Balloon-Borne Seismology for Subsurface Exploration

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Funded by
The Research
Council of Norway

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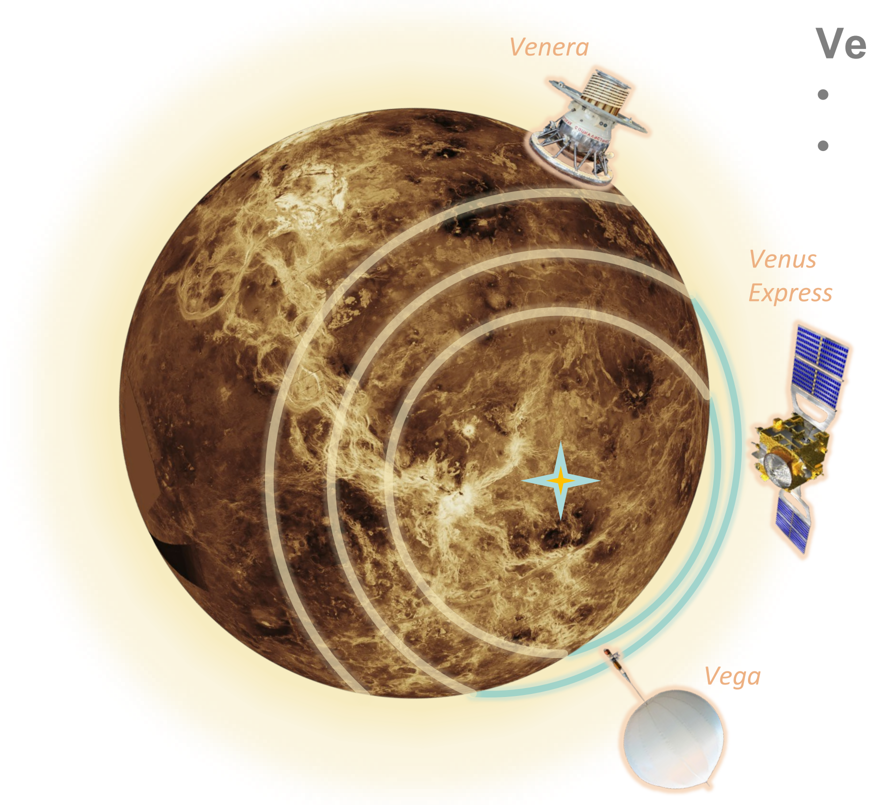
Listening to the Earth

Venus seismology concepts



Venus:

- Hot surface (~470°C)
- Dense atmosphere (~60 × Earth)

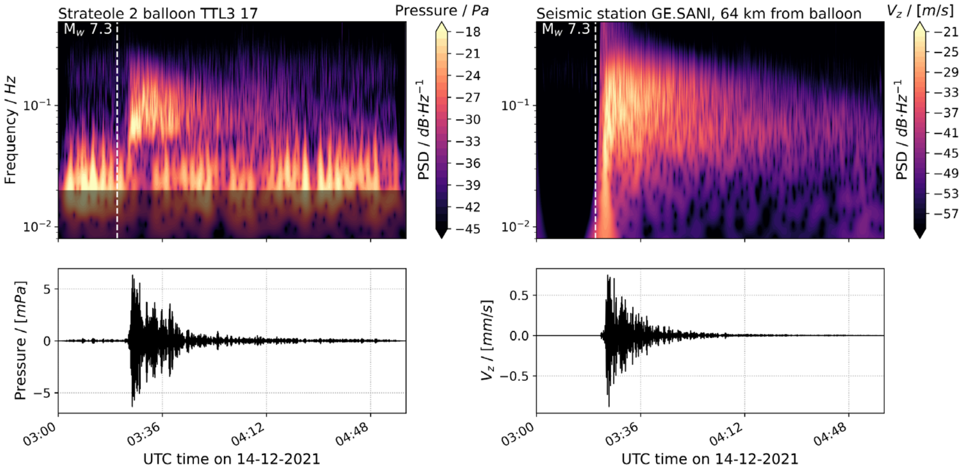
Garcia, R. F., et al. *Earth and Space Science*, **11**, (2024). 10.1029/2024EA003670

Surface sensor. Deployed seismometer. < 24 h.

Remote sensor. Airglow modulation by acoustic perturbation. Years, *Mw* > 5-6, *f* < 1 Hz.

Airborne sensor. Balloon-borne infrasound sensor. Months to years, *Mw* > 5, *f* < 10 Hz.

Balloon seismology on Earth



Dec. 14, 2021, Mw 7.3 Flores Sea earthquake recorded by Strateole2.

- Good agreement between seismic ground sensors and airborne infrasound recordings.
- Multiple sources of noise in data.

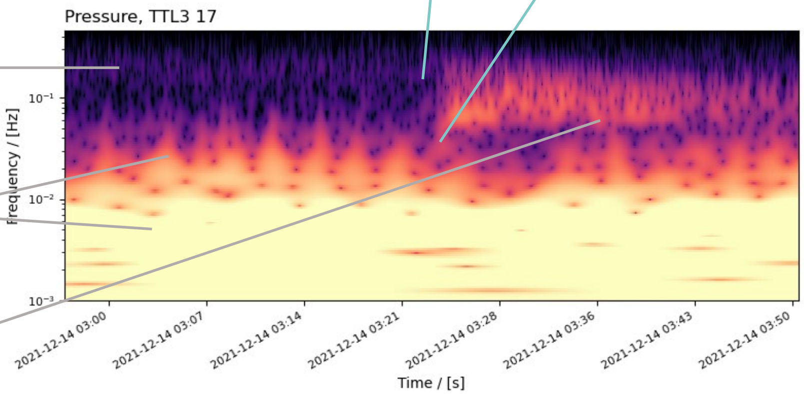
P

RW

Microbaroms

Balloon Buoyancy oscillations

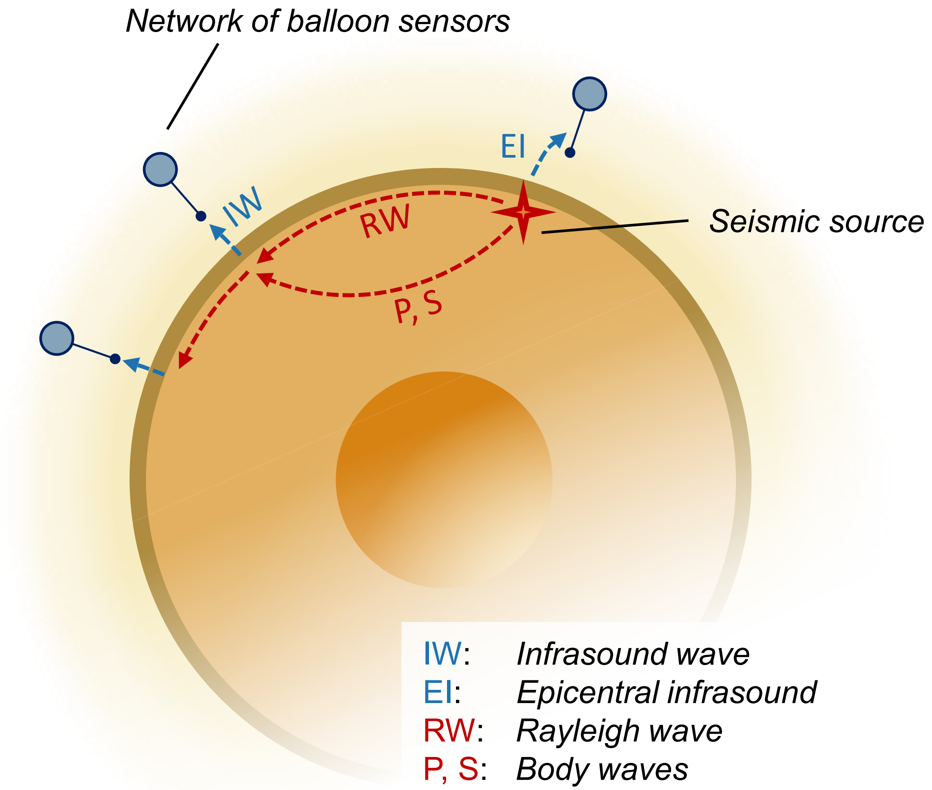
Scattering



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

Balloon seismology for planetary exploration



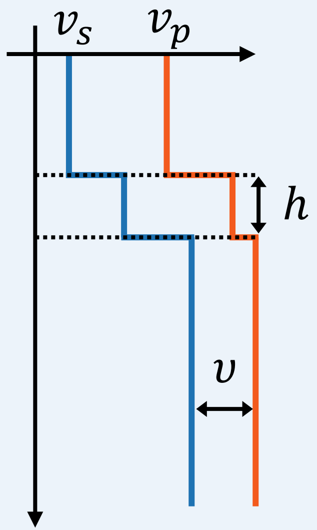
Inversion challenges

- How to process seismic data of unknown origin to **simultaneously invert source & subsurface?**
- Validation of inversion method?
- How sensitive is the inversion to number of balloons & detected phase types?
- What is the uncertainty of inverted source & subsurface parameters?

Source origin? Subsurface velocities?

Inversion method - McMC

Subsurface model



Source location and time

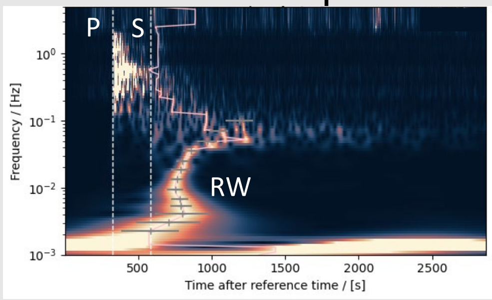
t_s h_s lat_s lon_s

Forward model

Arrival times

$$t_s + \underbrace{\begin{matrix}\Delta t_P \\ \Delta t_{RW}(f) \\ \Delta t_S\end{matrix}}_{\text{Seismic propagation}} + \Delta t_{air}$$

Data: arrival picks



$\neq$

Misfit + **Priors**

(bounds on $v_s, h, r_s \ldots$)

Bayesian approach: Markov chain Monte Carlo to explore the parameter space.

