A Very Broadband Seismometer Within the IceCube Upgrade

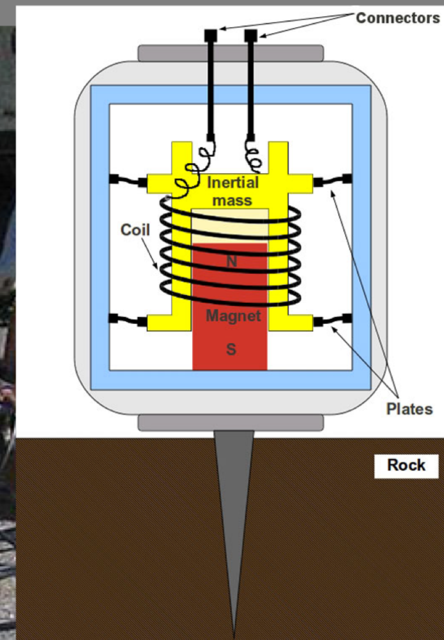
Robert Anthony, Adam Ringler, David Wilson

U.S. Geological Survey

USGS
science for a changing world

IRIS

What do I mean by "very broadband"



Seismometer Response

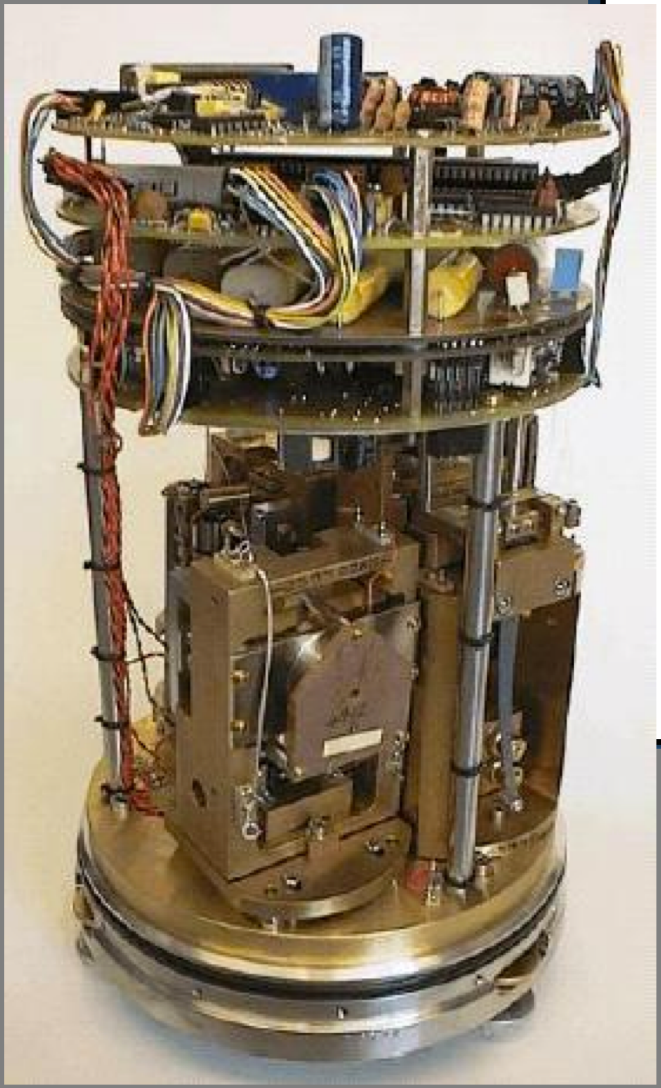
$$x(t) = s(t) \star g(t) \star r(t)$$

Seismogram

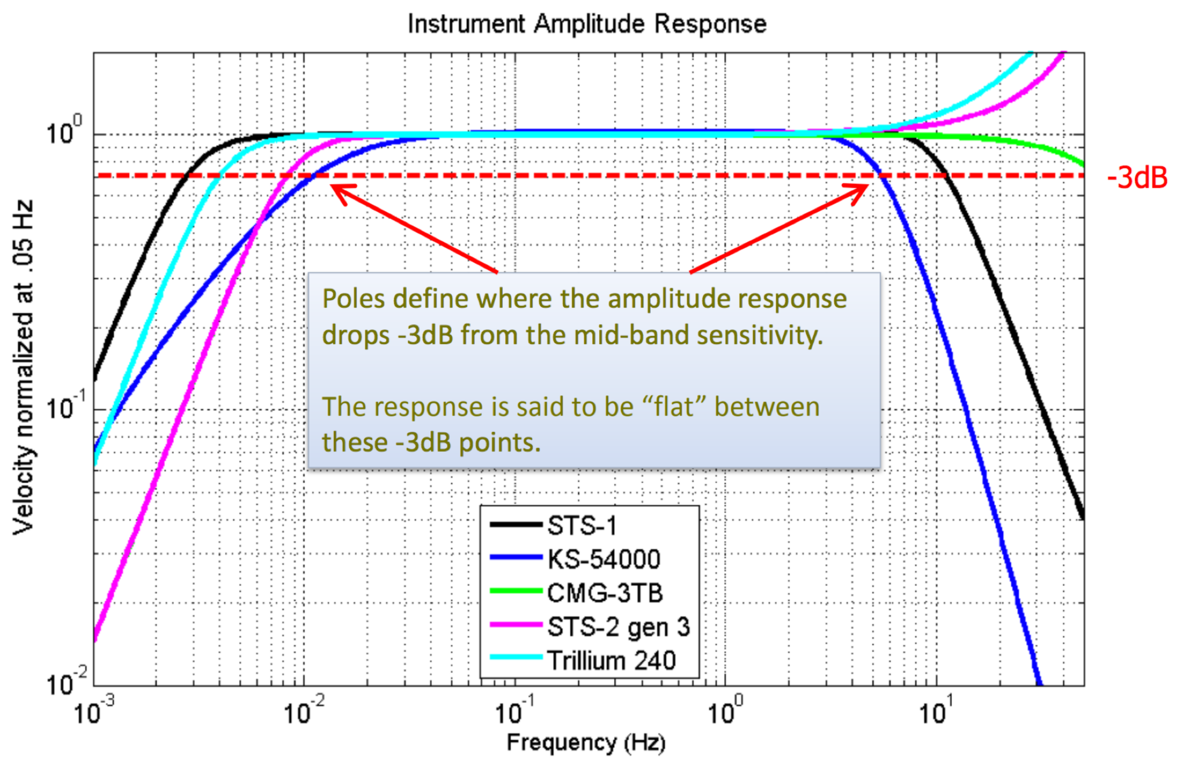
Source

Geologic Structure

- Good for "shallow" (< a few km) imaging surveys – record high-frequency (> 1 Hz) ground motion
- Not good for examining Deep-Earth Structure or monitoring global seismicity



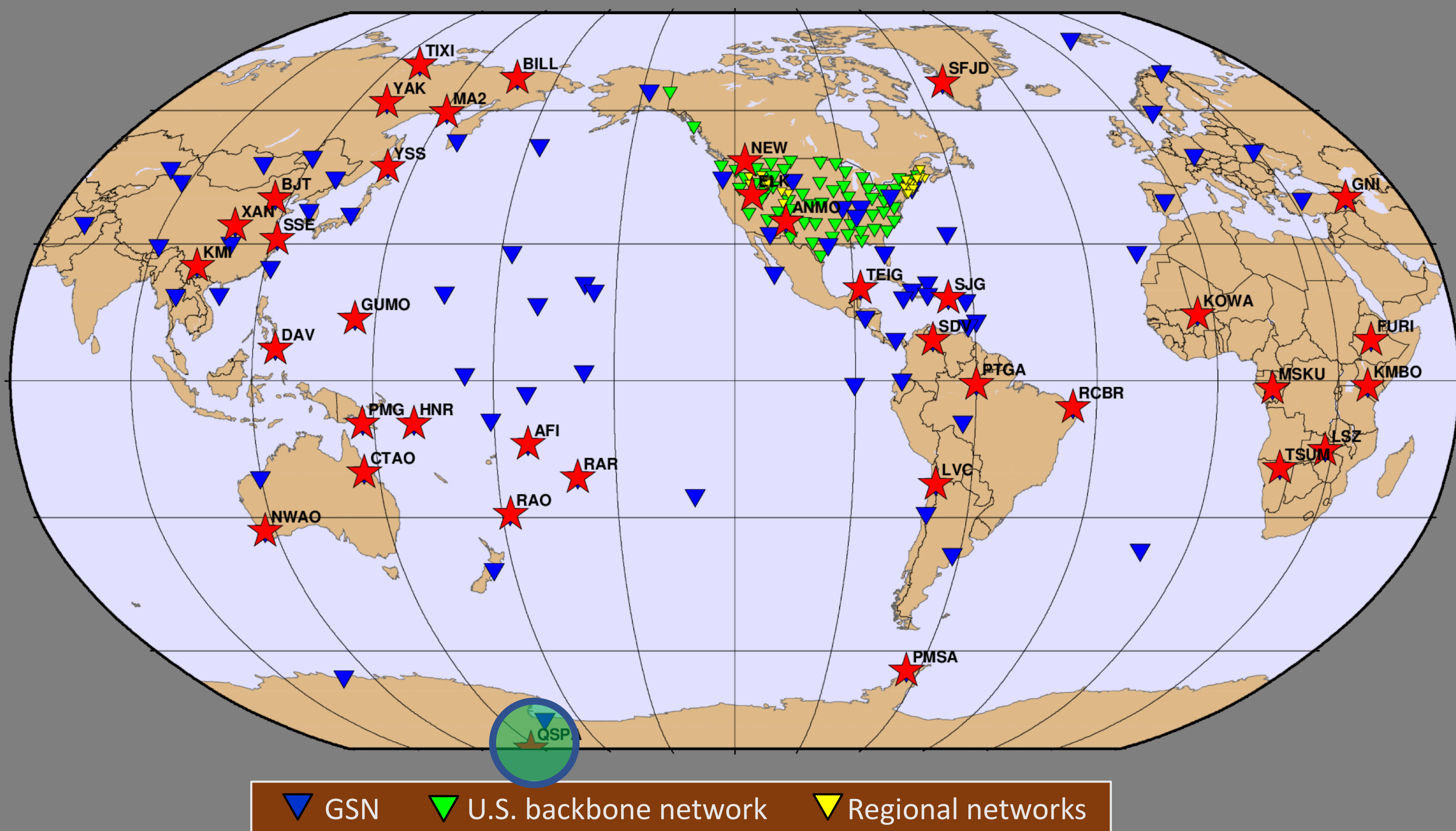
Guralp CMG-3T (we have 2 of these at South Pole)



- "Force Feedback Seismometer" – Instrument response function is tuned by Op-Amp style feedback loop (not mechanical resonance frequency)
- Can observe ground motions of 24 hours period*!

*Disclaimer: Ground motions must be large (e.g. solid Earth tides at mid-latitudes) and instrument must be isolated from non-seismic sources. We'll get to these!

Very Broadband Seismometers Operated by USGS



USGS-ASL has MOU's and agreements with 54 different countries.

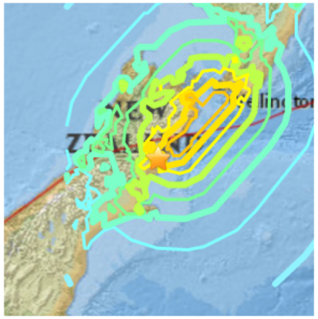
All data publicly available and distributed through an NSF-funded facility

USGS Event Pages

M7.8 - 53km NNE of Amberley, New Zealand

2016-11-13 11:02:56 UTC | 42.757°S 173.077°E | 23.0 km depth

Interactive Map



Contributed by US [2]

Regional Information

Contributed by US [2]

Felt Report - Tell Us!

0 0 0 5 4 8

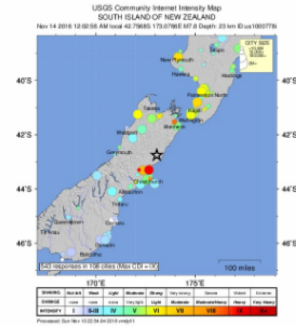
Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

Did You Feel It?

