SnT 2019
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

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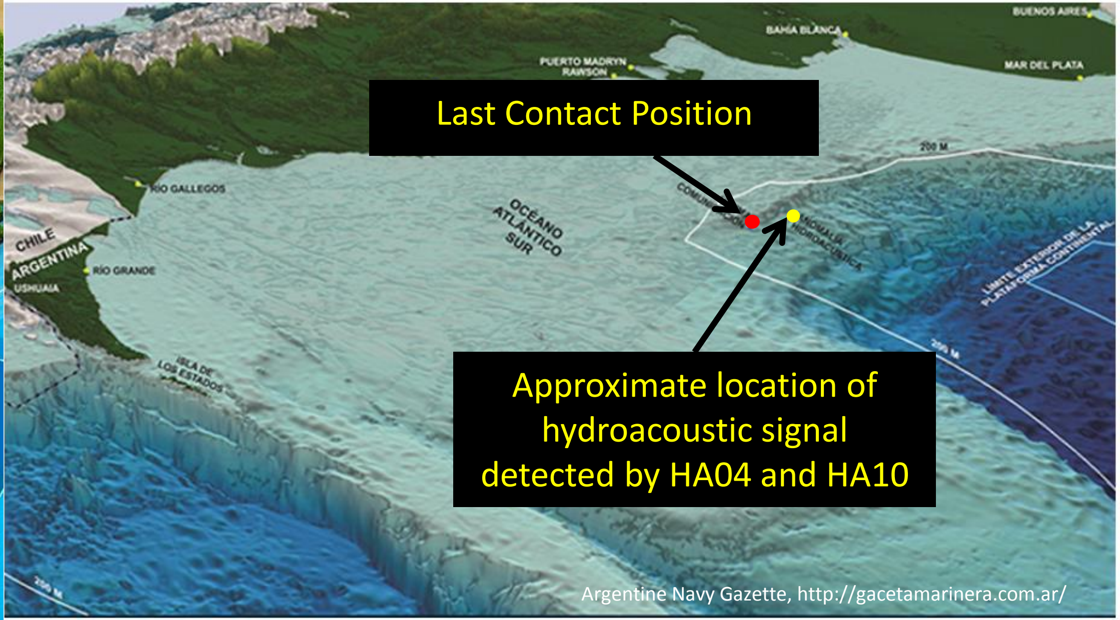
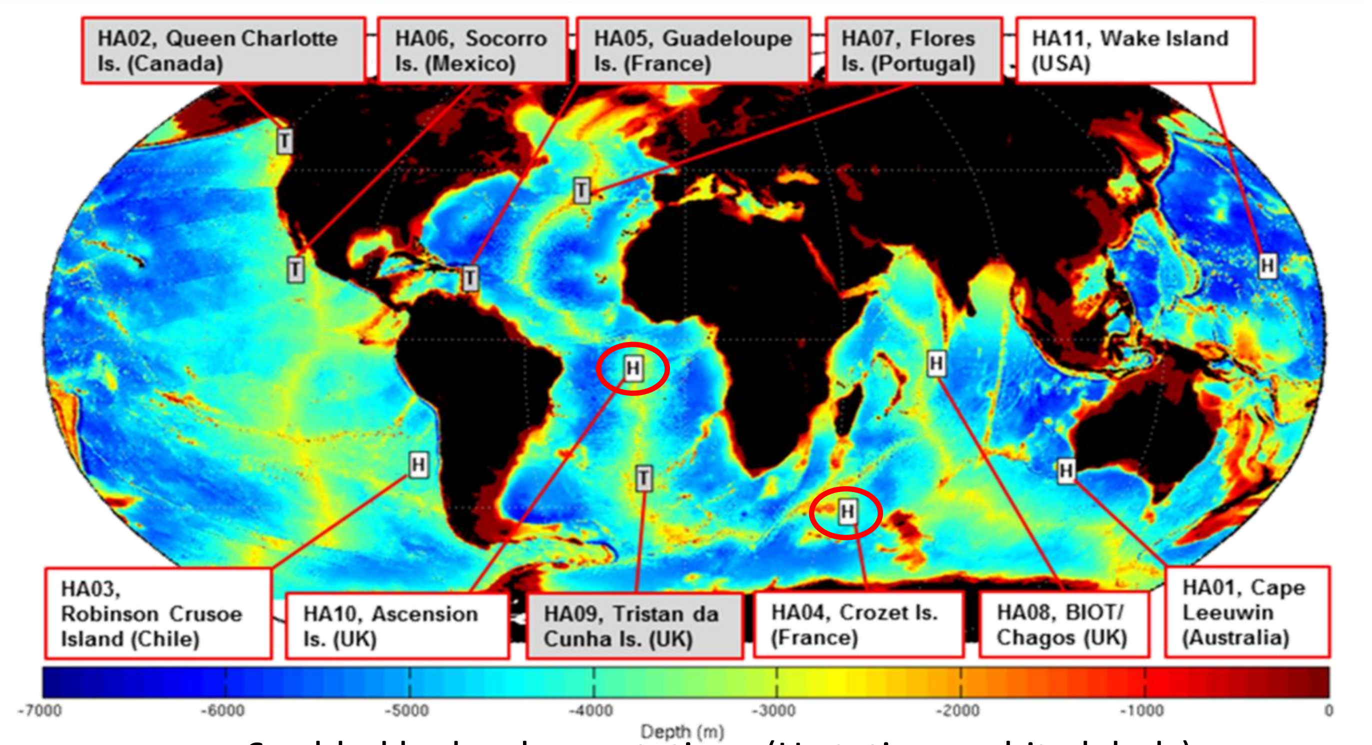
Comprehensive Nuclear-Test-Ban Treaty Organization, Vienna, Austria

