CTBTO PREPARATORY COMMISSION | COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION

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High-fidelity ocean seismo-acoustic propagation modelling for signal interpretation at the CTBT IMS hydroacoustic stations

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Outline

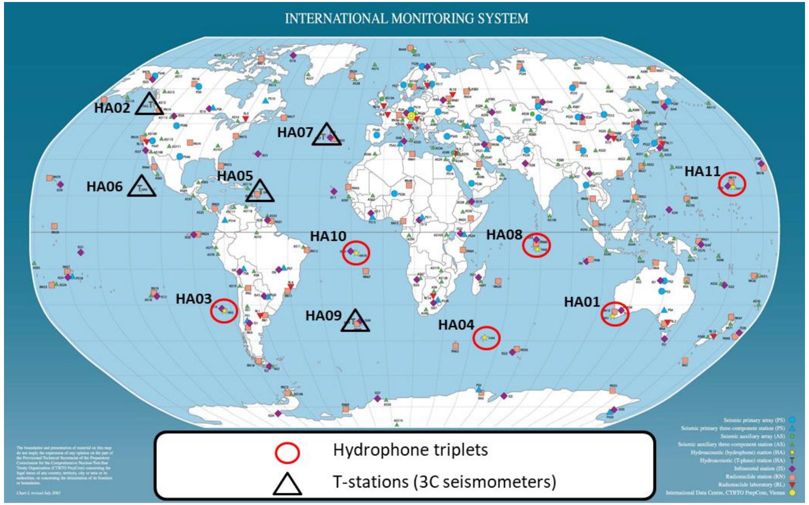
- Objectives of high-fidelity ocean seismo-acoustic propagation modelling
- Seismic survey data interpretation by 2D fluid underwater acoustic propagation modelling.
- Refraction and diffraction of acoustic signal propagation using 3D fluid underwater acoustic propagation models.
- Estimation of signals at a virtual seismometer or hydrophone by computation of the transfer function from in-ocean pressure signals to in-ground seismic signals at T-stations.
- Exploiting 3D modelling results to enhance IDC hydroacoustic data processing and signal interpretation by human analysts.
- Summary.

Objectives – Methodology – Expectations

- Overarching Objectives:
  - Use High-fidelity seismo-acoustic models to support the interpretation of received signals and improve detection, identification and localization.
- Methodology:
  - Apply high-fidelity 3D fluid propagation models to compute signal propagation in the oceans.
  - Apply high-fidelity elastic signal propagation models to estimate in-water pressure signals at virtual hydrophones by observed seismic signals originating from events in the ocean.
  - Exploit the modelled signal features for implementation into the IDC automatic processing of hydroacoustic signals.
- Expectations:
  - Improve automatic detection, classification and localization of events in the oceans.
  - Provide tools and assist human analysts in interpreting these complex signals by incorporating knowledge obtained from high-fidelity seismo-acoustic modelling capabilities in the processing procedures.

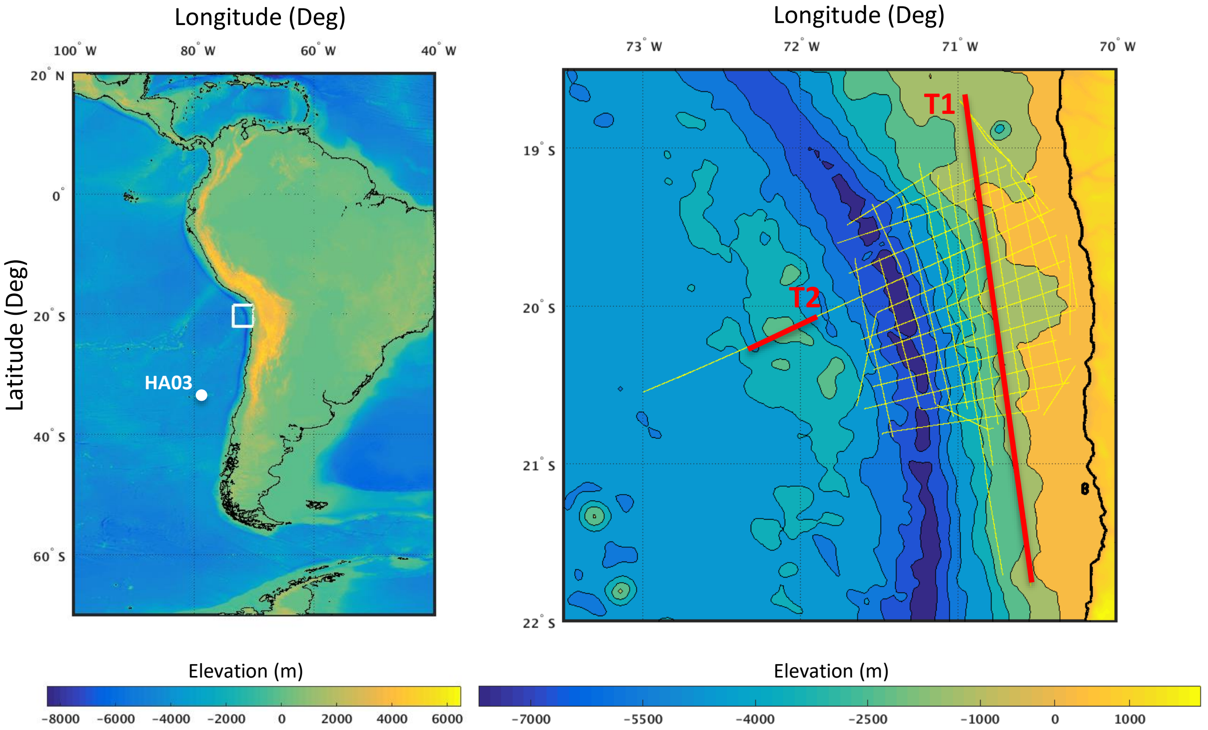
The CTBT IMS hydroacoustic network

- Hydroacoustic data are transferred continuously from CTBT IMS hydrophone triplets and T-stations to the Vienna International Centre, Austria.
- The data are processed by an automatic processing algorithm at CTBT IDC following an evaluation and eventual modification by human analysts to produce bulletins characterizing events originating anywhere in the oceans.
- Interpretation of the recorded signals and their features can be difficult because signals in water may propagate thousands of kilometers in a complex underwater environment which varies spatially and temporally.
- The interpretation becomes increasingly complex when the in-water pressure signal converts to in-ground seismic signals at the CTBT IMS T-stations.
- Examples of applications of 2D (RAM [Collins 1993]) and 3D (SSF PE [Lin 2013]) fluid-only underwater acoustic propagation models are presented which reveal characteristics of the signals that otherwise would be difficult to achieve.
- A hybrid combination of a 2D fluid-only (RAM [Collins 1993]) underwater acoustic propagation model and the 2D elastic seismo-acoustic model SPECFEM2D [Tromp 2008] is applied to predict a signal recorded at a hydrophone in the ocean based on observations recorded at a closely located seismometer [Stevens 2020].
- An illustration on how results from these high-fidelity models can be exploited by the CTBT IDC automatic processing algorithm is presented as work in progress.



