Reducing ambiguity in hydroacoustic triangulation through consideration of three-dimensional propagation features

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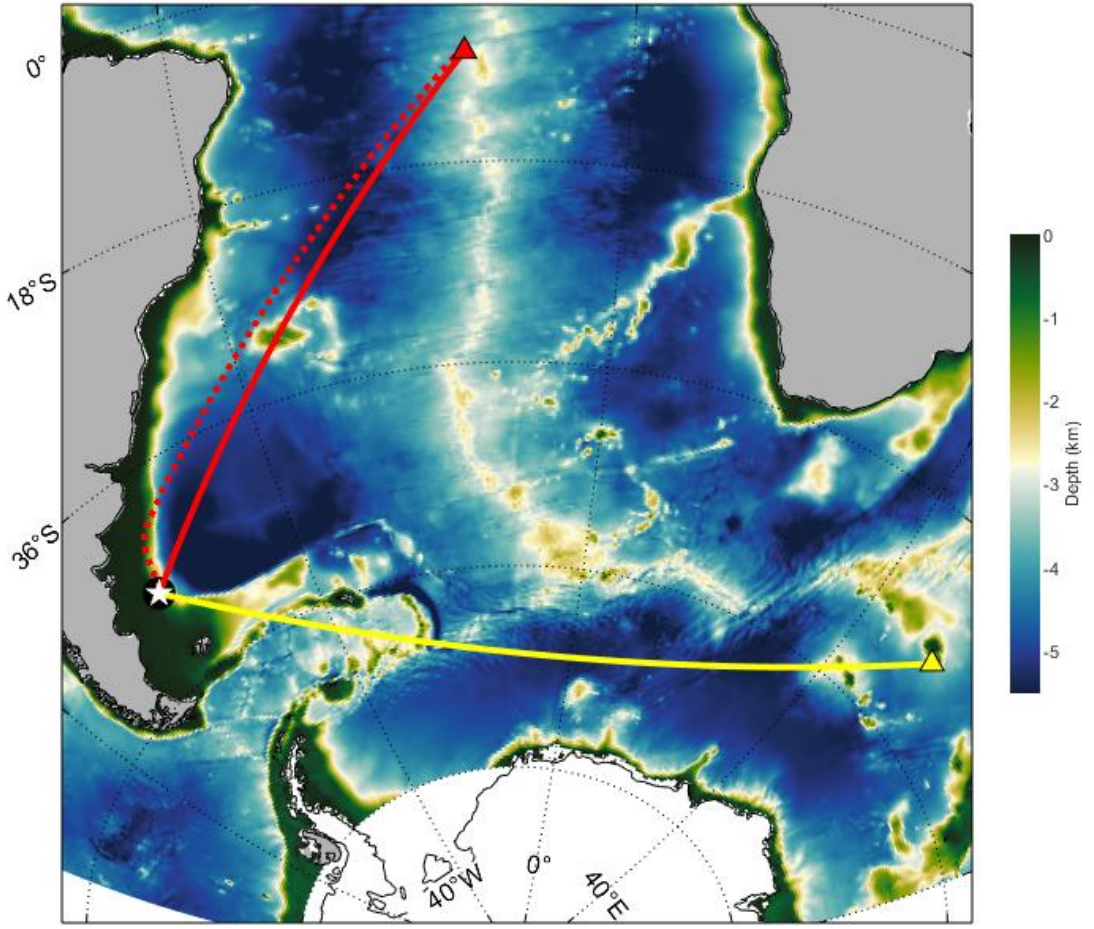
How many hydroacoustic (HA) stations are necessary?

- One HA station:
  - bearing of arrival (back azimuth)
  - signal dispersion characteristics (ranging)
  - 3D arrivals (to add “virtual” stations)
- Two HA stations:

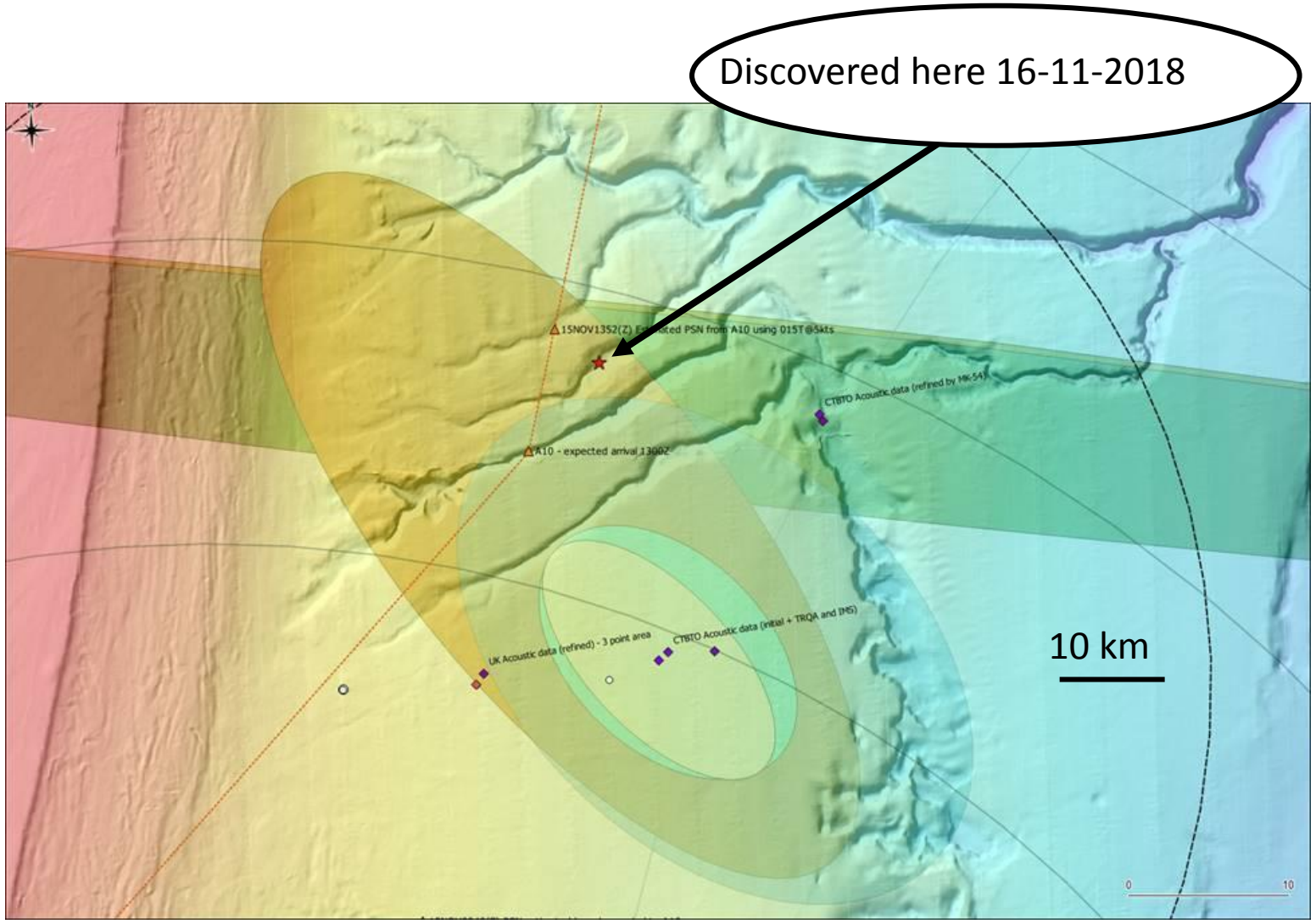
  provide location given event time, or viseversa
- Three HA stations:

  provide event time and location

apply to hydroacoustic signals from ARA San Juan



ARA San Juan: Lost 15-11-2017



Ocean Infinity search map and location of ARA San Juan

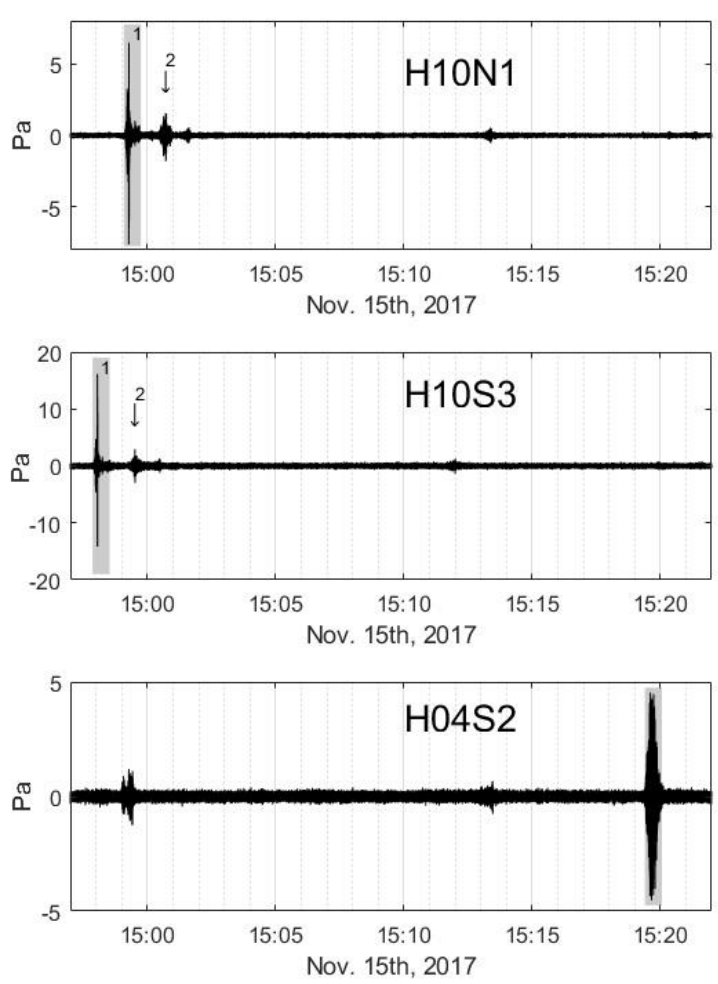
Image courtesy of Proceedings of U.S. Naval Institute (circa 2010)

Immediate response by CTBTO:

- Acoustic reanalysis based on known source *depth charge deployed on Dec. 1st*
- Refinement based on seismic detections