CTBTO's contribution to the search of the missing Argentine submarine ARA San Juan


Búsqueda y rescate del
SUBMARINO ARA "SAN JUAN"
Ministerio de Defensa
Presidencia de la Nación
Mar del Plata
Puerto Madryn
Comodoro Rivadavia
125 km
430 km
6000 m
Ushuaia
https://www.diariopopular.com.ar/general/


BUENOS AIRES
BAHÍA BLANCA
PUERTO MADRYN
RAWSON
MAR DEL PLATA
Last Contact Position
200 M
RÍO GALLEGOS
OCÉANO ATLÁNTICO SUR
CHILE
ARGENTINA
RÍO GRANDE
USHUAIA
LÍMITE EXTERIOR DE LA PLATAFORMA CONTINENTAL
Approximate location of hydroacoustic signal detected by HA04 and HA10
Argentine Navy Gazette, http://gacetamarinera.com.ar/

The HA component of the IMS



- 6 cabled hydrophone stations (H-stations, white labels)
- 5 near-shore seismometer stations (T-stations, grey labels)

Hydroacoustic signals recorded at IMS stations

- **November 15th event:**

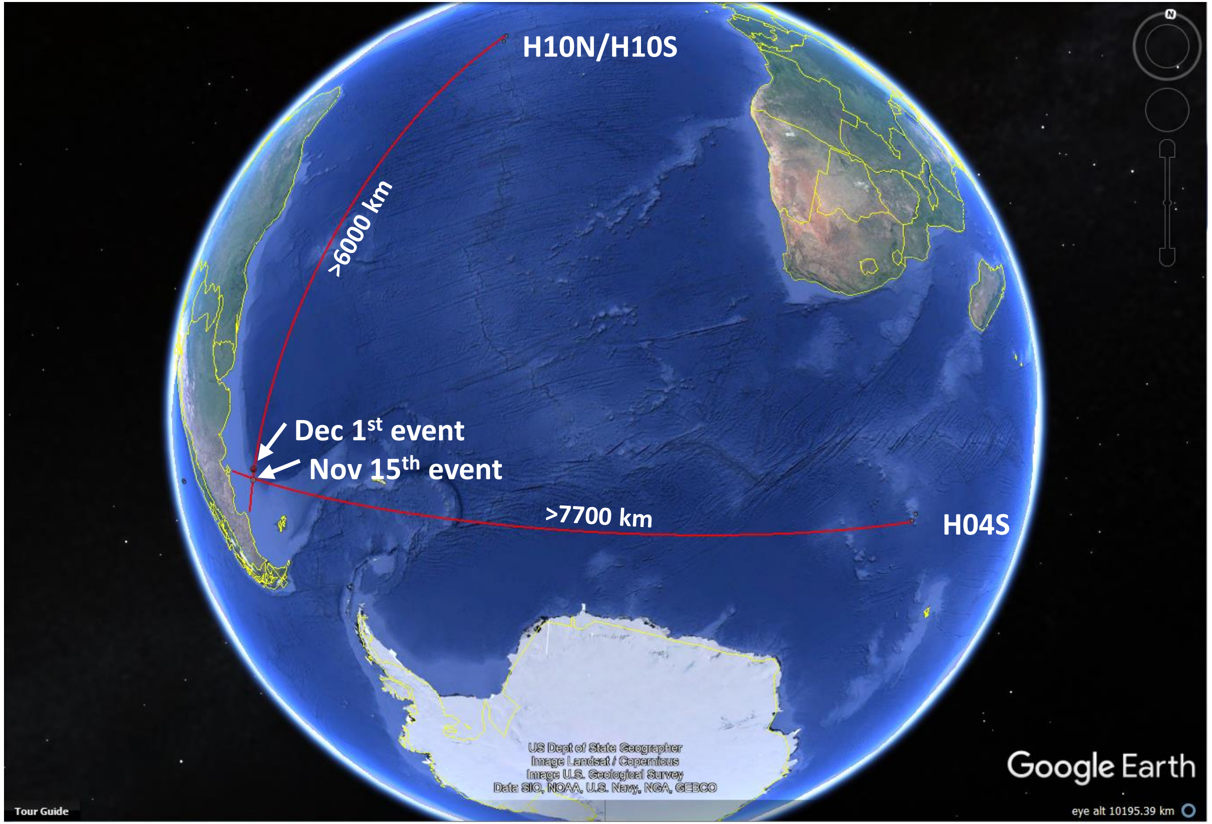
Signal of unknown origin on November 15th 2017

