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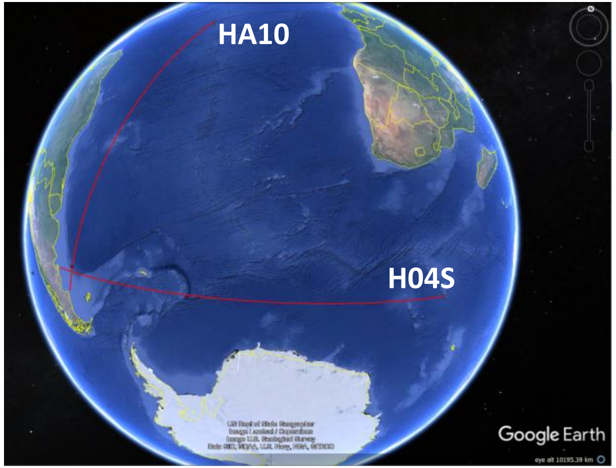
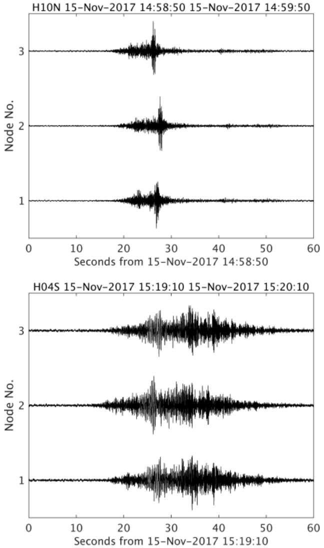
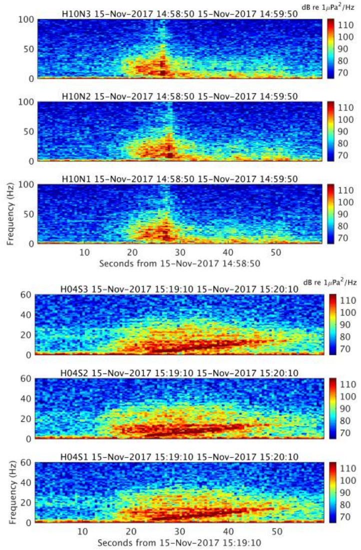
Observation and interpretation of ocean waveguide impact on long-range, underwater acoustic propagation of recorded hydrophone signals







Peter Nielsen[(1)], Mario Zampolli[(1)], Ronan Le Bras[(1)], and Georgios Haralabus[(1)]
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The views expressed herein are those of the author(s) and do not necessarily reflect the views of the CTBT Preparatory Commission.

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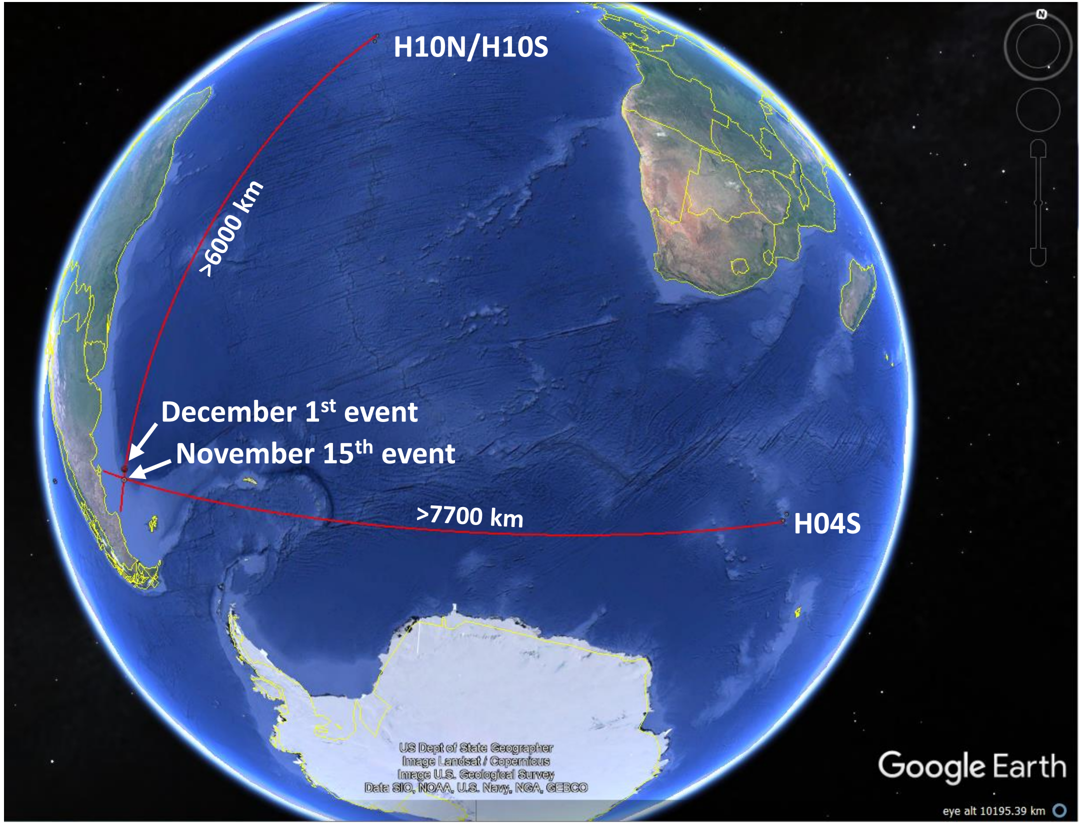
Hydroacoustic signals recorded at IMS stations

- Signal of unknown origin detected on November 15th 2017 in the vicinity of the last known position of the lost Argentine submarine ARA San Juan.
- Controlled explosion test conducted by Argentine Navy on December 1st 2017, with source position and time information.
- The November 15th signal and the December 1st test source were both detected on CTBT IMS hydrophone stations HA10 and HA04.



Peter L. Nielsen, Mario Zampolli, Ronan Le Bras, Pierrick Mialle, Paulina Bittner, Alexander Poplavskiy, Mikhail Rozhkov, Georgios Haralabus, Elena Tomuta, Randy Bell, and Patrick Grenard, "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", EGU2018-18559 PICO presentation European Geosciences Union General Assembly, Vienna, Austria, 2018