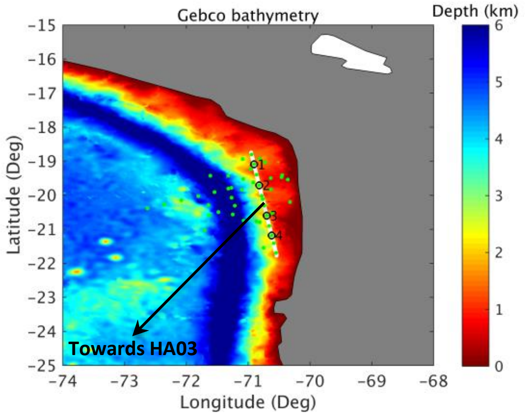
PICTURES scientific sea trial

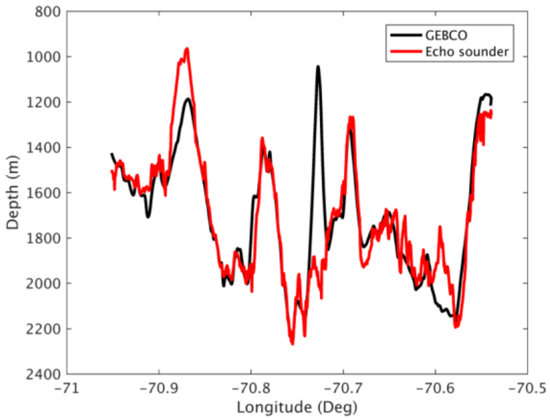
- PICTURES [Tréhu 2017, Le Bras 2018, 2019] is a scientific sea trial conducted off the Chile in the fall of 2016 (left panel).
- Towed airgun and streamers to map the subduction zone in a criss-cross survey pattern (yellow tracks in the right panel).
- Contemporary oceanographic measurements such as eXpendable BathyThermographs (XBTs), single-beam and multibeam swath bathymetric data.
- Log of sea trial provides accurate information about airgun source depth, source transmission time and location of both vessel and airgun.
- Two tracks T1 and T2 (red in right panel) used to investigate the ability to model the recorded acoustic data at the northern triplet of HA03 (white dot in left panel) and to explain observations.
- Oceanographic data used in the modelling were extracted from databases.

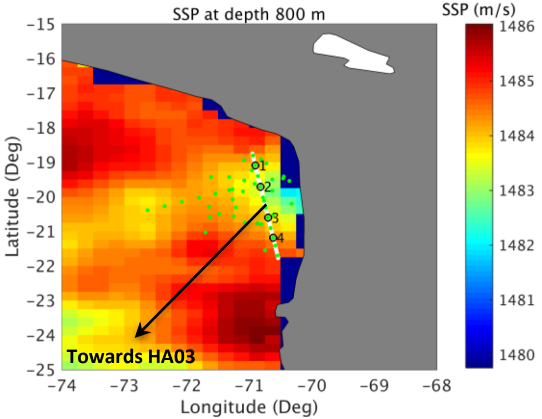


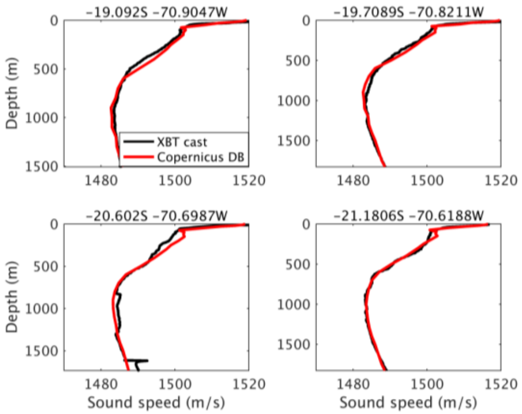
PICTURES T1: Environment

- GEBCO bathymetry data in the region of T1 (white line) with relive shallow water along T1 and the more than 8000 deep ocean trench at the subduction zone to the west of the track (upper left panel).
- The green dots 1-4 are locations of XBTs acquired along T1 during the acoustic transmissions (upper left panel).
- There is an impressive agreement between single-beam echosounder bathymetric data (red) and interpolated GEBCO database information (black) along T1 (upper right panel).
- Ocean sound-speed at 800 m depth calculated using Copernicus temperature and salinity data in the region of T1 (white line in lower left panel).
- There is an impressive agreement between the XBT measurements (black) and the Copernicus derived sound speed data (red) along T1 (lower right panel).
- The calculated XBT sound speed was added 5 m/s because of too low salinity of 30 ppt was reported in the data files.