- **December 1st event (calibration signal):**

Controlled explosion test conducted by Argentine Navy on December 1st 2017

- Both events detected by IMS hydroacoustic stations HA10 and HA04

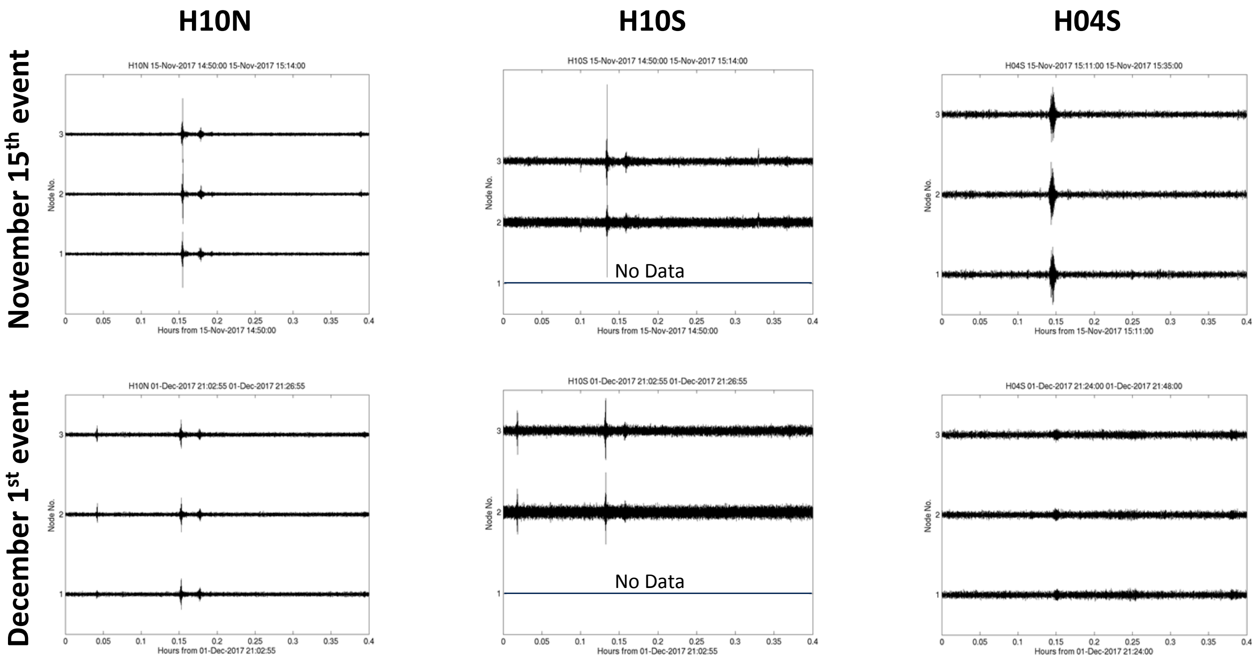
- The estimated* location of the test source was found to be 37 km East of the actual source location, as declared by the Argentine authorities.



(*) Centre of the 90% confidence ellipse determined based on HA10 and HA04 signals – see IDC Processing of Seismic, Hydroacoustic and Infrasonic Data IDC-5.2.1 Rev 1 (2002)

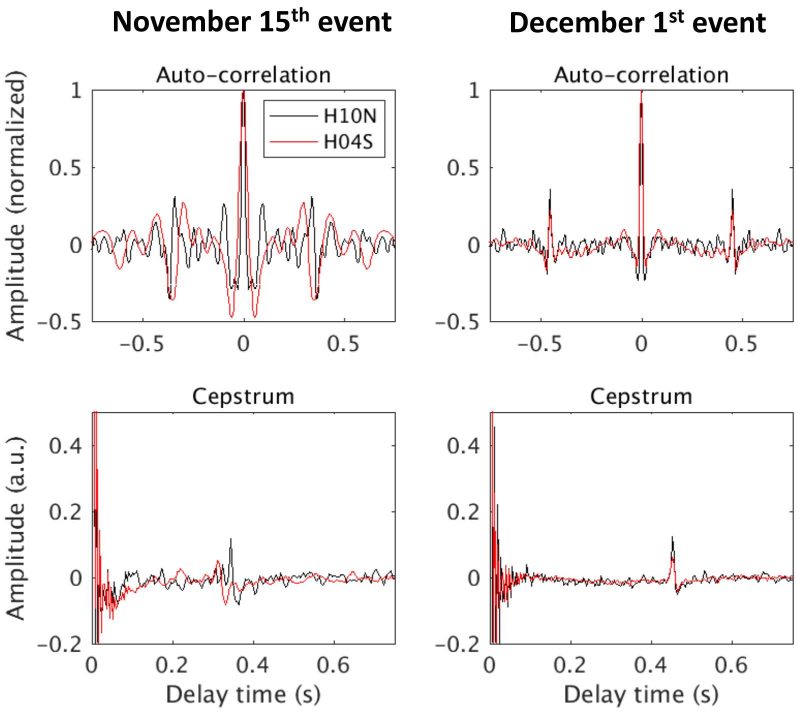
Time series recorded from both events

- 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 <u>possible to associate the recordings to the same event</u>.



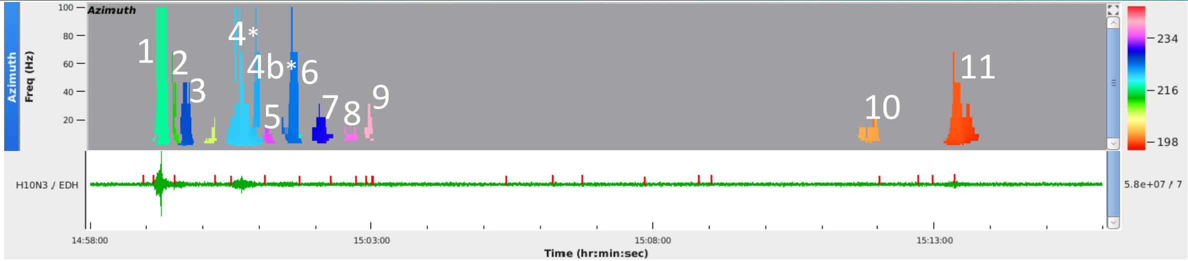
Signal auto-correlation and Cepstral features

