



Balloon-Borne Seismology for Subsurface Exploration

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AGU24

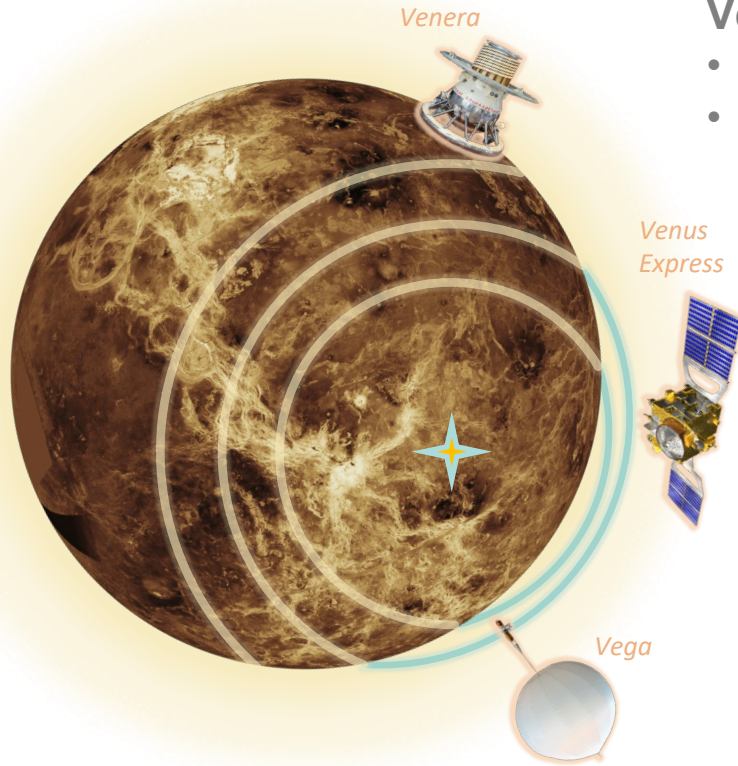


Funded by
The Research
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NORSAR
Listening to the Earth

Venus seismology concepts



Venus:

- Hot surface ($\sim 470^{\circ}\text{C}$)
- Dense atmosphere ($\sim 60 \times \text{Earth}$)

Garcia, R. F., et al. *Earth and Space Science*, **11**, (2024).
[10.1029/2024EA003670](https://doi.org/10.1029/2024EA003670)

Surface sensor.

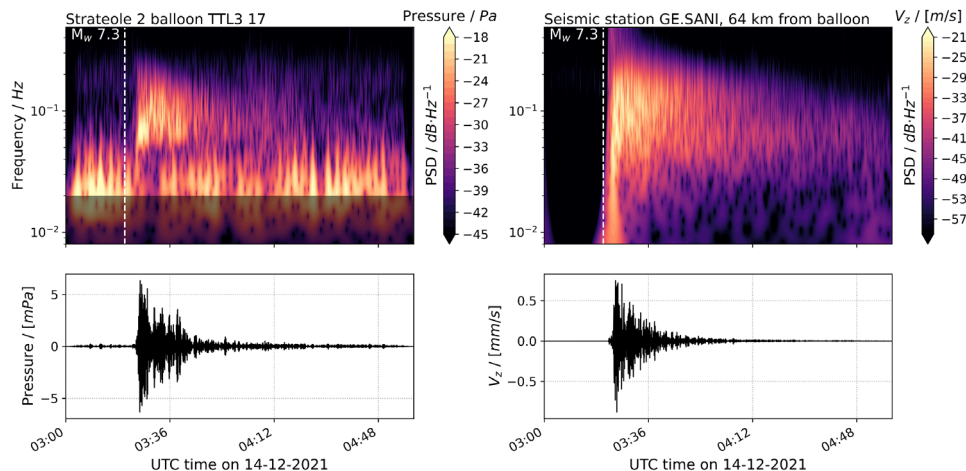
Deployed seismometer. **< 24 h.**

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

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



Balloon seismology on Earth



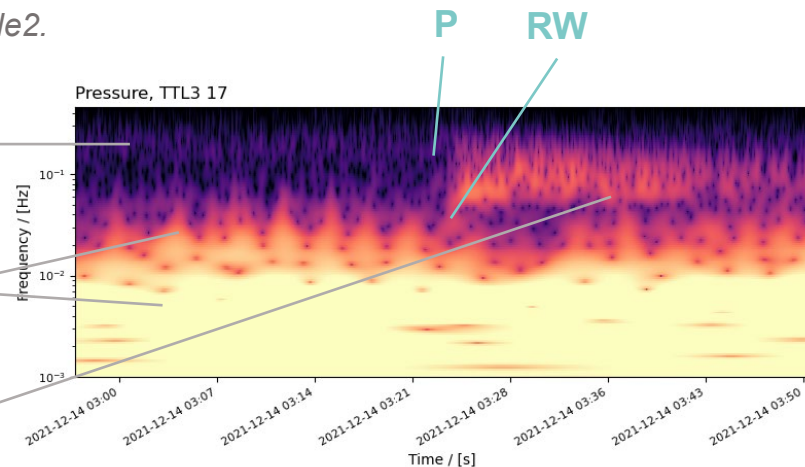
- Good agreement between seismic ground sensors and airborne infrasound recordings.
- Multiple sources of noise in data.

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

Microbaroms

Balloon Buoyancy oscillations

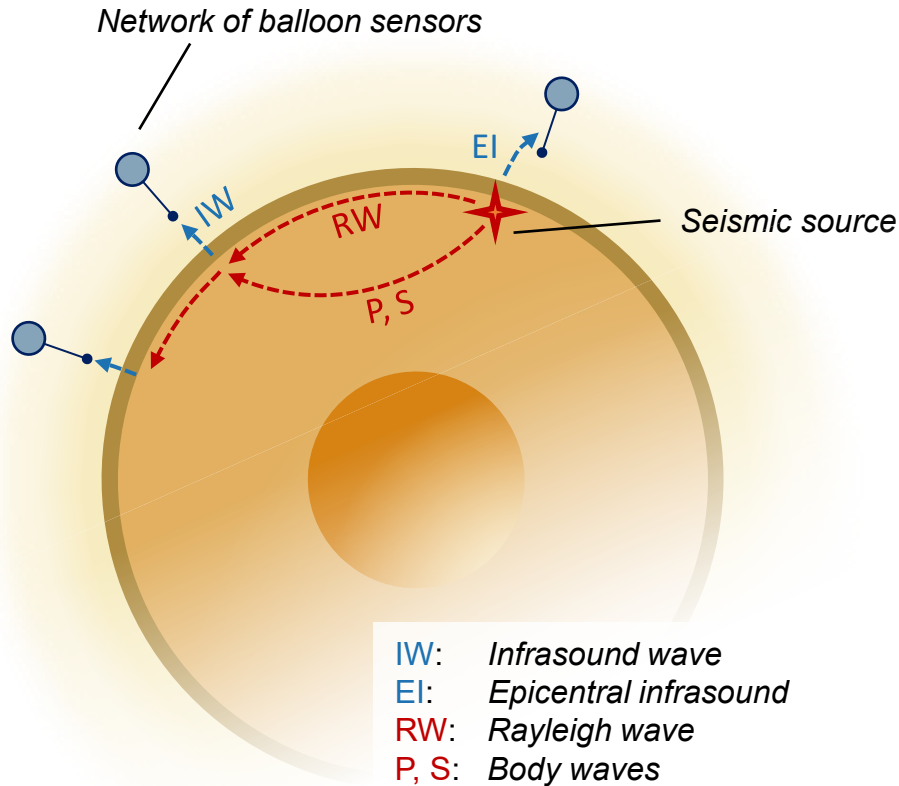
Scattering



Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), [10.1029/2022GL098844](https://doi.org/10.1029/2022GL098844)

Brissaud, Q. et al. *Geophysical Research Letters* **48**, (2021), [10.1029/2021GL093013](https://doi.org/10.1029/2021GL093013)