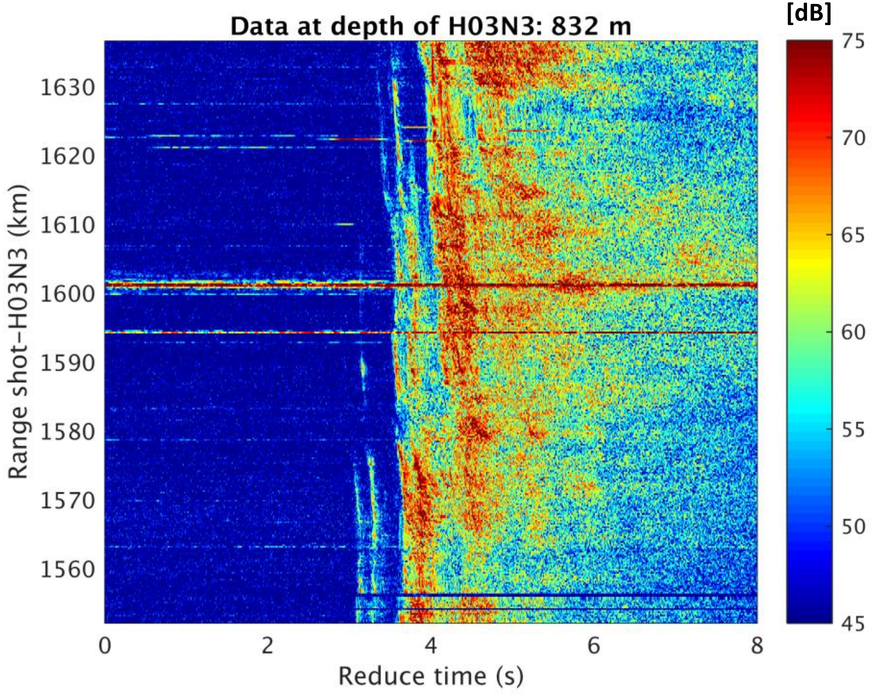




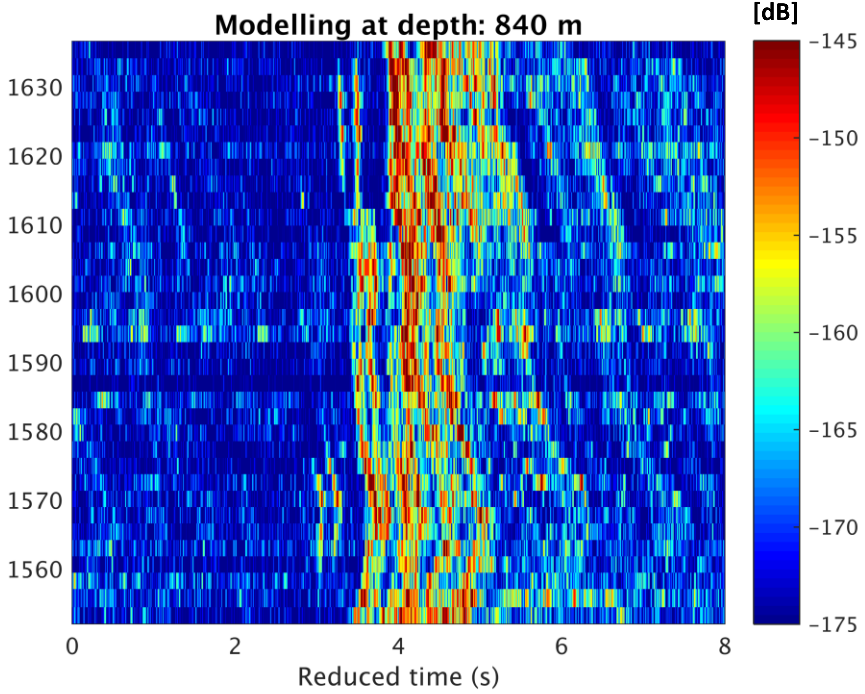


PICTURES T1: Time series

Envelope of recorded time series as the vessel proceeds along T1

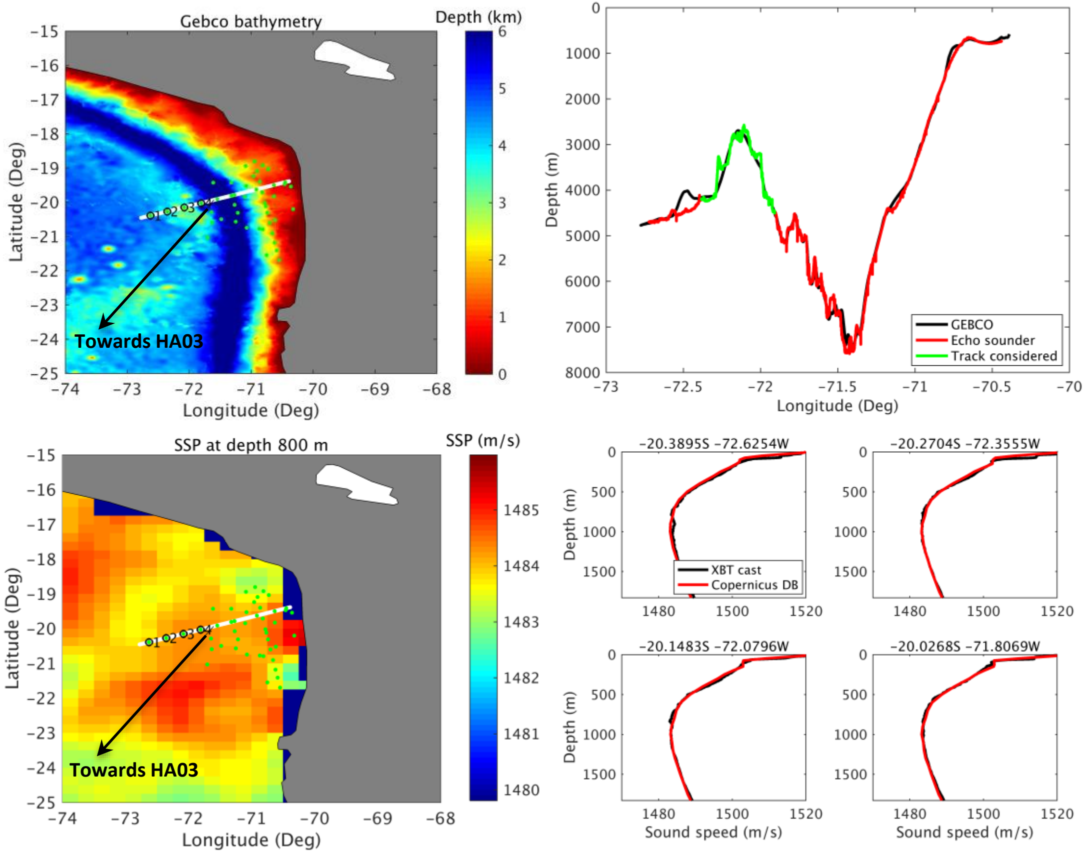


Modelled bandlimited impulse as the vessel proceeds along T1
2D Parabolic Equation model RAM [Collins 1993]



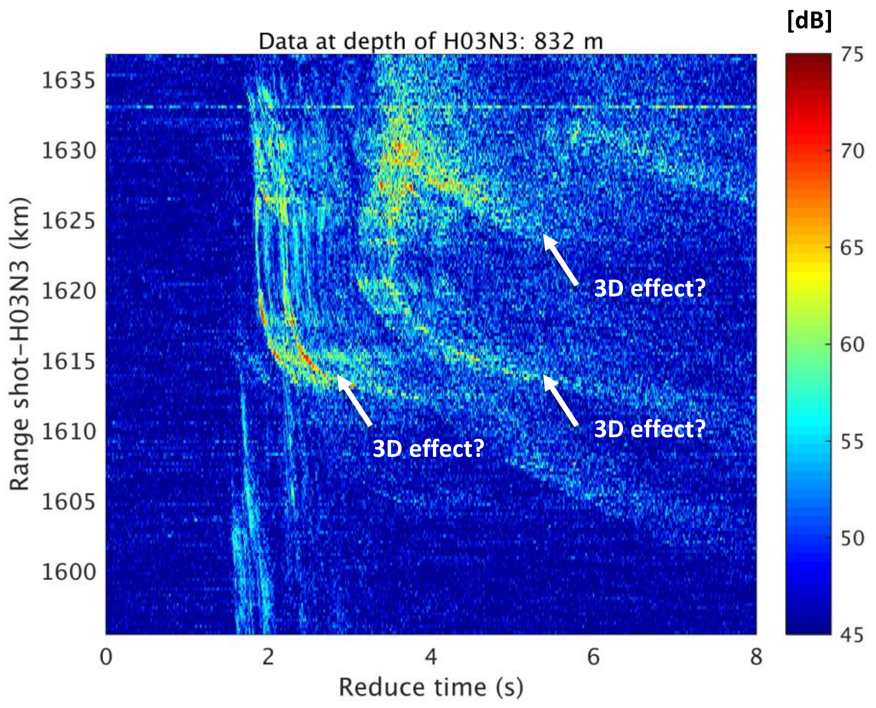
PICTURES T2: Environment

- GEBCO bathymetry data in the region of T2 (white line) with relative shallow water at the beginning of T2, crossing the ocean trench and reaches small seamounts (upper left panel).
- The green dots 1-4 are locations of XBTs acquired along T2 during the acoustic transmissions (upper left panel).
- There is an impressive agreement between single-beam echosounder bathymetric data (red) and interpolated GEBCO database information (black) along T2 (upper right panel).
- The part of T2 corresponding to the bathymetry in green is considered further (upper right panel).
- Ocean sound-speed at 800 m depth calculated using Copernicus temperature and salinity data in the region of T2 (white line in lower left panel).
- There is an impressive agreement between the XBT measurements (black) and the Copernicus derived sound speed data (red) along T1 (lower right panel).
- The calculated XBT sound speed was added 5 m/s because of too low salinity of 30 ppt was reported in the data files.