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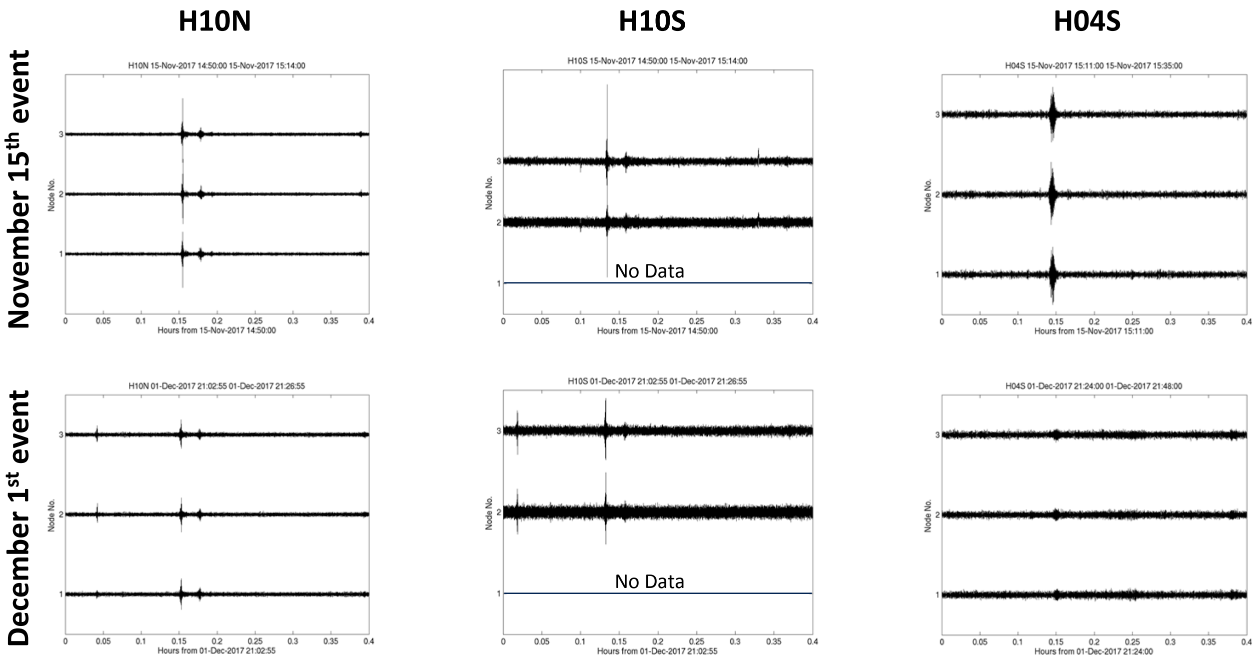
Time series recorded from both events

- 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.



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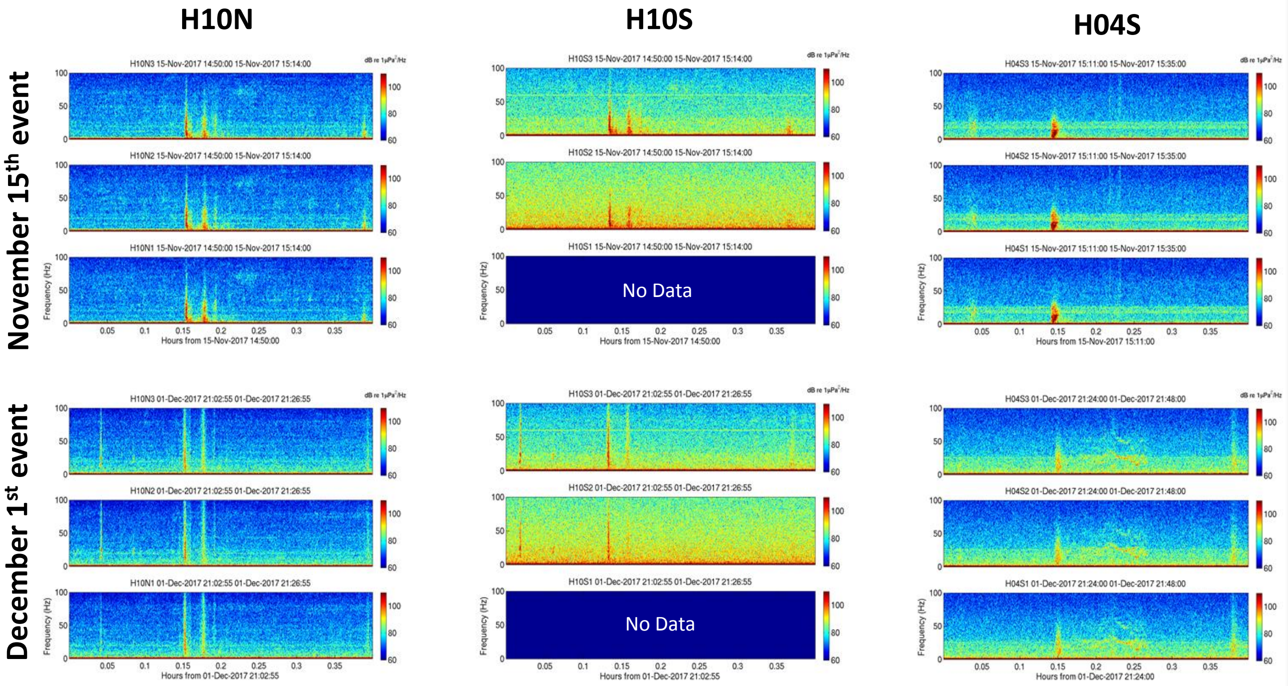
Calibrated spectrograms of both signals

- 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.



Title
Introduction
Focus on H04S data
Modelling and ice
Comparison and ice
Precursor
Conclusions

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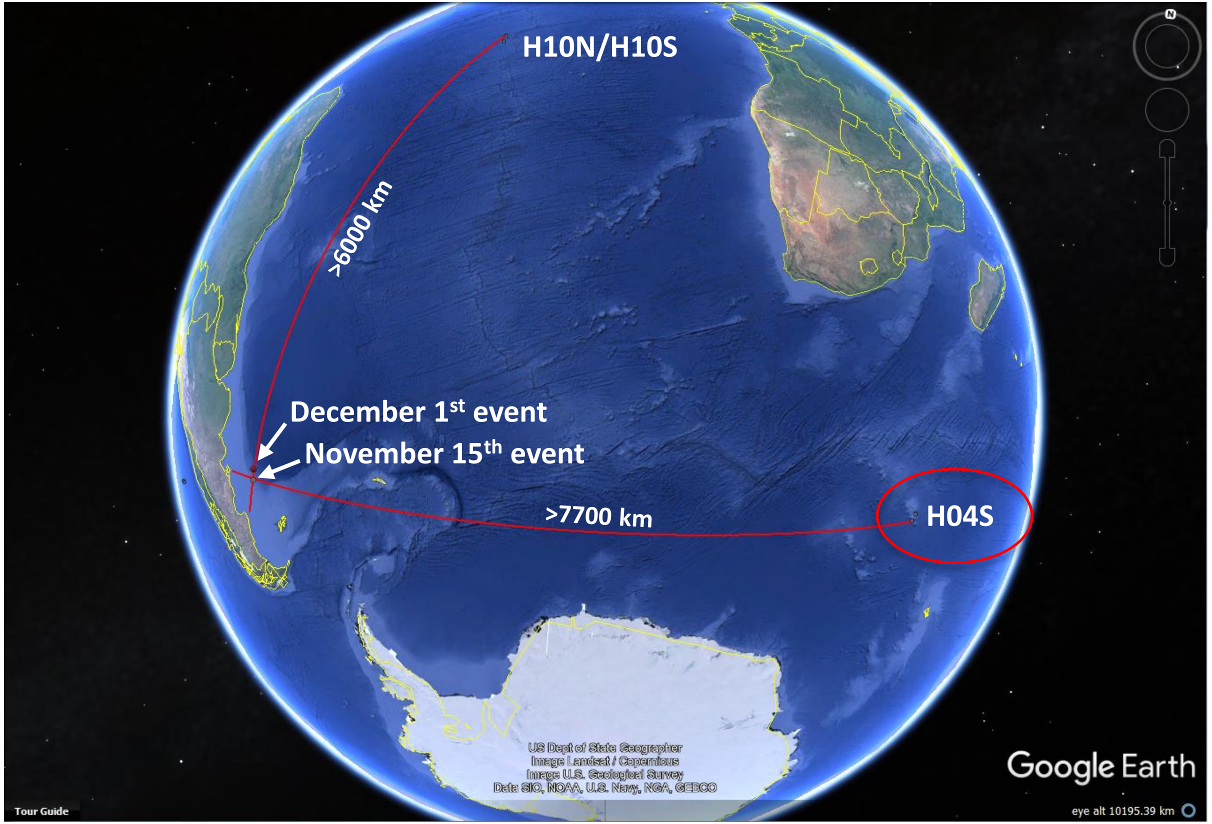
Hydroacoustic signals recorded at IMS stations