Balloon seismology for planetary exploration



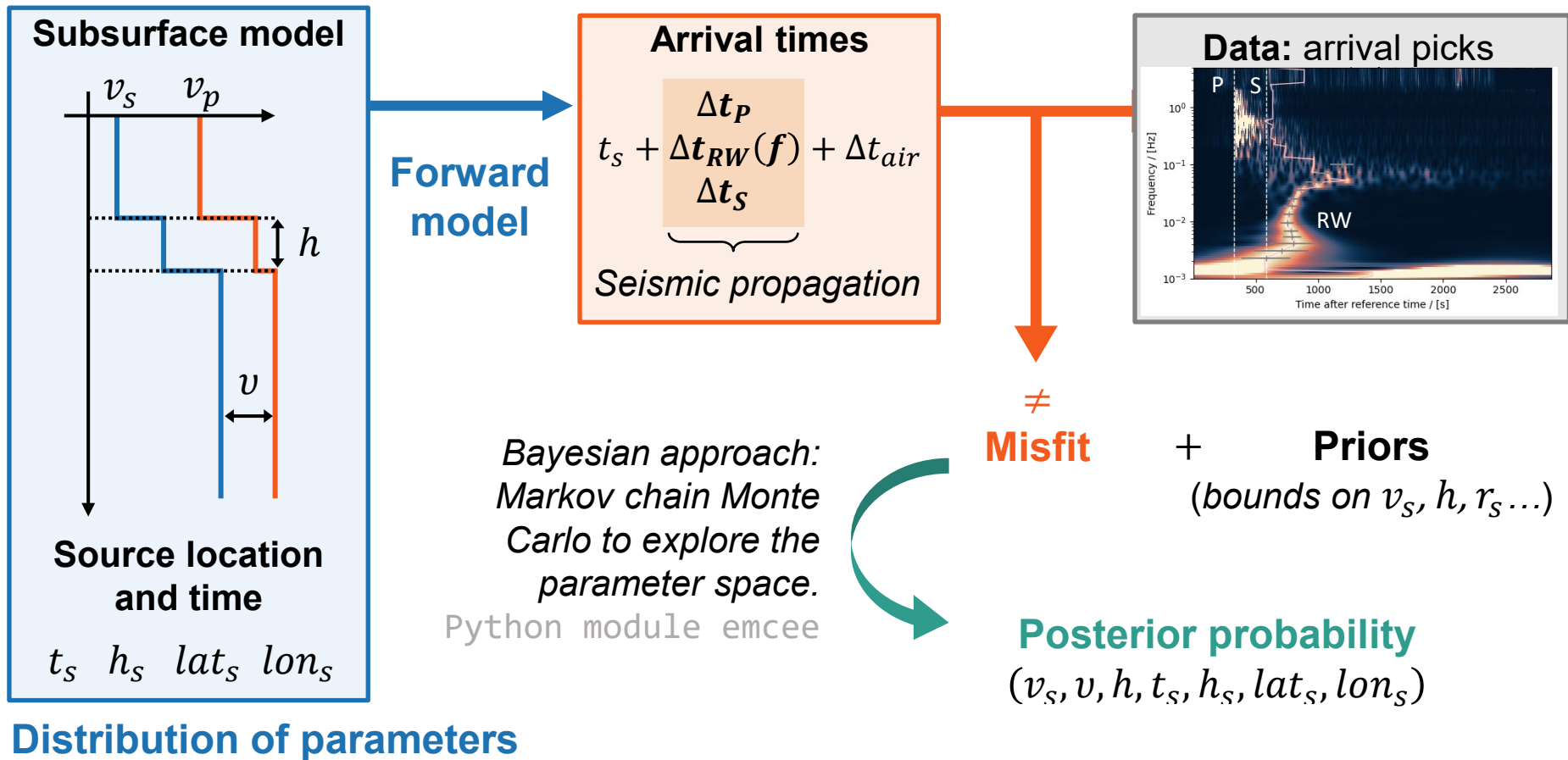
Inversion challenges

- 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?



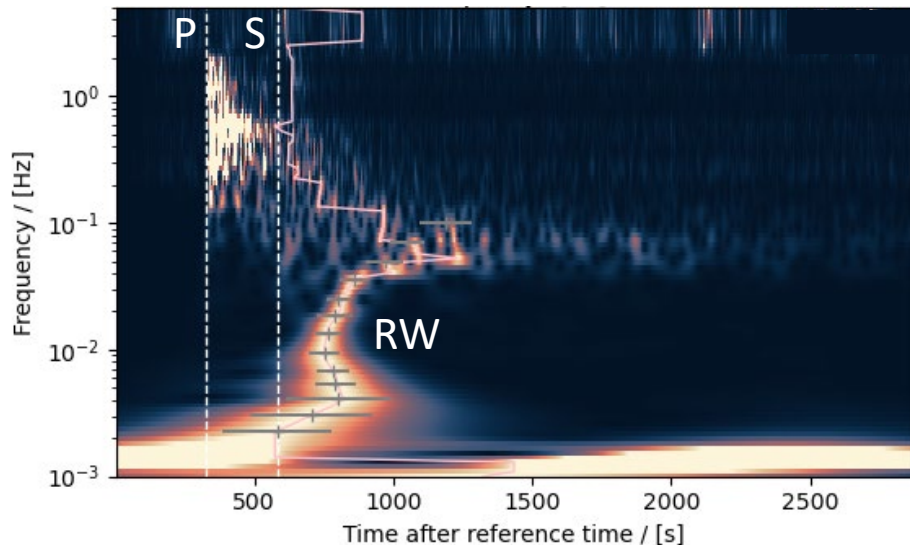
Inversion method - McMC



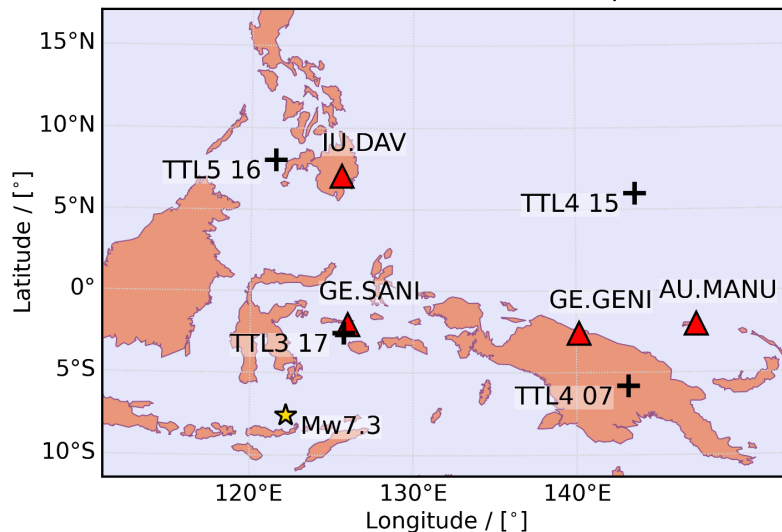
Validating the inversion with the Flores event

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.



Station and event considered for the 14-12-21 Flores earthquake

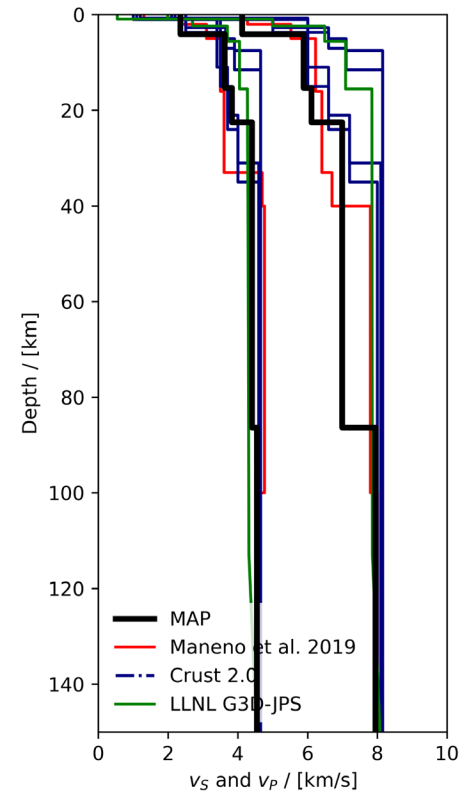
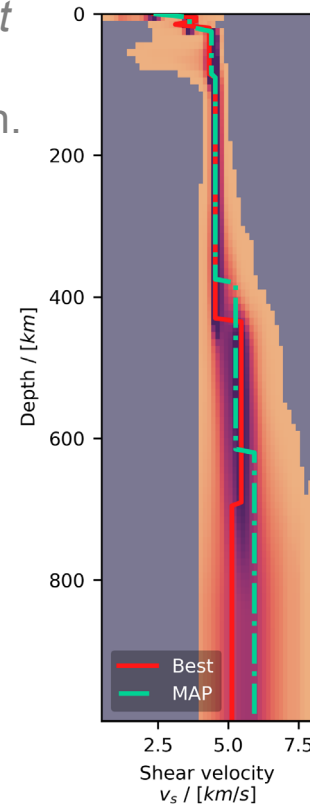
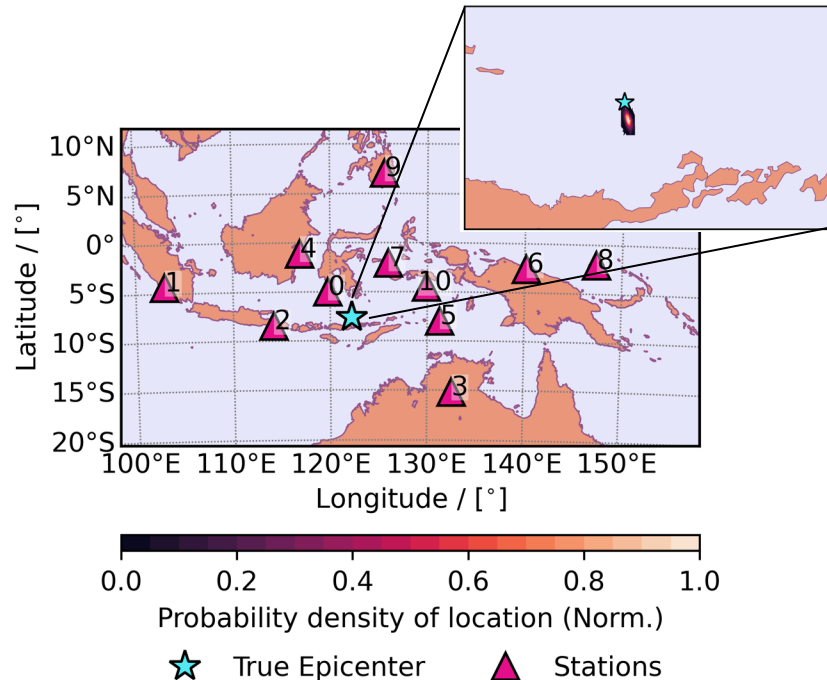


Picks selected using filter banks and Frequency-Time analysis at a station MANU.

