SEISMIC CHARACTERIZATION OF UNDERWATER EXPLOSIONS AND UNDERSEA EARTHQUAKES USING SPECTRAL/CEPSTRAL MODELING AND INVERSION

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ABSTRACT

This study has investigated using seismic data to characterize underwater explosions and discriminate underwater blasts from earthquakes. Seismic recordings of underwater blasts can be used to characterize the source itself, based on identification of bubble pulses, and the *in-situ* water depths from mode-converted acoustic signals reflecting in the vicinity of the source. Thus, regional phases from undersea events, such as *Pn*, *Sn*, and *Lg*, may provide more information about the source and *in-situ* characteristics than later arriving T phases, usually recorded hydroacoustically, since the latter signals may be strongly distorted by heterogeneities in the water-column propagation path. Bubble pulses and near-source water column reflections cause time-independent scalloping of the spectra of regional phases that can be analyzed to infer depth and yield of the explosion.

An inversion algorithm has been prototyped in Matlab to characterize the regional-phase cepstra from underwater explosions recorded at seismic stations. The algorithm matches synthetic against observed cepstra for suspected underwater blasts. The observed cepstra are computed for regional phases (e.g., *Pn, Pg, Sn,* and *Lg*) by taking the logarithm of the trend-corrected spectrums for each phase, stacked across a regional array if array data are available, and then taking the inverse Fourier transform of log amplitude spectrum. The result is the so-called signed cepstrum. Each of the individual phase cepstra is then stacked to produce a composite cepstrum for the event. The signed cepstra for regional phases from underwater explosions have negative peaks caused by the reflections of the acoustic wave from the surface and positive peaks from the bubble pulse. Undersea earthquakes may only have the negative water-column reflection peaks or no peaks at all. Cepstra of the background noise to *Pn* are also computed in order to check if the peaks are caused by noise or processing artifact. Synthetic cepstra are computed for assumed minimum-phase wavelets caused by an explosion of specified yield and depth in the water, which can be constrained by known bathymetry. The depth and yield of the underwater blast are determined by finding a synthetic cepstrum that most closely matches the observed cepstrum. Match statistics considered include the cross-correlation coefficient and the L1 and L2 norm of the difference between synthetic and observed cepstra. The algorithm seeks to either maximize the cross-correlation coefficient or minimize the L1 or L2 norms. The best matching cepstrum can be found by optimal search algorithms, which includes the simplex search and simulated annealing. This algorithm can identify undersea events as either blast or earthquake based on the degree of correlation between a best fitting underwater explosion model cepstum and the observed cepstrum.

The algorithm has been tested on offshore events including both earthquakes and suspected underwater chemical blasts. Offshore events have been collected by a survey of the Reviewed Event Bulletins (REB) of the prototype International Data Centre (pIDC). The main focus initially has been on events around Scandinavia, in the Norwegian, North, and Baltic Seas, and the Gulf of Bothnia, recorded at one or more of the Scandinavian arrays. Most of these events appear to be earthquakes. However, at least one previously unidentified underwater blast has been found that occurred in the Norwegian Sea on November 25, 1998. Spectral modulations have been observed in all phases that were likely produced by bubble pulse and a water-column bounce. The event has small *Pn*/*Sn* and *Pn*/*Lg* amplitude ratios because of the large amount of shear-wave energy, relative to the *Pn*, which makes the event look like an earthquake. Large shear waves are unexpected for a pure compressional underwater explosion. Possible origin of the strong shear waves or weak *Pn* from a blast might include scattering in the source region or along the path or reduction of the *Pn* amplitude by spectral scalloping. However, strong scalloping is apparent in the spectra of all phases. Applying the cepstral inversion algorithm to the event, a synthetic cepstrum for an 1800 kg explosion at a depth of 130 m matches the observed cepstrum with a correlation coefficient of 0.73. This algorithm has also been tested on other events suspected of being underwater explosions as well as earthquakes and also synthetic underwater explosion and earthquake waveforms. When completed, the algorithm may have potential for event screening of underwater chemical blasts as well as for special-event analysis of suspected underwater nuclear blasts.

Key Words: underwater explosion, undersea earthquake, discrimination, cepstrum

OBJECTIVE

The problem of the identification of underwater blasts has gained increased interest recently in the context of the monitoring of the Comprehensive Nuclear Test-Ban Treaty (CTBT) which was opened for signature by the United Nations on 24 September 1996. Annex 1 to the Protocol of the CTBT calls for the installation of an International Monitoring System (IMS) including six hydroacoustic stations and five so-called "T-phase" stations. T-phase stations are seismic sensors located near the coast that can detect hydroacoustic phases converted to seismic phases at the coast. Thus, only 11 stations will be available specifically for monitoring underwater events. If an explosion occurs in the ocean, but near the coast outside of the SOFAR channel, long-range propagation of hydroacoustic signals may be blocked, and there is a possibility that the events may not be easily detected by the IMS hydroacoustic and T-phase assets directed toward the underwater explosions. Because of the relatively larger number of seismic stations, 170 primary plus auxiliary stations, called for the CTBT Protocol for the IMS, near-coast seismic stations may have a better chance of detecting and characterizing underwater events on the continental slopes, outside of the SOFAR channel, or in confined seas. Moreover, early-arriving seismic signals, such as *Pn*, *Pg*, *Sn*, and *Lg*, produced by mode conversion of acoustic waves in the water in the vicinity of the source, may carry more useful information about in-situ source conditions than later arriving T phases that may be affected by propagation path effects in the oceanic water column.