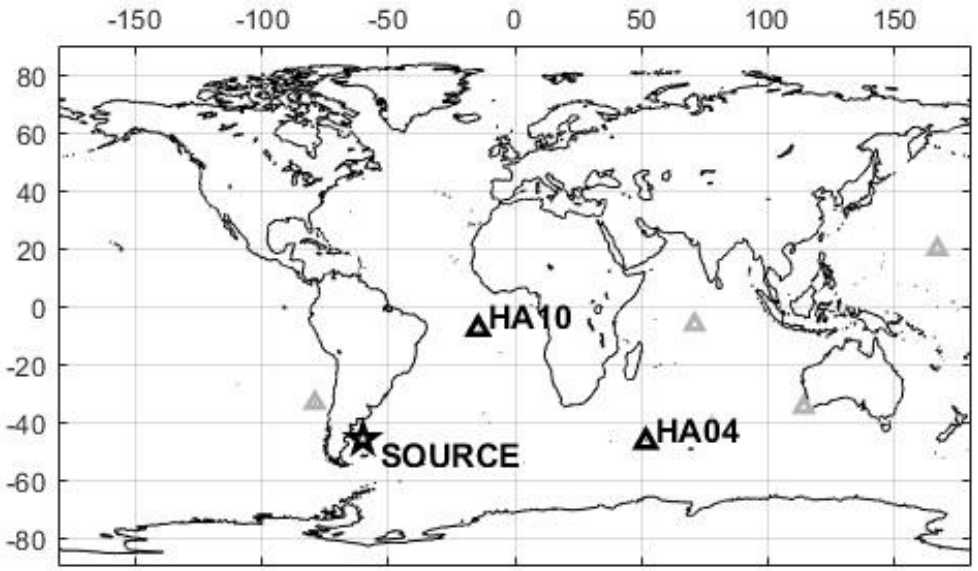
Example: signal from the ARA San Juan

Impulse received at two HA stations Nov. 15th, 2017



HA10 - Ascension

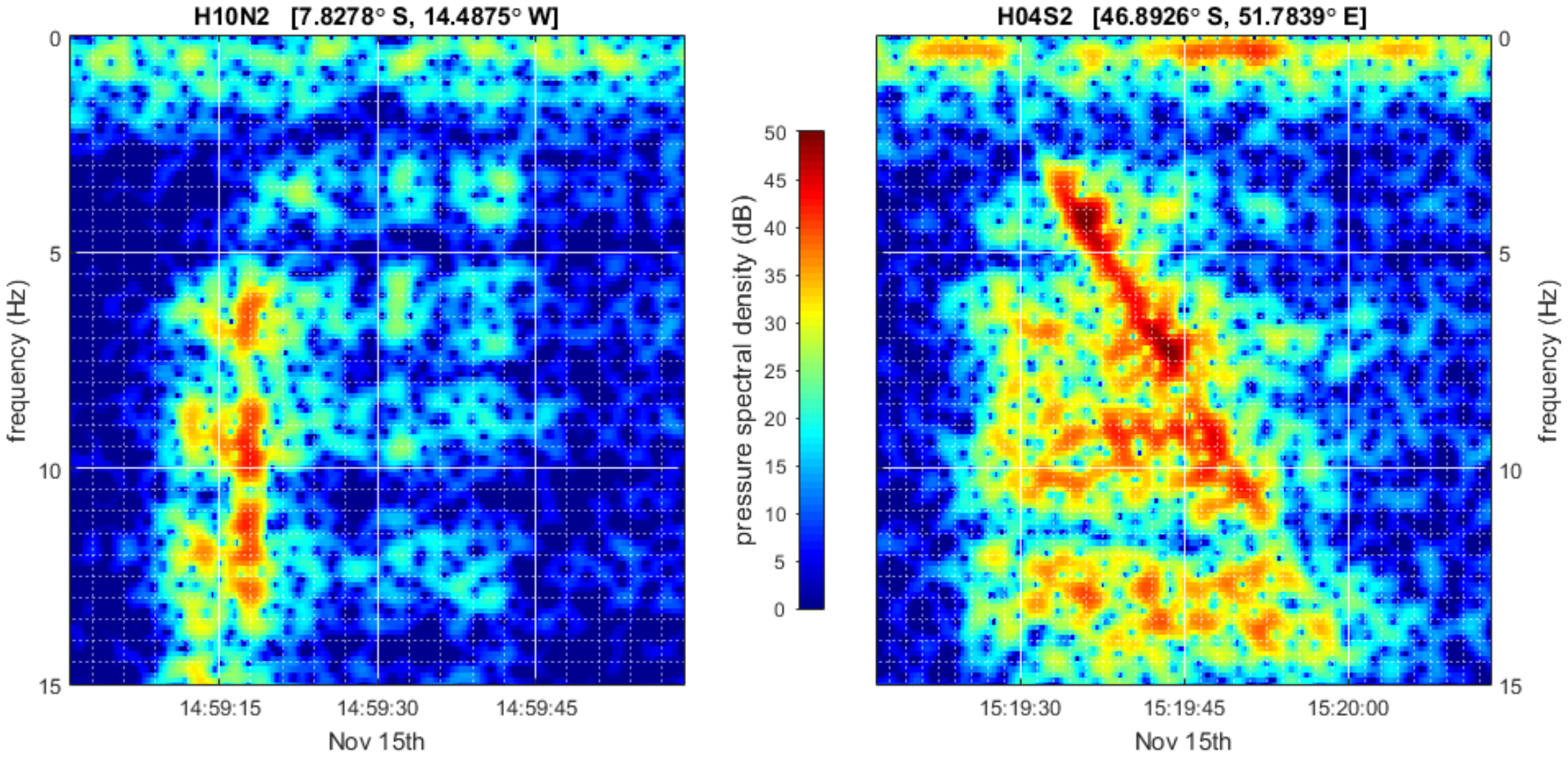
HA04 - Crozet



Observed Modal Dispersion on Direct Path

Ascension (HA10) – SOFAR channel

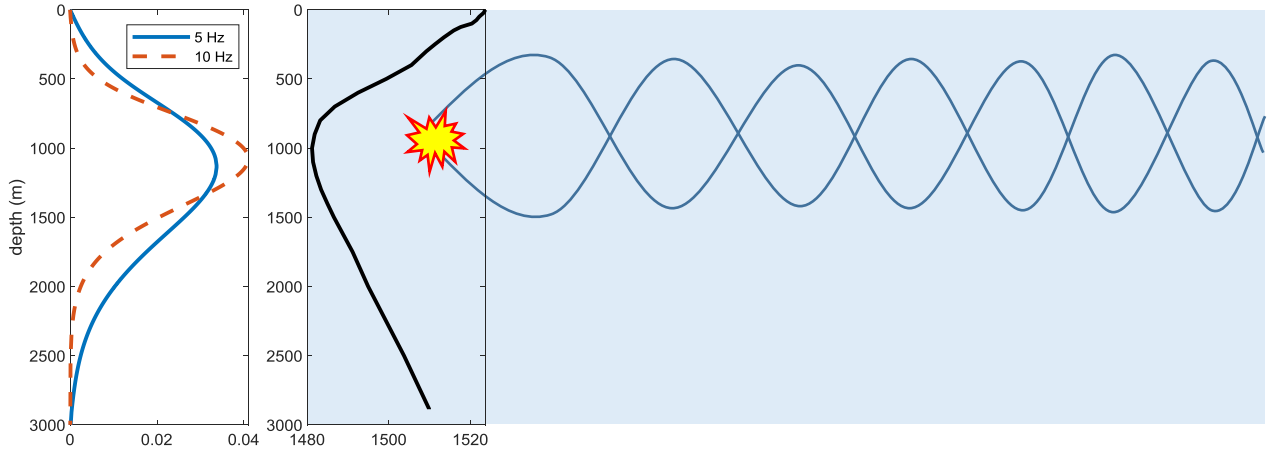
Crozet (HA04) – upwards refracting



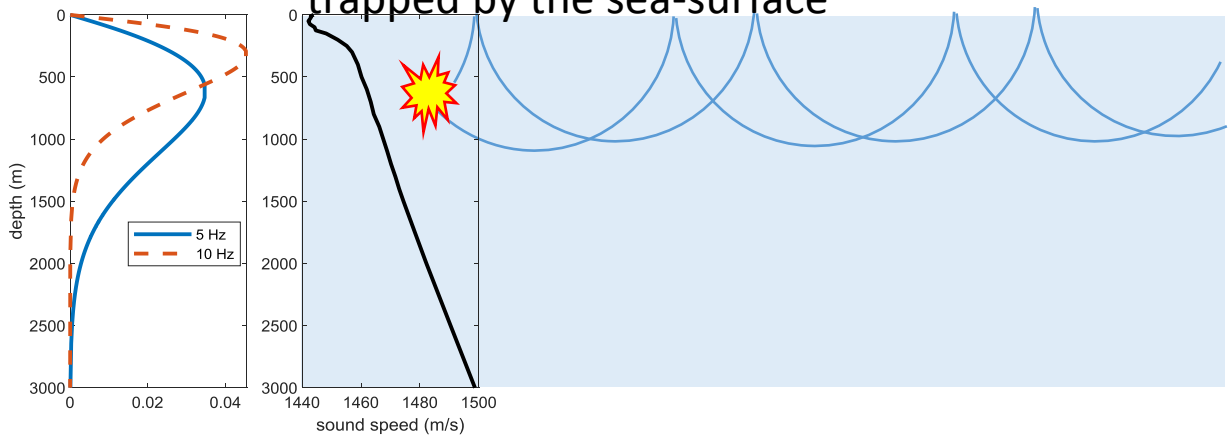
Acoustic Modes

mode functions *describe depth dependent intensity of trapped propagation paths*

trapped by the sound speed channel



trapped by the sea-surface