Flores, pure seismic inversion with 11 stations

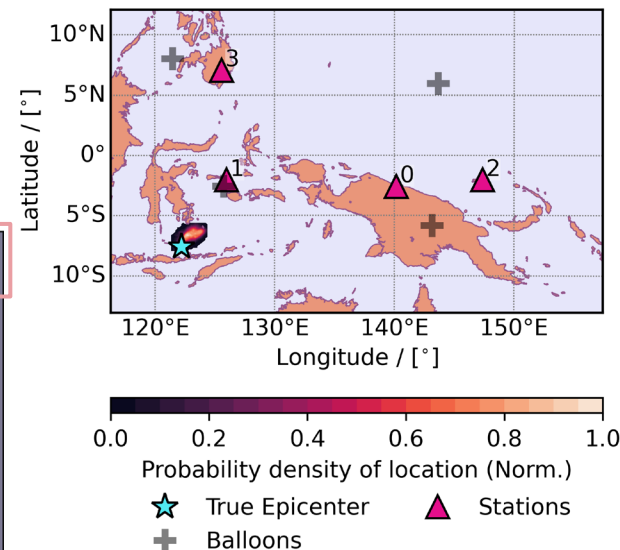
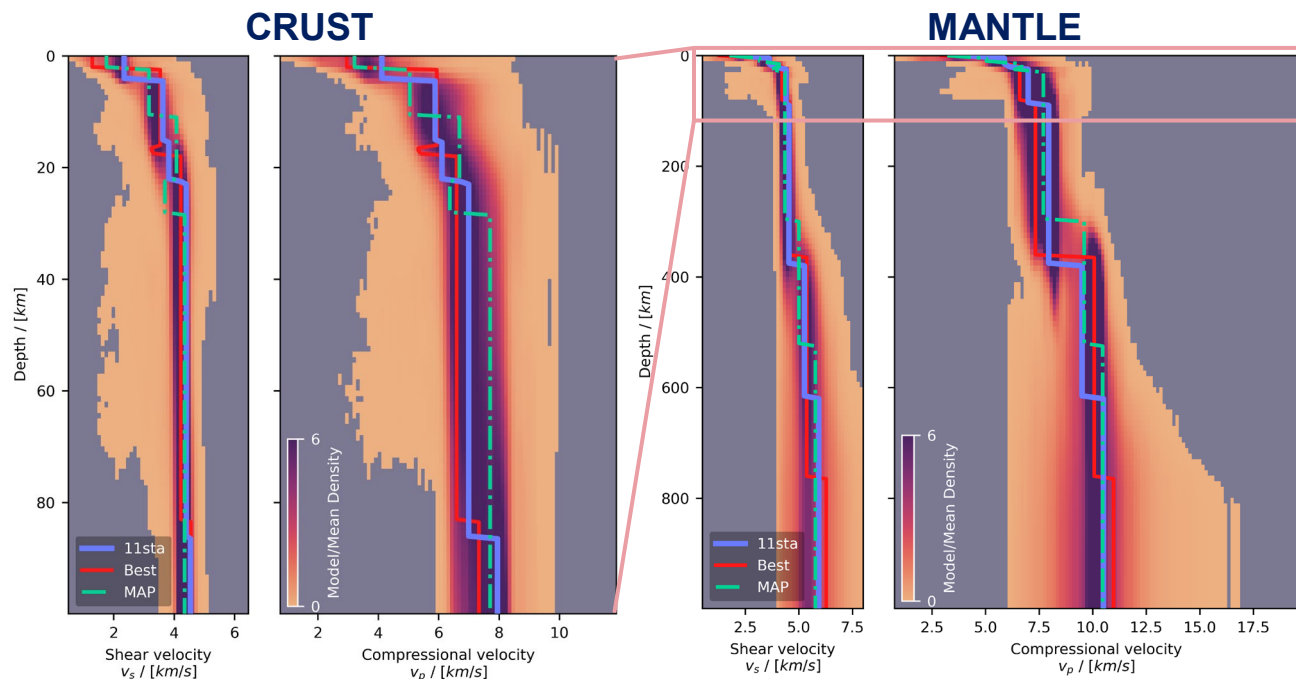
→ P, S and RW arrivals from the *vertical component* of 11 seismic stations.

→ 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.

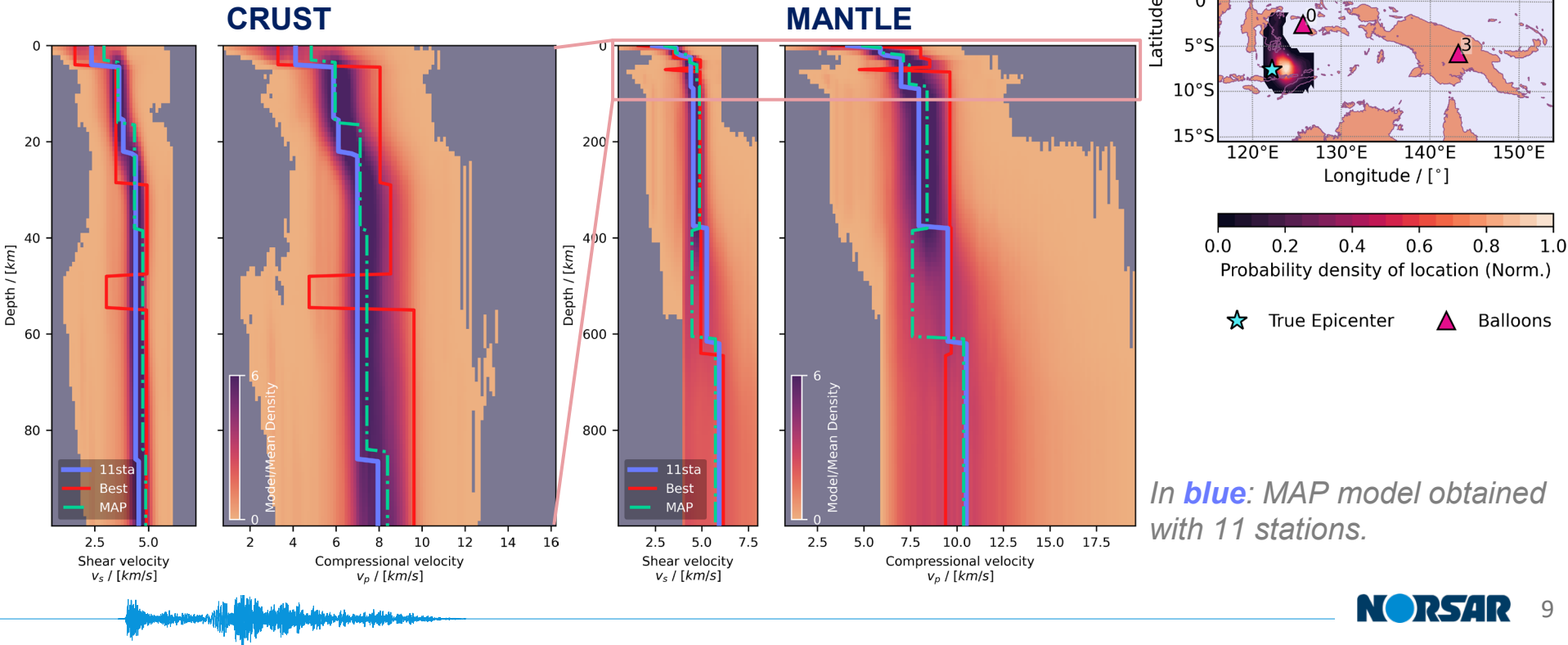


In blue: MAP model obtained with 11 stations.