- 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 an oscillating bubble, as expected by the controlled experiment.
- These same findings are confirmed by cepstrum analysis of the signals (lower plots).
- 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*).
- Conclusions regarding the absolute strength of each source cannot be drawn from the comparison of the received levels and PSD analysis.
- Modelling for HA10 indicates that a shallow source depth (e.g. 50 m) results in 15 dB lower received levels (depth and frequency averaged) than deeper sources (e.g. 500 m)



*) Tomoaki Yamada, Mario Zampolli, Georgios Haralabus, Kevin Heaney, Mark Prior, Takeshi Isse, "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.*

Arrivals include many reflections

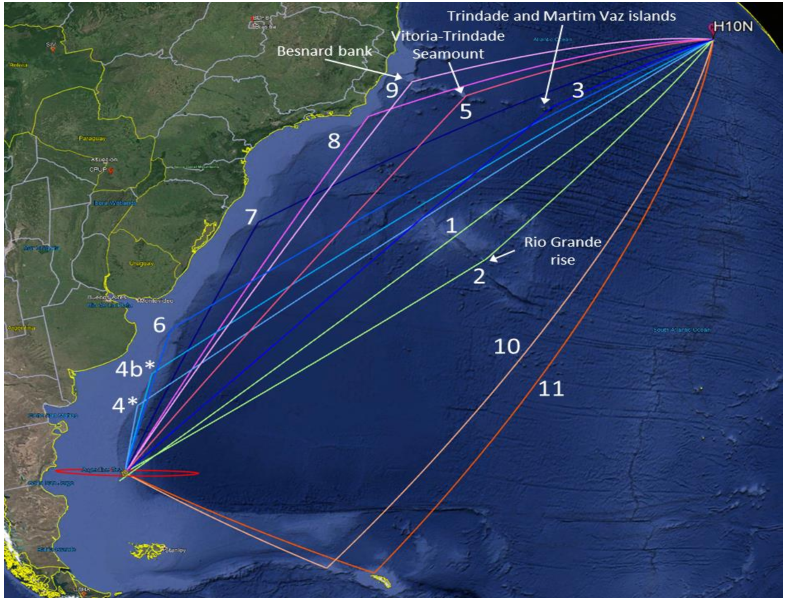


- Focus on November 15^{th} signal received on H10N using a Progressive Multi Channel Cross-correlation (PMCC[*,**]) processing algorithm.

- 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.

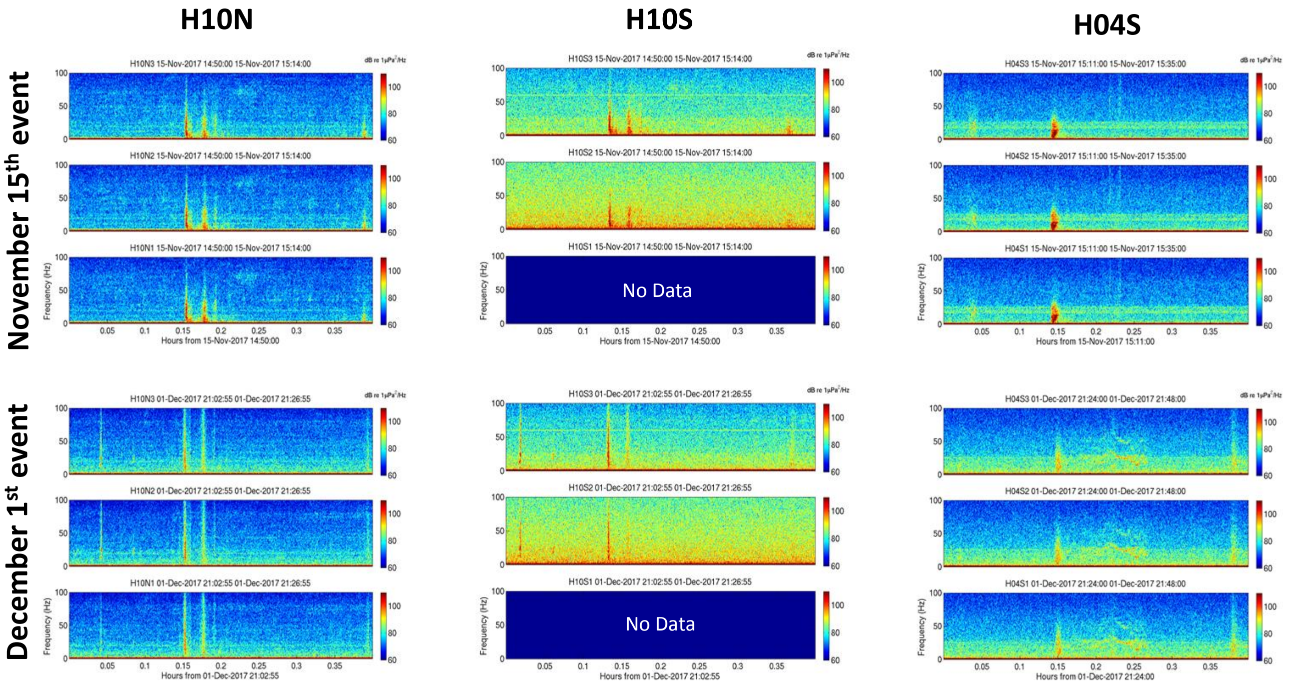
- Fewer late arrivals are observed on H10N from the December 1^{st} event.



