Analysis of hydro-acoustic and seismic signals originating from a source in the vicinity of the last known location of the Argentinian submarine ARA San Juan

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Hydroacoustic signals recorded at IMS stations

- Signal of unknown origin on November 15th 2017.

- Controlled explosion test conducted by Argentine Navy on December 1st 2017, with source position and time information.

- The test source was detected on CTBT IMS hydrophone stations HA10 and HA04.

- The location of the test source (centre of the 90% confidence ellipse determined based on HA11 and HA04 signals) is 37 km East relative to source location declared by the Argentine authorities.
Time series recorded from both events

- Time series for both the November 15th event (top row) and the December 1st calibration signal (bottom row).

- Recorded time series on H10N and H10S indicate an impulse-like event.

- The arrival times of the signals on H10N, H10S and H04S make it possible to associate the recordings to the same event.
Calibrated spectrograms indicate broadband signals arriving on H10N and H10S.

Attenuation of the higher frequency components of the signal recorded on H04S is evident.

Stronger propagation channel dispersion is observed on H04S.
Arrivals include many reflections

- Focus on November 15th signal received on H10N using a Progressive Multi Channel Cross-correlation (PMCC) processing algorithm.

- A sequence of 10 late arrivals following the direct main arrival (path number 1) is identified by analyzing a 15 min time window after the main arrival.

- Late arrivals are attributed to reflections off underwater bathymetric features.

- Fewer late arrivals are observed on H10N from the December 1st event.
Auto-correlation of the main arrival recorded on H10N and H04S reveals an echo with a delay time of approximately 0.32 s for the November 15th event (upper-left plot).

Auto-correlation of the main arrival from the controlled experiment on December 1st also shows such an echo with a delay time of approximately 0.45 s (upper-right plot).

The echo in the December 1st event is consistent with the oscillating bubble generated by the controlled explosion.

These same findings are confirmed by cepstrum analysis of the signals (lower plots).

However, similar time delayed echoes may also be caused by multipath effects (see modelling slides further below).

For both events, the respective delay time is the same at stations H10N and H04S, independent of the difference in propagation distance.

The preservation of such delay times over long propagation distances has been documented in previous experiments with explosive sources\(^1\).

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\(^1\) Tomoaki Yamada, Mario Zampolli, Georgios Haralabus, Kevin Heaney, Mark Prior, Takeshi Ise, “Analysis of recordings from underwater controlled sources in the Pacific Ocean received by the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO),” EGU 2016 Poster, 17-22 April, 2016.
Calibrated Power Spectral Density (PSD) levels allow comparison between signals (black) and ocean background noise (red).

The ocean noise level was found to be lower for the November 15th than the December 1st event at stations H10N and H04S.

The November 15th signal has up to 20 dB higher Power Spectral Density levels at lower frequencies compared to the December 1st event.

The differences in received levels are affected by the source strength, source depth and propagation conditions.

Conclusions regarding the absolute strength of each source cannot be drawn from the comparison of the received levels.
Two dimensional Parabolic Equation (2-D PE*) propagation model out to a range of 6050 km from the source.

- Full range-dependent environmental input from oceanographic database information.
- Coupling of acoustic energy into the Sound Fixing and Ranging (SOFAR) channel is largely independent of the source depths > 300 m in this area.
- Shallow source depth (source depth for the December 1st event is 47.5 m) results in 15 dB lower received levels (depth and frequency averaged) than deeper sources (source depth for the November 15th event is unknown).
- Acoustic energy is scattered at the Rio Grande Rise and couples back into the SOFAR channel, propagating with a low loss to H10N.
- Further analysis using propagation models may provide information about the source level.

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Time-domain propagation modelling from the estimated source location of the November 15th event to H10N at a range of 6050 km.

- Full time-series modelling in the frequency band from 1 to 100 Hz with the PE model RAM*).

- The source pulse is modelled as a band-limited impulse (sync function). No bubble pulse modelled.

- The propagation modelling of the band-limited impulse does not show an additional reflected or refracted arrival clearly separated in time from the main arrival caused by propagation channel properties or bathymetry.

- Auto-correlation analysis of the modelled time series indicates a small echo with delay time close to 0.32 s as observed in the November 15th event data.

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Inclusion of non-IMS seismic station data

Two non-IMS seismic stations recorded events which are compatible with the location of the November 15th hydroacoustic signal:

- Tornquist, GSN - IRIS/USGS (TRQA)
- Mount Kent, IRIS/IDA (EFI)
The signal-to-noise at EFI was low and did not improve the localization of the November 15\textsuperscript{th} event significantly.

Polarization and particle motion analysis of the TRQA data supported the location of the event obtained by the CTBT IMS hydroacoustic stations.

A stable azimuth and inclination, and a growing rectilinearity, support the hypothesis of a P-wave arrival.

Particle motion hodograph in the horizontal plane provides an estimation of azimuth (red arrow in the upper-right plot), compatible with the direction of the November 15\textsuperscript{th} event.
Reducing the localization error ellipse

- Reduced localization uncertainty of the November 15th event by combining data analysis from seismic (TRQA,EFI) and hydroacoustic stations (H10N and H04S).
- Location error ellipse estimate¹ from the CTBT IMS acoustic stations H10N and H04S only:
  - S46.1180°, W059.6880°
  - Semi-major error ellipse axis: 487 km
  - Semi-minor error ellipse axis: 22 km
  - Ellipse strike/orientation: 98°
- Location error ellipse estimate¹ from H10N and H04S combined with TRQA (EFI) seismic station:
  - S46.1175°, W059.7257° (S46.1218°, W059.7340°)
  - Semi-major error ellipse axis: 19 km (19 km)
  - Semi-minor error ellipse axis: 12 km (9 km)
  - Ellipse strike/orientation: 137° (139°)
- An alternative localization approach by Dr Ronan Le Bras “Relative localization method in hydroacoustics and application to several examples including a seismic survey for which ground truth is available” to be presented at EGU 2018 in session OS4.1: Open session on observing the ocean, PICO Spot 4.