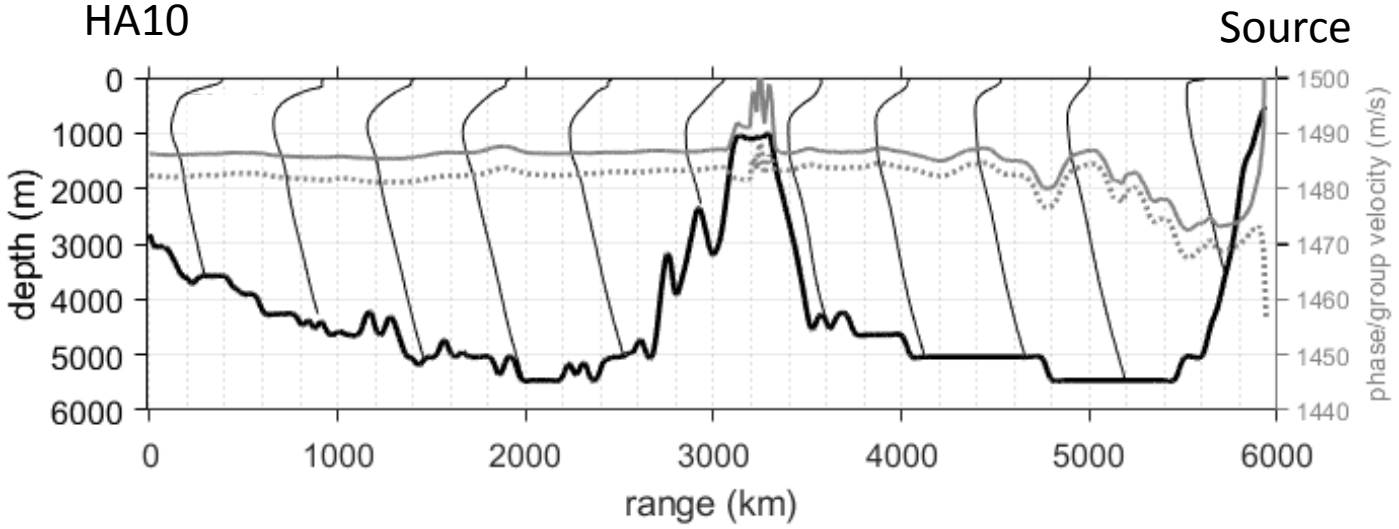
Group speed

equates to the sound speed times square of the mode function integrated in depth

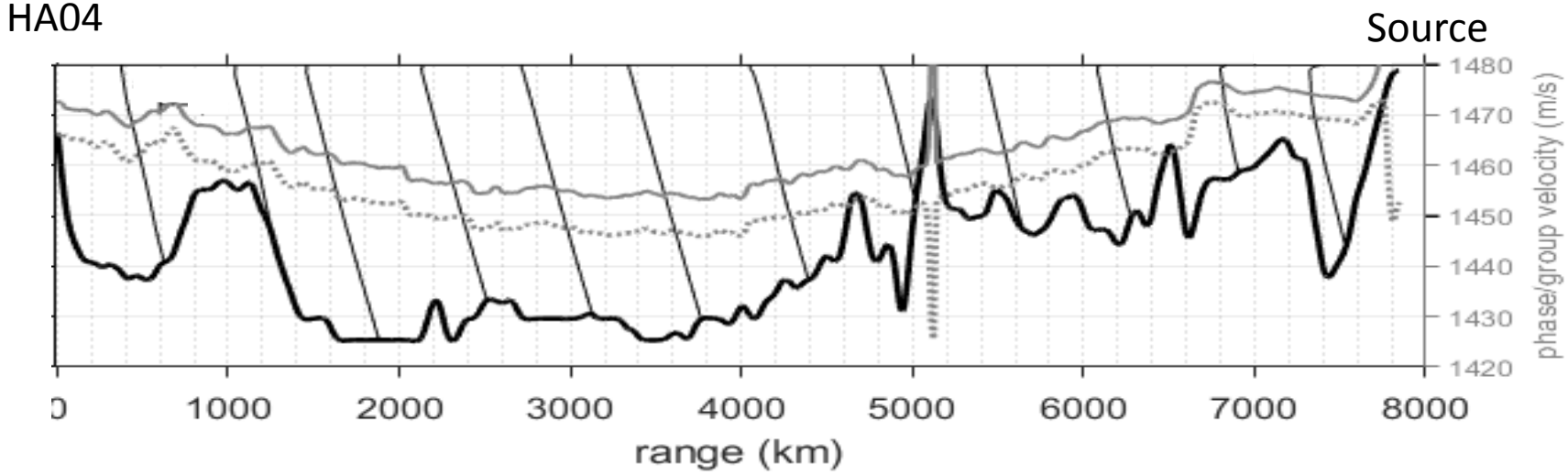
- effectively frequency independent in the sound speed channel (SOFAR)
- linear frequency dependence in upwards refracting profile

Example: range dependent group speed of mode 1 @ 10 Hz

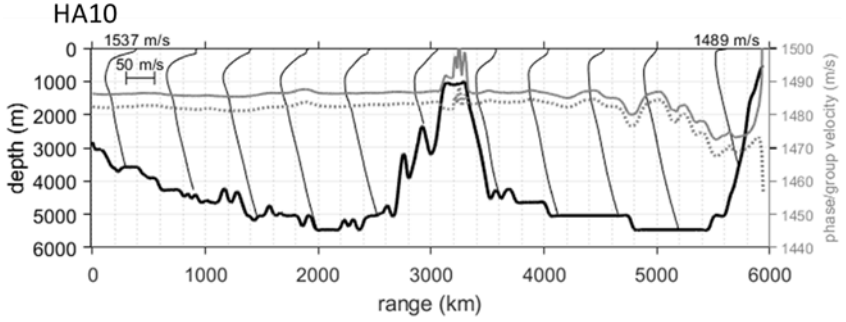
HA10

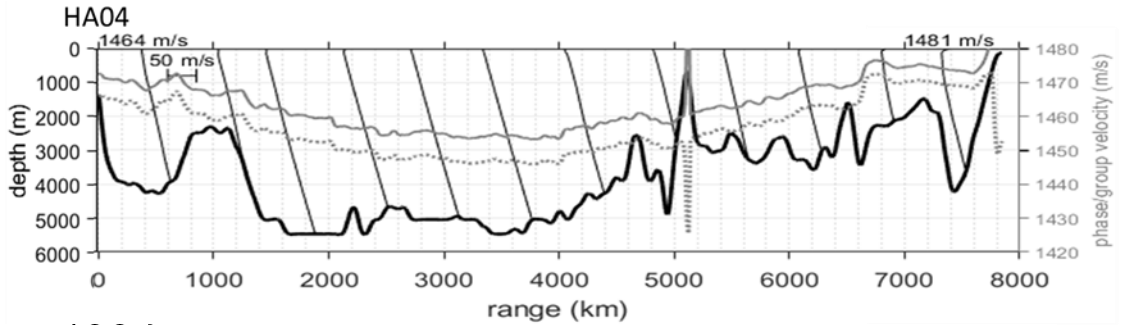


HA04

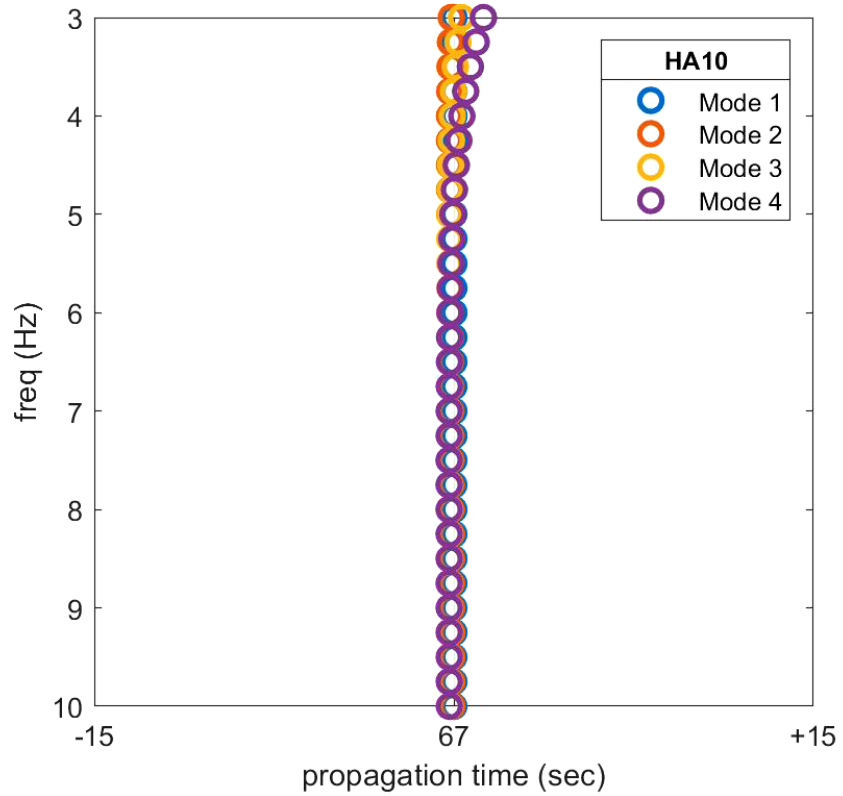


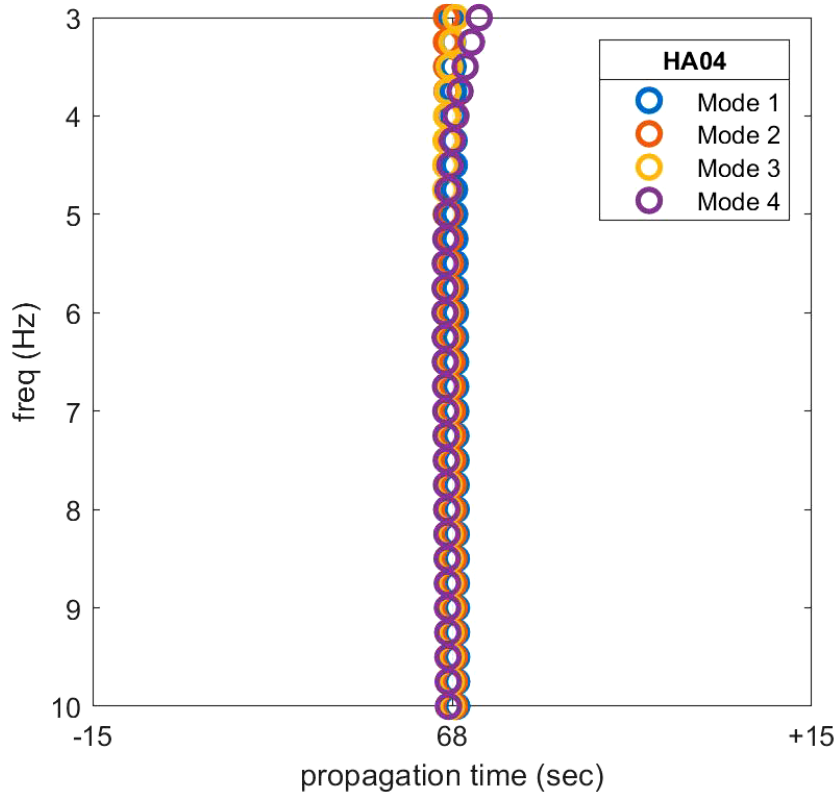
Propagation time via integration along geodesic