Python module emcee

Posterior probability

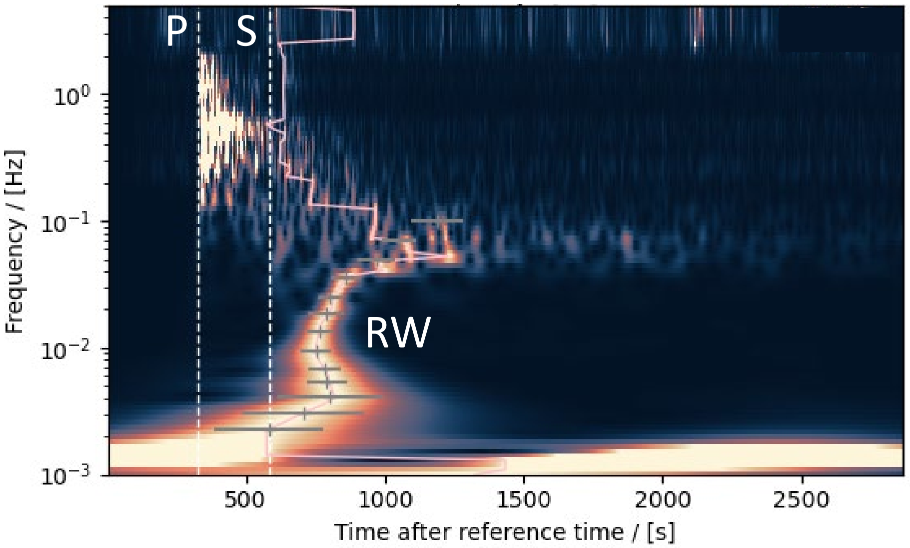
$(v_s, v, h, t_s, h_s, lat_s, lon_s)$

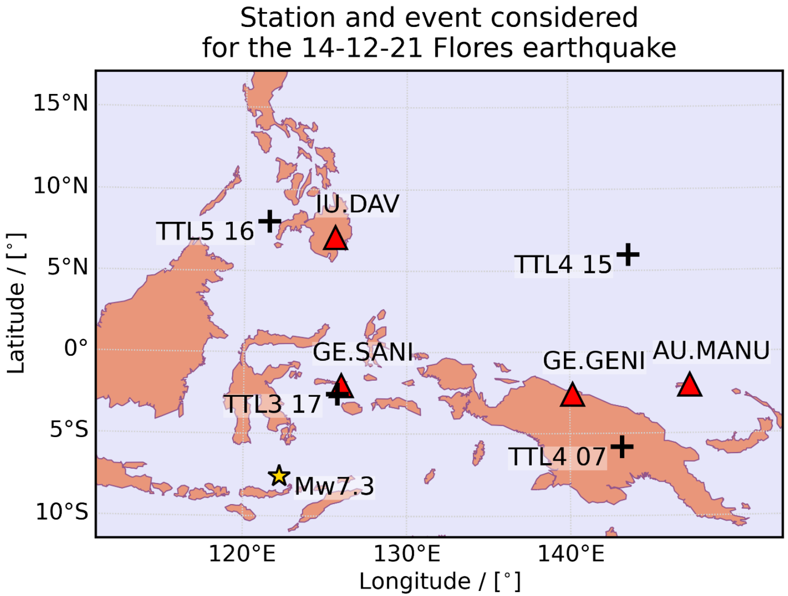
Distribution of parameters

Validating the inversion with the Flores event

Test of the inversion method with:

1) **Pure seismic data**, using only vertical component to pick P, S, RW.
2) **Pressure traces** from four Strateole2 balloons.

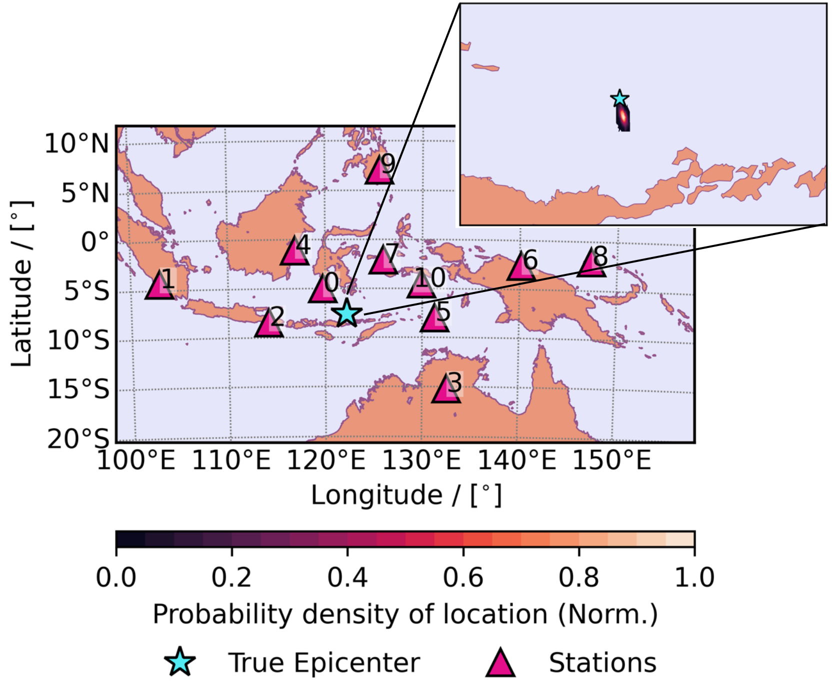


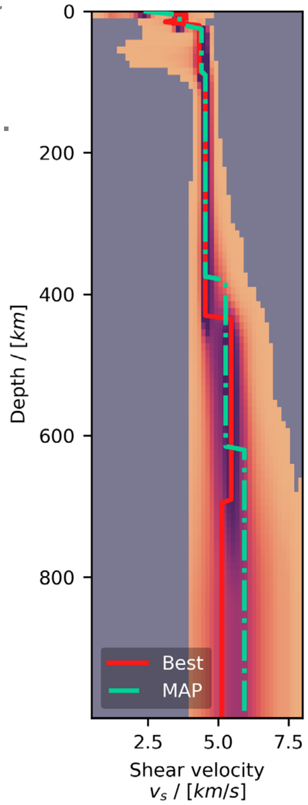


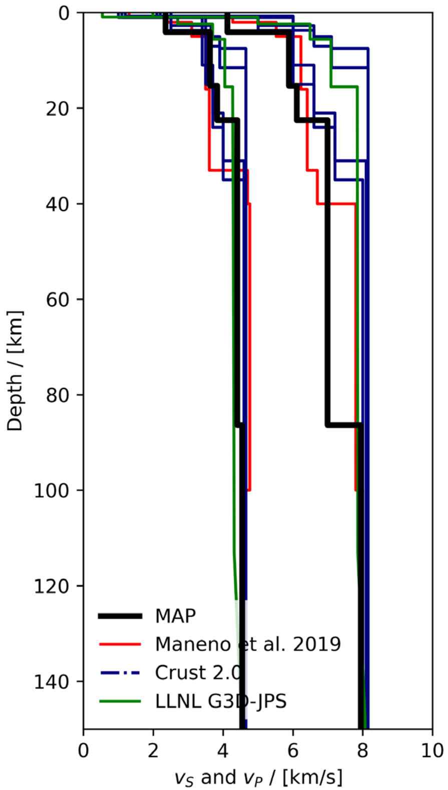
Picks selected using filter banks and Frequency-Time analysis at a station MANU.

Flores, pure seismic inversion with 11 stations

→ P, S and RW arrivals from the *vertical component* of 11 seismic stations.
→ Build a reference subsurface model for the region. (Maximum A Posteriori).