Baumgardt and Der (1998) showed numerous examples of underwater explosions recorded at seismic stations and how they can be characterized by spectral and cepstral analysis. A simple model for underwater explosions was developed and synthetic cepstra were produced that reproduced most of the essential features of observed underwater explosion cepstra. The main features were bubble pulses, which produce positive cepstral peaks, and the first surface reflection that produces a strong negative cepstral peak. The timing and relative amplitudes of these cepstral peaks provide useful constraints on the depth and yield of underwater explosions.

The following are the objectives of this study:

1. Collect appropriate seismic data from explosions and earthquakes in water-covered and nearby areas for study, preferably with corresponding hydroacoustic data that may be used to validate results of calculations.
2. Gain an improved understanding of the effects of the water column on the seismic data, and use this understanding to determine parameters such as in the water column/not in the water column, water depth, and others.
3. Develop an algorithm to extract information from seismic records of events in and near water-covered areas to aid in monitoring the CTBT.

RESEARCH ACCOMPLISHED

In this study, we have collected and analyzed events, reported in the Reviewed Event Bulletin (REB), located offshore near the coastlines. In most cases these events have turned out to be earthquakes. However, a number of events have been found that have characteristics of underwater explosions, i.e., spectral scalloping as described by Baumgardt and Der (1998). In this paper, we describe one of these events that occurred on November 25, 1998, and use it to demonstrate a new cepstral characterization method for identifying underwater explosions. We also contrast this event to a nearby earlier event that also has spectral scalloping but of a different nature that indicates that it is a shallow undersea earthquake.

PRESUMED UNDERWATER EXPLOSION NEAR TROMSO

On November 25, 1998, an event occurred off the coast of Norway that appeared in the Reviewed Event Bulletin (REB) for the PIDC with the following event parameters:

EVENT 20230910

Date	Time	Latitude	Longitude	Depth	Ndef	Mag1	N
1998/11/25	11:34:29.5	69.0645	16.4273	0.0 f	12	ML 3.5	4

This event was recorded by 4 seismic arrays, ARCES, FINES, HFS, and NOA and was located just off the coast of Northern Norway in the vicinity of Tromso.

Figure 1 (a) shows a map with the great circle propagation path from the event location reported in the REB to the ARCES array center element. Figure 1 (b) shows part of the bathymetric/topographic data for the first 50 km of the path from the source to the receiver. The bathymetry gives a water depth of 130 m in the vicinity of the source, although the water depth varies from between 50 to 300 m along the path. Also, Figure 1 (b) shows that the event was only within about 13 to 15 km of the land of the offshore islands, which is less than the REB epicenter error ellipse long axis of about 21 km. However, as we will show below, the spectral/cepstral characteristics of the signal are consistent with a water depth of 130 m.

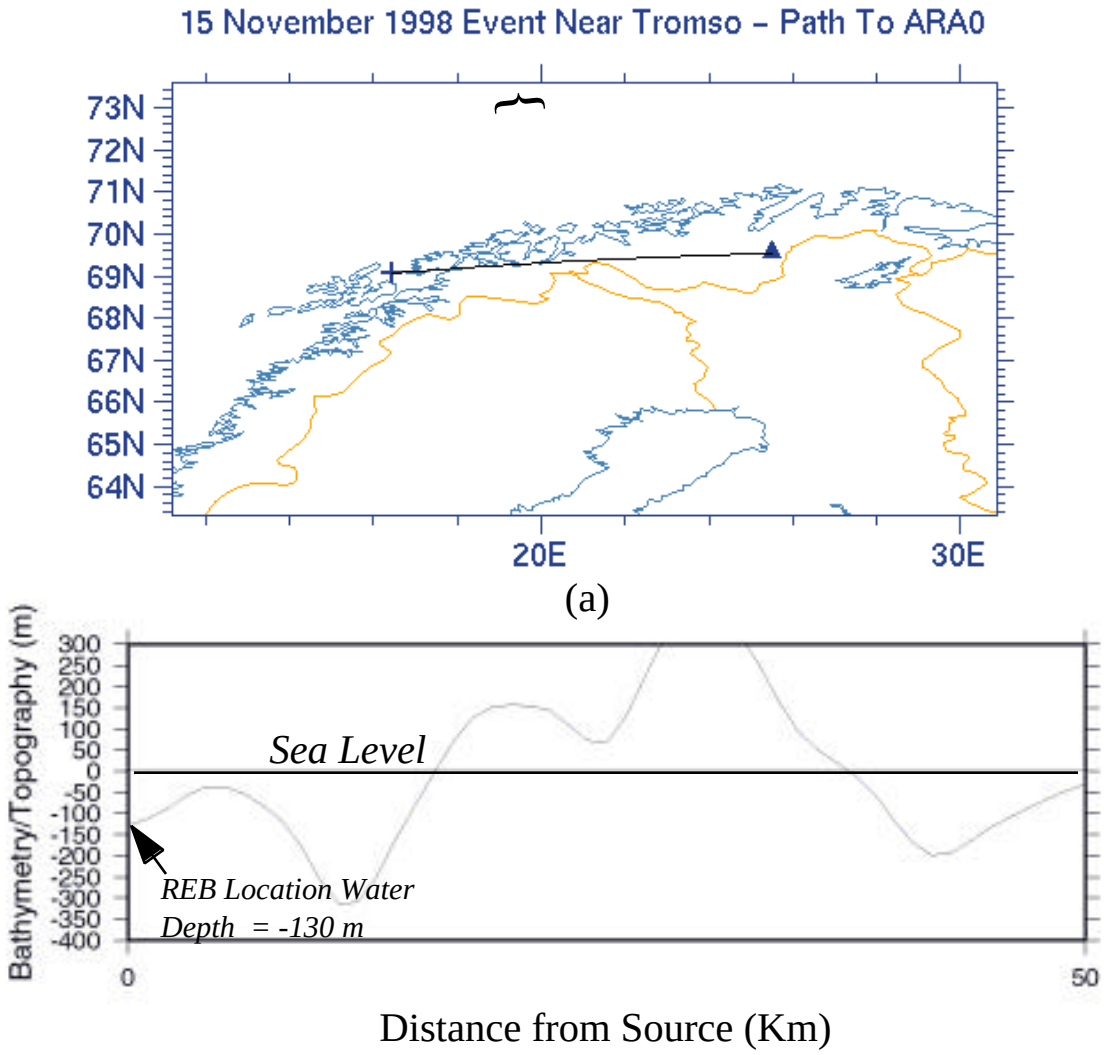


Figure 1: (a) Map showing path from November 25, 1998 event to the ARCES array center element (ARA0). (b) Bathymetric/topographic profile in the vicinity of the source.

