Probing a planet from the subsurface to the atmosphere with infrasound data

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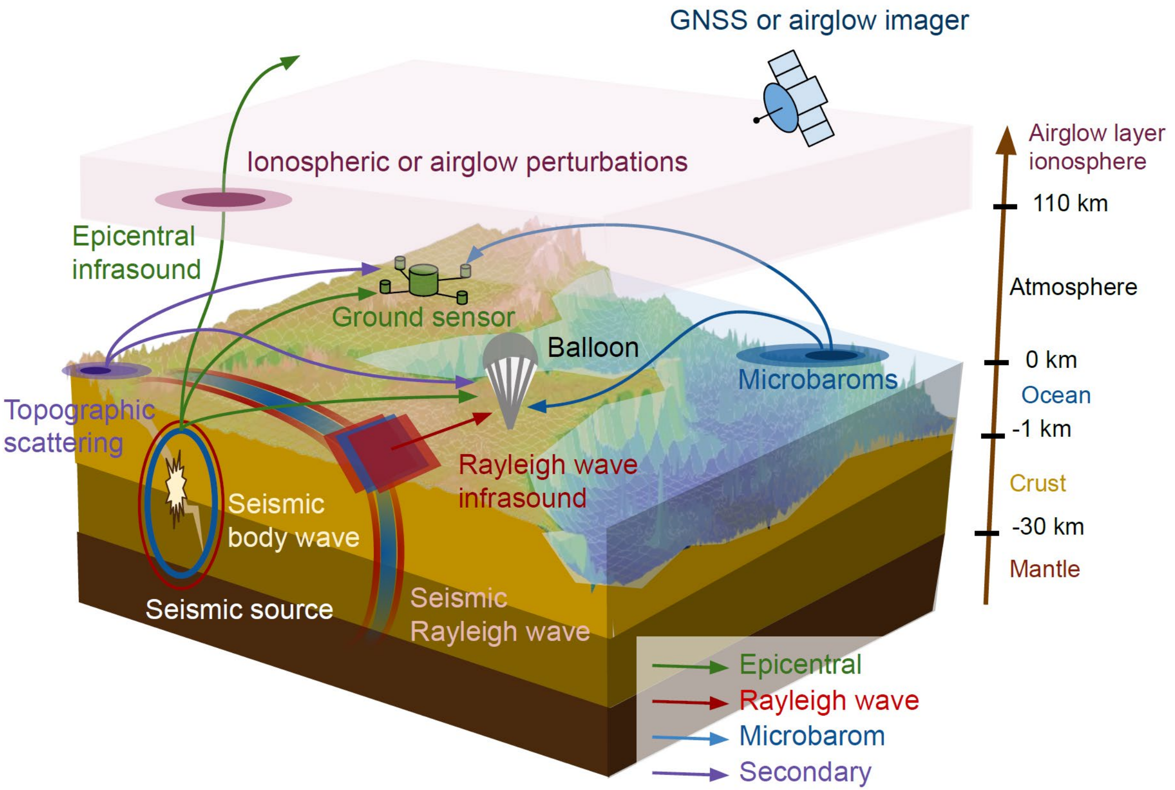
Listening to the Earth

Seismo-acoustics: linking subsurface and atmosphere

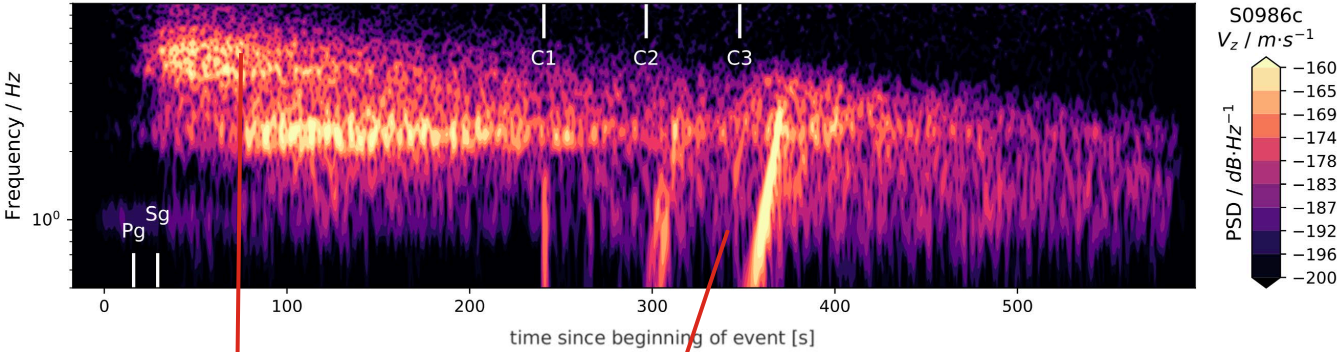
- Earthquake epicentral motion and seismic waves couple to the atmosphere
- Recording is possible through ground infrasound sensors, balloons, or remote sensing (GNSS, Airglow imagers)
- Can we extend infrasound inversion problems to study subsurface processes ?

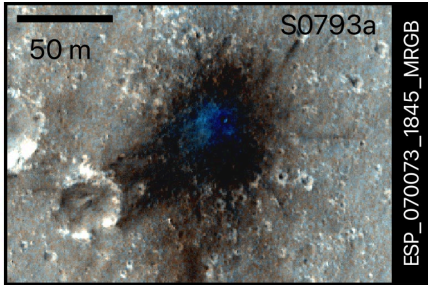


Inversions using infrasound: recent examples

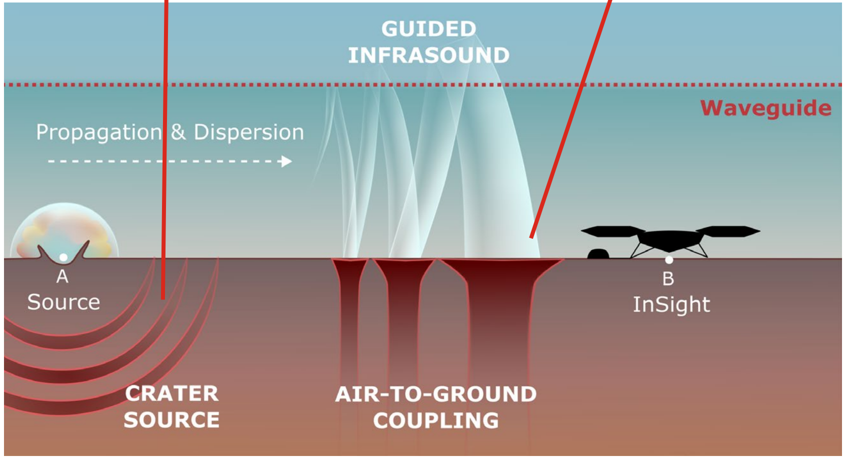
Authors	Seismo-acoustic source	Inverted parameters	Inversion Method
Blixt et al (2019)	Explosions	Stratospheric cross-wind	Arrival time, backazimuth
Amezcua et al. (2020)	Explosions	Stratospheric cross-wind	Data assimilation
Vera Rodriguez et al. (2020)	Explosions	Stratospheric w and T	Heuristic learning solver
Park et al (2022)	Explosion Epicentral Infrasound	Stratospheric w and T	Bayesian, Empirical Orthogonal Functions
Vorobeva et al. (2024)	Microbaroms	Stratospheric polar wind	Machine Learning
Froment et al. (2024)	Coupled meteorite blast	Boundary layer c, w	Bayesian, Markov chain Monte Carlo
Shani-Kadmiel et al. (2018, 2021), Hernandez et al. (2018)	Remote Earthquake Epicentral Infrasound	Source acoustic intensity	Back-propagation of arrivals, Grid search
Turquet et al. (2024)	Minequake Epicentral Infrasound	Focal depth, mechanism	Full Waveform, McMC
Averbuch et al. (2020)	Synthetic underwater source	Depth, strength	Bayesian
Rakoto et al. (2018)	Earthquake TEC	Tsunami height	Least Square inversion
(…)	Air-coupled earthquakes ?	Subsurface vs, vp ?	