range = 100 km





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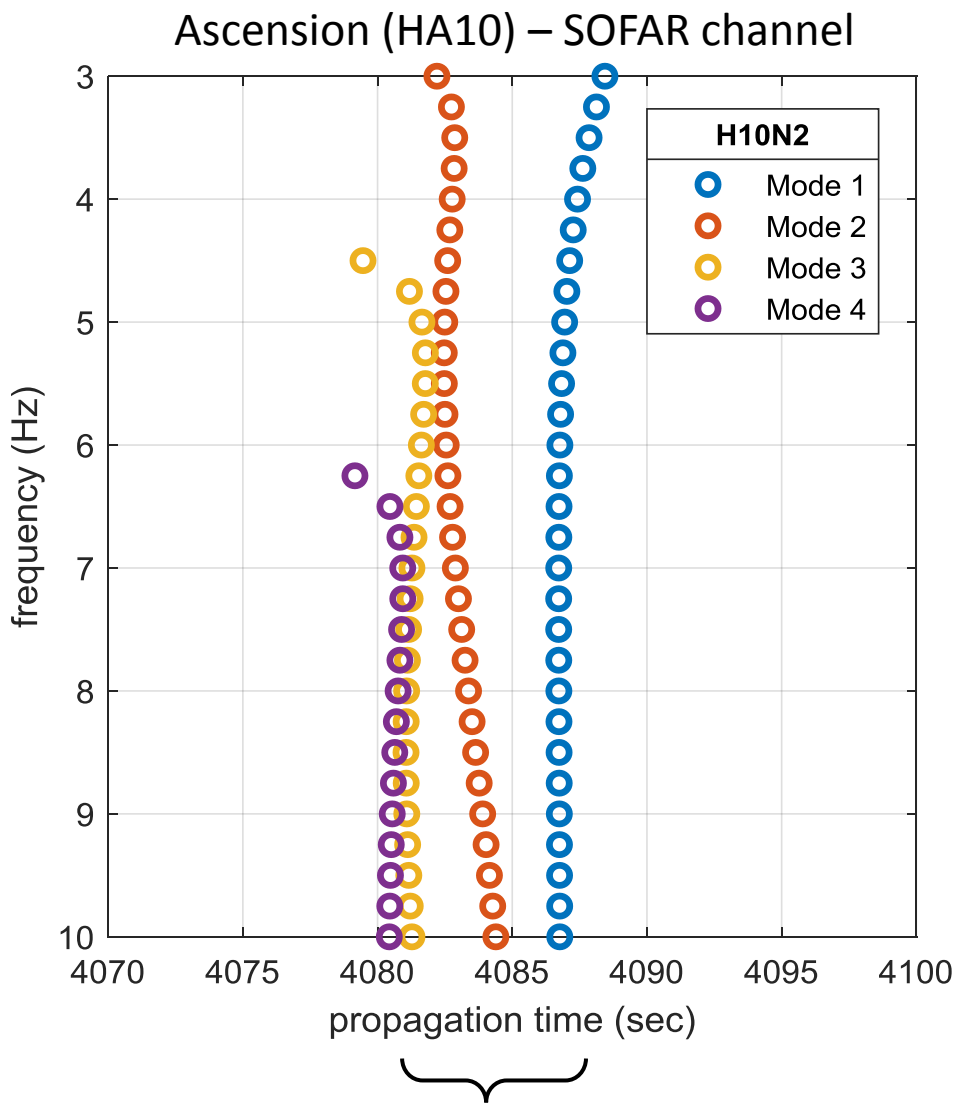
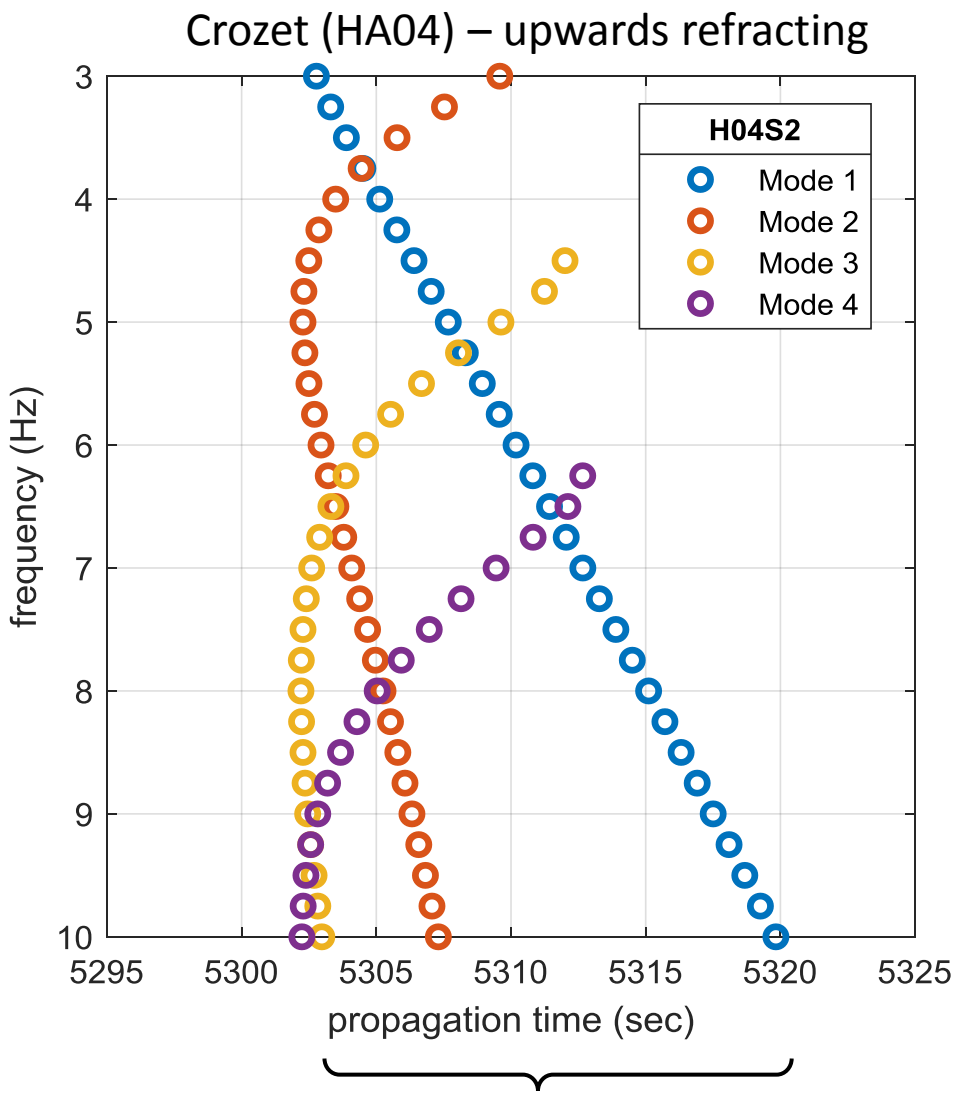


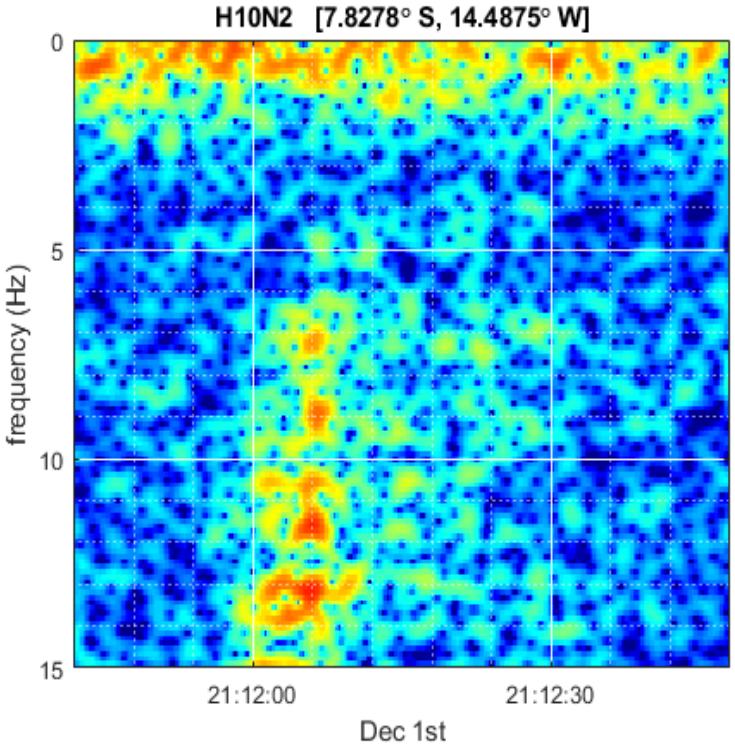
6 second delay of mode 1 from first arrival