Figure 2 shows a 2 Hz high-pass filtered waveform recorded at the ARCES center element, ARA0, indicating the picked phases, *Pn*, *Pg*, and *Lg*. These phase picks were used to set the start points of the windows for spectral analysis.

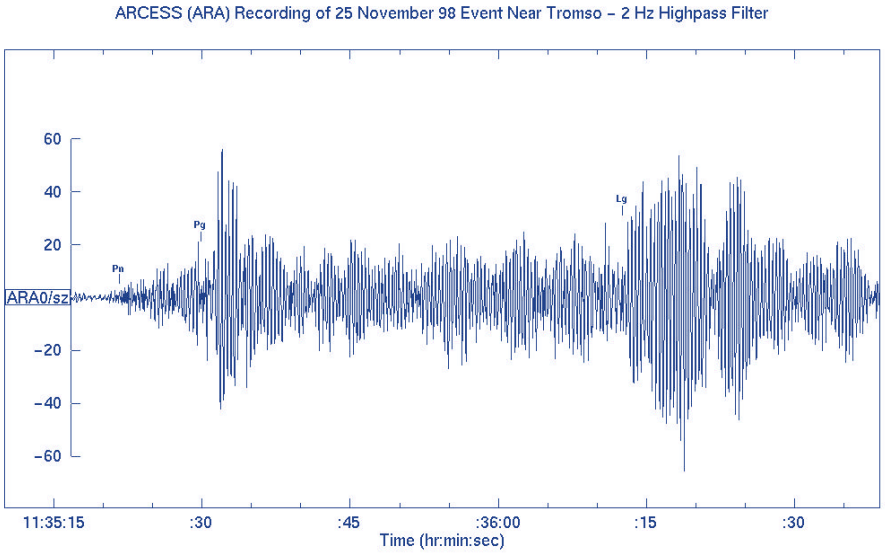


Figure 2: ARA0 vertical-component waveform of the November 25, 1998 event, highpass filtered from 2 Hz, showing regional phase picks.

Figure 3 shows a bandpass filter analysis of the waveform, with frequency bands from 0.5 to 2.5 Hz up to 10 to 16 Hz. The signal-to-noise ratio is quite high through the entire spectral band. The *Pg* and *Lg* phases are notably large throughout the band from 2 to 7 Hz and the first arrival *Pn* is emergent. *Pn*/*Lg* ratios are generally less than 1, except at frequencies above 8 Hz, indicating significant shear-wave excitation. Baumgardt and Der (1998) showed that, under certain circumstances, the *Pn*/*Lg* or *Pg*/*Lg* ratio might discriminate earthquakes and explosions for screening purposes. However, it is doubtful that a *Pn*/*Lg* or *Pg*/*Lg* ratios would confidently screen this event out as an earthquake.

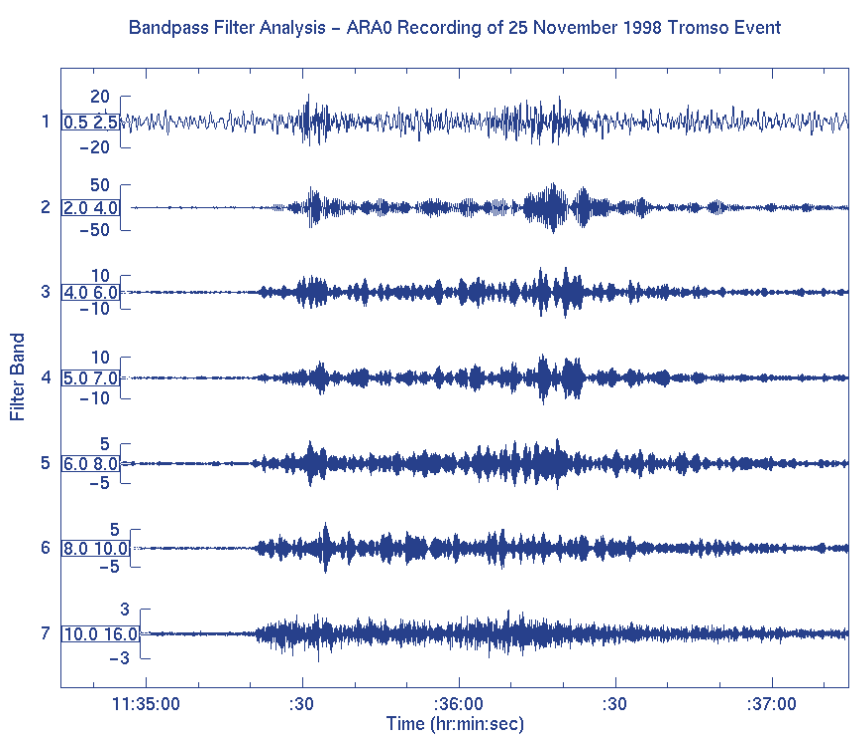
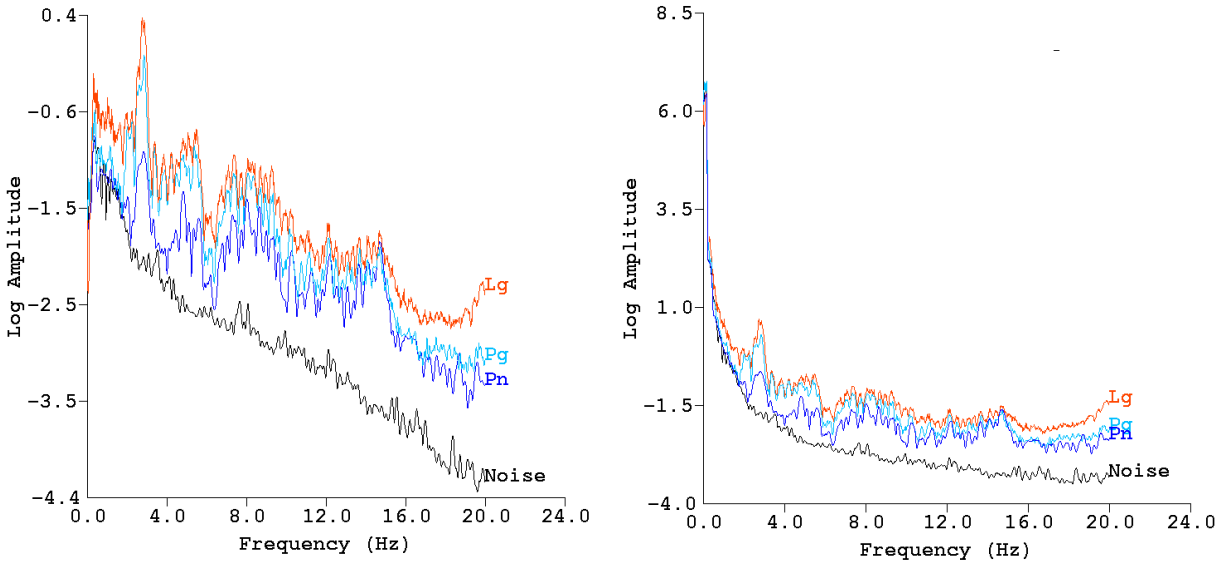