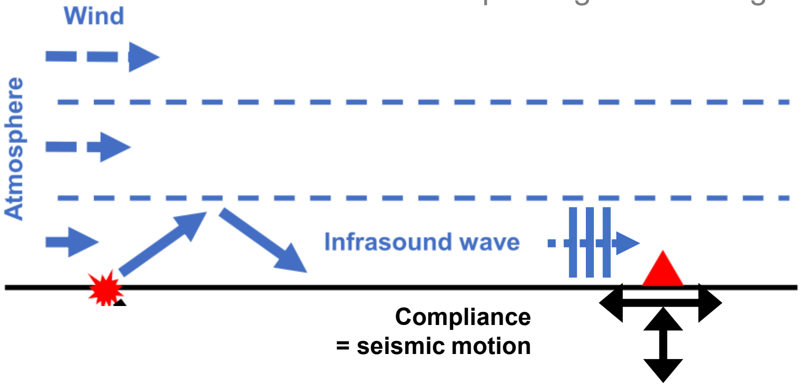
Seismo-acoustics beyond Earth





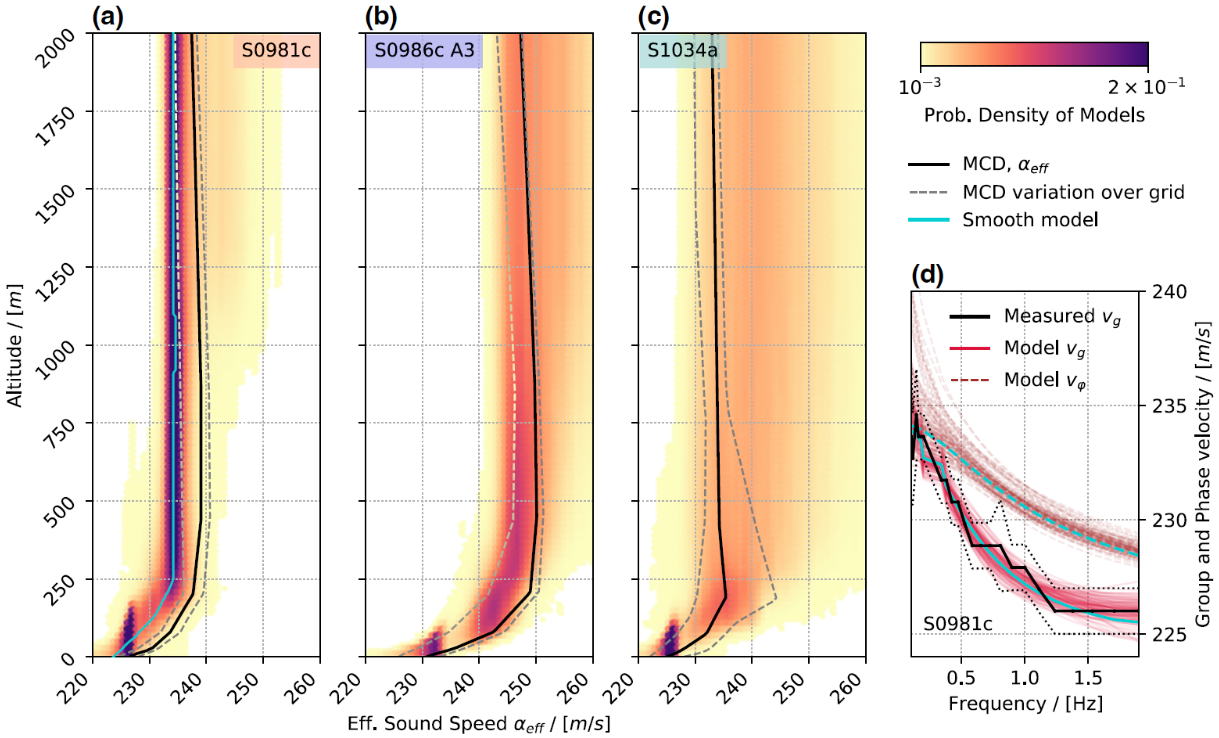
6 small craters (<10m) were associated to air-to-ground coupled signals at InSight





Garcia, R.F., Daubar, I.J., Beucler, É., Posiolova, L.V., Collins, G.S. et al. *Nature Geoscience*, 2022. https://doi.org/10.1038/s41561-022-01014-0

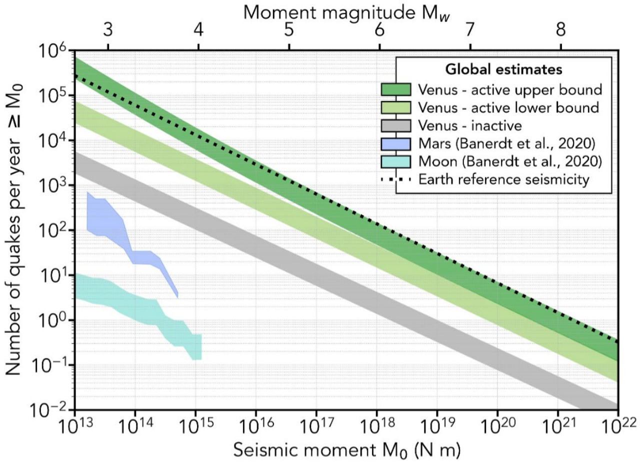
Inverting the speed of sound and wind in the Martian boundary layer



Infrasound produced by meteorite impacts on mars was dispersed in a low-altitude nighttime waveguide.

The dispersed infrasound coupled to the ground: the structure of speed of sound in the Martian atmosphere can be inferred from its group velocity.

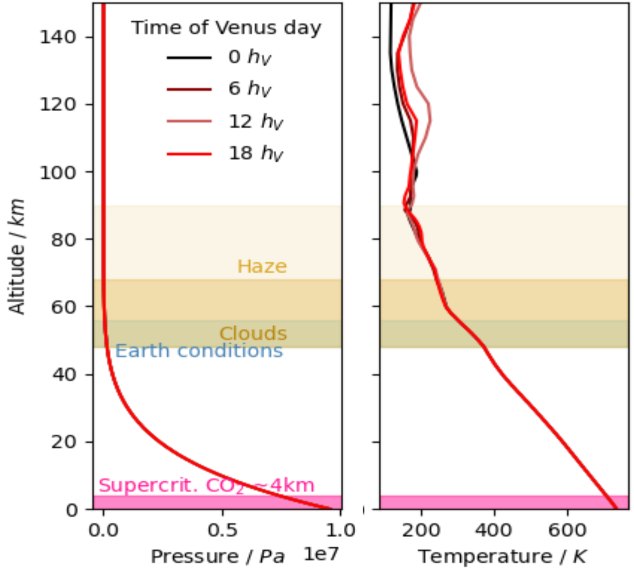
Seismoacoustics on Venus?



Venus does not have plate tectonics. However, several other regions could be active: Rifts, “Coronae”, Volcanoes.

van Zelst, I., Maia, J. S., Plesa, A.-C., Ghail, R. & Spühler, M. Estimates on the Possible Annual Seismicity of Venus. *Journal of Geophysical Research: Planets* **129**, e2023JE008048 (2024).
Garcia, R. F. *et al.* Seismic wave detectability on Venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers, *Preprint*, 2024.

Venus is a pressure cooker under a lid of clouds, very stable throughout the day: a challenge for ground-based seismology, but an advantage for infrasound studies!

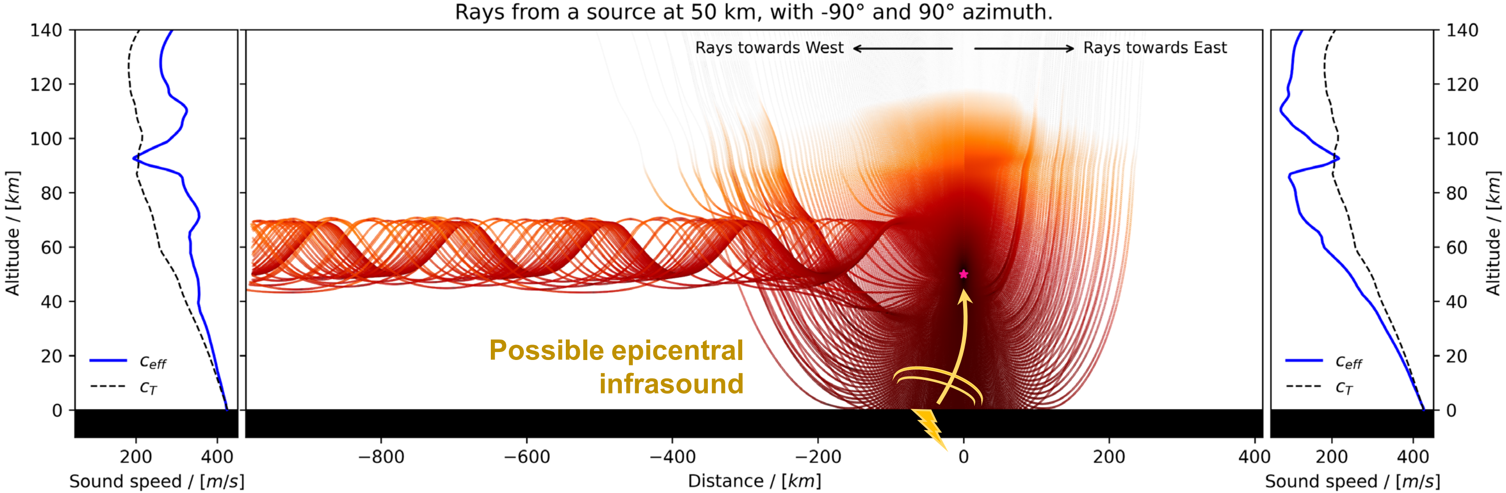


Venus Climate Database outputs for pressure and temperature near the equator.

Exploring Venus interiors using balloons

Rays coming from the ground (Epicentral Infrasound, coupled Rayleigh waves) have simple propagation paths. Waveguides may exist at higher altitude due to the strong E→W, 100 m/s winds ("*superrotation*").

