Range estimates of whale signals recorded by triplets of hydrophones

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Abstract

The International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) includes a hydro-acoustic network as one of the monitoring technologies. The underwater part of this network includes six stations each composed of two sets of three hydrophones or triplets, except for HA01 (Cape Leeuwin, Australia) which is composed of a single triplet. The hydro-acoustic network is now complete with the recent installation of the HA04 station located in the Southern Ocean island of Crozet (France). A large number of calls emanating from marine mammals are recorded by the hydrophones, and we present examples where the animals are sufficiently close to attempt a range estimate. We also present examples of scattered arrivals and related interpretations. One striking example of extremely accurate range estimation is obtained for a whale in the neighborhood of the Cape Leeuwin (Australia) HA01 IMS stations. The proximity to the station and in particular to hydrophone H01W2 was first hypothesized because a running cross-correlation computation showed that the apparent velocity of the source was very high and could not be explained by hydro-acoustic waves travelling within the SOFAR channel. Since the far-field, plane wave assumption does not apply anymore in this case, a grid search was implemented to locate the source of the signal with the added assumption that the source is close to the ocean surface. As a further confirmation of the proximity of the source to the hydrophones, and given the expectation that such a source would generate scattering from the ocean floor and from the free surface, reflections are observed and the travel time of the scattered waves confirm the position calculated from the grid search using the direct arrivals.

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One striking example of extremely accurate range estimation is obtained for a whale in the neighborhood of the Cape Leeuwin (Australia) HA01 IMS stations. The proximity to the station and in particular to hydrophone H01W2 was first hypothesized because a running cross-correlation computation showed that the apparent velocity of the source was very high and could not be explained by hydro-acoustic waves travelling within the SOFAR channel. Since the far-field, plane wave assumption does not apply anymore in this case, a grid search was implemented to locate the source of the signal with the added assumption that the source is close to the ocean surface. As a further confirmation of the proximity of the source to the hydrophones, and given the expectation that such a source would generate scattering from the ocean floor and from the free surface, reflections are observed and the travel time of the scattered waves confirm the position calculated from the grid search using the direct arrivals.

OBJECTIVES

There are many objectives to this research including:

- To develop knowledge about the environment in which the in-water hydro-acoustic stations of the IMS network operate
- To develop experience with the type of signals emitted by large marine mammals, potentially discovering new types of signals.
- To help development of useful algorithms in tackling automatic determination of this type of signals and their automatic identification as marine mammal signals and not signals of interest for the core mission of the CTBTO.
- Although much of the below is beyond the author's expertise and immediate scope of this poster, this research can help inferring knowledge about the marine mammals themselves:
  - Migration pattern
  - Abundance
  - Acoustic emissions characteristics – Depth at emission – Source level – Propagation
  - Significance of the calls – Echolocation – Communication - Social functions