Figure 3: Bandpass filter analysis of the ARA0 vertical-component waveform of the November 25, 1998 event. Strong shear waves at high frequency and the complex coda waves in the 8-16 Hz band are noted.

SPECTRAL/CEPSTRAL ANALYSIS

Figure 4 (a) and (b) show the array-averaged spectra for the different phases and background noise. The spectra are computed on each individual ARCES vertical-component channel by windowing the phases, starting at the time picks shown in Figure 2, for 20 seconds and applying a Parzen window. The spectra for each channel are then averaged across the array, which produces much smoother spectra than the individual channel spectra. The spectra in Figure 4 (b) have had instrument response removed.



(a) (b)

Figure 4: (a) Spectra of the *Pn*, *Pg*, and *Lg* phases and *Pn* background noise. 20 sec time windows smoothed with Parzen window. (b) Spectra after instrument correction.

These figures show a very distinct spectral modulation or scalloping in all phases, and a strong spectral peak at about 3 Hz. None of these features appear in the noise. Spectra of this kind have been shown to be caused by source multiplicity, either due to ripple fire in mine blasts (Baumgardt and Ziegler, 1988) or by water column reverberations and bubble pulses in underwater explosions (Baumgardt and Der, 1998). Since the event occurs off the coast, it is likely to be an underwater explosion, as can be shown by cepstral analysis.

Figure 5 shows cepstra for the three phases, the stack of the three cepstra, and the cepstra of the background noise. The cepstra are computed by removing the trend in the instrument-corrected spectra in Figure 4 (b), using a polynomial fit, taking the log and another Fourier transform of the real part of the original complex spectrum. The resultant cepstra are a function of delay time between the multiple pulses, called "quefrency" in units of time (sec), and are signed. A cepstrum for the noise spectrum is also computed in order to check for cepstral features that may be due to processing artifact rather than source effects. We look for cepstral peaks in the individual phase cepstra that do not appear in the noise cepstra. The cepstra in Figure 5 have been shifted for display purposes and the absolute amplitudes are arbitrary. Positive cepstral peaks indicate pulses which are correlated with the same polarity and negative peaks, or troughs, are produced by pulses with reverse polarity. As shown by Baumgardt and Der (1998), positive peaks are caused by bubble pulses with positive polarity and negative peaks are produced by reflections of acoustic waves off the water-air interface.