- Focus on November 15th signal received on H04S.
- Explain the difference in the arrivals recorded on H10N and H04S through modelling of underwater acoustic propagation.



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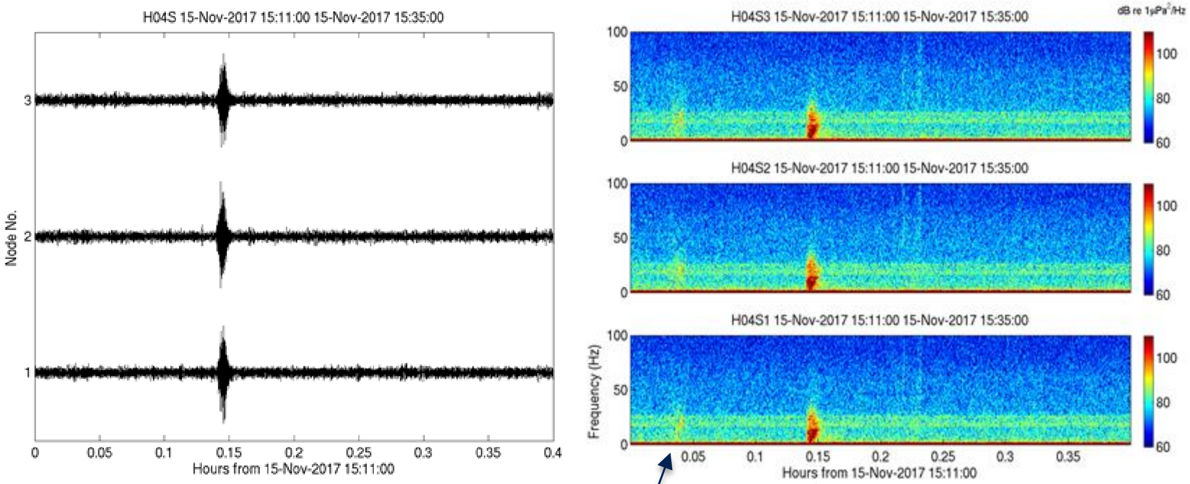
Time series recorded on H04S from the November 15th event

- Recorded time series on H04S.
- Low-pass filtering and time dispersed compared to the H10N signal.
- Precursor visible in the spectrogram before the main arrival.

November 15th event recorded on H04S



Precursor (Path 2)

Main arrival (Path 1)

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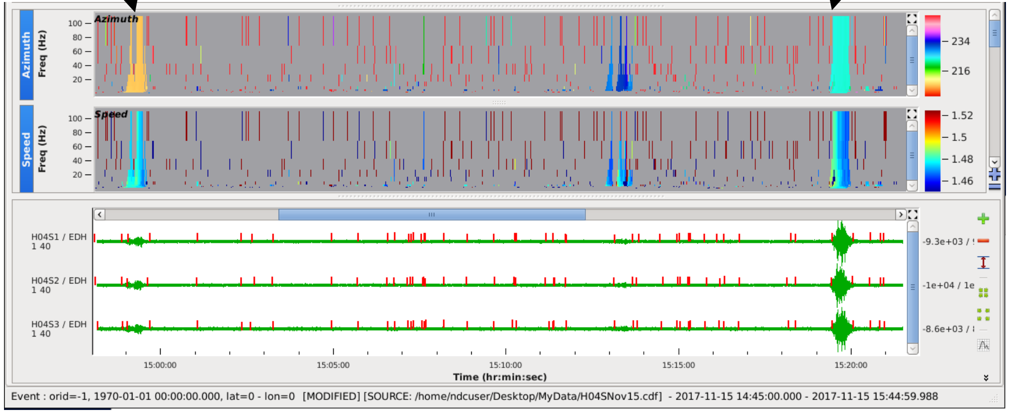
Possible precursor signal at H04S

- 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:
  - Hypothesize on low-pass filtering and time dispersion of the main arrival at H04S.
  - Verify if the early arrival could be a precursor of the main arrival.

Path 2: Azimuth 207.8
Possible precursor

Path 1: Azimuth 223.6
Main Arrival

Multi Channel Correlation DTK-GPMCC*)**)



*) 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.

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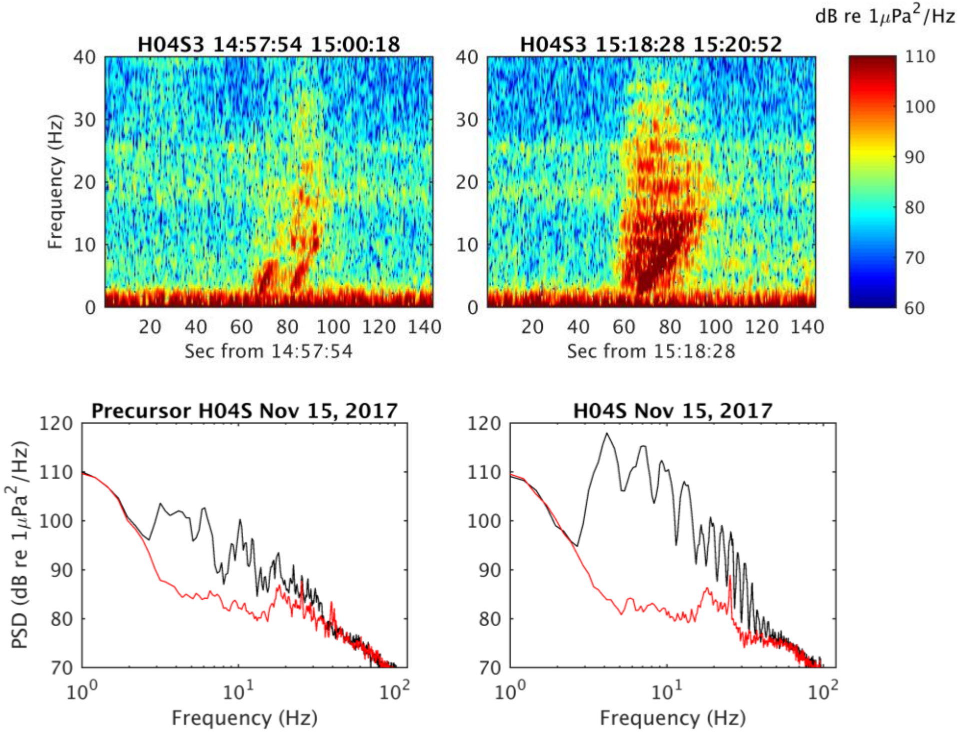
Comparison of precursor and main signals at H04S

- Main arrival: Path 1.
- Possible precursor: Path 2.
- Similarities in spectrograms:
  - Similarities in locations of main spectral peaks.
  - Similarities in spectral roll-off.
- The Path 2 precursor 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 precursor comparable to the main arrival.