Flores, balloon inversion

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



Perspectives for Venus seismology

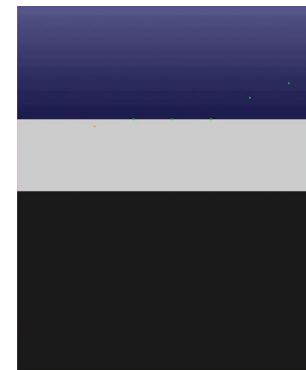
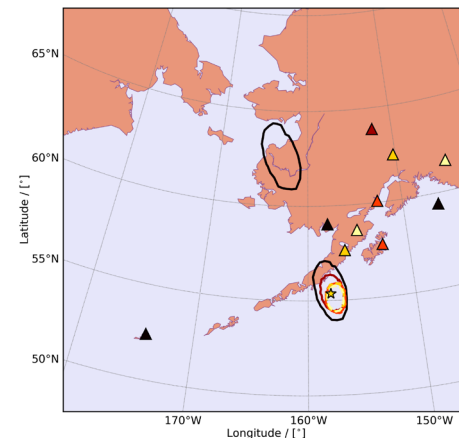
We now have a validated framework to invert source information and subsurface properties based on P, S and RW arrival times at a balloon station.

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:

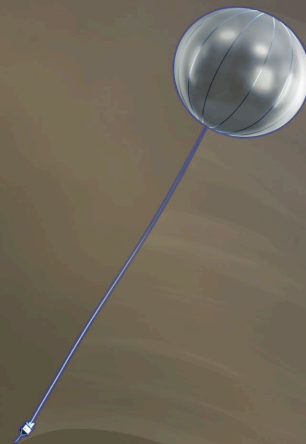
- Generate synthetic data (normal modes, SPECFEM2D-DG).
- Establish a realistic noise environment.
- Apply to different inversion scenarios.



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 !

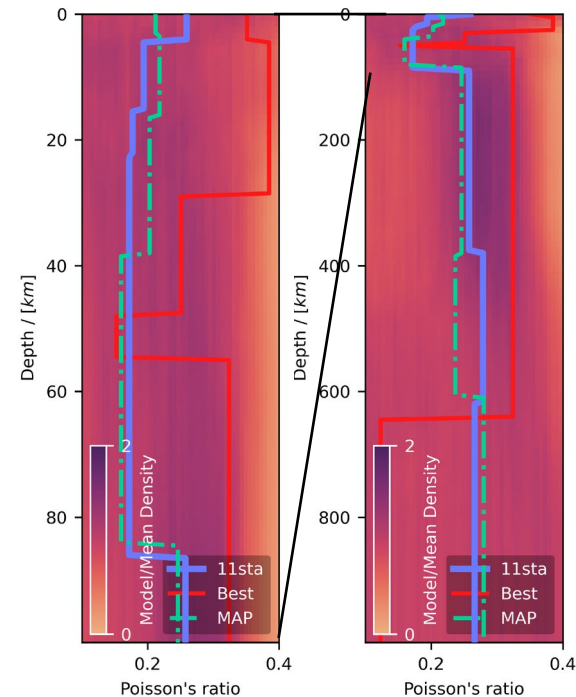
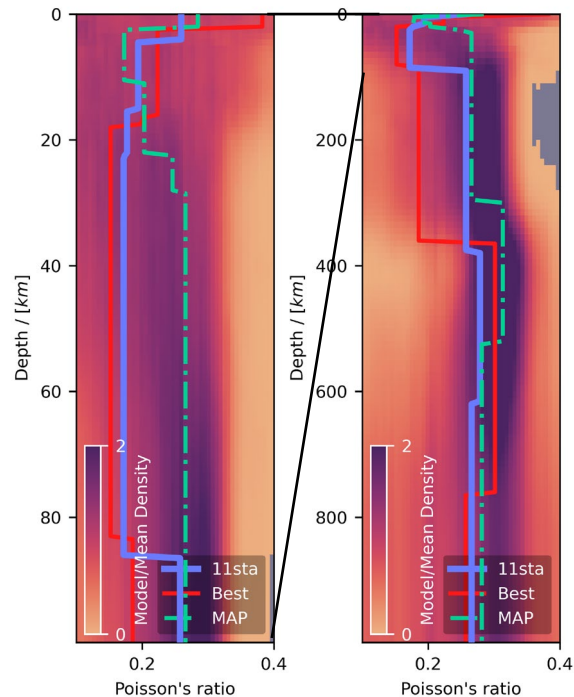
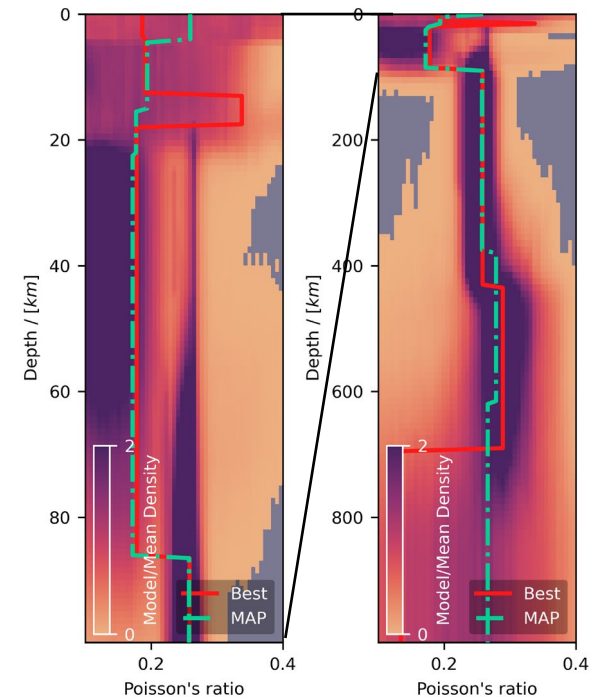
Inversion results: Poisson ratio

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

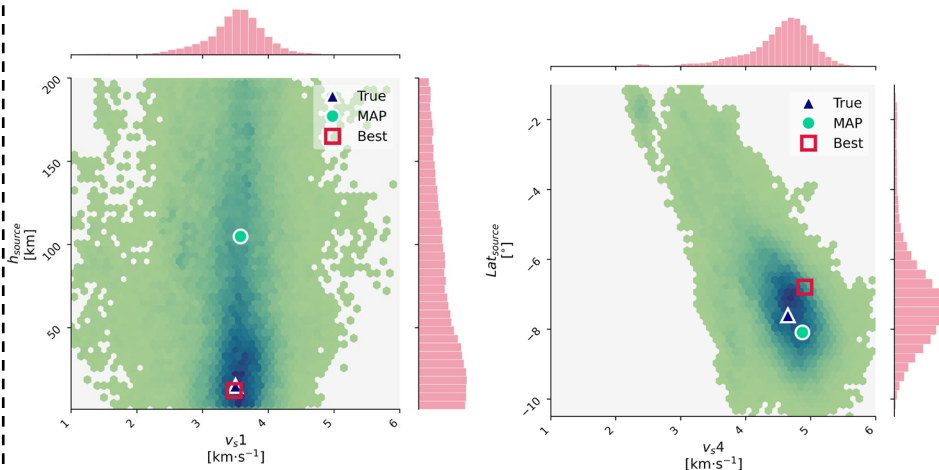
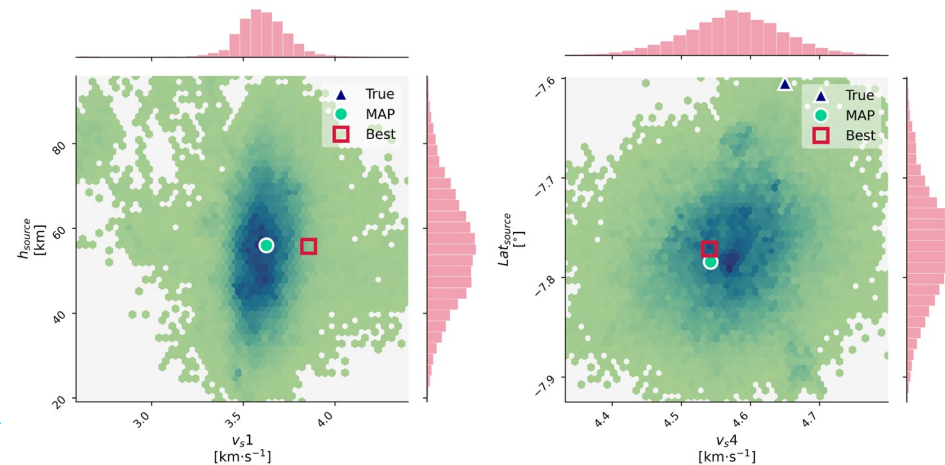
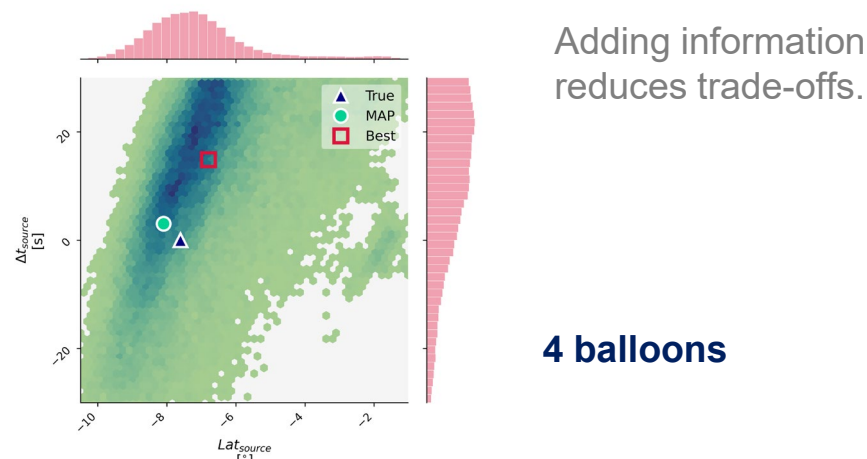
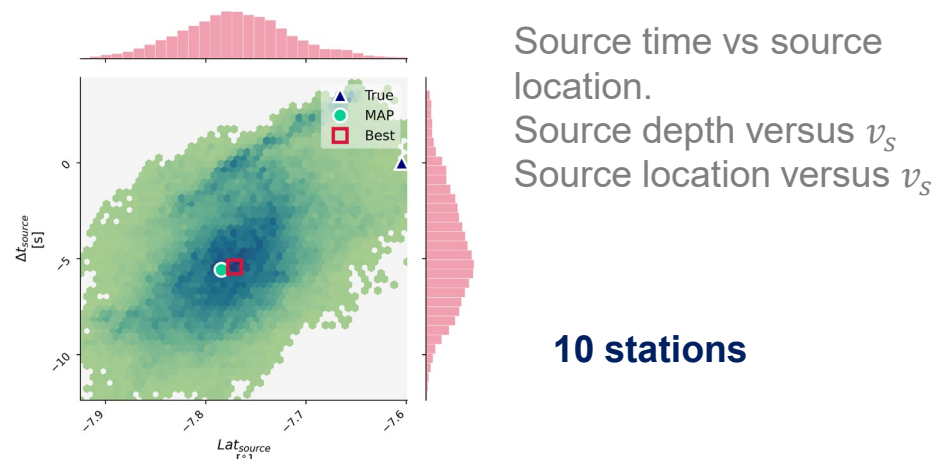
11 stations