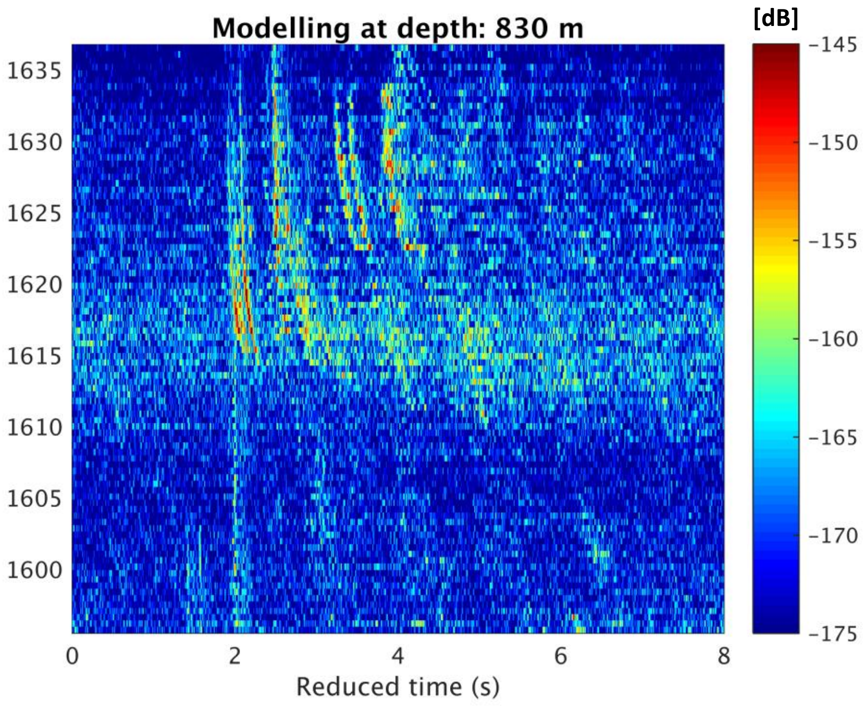


PICTURES T2: Time series

Envelope of recorded time series as the vessel proceeds along T2

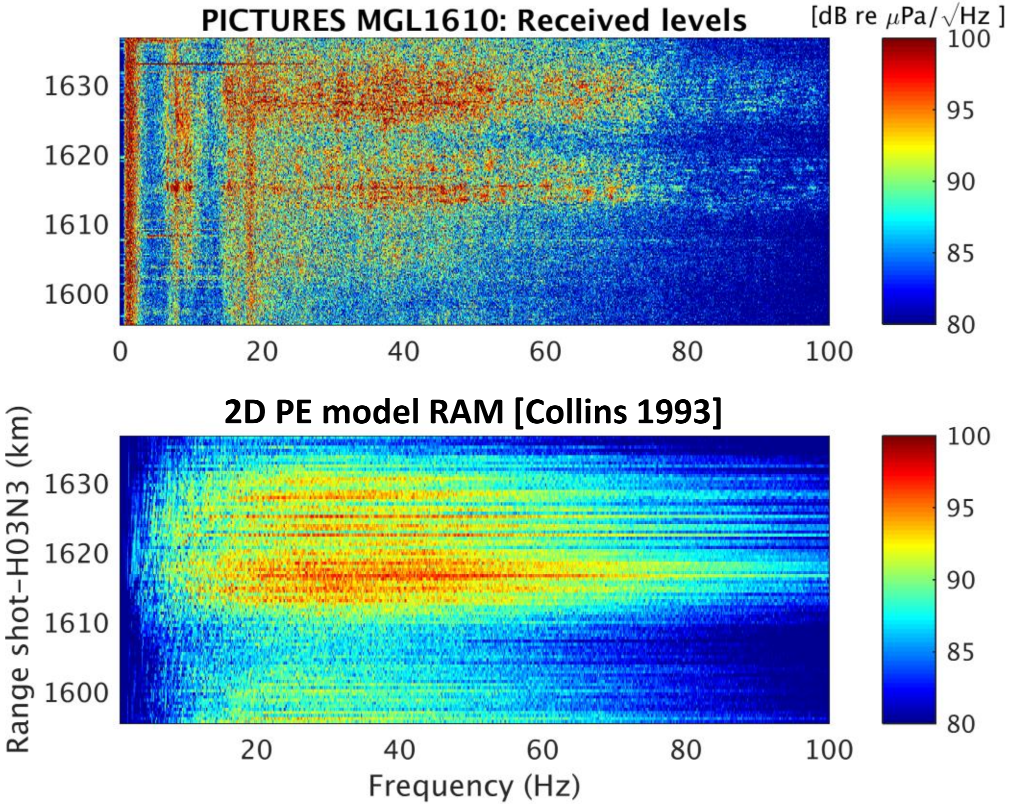


Modelled bandlimited impulse as the vessel proceeds along T2
2D Parabolic Equation model RAM [Collins 1993]



PICTURES T2: Calibrated received levels at hydrophone versus frequency

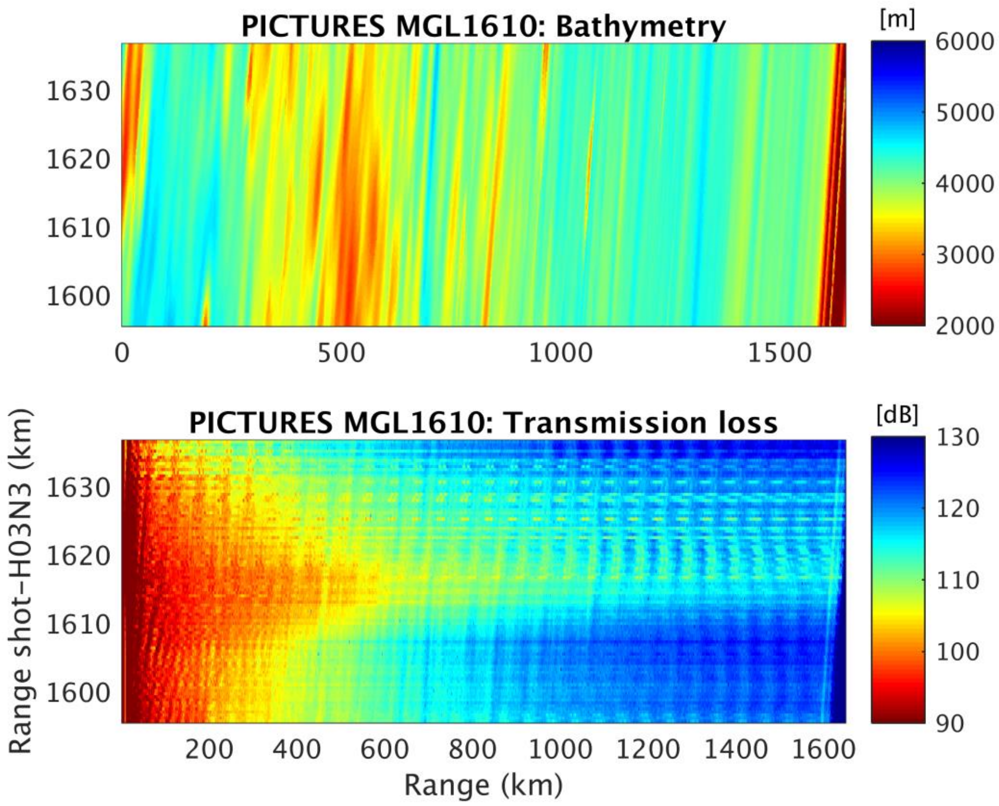
- The upper panel shows the received amplitude spectral levels calculated by the inverse Fourier Transform of the recorded time series calibrated by a calibration factor assumed constant in the band from 10 to 100 Hz.
- The calculated amplitude spectral levels include the frequency dependent source characteristics.
- The vertical axis corresponds to the range between airgun and HA03 northern triplet shown in the previous slides.
- There is a clear low-pass filtering of the data at shorter airgun-receiver ranges of around 1612 km that also is observed in the time series.
- The modelled amplitude spectral levels show the similar behaviour as the data. The acoustic source in the model is assumed to have an amplitude spectral level of 220 dB at 1 Hz and decaying 0.24 dB per Hz for comparison with the observations.



PICTURES T2: Prediction of transmission loss (TL) versus range

- The upper panel shows the bathymetry along the geodesic paths from 93 airgun source locations at geodesic distances from 1595.53 to 1636.78 km to node 3 of the northern triplet of the HA03 hydrophone station.
- The computed transmission loss (TL) using the 2D PE model RAM [Collins 1993] along the geodesic paths is shown in the lower panel for a source depth of 10 m. The pressure amplitude is averaged over receiver depths from 500 to 1000 m (the IMS hydrophone depth is around 832 m) and over frequency in the band from 40 to 80 Hz.
- There is a clear tendency of higher TL at shorter propagation ranges than around 1612 km.
- The minimum TL out to maximum propagation ranges and therefore maximum received levels are expected when the airgun transmission is conducted at the shallowest bathymetry along T2.
- The TL for airgun shot ranges to H03N3 greater than around 1612 km shows a convergence zone-type propagation pattern that results in minimum loss of the airgun transmissions.

