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Detections at IMS hydrophone stations of Primary and Tertiary phases from the sixth announced DPRK underground nuclear test

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ORAL PRESENTATION

O2.1-275

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Announced Event	Date (Year/Month/Day)	Origin time (UTC)	m_b *)	Number of IMS stations detecting DPRK events**)
DPRK1	2006/10/09	01:35:27	4.10	22 Seismic stations
DPRK2	2009/05/25	00:54:42	4.50	61 Seismic stations
DPRK3	2013/02/12	02:57:50	4.90	94 Seismic stations 2 Infrasound stations
DPRK4	2016/01/06	01:30:00	4.80	102 Seismic stations
DPRK5	2016/09/09	00:30:00	5.10	108 Seismic stations
DPRK6	2017/09/03	03:30:01	6.07	131 Seismic stations 2 Hydroacoustic stations***) 1 Infrasound station

*) m_b: Seismic body wave magnitude of the explosion.
**) Source: CTBT IDC Technical Briefs and Reviewed Event Bulletin (REB).
***) IDC automatic processing detections.

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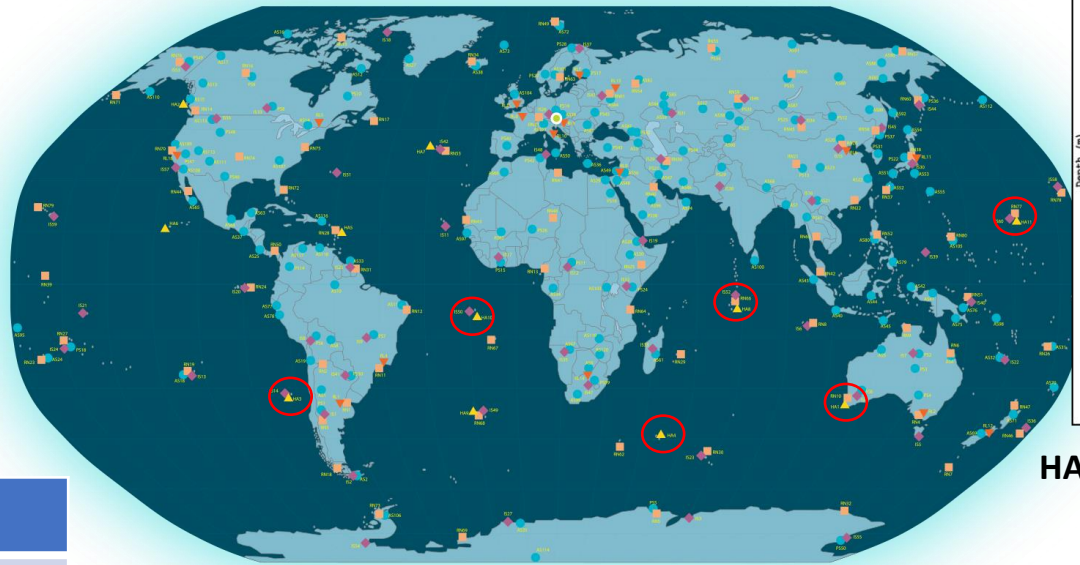
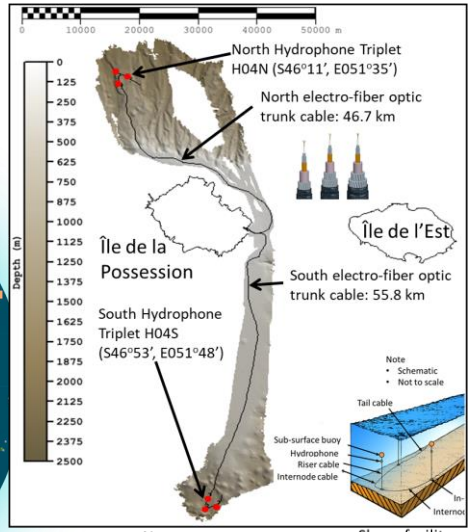
CTBT IMS hydrophone stations

- Seismic
- Hydroacoustic HA (hydrophones)
- Infrasound
- Radionuclide
- Radionuclide Labs
- International Data Centre

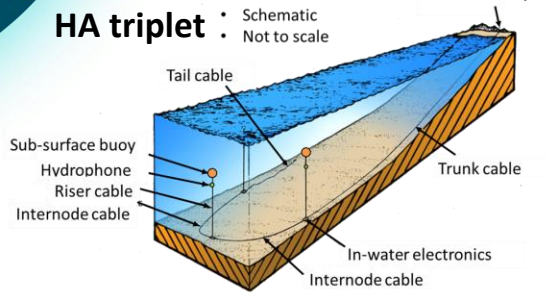


IMS Monitoring Facilities	
Certified (17th May 2021)	302
Total	337

Hydroacoustic Network is entirely certified as of June 2017



HA triplet



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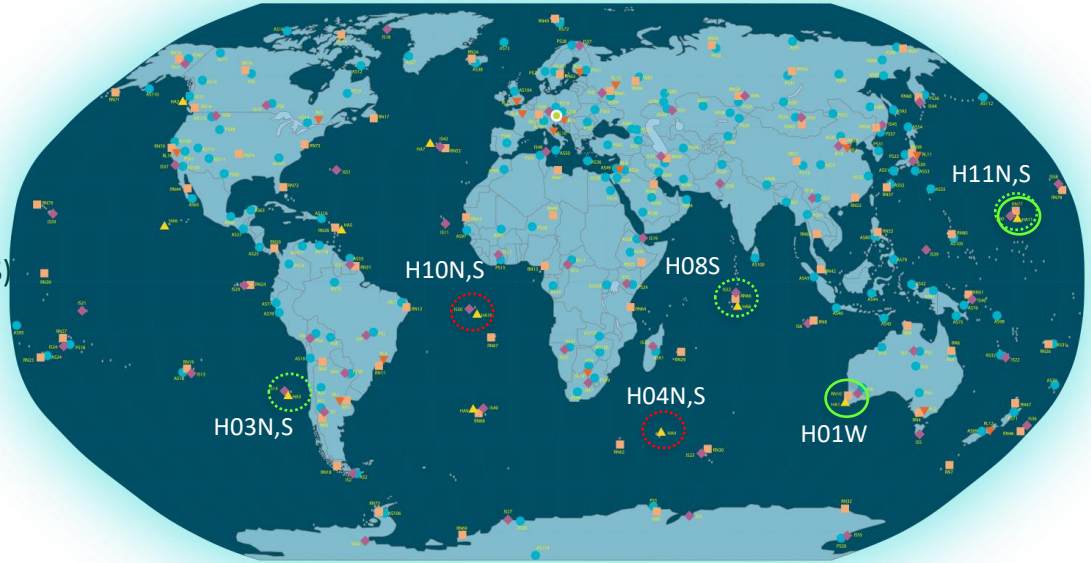
HA hydrophone detections of DPRK6