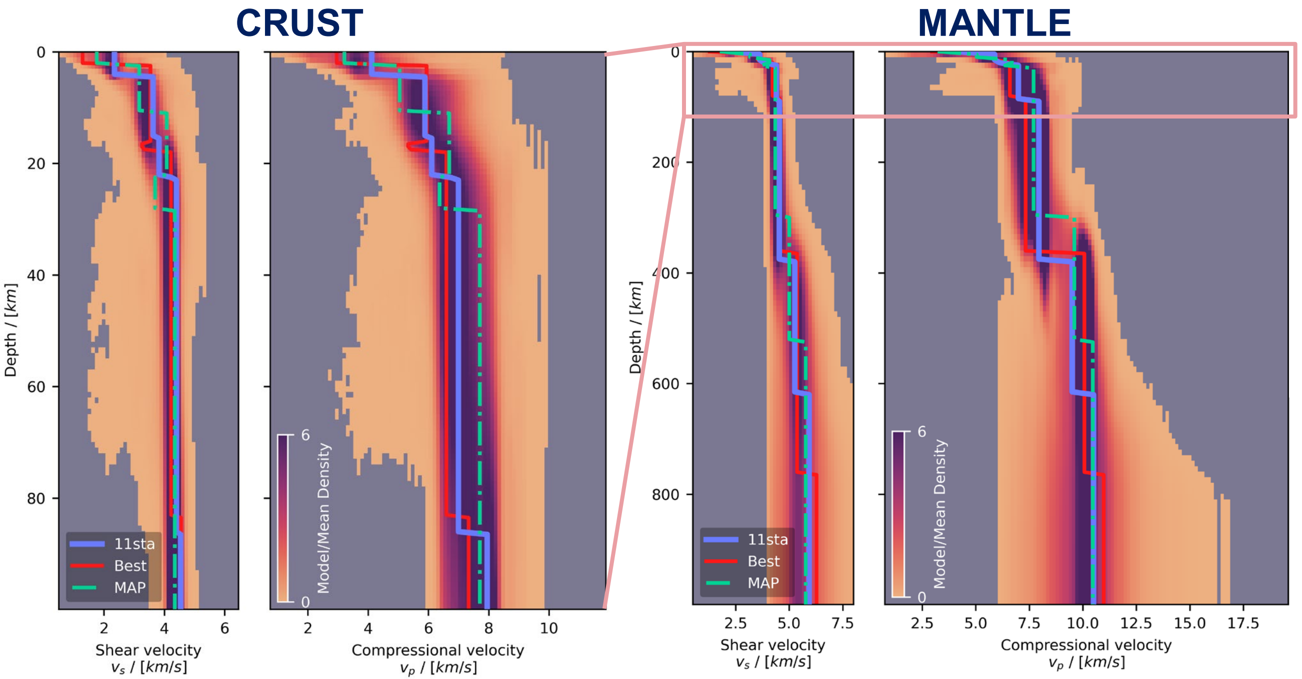


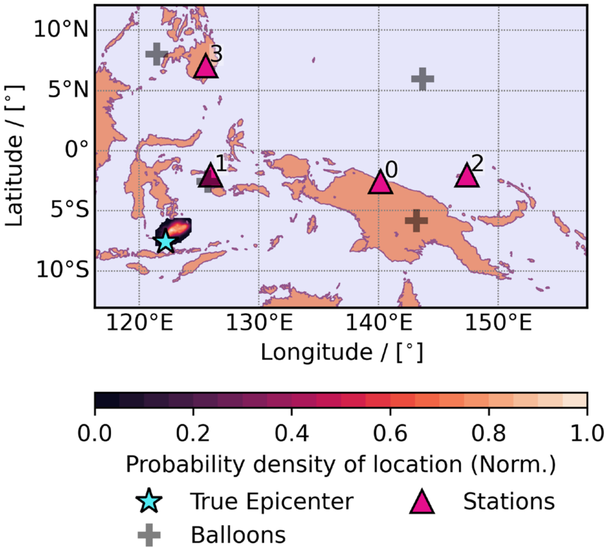




Flores, pure seismic inversion with 4 stations

Next, we restrict ourselves to the 4 seismic stations closest to the Strateole2 stations. A similar subsurface model is retrieved, with higher uncertainty.

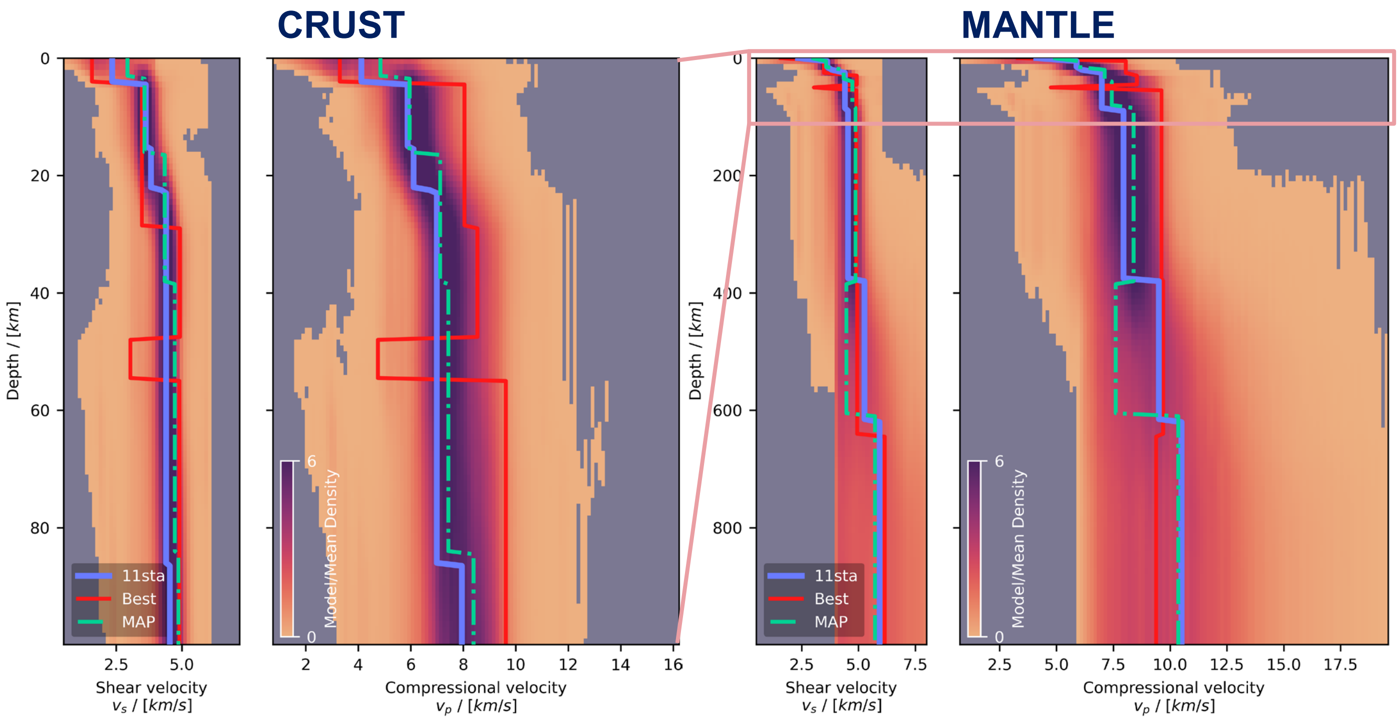


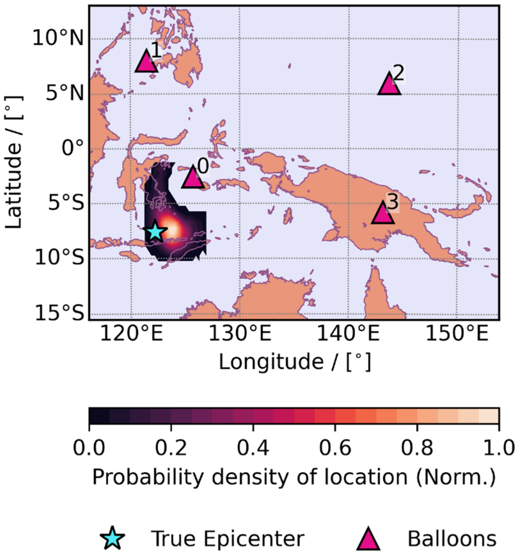


*In **blue**: MAP model obtained with 11 stations.*

Flores, balloon inversion

4 P picks, 2 S picks, 2 RW picks among the four balloons.

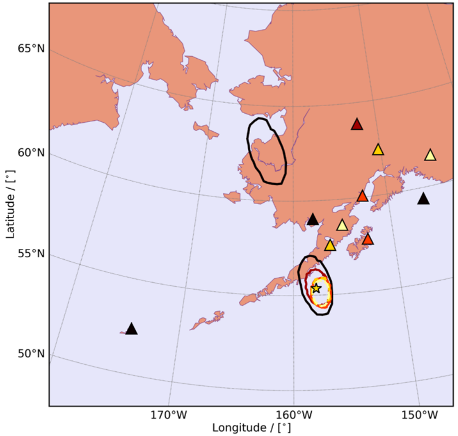




*In **blue**: MAP model obtained with 11 stations.*

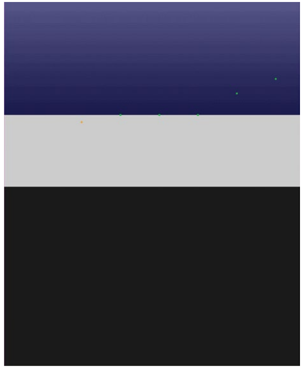
Perspectives for Venus seismology

We now have a validated framework to invert source information and subsurface properties based on P, S and RW arrival times at a balloon station.



Challenges on Venus:

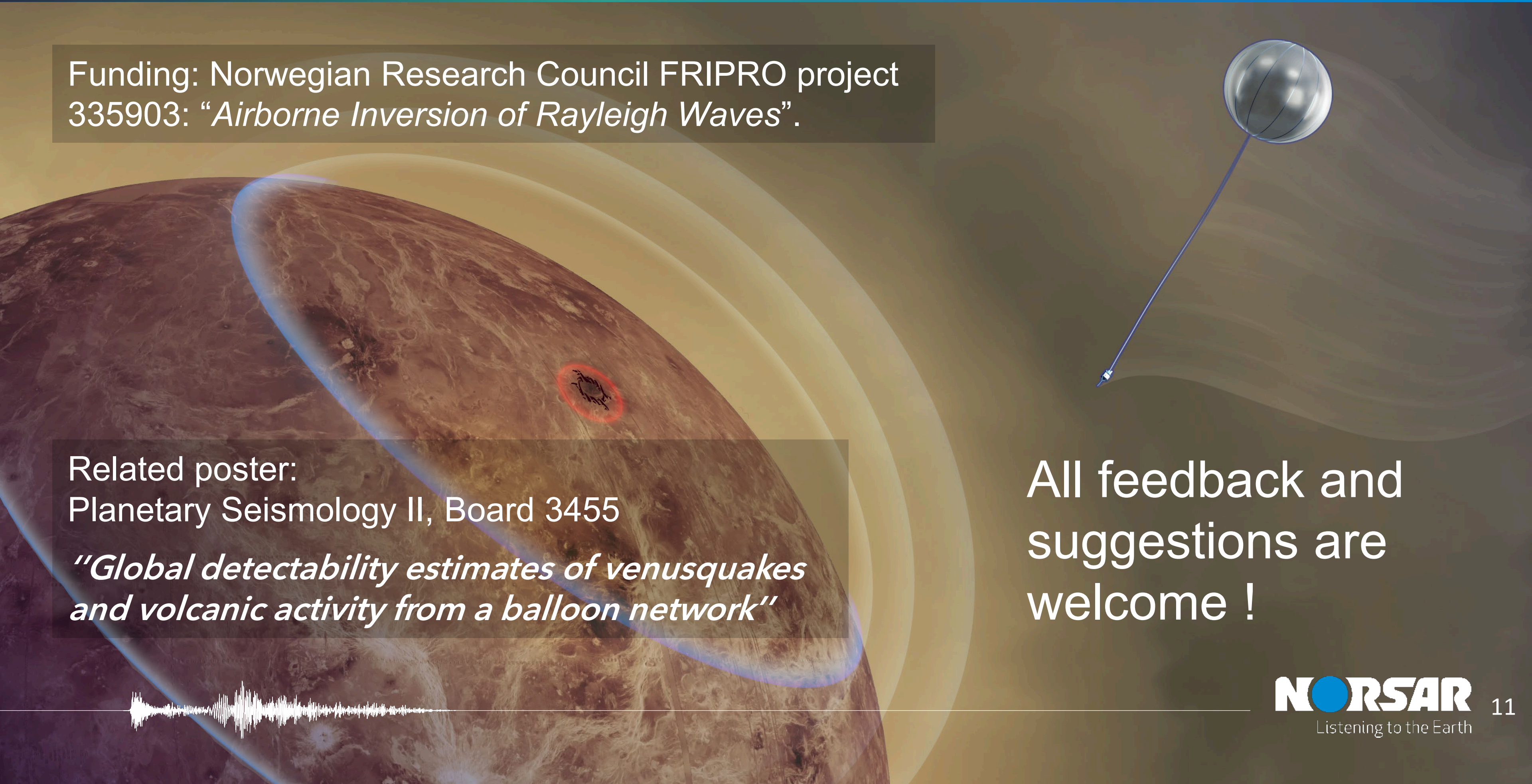
- Poor station coverage / poor azimuthal coverage.
- Effect of realistic noise patterns ? No microbaroms but turbulences...
- **How to best identify seismic phases with a single-component pressure signal and no directivity information?**
- Complementing balloon data with airglow imaging: refine prior source location and dispersion measurements?