4 stations

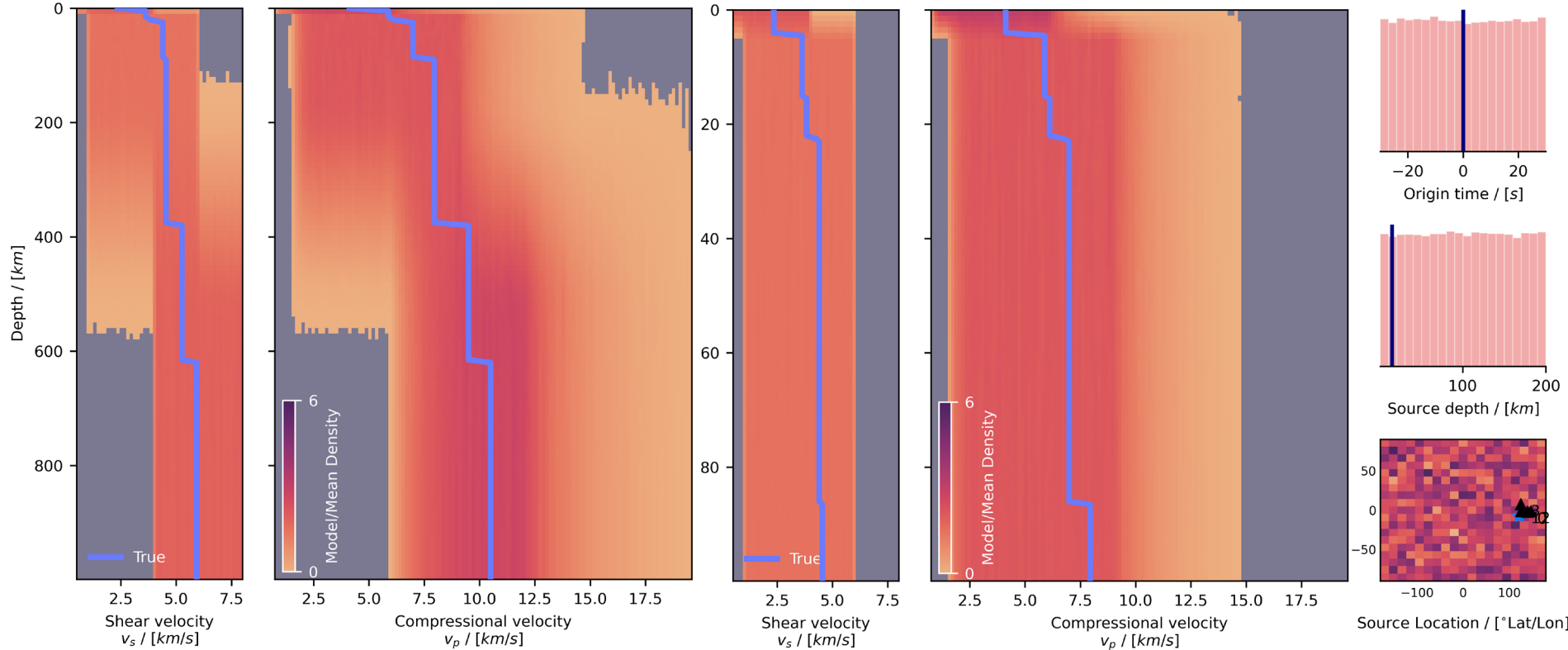
4 balloons



Marginal distribution of parameters

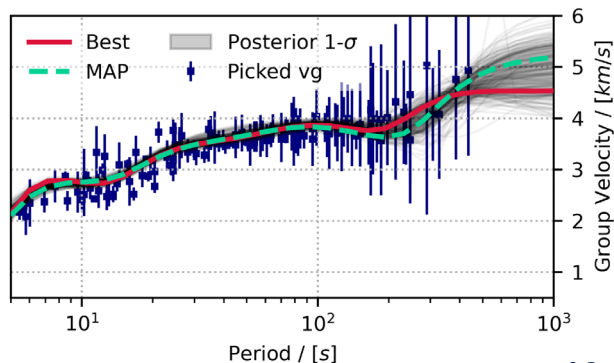


Prior distribution of model parameters

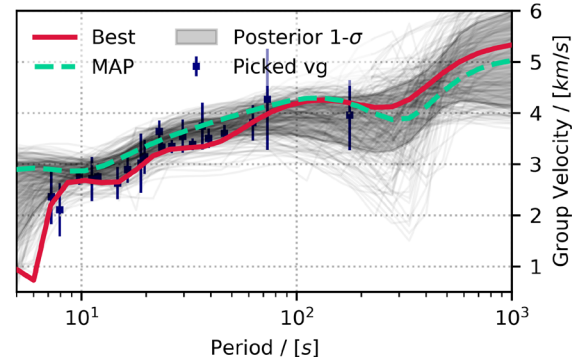


Quality of fit to the data

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

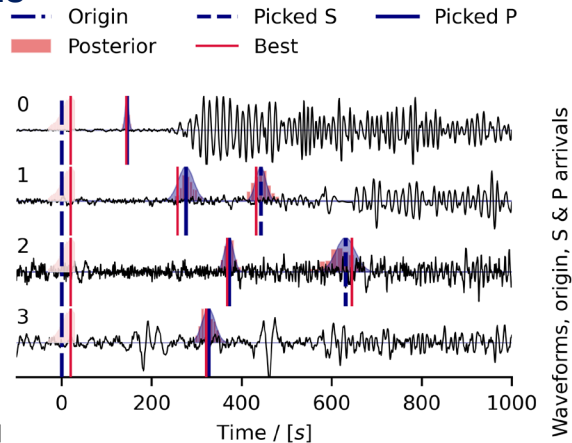
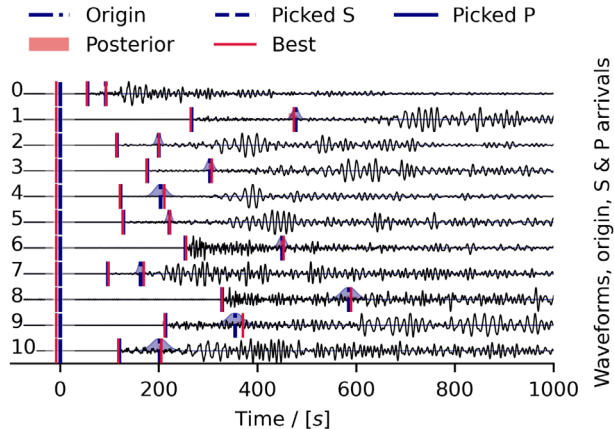


10 stations



4 balloons

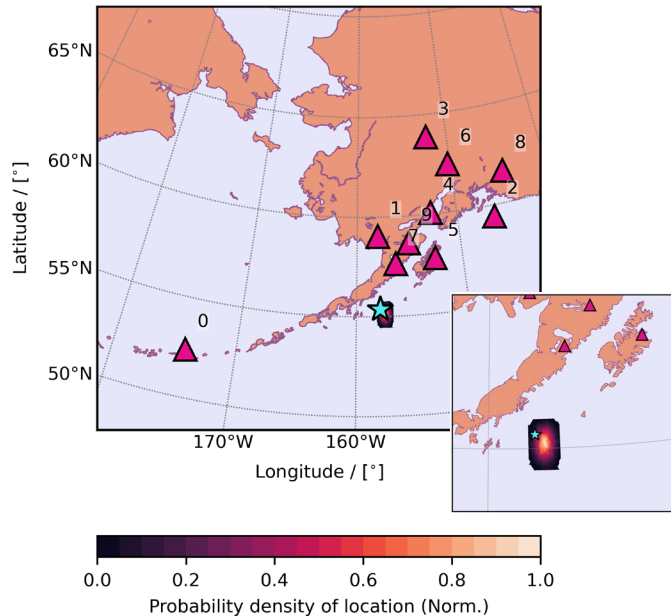
True origin time and picked S and P times, compared to the arrival time calculated from the posterior models.