- Primary phase (p-phase) detections:
  - Hydrophone triplets detecting DPRK6 by automatic processing system (H01W;H11S)
  - Hydrophone triplets used for manual detection of DPRK6 (H03N,S; H08S;H11N)
  - Hydrophone triplets not detecting DPRK6 (H04N,S;H10N,S)
- Tertiary phase (T-phase) detections:
  - Manual T-phase detection of DPRK6 (H11N; H11S)



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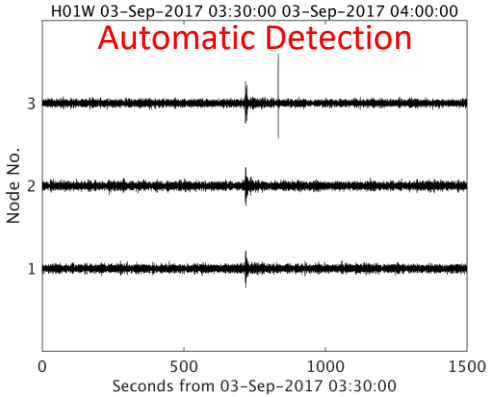
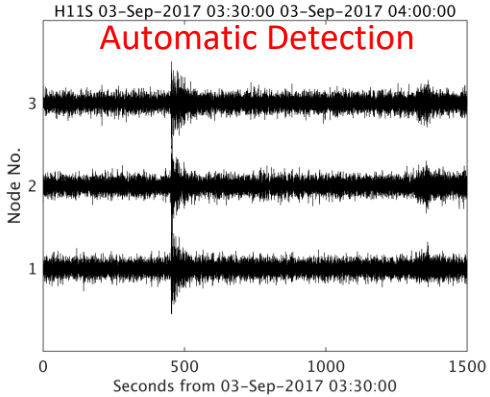
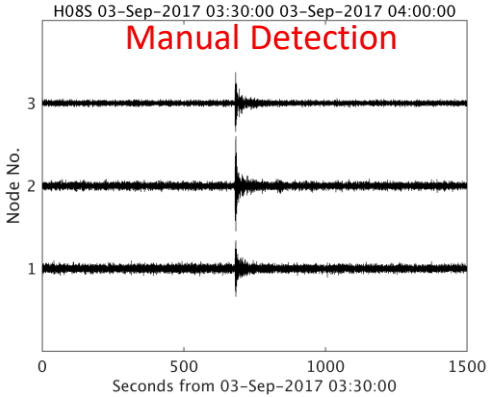
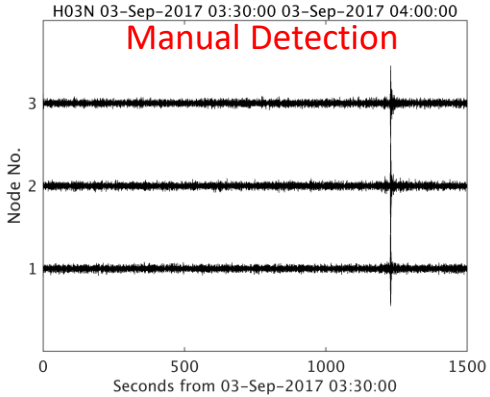
Time series recorded at H01W, H11S, H08S, H03N

- Recorded time series at H01W, H11S, H08S and H03N hydroacoustic stations on 3rd September 2017.
- Signals received at H01W and H11S (upper panels) were detected by the IDC automatic processing system as P-phases.
- Signals received at H08S and H03N were detected manually.
- All time series shown are filtered using a 3rd order Butterworth bandpass filter in the band 0.8-4.5 Hz (seismic band).









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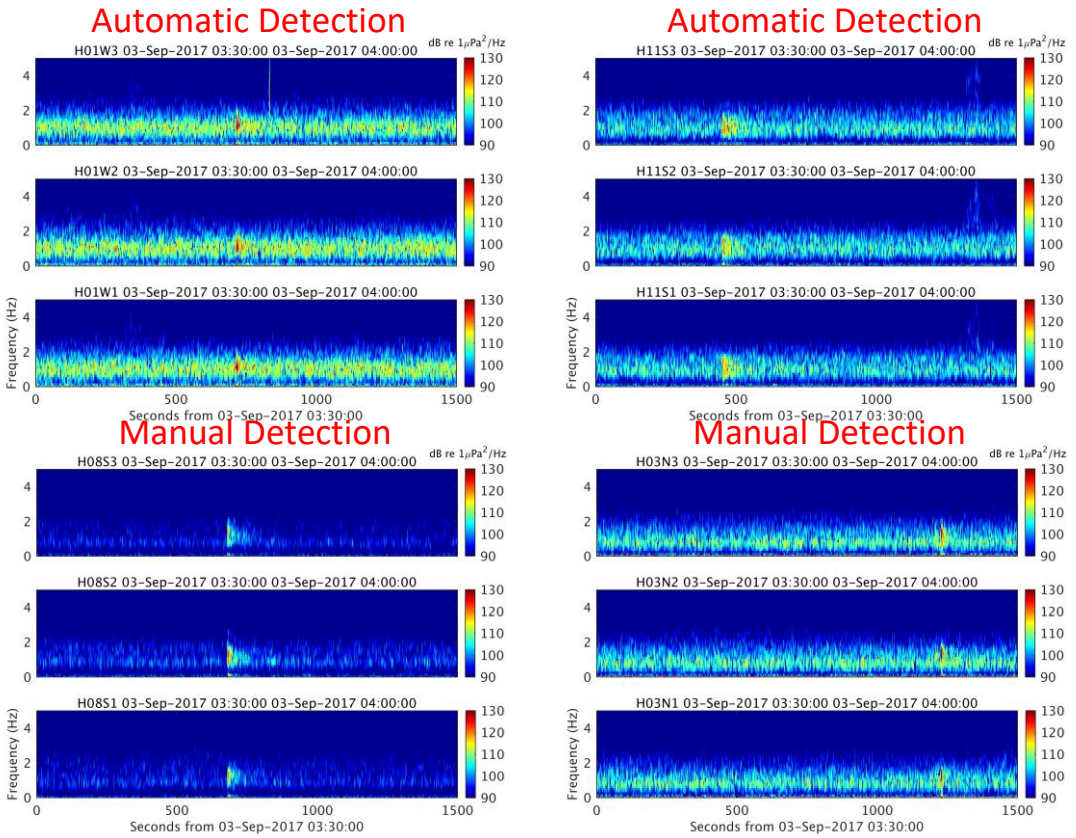
Calibrated spectrograms at H01W, H11S, H08S, H03N

