ENHANCING THE CONTRIBUTION OF THE T-STATIONS OF THE IMS HYDROACOUSTIC NETWORK TO IDC PROCESSING AND TSUNAMI WARNING

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ABSTRACT

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is exploring methods to enhance the operational hydroacoustic processing system for its International Monitoring System (IMS). The hydroacoustic IMS network includes two types of stations, the in-water hydroacoustic stations, consisting of multiple sets of hydrophone triplets, and the land-based T-stations, consisting of multiple seismometers. Hydrophone triplets record signals that efficiently propagate in the SOFAR channel over large distances. Processing at the International Data Centre (IDC) classifies these signals into three types (T for underground-generated, H for in-water generated, and N for noise) and determines a direction of propagation, exploiting the multiplicity of sensors. Current efforts are underway to enhance the accuracy of the classification methods. However, the processing in place at the IDC is already quite mature for hydrophone stations. T-stations, on the other hand, present the double disadvantages of a lower detection threshold for in-water propagated hydroacoustic signals and high sensitivity to the geometry and geology of the seismometer emplacements, as opposed to hydrophone triplets located in the much more homogeneous water medium.

In spite of these handicaps, the T-stations do already contribute to the IDC bulletins, mostly by detecting T-phases from events at a higher threshold than hydrophone stations. It would be desirable however to augment the quantity and quality of their contribution to the IDC bulletins. We are presenting the results of attempts at using the multiplicity of seismometers to determine a direction of propagation at the T-stations. In the course of exploring several avenues, including the study of polarization of signals recorded at the two three-component H06 (Socorro Island, Mexico) broad-band seismometers, we have also re-discovered their potential for civil application to tsunami warning because of their recording of long-period horizontally polarized oscillations concomitant with the arrival of the tsunami at the island’s coast.

OBJECTIVES

Near-coast seismometer stations (T-stations) are used in the IMS because of their potential (deGroot-Hedlin, 2001) to detect water-borne signals from in-water explosions (H-phases) and crustal events (T-phases). Detection of such signals is complicated by losses in signal intensity and distortions in signal shape incurred when in-water signals couple into seismic waves across the coastal margin. Coastal seismometers suffer further from high levels of surf noise and this problem is particularly strong on horizontal channels. This makes it difficult to estimate arrival azimuth from polarization analysis of seismometer signals. Such azimuth information would be valuable in signal association processing that estimates source time and location, based on observations of arrival properties on spatially distributed sensors. The objective of the research reported here was to investigate two possible methods by which some measure of arrival azimuth could be extracted from seismometer signals from IMS T-stations.

RESEARCH ACCOMPLISHED

Two separate approaches were followed in an attempt to extract arrival azimuth information from seismometer recordings. In the first, polarization analysis was performed on the horizontal channels of coastal seismometers. In the second, envelope correlation was used to determine time lags between signal arrivals at spatially separated seismometers in the same T-station. These approaches are now described separately.

Polarization Analysis

The basic task of the vector signals polarization analysis is the determination of the degree of fluctuation of the linearity of a displacement vector signal and its orientation. The best-known methods of polarization analysis consist of those based on the use of sign and time dependences of orthogonal components of a displacement vector, spectral and covariance methods, etc. They interpret the movement of the end of a displacement vector of a seismic wave either on a line or on an ellipsoidal surface. Such vector signal presentation is not optimal, as it results in the loss of important information concerning polarization structure in a number of cases. A vector harmonic signal polarization is characterized by a flat figure, namely an ellipse, which can degenerate into a line or a circle in some cases. Thus the geometrical parameters of this ellipse such as the location of the plane containing the polarization ellipse in space as well as the ellipse in this plane is often used to estimate the direction to the source or the wave type. When the signal is not harmonic and the vector describes an ellipsoid, this information is lost. In addition, the usual methods of polarization analysis are integral and thus degrade the time resolution. They assume the processing of a part of records with the usual duration of not less than a fluctuation period for finding of the averaged parameters of the equivalent ellipsoid. In cases when the parameters change within a shorter period of time, data connected with these changes is lost.