[*] Cansi, Y., An automatic seismic event processing for detection and location: the PMCC method, *Geophys. Res. Lett.*, 22, 1021-1024, 1995.
[**] Cansi Y. and Y. Klinger, An automated data processing method for mini-arrays, *CSEM/EMSC European-Mediterranean Seismological Centre*, NewsLetter 11, 1021-1024, 1997.

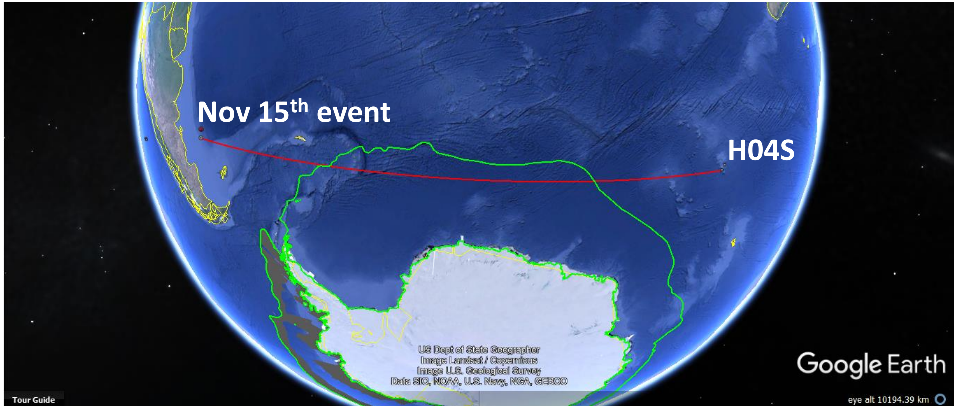
Calibrated spectrograms of both signals

- 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.

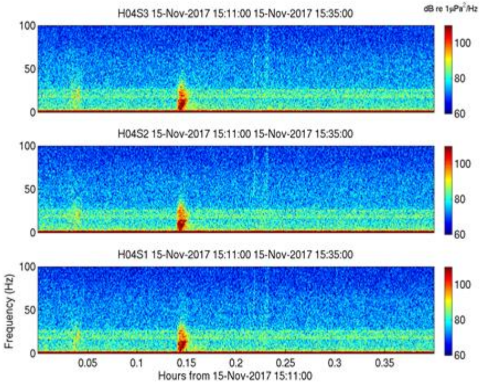


Possible pre-cursor signal at H04S

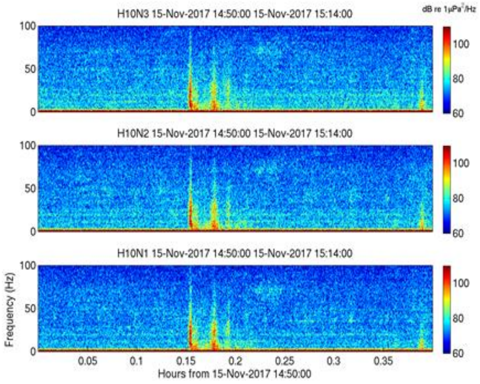
- The Geodesic propagation path (Path 1) from the November 15th event to H04S (7750 km):
  - Crosses ridges between islands.
  - Intersects the seasonal Antarctic ice-sheet (green line) in two points.
- Seasonal Antarctic ice-sheet for November 15th from U.S. National Ice Center / Naval Ice Center. [http://www.natice.noaa.gov/products/daily_products.html]
- 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*):
  - Compressional sound-speed c_p = 3500 m/s.
  - Shear sound-speed c_s = 1800 m/s.



H04S



H10N



*) F.B. Jensen et al. *Computational Ocean Acoustics*, Springer, 2011

Inclusion of non-IMS seismic station data

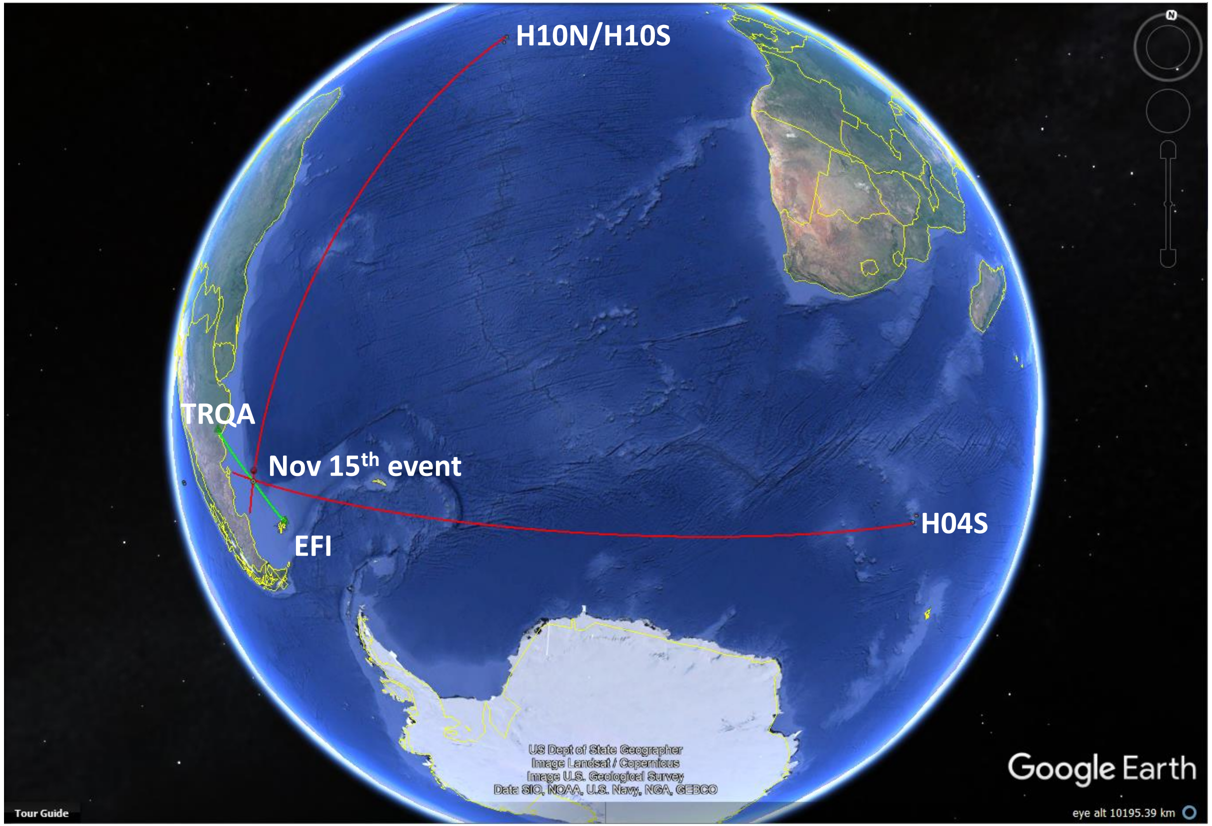
- Two non-IMS seismic stations recorded events which are compatible with the location of the November 15th hydroacoustic signal:

  - Tornquist, GSN - IRIS/USGS (TRQA)

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

  - Mount Kent, IRIS/IDA (EFI)

  The signal-to-noise at EFI was low and did not improve the localization of the November 15th event significantly.

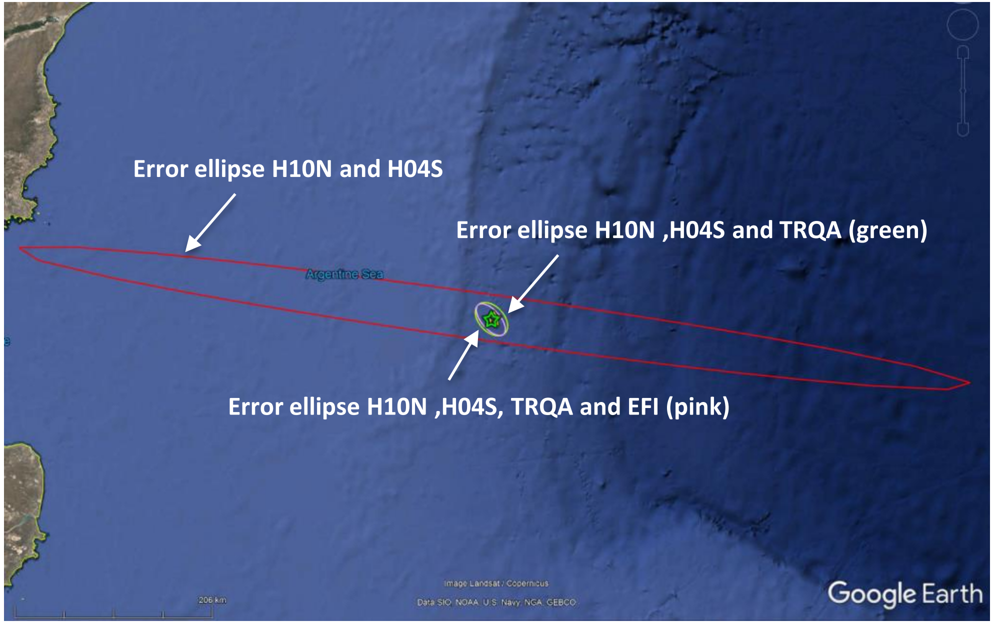


Reducing the localization error ellipse

- 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 estimate*) from the CTBT IMS acoustic stations H10N and H04S only:
  - S46.1180º, W059.6880º
  - Semi-major error ellipse axis: 487 km
  - Semi-minor error ellipse axis: 22 km
  - Ellipse strike/orientation: 98 °