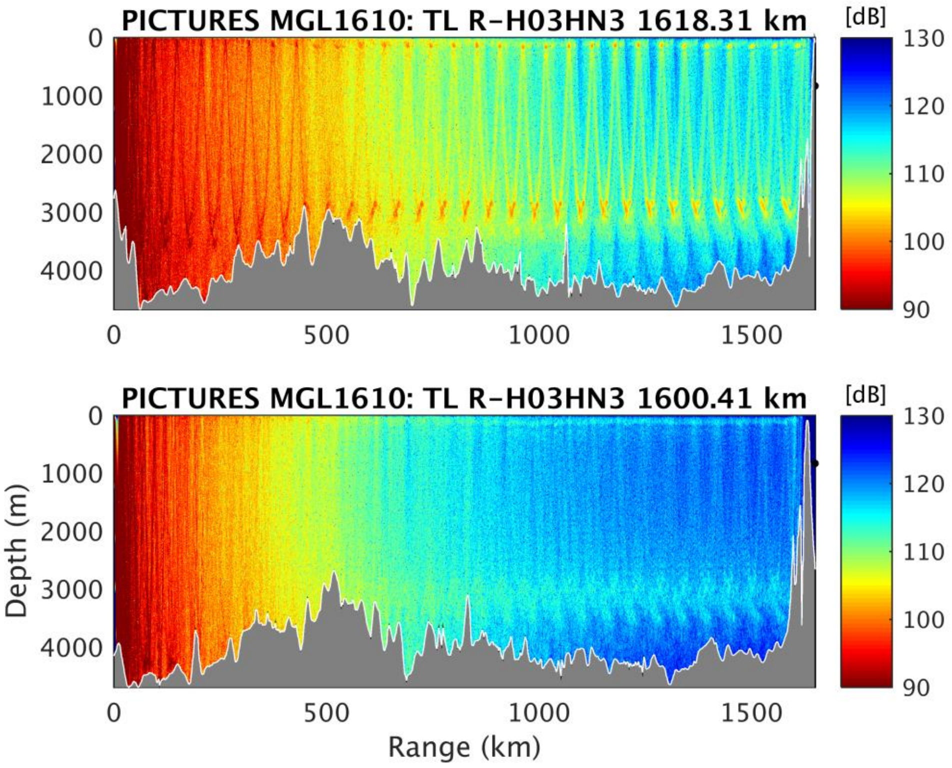
2D Parabolic Equation model RAM [Collins 1993]



PICTURES T2: Prediction of (TL) versus depth and range

- These two panels show the computed TL as a function of receiver depth and propagation range along the geodesic path from the airgun location to node 3 at the northern triplet of HA03.
- The computed transmission loss (TL) using the 2D PE model RAM [Collins 1993] along the geodesic path for airgun shot at 1618.31 km distance (upper panel, low loss at the receiver) and 1600.41 km (lower panel, high loss at the receiver).
- The airgun source depth is 10 m and the TL is averaged in the frequency band from 40 to 80 Hz.
- The TL is low across the entire water column for airgun shot at 1618.31 km distance compared to the shot at 1600.41 km.
- The TL for airgun shot at 1618.31 km distance clearly shows convergence zone-type acoustic propagation paths that are very weak for the shot at 1600.41 km.
- The convergence zone propagation paths are created by the reflection of the acoustic signal from the bathymetry close to the airgun (zero range) that redirect the propagation path to be refracted in the water column by the sound speed profile with very little sea surface interaction.
- This is NOT the traditional SOFAR channel propagation associated with global-scale ocean propagation scenarios.

2D Parabolic Equation model RAM [Collins 1993]



- Certain observed signal features can be explained by 2D signal propagation modelling providing sufficiently accurate knowledge about environmental information from oceanographic databases and measurements, and knowledge about acoustic source-receiver geometry. Data from scientific sea trials are very valuable as they typically are well documented and can provide ground-truth for underwater acoustic system performance evaluation.
- Three-dimensional underwater acoustic propagation effects such as horizontal diffraction and refraction have been identified in CTBT IMS recorded hydroacoustic data. These features cannot be explained by 2D propagation modelling. CTBTO has revisited these scenarios and applied high-fidelity 3D propagation model to these events which confirm previous modelling results and observations.
- Efforts in computing phase conversion from in-water pressure signals to in-ground seismic signals at ocean-island boundaries suggest that the modelled transfer function potentially can be convolved with the in-water pressure to estimate a seismic signal at a virtual seismometer and *vice versa.* This approach has been demonstrated both on pure synthetic data and observations. The modelled transfer function can possibly reveal signal features originating from an in-ocean event and recorded at a virtual hydrophone that otherwise would be masked if only seismic signals were available at the T-station.
- Three-dimensional propagation modelling results and the transfer function estimate at T-stations are proposed implemented in the CTBT IDC automatic processing algorithm to enhance processing capabilities and assist human analysts in signal interpretation.

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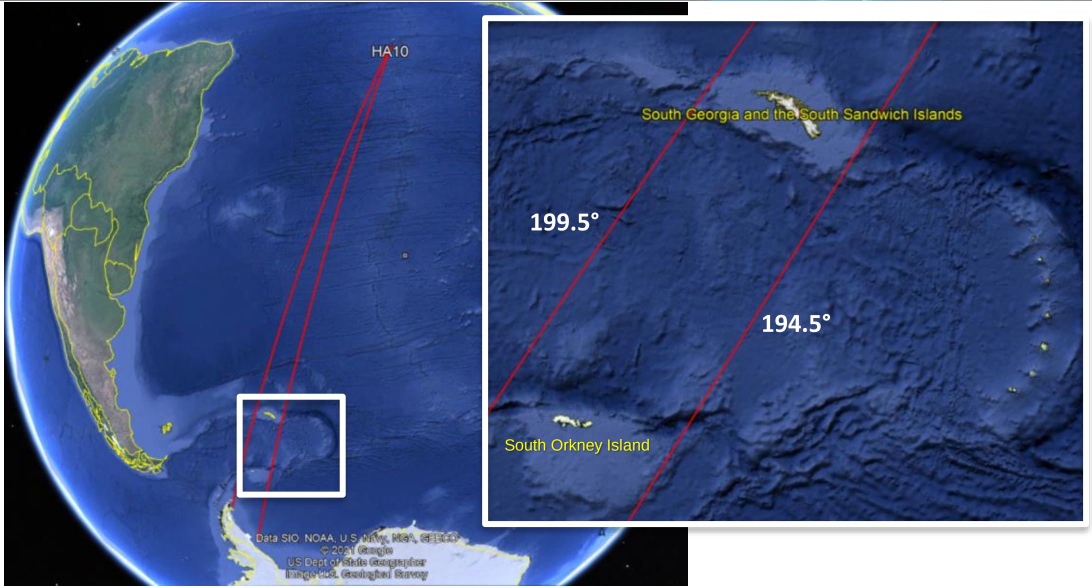
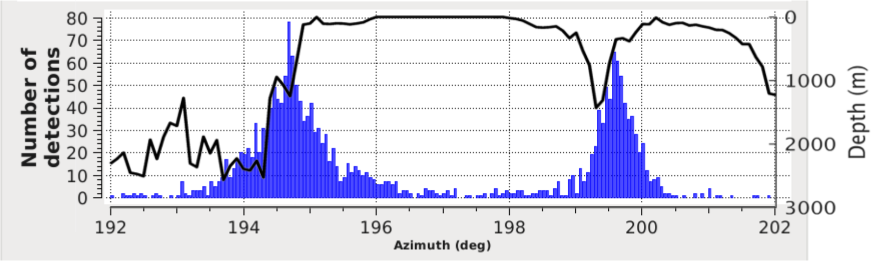
Observed 3D diffraction of signals

- Sound in the southern Atlantic ocean generated by earthquakes in the region between South Georgia and South Orkney Island is detected at H10N [Heaney 2017].
- The underwater acoustic path is close to blocked for azimuths 194.5° between 199.5° by the South Georgia Island and its underwater plateau.
- The arrivals are not identified as T-phases propagating in the ground and coupled into the ocean North of South Georgia as the travel times correspond to signals travelling at the ocean sound speed.
- Relative narrow trench-like underwater acoustic paths at azimuths 194.5° and 199.5° (red lines in upper panels) where sound can escape around South Georgia Island.
- A typical number of detections at H10N for 24 hours of acquisition is shown in the lower panel with a distribution centred around azimuths of 194.5° and 199.5°. Minimum water depth along 500-km radials centred around South Georgia Island is shown as the black line.
- The detection of signals originating from behind and blocked by South Georgia Island can be explained by 3D diffraction of the signals around South Georgia Island.