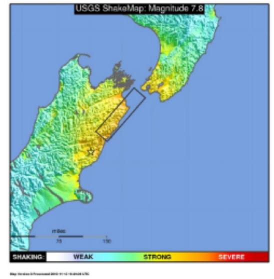
IX



Contributed by US [2]

ShakeMap

VIII

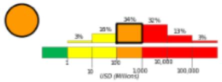


Contributed by US [2]

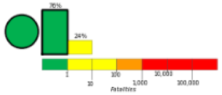
PAGER

ORANGE

Estimated Economic Losses



Estimated Fatalities



Contributed by US [2]

Origin

Review Status
REVIEWED
Magnitude
7.8 mww
Depth
23.0 km
Time
2016-11-13
11:02:56.970 (UTC)

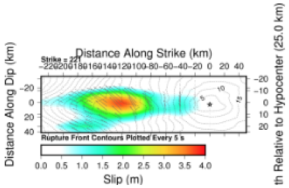
Contributed by US [2]

Moment Tensor

Contributed by US [2]

Finite Fault

Cross-section of slip distribution



Contributed by US [2]

Tsunami

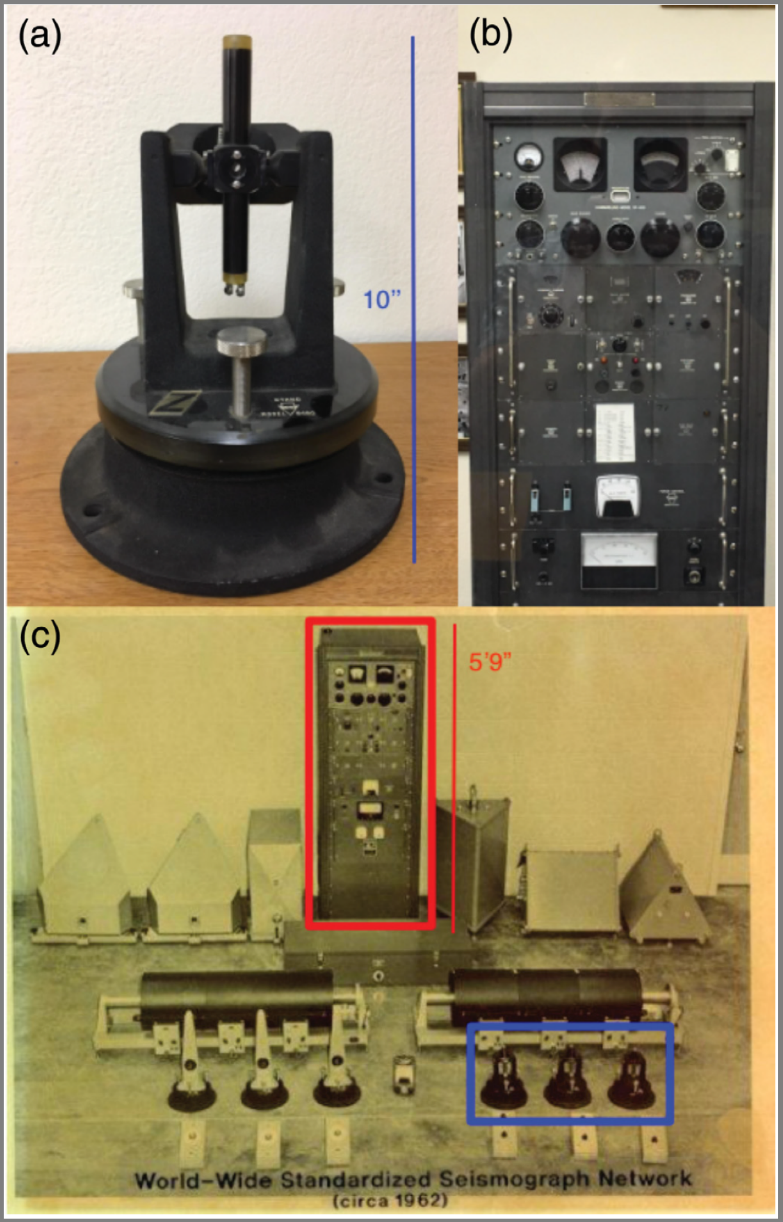
To view any current tsunami advisories for this and other events, please visit http://www.tsunami.gov.

NOAA

Lynda Lastowka, Jeremy Fee, Eric Martinez, HAZDEV Team

Brief History of Seismic Observations at South Pole

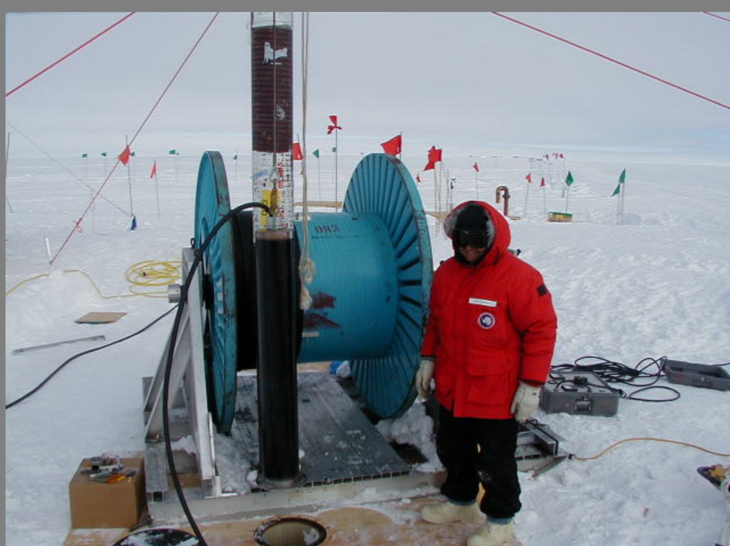
- 1957 – Installed 2 horizontal component and 1 vertical component seismometer in association with 1957-1958 International Polar Year efforts
- 1963 – Converted to a World-Wide Standardized Seismographic Network (WWSSN) station "SPA"
- ~1975 – Station moves when the dome is constructed

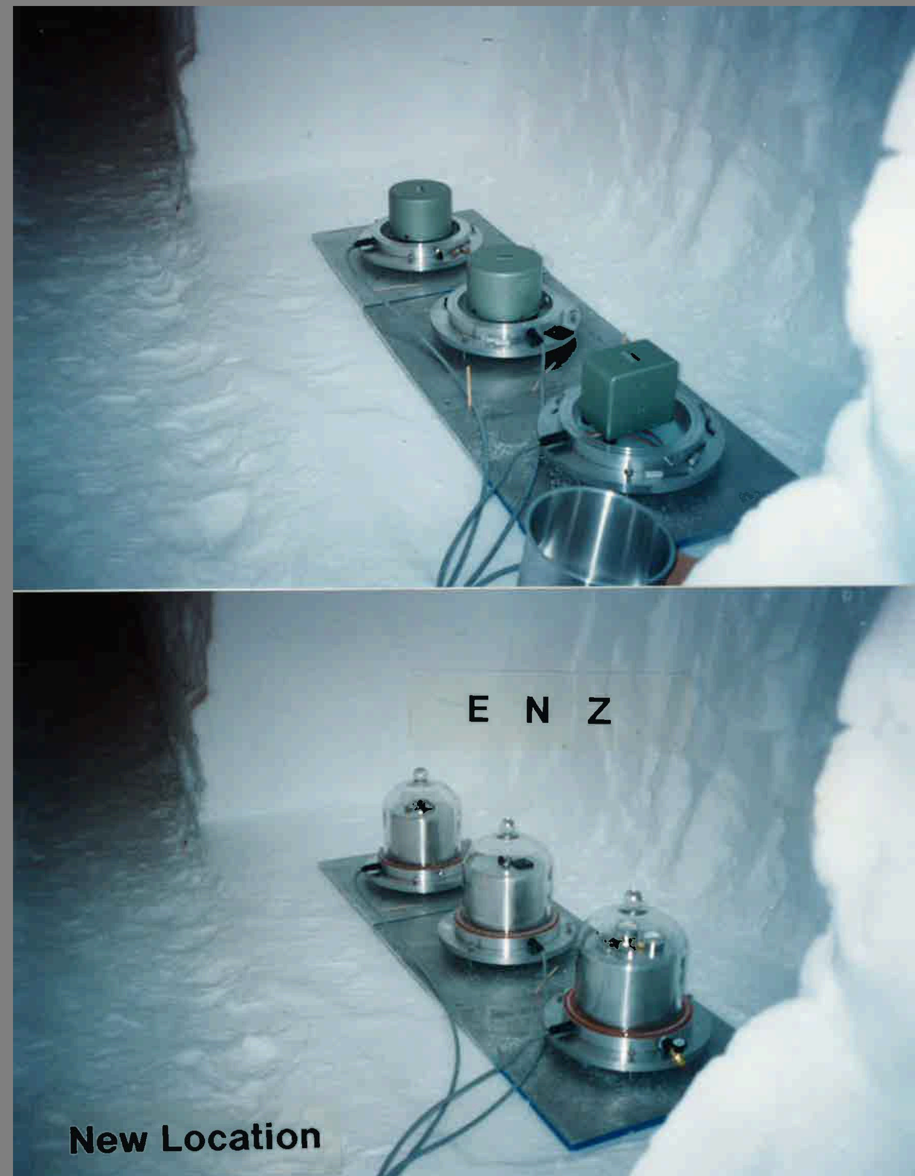


Brief History of Seismic Observations at South Pole

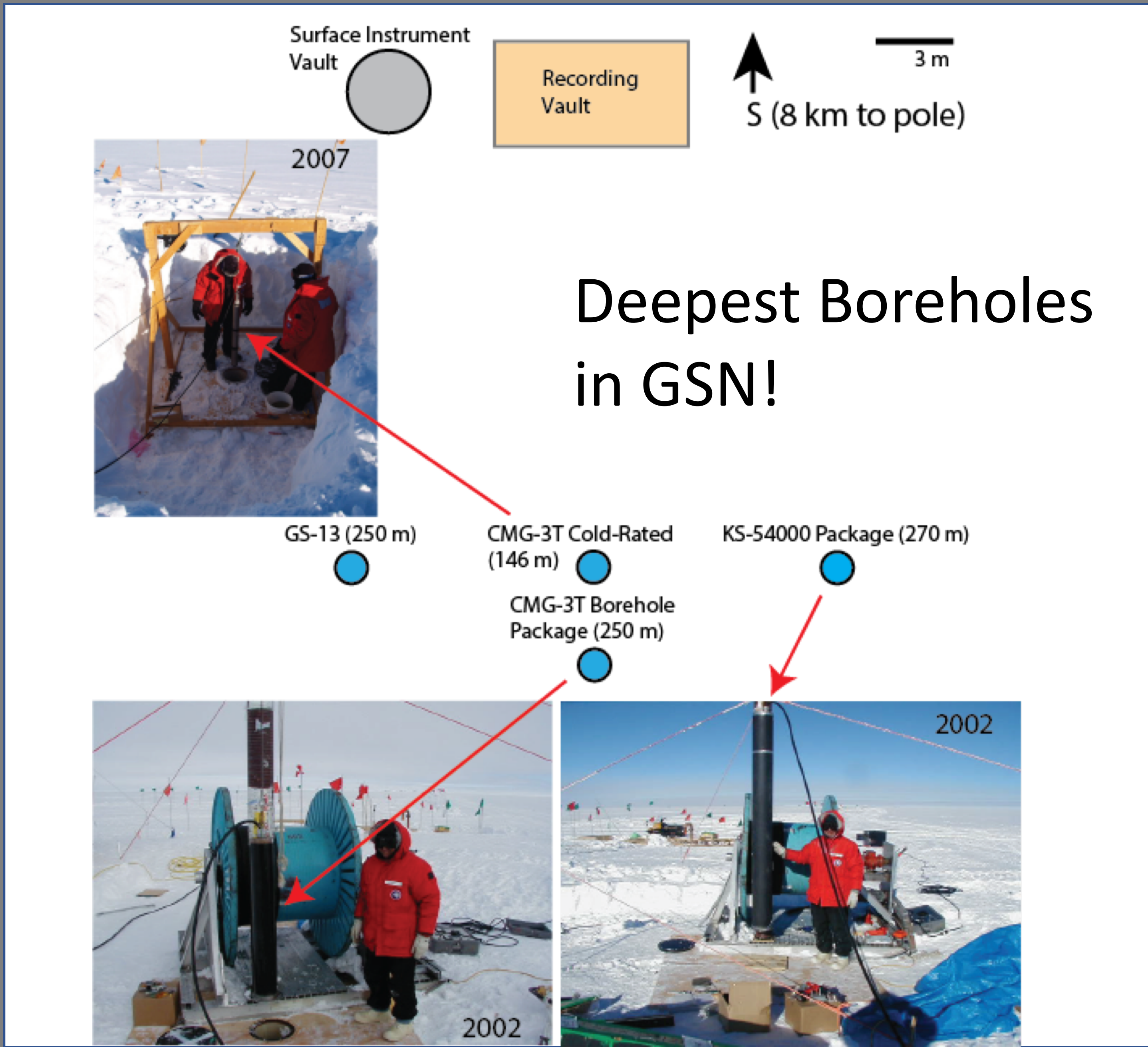
- 1991 – Station incorporated into Global Seismographic Network (GSN). Sensors replaced with force-feedback seismometers, GPS timing (1993), Digital Records

- 2003 - Station moved 8 km to the SPRESSO site “QSPA”. Primary and secondary sensors in ~250 m boreholes in the Icecap.