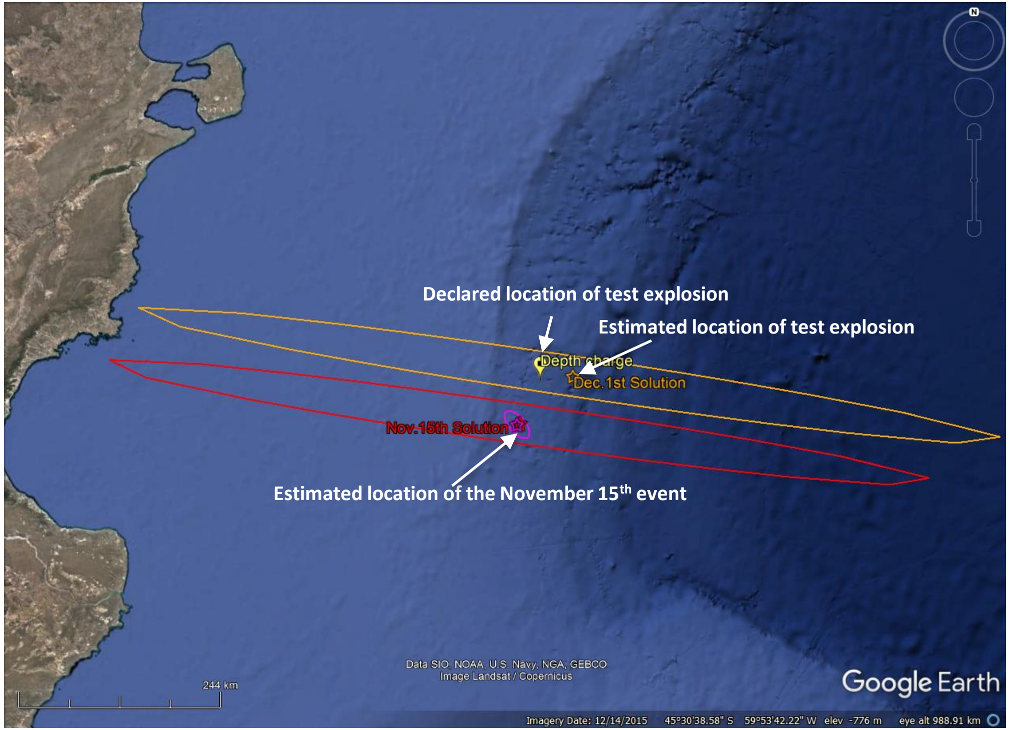
- Location error ellipse estimate*) from H10N and H04S combined with TRQA (EFI) seismic station:
  - S46.1175º, W059.7257º (S46.1218º, W059.7340º)
  - Semi-major error ellipse axis: 19 km (19 km)
  - Semi-minor error ellipse axis: 12 km (9 km)
  - Ellipse strike/orientation: 137 ° (139°)



*) IDC Processing of Seismic, Hydroacoustic and Infrasonic Data IDC-5.2.1 Rev 1 (2002)

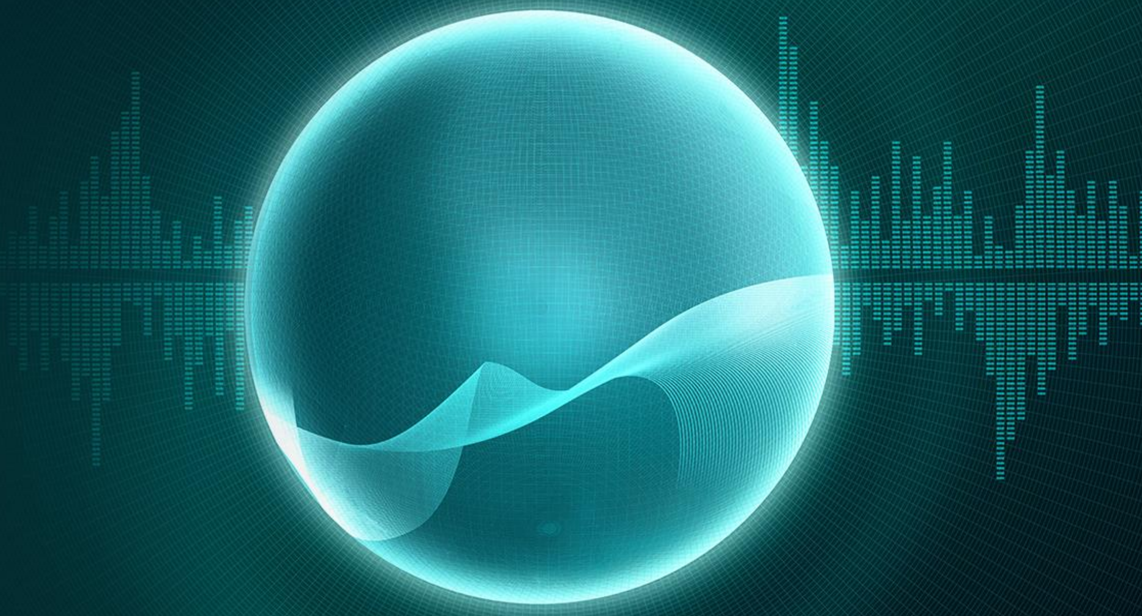
Localization error ellipse for the test explosion

- 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):
  - (S45.6185°, 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



Conclusions

- Signal recorded on November 15th 2017 at HA10 and HA04 originated from the vicinity of the last known position of ARA San Juan (3.5 hours 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 1st localized by IMS stations HA10 and HA04 to within 37 km from the declared location.
- Inclusion in the analysis of a signal recorded on November 15th by a non-IMS seismic station and compatible with the hydroacoustic signal led to a significant reduction of the location error ellipse.
- The Argentine authorities were timely and continuously informed about the progress and findings from the CTBTO data analysis of the November 15th and December 1st events.
- During the night between November 16th and 17th, 2018, the ARA San Juan was found on the seabed at 900 metres depth very near to the CTBTO location of the November 15th signal [http://www.ara.mil.ar/submarino/sanjuan/Gacetilla1711.html]