Next steps:

- Generate synthetic data (normal modes, SPECFEM2D-DG).
- Establish a realistic noise environment.
- Apply to different inversion scenarios.

Thank you for your attention



Funding: Norwegian Research Council FRIPRO project 335903: “*Airborne Inversion of Rayleigh Waves*”.

Related poster:
Planetary Seismology II, Board 3455

"Global detectability estimates of venusquakes and volcanic activity from a balloon network"

All feedback and suggestions are welcome !

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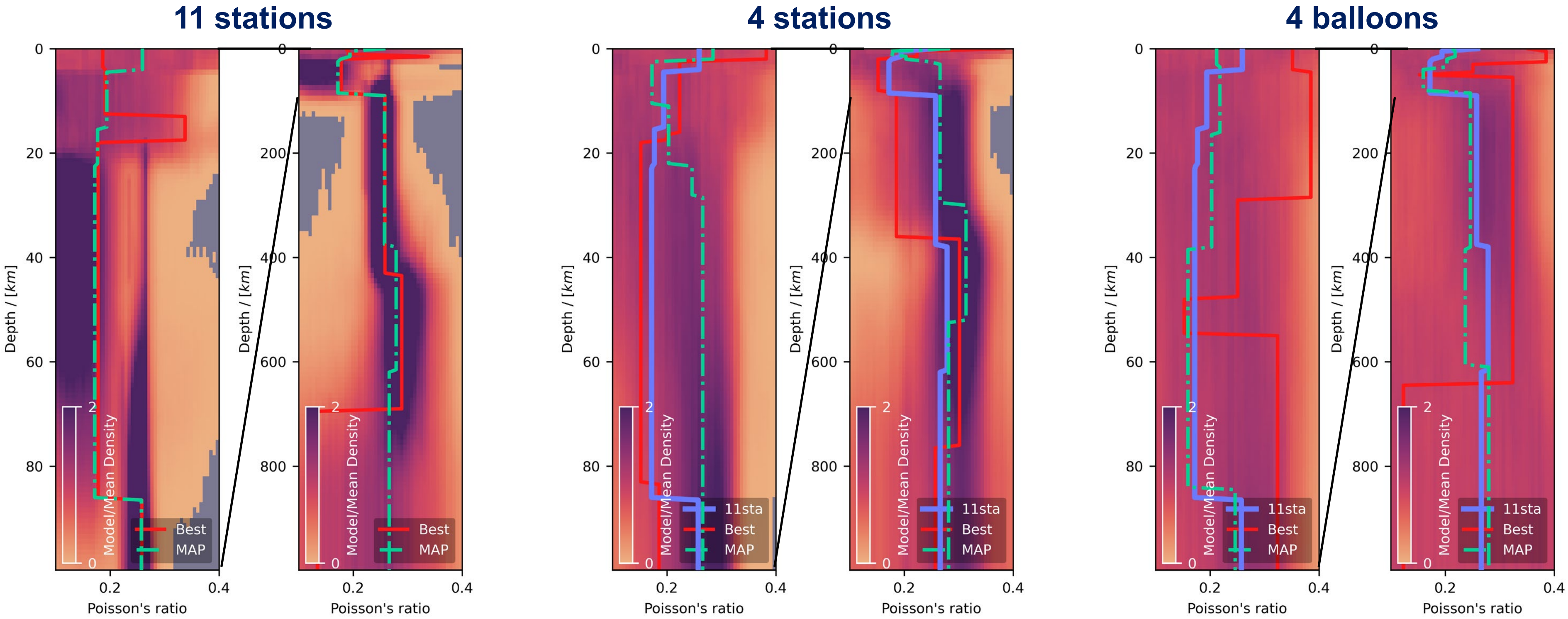
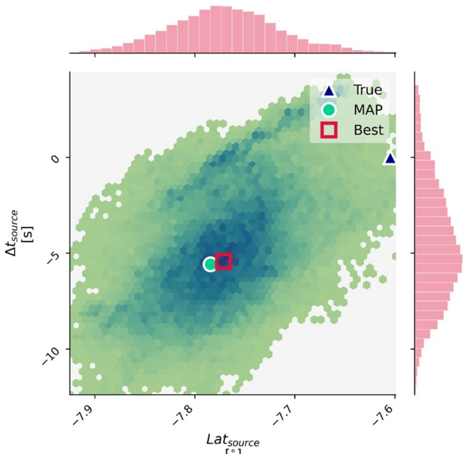
Inversion results: Poisson ratio

With 4 balloons, P-wave measurement are too uncertain to constrain the Poisson ratio in the crust or mantle.

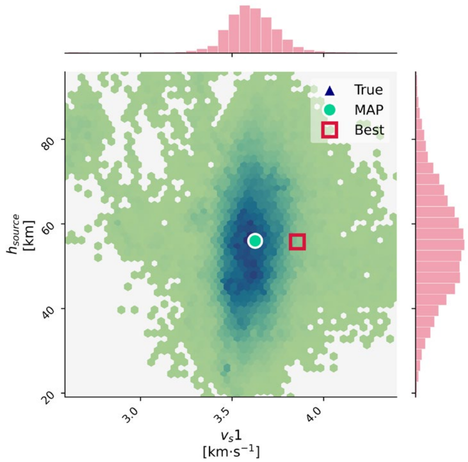


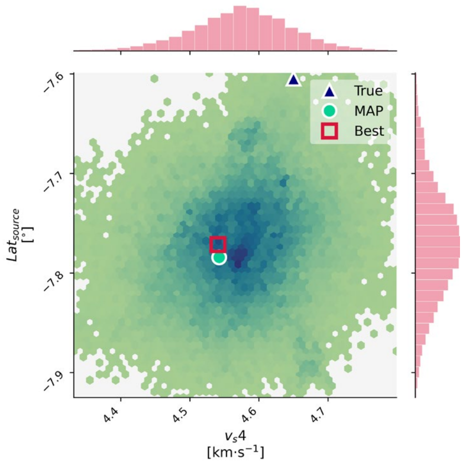
Marginal distribution of parameters

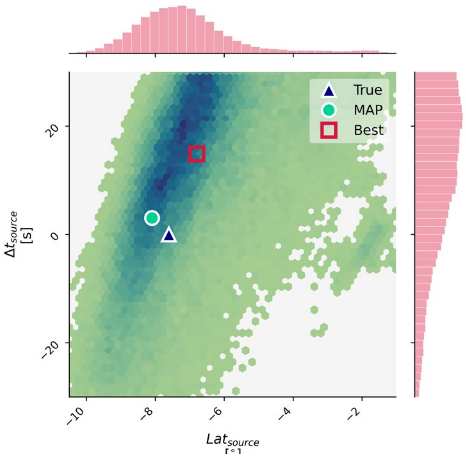


Source time vs source location.
Source depth versus v_s
Source location versus v_s