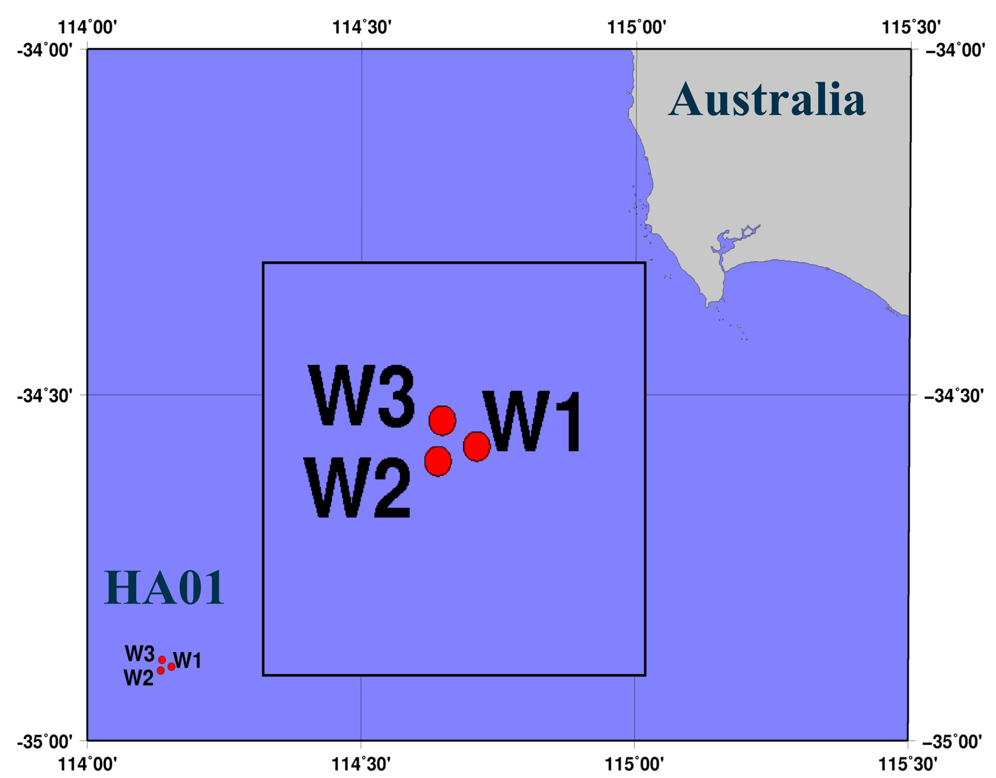
Conclusions

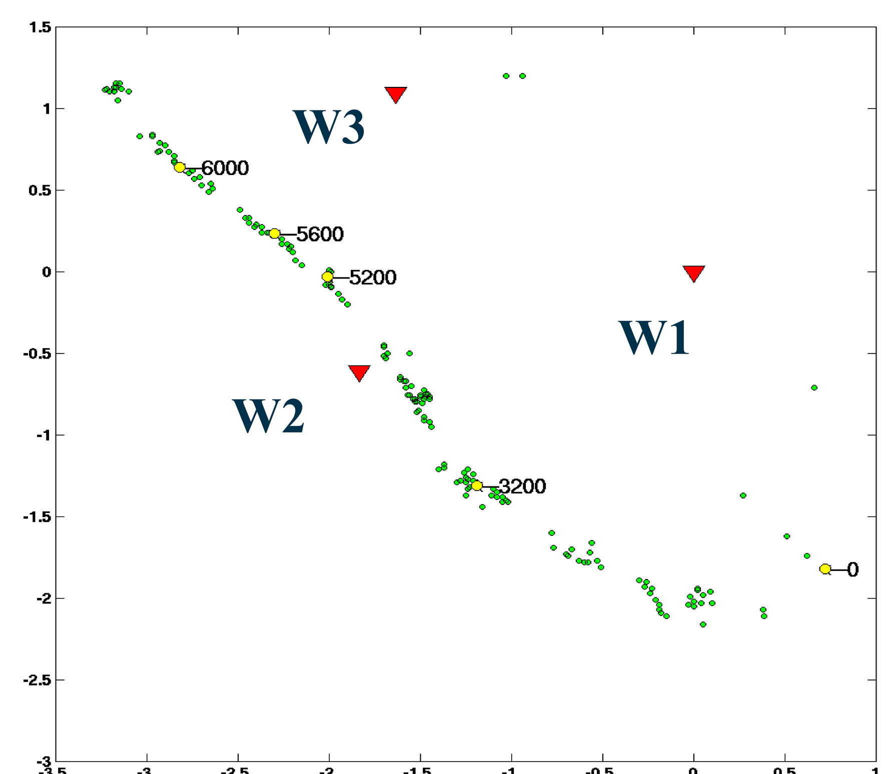
- We have observed the passage of two different types of whales by the CTBTO hydro-acoustic station at Cape Leeuwin and have been able, assuming a constant velocity model, and that the animal is close to the surface in both cases, to image the track of the animal for a period of two hours in the case of the observation on July 26, 2017, and for one hour in the case of the observation on October 15, 2017.
- In addition to the imaging of the whale track, we have also observed scattered arrivals in the July 26 case. We have been able to interpret these as the sea bottom reflection and a subsequent path with a first bounce from the sea bottom and then the sea surface.
- There is a hint for the observation on 26 July that an initial sea surface reflection of the initial call is causing a double peak on the autocorrelation.