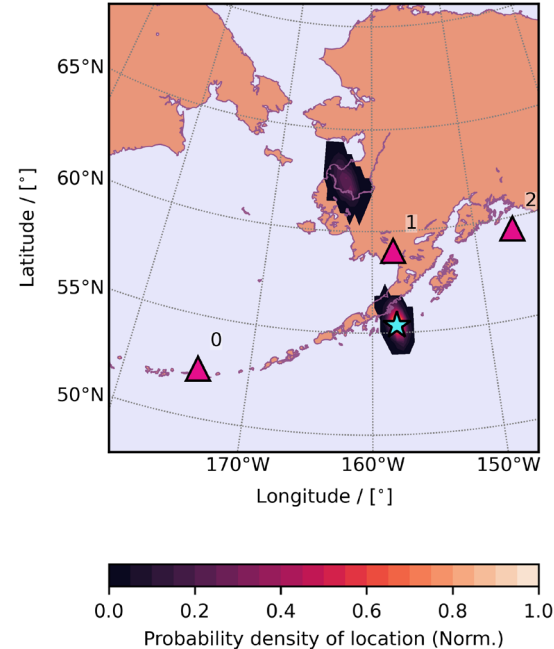
Inversion results: Alaska

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

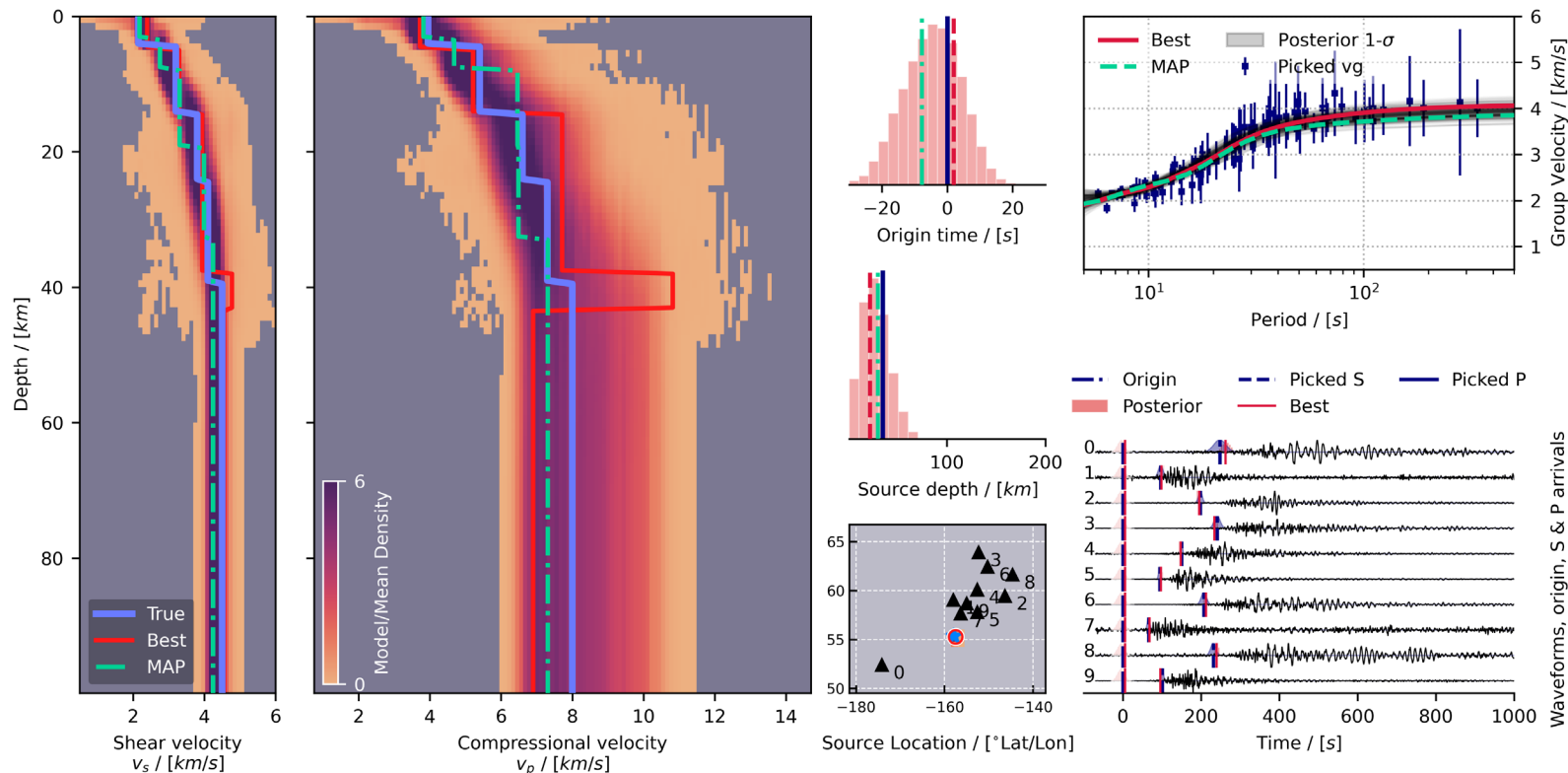


3 stations



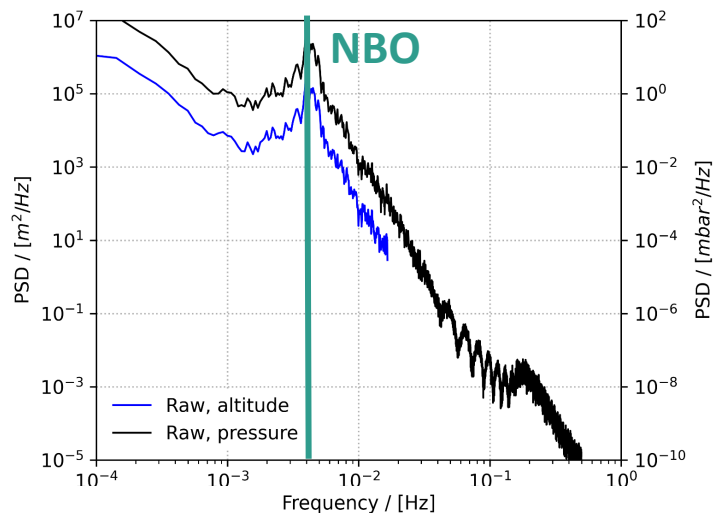
Inversion results: Alaska

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10 stations

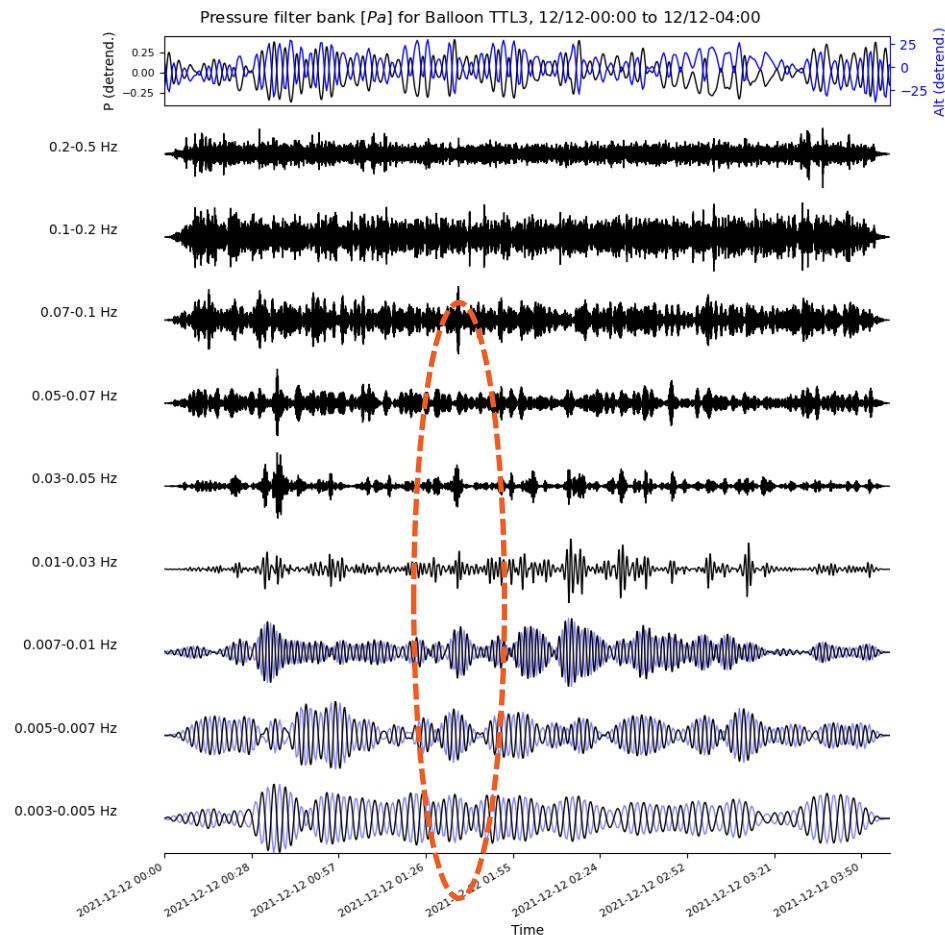
Balloon oscillation and noise



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

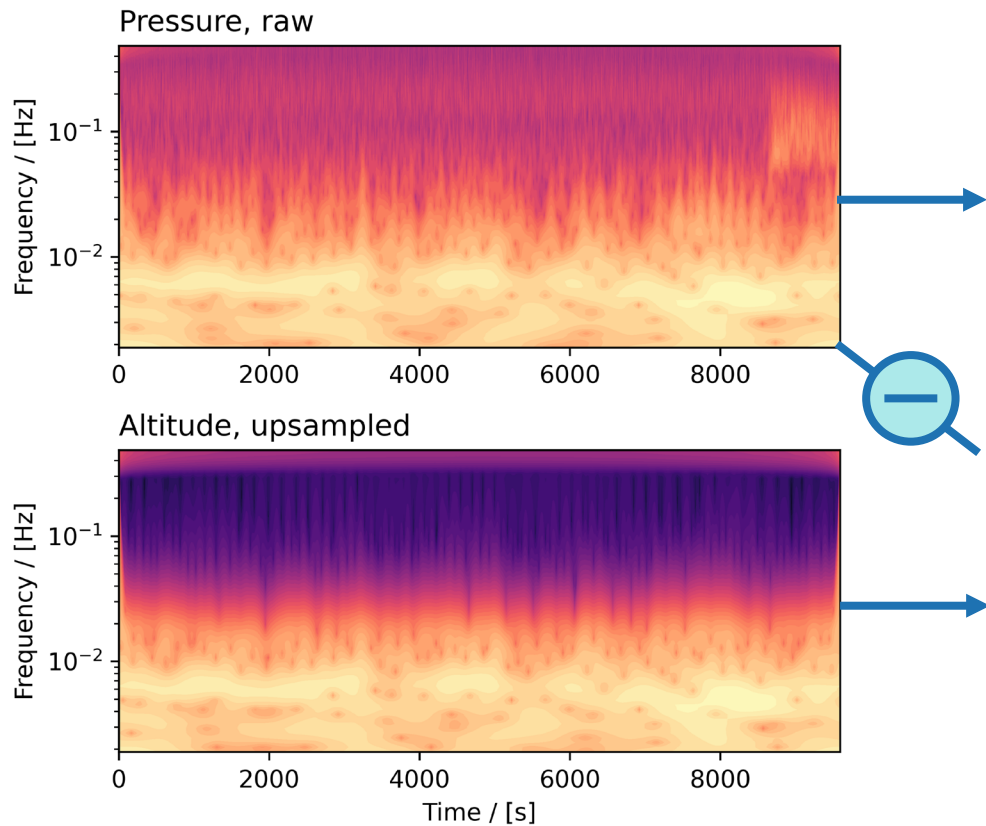
Good coherence up to GPS Nyquist frequency, perhaps even higher: **broadband energy bursts** follow altitude changes.

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

