 correspond to signal phase 0 and π radian is the commonly used technique in underwater tectonic plate monitoring applications. The highest accuracy achieved in TOA estimation is of the order of ±5μs which is equivalent to 4mm of distance [3, 7].

3.3 Reduction to static geometry

The ship in the open sea, even when stationary as during an acoustic measurement, is expected to drift slowly and rotate around one or more axes because of wind, wave, tide and current action. As a consequence, the position of the transducer will change between the times of transmission and reception of an acoustic signal. For example assuming a drift speed of 1knot (0.5m/sec) and a two-way travel time of 3sec the change of position will be 1.5m. Similarly to other dynamic situations, the problem can be reduced to a static one. The transducer position can be considered to be fixed during an acoustic measurement at the mean geometric position between the two true positions at the times of transmission and reception (Fig.2).

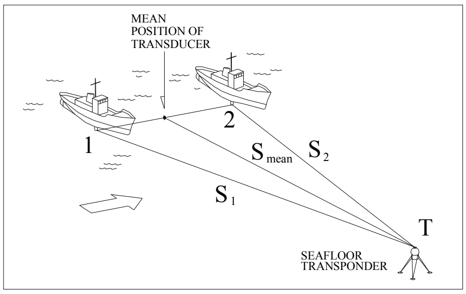

Figure 2. Reduction to static geometry

Given that the distance 1-2 is very short compared to the slant range, taking $S_1+S_2=2S_{mean}$ does not introduce a significant error. A more accurate estimation of the mean transducer position would involve modeling of the motion of the transducer based on the continuous GPS data [2, 10].

3.4 Quantity and Distribution of the measurements

For a static problem, the quantity of the available measurements determines the number of simultaneous equations that can be formed to estimate the state vector. For a dynamic problem, the quality of the measurements alone does not guarantee that a reliable estimation can be obtained. Rather, it is the combination of the state transition matrix and the available measurements that govern the observability of the system.

The ability to obtain a highly accurate estimate for the state vector depends not only on the quality of the measurements but also depends heavily on the distribution of the measurements. The distribution is governed by the relative geometry between the transducer and the transponders and a measure for this is the Geometric Dilution of Precision (GDOP). The GDOP is computed from the matrix Q_x which is obtained by taking the inverse of the Jacobian matrix H, so Q_x and GDOP depends on the model used. As an example:

$$Q_x = (H^T H)^{-1} = \begin{bmatrix} q_{xx} & q_{yx} & q_{zx} & q_{tx} \\ q_{xy} & q_{yy} & q_{zy} & q_{ty} \\ q_{xz} & q_{yz} & q_{zz} & q_{tz} \\ q_{xt} & q_{yt} & q_{zt} & q_{tt} \end{bmatrix} \quad (3.2)$$

Where GDOP is defined as (this definition for GDOP is the most common)

$$GDOP = \sqrt{q_{xx} + q_{yy} + q_{zz} + q_{tt}} \quad (3.3)$$

The GDOP matrix is a matrix without dimensions that characterizes the geometrical effects on the accuracy for each variable in the state vector [9].

In practice, it would seem that the optimum positioning of a transponder as the intersection of spheres (or circles for the 2-D solution) centered at the various positions of the ship's transducer, would be accomplished when the angles of intersection are close to 90°.

In deep water acoustic positioning an angle of intersection close to 60° or less is preferable. This reduces the amount of ray bending that occurs, as the more vertical the ray path the less the bending. Also for ray paths closer to the vertical, the most efficient part of the transducer beam is used and a greater SNR will be provided. An intersection angle of 60° gives a horizontal distance from the points of observations to the transponder of about 0.6 the transponder depth.

The best method of determining the coordinates of a sea floor transponder is to perform slant range measurements from symmetrical positions around the transponder. Two sets of measurements along N-S and E-W axis are sufficient.

Potentially the most significant degradation of positioning accuracy results from sound speed estimation error. A timing error of the acoustic system will also show itself as a constant error. By balancing the observations, the effect of both errors is eliminated to a large extent in the 2-D horizontal position determination (Fig.3).

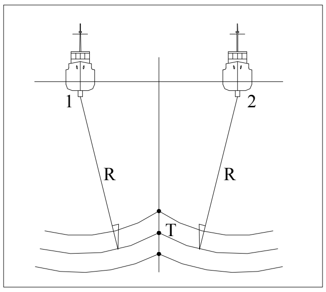

Figure 3. Symmetrical measurements around a transponder

As can be seen, symmetrical measurements, even with slant ranges that are shorter or longer than the correct, place all possible locations of T on a vertical line. A good geometry with less precise observations can actually provide a far better result than precise observations with weak geometry.

Of course, the errors will be evident in the determination of depth. By taking a measurement directly above the transponder, a sound speed error will be highlighted, as this path is less affected. The transponder pressure sensor is the most reliable source of information for depth estimation.

4 Underwater Geodetic Networks

Objective quality control is a requirement for any survey independent of the actual accuracy of the survey. Least-squares adjustment has been associated mainly with high – precision surveying. In deformation monitoring the detection of the motion can be verified only with the help of least-squares formalism and inherent statistical analysis capability. This is particularly true if the magnitude of the suspected motion is nearly that of the measurement precision.

Any least-squares adjustment deals with 2 equally important components: mathematical and stochastic models. The observations are the primary input to the adjustment and are random variables. The true values of the observations are estimated during the adjustment on the basis of the particular set of observations made. The variances of these observations comprise the stochastic model which introduces information about the relative precision of observations [9].