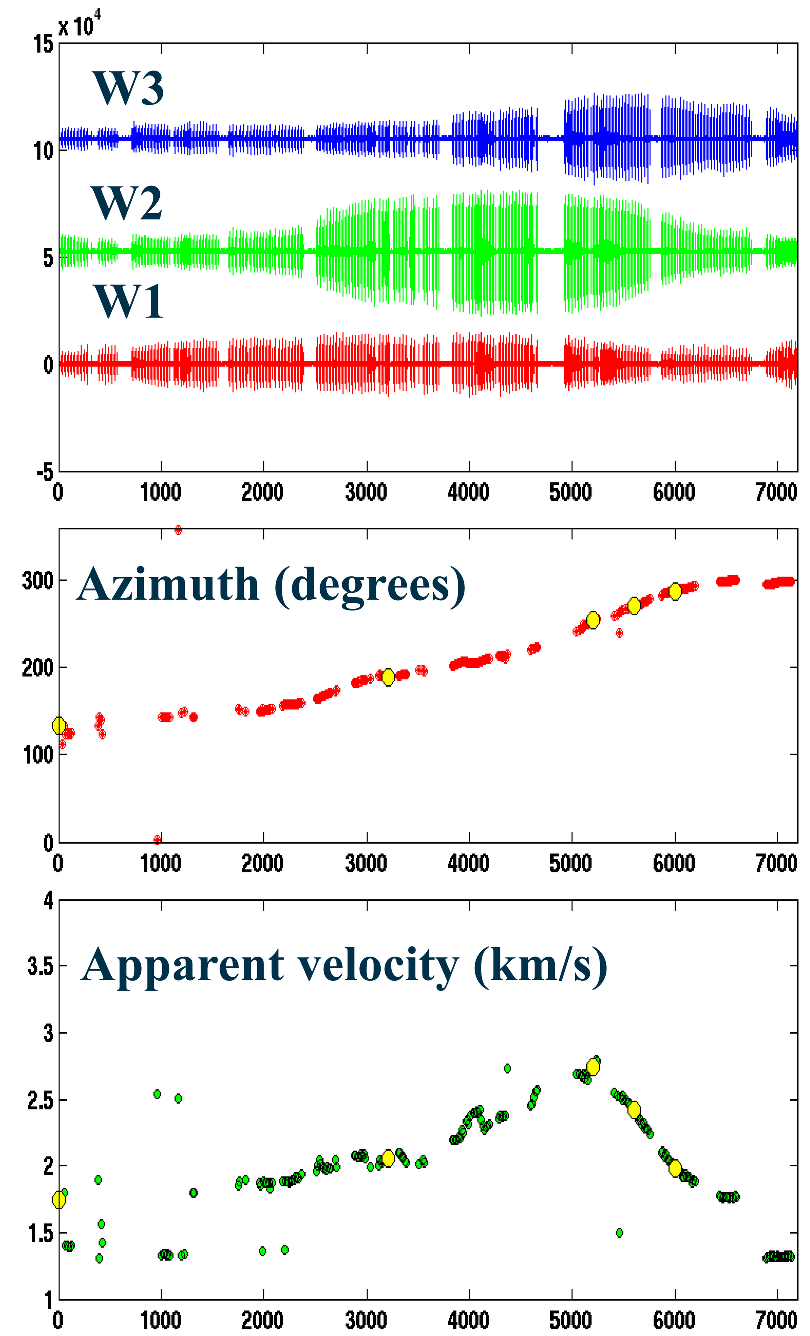
Recommendations

- More elaborate signal processing techniques may be able to better evidence a possible initial sea surface reflection which would be quite useful to help whale scientists remotely evaluate the depth at which the species observed emit their calls.
- It may be a worthwhile project to automatically detect the proximity of whales to hydro-acoustic triplets using an automatic detection algorithm based on large slowness indicating a steep incidence angle a expected when the animal is close. This would afford the collections of a lot of data concerning the density and seasonality of different marine mammal species in the proximity of each hydro-acoustic stations.
- The observation of scattered arrivals from the calls should also be of use to get very precise depth estimation of the animals.