THANK YOU

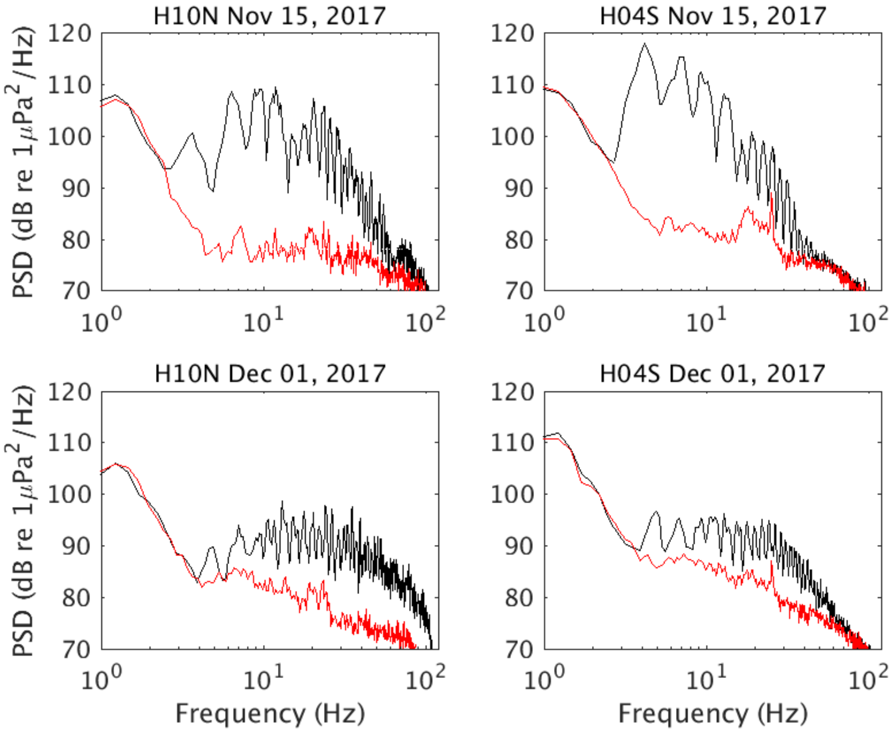
Back up slides

The Virtual Exploitation Centre

- The virtual Data Exploitation Centre (vDEC) provides scientists and researchers from many different disciplines and from around the globe with access to International Monitoring System (IMS) data to conduct research and to publish new findings.
- vDEC is a zero-cost contract. It is a contract which does not contain any monetary remuneration between the parties for services or property, but contains legal requirements.
- Strong relationship between the scientific and technological community and the CTBTO helps to ensure that the IMS remains at the forefront of technological innovation and that no nuclear explosion goes undetected.

Signal Power Spectral Density

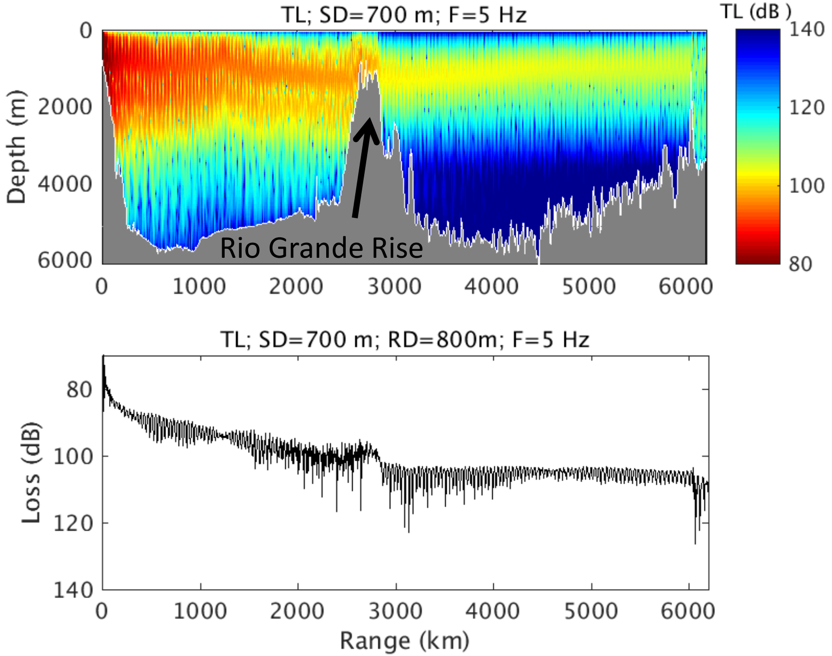
- Calibrated Power Spectral Density (PSD) levels allow comparison between signals (black) and ocean background noise (red).
- The ocean noise level was found to be lower for the November 15th than the December 1st event at stations H10N and H04S.
- The November 15th signal has up to 20 dB higher Power 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.

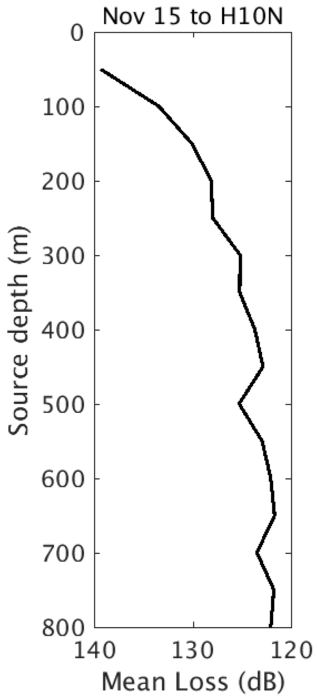


Long-range propagation modelling to H10N

- 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.

2-D Parabolic Equation (PE) Model (RAM*)





*) M.D. Collins, "A split-step Padé solution for the parabolic equation method," *J. Acoust. Soc. Am.* **93**, pp. 1736-1742, 1993.

Analysis of seismic signals

- The signal-to-noise at EFI was low and did not improve the localization of the November 15th 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 15th event.

Time series at TRQA

Particle motion hodograph