A mathematical model expresses a simplification of the existing physical reality and it attempts to express mathematically the relations between observations and parameters or unknowns of the adjustment (i.e. the coordinates of the network nodes in this application).

In underwater acoustic positioning systems the fundamental observable is a timing measurement which is converted to a range measurement based upon a presumed propagation velocity. Using these measurements and the coordinates of the ship's transducer at the times of the measurements yields a set of non-linear equations that simultaneously must be solved to obtain an estimation of the transponder position. Position estimation problems can utilize 3 types of mathematical models – spherical, hyperbolic and elliptical – depending on the particular problem.

In this situation the reference transducer transmits an acoustic signal at time t^e which the transponder detects and, after a known delay-time t^d, sends a reply which arrives back at the transducer at time t^a. The mathematical positioning model is:

$$2R_i = c_i(t_i^a - t^e + t^d + t^b), \qquad i = 1,2,......,N \quad (4.1)$$

Where

$$R_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} \quad (4.2)$$

R_i: is the geometric slant range between transducer and transponder, t^b the unknown acoustic system timing bias and c_i the 'mean' sound speed for the particular measurement.

Ray-based models have been used for many years in underwater acoustics and are still used extensively in the operational environment where speed is a critical factor and environmental uncertainties pose severe constraints on the attainable accuracy [11].

In an inhomogeneous medium the propagation velocity varies spatially and conversion from transit time to distance is not straightforward. Under some assumptions this can be handled. First, the ray theory is valid and a ray-tracing model based on Snell's law can be used to model the underwater sound propagation. Second, the propagation from the transducer to transponder is direct and third, the speed of sound varies only with depth.

In this application the depths of the ship's transducer and the sea floor transponders are known. Ray-tracing can be performed a priori to create a table with sound speed values for the particular ray paths only. This avoids to some extent the conventional time consuming iterative procedure. Also it provides a means of incorporating the earth's curvature through the use of an ellipsoidal coordinates system which matches well deep sea underwater positioning.

The basis of the network is a rectangle, as this is the minimum shape that provides information with redundancy. To cover larger areas this can be extended as needed. The coordinates of the network nodes provide the necessary information to determine the absolute movement of the underlying tectonic plate, as well as the relative movement between adjacent plates (i.e. rotation, divergence or convergence and sliding).

To determine the absolute movement of a plate, the network should be placed at a steady location, well away from the plate boundaries. Long baselines are advantageous in this application.

Many times though, the relative movement between adjacent plates is equally important. In that case the network must be placed close to the common boundary and the design of the network depends heavily on the characteristics of the deformation zone. If deformation is confined to a relatively narrow area along a plate boundary (less than about 800m wide), direct baseline measurements are feasible. As discussed above, these measurements between sea floor transponders offer high accuracy but limit baseline length to about 1500m. Two pairs of transponders at opposite sides of the deformation zone, about 1000m apart, constitute the basic network (Fig.4).

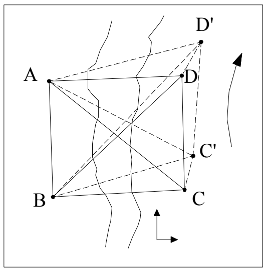

Figure 4. The basic network for a narrow deformation zone

The relative movement between the two adjacent plates can be traced directly as the change of the internal geometry of the network as well as a change of the network nodes coordinates. In situations where the deformation zone is wide, it is best to use two separate networks, outside the deformation zone (Fig.5).

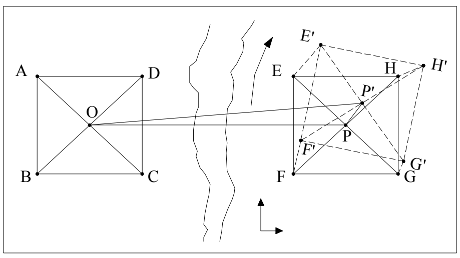

Figure 5. Separate networks for a wide deformation zone

Each network determines position and orientation of its respective plate. The relative movement between the two adjacent plates can be traced as a change of orientation of the two networks and a change of the vector between the centers of the two networks. In this case no change of the internal geometry of the networks is expected and there is no need to limit baselines as before.

5 Conclusions

Monitoring of underwater plate motion and deformation with the establishment of sea bottom networks can provide valuable information to supplement terrestrial observation and provide global coverage. For the collected data to be meaningful, the network nodes have to be estimated with an accuracy of a few centimeters in a global reference datum.

Today, this seems to be a difficult but achievable goal by using combined GPS/Acoustic Systems. Potentially any iterative least square solution will provide the optimum results, as long as the mathematical model chosen describes correctly the actual physical situation, the correct algorithm is applied, the geometry of the measurements is rigorous, the observations are of high quality and, perhaps most significantly, the correct weights are assigned to the individual observations.

Systematic errors due to limited knowledge of the sound speed in sea water and timing bias have to be handled carefully. It is proposed that such errors be addressed as additional parameters to be estimated simultaneously with the coordinates of the network nodes. This modeling of errors prevents error propagation to the coordinates and allows the establishment of reliable, high accuracy underwater geodetic acoustic networks.

A ray-tracing method that calculates a priori a table of sound speed values facilitates the iterative procedure of the estimation of the 'mean' sound speed, provided that detailed sound speed profiles have been constructed.

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