10 stations

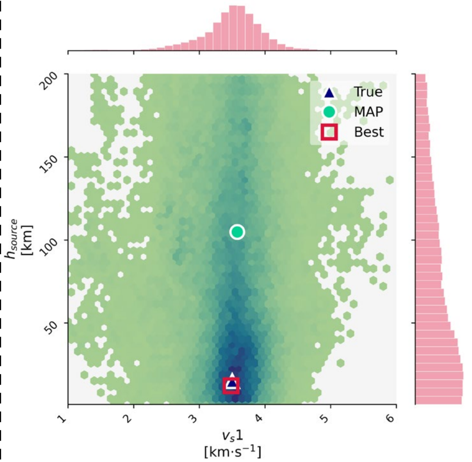


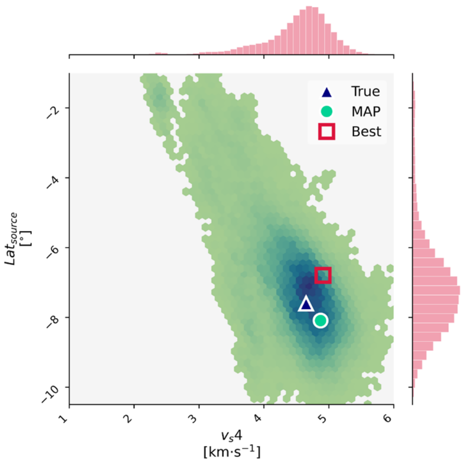




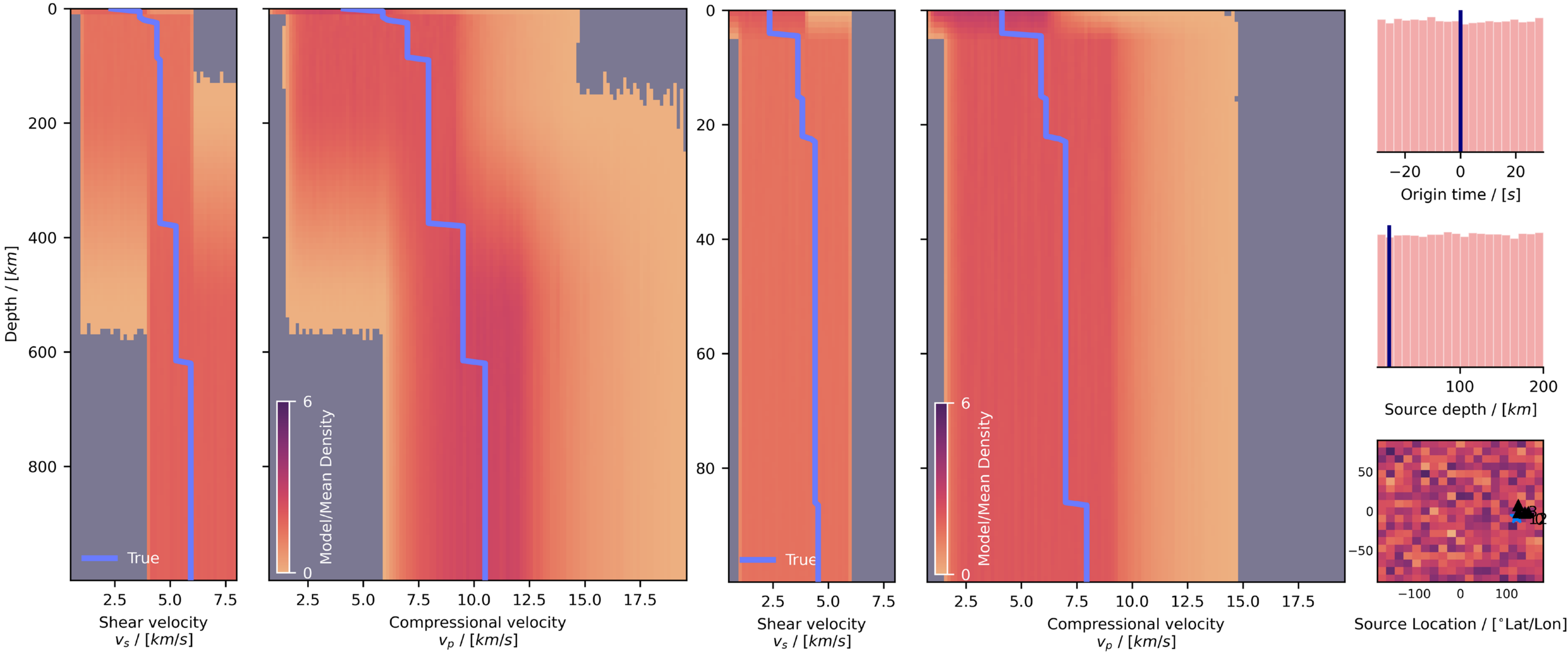
Adding information reduces trade-offs.

4 balloons

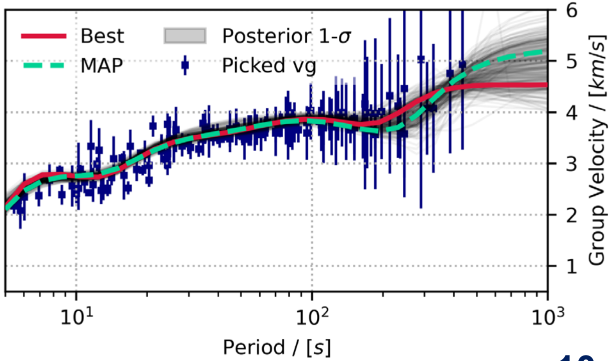


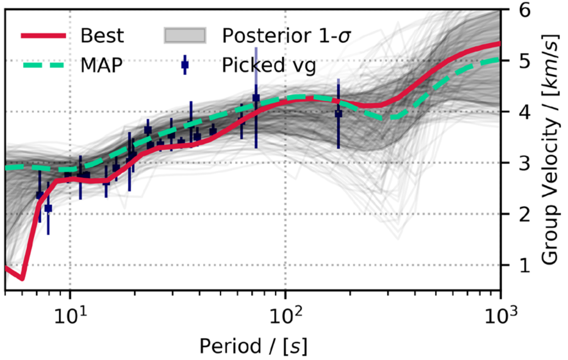


Prior distribution of model parameters



Quality of fit to the data

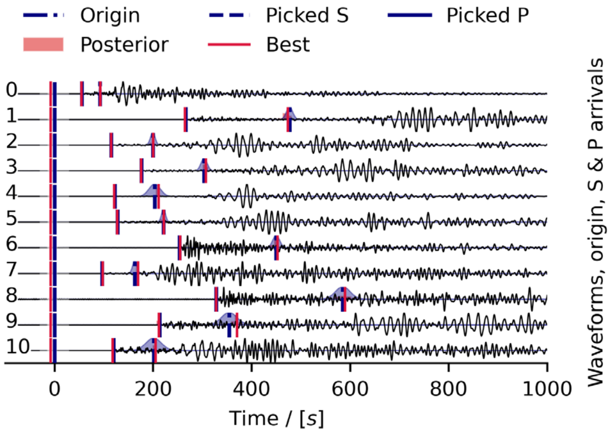




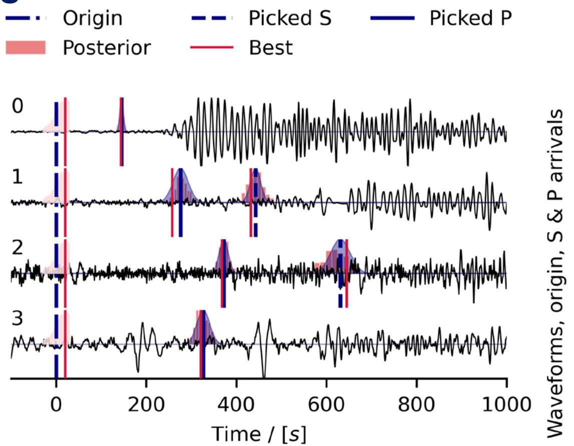
Group velocity curves from measured arrival times (blue) compared to the group velocity curves of the posterior distribution.

10 stations

4 balloons



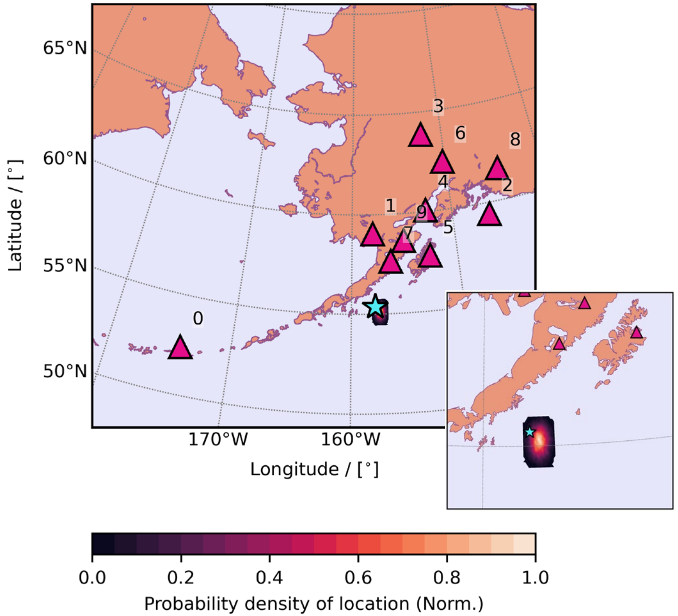
True origin time and picked S and P times, compared to the arrival time calculated from the posterior models.



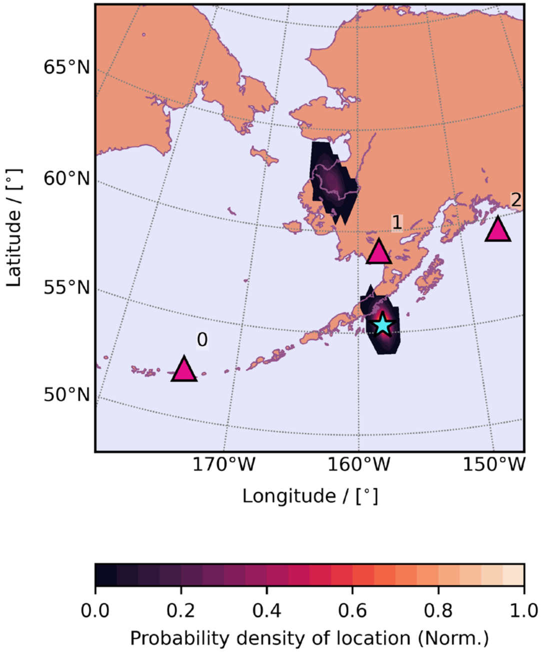
Inversion results: Alaska

We use pressure recordings from barometers collocated with seismic stations during a Mw 8.2 earthquake. We only pick S and Rayleigh waves.