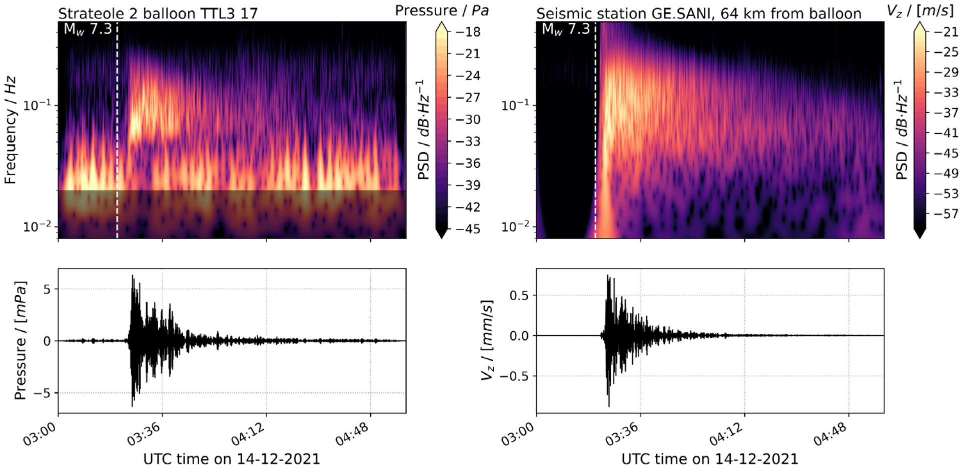
Soviet missions have sent balloons to Venus (Vega 1 & 2, 1985)



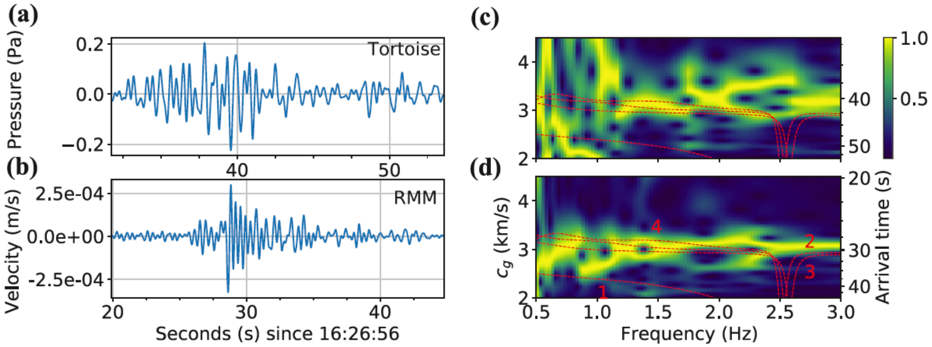
Hypothesis: Earthquake Infrasound suffer little distortion when propagating vertically

→ What information from the source/subsurface can we infer ?

Balloon seismology on Earth



The 14/12/2021 Flores Sea earthquake recorded by Strateole2 balloons.



Event R1b of the 2019 Ridgecrest sequence recorded by Tortoise balloon.

A complex sensor:

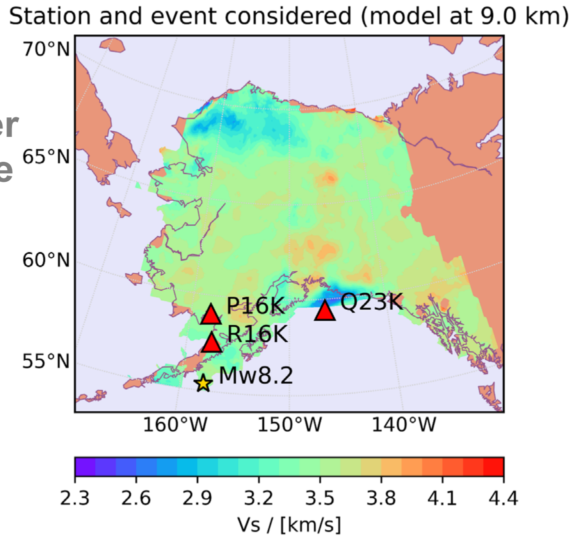
- Balloons position determined by buoyancy, wind forces, gravity.
- Presence of a Neutral Buoyancy Oscillation = balloon normal mode.
- Pressure recordings affected by atmospheric noise

Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), 10.1029/2022GL098844
Brissaud, Q. *et al. Geophysical Research Letters* **48**, (2021), 10.1029/2021GL093013

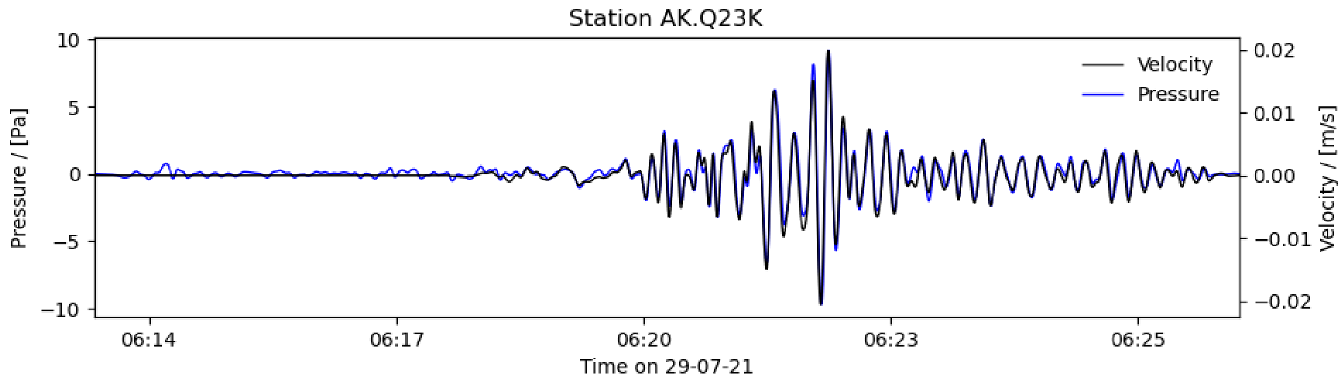
Inverting the subsurface from coupled earthquake signals

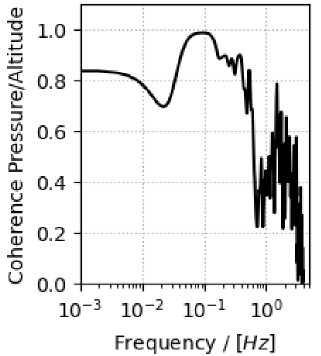
Stations of the Alaska Network (AK) have collocated pressure and seismic sensors. Excellent coherence between pressure and seismic instruments between 2e-2 and 2e-1 Hz. **We suppose that coupled Rayleigh waves suffer little distortion while propagating upward in the air, thus these signals are good proxies for balloon infrasound**.

Several Mw>7 events recorded by both instruments.
We select an Mw8.2 event on 29/07/21 to test the inversion.
Our "truth" model: 4-layer model reproducing the mean of Berg et al. (2019) at the three stations.

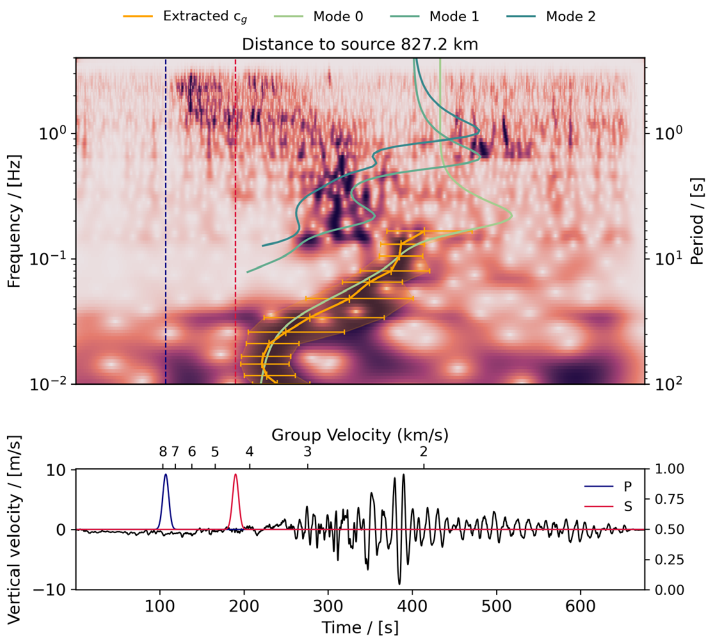


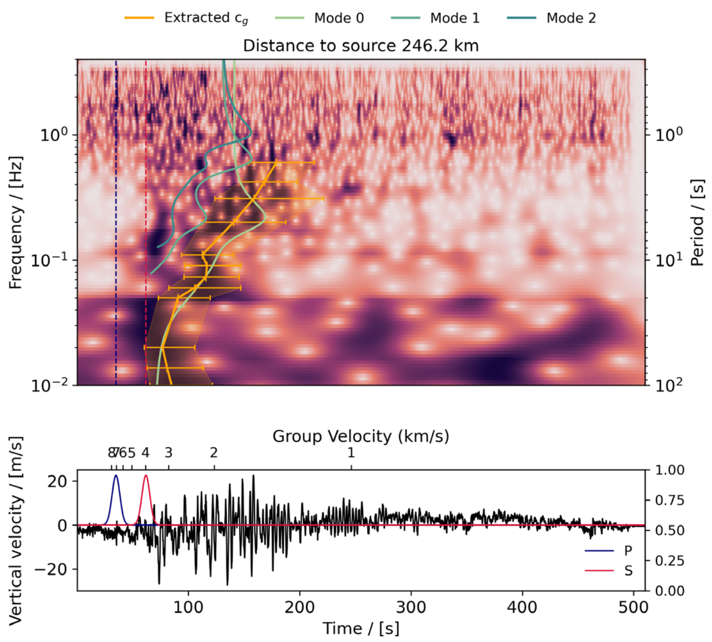
Berg, E. M. et al (2020) *JGR: Solid Earth* **125**, http://doi.org/10.1029/2019JB018582
Macpherson et al. 2023 (2023) *BSSA*, **113**, https://doi.org/10.1785/0120220237





Picking the Rayleigh and S waves

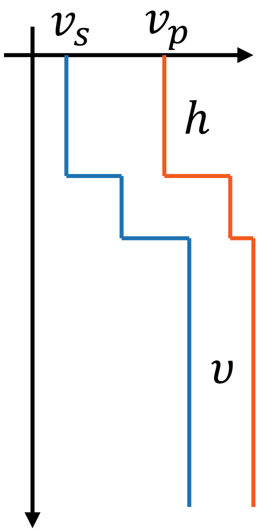




Unfiltered signals at two different distances: Frequency-Time ANalysis is used to pick the RW by hand. S picks are the values predicted from a 1D model, associated to an uncertainty of 5s.