Thus, it is useful to test the Differential Polarization Analysis (DPA), which is described in Shevchenko, (2002), which allows interpretation of the movement of displacement vector in space along an equivalent polarization ellipse in each point of the real three component seismic records. The standard Flinn's Polarization Analysis (FPA) interprets movement of a displacement vector on a surface equivalent ellipsoid. As a result, the DPA has new specific features: the ability to allocate the current position of a plane containing an ellipse of polarization of a seismic wave. On a normal to this plane, it is possible to search for the direction of the source through the transversal S-waves in the short-period band, and the Rayleigh-LR surface waves in the long period band. This constitutes an advantage over the FPA method.

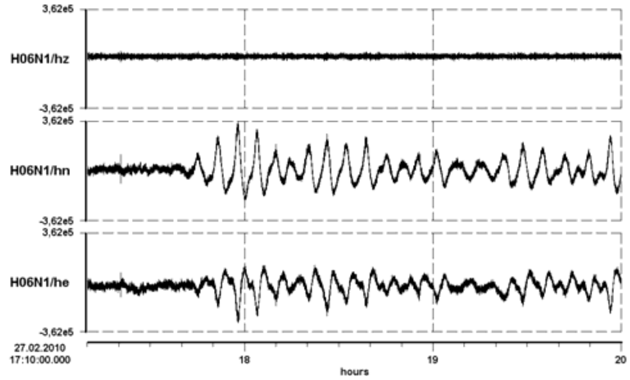

Figure 1. **Long-period fluctuations on the raw broad-band seismograms at station H06N1, beginning at the expected arrival time of the tsunami wave from the Maule event. The wave is seen on the horizontal components (*he* and *hn*), but not on the vertical (*hz*).**

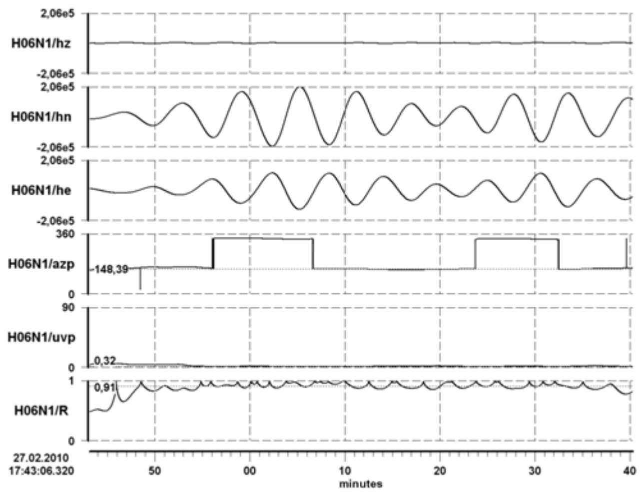

Figure 2. **Long period observations record at stations H06N1 in the 0.001-0.004 Hz frequency band.**

The method was tested on the H06 (Socorro island) T-station to determine if a polarization could be discerned on the three-component seismometer at the time of arrival of T-phases. The results were disappointing. One basic problem noted at T-stations is the strong micro-seismic noise from ocean surf. The noise spectrum occupies a wide frequency band, and the recording of T-phase signals in the short-period band is especially affected by this noise. It has not been possible to determine a direction of polarization for T-phases at T-stations, and therefore no enhancement of the system is possible along these lines.

In the course of investigating the signals at T-stations however, in a frequency pass-band at much lower frequency than the band optimal for T-phases, we re-discovered the potential for T-stations to be used in a tsunami alert system, as was first suggested by Okal (2007) and we made the observation that two of the stations at Socorro observed low-frequency signals on the horizontal components. The signals are associated with the passage of the tsunami wavetrain from two different tsunamigenic events. Figure 1 shows the long period fluctuations recorded by the northern seismometer H06N on Socorro Island during the passage of the tsunami generated by the February 27, 2010, Maule, Chile earthquake. The same components are displayed in Figure 2 along with the rectilinearity trace, *R* and the azimuthal direction trace, *azp* determined by the polarization analysis. The seismic traces are shown filtered in the 0.001-0.004 Hz frequency band in the first hour of the fluctuations. It is clear from this figure that the rectilinearity of these fluctuations is very good and the azimuth of the polarization is constant during that time.