- Calibrated spectrograms of signals received at H01W, H11S, H08S and H03N hydroacoustic stations on 3rd September 2017.
- Signals labelled as P-phases (Primary Phases) clearly visible above the background noise.
- Filtering using a 3rd order Butterworth bandpass filter in the band 0.8-4.5 Hz (seismic band).



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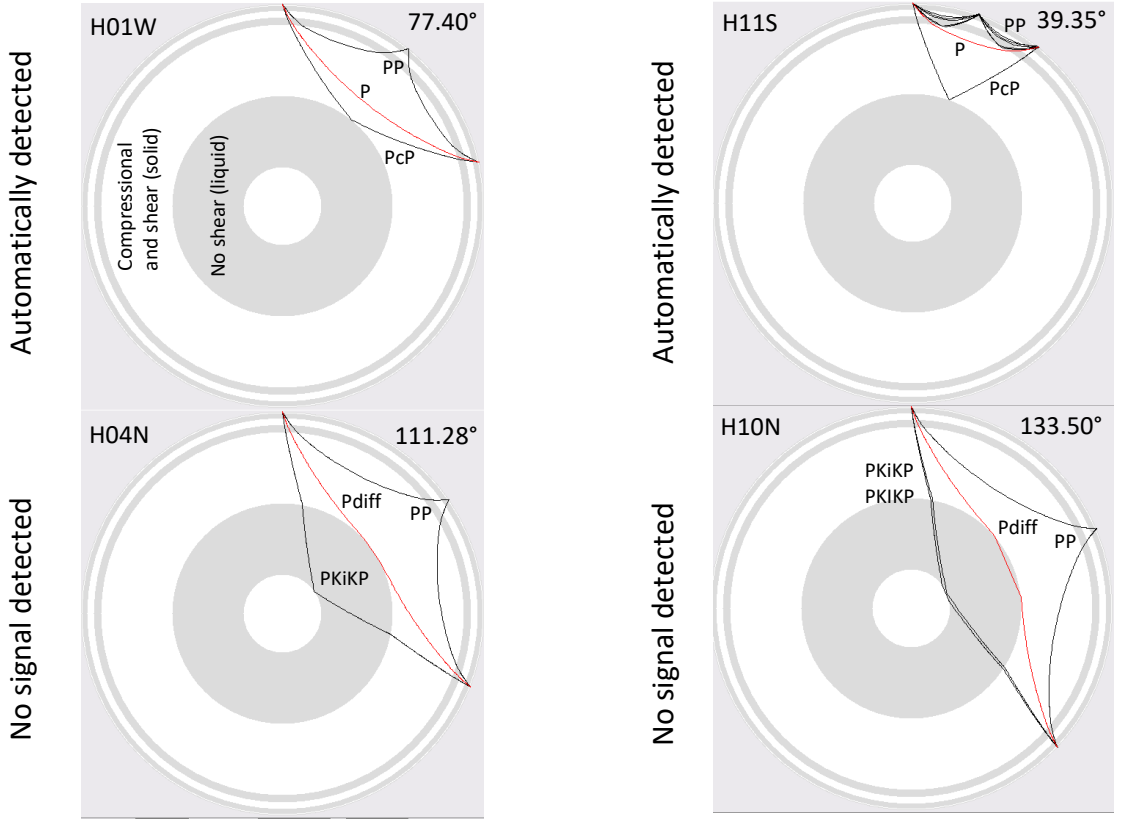
Seismic ray paths: Automatic Detections and No Detections

- The IDC automatic processing system detected the DPRK6 event on stations H01W and H11S.
- Direct P-phase arrival (red trace in upper panels) and reflected paths (black trace in upper panels).
- Stations H04N and H10N did not detected the DPRK6 event.
- Diffracted (red trace in lower panels) and reflected arrivals (black in lower panels).
- No signal detected at HA04 and HA10: shadow zone of core phases in arc-distance ranges between 104° and 140°.

Crotwell, H. P., T. J. Owens, and J. Ritsema "The TauP Toolkit: Flexible seismic travel-time and ray-path utilities", Seismological Research Letters 70, pp. 154–160, 1999.



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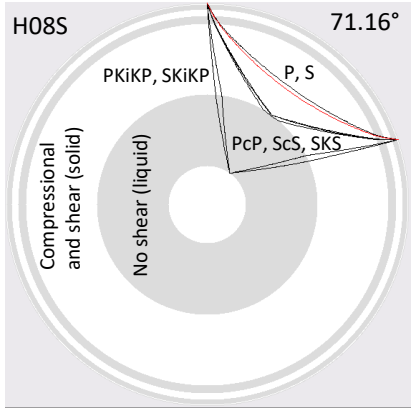
Seismic ray paths: Manual Detections

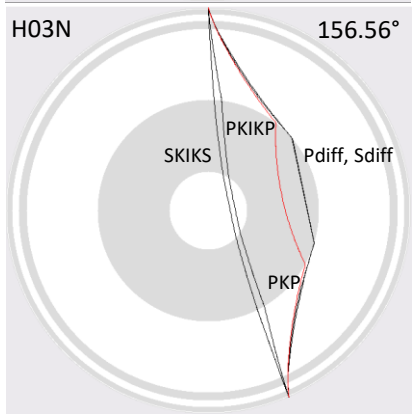
- The IDC automatic processing system did not detect the DPRK6 event on stations H08S and H03N .
- However signals were detected at these two stations by ad-hoc (“manual”) signal analysis.
- H08S: Direct P-phase arrival (red trace in upper panel) and reflected paths (black trace in upper panel).
- H03N: All refracted paths (red and black trace in lower panel).