- Subsequent analysis:
  - Impact of possible under-ice signal propagation on recordings (main arrival along Path 1).
  - Hypothesis for possible precursor signals propagating in the ice (precursor along Path 2).

Path 2: Azimuth 207.8
Arrival 1234 sec before main arrival

Path 1: Azimuth 223.6
Main arrival



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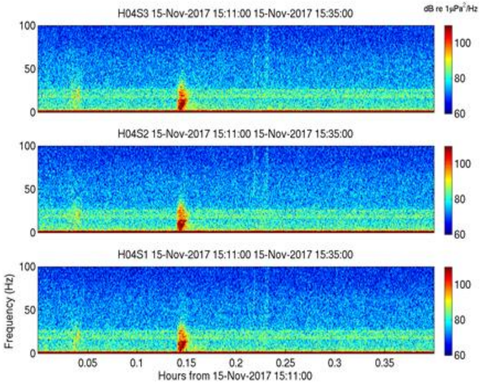
Signal propagation through and under Antarctic ice-sheet

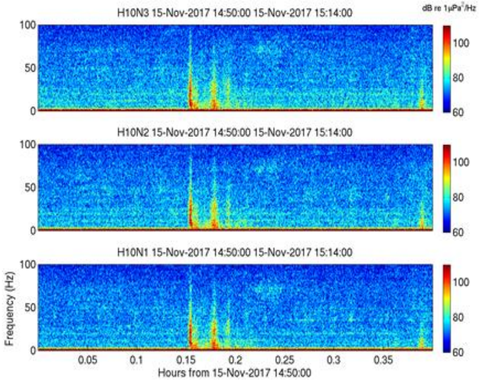
AS5.1/NH1.18/SM5.3

- The Geodesic propagation path (Path 1) from the November 15th event to H04S (>7700 km):
  - Crosses ridges between islands.
  - Intersects the seasonal Antarctic ice-sheet (green line) in two points.
- Seasonal Antarctic ice-sheet for November 15th, 2017, 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.

H04S



H10N



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Impact of ice-cover on underwater acoustic propagation

- How can so diverse recorded signals originate from the same source?
- Detailed analysis of the underwater acoustic propagation path from the estimated November 15th event location to H04S.
- Numerical calculation of propagation characteristics from the November 15th event location to H04S including high-resolution oceanographic database information (sound speed*)) and bathymetry**)).
- Determine properties of an effective fluid ice-cover based on published elastic parameters of ice-sheets***).
- Modify the RAM Parabolic Equation underwater acoustic propagation model to include a partly covered sea surface by an ice-sheet with effective fluid properties (this modified RAM version is here referred to as SCATRAM).
- Full time-series modelling demonstrating the impact of the oceanographic conditions and ice-cover on the simulated acoustic propagation.
- A simplified source pulse is modelled as a 1-100 Hz band-limited impulse (sync function).
- Demonstrate similarities between the modelling results and the hydroaocustic recordings at the H10N and H04S.

*) Generated using E.U. Copernicus Marine Service Information. http://marine.copernicus.eu/services-portfolio/access-to-products/
**) The GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO, 2003. https://www.gebco.net/data_and_products/gridded_bathymetry_data/

***) Kevin Heaney and Richard Campbell, "Effective ice model for under-ice propagation using the fluid-fluid parabolic equation". Proceedings of Meetings on Acoustics, Vol. 19, 070052 (2013).

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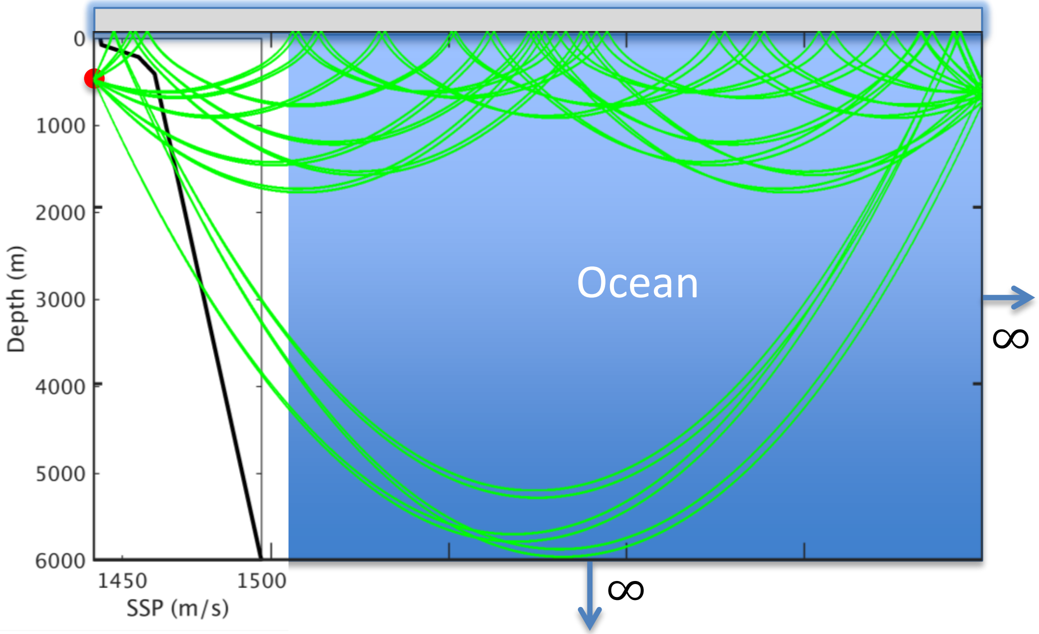
Impact of ice-cover on long-range propagation

- ***Range-independent*** ice-cover overlying upward refracting infinite halfspace.
- Source at depth of 551 m.
- Ice1: In-ice bulk sound-speeds:
  - Compressional sound-speed c_p = 3564 m/s.
  - Shear sound-speed c_s = 1442 m/s **(chosen to absorb acoustic energy from the water column)**.
- Ice2: In-ice bulk sound-speeds*)**)
  - Compressional sound-speed c_p = 3564 m/s.
  - Shear sound-speed c_s = 1705 m/s.
- Common ice properties:
  - Density ρ=0.9 g/cm^3.
  - Compressional attenuation α_p = 0.5 dB/λ.
  - Shear attenuation α_s = 1.0 dB/λ.
  - Thickness 2-10 m.