DTKGPMCC [Cansi (1995, 1997] : H10N 16/12/2020 24 hours



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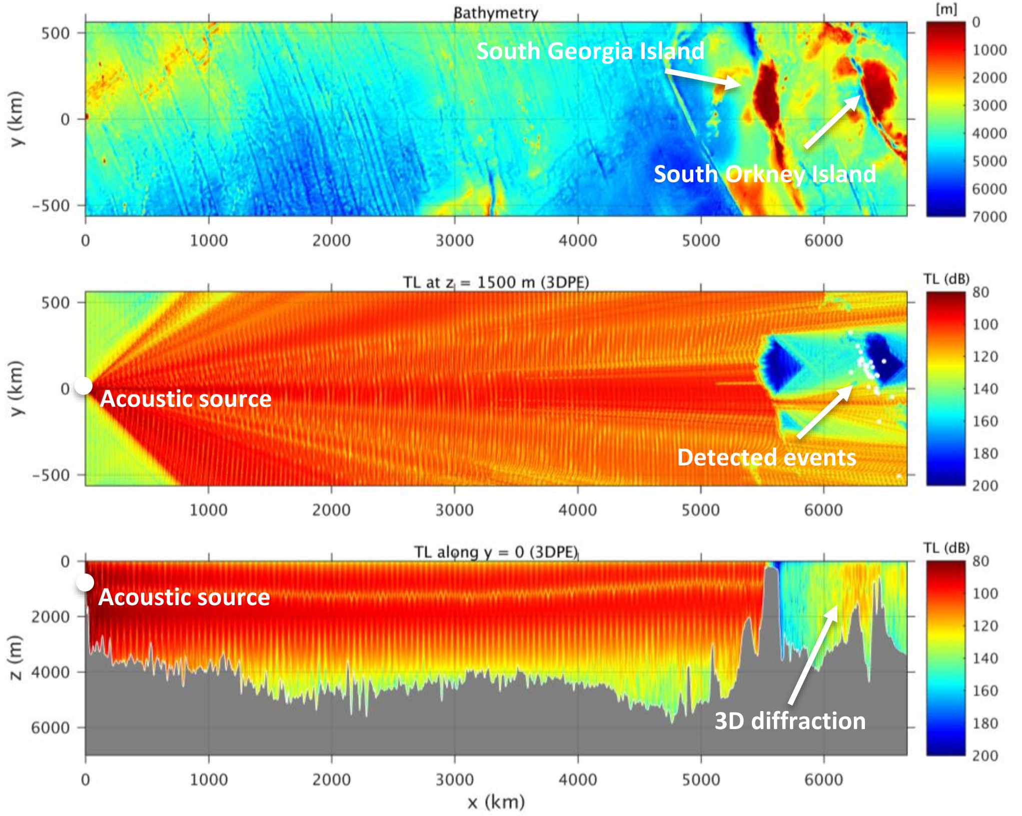
Modelling of 3D diffraction of signals

Diffraction around seamounts and Islands

- GEBCO bathymetry swath along a geodesic path from triplet H10N at (0,0) to a location close to South Orkney Island (6850,0) passing through South Georgia Island (upper panel).
- Computation of 3D underwater signal propagation presented as TL at 5 Hz using the SSF PE [Lin 2013, Kushida 2020] from H10N towards South Orkney Island at a depth of 1500 m (middle panel).
- At least 32 events in the period 2006-2014 detected and stored in the Standard Event Level 3 from the automatic processing although line-of-sight blockage by South Georgia Island (white dots beyond 6000 km).
- Diffraction of sound around South Georgia can make T-phase arrivals visible at H10N when blockage based on 2D computations predict they would not be seen (middle panel) [Heaney 2017].
- Diffraction fills the entire water column behind South Georgia making it possible to detect the sound source at any receiver depth.

3D Parabolic Equation model SSF PE [Lin 2013, Kushida 2020]

The authors are gratefully acknowledged making the 3D SSF PE available



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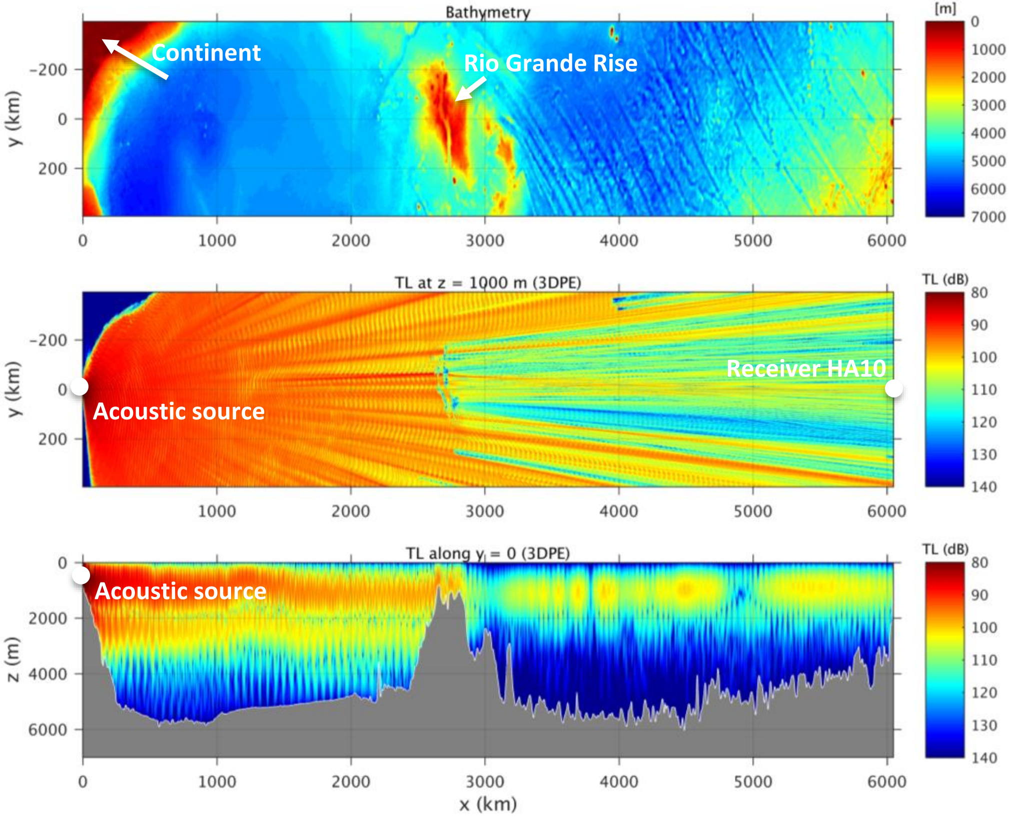
Modelling of 3D refraction and diffraction of signals

Refraction and diffraction from seamounts, Islands and continents

- The in-water acoustic anomaly associated with the loss of ARA San Juan was detected at the hydrophone station HA10.
- Horizontally refracted arrivals from the same event were detected up to 15 minutes after the primary arrival following the geodesic propagation path.
- Refraction and diffraction can be observed from the top of Rio Grande Rise (middle panel).
- The acoustic signal propagates in the SOFAR channel, interacts with the Rio Grande Rise and reflected off the ocean bottom to pass the Rise. The signal is again trapped in the SOFAR after the Rise (lower panel).
- The acoustic signal propagating in the ocean after the Rio Grande Rise is a combination of 3D refracted and diffracted propagation paths.
- K. Heaney on “Validation of 3-dimensional ocean acoustic propagation models from benchmarks to global problems”, EGU21-16337, following this presentation.