Crotwell, H. P., T. J. Owens, and J. Ritsema “The TauP Toolkit: Flexible seismic travel-time and ray-path utilities”, Seismological Research Letters 70, pp. 154–160, 1999.

Signal detected manually



Signal detected manually



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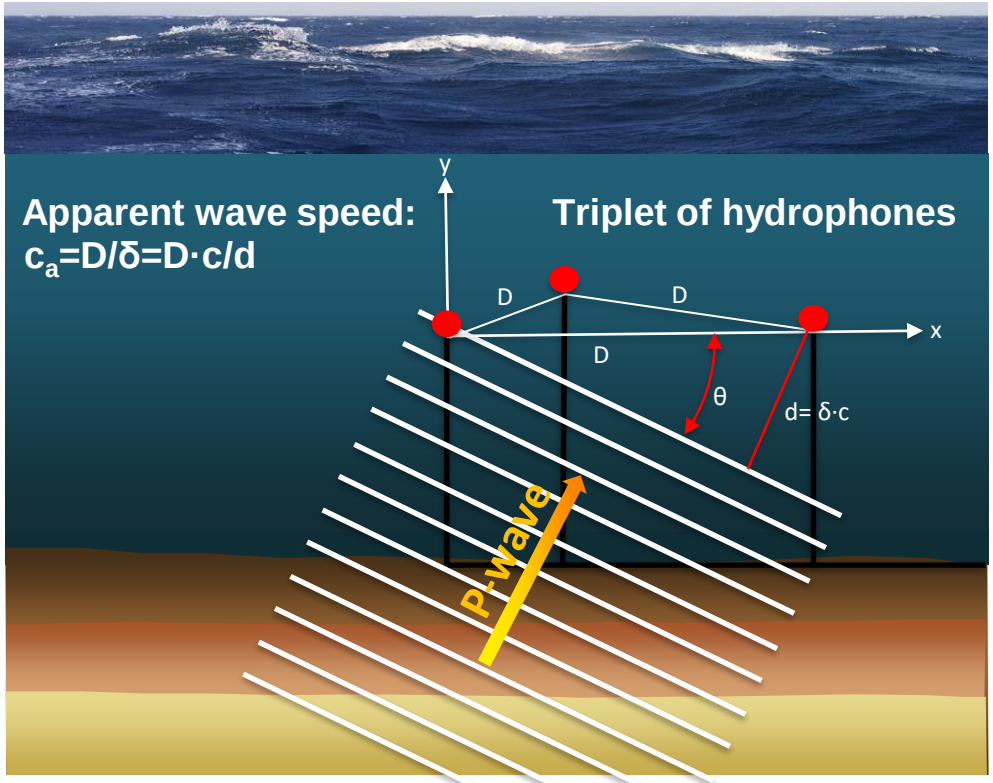
Apparent horizontal wave speed

- Triplets are composed of three hydrophones equally spaced at a horizontal distance D of approximately 2000 m and at equal depth.
- Apparent wave speed at hydrophone stations are computed on the basis of inter-hydrophone time of arrival δ, and the horizontal distance between the hydrophones D.
- This configuration provides a wave speed close to the speed of sound in water assuming horizontally propagating waves.
- P-waves arrive at the hydrophones at angles θ close to vertical.
- Therefore, P-waves have an apparent wave speed c_a much higher than the speed of sound in water c.



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Example: Direction of Arrival at triplet H11S

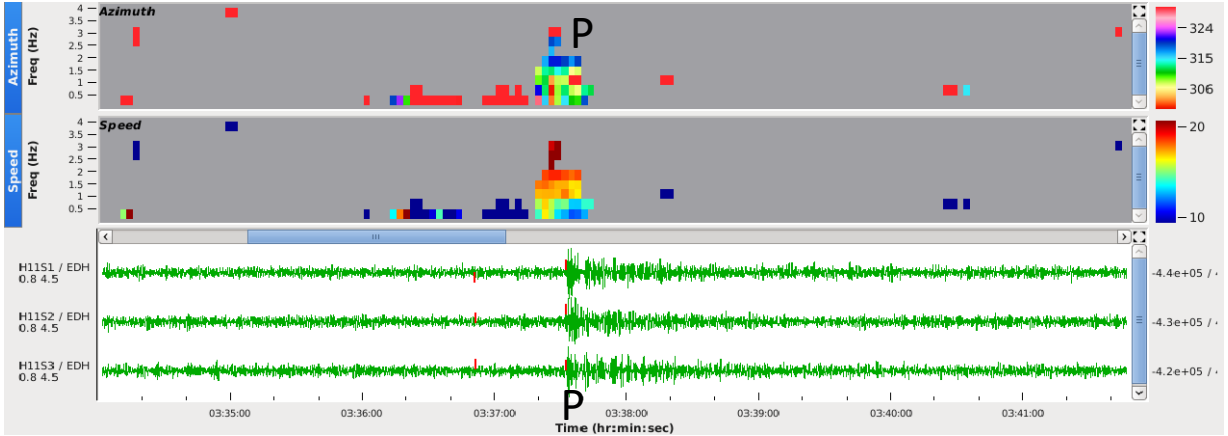
- Progressive Multi Channel Correlator (DTK-GPMCC) applied on time series recorded at H11S.

- Azimuth:
  - Mean: 313.4°.
  - Median: 312.7°.
  - σ: 0.699 °.
  - Min: 299.6 °.
  - Max: 354.8 °.

- Apparent wave speed:
  - Mean: 16.5 km/s.
  - Median: 16.9 km/s.
  - σ: 0.203 km/s.
  - Min: 12.0 km/s.
  - Max: 24.8 km/s.

- Similar analysis of all hydrophone stations detecting the DPRK6 test.