Ice-cover on infinite deep ocean (no bottom)



*) Kevin L. Williams *et al.* Noise Background Levels and Noise Event Tracking/Characterization Under the Arctic Ice Pack: Experiment, Data Analysis, and Modeling. *IEEE Ocean. Eng.* **43,** 145-159, 2017
**) F.B. Jensen *et al.* *Computational Ocean Acoustics*, Springer, 2011

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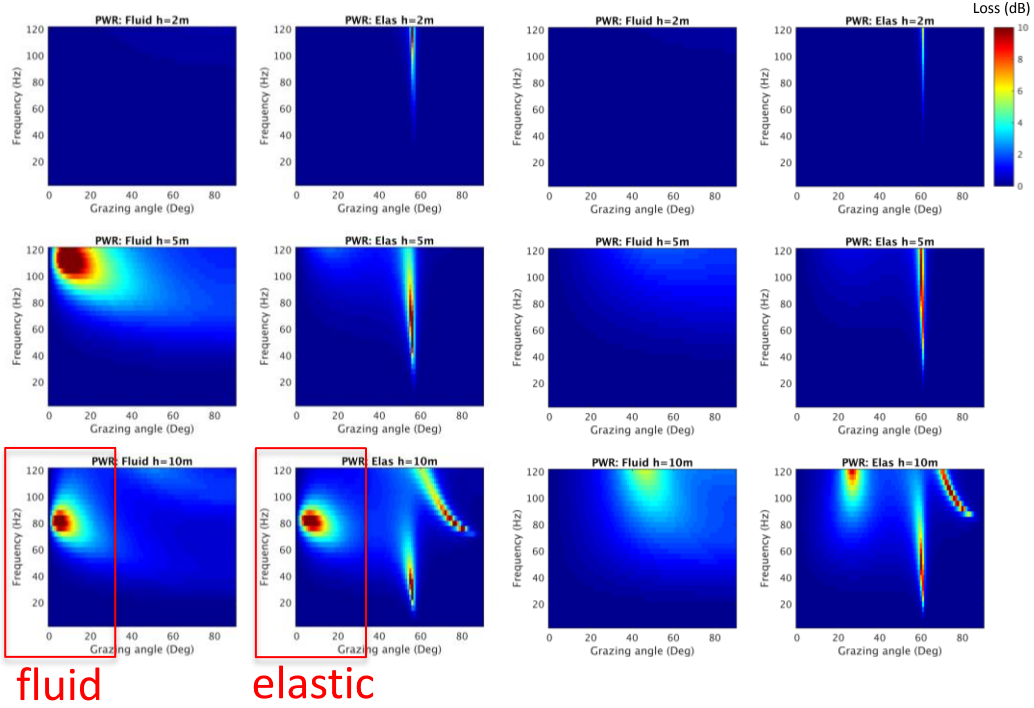
Fluid and elastic ice plane wave reflection coefficient

- ORCA *) Plane Wave Reflection computation:
- Ice thickness: 2, 5 and 10 m.
- Left panel:
  - Reference Elastic Ice:
  - Compressional sound-speed c_p = 3564 m/s.
  - Shear sound-speed c_s = 1442 m/s.
  - Compressional attenuation α_p = 0.5 dB/λ.
  - **Equivalent** Fluid Ice:
  - Compressional sound-speed c_p = **1320 m/s.**
  - Compressional attenuation α_p = **0.8 dB/λ.**
- Right panel:
  - Reference Elastic Ice:
  - Compressional sound-speed c_p = 3564 m/s.
  - Shear sound-speed c_s = 1705 m/s.
  - Compressional attenuation α_p = 0.5 dB/λ.
  - **Equivalent** Fluid Ice:
  - Compressional sound-speed c_p = **1720 m/s.**
  - Compressional attenuation α_p = **1.8 dB/λ.**

Ice 1: c_s = 1442 m/s   Ice 2: c_s = 1705 m/s



*)E. K. Westwood , C. T. Tindle, and N. R. Chapman, "A normal mode model for acoustoelastic ocean environments," *J. Acoust. Soc. Am.*, **100**, 3631-3645 (1996).

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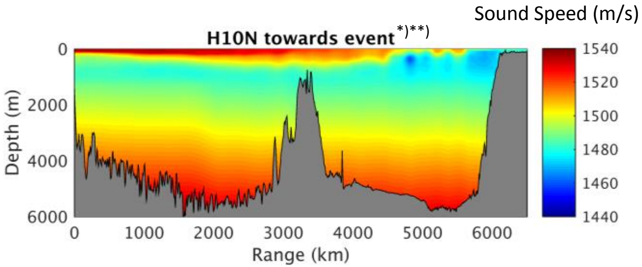
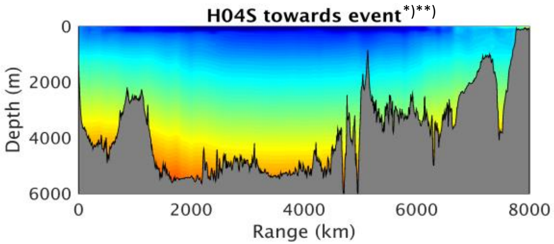
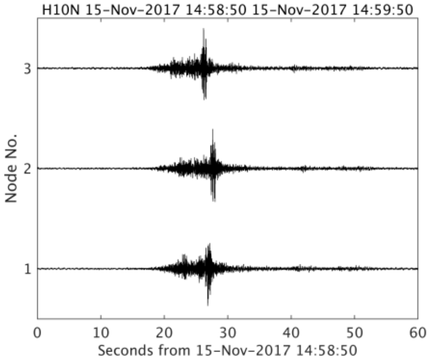
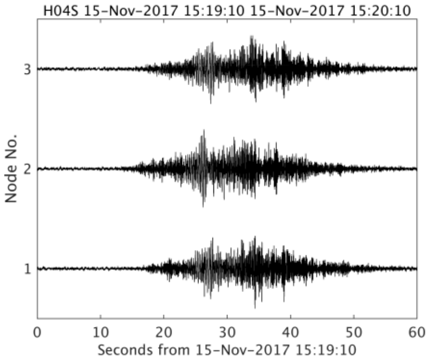
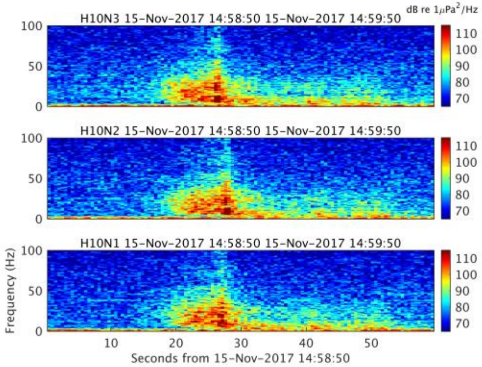
Recorded time-series and calibrated spectrograms