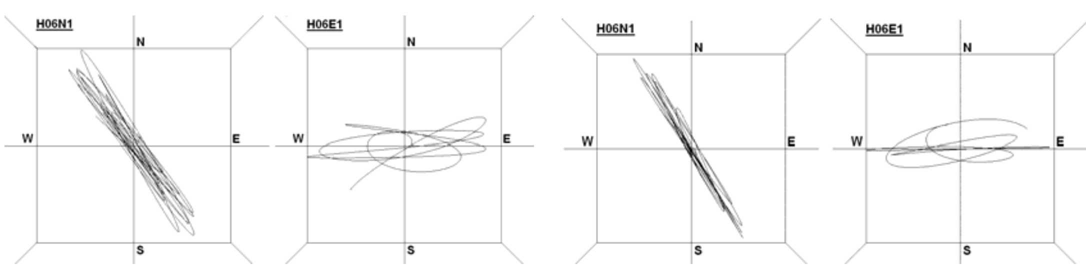

Figure 3. **Particle-motion hodographs in the horizontal plane for long period fluctuations at station H06N1 and at station H06E1 from the Samoa event (left) and the Maule, Chile event (right). Note the similar long-period elastic response to the tsunami loads from two events located at opposite ends of the Pacific.**

Figure 3 shows a particle motion hodograph of the fluctuations during the same time period as shown on Figure 2 for both the H06N and H06E stations. In both cases, the direction of polarization is clear, particularly for the northern station. The direction of polarization for the northern station H06N corresponds quite closely with the direction of propagation of the tsunami from the Maule event, which would fit well with the explanation given by

Okal (2007) for the observation of long period fluctuations coincident with the passage of tsunami waves. This is however purely coincidental, and this is demonstrated by the fact that the same polarization pattern is found for a tsunami generated by the September 29, 2009, earthquake from the Samoa Islands region. Furthermore, the polarization on the H06E station is in a different direction. In both cases, the polarization is the direction of the nearest shoreline. These observations, based on two different tsunamis whose sources are located at opposite ends of the Pacific Ocean indicate that we are observing a local disruption in the strain field of the island due to the passage of the tsunami. Our preferred explanation, elaborated on in a separate future publication, is that the island's strain field is responding elastically to the load of the very long wavelength tsunami on the walls of the island. The wavelength of the open ocean tsunami is long compared to the size of the island and the passage of the tsunami can be modeled as a slow rising and lowering of the water level around the island, inducing lateral pressure on the island's shore at sea level which successively squeezes and releases the body of the island.

Envelope Correlation

Seismic waves generated when in-water sound hits the coast are attenuated rapidly with distance from the coast. For this reason, T-stations in the IMS include multiple seismometers, installed near coastlines that face in different directions. While this geometry is not ideal for the detection of individual signals on multiple seismometers, there remains the possibility that such detections may occur. If the time lag between arrivals at separate seismometers could be estimated reliably then it could be possible to estimate arrival azimuth on the basis of that time lag. Similar lag-based processing is used when processing IMS hydrophone data but the situation is more complicated for seismometer stations for many reasons. First, the seismo-acoustic medium is not homogenous for the seismometer stations and the propagation between sensors may take place partly in water, partly in rock. Second, attenuation in the crust is higher than in the water so a signal clearly detected on one seismometer might be below the noise level at the other if its path has a significantly greater crustal element. Further problems arise from reduced signal-to-noise ratios and increased signal distortions, relative to the hydrophone sensors.

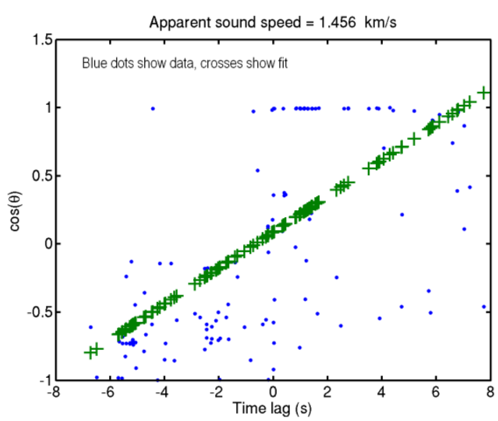

Figure 4. Relationship between time lag between arrival at two seismometers and cosine of angle made with line joining those seismometers.