Inversion method

Subsurface model



Source location and time

t_s h_s r_s

Distribution of parameters

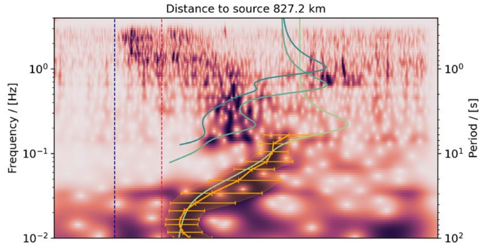
Forward model

Arrival times

$\boldsymbol{t_{RW}(f_i)}$

$\boldsymbol{t_S}$

Data (RW and S picks)



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Misfit + **Priors**

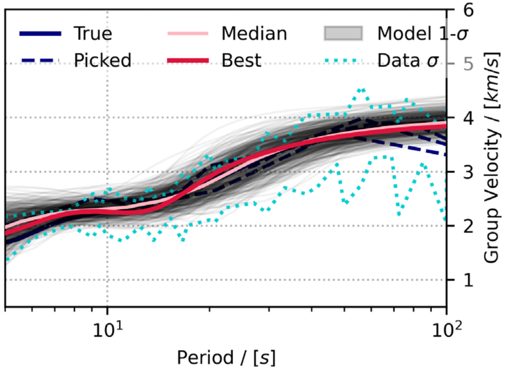
(bounds on v_s, h, r_s ...)

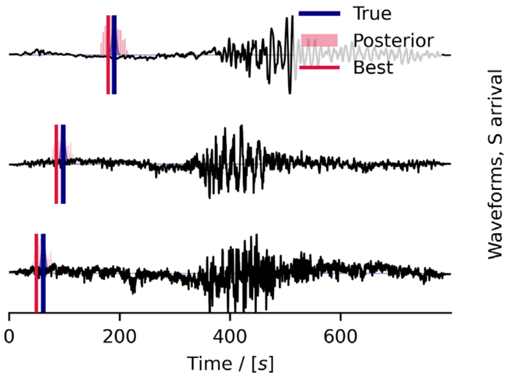
Bayesian approach (Markov chain Monte Carlo for the exploration of the parameter space)

Posterior probability of

$(v_s, v, h, t_s, r_s, h_s)$

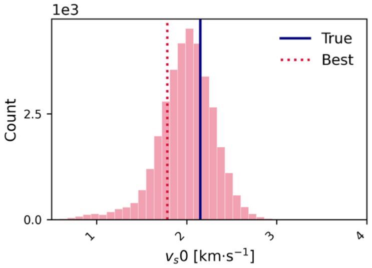
Inversion results: 3signals with S and Rayleigh waves

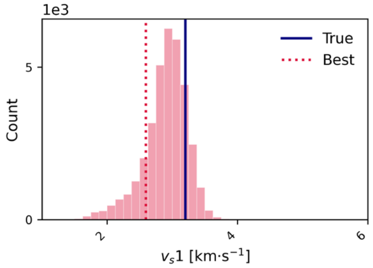


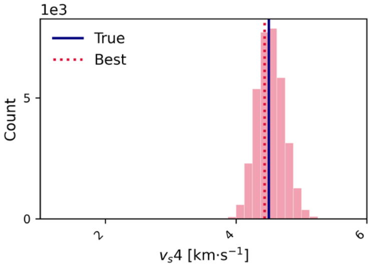


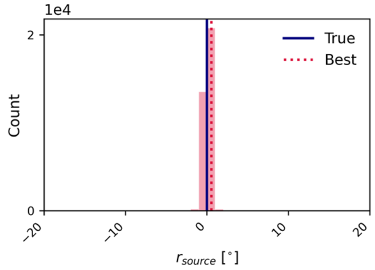
Inversion results: parameters and histograms

Parameters **constrained much better than the priors**: distance, shear wave velocity

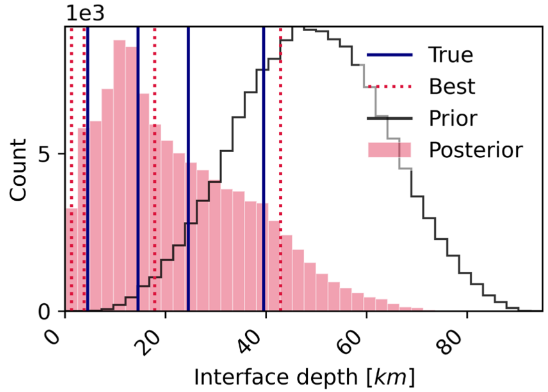


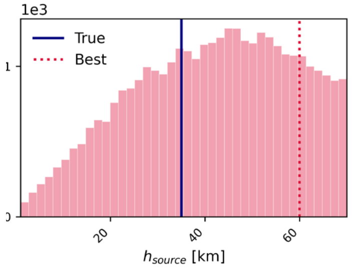


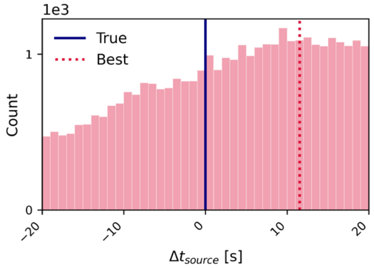


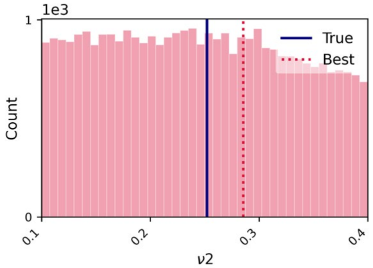


Parameters **less constrained**: Source depth, interface depth.