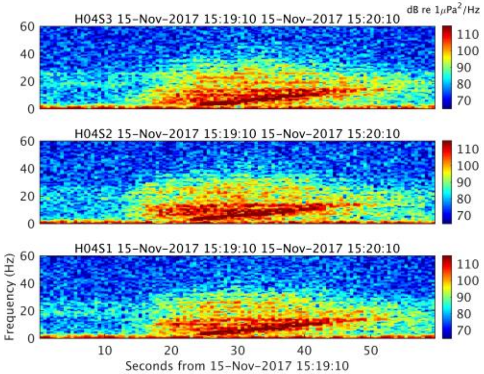












*) Generated using E.U. Copernicus Marine Service Information. http://marine.copernicus.eu/services-portfolio/access-to-products/

**) The GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO, 2003. https://www.gebco.net/data_and_products/gridded_bathymetry_data/

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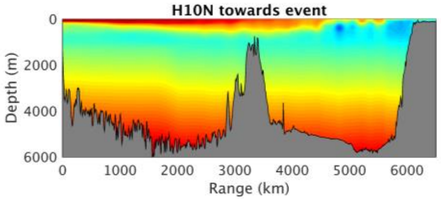
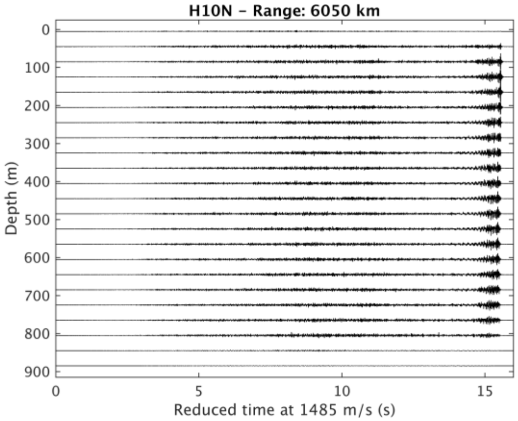
Time-series modelling H10N to event

AS5.1/NH1.18/SM5.3

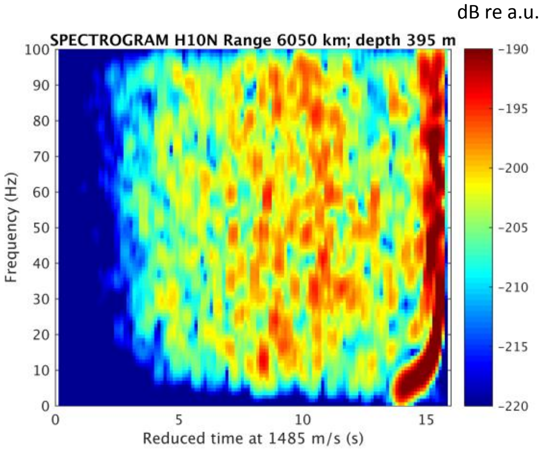


- Modelled (left two panels) and recoded (right panel).
- Source spectrum not included in the modelling
- Early low spectral levels in both model and data
- Strong broadband spectral levels at late arrival time in both model and data.

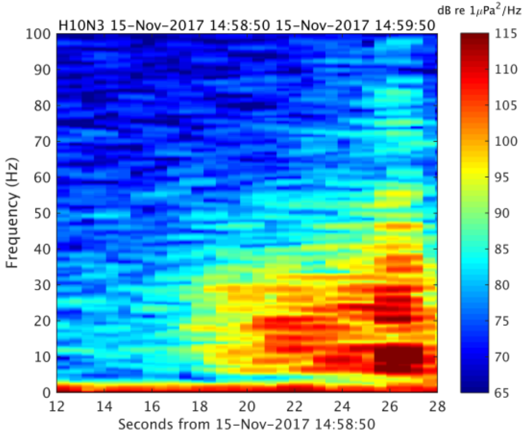
RAM time-series modelling



RAM spectrogram modelling



Spectrogram of recorded data



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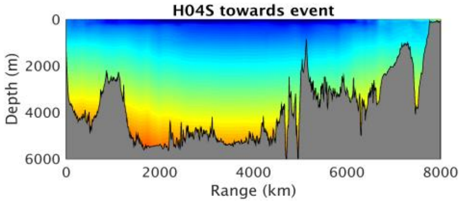
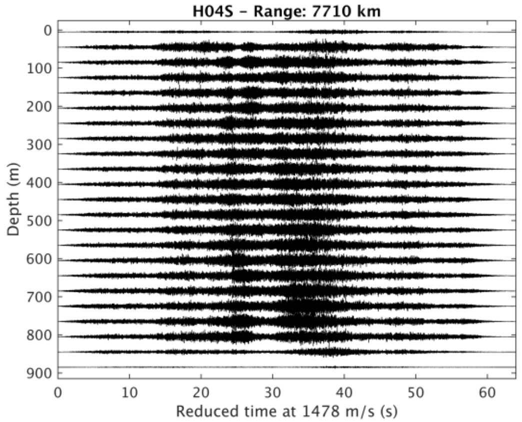
Time-series modelling H04S to event (no ice)

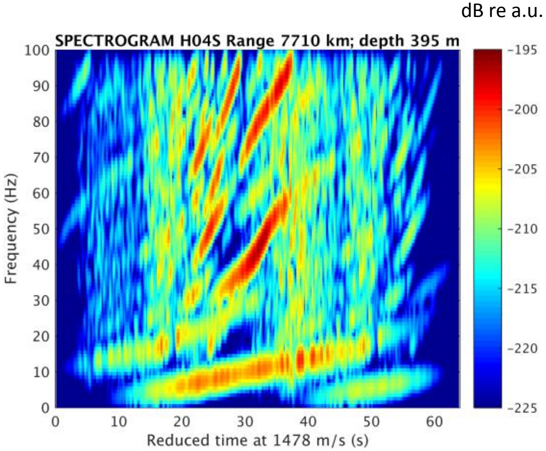


- Modelled (left two panels) and recoded (right panel).
- No partly covering ice-sheet included in the modelling.
- Source spectrum not included in the modelling.
- Spectral levels more uniform over arrival time in model and data.
- Strong striation below 20 Hz in both model and data.