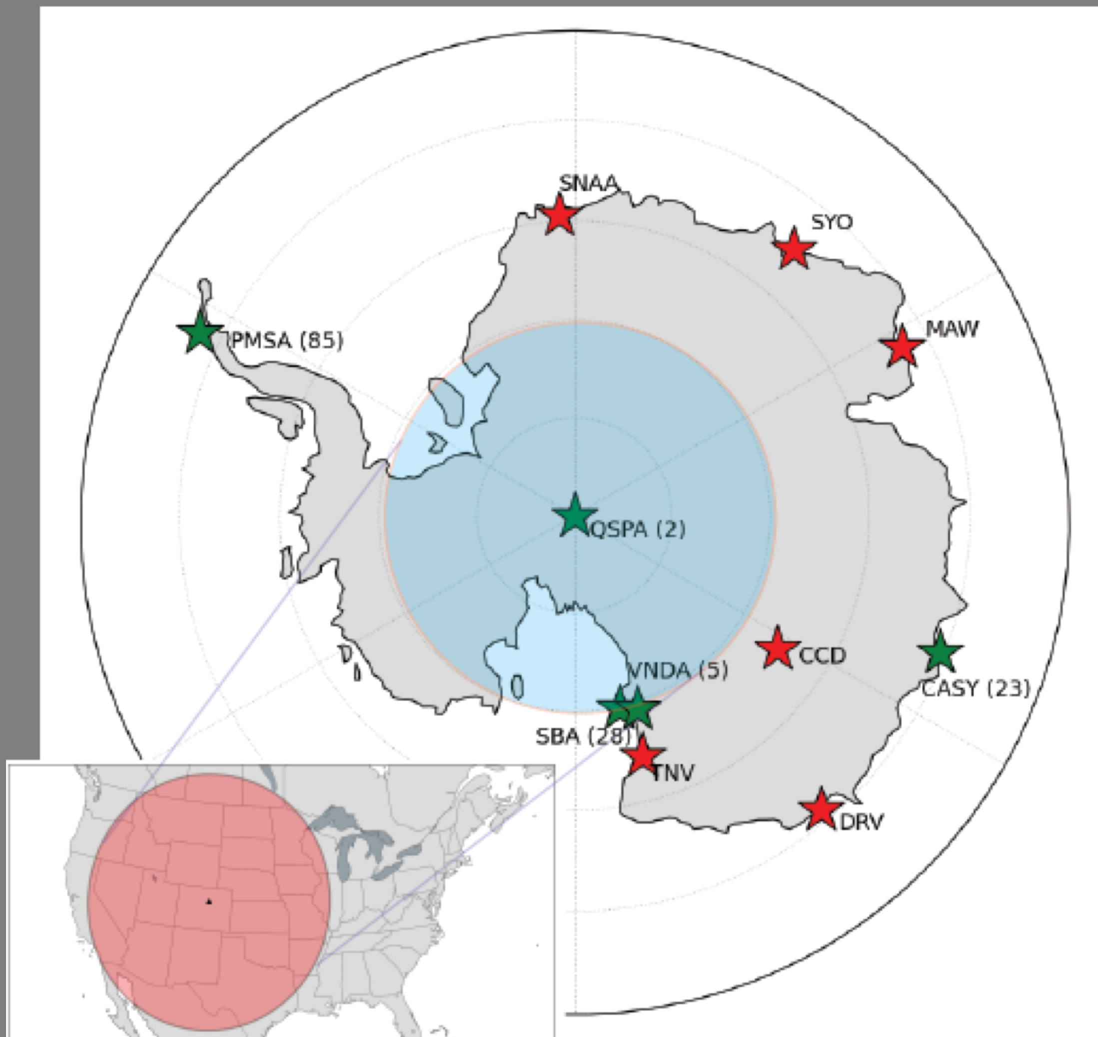


Construction of QSPA



Importance of Seismic Observations at South Pole

1) Fills a large hole in global seismic station coverage

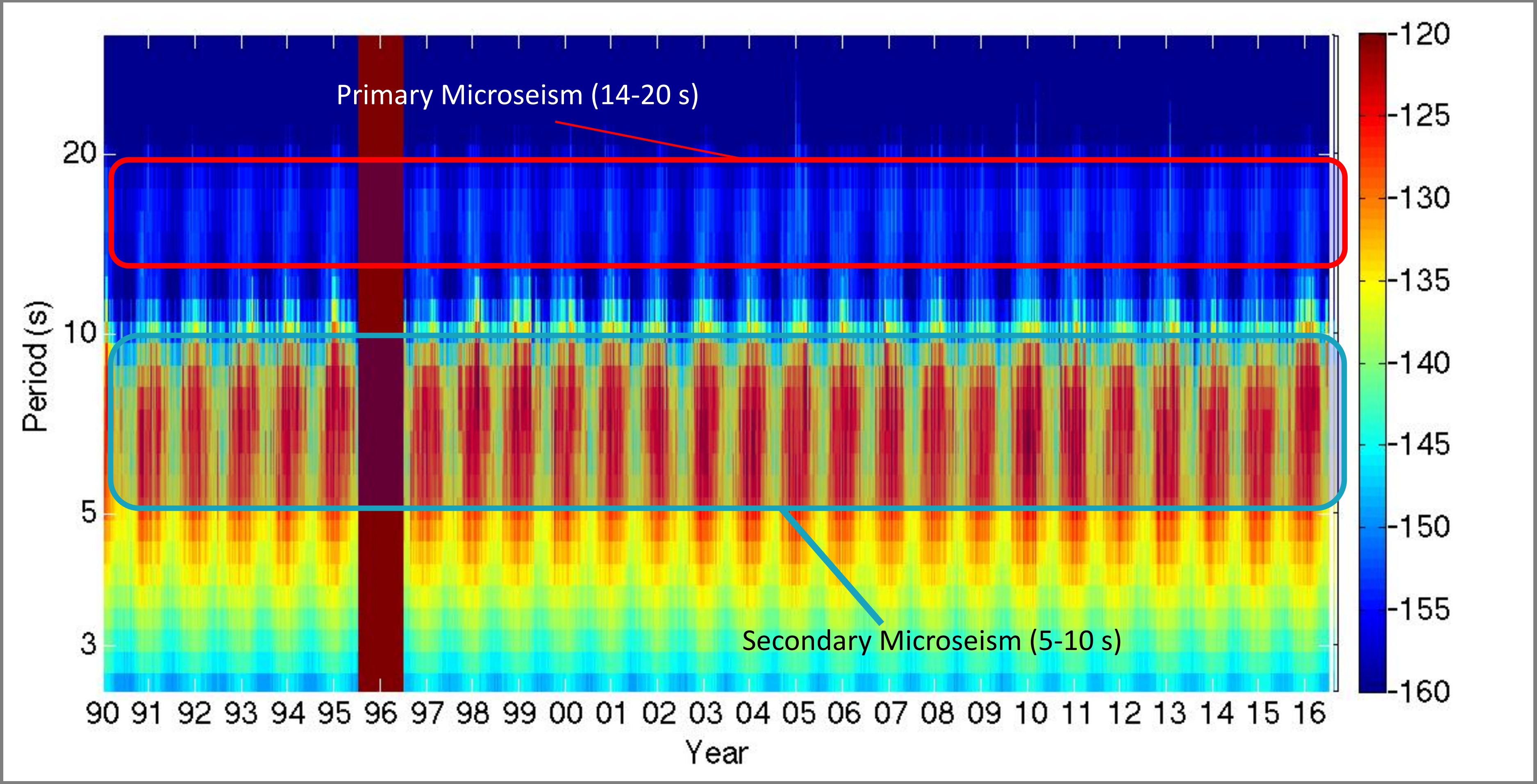


Of 150 GSN stations, QSPA is used the 2nd most often to identify and characterize global earthquakes.

Cool Aside – VNDA and QSPA were used to detect tidally-modulated stick-slip motion on the Whillans Ice Stream (Wiens et al., 2008; Nature)

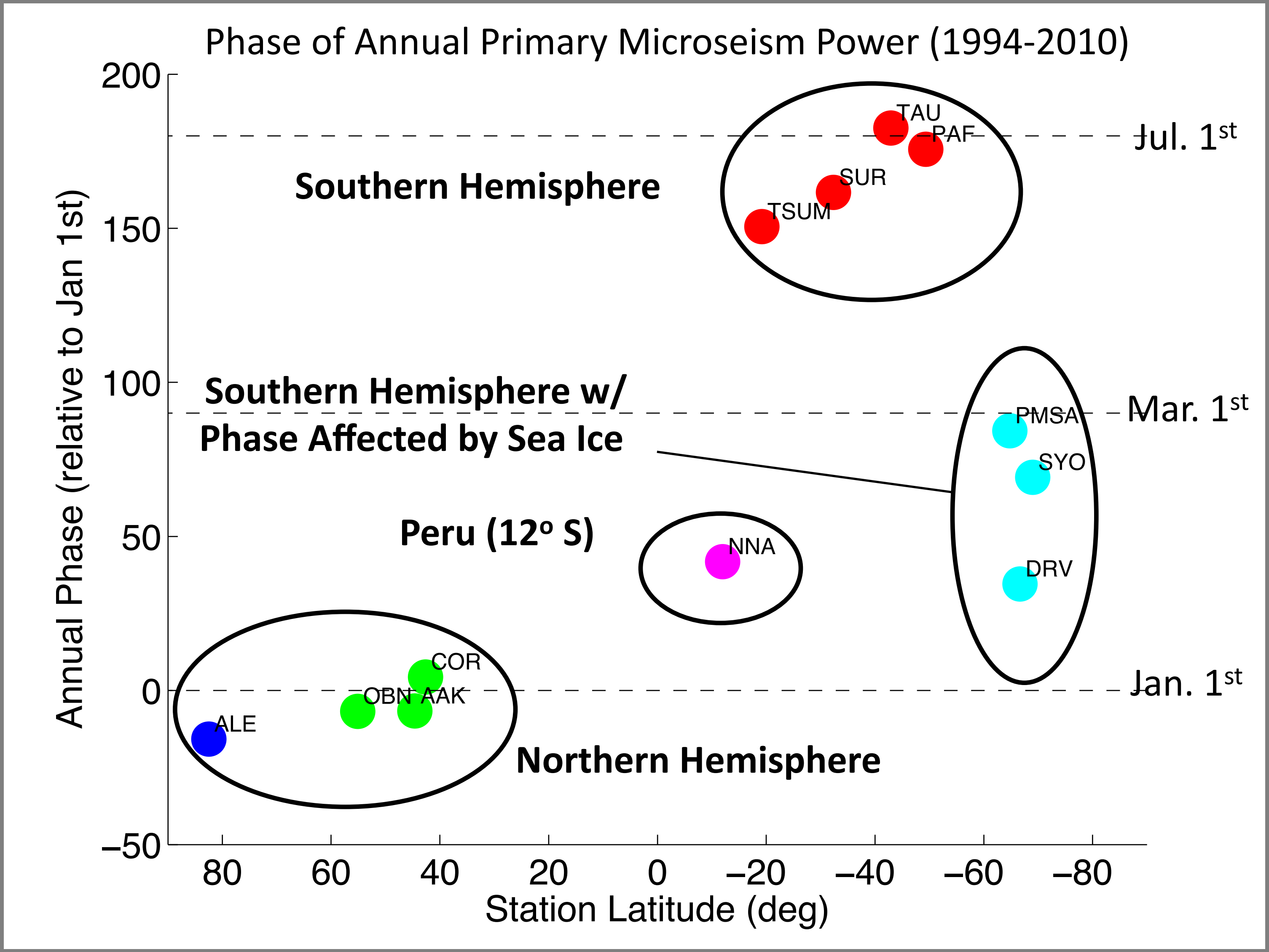
Anthony et al., (in Review)

2) "Long" (63 years) History of operation makes seismic data from South Pole suited for use as a climate proxy prior to the satellite era.