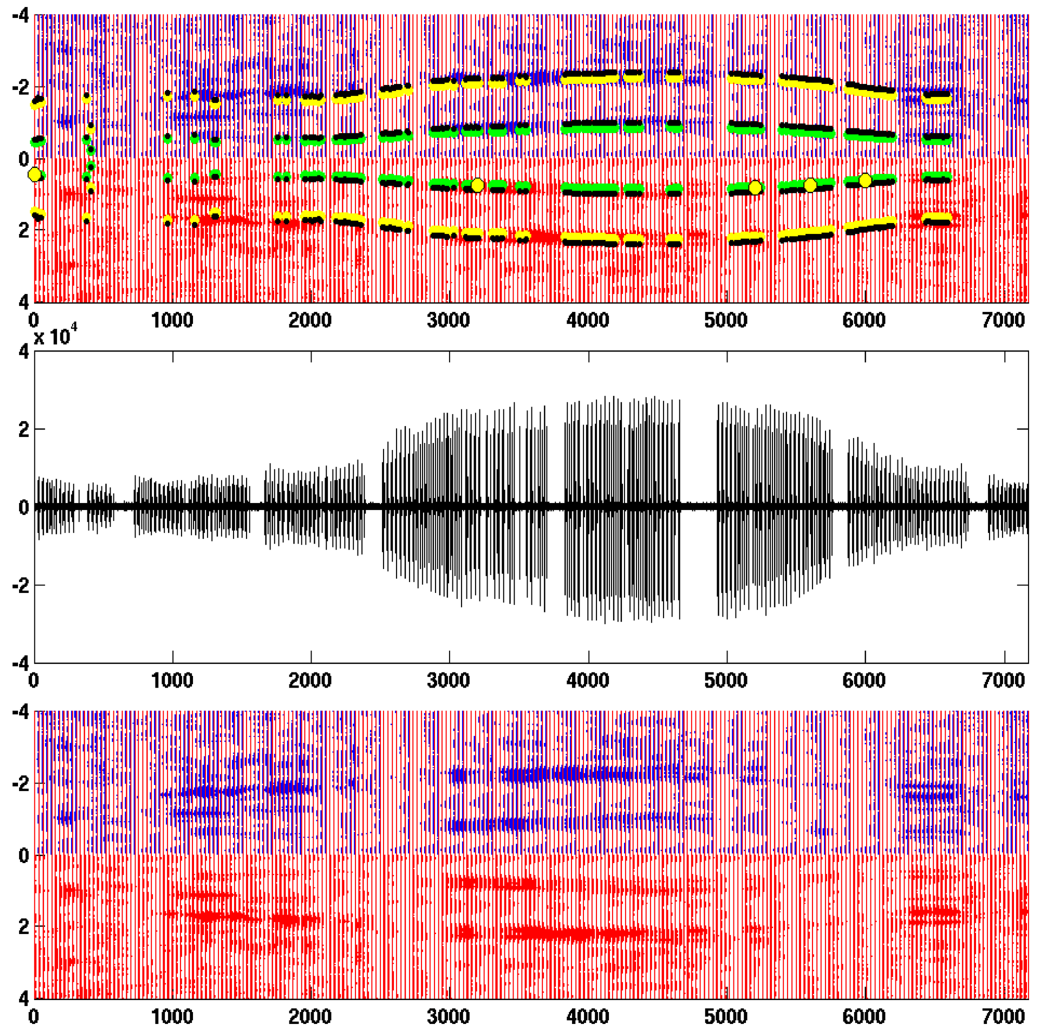
Example of very near-field observation at the IMS HA01 station in Cape Leeuwin, Australia, on July 26 and July 27, 2017.