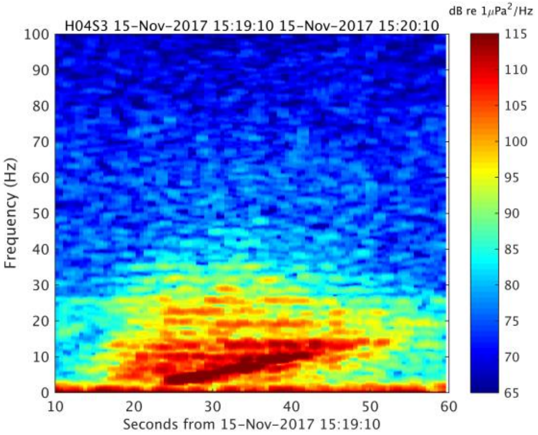
RAM time-series modelling



RAM spectrogram modelling



Spectrogram of recorded data



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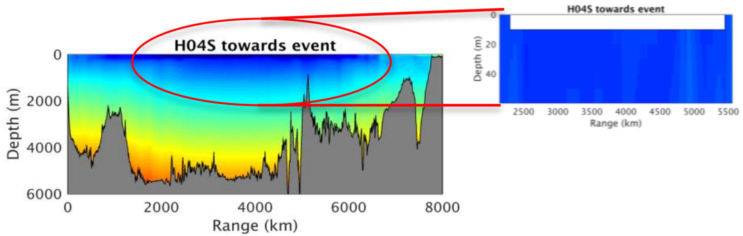
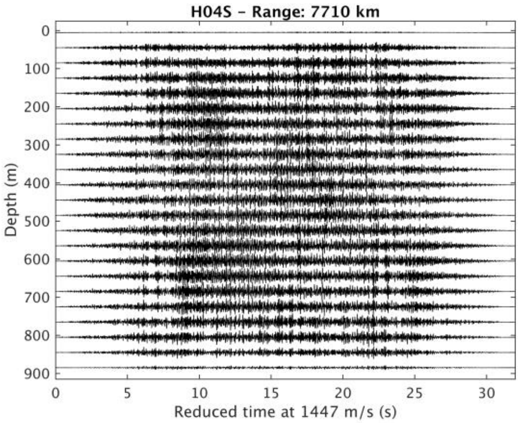
Time-series modelling H04S to event (ice)

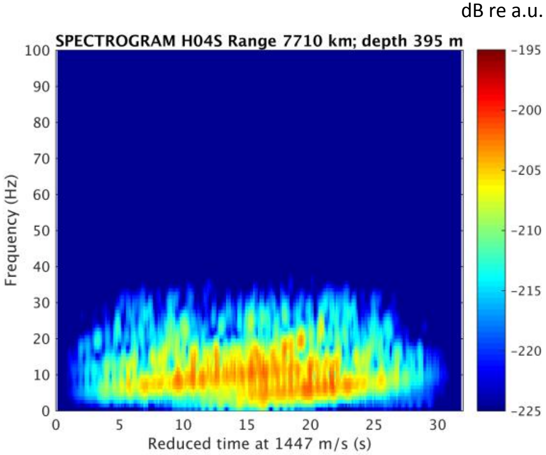


- Modelled (left two panels) and recoded (right panel).
- Partly covering ice-sheet included in the modelling.
- Source spectrum not included in the modelling.
- Low-pass filtering by expedient fluid ice-sheet.

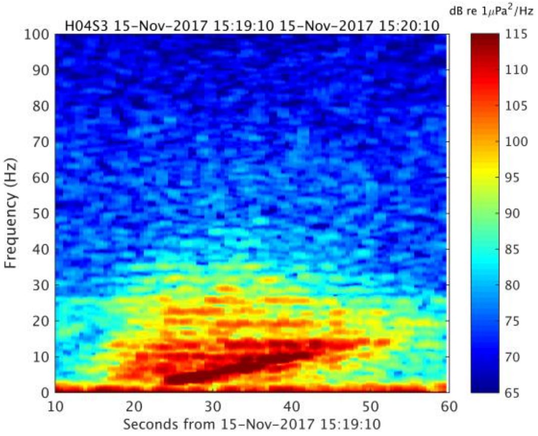
SCATRAM time-series modelling



SCATRAM spectrogram modelling



Spectrogram of recorded data



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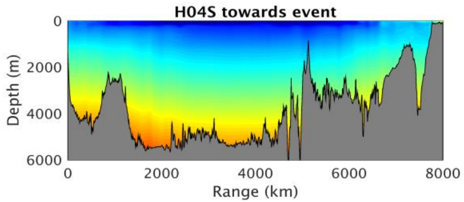
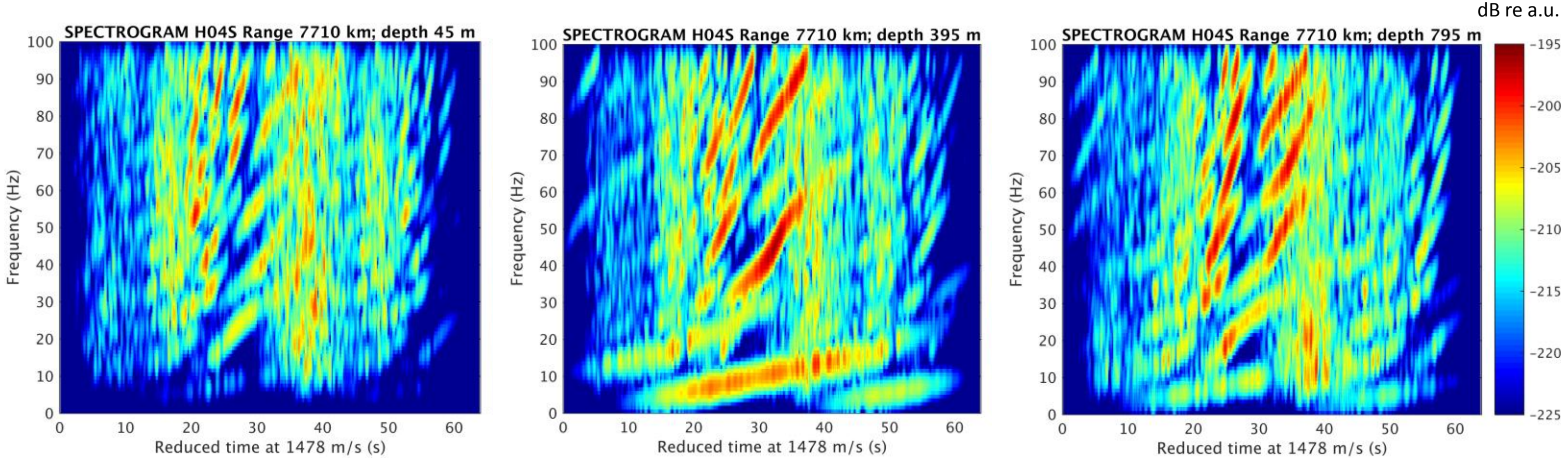
Time-series modelling H04S to event (no ice)



- Modelled depth varying spectrogram.
- No fluid ice-cover.
- Striations weaker and more diffuse close to boundaries.
- November 15th event most likely not close to the sea surface or bottom.