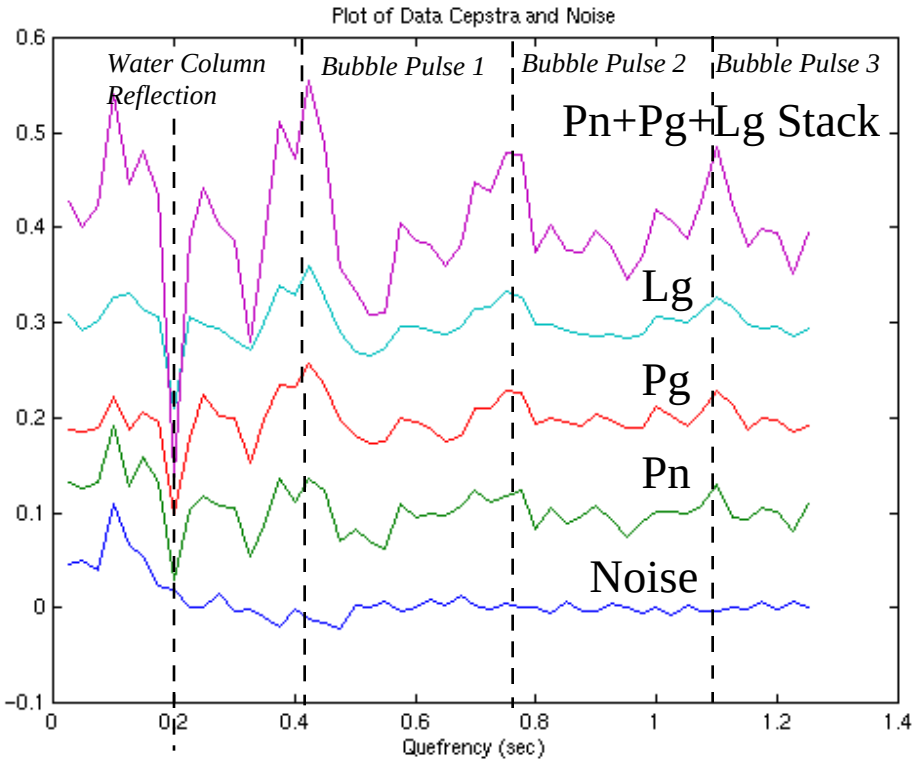


Figure 5: Cepstra of the *Pn*, *Pg*, and *Lg* phases, stack cepstrum, and *Pn* background noise cepstrum. The dashed lines indicate peaks identified in the signal cepstra but do not show up in the noise cepstrum. The first trough is interpreted to be the surface reflection, with reversed polarity, and the subsequent peaks to be caused by bubble pulses.

Figure 5 shows the clear signs of an underwater explosion, as shown in Baumgardt and Der (1998). As in the case of the recent Murmansk explosion (Baumgardt, 1998), the event has a clear negative trough at around 0.2 seconds, which we interpret as the surface reflection, and positive peaks at greater delay time, caused by bubble pulses. In our interpretation of the cepstra in Figure 5, we identify at least 3 bubble pulses. Both the reverberation peak and the bubble pulses are notably stronger on the stack cepstrum than on the individual phase cepstra

CEPSTRAL MODELING AND INVERSION

We have developed a modeling and inversion algorithm for the characterization of cepstra of underwater blasts. Because the cepstrum reflects the correlation structure of the source-produced pulses, it is easier to model than the waveforms themselves. The removal of the polynomial trend in the spectra also eliminates the spectral effects of the propagation path and thus, only the source correlation structure is retained in the cepstra. We showed in our earlier study (Baumgardt and Der, 1998) that modeling cepstra does not require information about the propagation path or receiver function, nor does it even require much information about the source time function. Thus, modeling cepstra requires many fewer parameters that modeling waveforms or spectra.

The modeling techniques described by Baumgardt and Der (1998) are used to interpret this event. The model construction is illustrated in Figure 6. We compute wavelets for the bubble pulse, shown on top, and water column reverberation, shown as the second trace, for a given assumed yield and depth in the water. The theory for calculating bubble pulse wavelets was taken from the literature and is described by Baumgardt and Der (1998). Other parameters that must be specified include average water column depth, that can be obtained from the bathymetry, and the surface and water bottom reflection coefficients, which we assume to be -0.9 and 0.3, respectively. As in the case of water depth, these parameters can be estimated with some degree of accuracy, but it is also conceivable that they can be inferred from the data. We assume that the acoustic waves in the water reflect from first-order discontinuities at the bottom and the surface.

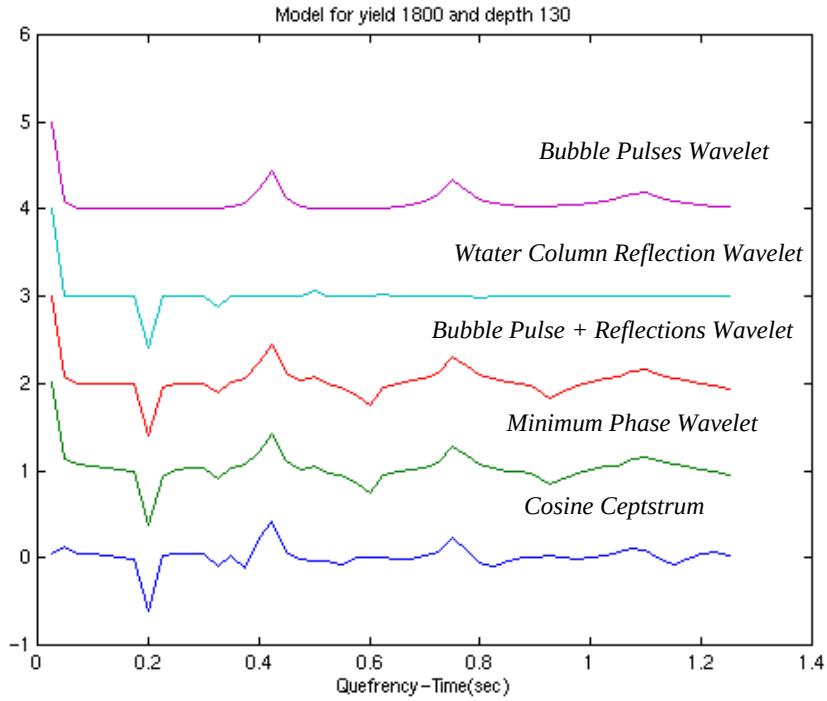
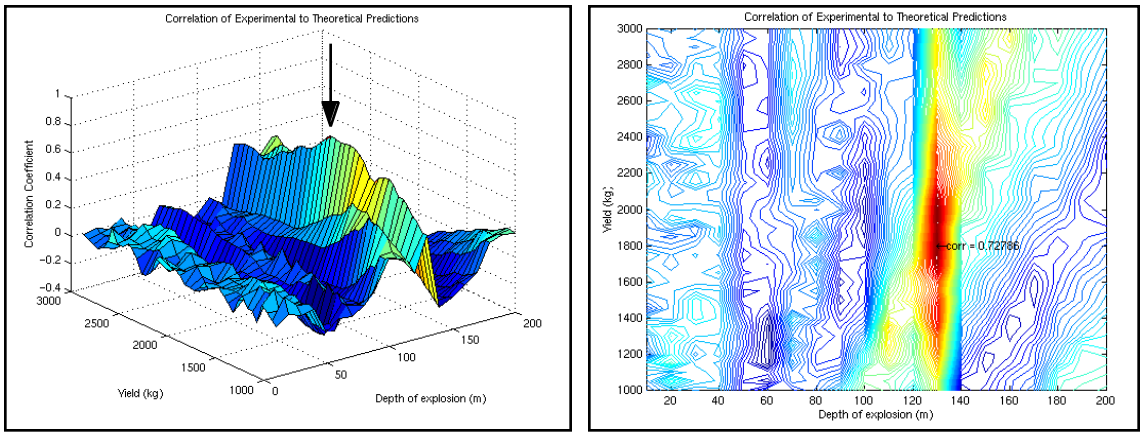