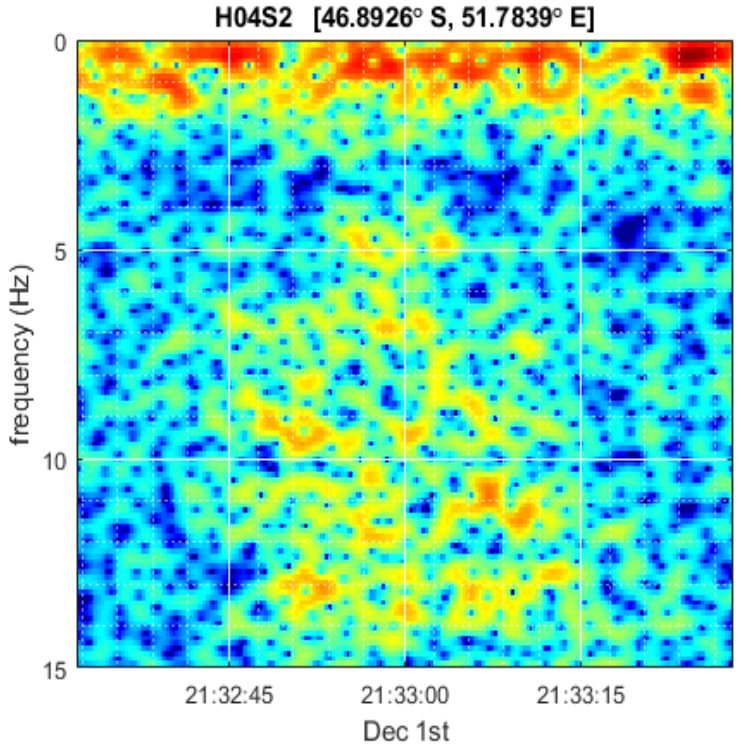


18 second delay of mode 1 @ 10 Hz

Matching modal dispersion features for ranging

Depth Charge Signal from Dec. 1st, 2017





Caveat on accuracy:

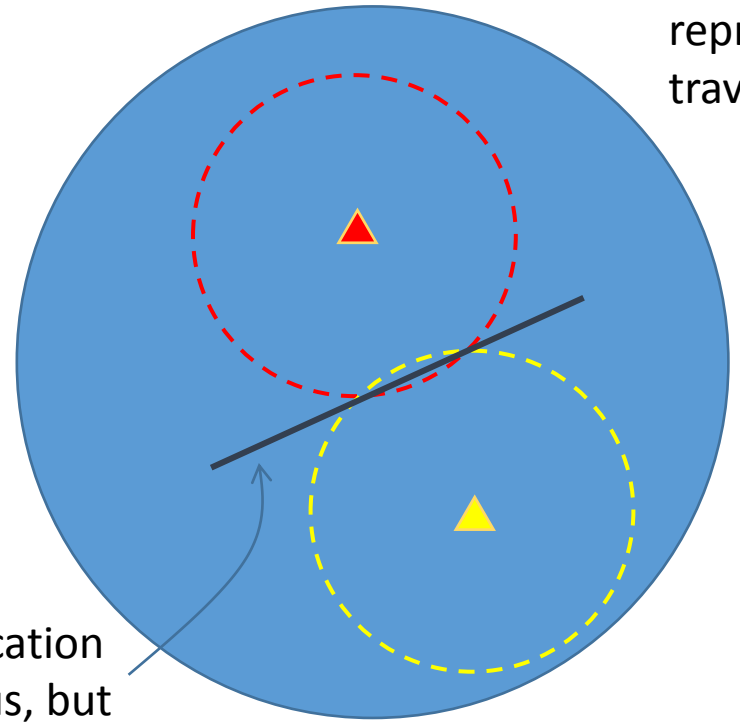
- modes not always identifiable
- group/phase speed greatly effected by bottom proximity

The most precise estimate of position comes from timing of acoustic arrivals on multiple station

Precise timing of arrivals on multiple stations allows for triangulation

- Two Stations

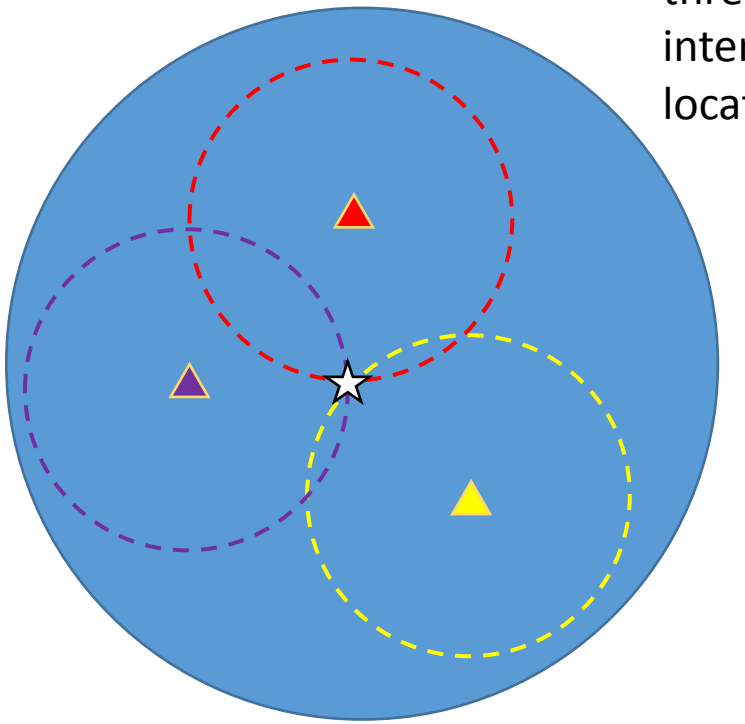
dashed circles (isochrones) represent surfaces of equal travel time