These considerations meant that it was first necessary to determine if a functional relation actually existed between observed time lag and arrival azimuth. The data in Figure 4 show the results of such an investigation. The Reviewed Event Bulletin (REB) produced from automatic and analyst processing of IMS data was inspected for events that generated T-phases that were detected at both the north and east seismometers of the T-stations at Socorro Island, off the Pacific coast of Mexico. Envelope correlation of these signals was performed and the time lag between signals that showed significant correlation was determined. The arrival azimuth of the signals was taken from the "map azimuth" between the mean seismometer location and the REB event location. The cosine of the angle between the line joining the two seismometers and the arrival's incident direction is plotted on the y-axis in Figure 4 and the time lag is shown on the x-axis. The dots in the figure show the individual points and there is considerable scatter but a noticeable trend from bottom-left to top-right. The crosses show a linear curve fit to the cosine and time-lag data. Evidence for the existence of a functional relationship between cosine of angle and time lag is taken from the slope of the linear fit. For a homogenous medium, this gradient is determined by the seismometer separation and the local sound speed. Since the seismometer separation is known, the gradient of the line can be used to produce an effective local sound speed. As stated in the figure, this value was 1.456 km/s, a value close to a physically sensible estimate for the seawater sound speed.

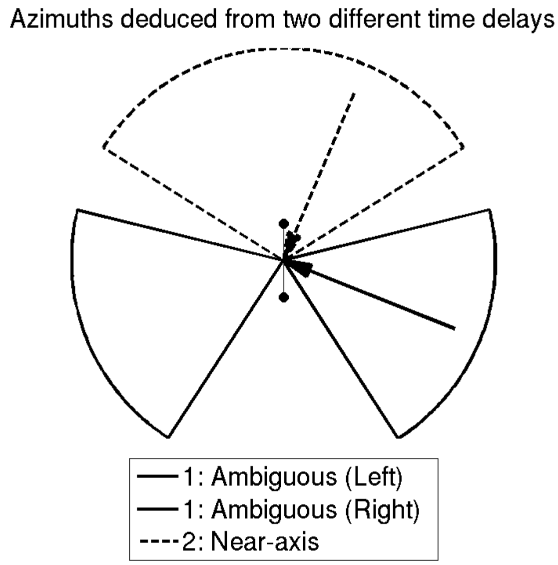

Figure 5. How measurement precision changes with azimuth.

The data shown in the figure were taken as confirmation of a functional – if noisy – relationship between lag and angle and the analysis proceeded. The precision of the relation was taken from the standard deviation of the residual between observed and line-fit values of the cosine. It was deduced that it was possible to determine cosine of incident angle on the basis of an observed time lag to a precision of +/- 0.5.

The important features of the relationship between the arrival azimuth of a signal and the precision to which it can be measured are illustrated in Figure 5. The solid arrow shows the direction at which a signal arrives from the right of the line joining the lower seismometer to the upper. The cosine uncertainty of +/- 0.5 translates into an azimuth uncertainty represented by the sector on the right-hand side, marked in a solid line. However, this single sector does not represent the whole uncertainty since the same time lag would have been observed had the signal arrived from the left-hand side at the same angle to the line joining the seismometers. Thus, the arrival represented by the arrow gives rise to a time lag that identifies the arrival azimuth as being anywhere within the left OR right-hand sectors. This situation represents a left-right ambiguity. If the arrival direction is changed to lie closer to the line joining the two seismometers, two effects occur. First, the width of the two sectors increases as the constant uncertainty in the cosine of the angle equates to an increasingly large uncertainty in that angle. Eventually, the left and right sectors overlap and the conditions for left-right ambiguity are no longer satisfied. Instead, a situation shown by the dashed lines in Figure 5 occurs. Here the signal results in a time lag between the two seismometers that allows the arrival to be located as lying within a single, wide sector. There is no longer any left-right ambiguity for these 'axial' arrivals but the angular uncertainty is high.

To investigate the usefulness of this ability to obtain a crude measure of arrival azimuth, a global association code (GA, Hanson et al, 2001) was run twice; first without azimuth information, then with the crude azimuth information quantified as a "delta azimuth" value attached to each arrival. This association process used not only the arrivals at the Socorro IMS station but also all arrivals at all IMS seismic, hydroacoustic and infrasound stations received within the same time period. Signals were extracted from a database to cover the periods of all detections made at Socorro: from March 2006 to June 2010. In cases where arrivals at Socorro were detected at times that indicated the possibility of the same seismic phase being detected at the two seismometers, the waveforms of the arrivals were envelope-correlated and, if the correlation passed a threshold, the two arrivals were paired. The time lag between the pair was then used to estimate the arrival azimuth and the azimuth uncertainty was calculated on the basis of this and the observed uncertainty in cosine of +/- 0.5. For left-right-ambiguous cases, the two arrivals were retained and each was given one of the two possible arrival azimuths, along with the relevant value of "delta azimuth". For axial arrivals, one arrival was removed from consideration and the other arrival was assigned the deduced azimuth and "delta azimuth" values.