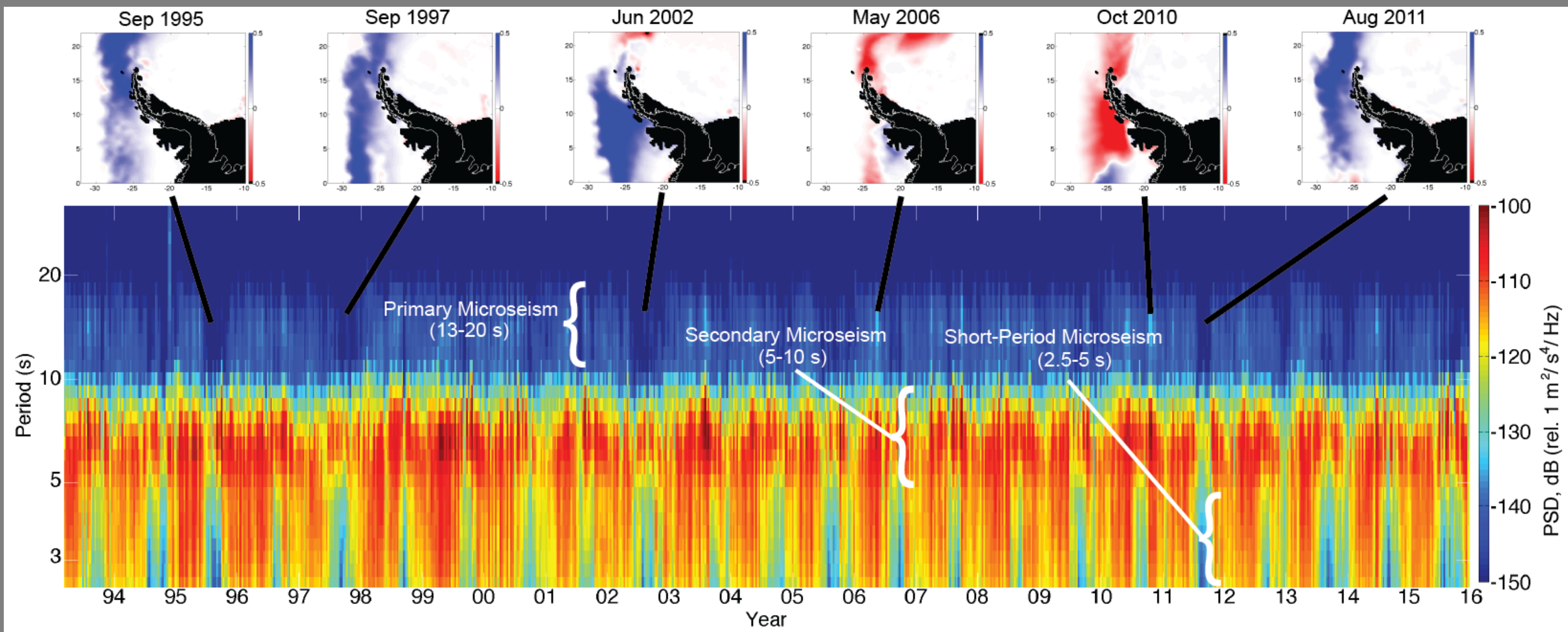


***ANMO* (Albuquerque, New Mexico)**

Annual Phase of Primary Microseism Power at Selected Global Sites

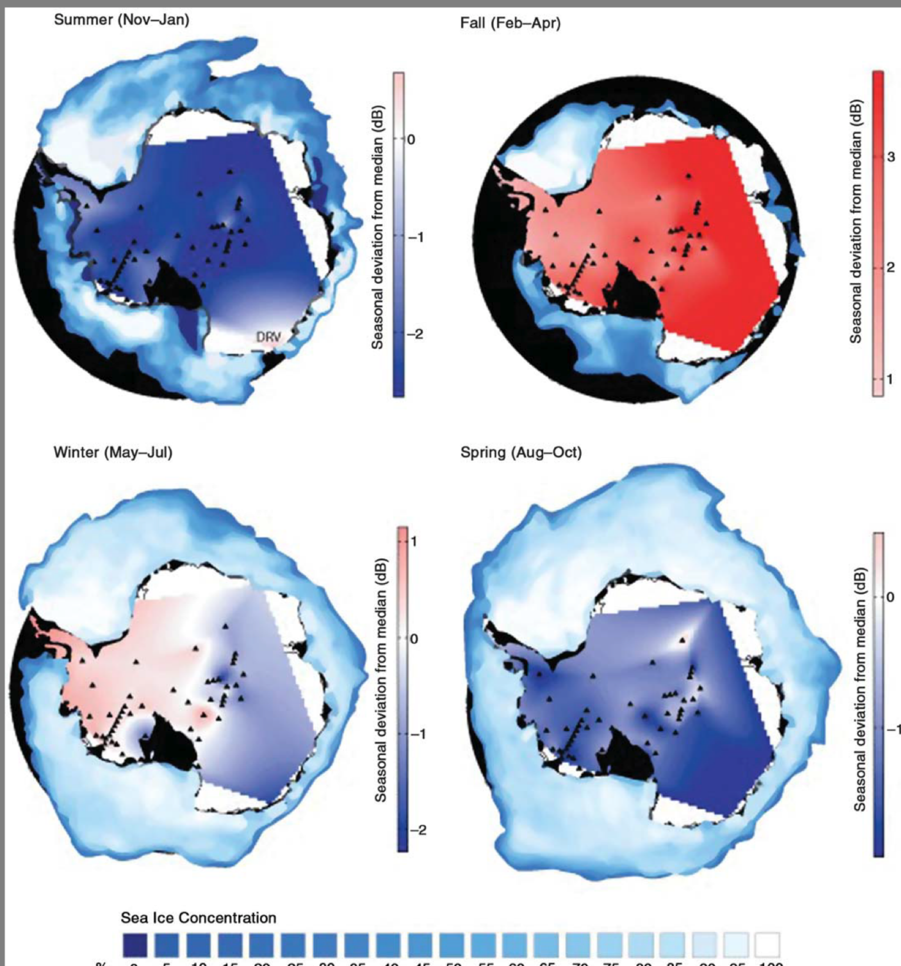


Sea ice anomalies on the Antarctic Peninsula and seismic signals

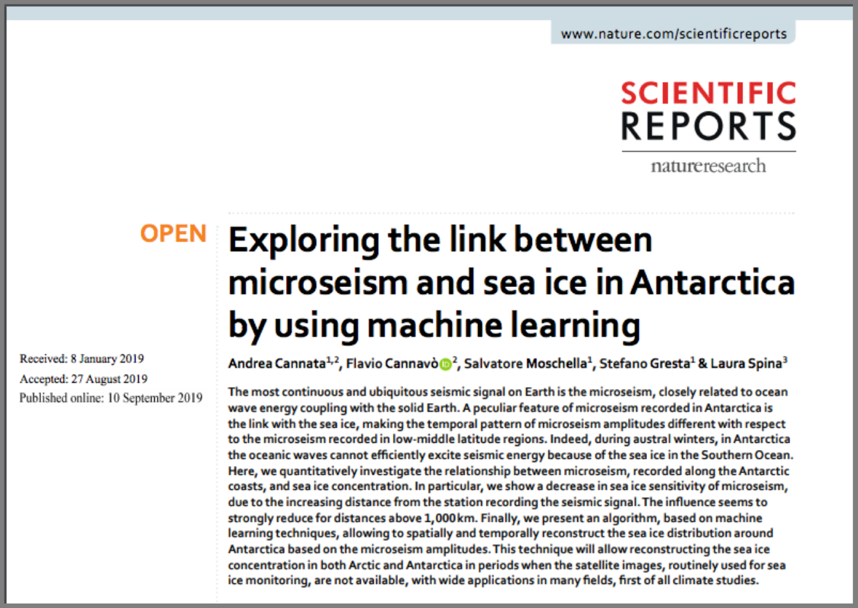


Anthony et al., SRL (2017)

More Sea Ice and Seismic Signals



Anthony et al., SRL (2015)



www.nature.com/scientificreports

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Exploring the link between microseism and sea ice in Antarctica by using machine learning

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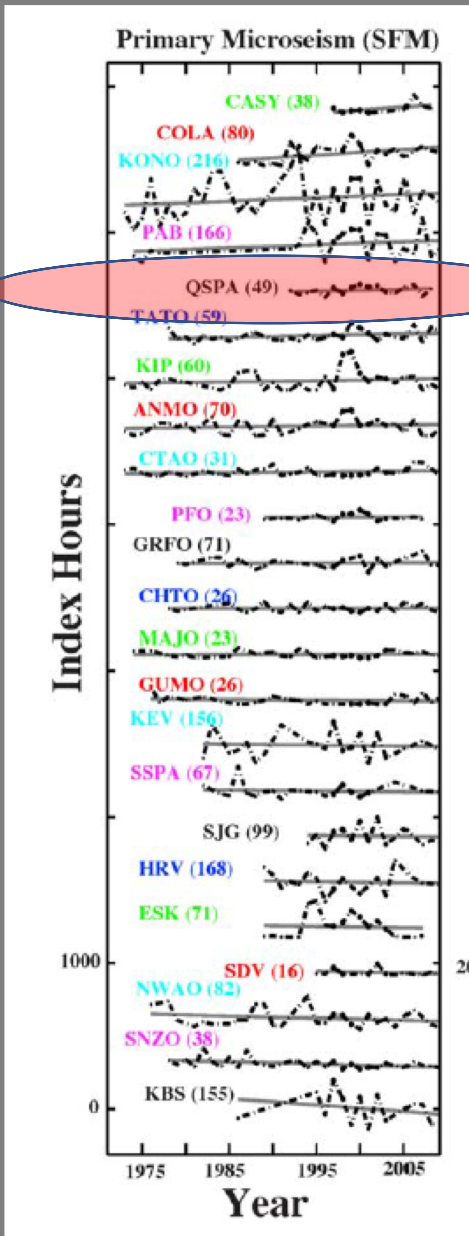
Andrea Cannata[1,2], Flavio Cannavò[2], Salvatore Moschella[1], Stefano Gresta[1] & Laura Spina[3]

The most continuous and ubiquitous seismic signal on Earth is the microseism, closely related to ocean wave energy coupling with the solid Earth. A peculiar feature of microseism recorded in Antarctica is the link with the sea ice, making the temporal pattern of microseism amplitudes different with respect to the microseism recorded in low-middle latitude regions. Indeed, during austral winters, in Antarctica the oceanic waves cannot efficiently excite seismic energy because of the sea ice in the Southern Ocean. Here, we quantitatively investigate the relationship between microseism, recorded along the Antarctic coasts, and sea ice concentration. In particular, we show a decrease in sea ice sensitivity of microseism, due to the increasing distance from the station recording the seismic signal. The influence seems to strongly reduce for distances above 1,000 km. Finally, we present an algorithm, based on machine learning techniques, allowing to spatially and temporally reconstruct the sea ice distribution around Antarctica based on the microseism amplitudes. This technique will allow reconstructing the sea ice concentration in both Arctic and Antarctica in periods when the satellite images, routinely used for sea ice monitoring, are not available, with wide applications in many fields, first of all climate studies.

Canata et al., Sci. Rept. (2019)

What can we say about sea ice concentration and extent from broadband seismic data?



Focus Section: Historical Seismograms

On the Extraction of Microseismic Ground Motion from Analog Seismograms for the Validation of Ocean-Climate Models

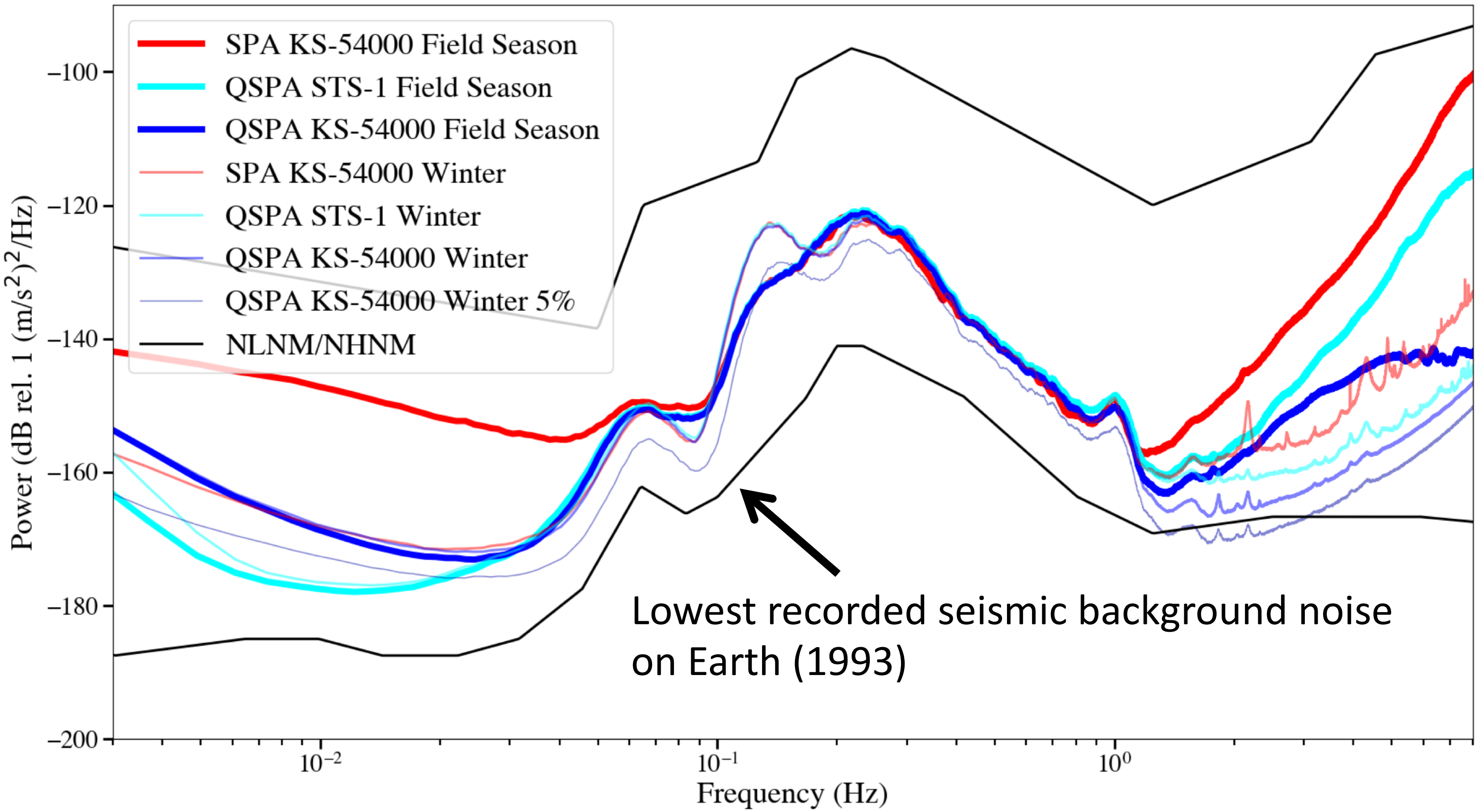
Thomas Lecocq*[1], Fabrice Ardhuin[2], Fabienne Collin[1], and Thierry Camelbeeck[1]

Lecocq et al., SRL (2020)

How has wave and storm activity changed in the Southern Ocean in the last 65 years?

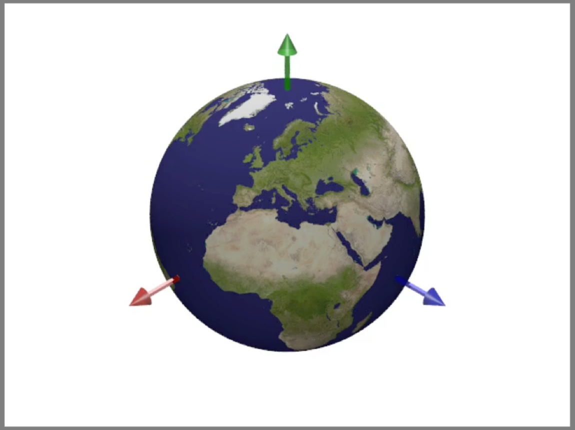
Aster et al., GRL (2010)

3) The quietest station on Earth at High-Frequencies*

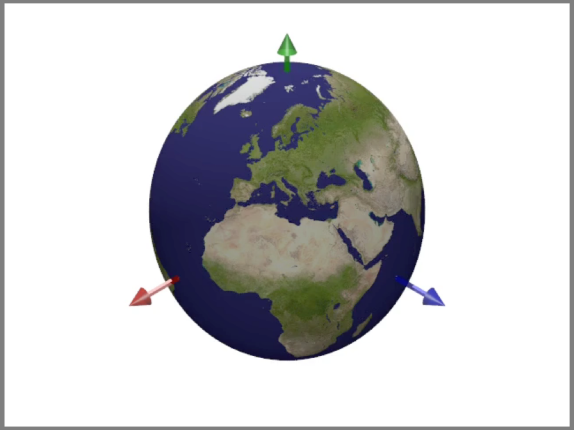


*Disclaimer: During the winter. Definitely not during neutrino-detector construction season.