10 stations



3 stations



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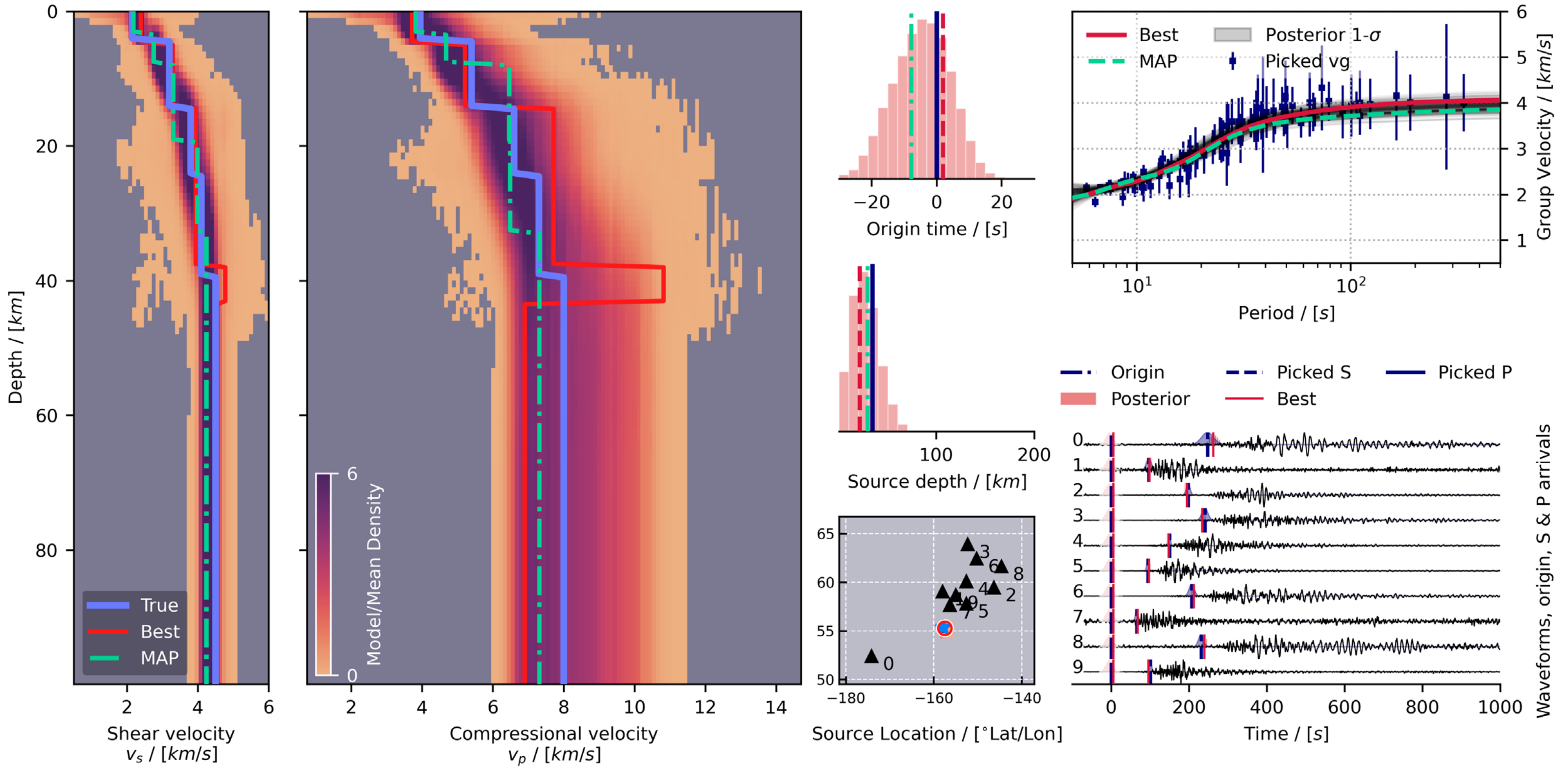
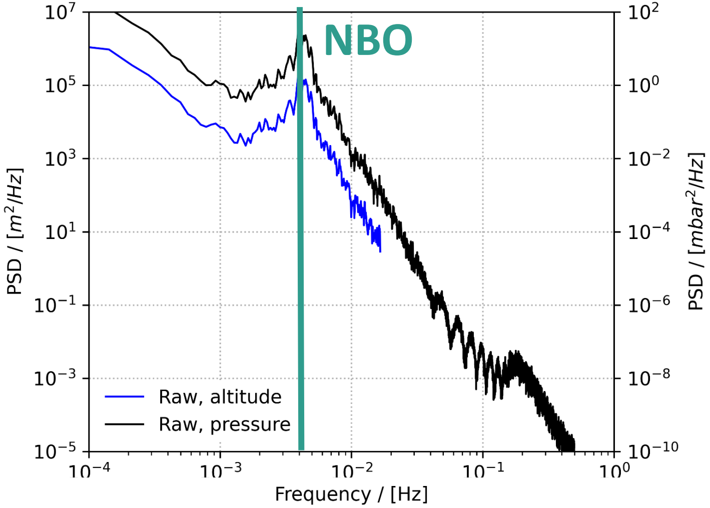
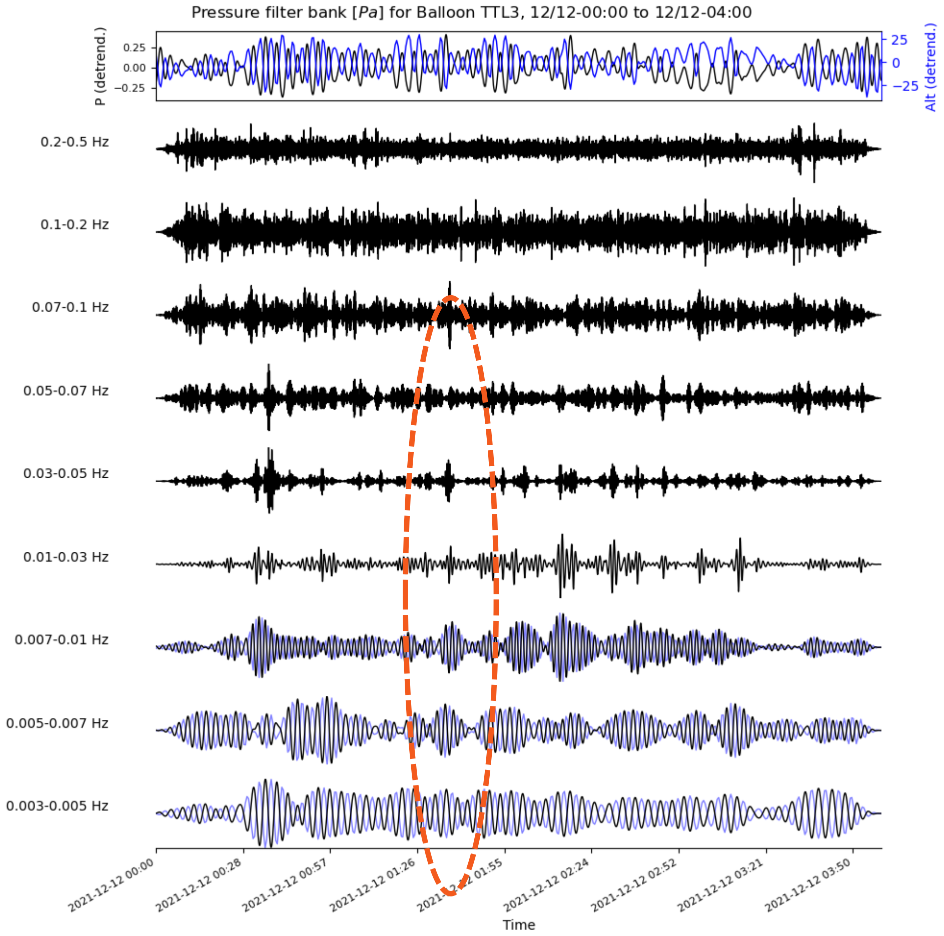


10 stations

Balloon oscillation and noise





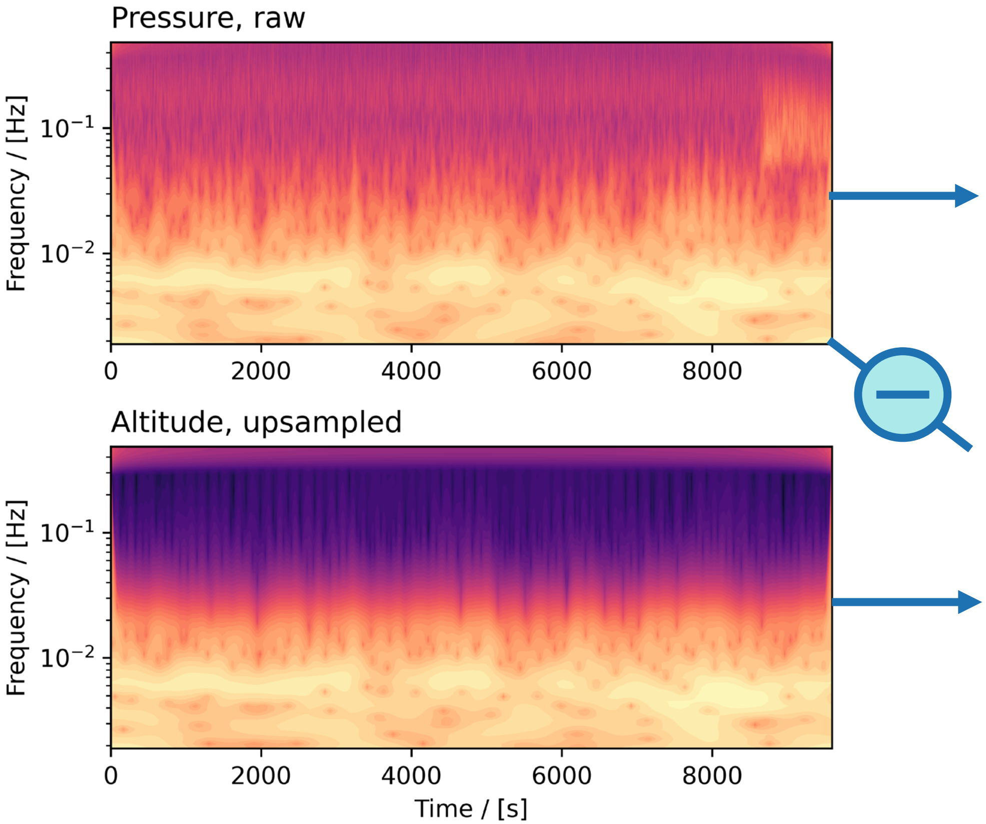
Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

Good coherence up to GPS Nyquist frequency, perhaps even higher: **broadband energy bursts** follow altitude changes.