Figure 6: Example of construction of synthetic spectrum for an explosion of 1800 kg detonated at 130 m in the water.

The final synthetic cepstrum is the convolution of the source plus bubble pulse wavelet and reflection wavelet. We then compute the cepstrum of this composite wavelet, which is shown at the bottom of Figure 6. We also show a minimum phase wavelet reconstruction from the cepstrum which is identical to the original wavelet. This shows that our modeling method assumes minimum phase wavelets.

Finally, we seek a synthetic cepstrum that matches the observed cepstrum. For this purpose, we compute the correlation coefficient between the stacked observed cepstrum and the synthetic cepstrum and seek a cepstrum that provides the maximum correlation. (Note: We have also considered the L1 and L2 norms of the difference between the observed and synthetic cepstra as well as the correlation coefficient.) We first have considered an exhaustive search method, where the parameter space of blast yield and depth in the water is gridded and synthetic cepstra are computed for each grid point. Then, we correlate the synthetic cepstra at each grid point and compute a correlation coefficient surface over the depth/yield parameter space and look for the peaks in the depth/yield surface. Optimal search algorithms, such as simplex search and simulated annealing, are also being investigated.

Figure 7 shows he resultant correlation coefficient surface plotted as an object (a) and as a contour plot (b). Both displays have a distinct peak in the correlation, with a maximum correlation coefficient of 0.73, corresponding to a water depth of 130 m and yield of 1800 kg or about 1.98 tons. It is evident in Figure 7 that depth is well constrained but yield is less well constrained. The yield is controlled exclusively by the bubble pulse delay time, although the bubble pulse delay is also a function of depth. However, depth is constrained also by the negative peak delay time, corresponding to the two-way water-column reflection time.



(a) (b)

Figure 7: (a) Correlation surface for synthetic cepstra matched against the observed stack cepstra for the November 25, 1998 event. Arrow indicates the peak of the surface which gives the model with the maximum correlation. (b) Contour plot of the maximum peak.

It is notable that the inferred explosion depth of 130 m is close to the actual water depth of the source location as inferred from bathymetry, shown in the cross section in Figure 1. This suggests that the explosion may have occurred near the bottom or on the bottom. Note, however, that knowledge of the water depth is not actually required to infer the explosion depth in the water, since the reflection from the surface is by far the strongest signal. We actually assumed a water depth of 225 m in our model. Reflections from the bottom may, in principle, be observed and reveal water depth, but they are very weak, as is evident in Figure 6. Because of the roughness of the bottom itself and the extremely low reflection coefficients, it is doubtful that bottom reflections will be observable. However, water depths at given locations in the ocean are usually well known and need not be inferred by this method. However, knowing the maximum water depth is useful because it constrains the required search space.

The sensitivity to yield is illustrated in Figure 8, which shows the correlation coefficient as a function of yield for the depth of 130 m.

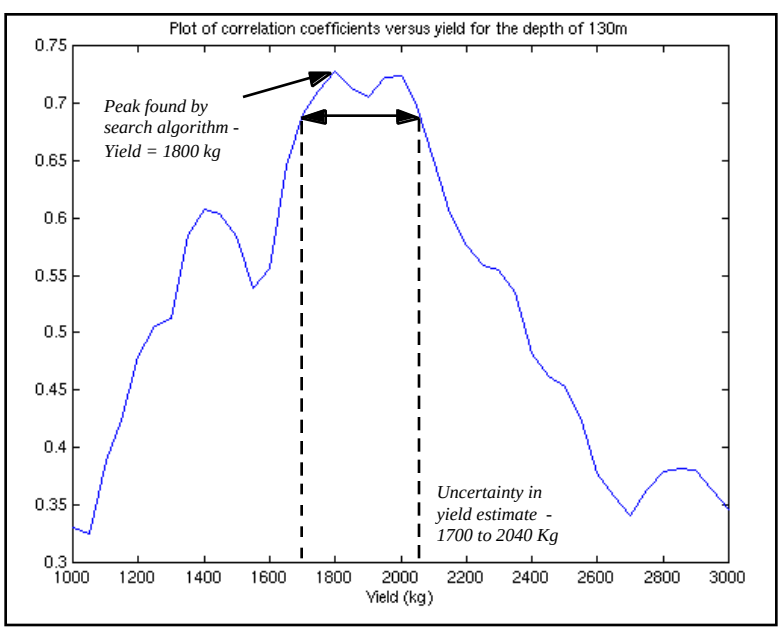


Figure 8: Maximum correlation peak plot at depth of 130 m. Dashed lines indicate that uncertainty of yield given by the peak width.