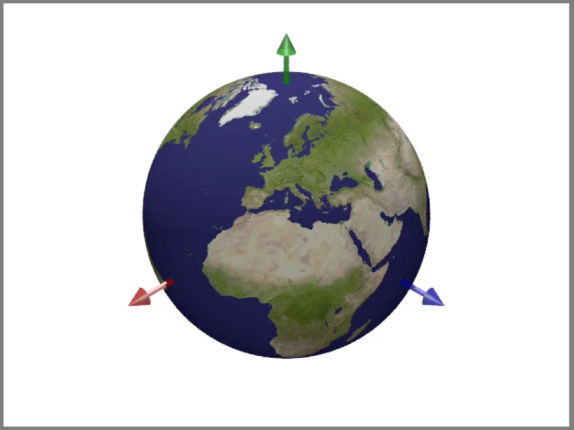
4) Unique location to observe Earth's free oscillations and isolate ocean tide loading signals



$_0S_0$: ~20 Minutes



$_0S_2$: ~54 Minutes

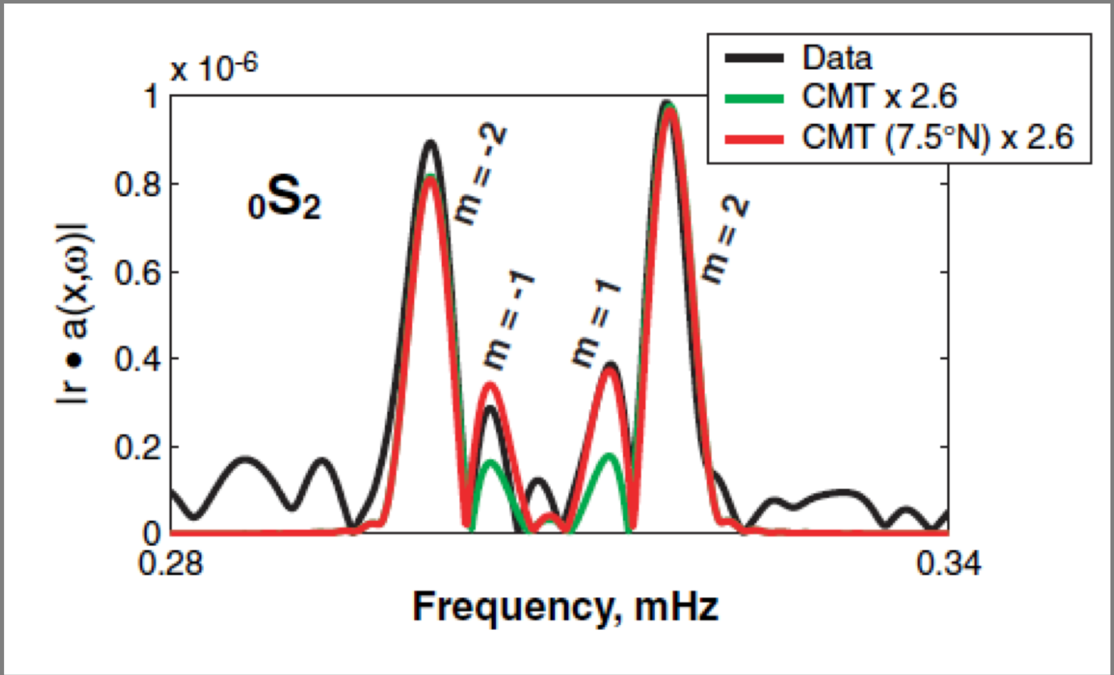


$_0T_2$: ~44 Minutes

- Can constrain location, moment tensor, and magnitude of large earthquakes
- One of the few ways to get at density structure of the deep-earth
  - Conclusively verified that the inner core is solid
  - Demonstrated Anisotropy of the Outer Core

Animations From: https://saviot.cnrs.fr/terre/index.en.html

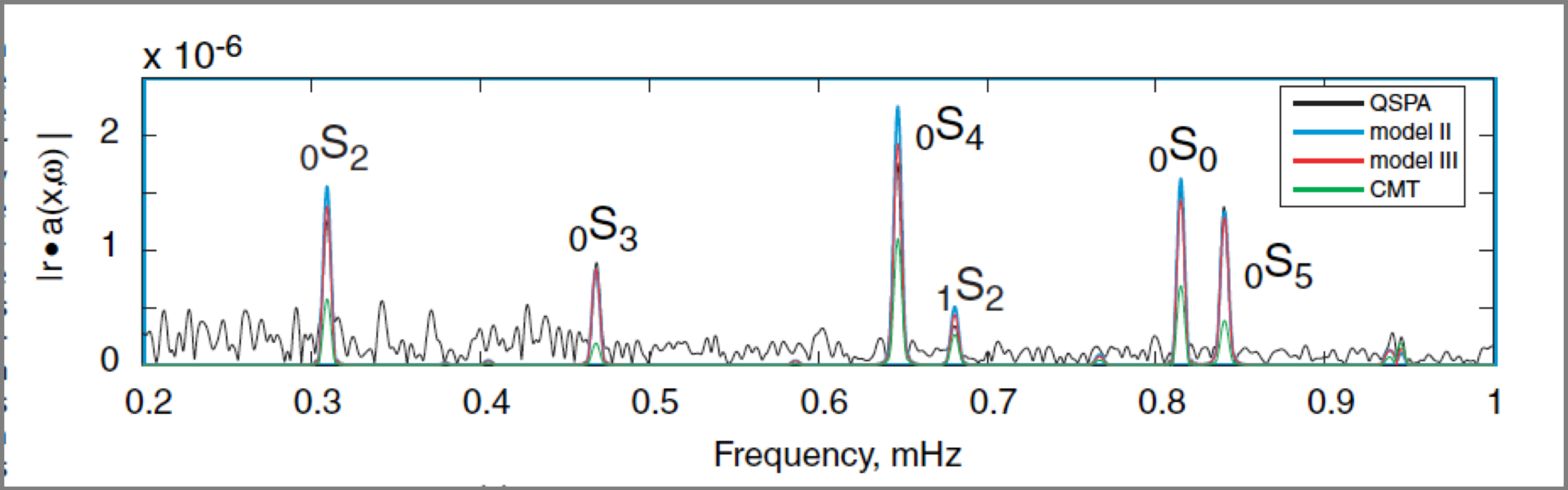
Normal Mode Splitting



${}_0S_2$ has *m = 2l +1* degeneracies. Coupling of modes with Earth's rotation causes the frequencies to split (Data Recorded in California from the M 9.1 Sumatra-Andaman Earthquake)

Park et al., Science (2005)

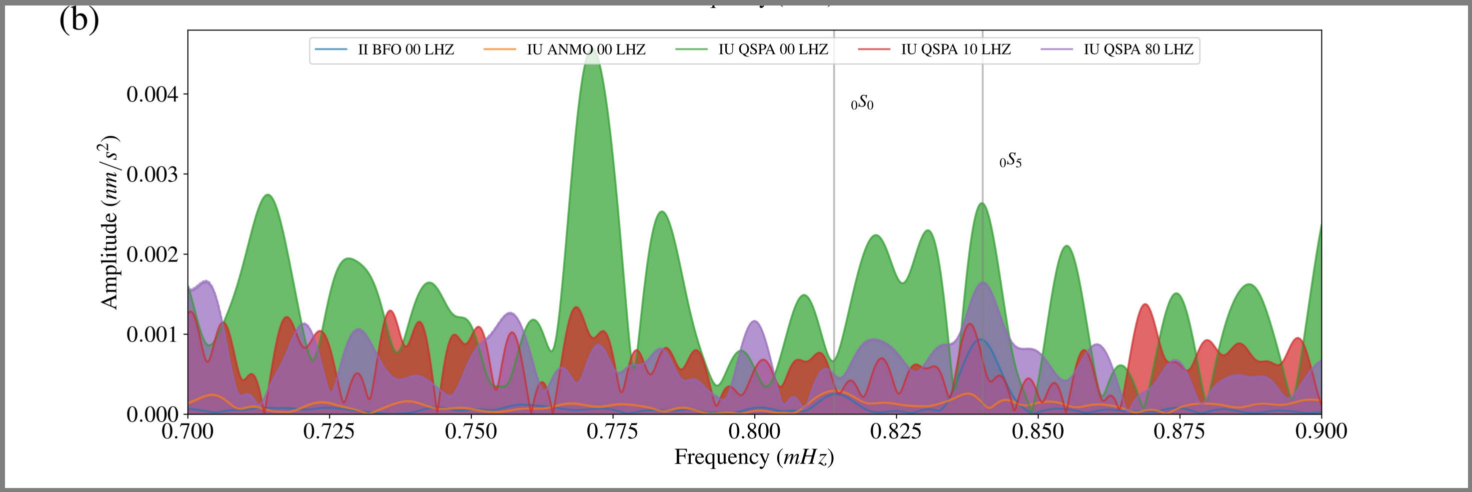
No Normal Mode Splitting at South Pole



- South Pole is the only place on Earth that the m=0 singlets can be isolated
- Some singlets, such as the inner core sensitive ${}_3S_2$ have never been observed
  - Possibly due lack of low-noise records at South Pole

Park et al., Science (2005)

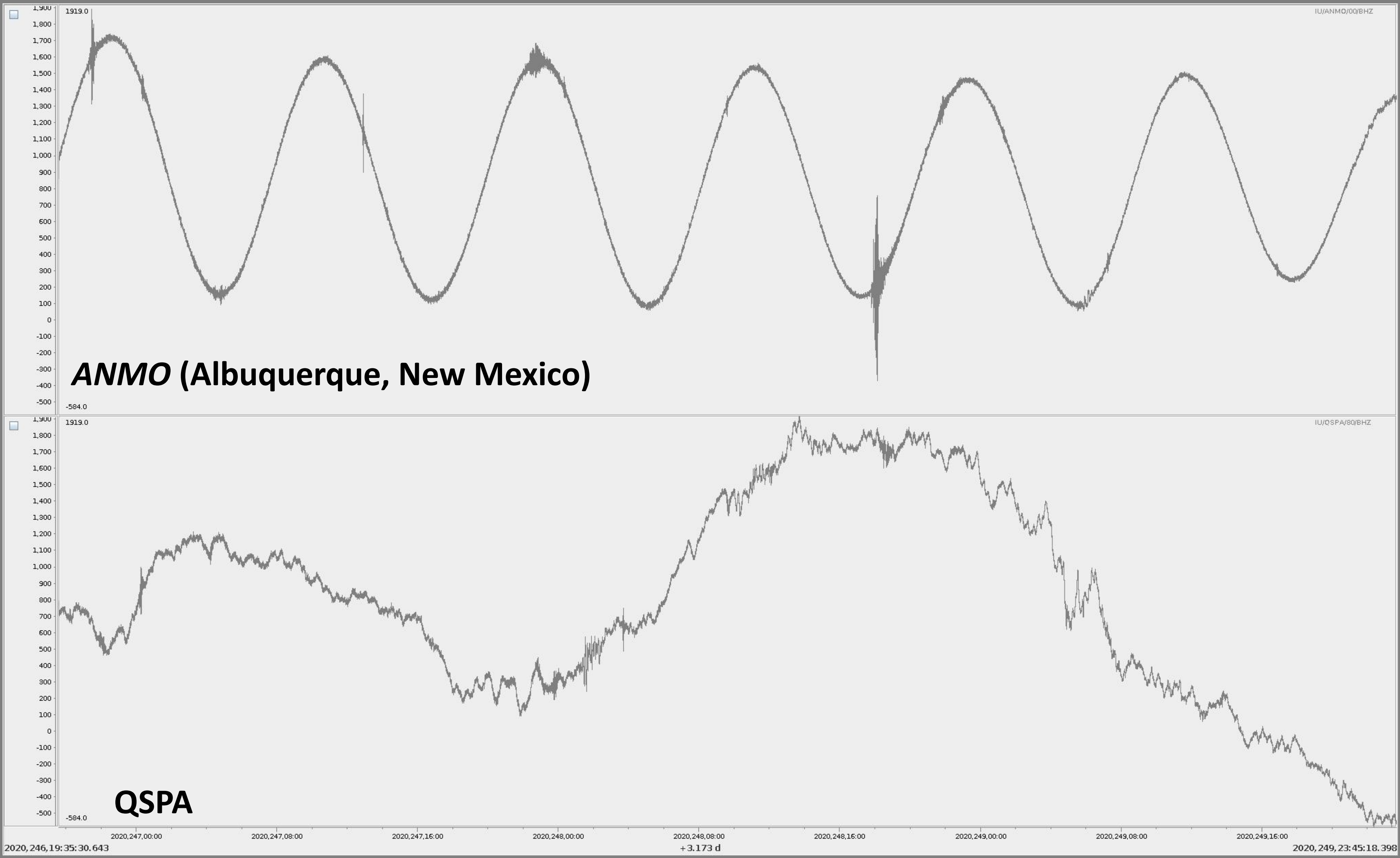
Current Sensors at South Pole are too noisy to observe normal modes



Normal Mode Spectra after the 2020 M 8.2 Fiji earthquake. $_0S_0$ should be the same amplitude for all stations but could not be observed at any station due to instrument noise.