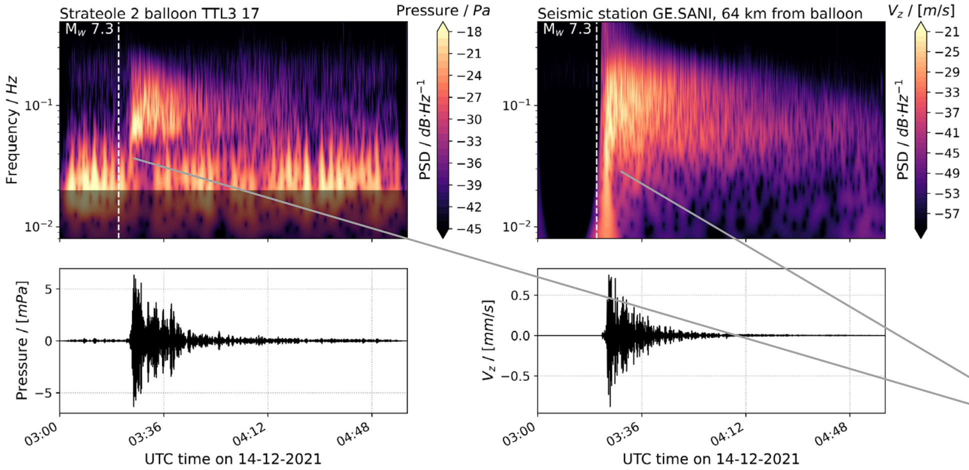
Massman, W. J. *Journal of Applied Meteorology* **17**, 1351–1356 (1978).

Improving the SNR at low frequency

There is an exponential relation between pressure and altitude: use the low frequency GPS data to correct the pressure recordings



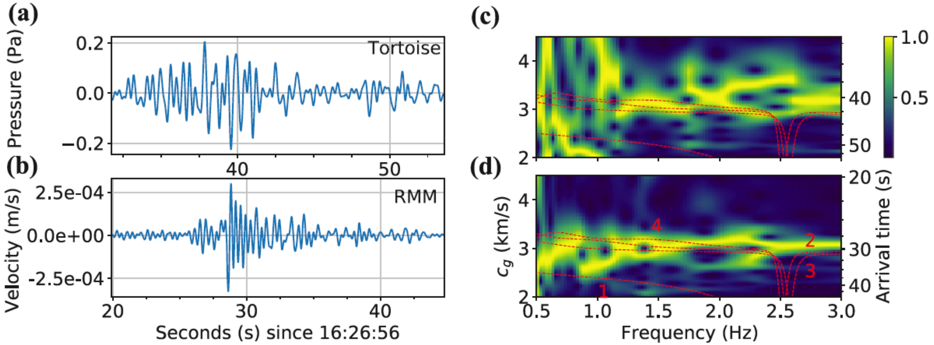
Balloon seismology on Earth



Good agreement between seismic ground sensors and airborne infrasound recordings

Dispersed Rayleigh Wave arrival

14/12/2021 Mw 7.3 Flores Sea earthquake recorded by Strateole2 balloons.

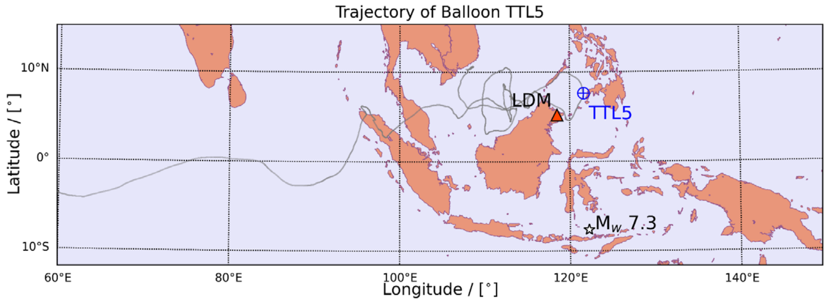


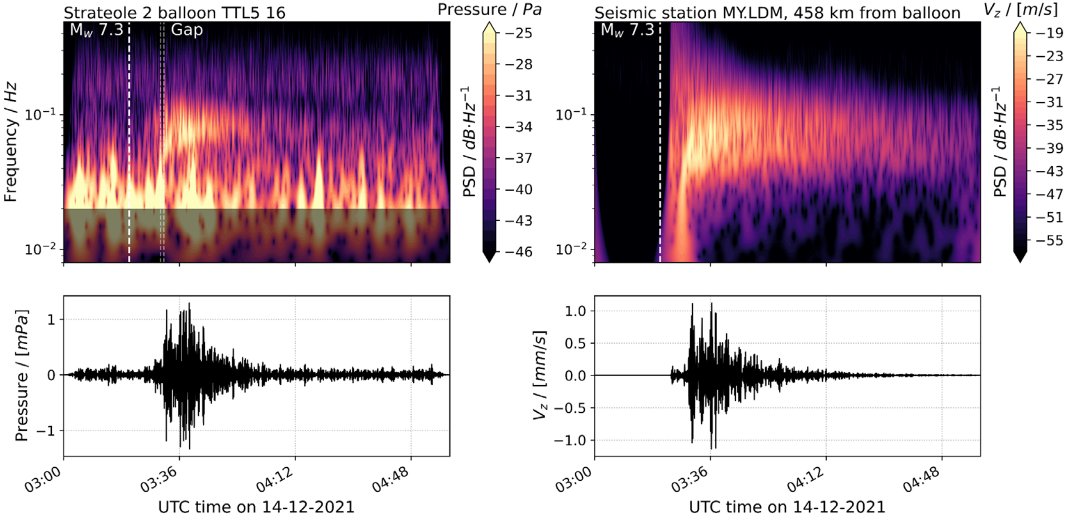
Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), 10.1029/2022GL098844

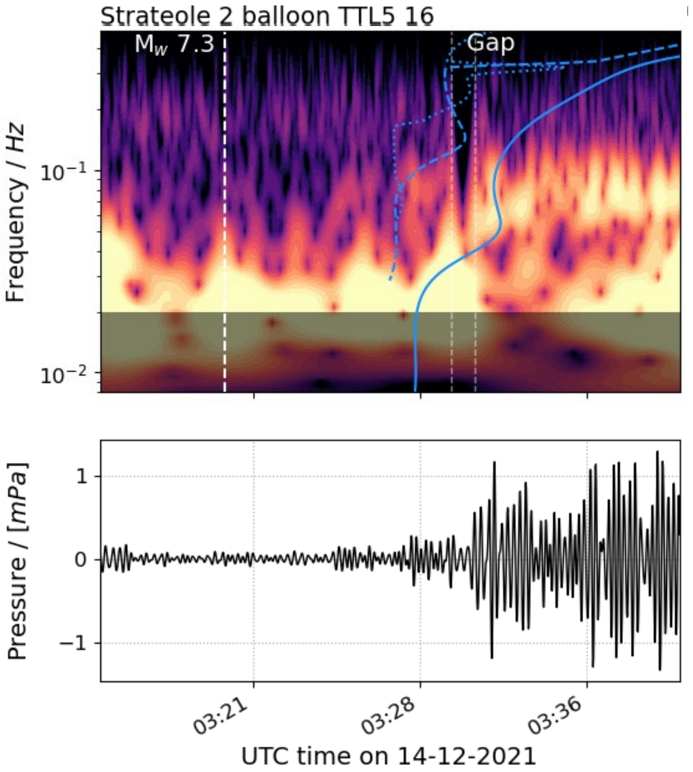
Brissaud, Q. *et al. Geophysical Research Letters* **48**, (2021), 10.1029/2021GL093013

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

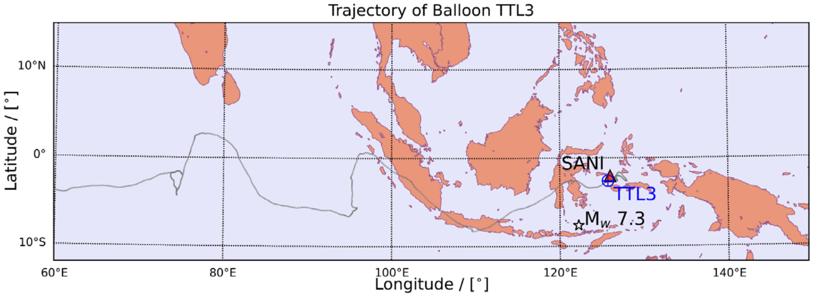
Picking the Rayleigh wave: example of balloon 16