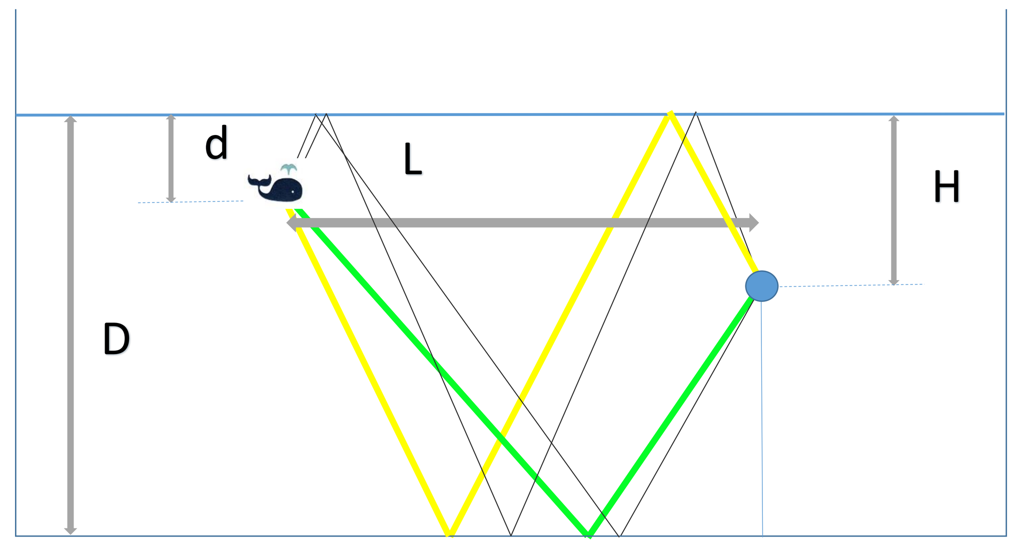






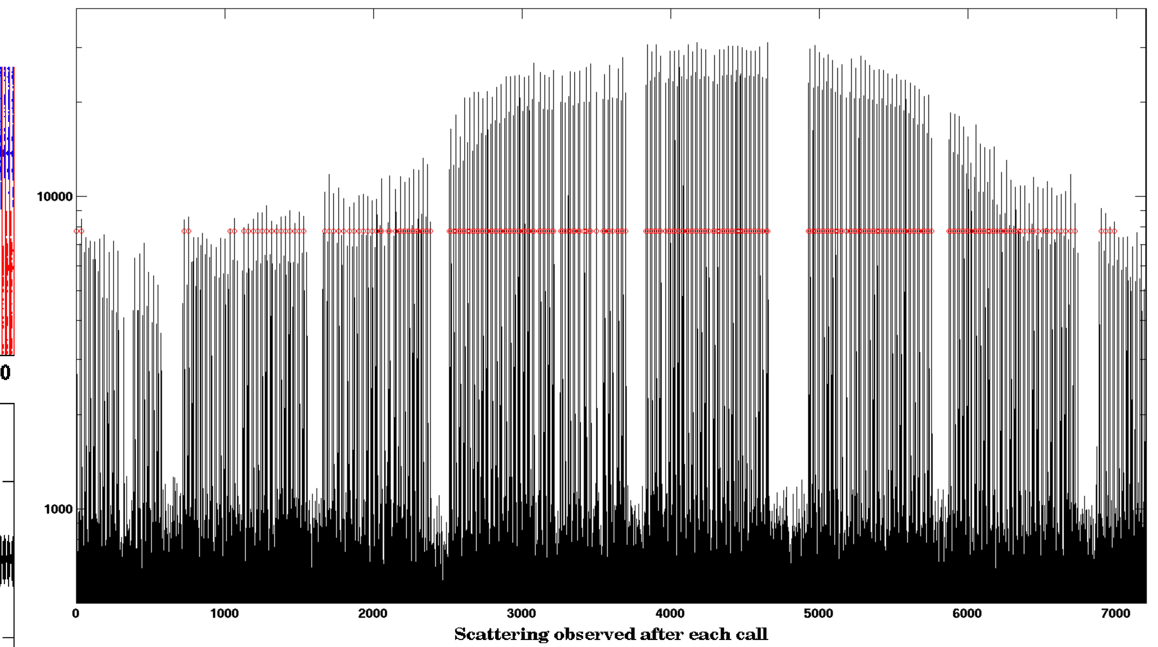
- The **top left map** shows the locations of the HA01 station and its three hydrophones with respect to the coast of Australia.
- The **panel to the left** shows the traces at the top and the azimuth and apparent velocity estimates for a two hour interval starting at 20:00 on July 26, 2017. The hydrophone traces are filtered between 3 and 100 Hz. The scale is the same for the three traces. It is apparent that the W2 hydrophone receives a higher level of energy from the moving source. It is also apparent that the received energy evolves from a low value, passes through a maximum around 4000s for W2, 5800s for W3, and 3600 for the W1 hydrophone. The energy maximum is better defined at the W2 hydrophone. The cross-correlations are computed every 5 seconds over a length of 10 seconds. Two cross-correlations between W1 and W2 and between W1 and W3 are computed for delays between -2s and 2s. The maximum of the two cross-correlations is picked giving two different delay values from which an estimate of the azimuth and apparent velocity is determined. The two plots below show the station to source azimuth and apparent velocity of an incoming wave, computed assuming a plane wave model for the signal detected at the three hydrophones. The scale for the azimuth is shown on the left side and spans 0 to 360 degrees. The scale for the apparent velocity is in km/s and spans 1 to 4 km/s. One would expect that a wave travelling horizontally in the SOFAR channel would have an apparent velocity of slightly less than 1.5km/s. The apparent velocity values detected on this signal allowed to determine that the source of the signal was likely in the very near field and the location could then be computed using this hypothesis.