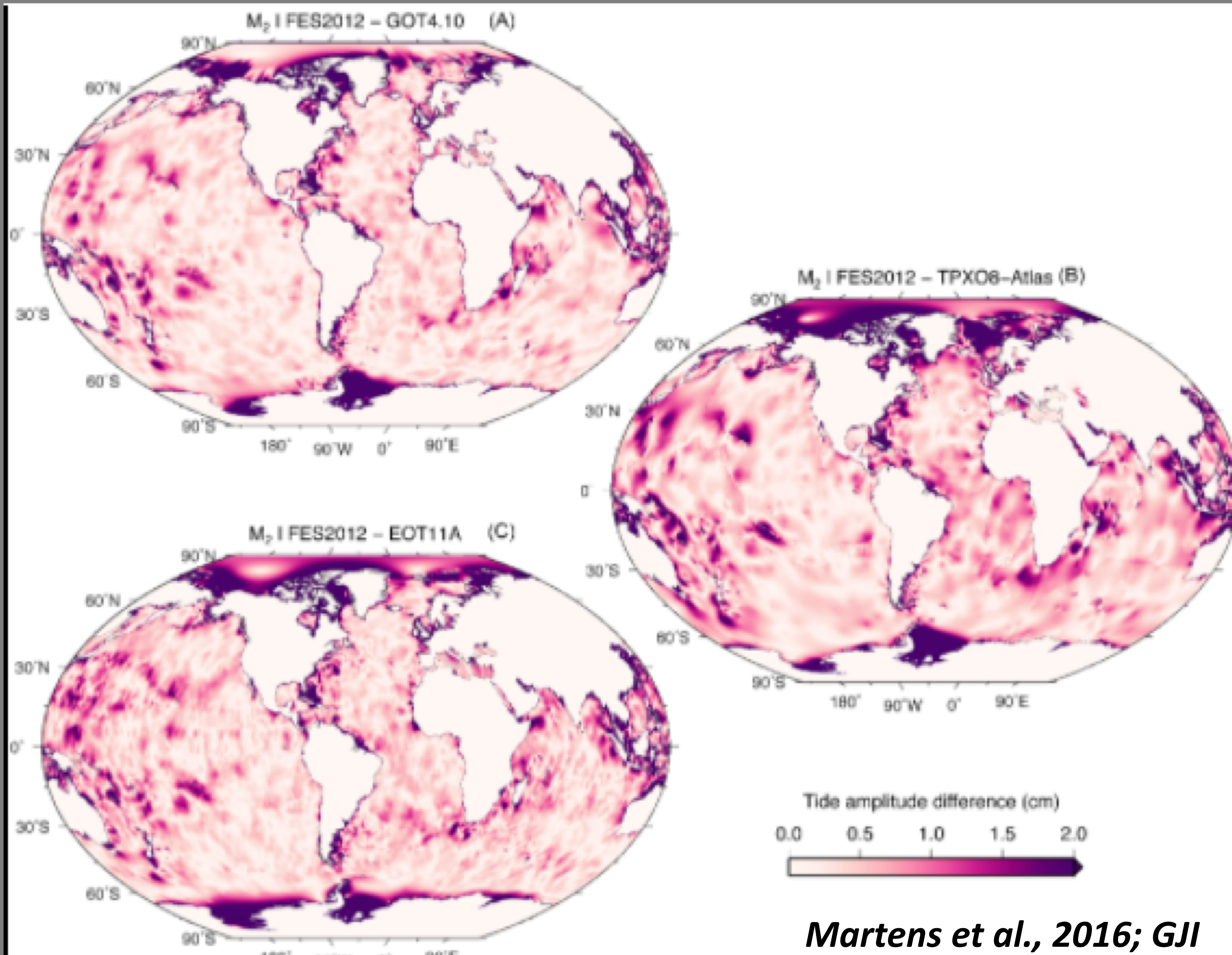
Anthony et al., (in Review)

No solid Earth tides at South Pole

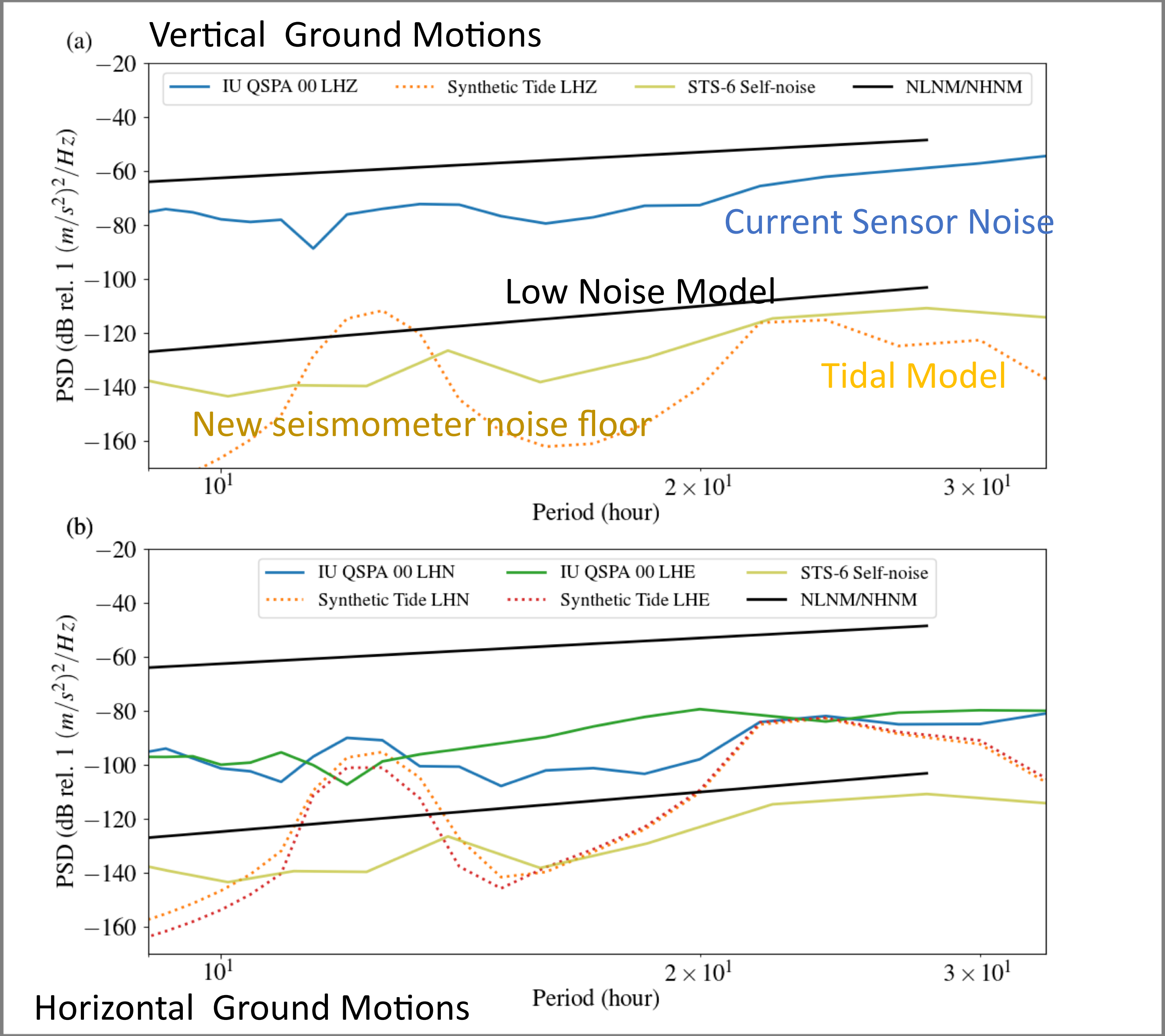


3 Days of Data

Largest Uncertainty in Ocean Tide Models is Under Ice Shelves

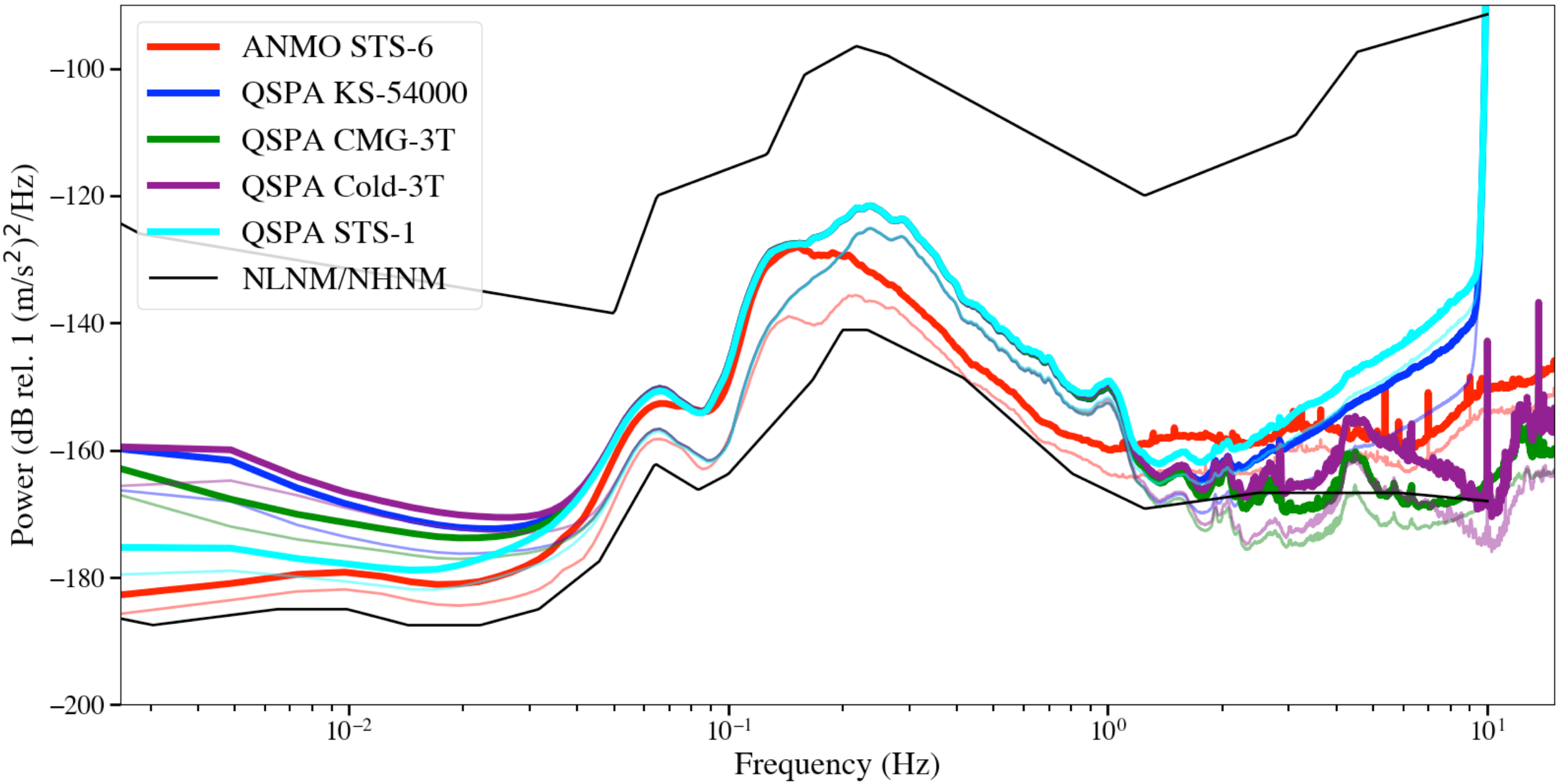


Martens et al., 2016; GJI



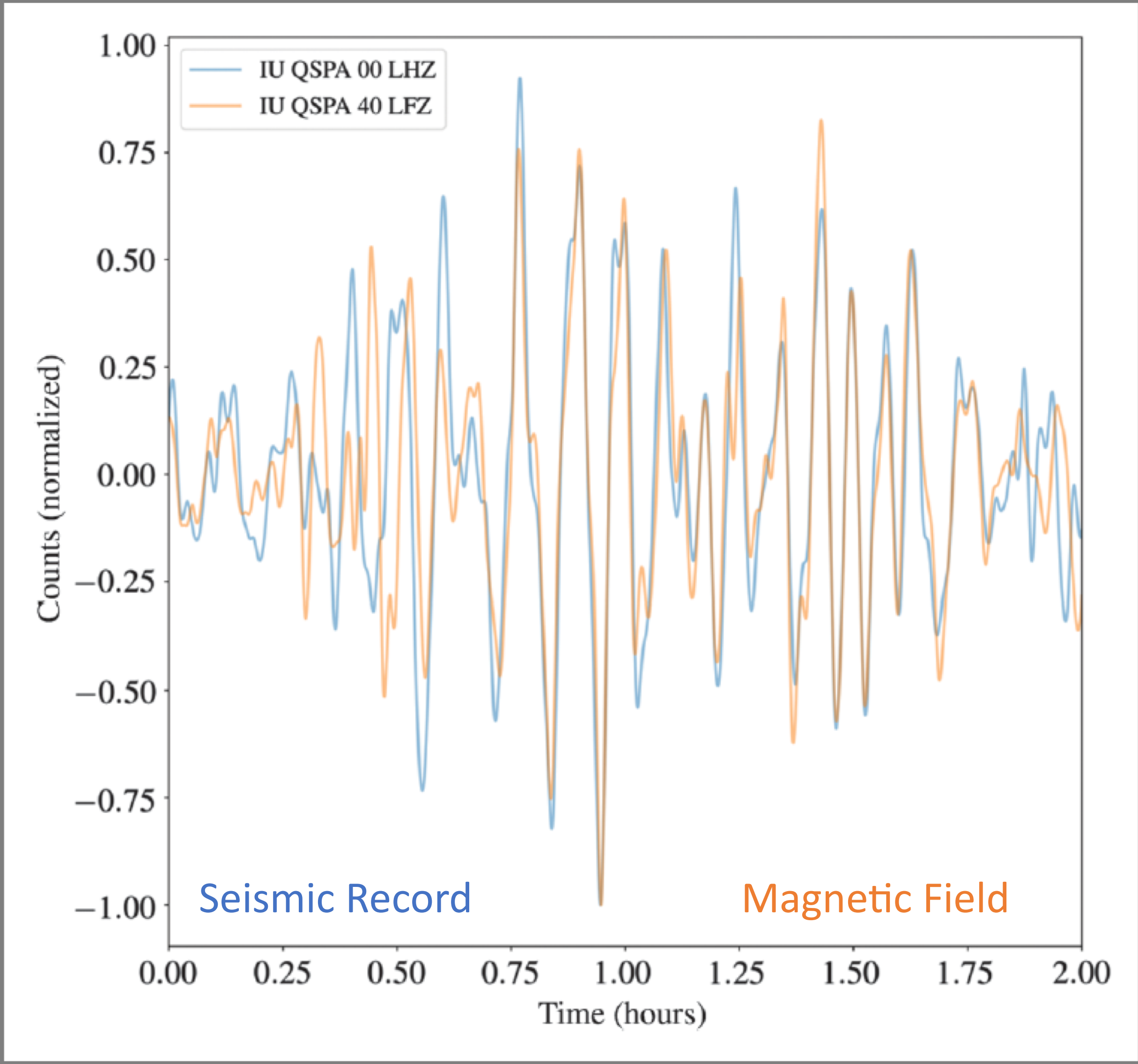
Anthony et al., (in Review)

Why are the borehole sensors at South Pole so bad at long-periods?