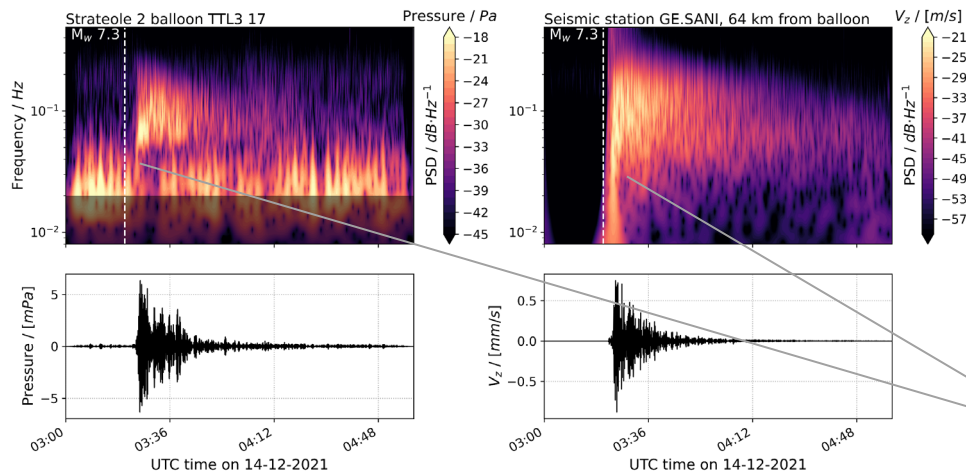


Improving the SNR at low frequency

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

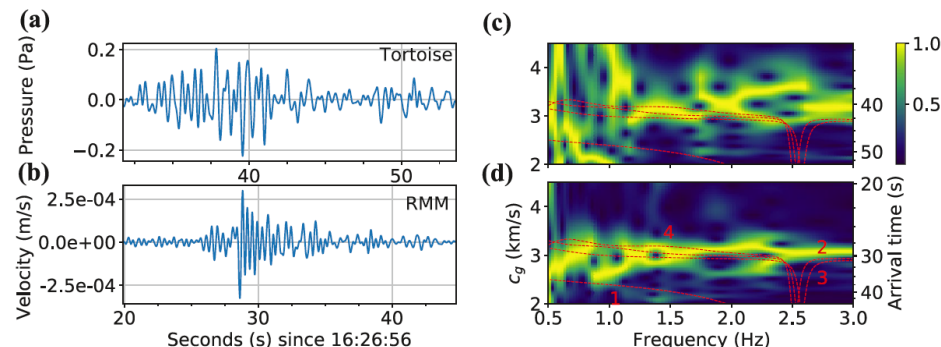
Dispersed Rayleigh Wave arrival

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



Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), [10.1029/2022GL098844](https://doi.org/10.1029/2022GL098844)

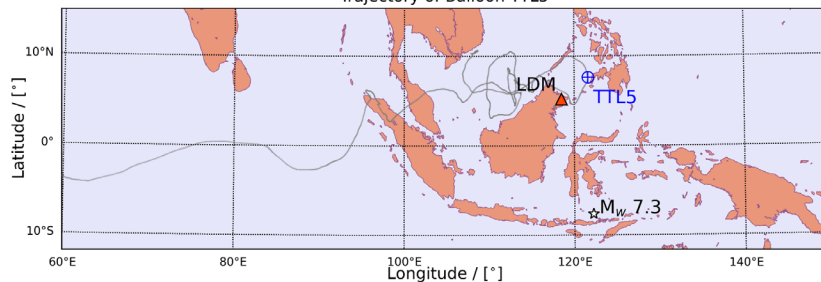
Brissaud, Q. et al. *Geophysical Research Letters* **48**, (2021), [10.1029/2021GL093013](https://doi.org/10.1029/2021GL093013)



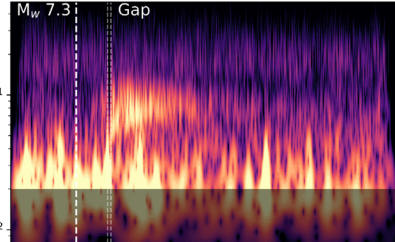
Event R1b of the 2019 Ridgecrest sequence recorded by Tortoise balloon.