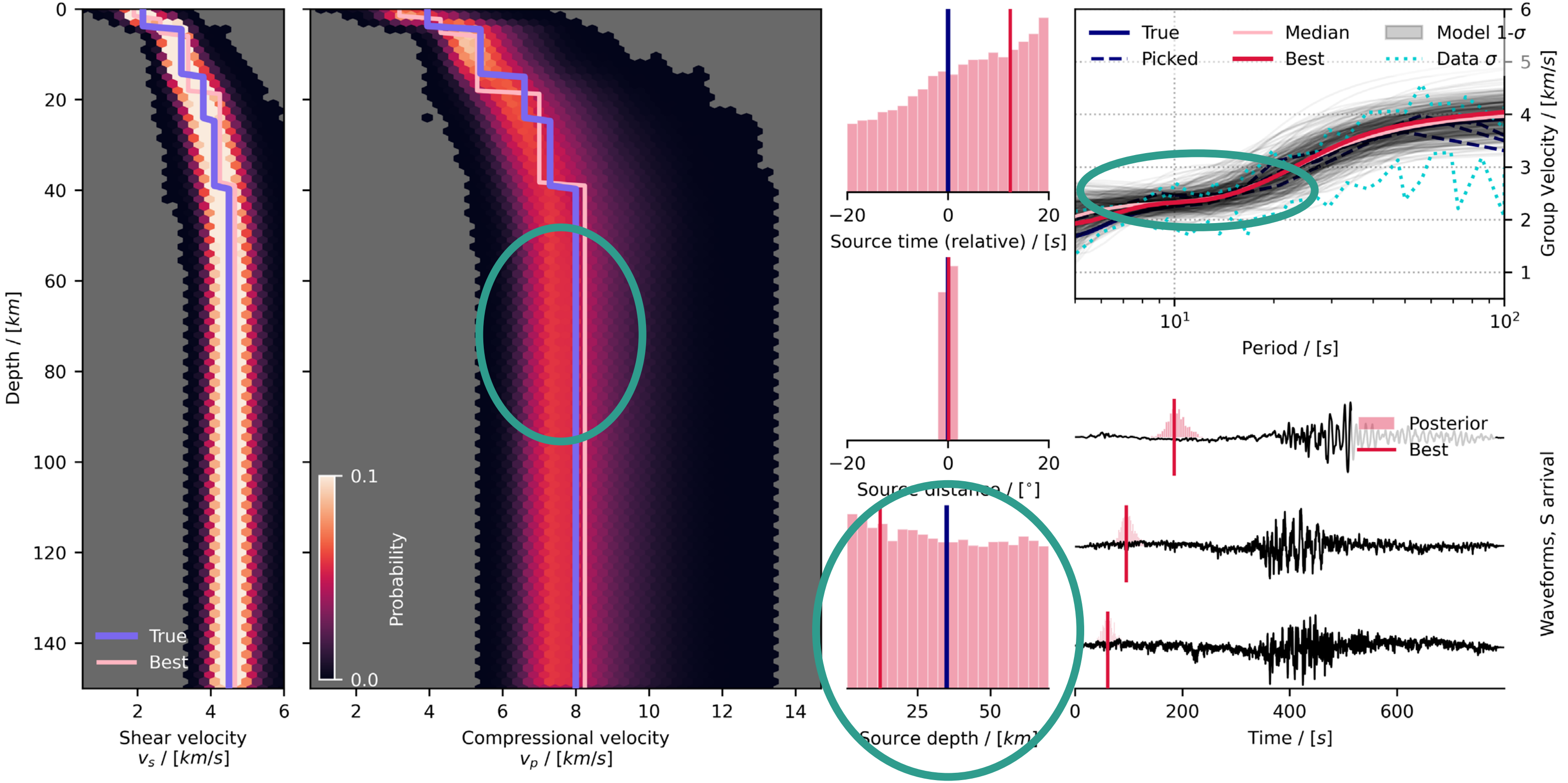




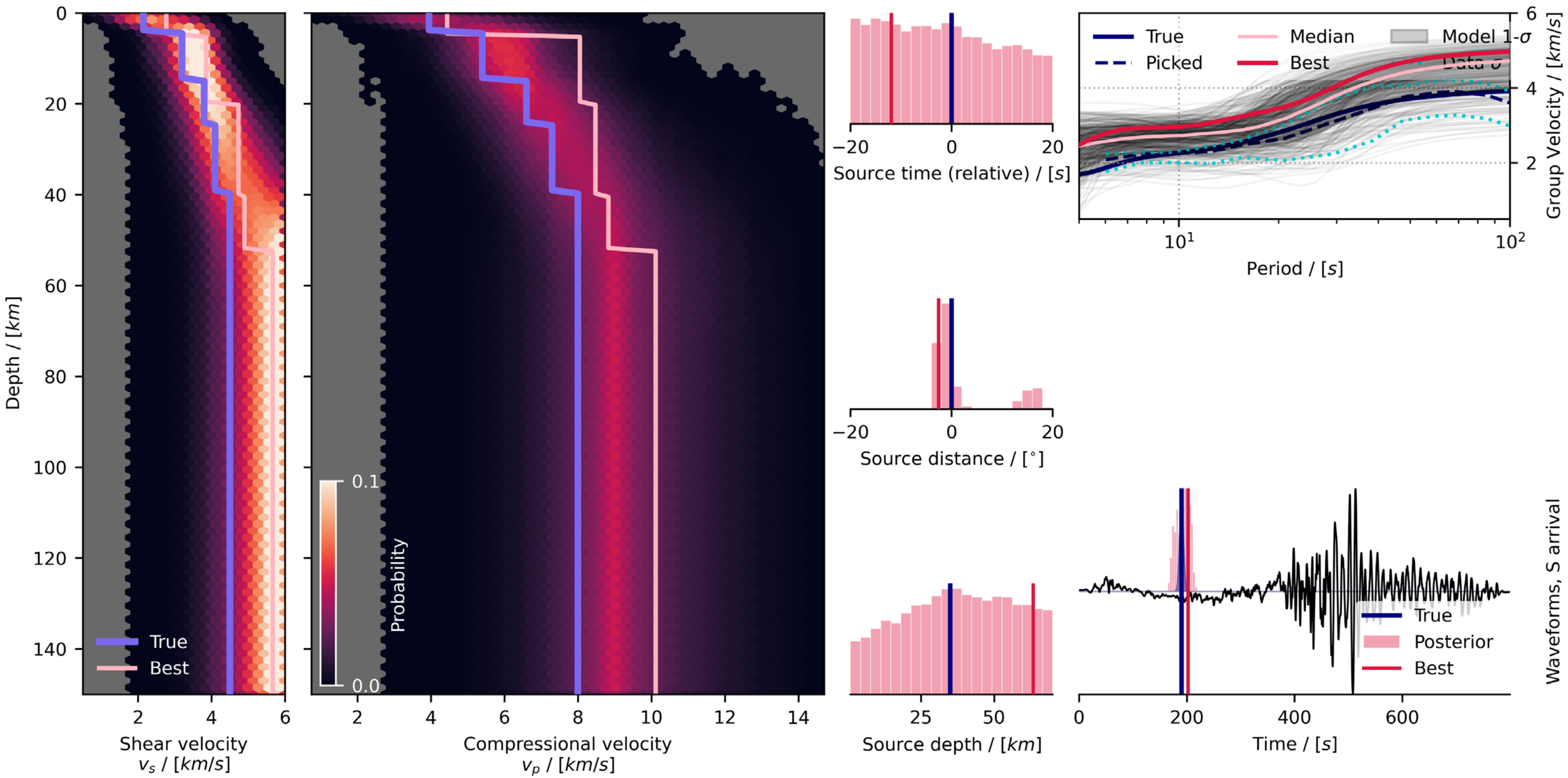


Parameters **unconstrained**:
Poisson ratio, origin time.

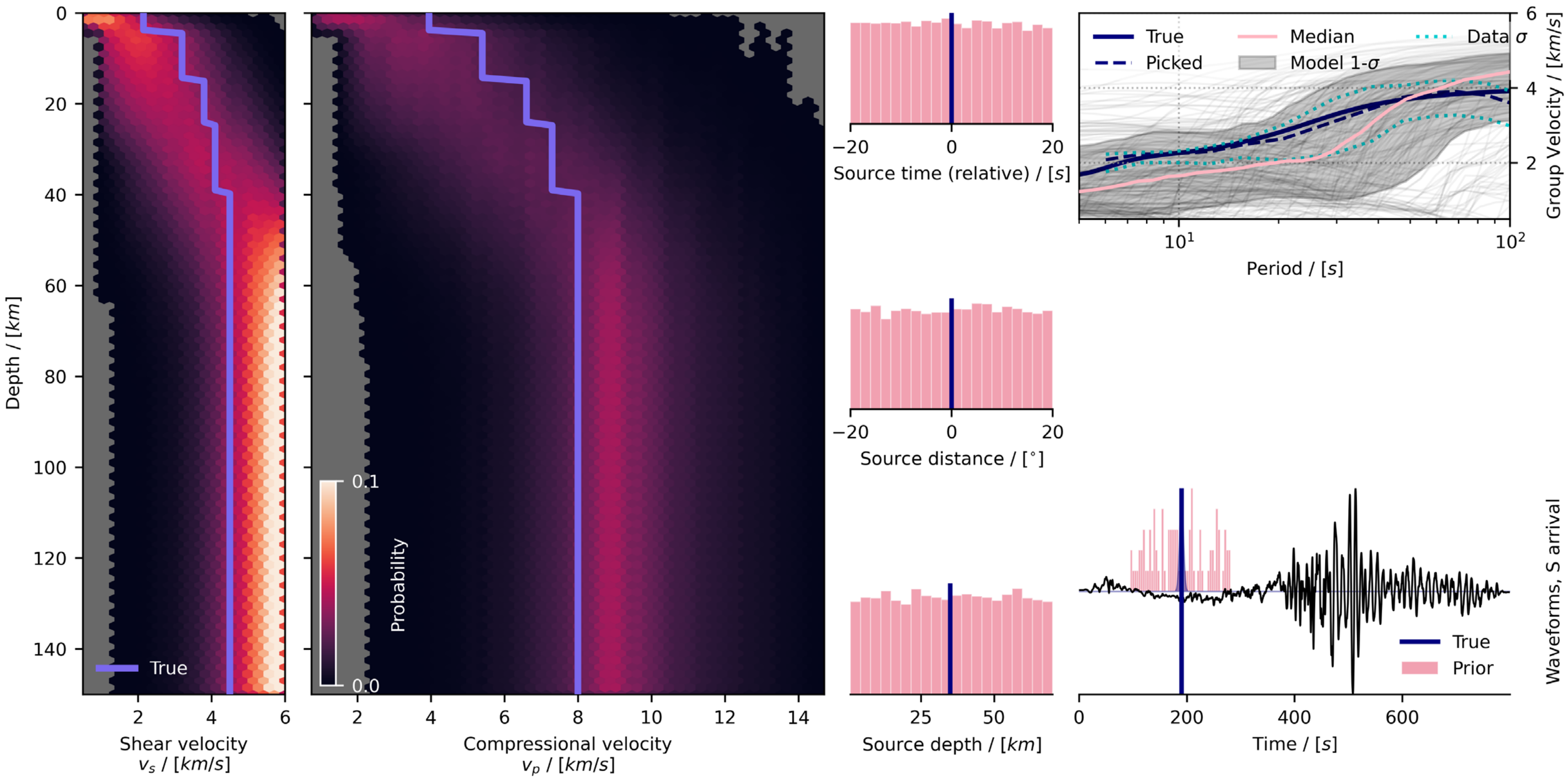
Inversion results: 3signals Rayleigh waves, no S



Inversion with a single balloon



For comparison: Priors for a single balloon



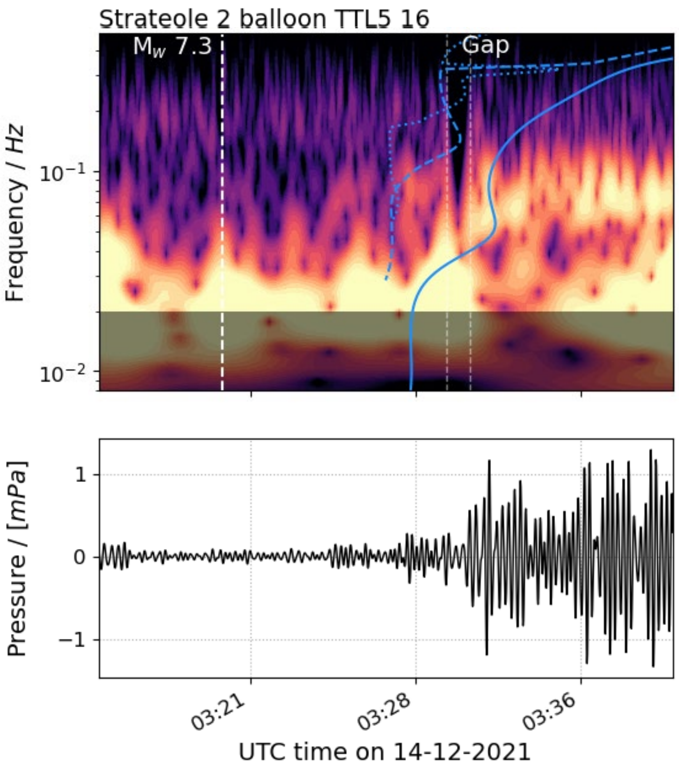
The next steps: a fully airborne inversion

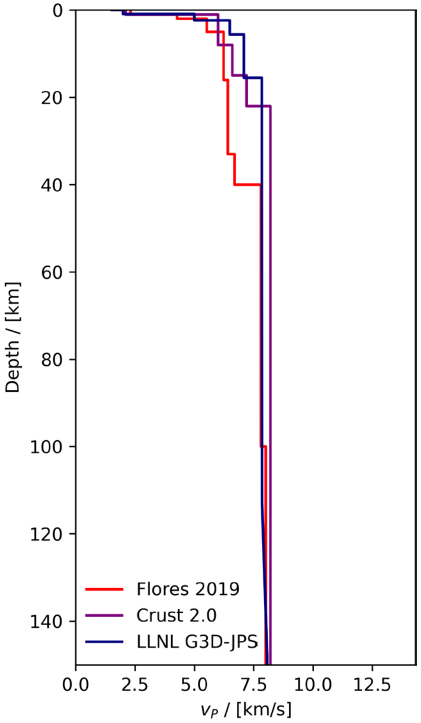
The Flores Earthquake

- Subsurface not well known in the region.
- A challenge in picking the RW and other picks: presence of a resonance (low velocity layers? Scattering?)
- Need better understanding of balloon response.