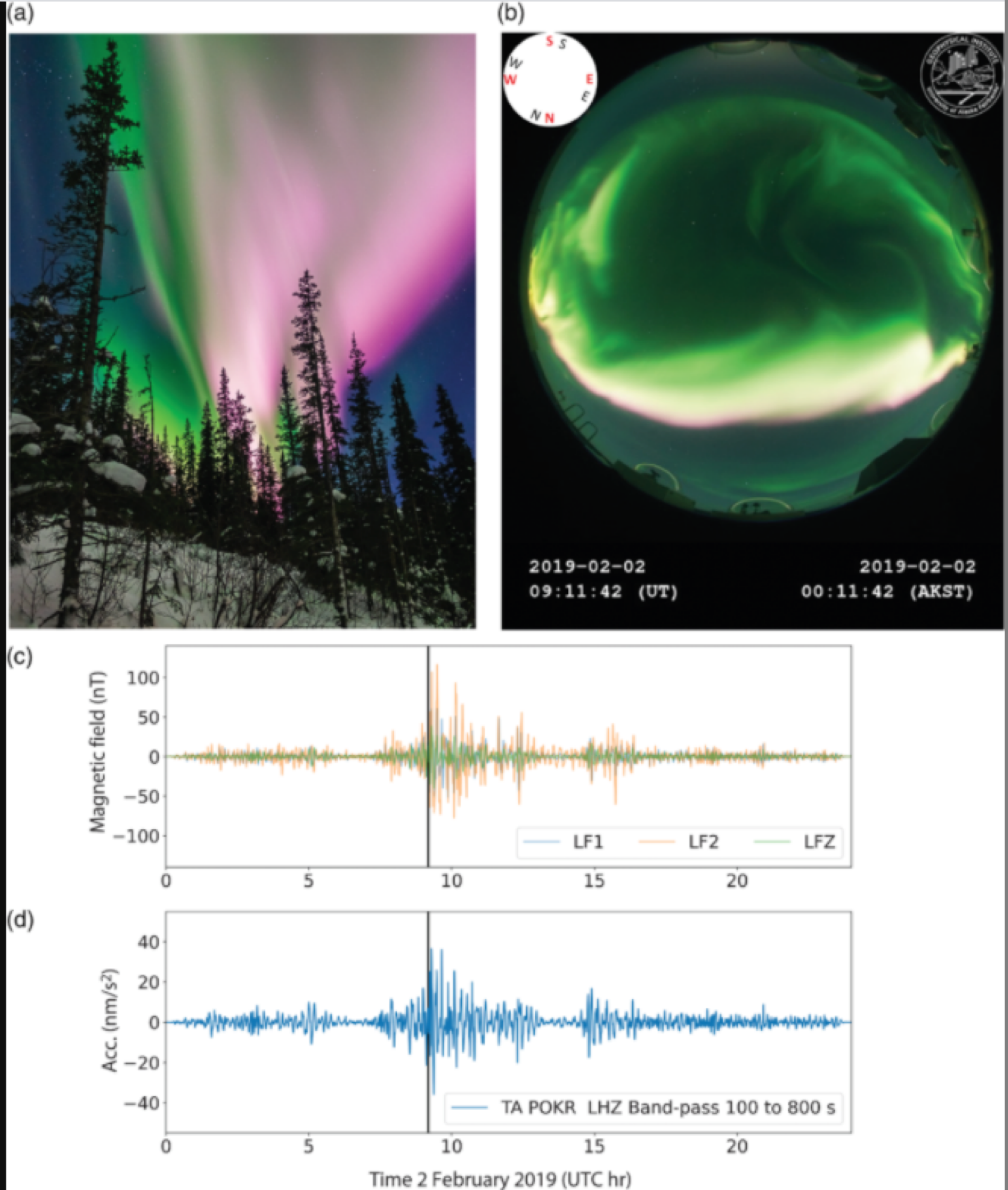


Anthony et al., (in Review)

Answer: Because it's mostly recording magnetic field changes and not ground motion between 200-2000s

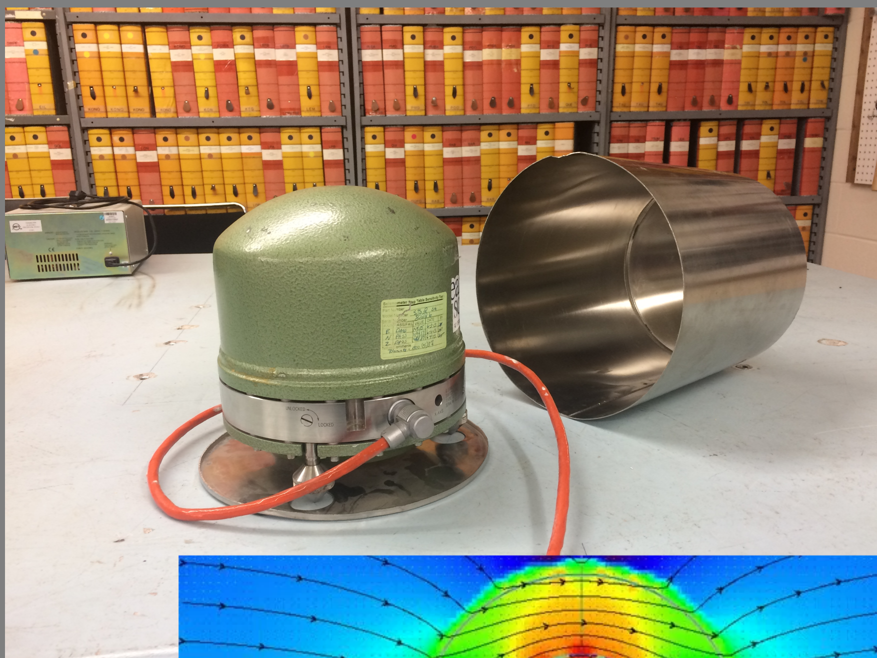


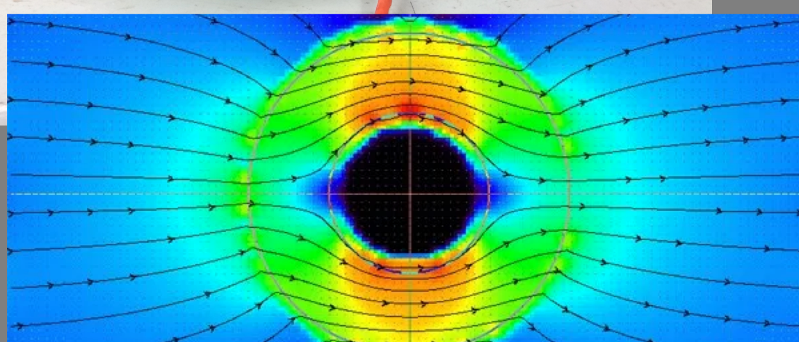
Ringler and Bastien, 2020; SRL



Ringler et al, 2020; SRL

Answer to this problem: Shield Sensor in Mu Metal

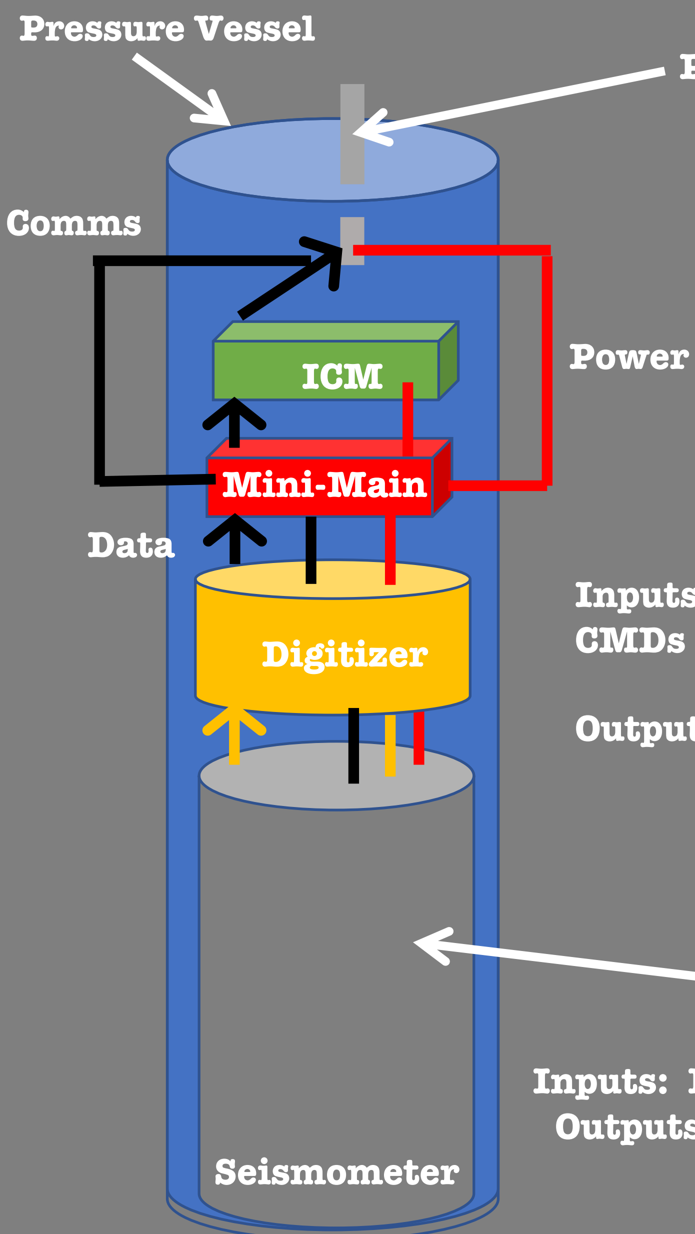




https://mumetal.co.uk/?p=82

- μ-metal provides a path of least resistance to channel magnetic field around the seismometer
- Reduces effective magnetic sensitivity by a factor of 20-40
- Very expensive, rarely used in temporary deployments

Block Diagram of Component



Digitizer:

Inputs: Ground Motion, Mass Positions, Gimbal Orientation, Timing, CMDs

Outputs: Data Packets, SOH

Sensor:

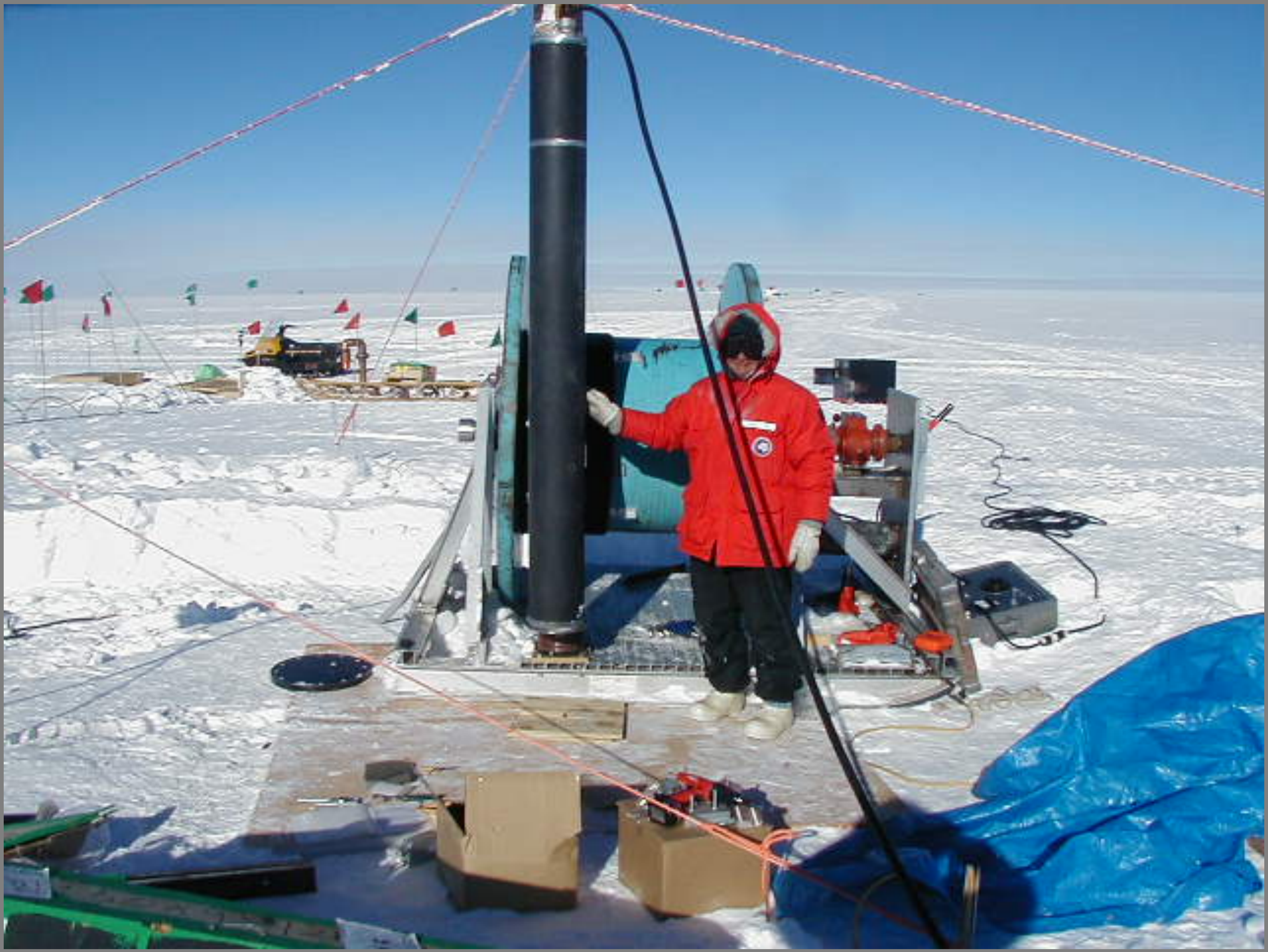
Inputs: Power, Centering, Gimbal Leveling, Calibration Signals