Progressive Multi Channel Cross-correlation on P-phase



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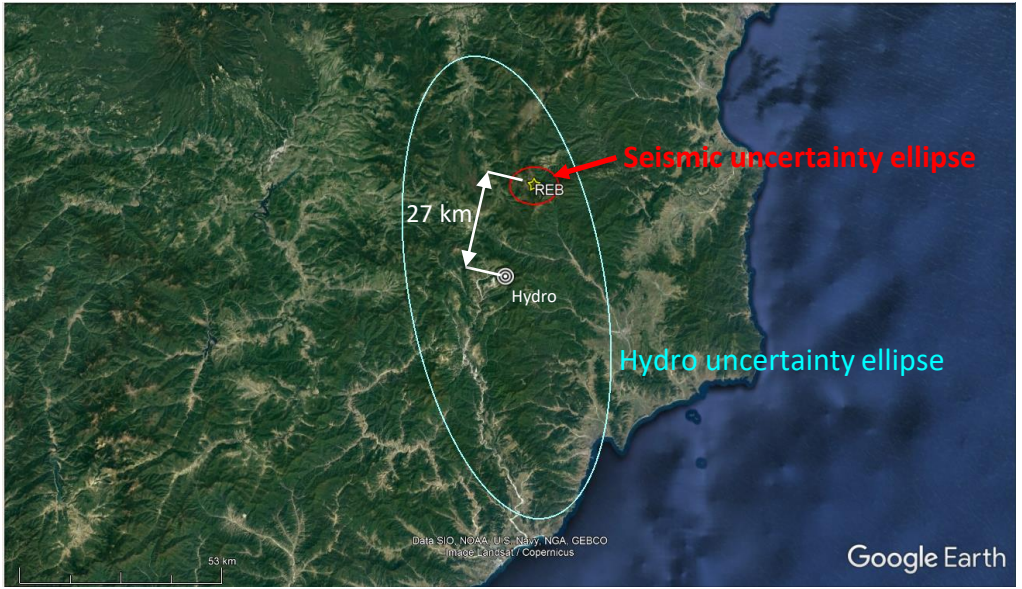
- Estimate of location and uncertainty ellipse using 125 seismic IMS stations (red ellipse) and hydrophone stations only (cyan ellipse).
- Difference in event location using 125 seismic IMS stations and hydrophone stations only:
  - Difference: 27 km.
- Dimension of location uncertainty ellipse using 125 seismic IMS stations:
  - Semi-major error ellipse axis: 6 km.
  - Semi-minor error ellipse axis: 5 km.
  - Ellipse strike/orientation: 88°.
- Dimension of location uncertainty ellipse using hydrophone stations only:
  - Semi-major error ellipse axis: 64 km.
  - Semi-minor error ellipse axis: 27 km.
  - Ellipse strike/orientation: 171 °.



Uncertainty ellipse = 90% confidence interval of the source location, using estimates of arrival times uncertainties at receivers.

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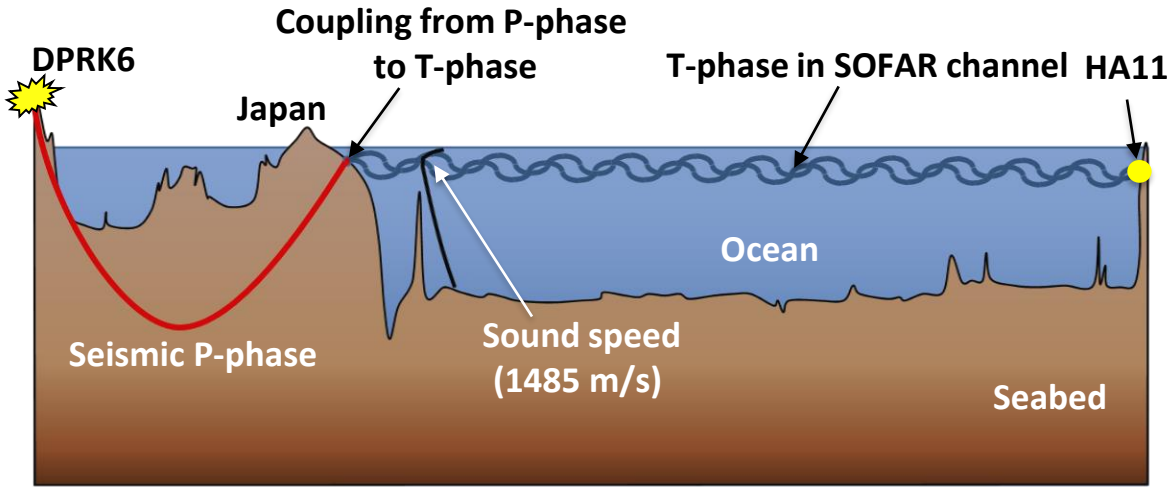
Hypothesized T-phase excitation

- Seismic P-phase propagates in ground from DPRK6 to the South-East coast of Japan (~1200 km).
- P-phase couples to T-phase (Tertiary Phase) at ground-ocean boundary.
- Coupling assumed to be close to the ocean SOFAR*) channel (approximately 1485 m/s).
- Acoustic T-phase propagates in the ocean from coupling location to the HA11 station (~3200 km).



*)SOund Fixing and Ranging

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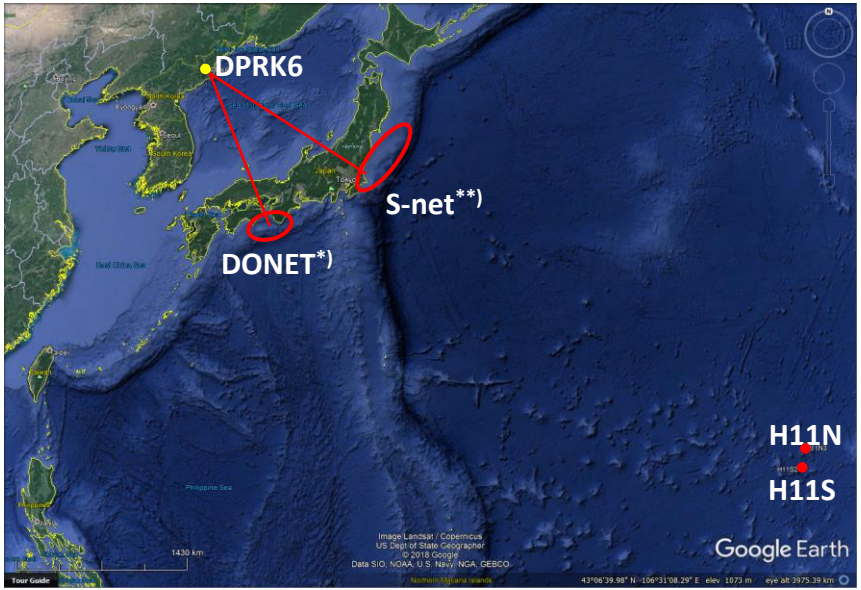
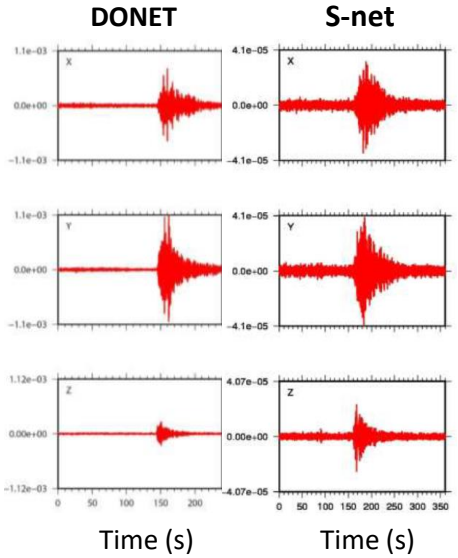
Data from non-IMS seismometers