The maximum peak was at 1800 kg, but another peak of comparable strength appears at closer to 2000 kg. However, the overall broad peak is about 200 or 300 kg in width, which provides an estimate of the resolution of the method to yield. Thus, a better estimate of yield might be 1900 kg + or - 200 kg.

Finally, Figure 9 shows a direct comparison of the observed stack cepstrum and the best-matching synthetic cepstrum.

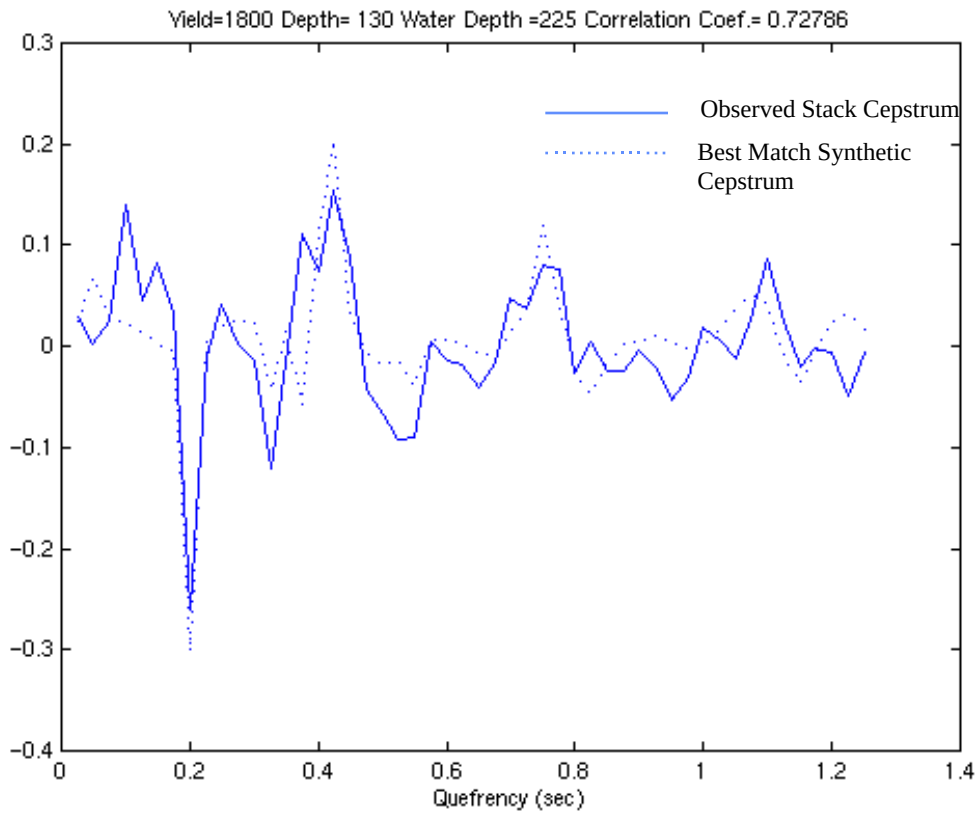


Figure 9: Comparison of the observed stack cepstrum of the November 25, 1998 event and best matching synthetic cepstrum for depth of 130 m and yield of 1800 kg.

This comparison shows that, although the match is not perfect, reasonably good matches of the essential features, the negative peaks of the water column reflection and the bubble pulses, have been attained.

COMPARATIVE EXAMPLE OF AN UNDERSEA EARTHQUAKE NEAR TROMSO

Shallow undersea earthquakes may also produce scalloped spectra if seismic energy is coupled into acoustic energy in the water column. However, the only scalloping possible would be from the water reverberations since no bubble pulses would be expected. An example of this difference can be seen in the February 5, 1993 shown in Figure 10, that occurred near the November 25, 1998 event near Tromso.

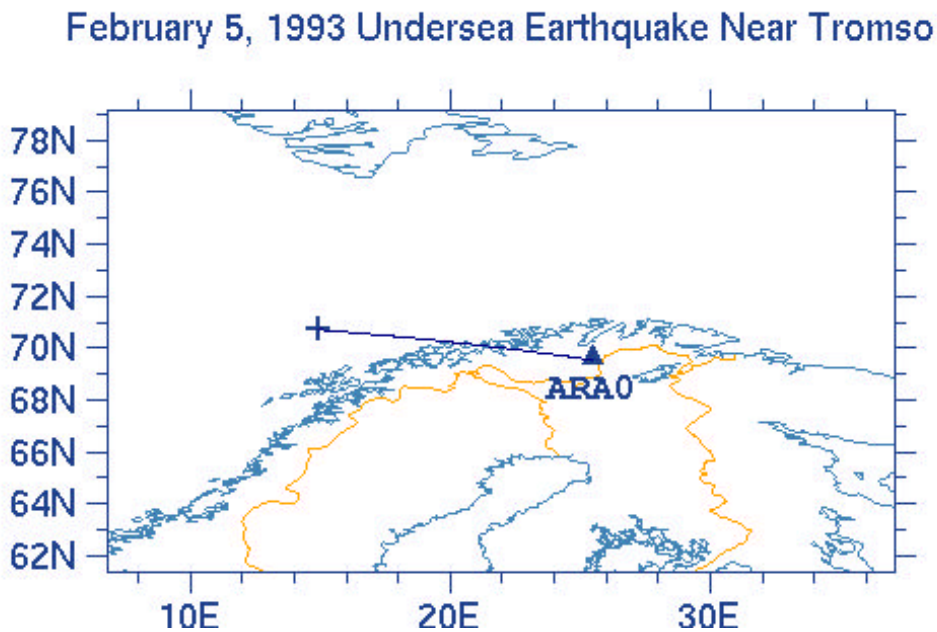
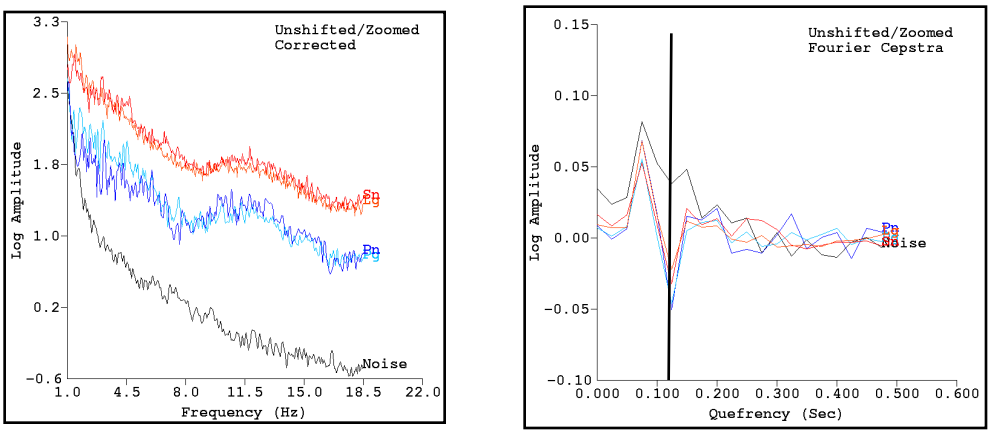