- The top centre **panel** shows the location of the source as a function of time using the hypothesis that the source of the signal is close to the surface. The most likely position of the source was computed using a grid search on a 4.5 by 4.5km with a grid spacing of 10m. To determine the position of the source for any point in time where the apparent velocity is larger than 1.5km/s, we minimize the RMS of the difference between the delay expected from that location and the observed delays. The small green dots are all the locations obtained for each 5s step. The larger yellow symbols are annotated with their corresponding time of detection and show the progression from the southeast towards the W2 hydrophone and then towards the northwest. The yellow symbols are also shown on the azimuth and apparent velocity plots.
- The figure to the top right shows the trace at W2 in the center and a repeat of an autocorrelation-derived trace at the top and bottom. The autocorrelation at time t0, a(t,t0), is computed with a window of 240s for delays between -4s and 4s, every 60s. The ramp function is applied to the autocorrelation t*a(t,t0) to minimize the central lobe and this allows scattered arrivals to be emphasized. When multiplying by the ramp function, the result becomes antisymmetric. The top part also shows the times of four different reflection times repeated on the positive and negative sides of the autocorrelation-derived traces. The paths for these reflectors are shown to the right and represent our preferred interpretation of the reflected arrivals. From a comparison with Haxel *et al*., (2013), we believe we are observing a fin whale.