- Recorded on Japanese ocean-bottom seismometers (OBS) of DONET and S-net *) **).
- Geodesic travel path from DPRK event to DONET/S-net approximately 1200 km.
- Seismic travel time from DPRK6 event to the DONET/S-net is approximately 145 s (IASPEI91).





*) Courtesy T. Nakamura, Y. Kaneda (NIED, Japan)

**) Courtesy H. Matsumoto, Y. Kaneda (JAMSTEC, Japan)

Y. Kaneda, H. Matsumoto, N. Takahashi, “Japanese Ocean floor network observatories and their applications”, International Hydroacoustic Workshop, CTBTO, Vienna International Centre, Sept. 11-13, 2017.

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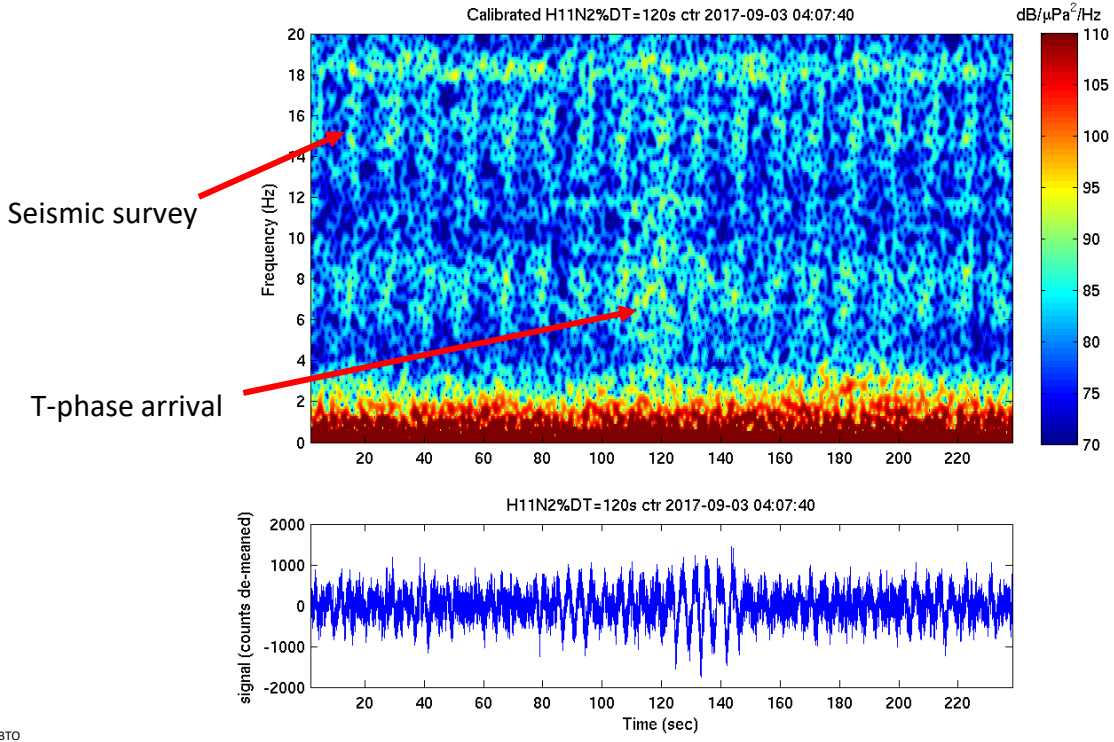
T-phase recorded at hydrophone triplet H11N

- Calibrated spectrogram at station H11N.
- The recorded signal is a superposition of a seismic survey (approximately 10-s repetition) and a hypothesized T-phase arrival.
- The T-phase arrival is hypothesized to be generated at the South-Eastern continental shelf of Japan.
- The recorded T-phase arrives at the H11N station at approximately 04:07:40 UTC.
- The arrival time corresponds to the nuclear explosion announced on 03:30:01 UTC, 3rd September 2017.