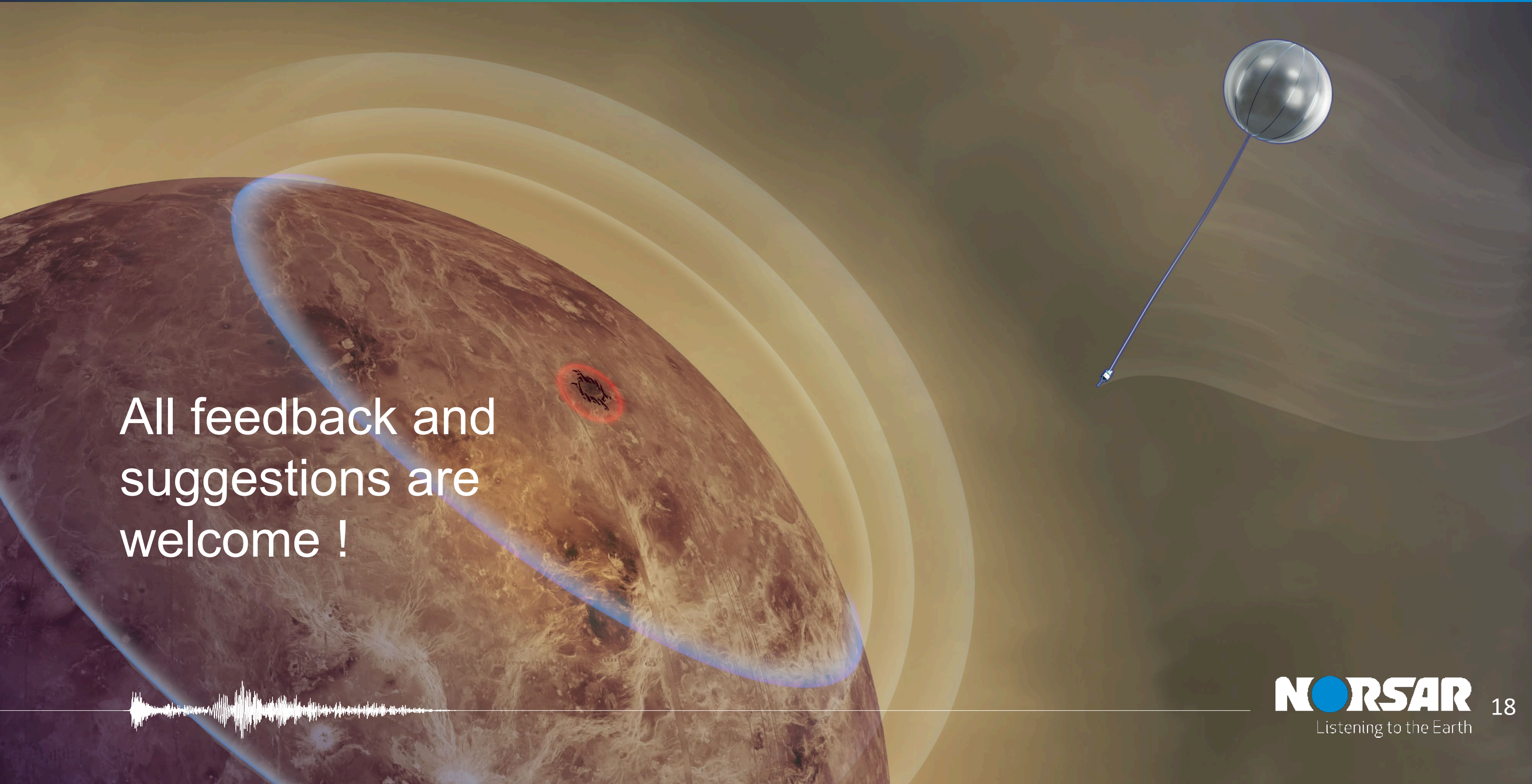
Venus:

- Difference in noise conditions with respect to Earth ?
- Test more inversion scenarios



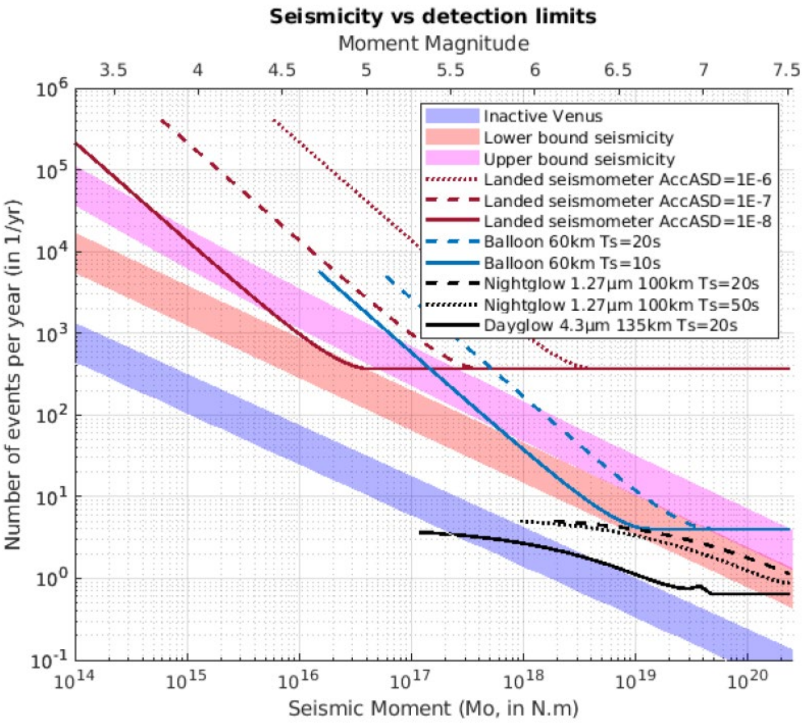


Thank you for your attention



All feedback and suggestions are welcome !

Different mission concepts for Venus seismology

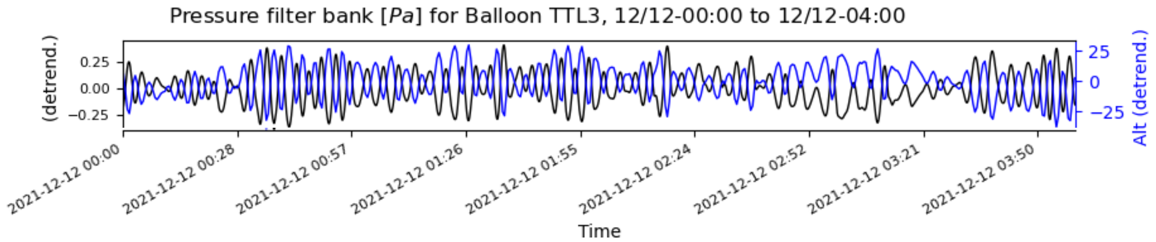


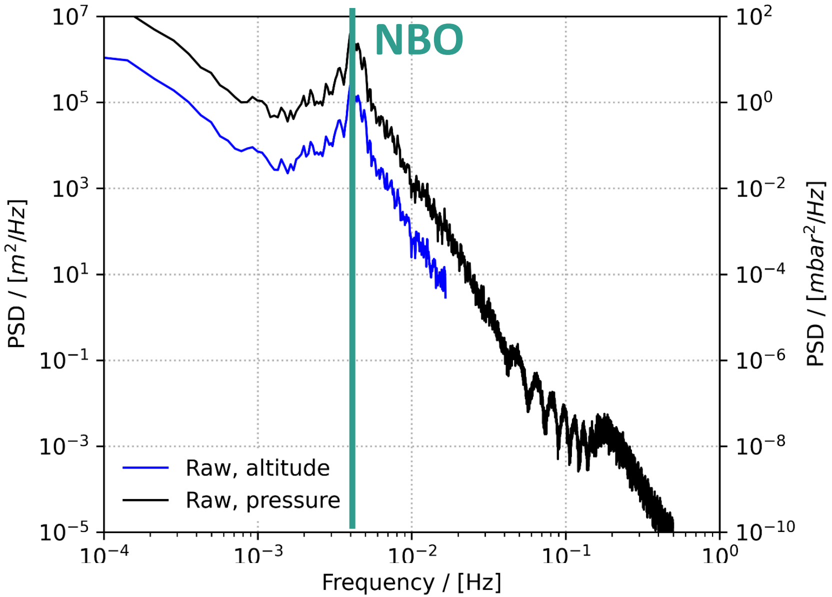
From: Garcia, R. F. *et al.* Seismic wave detectability on Venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers, *Preprint*, 2024, work of the International Space Science Institute (ISSI) team

Shaded: number of events per year for different magnitudes depending on Venus activity.