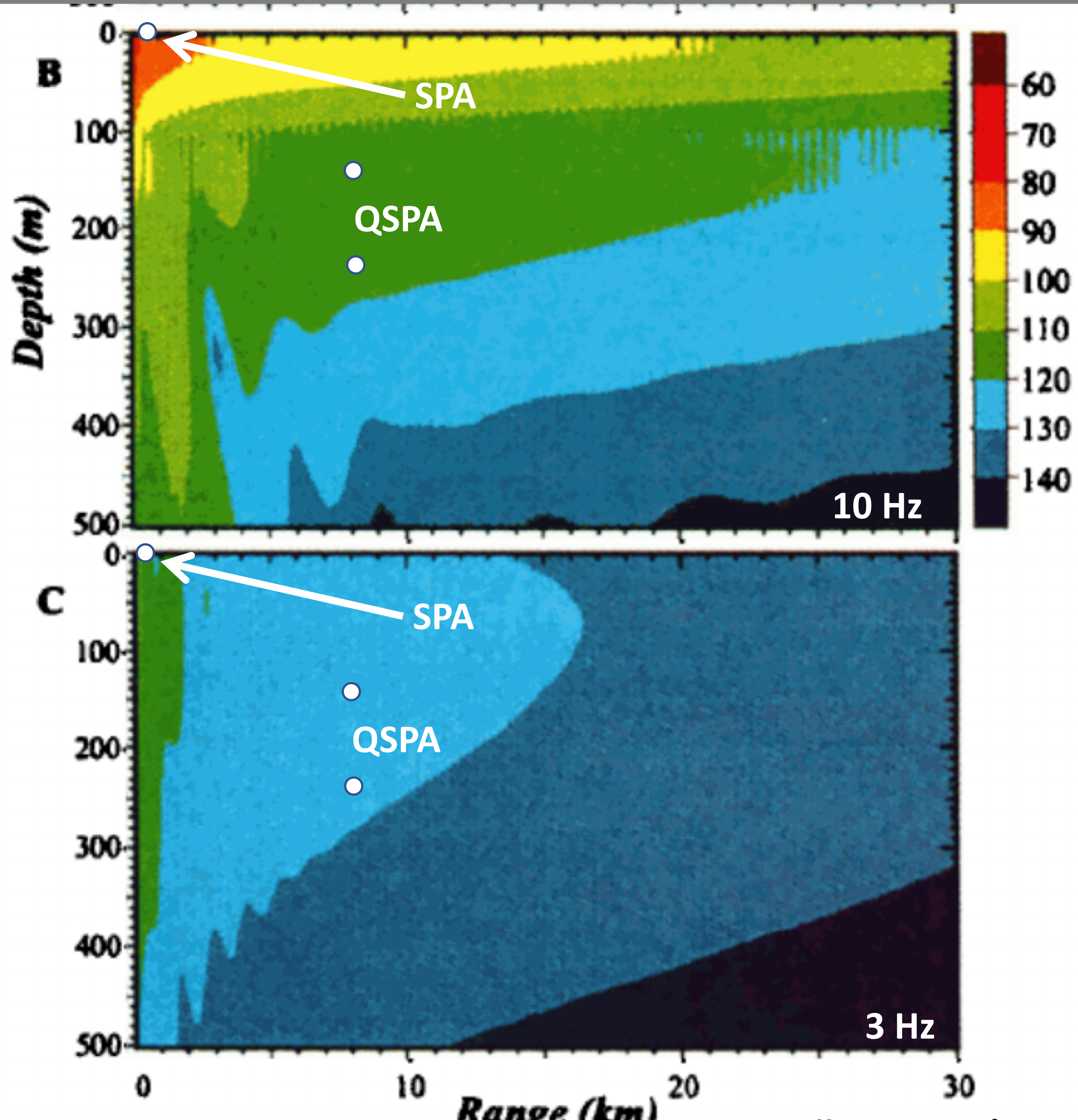
Outputs: Ground Motion, Mass-Positions, Gimbal Orientation

Unresolved Problems

- Interfacing the digitizer with the mini-main board
  - We currently interface with the digitizers at GSN stations over a Linux computer
- Ensuring accurate timing (< 1 ms accuracy to UTC desired)
  - Use RAPcal signal?
  - Ideally use PPS accurately timed to UTC
- Development and testing of a modern, cold-rated seismometer
  - Sensors from two venders have been purchased -> should have for testing in our temperature chamber in early 2021 (will not be able to test noise performance at low temperatures until we can travel again)
- Designing and building pressure vessel
- Splitting off Seismic Data and sending over USGS data stream

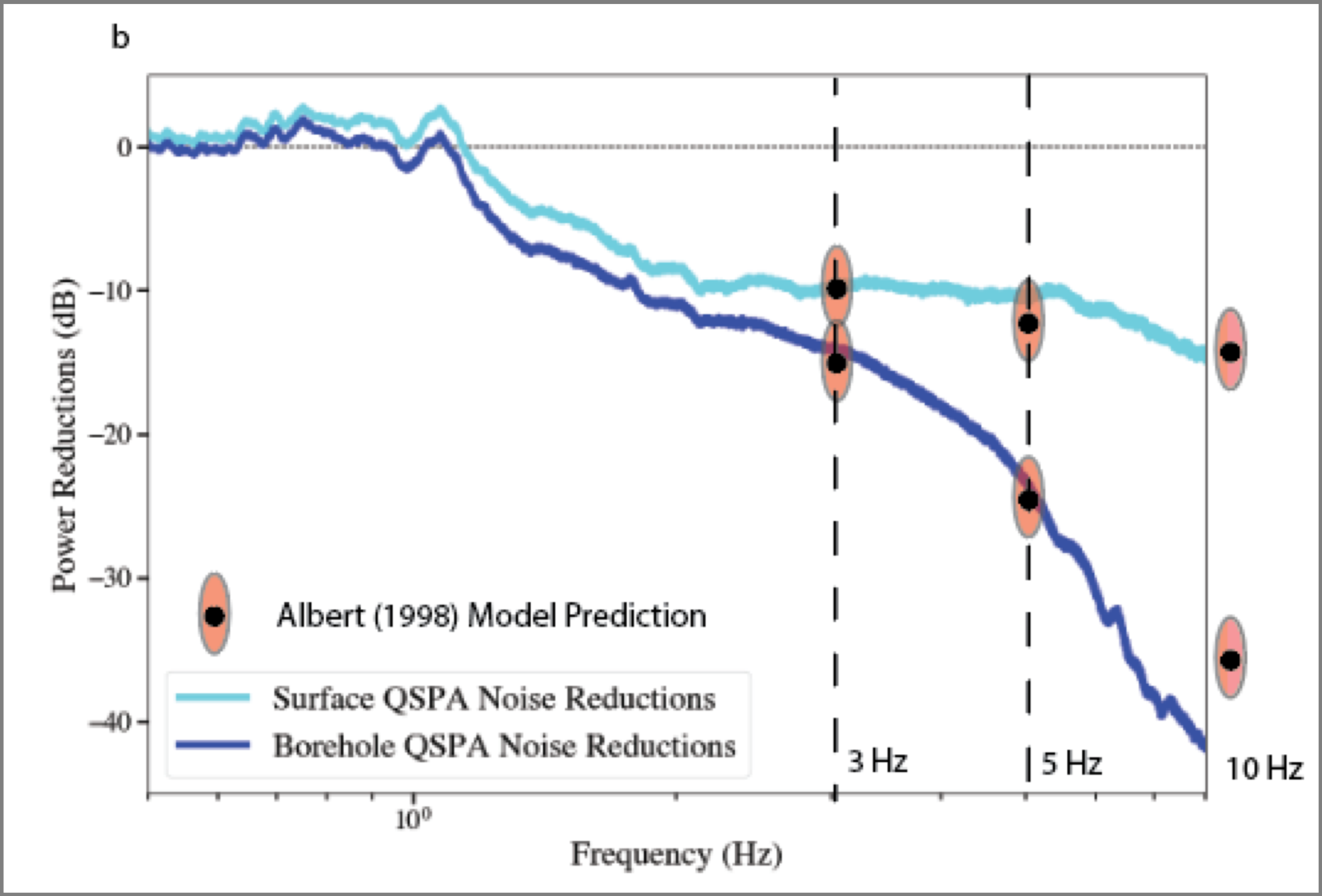
Questions?

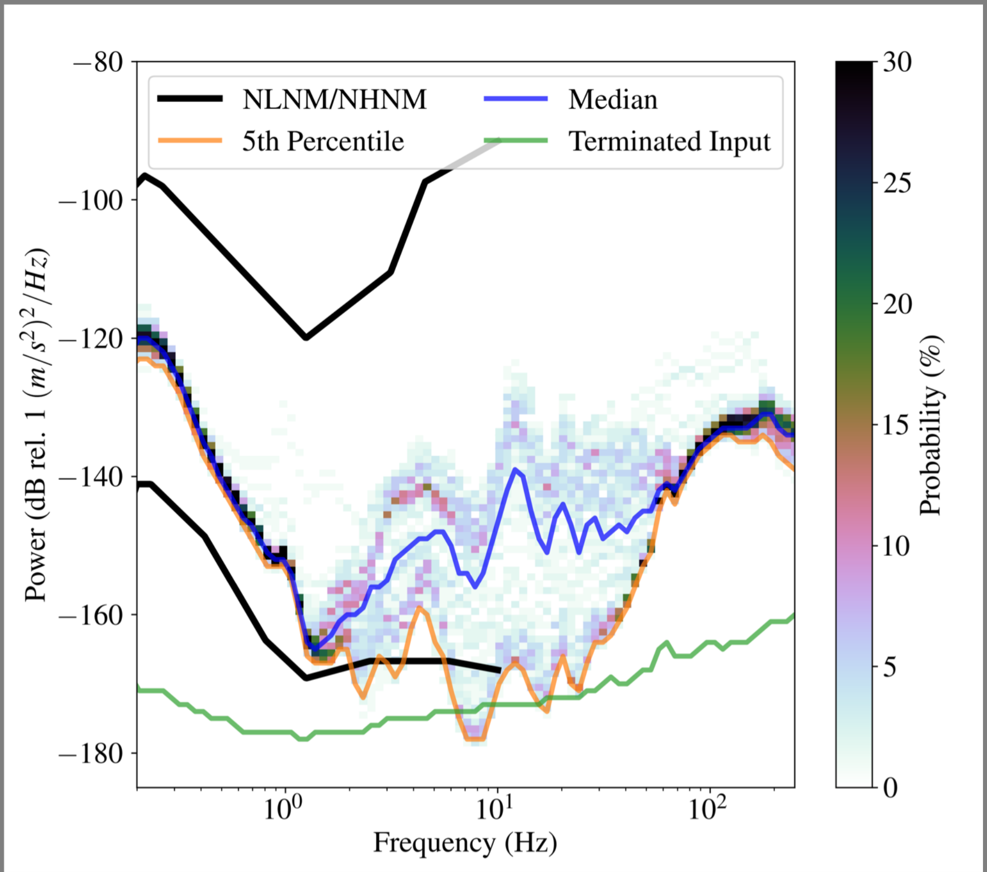


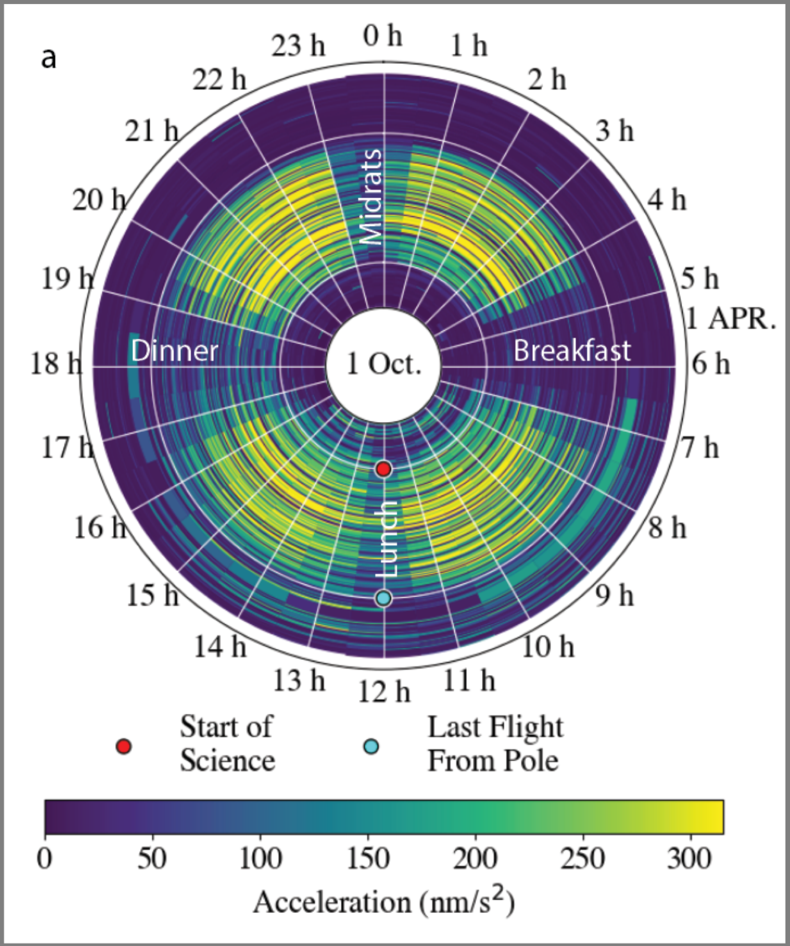


Albert, GRL (1998)

Albert's Model appears to be DARN good







In the absence of cultural noise, what processes govern ambient, high-frequency vibrations?

Anthony et al., (in Review)