3D Parabolic Equation model SSF PE [Lin 2013, Kushida 2020]

The authors are gratefully acknowledged making the 3D SSF PE available

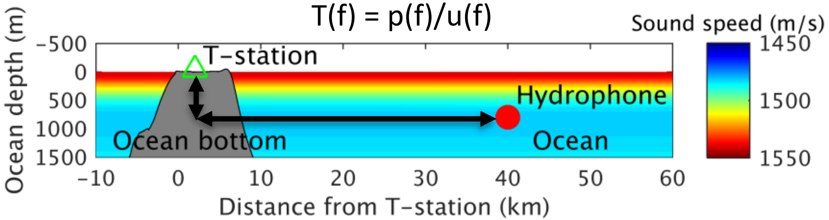


Concept of estimating transfer function from in-ocean to in-ground event

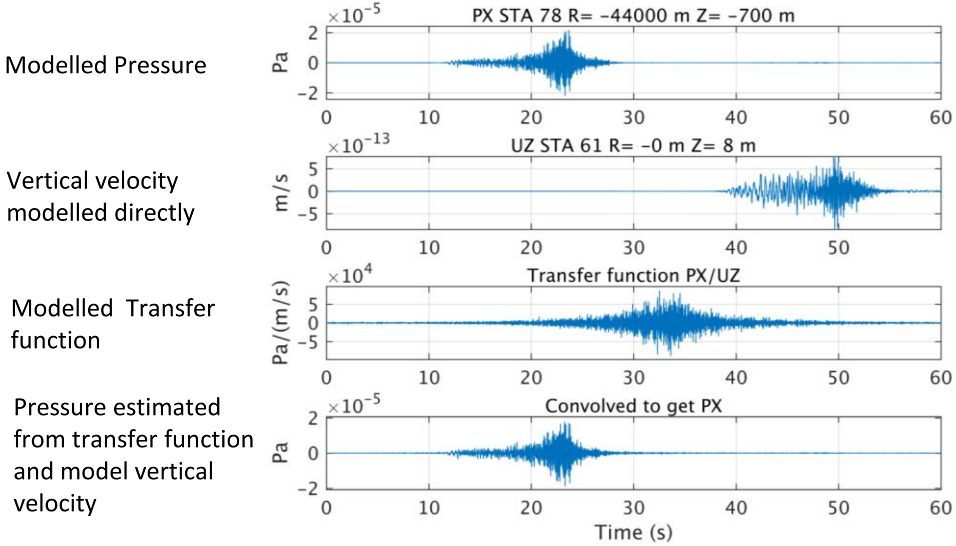
Detection of in-ocean events at on-land seismometers (modelling)

- Difficult to associate in-ocean events to signals recorded at the CTBT IMS on-land T-stations because of high ambient noise levels.
- In-ocean events are observed in recordings from on-land seismometers at different locations than CTBT IMS T-stations.
- Conversion from in-water pressure to in-ground seismic signals at T-stations may reduce or eliminate evidence of an in-ocean event.
- Accurate computation of the transfer function (Greens function) from in-water to in-ground signals may preserve these evidences.
- Convolution of a seismic signal recorded at a T-station with this transfer function may recover features of an in-ocean event at a virtual hydrophone closely located.

$$T(f) = p(f)/u(f)$$



Noise-free modelling results



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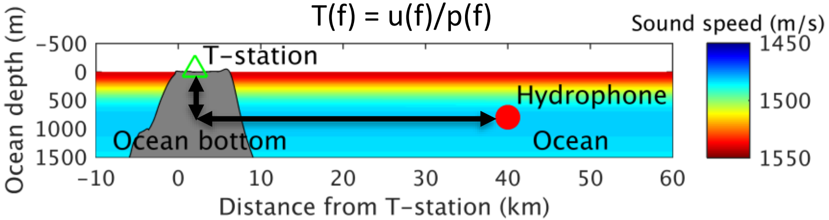
Estimate signal at virtual seismometer based on modelled transfer function

Detection of in-ocean events at on-land seismometers (model/data)

- Event recorded at the CTBT IMS hydrophone station H11N close to Wake Island and the close-to-collocated WAKE seismometer.
- The transfer function of an in-water pressure signal converted to an in-ground seismic signal is computed by the SPECFEM2D [Tromp 2008, Stevens 2020].
- Model-based estimate of a virtual hydrophone signal by convolution of the modelled transfer function with the recorded vertical component of the seismometer data.
- Experience reveals that it is more demanding to estimate the signal at a virtual hydrophone than a virtual seismometer.
- Improved similarity between estimates and observations of the virtual signals are sought by an inversion for optimum underwater environmental parameters.
- This is a new project and is still in progress.

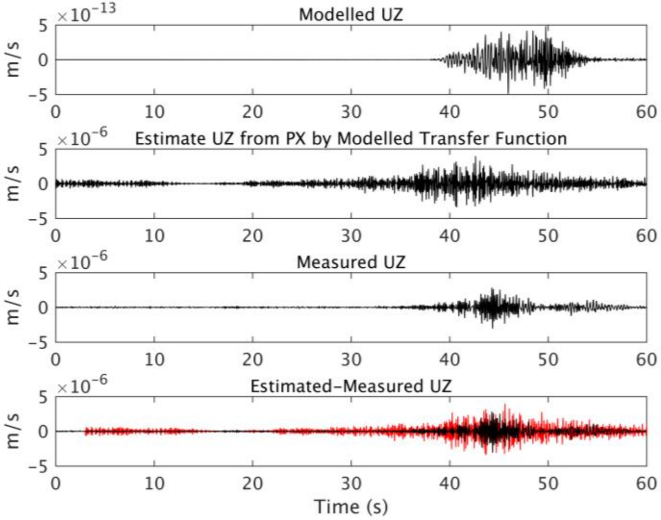


Vertical velocity modelled directly

Measured pressure convolved with modelled transfer function to estimated velocity

Measured vertical velocity on seismometer

Estimated (red) and measured (black) vertical velocity



Estimate signal at virtual hydrophone based on modelled transfer function

Detection of in-ocean events at on-land seismometers (model/data)

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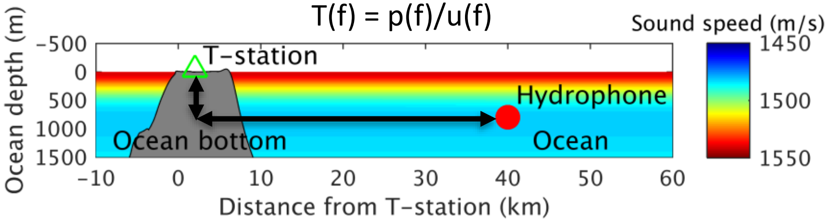
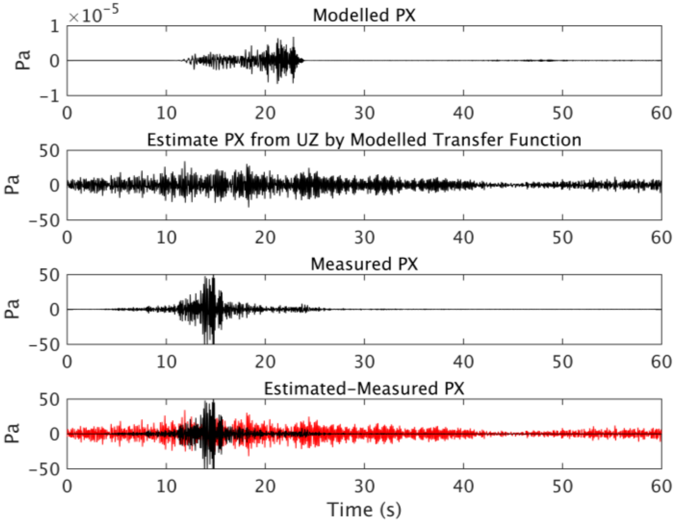