source location ambiguous, but falls on this line

- Three Stations

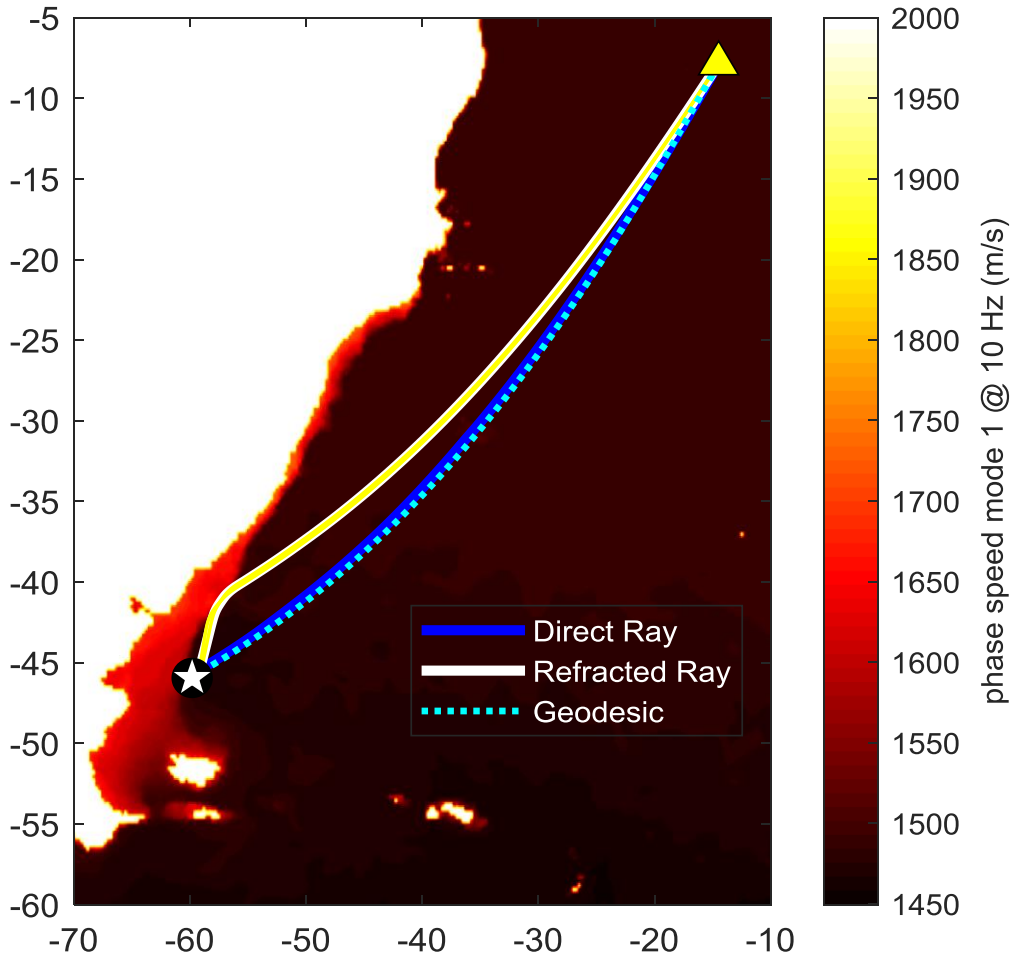
three isochrones intersect at location



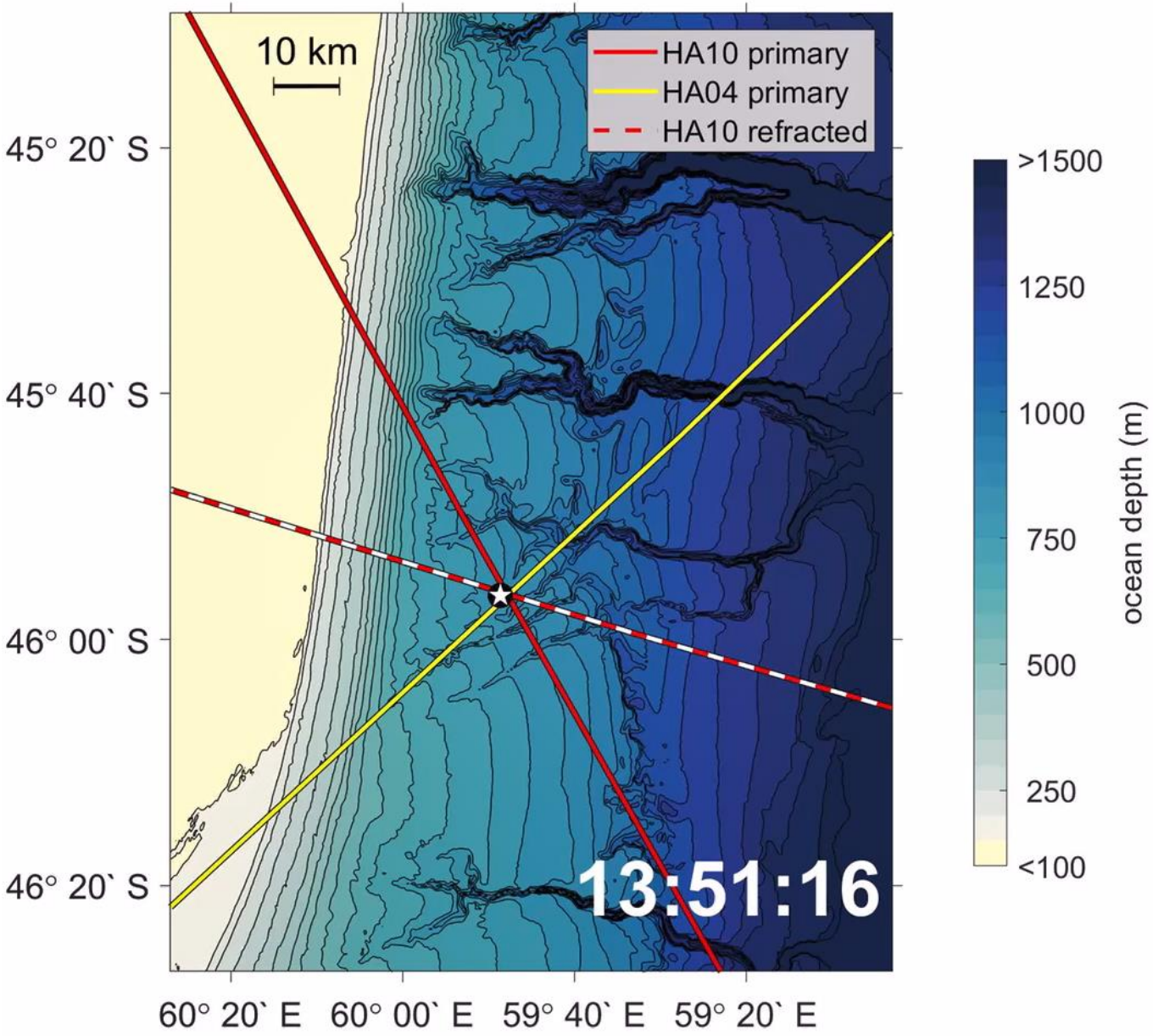
Modeling refracted paths to form virtual stations

- Isochrones are perpendicular to the energy path
- Geodesic representation is sufficient for direct energy path
- Modal rays depict energy path through refraction process

Refraction is governed by gradients in phase speed (as to maintain continuity of wavefield) most significant along the continental slope