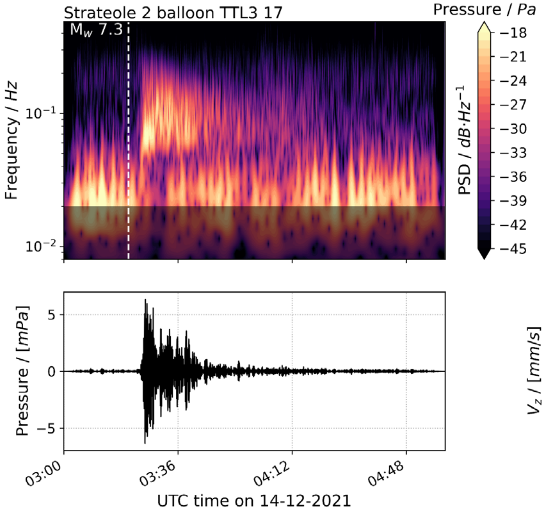


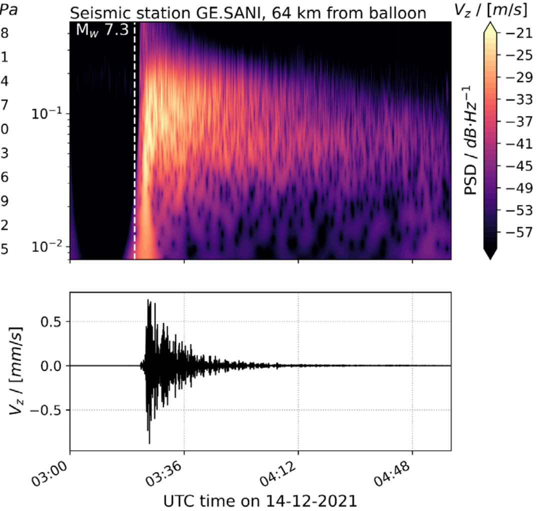


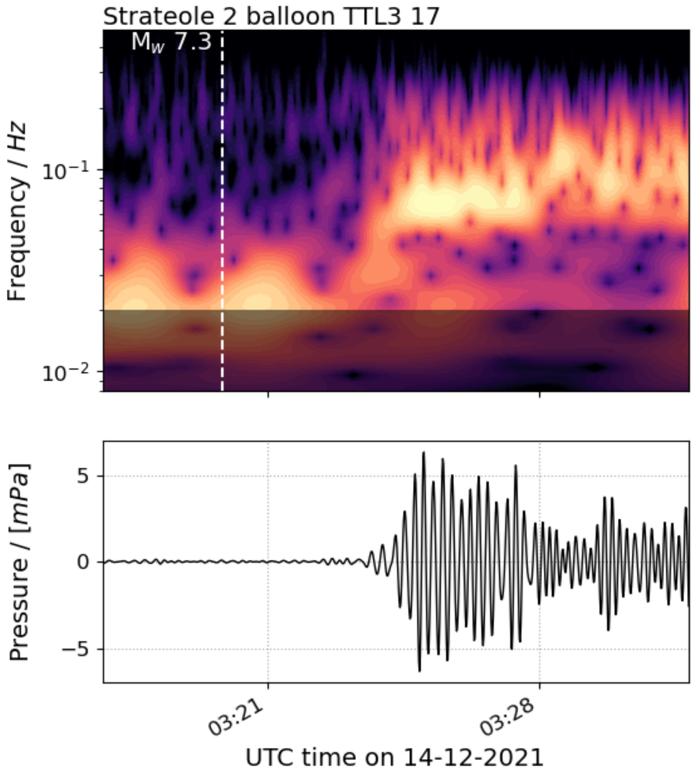


Picking the Rayleigh wave: example of balloon 17

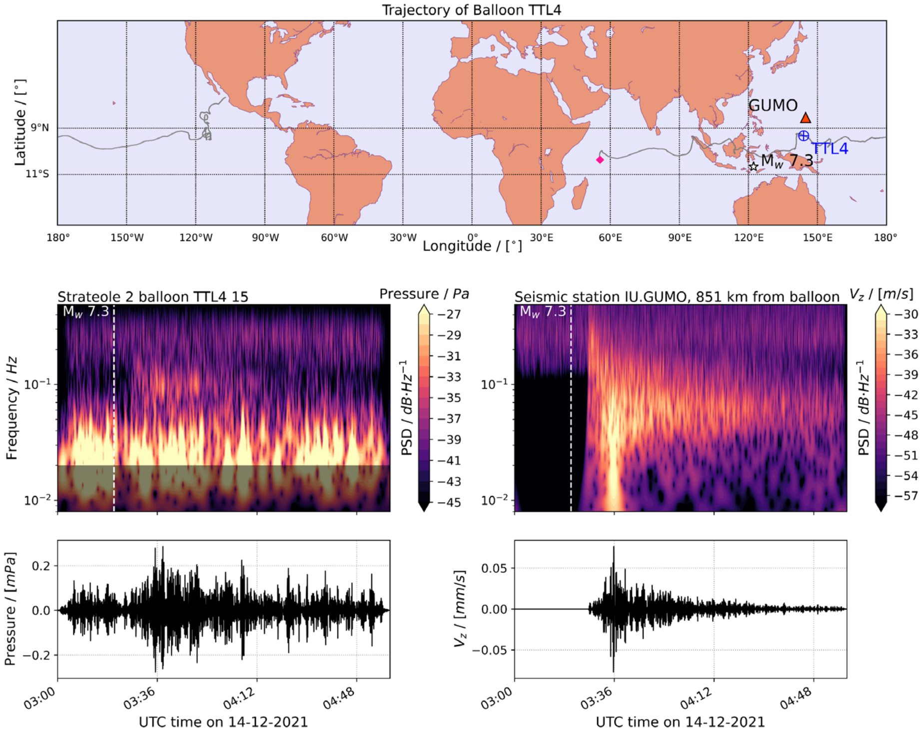


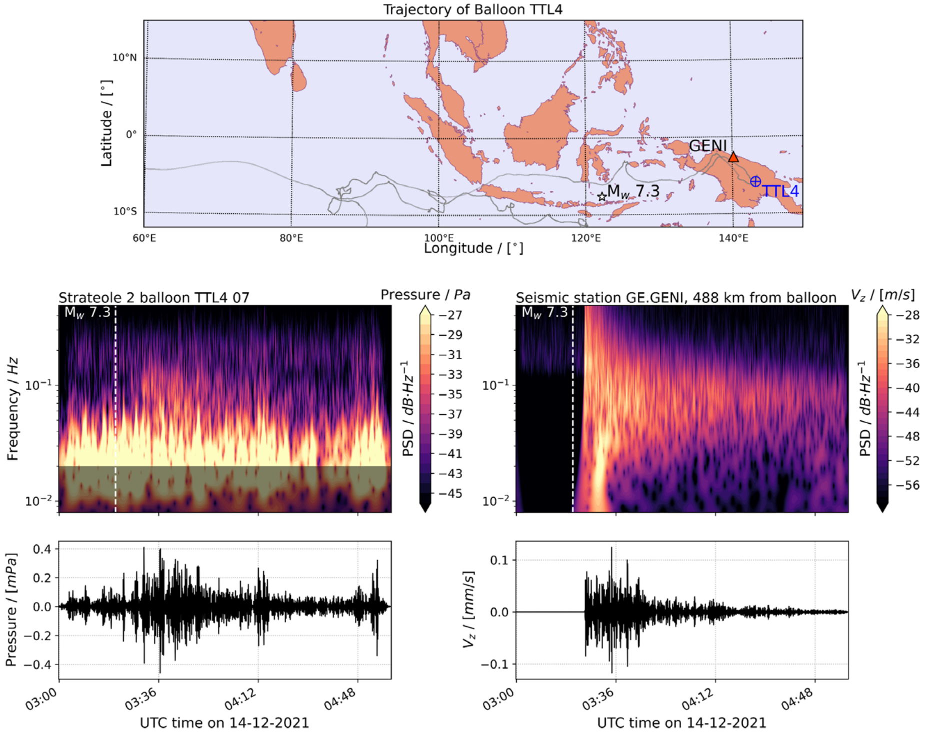






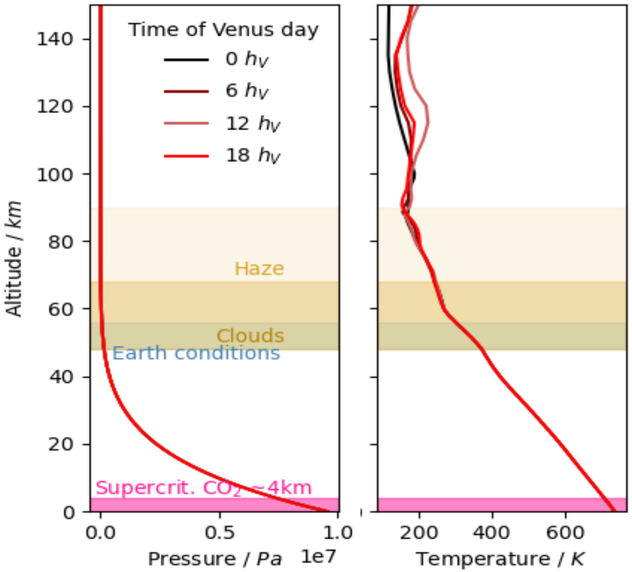
Balloon 15 and 07: a more difficult case





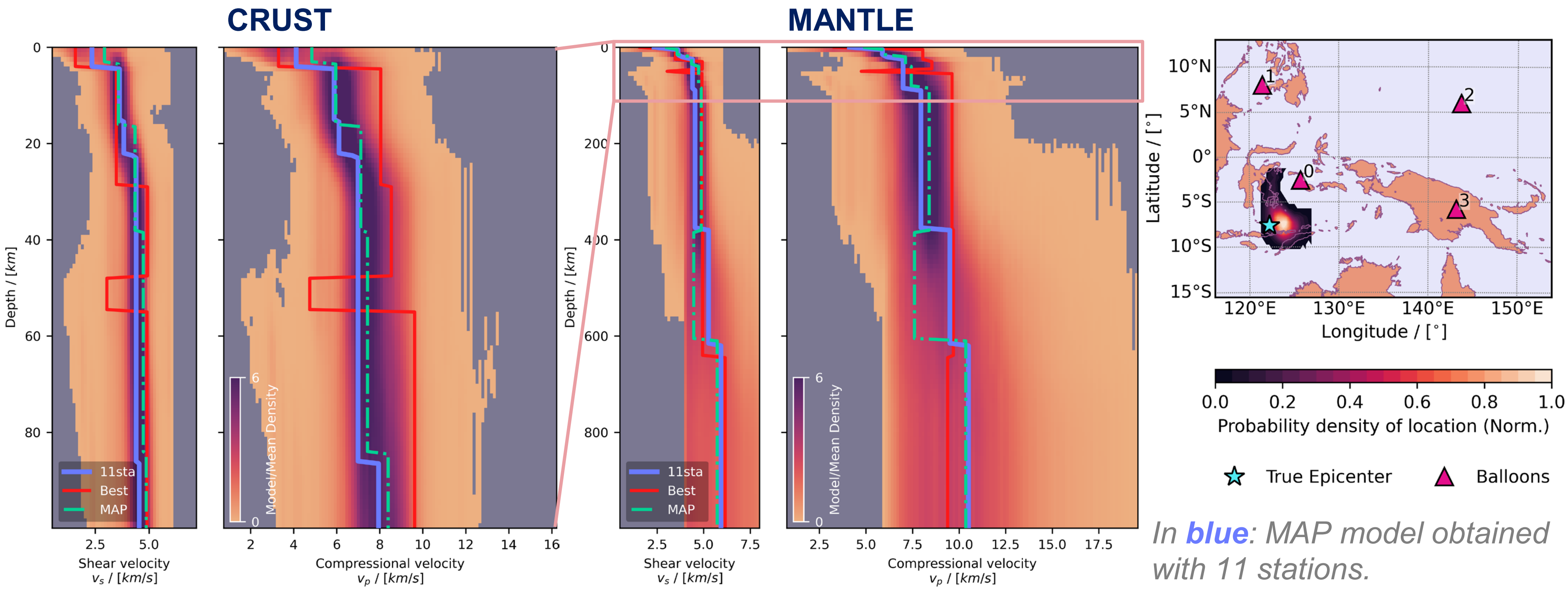
Infrasound propagation on Venus?

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.

Flores, balloon inversion



*In **blue**: MAP model obtained with 11 stations.*

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