Figure 10: Map showing the location of the February 3, 1993 undersea earthquake near Tromso and the propagation path to ARCES.

The magnitude and distance are similar to that of the November 25, 1998 event, and all four phases, *Pn*, *Pg*, *Sn*, and *Lg* were observed at ARCES. Figure 11 shows the spectra (left) and cepstra (right) of the phases and the background noise.



Delay Time = 0.12 Seconds
Water Depth = 1007 Meters

Figure 11: Spectra (left) and cepstra (left) of the February 5, 1993 undersea earthquake. The spectral scalloping only produces a negative peak in the cepstra, characteristic of an underwater reverberation from depth of 1007 m.

Note that the spectra of the phases are scalloped but the noise is not. This scalloping produces a negative peak (trough) only in the cepstra with a time delay of 0.12 seconds that is consistent with a two-way water reverberation of 1007 meters. No positive peaks, characteristic of bubble pulses, are observed in the cepstra, except for one at low quefrency just before the trough at about 0.06 seconds. However, note that this peak also appears in the noise which suggests it is a processing artifact, not a bubble pulse. The depth of 1007 meters is consistent with water depths from bathymetry of the region near the epicenter. Thus, we interpret this event to be a very shallow undersea earthquake and the spectral scalloping to be consistent with the time delay for a single pass of the acoustic pulse through the water column above the epicenter.

CONCLUSIONS AND RECOMMENDATIONS

This analysis has shown that the recent November 25, 1998 event off the coast of Norway near Tromso has spectral/cepstral features consistent with an underwater explosion. After consulting with NORSAR, there appears to be no confirmation of the event actually being an explosion. However, the region near Tromso has military activities and explosions have occurred in this region in the past. Baumgardt and Der (1998) presented data for a large number of events around the Scandinavian arrays that appear to have been underwater explosions, so blasting underwater for military or geophysical exploration purposes may not be uncommon.

The February 3, 1993 event near Tromso also has spectral scalloping but cepstral analysis shows it to be due to water column reverberations, not bubble pulses. The reverberations give a water column depth of about 1007 m, which is consistent with the bathymetry for the region. This illustrates a means of discriminating between underwater blasts and undersea earthquakes.

The cepstral modeling and matching method described above and demonstrated on the November 25, 1998 event provides a potential method for screening of underwater chemical explosions as well as for identifying larger nuclear explosions. For a given event located offshore, the cepstral modeling and matching algorithm would be run to try to find an explosion model that matches the observed cepstrum. If at match can be obtained, with a correlation coefficient that exceeds some specified threshold, the event would be identified as an underwater blast. If the estimated yield is small, again less than some threshold, the event would be identified as a chemical explosion and screened. If no such match can be attained, the event would be screened as a likely offshore earthquake. Also, additional research is required to determine whether the method could also be used to identify earthquakes. Synergy with location may be possible since the method provides an estimate of depth in the water. This depth must be equal to or less than the bathymetric depth at the location point, and thus provides a check on the estimate of distance of the event from land. This approach could be used for either explosions or earthquakes.

Although the hydroacoustic component of the IMS may be adequate to detect and identify nuclear explosions in the SOFAR channel of the deep ocean, explosions near the coasts of countries, which may occur outside the SOFAR channel, may be harder to detect and characterize by hydroacoustic sensors. For example, the November 25, 1998 event was in a location that all paths to the hydroacoustic stations were blocked and was not detected hydroacoustically. Thus, the seismic stations in the IMS may have to be relied on to monitor for such events.

Analysis of the regional seismic phases, such as *Pn*, *Pg*, *Sn*, and *Lg*, from underwater explosions, provides more in-situ information about the source environment than T phases. Early arriving seismic phases result from the conversion of hydroacoustic to seismic signals that occurs in the vicinity of the source. T phases, on the other hand, may result from long-range propagation of acoustic signals in the ocean before they convert to seismic signals, and thus, the source information in the spectrum may be contaminated by propagation effects.

Therefore, the overall conclusion of this study is that the IMS seismic stations can serve as an important complement to the hydroacoustic network for detecting and identifying underwater explosions. Moreover, in many instances, seismic stations may be better suited for the characterization of underwater explosions, such as those near coastlines, than hydroacoustic or T-phase stations. Thus, automated processing techniques developed for characterizing underwater events, such as the cepstral inversion method described in this paper, should be developed and applied to seismic data as well as to hydroacoustic data from offshore events.

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