Differences in origins formed by GA in the two cases were observed to be of two types: in some cases the azimuth information allowed new associations to be made, in others it prevented arrivals at Socorro being associated with events for which their arrival times matched event hypotheses but their azimuths did not. In all, the process was found to affect only a small proportion of events formed during the period of study. A map of event locations is shown in Figure 6, with black circles showing events involving arrivals at Socorro, green circles showing events that had new arrivals associated due to the presence of azimuth information and red circles showing events that had arrivals at Socorro removed because of azimuth information. The color shading in Figure 6 gives travel time to Socorro and ocean areas in white have no unblocked path to the island. Of around 580 events that had arrivals at Socorro associated with them, 7 had arrivals newly associated and 15 had arrivals disassociated due to azimuth information. In the vast majority of cases, no correlated arrivals were observed at the two seismometers and the process can be described as having only a small effect on GA processing.

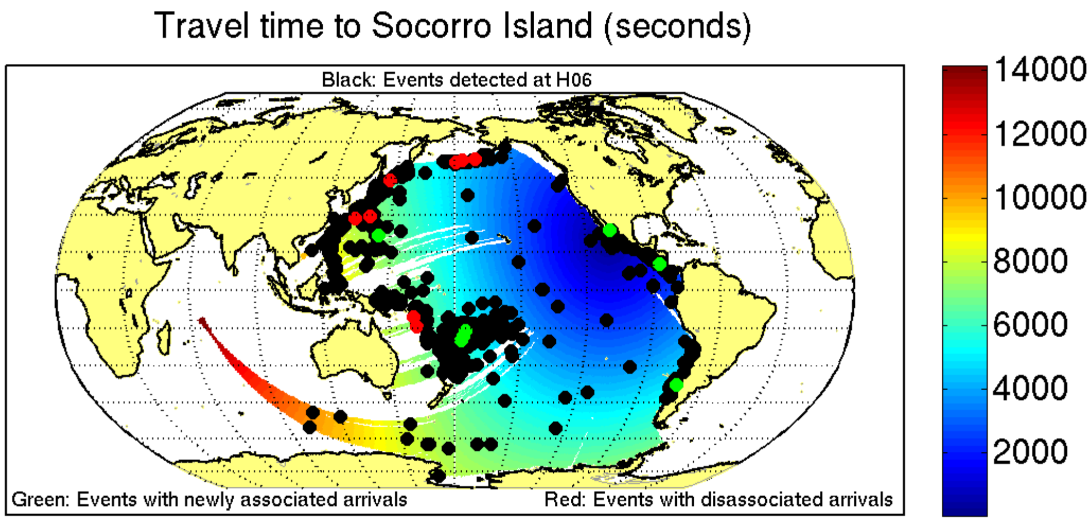

Figure 6. Event locations that included an arrival at Socorro Island (H06) formed by GA during the study period.

CONCLUSIONS AND RECOMMENDATIONS

The envelope correlation of near-simultaneous signals at two seismometers on Socorro Island was shown to allow a crude estimate of arrival azimuth to be derived. Significant correlation was achieved only in a small number of cases, reflecting the fact that the seismometer positions were chosen to give complete azimuth coverage, not to allow multiple detections of the same signal, as would be the case for a seismic array. Estimates of arrival azimuth were shown to change the results of global association processing for only 22 out of 580 events (4%) that were associated with arrivals at Socorro Island.

Polarization analysis in the frequency band of interest for T-phases did not yield any useful results partly due to the presence of surf noise in that frequency band and the lack of clear polarization for the T signals themselves. An unforeseen result of the investigation highlighted the potential use of near-coastal seismometers to complement tsunameters in the real-time tracking of an open ocean tsunami wavetrain. The mechanism generating long period fluctuation on horizontal components of near-coastal seismometers during the passage of a tsunami has now been shown to be very likely of near-field origin, and influenced by the geometry of the nearby coast.

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