Curves: Minimum number of events per year as a function of magnitude required to measure **at least one** event of this magnitude over the mission duration. Different instruments have different estimated lifetimes:
Seismometer = 1 day
Balloon = 3 months
Airglow = 2 years

Balloon oscillations and noise



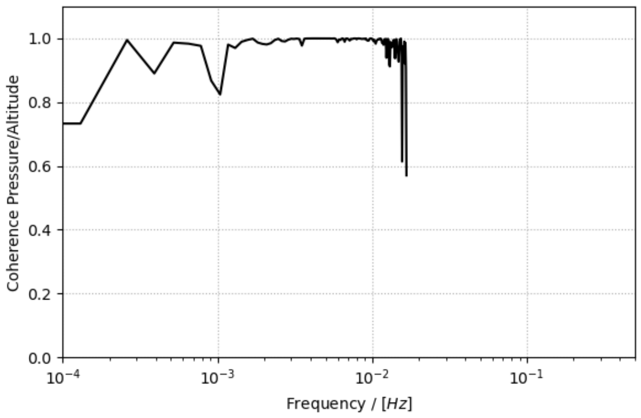


Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

Effect on pressure recordings ?

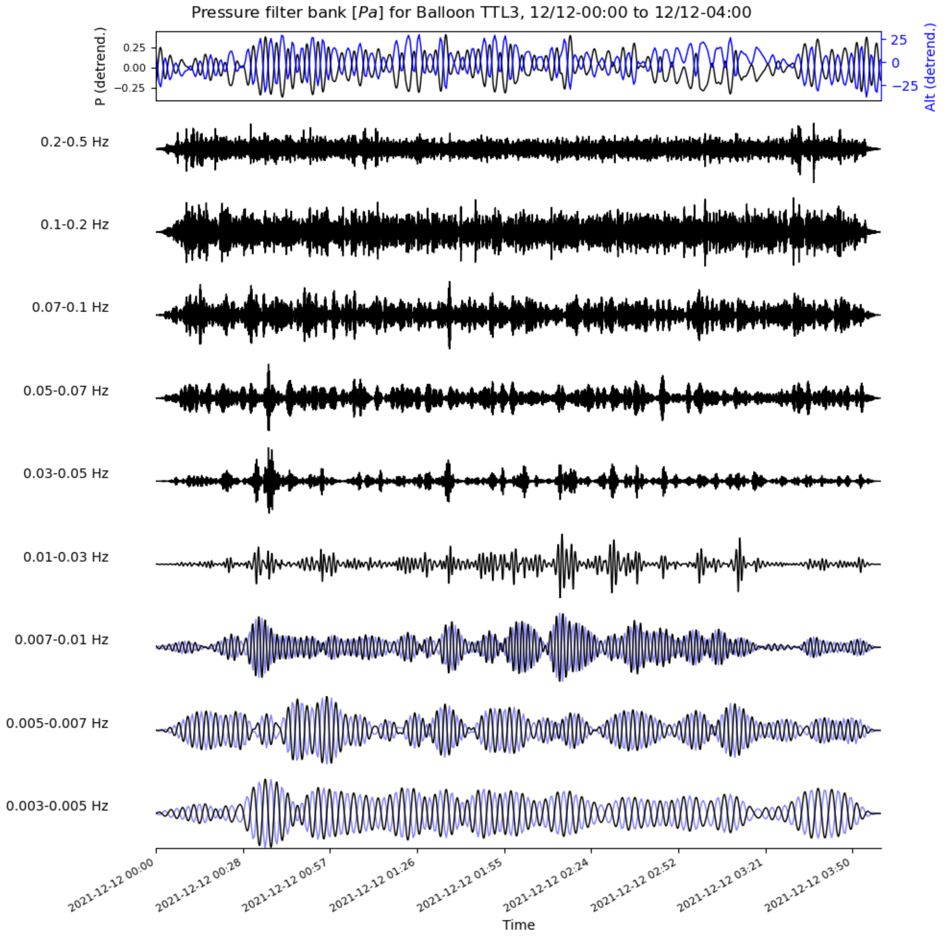
Massman, W. J. *Journal of Applied Meteorology (1962-1982)* **17**, 1351–1356 (1978).

Coherence of balloon pressure and altitude traces

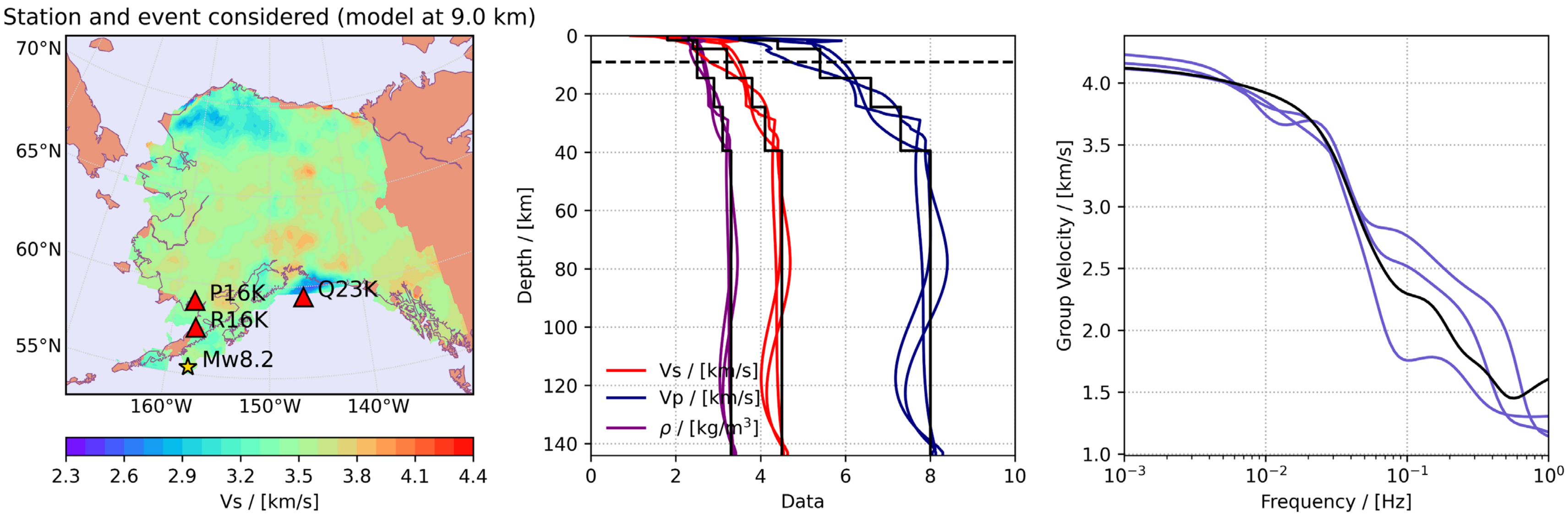


Example of Strateole2 balloon TTL3 17: high coherence up to the Nyquist frequency of the GPS.

Bursts of energy can be seen at higher frequencies when there is a strong altitude change: the coherence might go even higher.



Coherence of balloon pressure and altitude traces

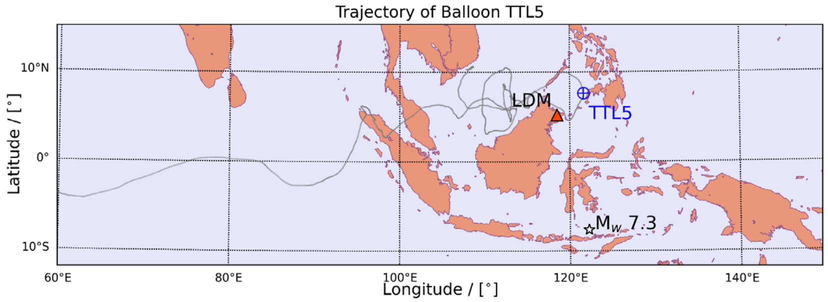


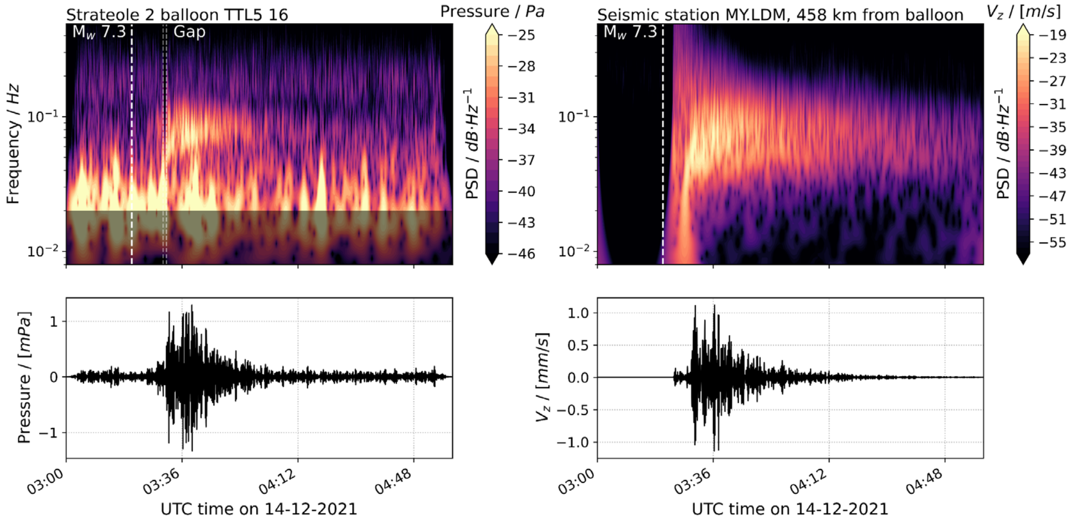
Models extracted from Berg et al. (2020) and a 4-layer model reproducing the trend.