Pressure modelled directly

Measured velocity convolved with modelled transfer function to estimated pressure

Measured pressure on hydrophone

Estimated (red) and measured (black) pressure



Modelled transfer function may reveal signal features at virtual sensors

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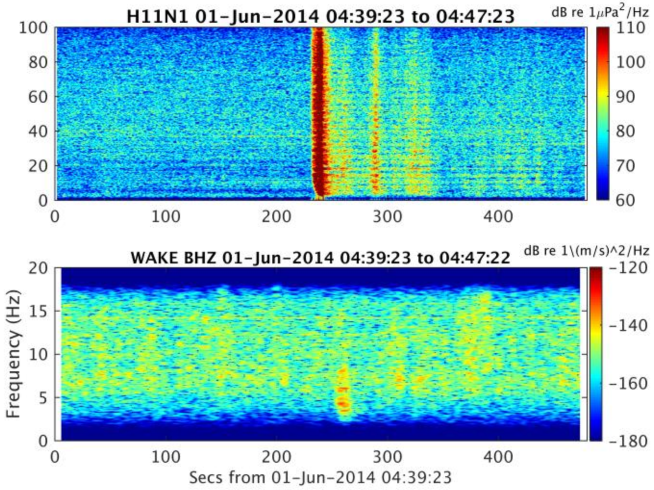
Preservation and recovery of in-ocean event signal features

- Scientific trial NOMAN14 deployed explosive charges off the coast of Japan in 2014 [Yamada 2016].
- Event recorded at the CTBT IMS hydrophone station H11N close to Wake Island and the close-to-collocated WAKE seismometer.
- Calibrated spectrograms by using system responses.
- Cepstra of filtered hydrophone and seismometer data.
- A cepstral peak is observed in the hydrophone data after 0.27 seconds from the primary arrival.
- Possibly a hydrophone pressure signal feature may be preserved or recovered by the modelled transfer function convolved with the recorded signal at the seismometer.

Calibrated spectrograms

Upper panel: Hydrophone data at H11N

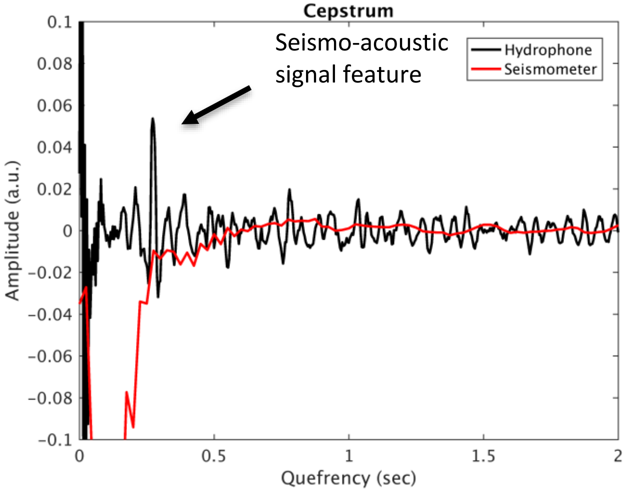
Lower panel: Seismic data at WAKE Island



Data filtered:

Hydrophone: 3-100 Hz

Seismometer: 3-18 Hz



CTBT IDC automatic processing

Processing flow of hydrophone data from triplets

1. **Raw data from hydrophone stations**
   · Real-time data transfer Via satellite link
2. **Detection and Feature eXtraction (DFX) algorithm**
   · STA/LTA detector
3. **Station Processing (StaPro)**
   · Grouping of arrivals on triplets
   · Phase identification (H, T, N)
4. **Hydro Azimuth and Slowness Estimator (HASE)**
   · Seismic phase identification (P)
   · Back-azimuth estimation of grouped arrivals on triplet by a Progressive Multi-Channel Cross Correlation algorithm (PMCC)
5. **Global Association/NET-VISA (contribute with arrival time)**
   · Blockage maps from 2D propagation modelling
   · A signal will be discarded from event association if the 2D geodesic propagation path is blocked
6. **Event localization**
   · LMS-type minimization of observed and computed 2D travel time differences
   · Can include back-azimuth from observations and computations assuming 2D geodesic propagation path differences

Processing flow of seismic data from T-stations

1. **Raw data from T-station seismometer**
   · Real-time data transfer Via satellite link
2. **Detection and Feature eXtraction (DFX) algorithm**
   · STA/LTA detector on vertical component only
   · Detector setting is different to hydrophone data
3. **Global Association/NET-VISA (no contribution to event localization)**
   · Blockage maps from 2D propagation modelling modified slightly to accommodate partly propagation in ground
   · A signal will be discarded from event association if the 2D geodesic propagation path is blocked
4. **Event localization**
   · No contribution to location

Long-term goals related to CTBT IDC processing

Envisage processing enhancement of hydrophone data (any stage convenient):

- Produce seasonal transmission loss maps from global-scale 3D propagation modelling for all IMS hydroacoustic stations to update existing blockage maps and to estimate probability of detection of in-ocean events anywhere in the ocean.
- Produce seasonal travel time tables with associated uncertainties from global-scale 3D propagation modelling for all IMS hydroacoustic stations to substitute the existing 2D travel time tables.
- Expand the IDC database tables to facilitate storage of multiple arrivals from the same in-ocean event with associated signal features for each arrival (in particular horizontally reflected/refracted/diffracted arrivals)
- Correlate observations and 3D modelling results for arrival consistency which may necessitate beamforming or similar direction-of-arrival calculation as in HASE.
- Pass signal features to the global associator and localization algorithm.

Envisage processing enhancement of seismic T-station data (any stage convenient):

- Produce transfer functions of in-ocean pressure to in-ground seismic signals for all CTBT IMS T-station elements which may necessitate full elastic 3D wave propagation modelling.
- Identify noise sources and eventually denoise data recorded at T-stations to improve signal-to-noise ratio.
- Estimate in-ocean signal at a virtual hydrophone by convolving the computed transfer function with the seismic signal recorded at the T-station elements.
- Extract relevant signal features from the estimated virtual hydrophone signal similarly to the procedures followed in the standard processing of hydrophone data to identify an arrival.
- Estimate direction-of-arrival utilizing the three components of the three-component seismometer at the T-stations similarly to the processing of the seismic arrays and/or introduction of artificial intelligence algorithms.
- Expand the IDC database tables to facilitate storage of signal features estimated at a virtual hydrophone.
- Pass signal features to the global associator and localization algorithm.

Summary

- High fidelity underwater seismo-acoustic propagation modelling can assist in hydroacoustic signal detection, identification and localization of in-ocean events during automatic processing or in human analysts' interaction.
- Two-dimensional underwater signal propagation models combined with oceanographic database information can explain distinct signal features assuming propagation paths along geodesics from event to hydrophone.
- Three-dimensional underwater signal propagation models are crucial in scenarios with significant horizontal diffraction, refraction and reflection for interpretation of observations that otherwise are excluded from the processing.
- Results from three-dimensional underwater acoustic signal propagation modelling in support of observations may significantly improve coverage of the IMS hydroacoustic network, reduce uncertainties in event localization and provide critical support in human review of automatic processing results.
- Estimates of hydroacoustic signals at a virtual hydrophone located close to an IMS T-station by convolution of a computed transfer function and an observed on-land seismic signal at a T-station may reveal signal features for improved detection, identification and localization of in-ocean events.
- CTBT IDC investigating the possibility of implementing criteria obtained from these high-fidelity modelling capabilities in future versions of the automatic processing algorithm and provide informative insights from the modelling results for signal interpretation during human analysts' interaction.

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