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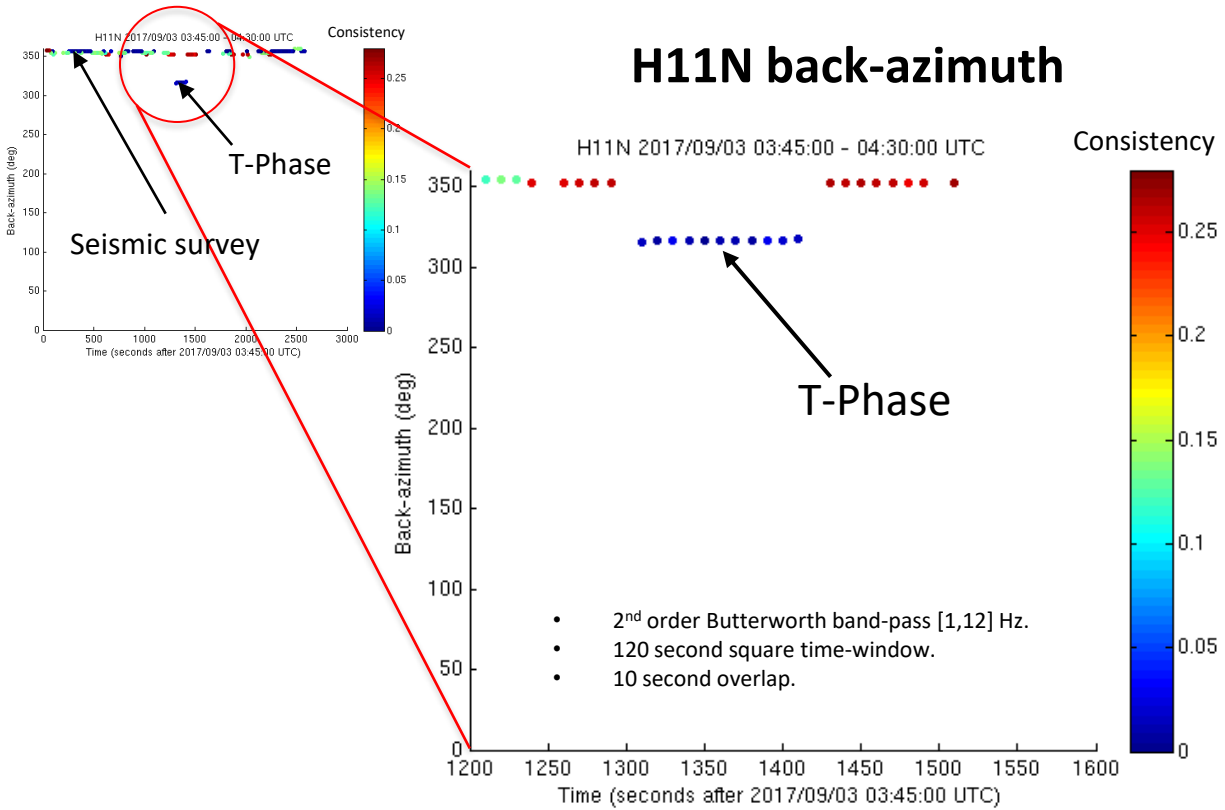
- Estimate of back azimuth at H11N by inter-node cross correlation.
- Colors indicate consistency (or closure relation) of the cross correlation.
- Lower consistency numbers indicate more confidence in the back azimuth estimate.
- The repetitive seismic survey is captured by the algorithm at 352° re North.
- The T-phase earliest arrival is captured at 316.35° re North at 04:06:50 UTC with a duration of 00:01:40.
- Observed T-phase arrival time from spectrogram is approximately 04:07:40 UTC.



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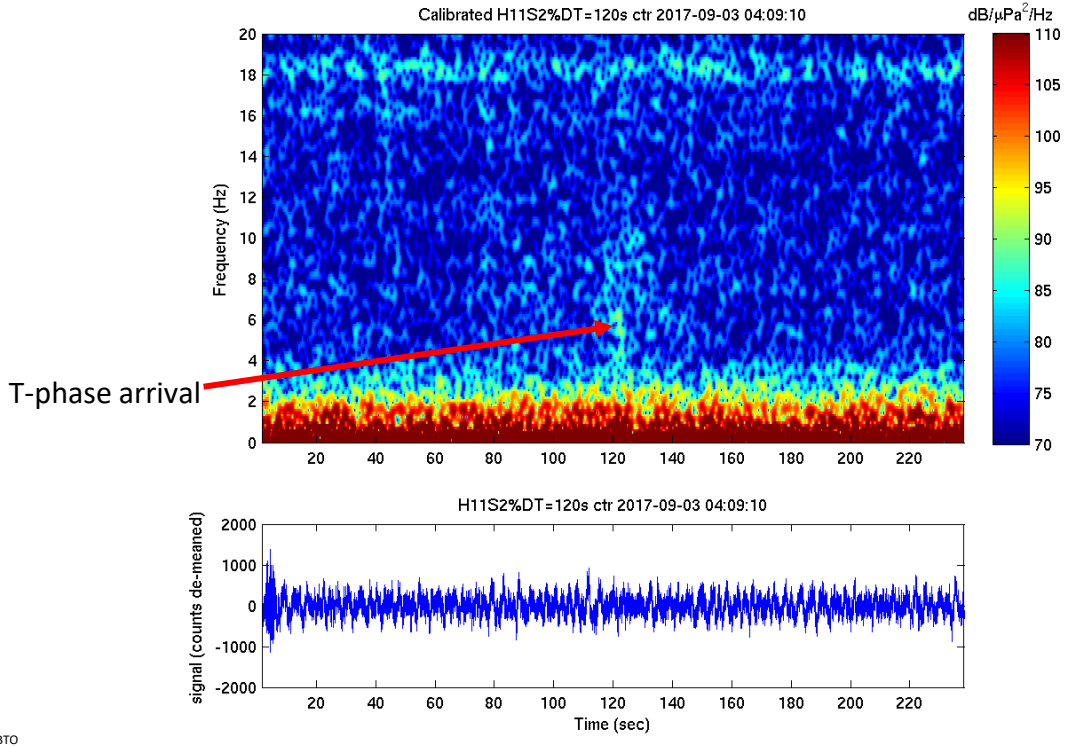
T-phase recorded at hydrophone triplet H11S

- The calibrated spectrogram at station H11S.
- The recorded signal is a hypothesized T-phase arrival.
- The T-phase arrival is hypothesized to be generated at the South-Eastern continental shelf of Japan.
- The recorded T-phase arrives at the H11S triplet at approximately 04:09:10 UTC.
- The arrival time corresponds to the nuclear explosion announced on 03:30:01 UTC, 3rd September, 2017.