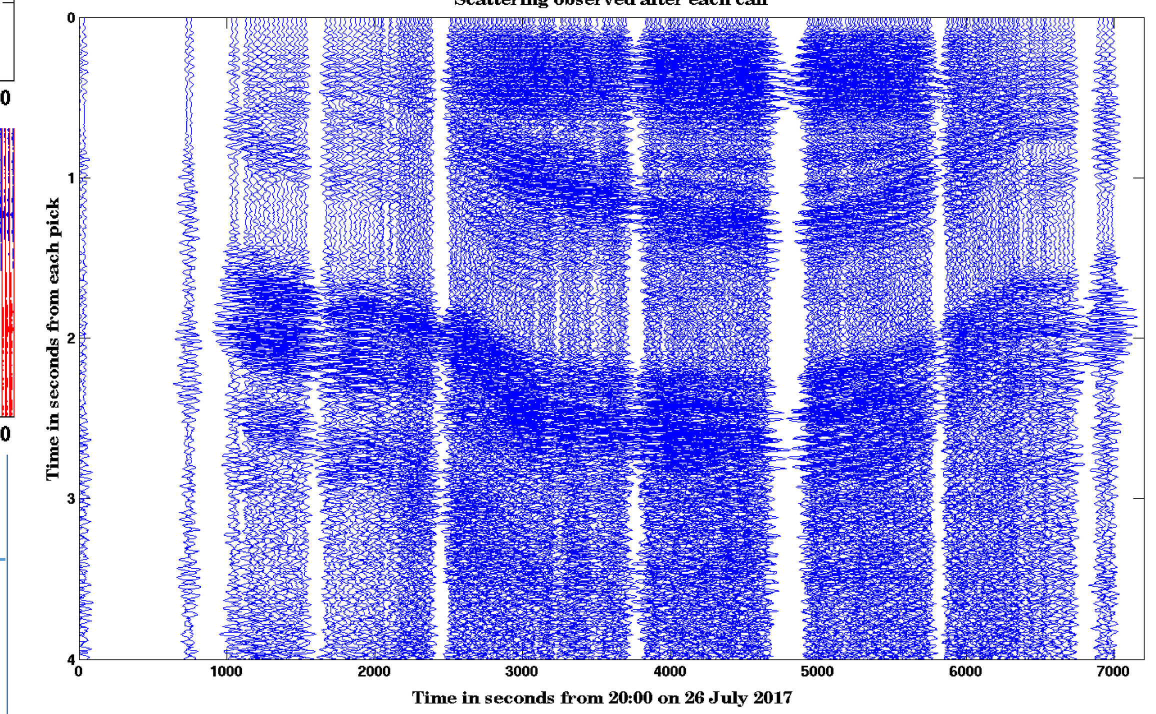




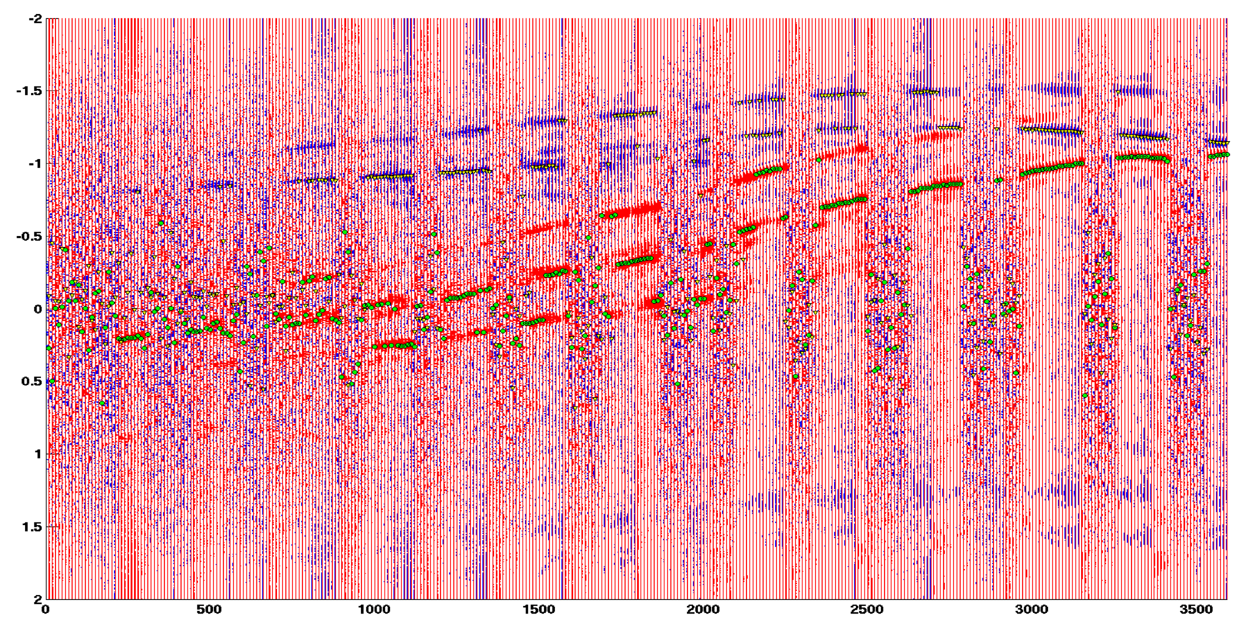
The above sketch shows the interpretation for the presumed scattering energy received during the transit of the whale through the set of H01W hydrophones. The ocean is locally at a depth D (D=1700m). The whale is presumed to be at a depth d (d=100m). The hydrophone's depth H is the database recorded value (H=1046m for H01W2). For these values, and using a simple flat model and the positions calculated and shown on the top center panel, the arrival times are computed and superimposed on the autocorrelation-derived traces. The color code matches the specific paths. Our interpretation of the observed scattering matches the travel times for this very simple model especially well when the animal is almost directly above hydrophone H01W2. The match is not as good before 2000s, perhaps due to three-dimensional effects. There are other observations to be made on this interesting sequence of calls:

- There are interruptions in the call sequences of a duration of about 1-4 minutes. We interpret these as being the periods when the whale is at the surface and breathing.
- The amplitudes of the signals are consistent with the interpretation that the animal is directly above H01W2 at about 4500s, where the maximum amplitude occurs.



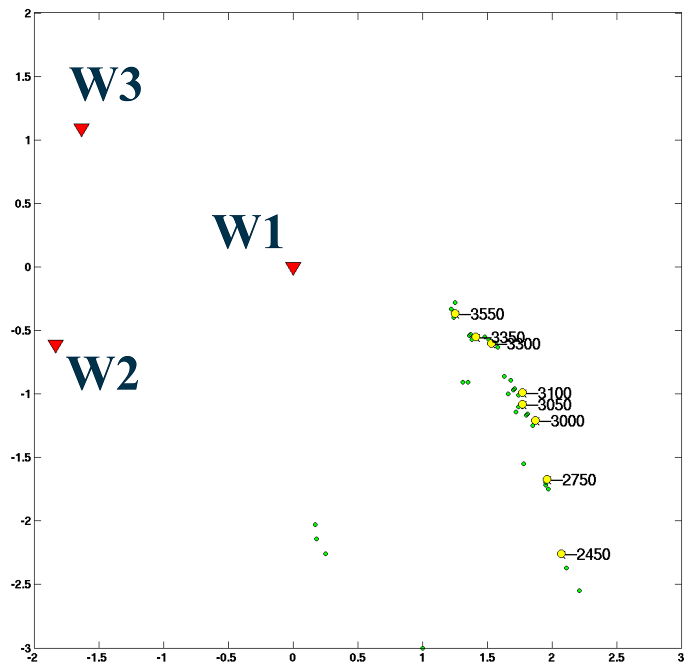


The top figure shows the envelope of the signal plotted in a log scale and the picks used to produce the section below. The section below is simply a plot of the W2 trace for 4s after each pick made on the envelope. This is another way to visualize the scattering from sea bottom and subsequent reflection from the sea surface, with the characteristic move-out expected when the source of the calls is above the W2 receiver and as shown in a different way by the autocorrelation figure at the top of the panel to the left.



Observation on October 15, 2017

Example of another set of calls (higher frequency, possibly a Minke whale). The tracking of this whale was also possible over a period of one hour between 10:00 and 11:00 UTC on October 15, 2017. There is also a hint that we observe the sea bottom reflection, but not as clearly as for the animal on July 26, 2017. The top figure shows the combined cross-correlations of W1-W2 (in red) and W1-W3 traces (in blue) indicating a strong variation of the cross-correlation delays with time, which indicate a source close to the hydrophone triplet and the possibility to use the same method as for the July 26, 2017 observation to compute a track. From the signal characteristics in time and frequency, we think it is a possibility that we are observing a Minke whale (Risch *et al.*, 2013).



From the analysis of the cross-correlations, a track can be computed assuming the whale is at the surface. The track is shown on the right with a few points labelled in seconds from the start of the analysis. In this case, the calls stopped before the animal was as close to the triad as in the case of the July 26 2017 observations.

Acknowledgements

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