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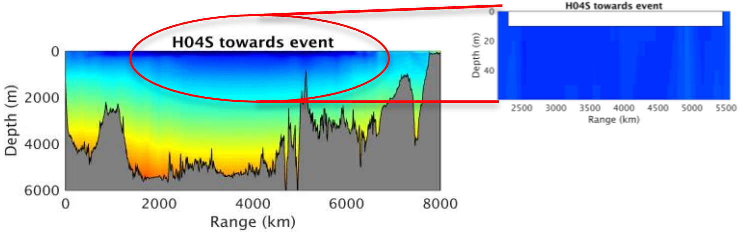
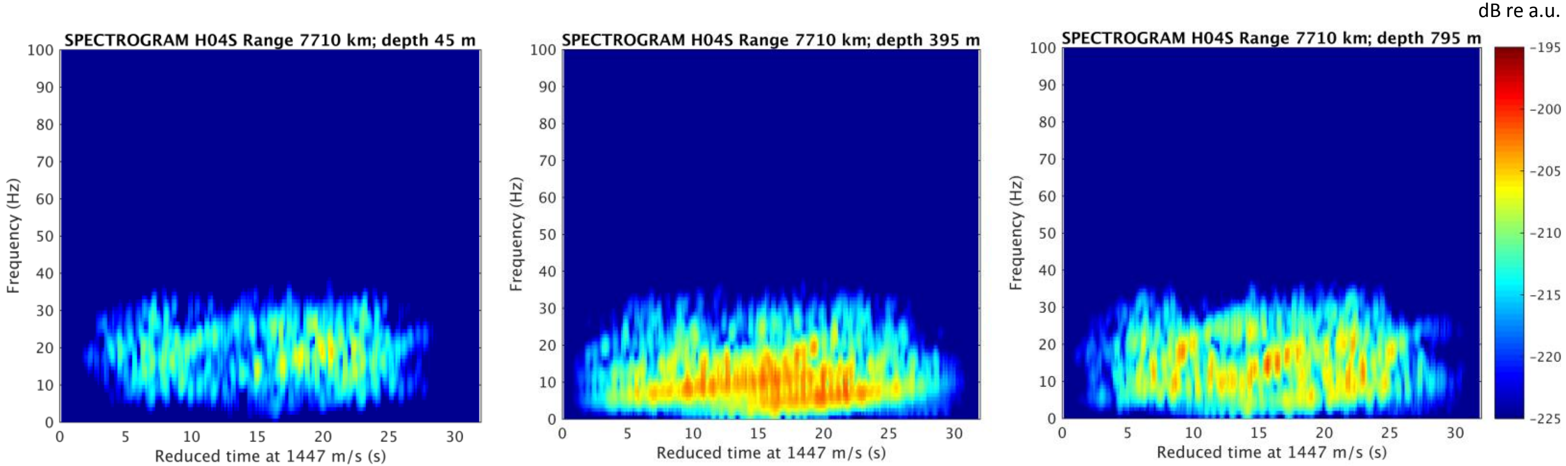
Time-series modelling H04S to event (ice)



- Modelled depth varying spectrogram.
- Fluid ice-cover.
- Striations weaker and more diffuse close to boundaries.
- November 15th event most likely not close to the sea surface or bottom.



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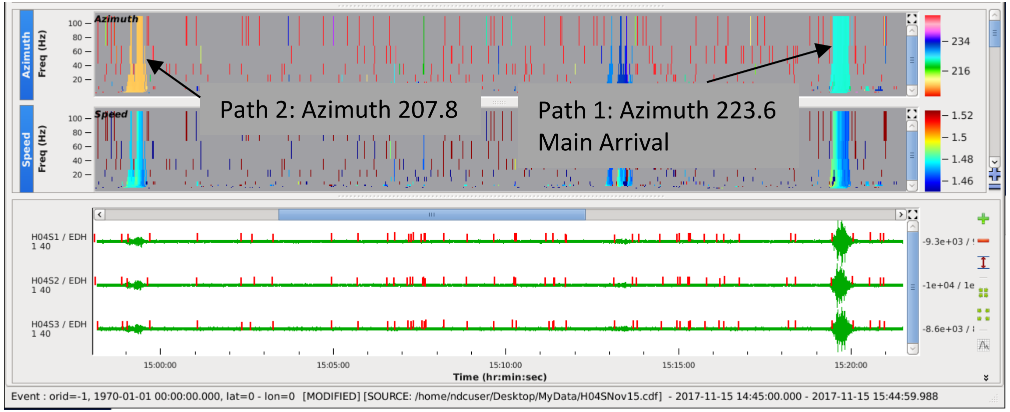
Possible precursor signal at H04S

- 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 precursor of the main arrival.

DTK-GPMCC*)**)



*) 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.

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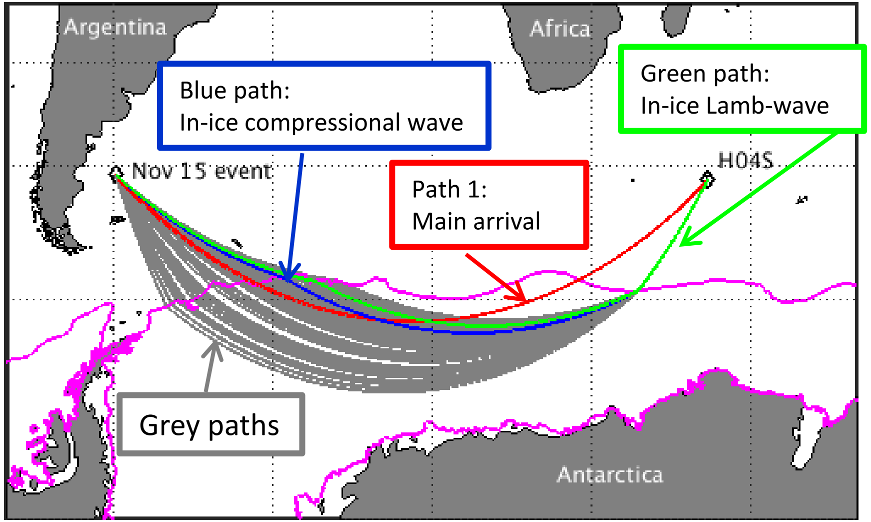
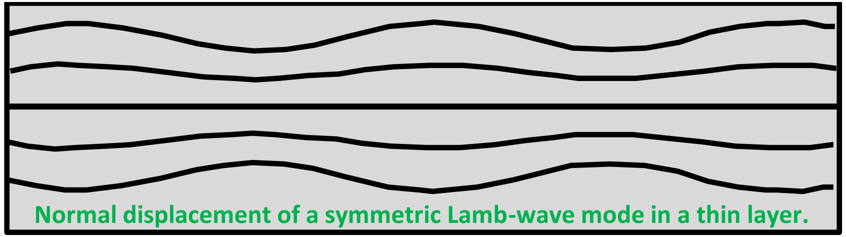
Ice-sheet guided precursor wave hypothesis

- **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**) precursor 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*) $2 \cdot c_s \cdot (1 - c_s^2/c_p^2)^{0.5} = 3087$ 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 precursor wave hypothesis (**Path 2**).





*) Frank Press and Maurice Ewing, "Propagation of Elastic Waves in a Floating Ice Sheet", Transactions, American Geophysical Union, Vol. 32, No. 2, pp. 673-678, 1951.

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Conclusions

- Polar sound speed causes significant time-dispersion of recorded time-series as observed in the data.
- Effective fluid to elastic ice-cover low-pass filters the time-series as observed in the data.
- Elastic ice-cover requires to have a relative low shear speed for the effective fluid ice-cover to have the same impact on the modelled time-series.
- Stable striation(s) in the modelling results of the signal recorded at H04S is also observed in the data.
- The modelled striations appear to become weak and diffuse close to the ocean surface and bottom.
- These observations indicate that the November 15th event most likely happened at distance from the ocean boundaries.
- Early arrival recorded at HA04 on November 15th 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.