¹IDC Processing of Seismic, Hydroacoustic and Infrasonic Data IDC-5.2.1 Rev 1 (2002)
Localization error ellipse for the test explosion

- Localization uncertainty of the December 1st test explosion by data analysis from the hydroacoustic stations (H10N and H04S).
- Location error ellipse estimate of the November 15th event from the CTBT IMS acoustic stations H10N and H04S only (red error ellipse).
- Location error ellipse estimate of the November 15th event from the CTBT IMS acoustic stations H10N and H04S combined with the TRQA seismic station (purple error ellipse).
- Location error ellipse estimate of the December 1st test explosion by data analysis from H10N and H04S (orange error ellipse):
  - (545.6185°, W58.9208°)
  - Semi-major error ellipse axis: 515 km
  - Semi-minor error ellipse axis: 23 km
  - Ellipse strike/orientation: 98°
- Distance between estimated and declared location of the December 1st test explosion:
  - Distance: 37 km
A signal (Path 2) arrived at H04S before the main November 15th arrival (Path 1).

The main arrival is from the direct geodesic line-of-sight between the estimated November 15th source location and H04S.

Observed azimuth of the main arrival Path 1: 223.6°.

Possible early arrival with more southern direction of arrival, pointing to the seasonal Antarctic ice-sheet.

Observed azimuth of the early arrival Path 2: 207.8°.

Observed time difference Path 1-2: 1234 s.

Subsequent analysis to verify if the early arrival could be a pre-cursor of the main arrival.
Main arrival: Path 1

Possible pre-cursor: Path 2

Similarities in spectrograms:
- Similarities in locations of main spectral peaks
- Similarities in spectral roll-off

The Path 2 pre-cursor has lower signal-to-noise ratio and higher frequency components less visible than for the main arrival.

No auto-correlation or cepstral peak delay found in the Path 2 pre-cursor comparable to the main arrival.

Hypothesis for possible pre-cursor signals examined next
The Geodesic propagation path (Path 1) from the November 15\textsuperscript{th} event to H04S (7750 km):

- Crosses ridges between islands.
- Intersects the seasonal Antarctic ice-sheet (green line) in two points.

Seasonal Antarctic ice-sheet for November 15\textsuperscript{th} from U.S. National Ice Center / Naval Ice Center. [http://www.natice.noaa.gov/products/daily_products.html]

H04S main arrival exhibits more dispersion and lower signal-to-noise ratio at higher frequencies than the main arrival at H10N.

These differences can be compatible with a strong loss mechanism in the waveguide, such as coupling of the acoustic signal to an ice-sheet.

Typical in-ice bulk sound-speeds\textsuperscript{)*}:

- Compressional sound-speed $c_p = 3500$ m/s
- Shear sound-speed $c_s = 1800$ m/s.

Path 1 (red) is the main arrival with a totally in-water travel path which passes under the ice-sheet.

Hypothesis that the earlier arrival (green) results as a combination of in-water and in-ice propagation:

- Propagation from the source (Nov 15th event) to the ice-sheet, where the sound couples into the ice.
- Propagation as ice-guided wave through the ice-sheet out to an exit point.
- Propagation from the exit point on the ice-sheet, along the geodesic path that arrives with azimuth 207.8° at H04S.

Path 2 (green) pre-cursor was observed 1234 s before the main arrival. This is attributed to:

- In-ice propagation via a symmetric Lamb-wave like mode with phase speed*) \( 2c_s \cdot \left(1 - \frac{c_s^2}{c_p^2}\right)^{0.5} = 3087 \text{ m/s} \).
- Lowest symmetric ice-guided mode for a floating ice-sheet in the limit of wavelength >> ice-sheet thickness [seasonal ice-sheet thickness O(1-10m)].

The blue path is in-water and in-ice propagation path using bulk compressional (p-wave) ice sound-speed of 3500 m/s.

The gray paths are partial in-ice propagation paths but with incompatible delay times.

In conclusion: The blue and green early arrivals are compatible with the ice-guided pre-cursor wave hypothesis (Path 2).

Conclusions

- Signal recorded on November 15\textsuperscript{th} 2017 at HA10 and HA04 originated from the vicinity of the last known position of ARA San Juan (3.5 h after last contact with the Navy base).
- No definitive conclusions can be drawn as to the nature of the source.
- Calibration test conducted by the Argentine Navy with a controlled source in the same area on December 1\textsuperscript{st} shows a source location capability of IMS stations HA10 and HA04 to within 37 km from the declared location.
- Inclusion in the analysis of a signal recorded on November 15\textsuperscript{th} by a non-IMS seismic station and compatible with the hydroacoustic signal led to a reduction of the location error ellipse.
- Arrival at HA04 shows more dispersion and loss of higher frequencies compared to the arrival recorded at HA10.
- Early arrival recorded at HA04 on November 15\textsuperscript{th} is compatible with the hypothesis of the signal coupling to a wave guided in the seasonal Antarctic ice-sheet.
- Further analysis of signal features and propagation is still on-going.
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