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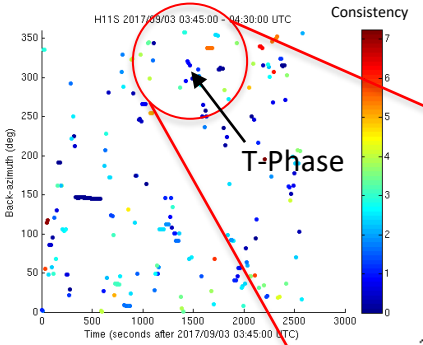
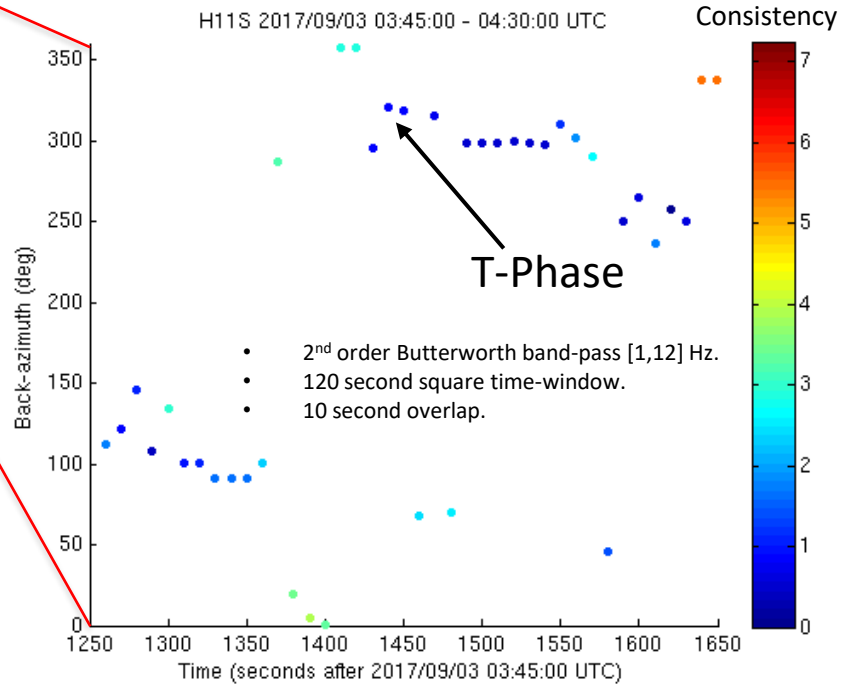
- Estimate of back azimuth at H11S by inter-node cross correlation.
- Colors indicate consistency (or closure relation) of the cross correlation.
- Lower consistency numbers indicate more confidence in the back azimuth estimate.
- The back azimuth estimate for H11S has significantly higher uncertainty than for H11N (higher value of consistency).
- The T-phase earliest arrival is captured at 318.23° re North at 04:09:00 UTC with a duration of 00:00:30.
- Observed T-phase arrival time from spectrogram is approximately 04:09:10 UTC.



H11S back-azimuth



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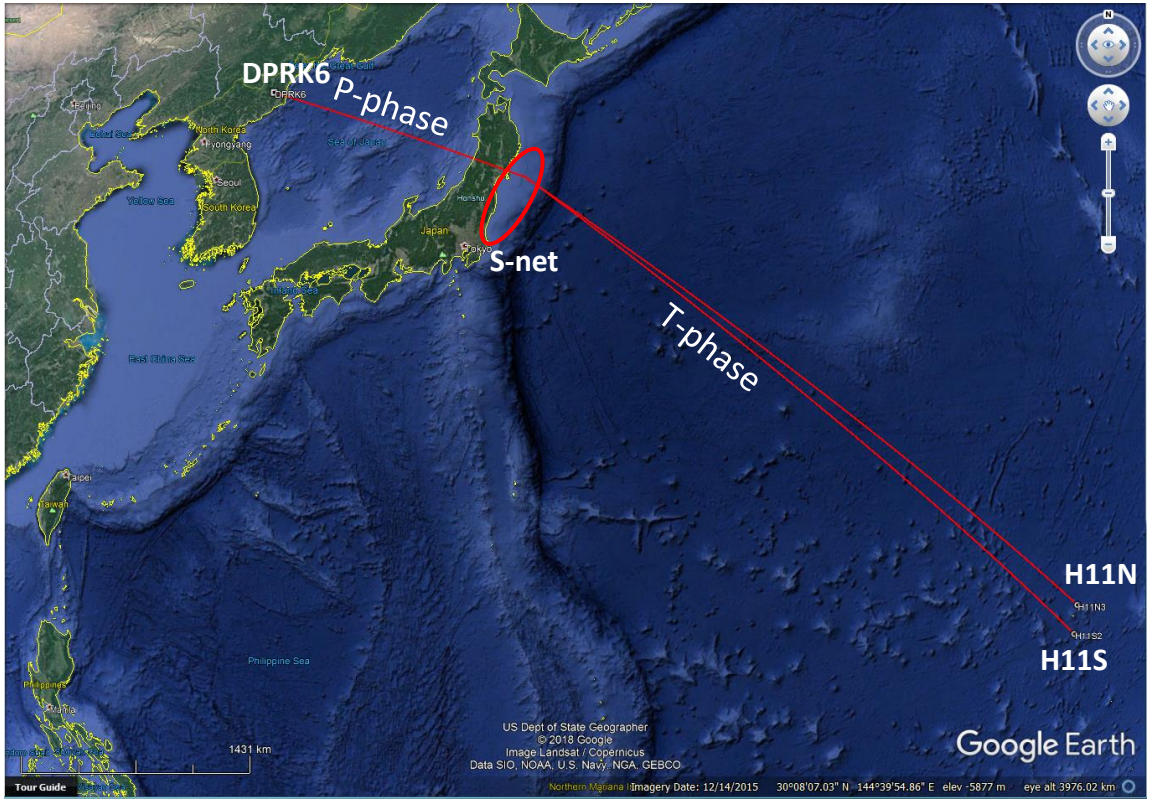
- Estimate of back azimuth at HA11 by inter-node cross correlation:
  - H11N mean azimuth 316.35° re North.
  - H11S mean azimuth 318.23° re North.
- The back azimuth estimate for H11S has significantly higher uncertainty than for H11N.
- Observed T-phase arrival time from wave form analysis:
  - H11N: 2210-2310 s re 03:30:01 UTC.
  - H11S: 2340-2370 s re 03:30:01 UTC.
- Estimated arrival time from in-ground seismic (IASPEI91) and in-water acoustic (1.485 km/s) travel times for the paths shown in the figure:
  - H11N: 2284 s re 03:30:01 UTC.
  - H11S: 2337 s re 03:30:01 UTC.
- Consistency between observed and estimated arrival time of a T-phase at the HA11 station.



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Conclusions

- All six announced DPRK events since 2006 detected by the CTBT IMS worldwide sensor network.
- The DPRK6 event was detected by a total of 134 CTBT IMS stations.
- For the first time, a DPRK event was detected by Hydroacoustics stations: 6 hydrophone triplets, including 2 automatic processing detections.
- The Hydroacoustic localization (P-phases) of the DPRK6 compares well with that by the seismic stations.
- In addition, the Wake Island hydrophone station (HA11) recorded a signal that is consistent with a T-phase generated on the Japanese South-Eastern continental slope and is attributed to DPRK6.
- Further studies are required to investigate which criteria in the automatic processing triggered the hydroacoustic automatic detections, and the reasons why HA03 and HA08 had no automatic detections despite high signal-to-noise ratio (SNR).
- These detections demonstrate again the detection capability of the IMS hydrophone stations, with event detection distances (surface geodesic paths) up to 17500 km from the source (P-phase).

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THE END

Thank you for your attention