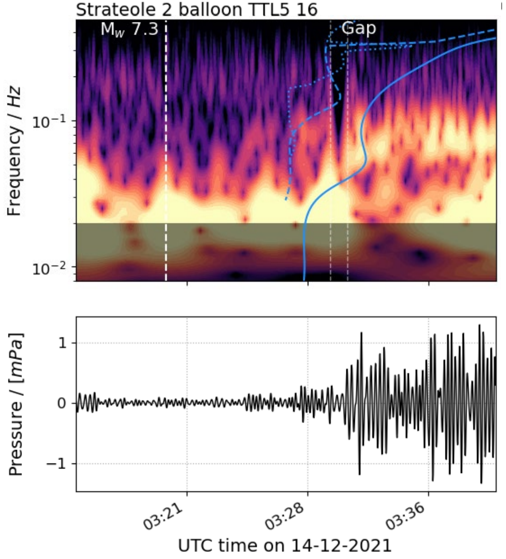
The RW group velocity predicted from each model is shown.

Berg, E. M. et al. Shear Velocity Model of Alaska Via Joint Inversion of Rayleigh Wave Ellipticity, Phase Velocities, and Receiver Functions Across the Alaska Transportable Array. *Journal of Geophysical Research: Solid Earth* **125**, e2019JB018582 (2020).

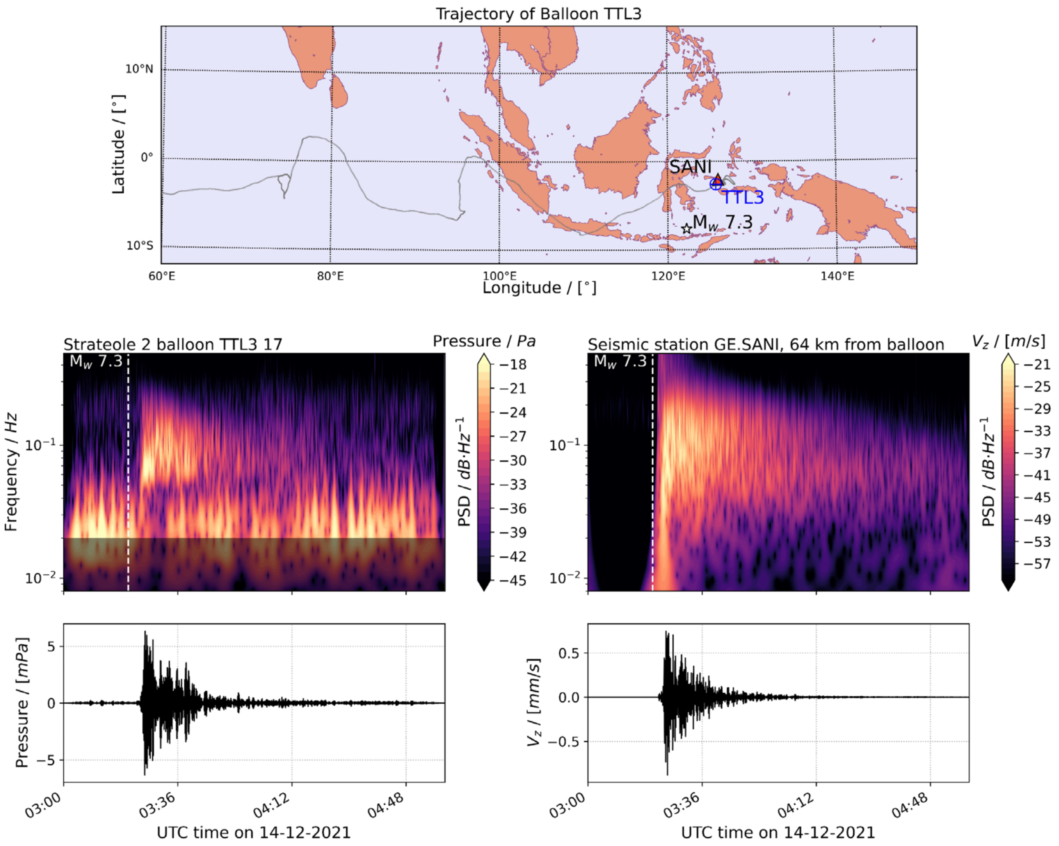
Picking the Rayleigh wave: example of balloon 16

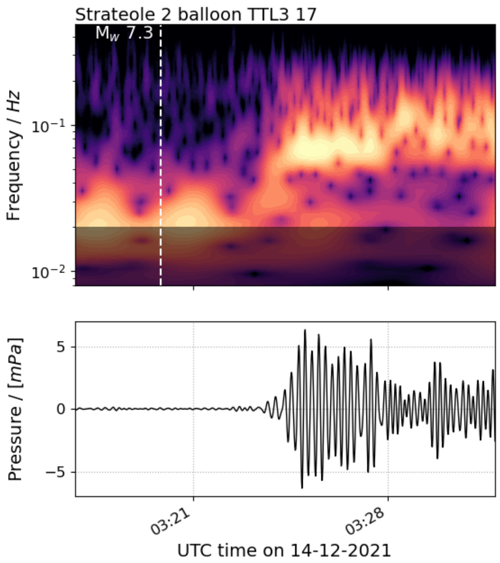




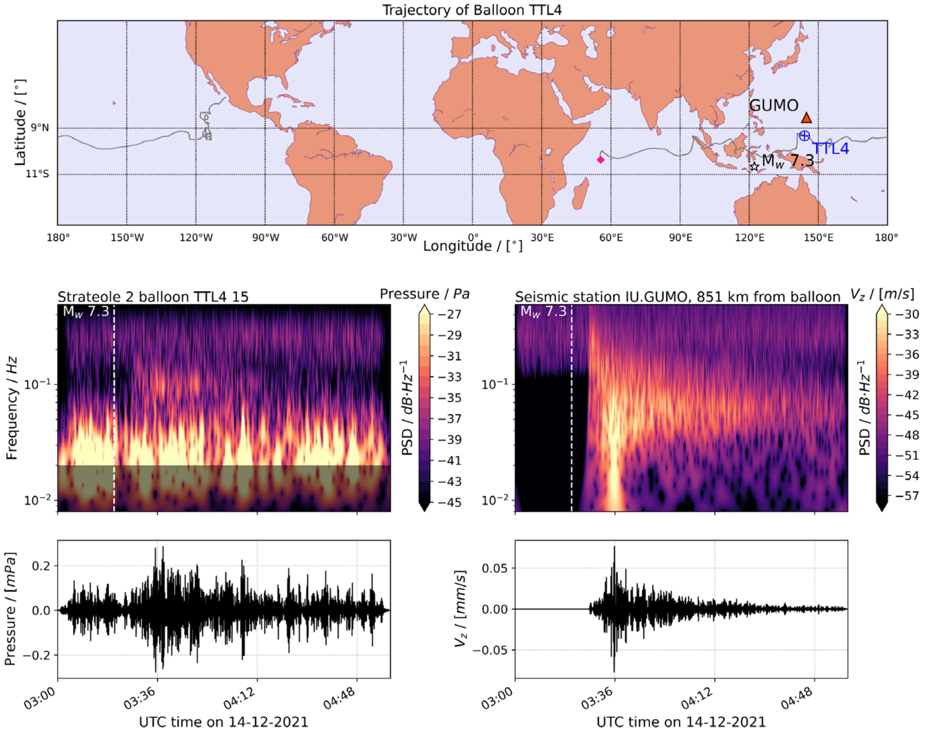


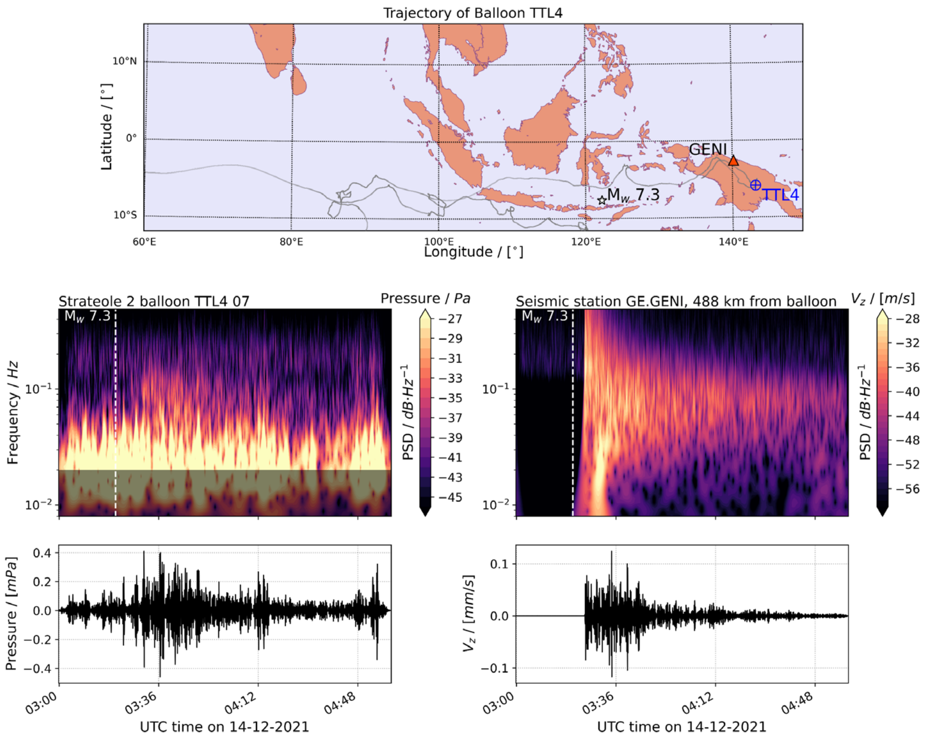
Picking the Rayleigh wave: example of balloon 17





Balloon 15 and 07: a more difficult case.





Sensitivity analysis for models of the Flores sea