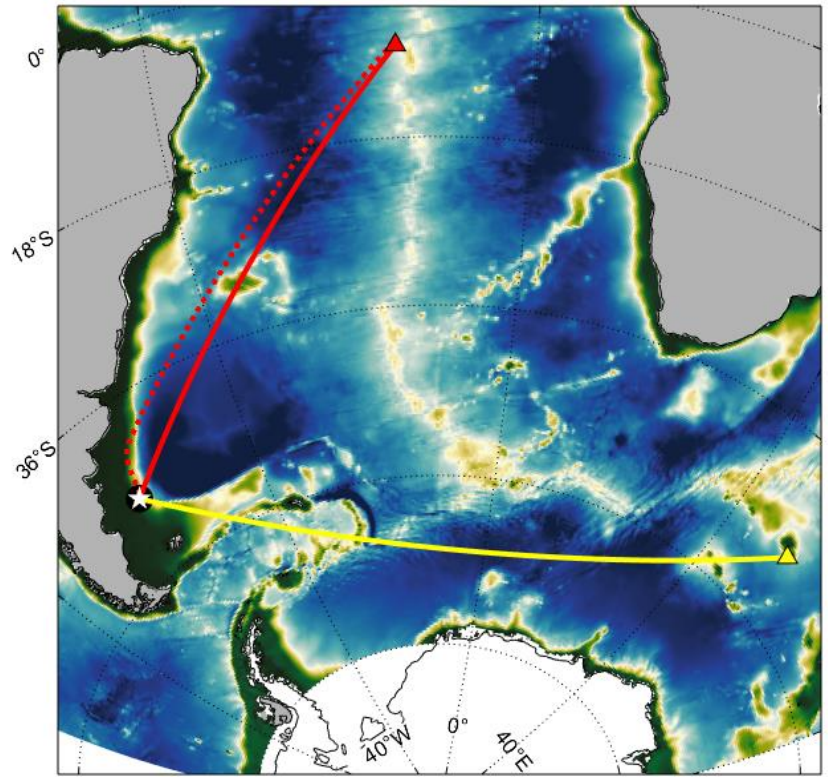


isochrones at candidate event times

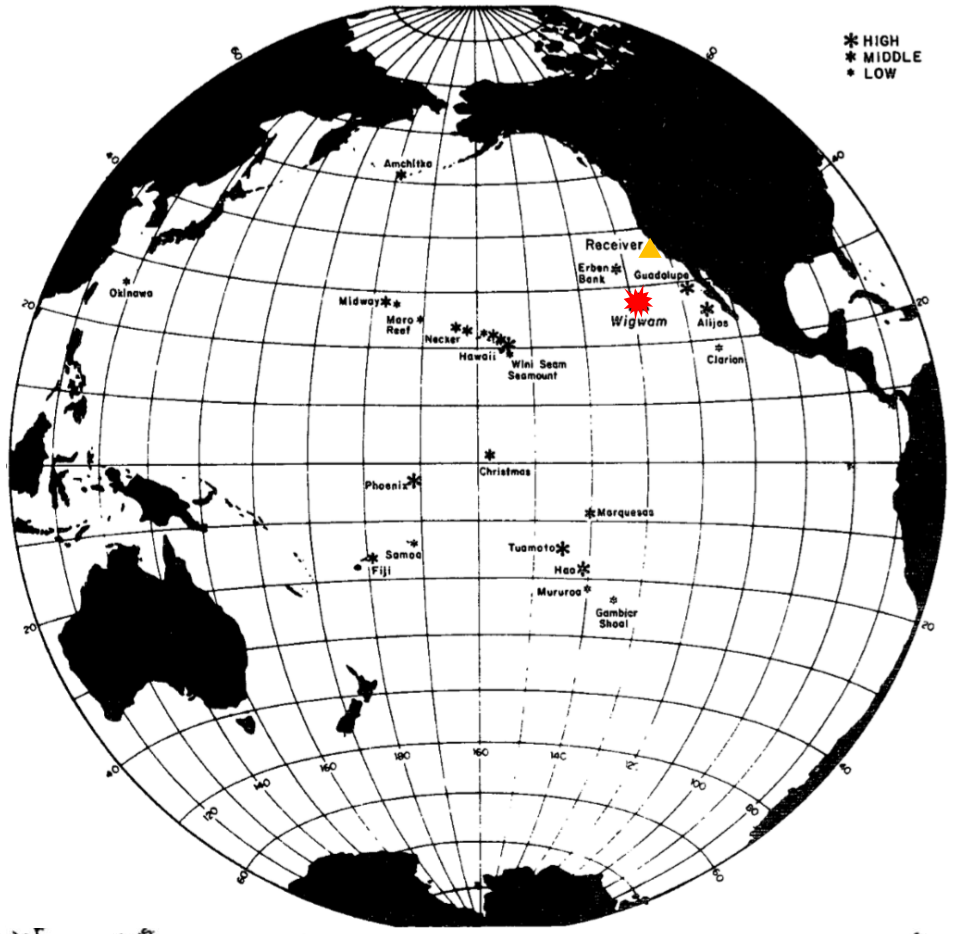


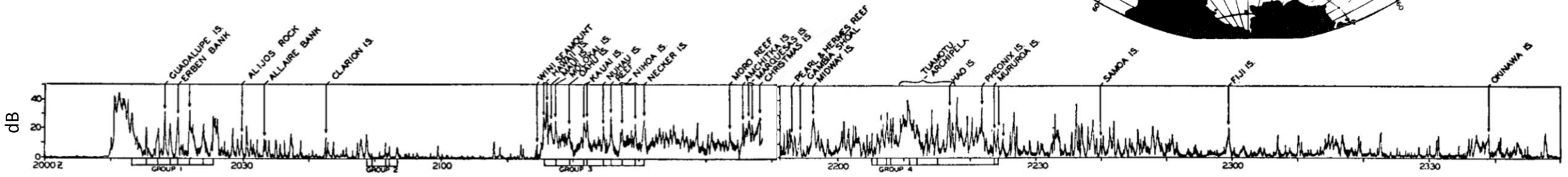
Triangulation of ARA San Juan

HA04, HA10 and one virtual station (refracted path to HA10)



Expect a plethora of 3D arrivals from nuclear tests

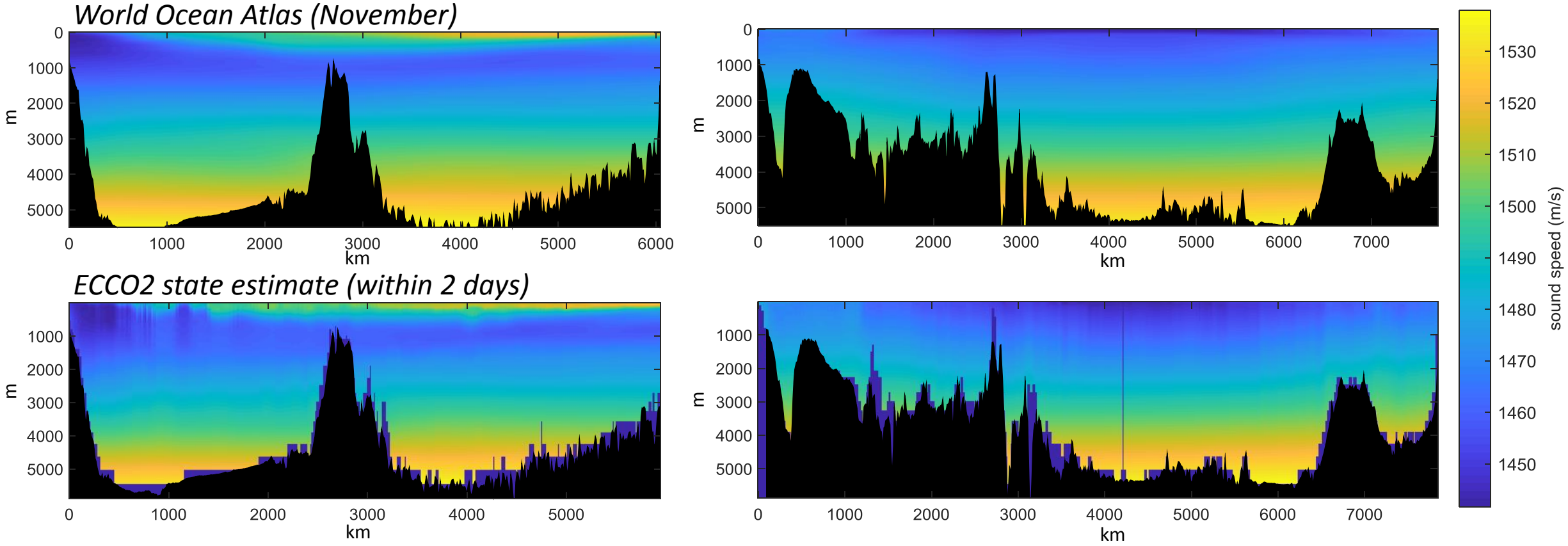




from Munk and Zachariasen, Refraction of Sound from Islands and Seamounts, Journal of Atmospheric and Oceanic Technology (1991)

Potential for CTBTO historical thermometry

While historical event detections on 3 hydroacoustic stations are unlikely, virtual stations built from refracted signals provide a means for tomography in absence of precise documentation of event locations or time



Summary

Propagation modeling, with high quality oceanographic and bathymetric maps, can greatly expand event localization capabilities by:

- identifying dominant modes for signal timing
- ranging via modal dispersion
- constructing virtual stations by considering 3D arrivals

Application to ARA San Juan showed by adding one additional virtual station from a bathymetrically refracted arrival, triangulation to within 1 km

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