Picking the Rayleigh wave: example of balloon 16

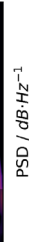
Trajectory of Balloon TTL5



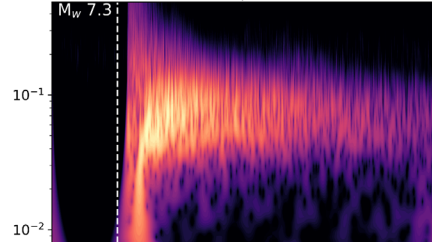
Strateole 2 balloon TTL5 16



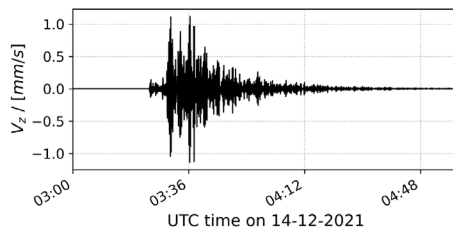
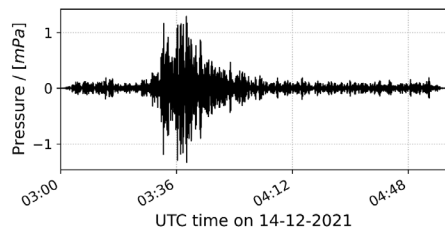
Pressure / Pa



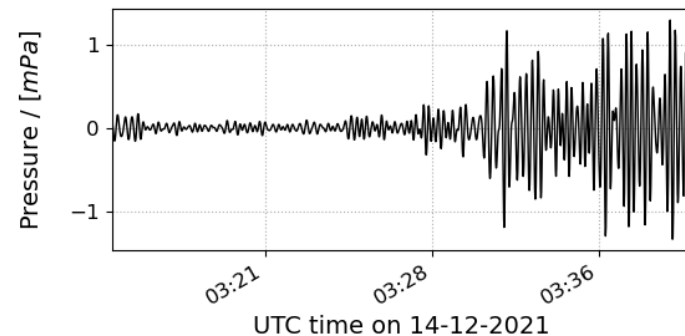
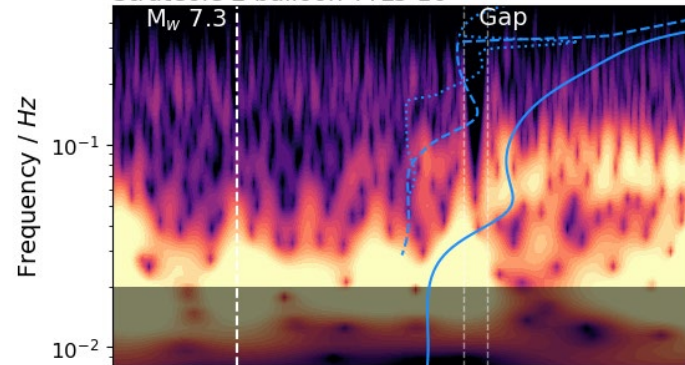
Seismic station MYLDM, 458 km from balloon



V_z / [m/s]

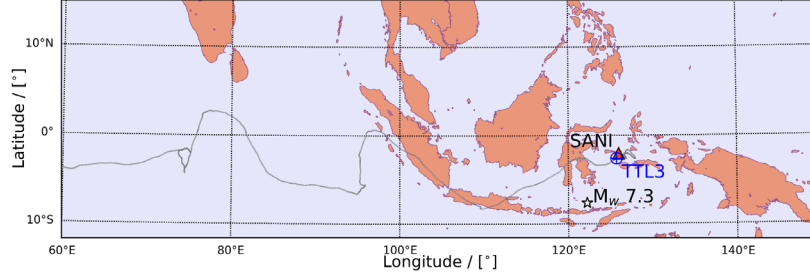


Strateole 2 balloon TTL5 16

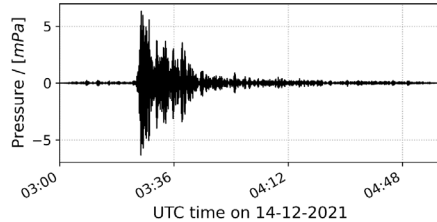
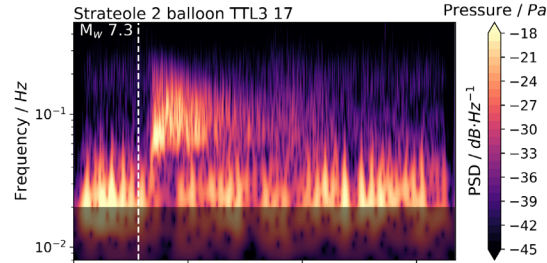


Picking the Rayleigh wave: example of balloon 17

Trajectory of Balloon TTL3

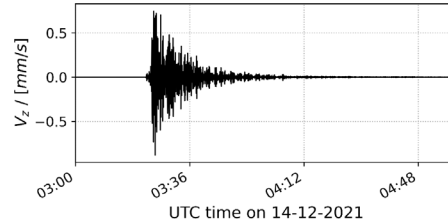
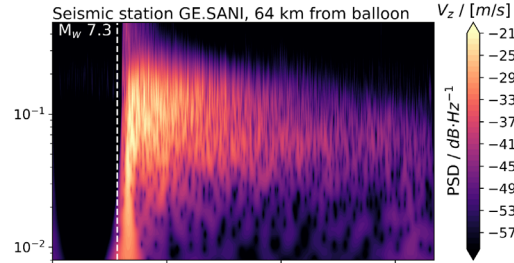


Strateole 2 balloon TTL3 17



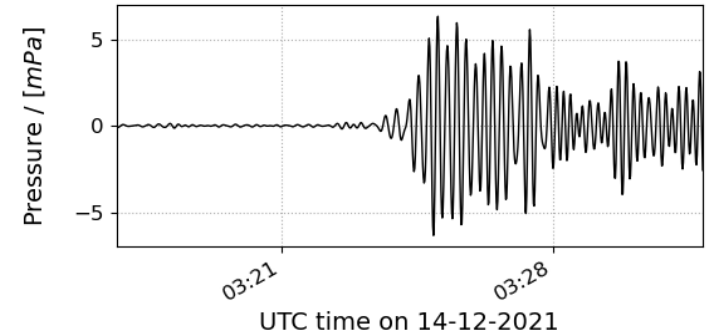
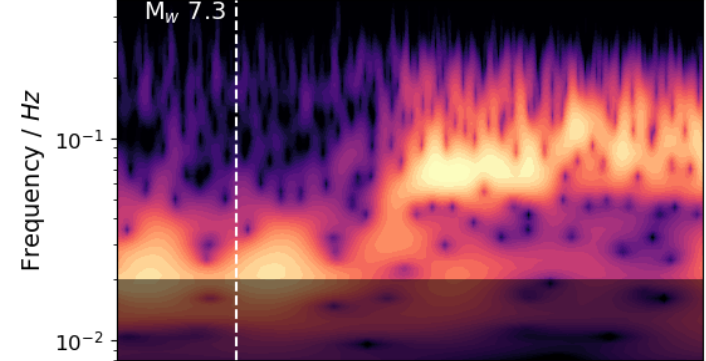
Pressure / Pa

Seismic station GE.SANI, 64 km from balloon



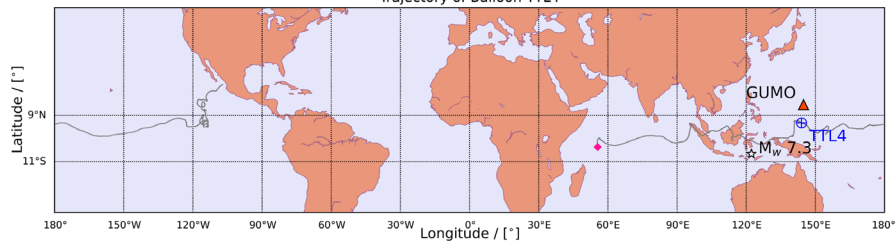
V_z / [m/s]

Strateole 2 balloon TTL3 17

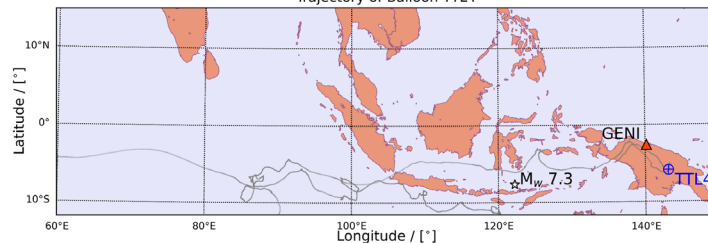


Balloon 15 and 07: a more difficult case

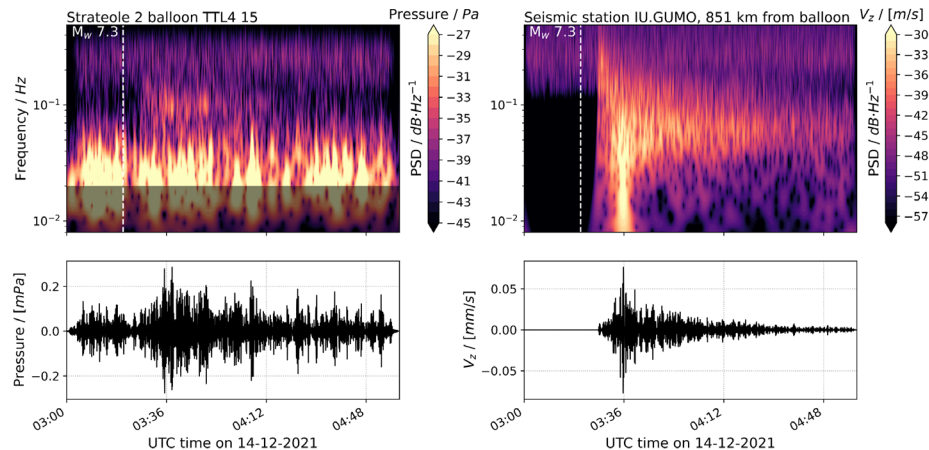
Trajectory of Balloon TTL4



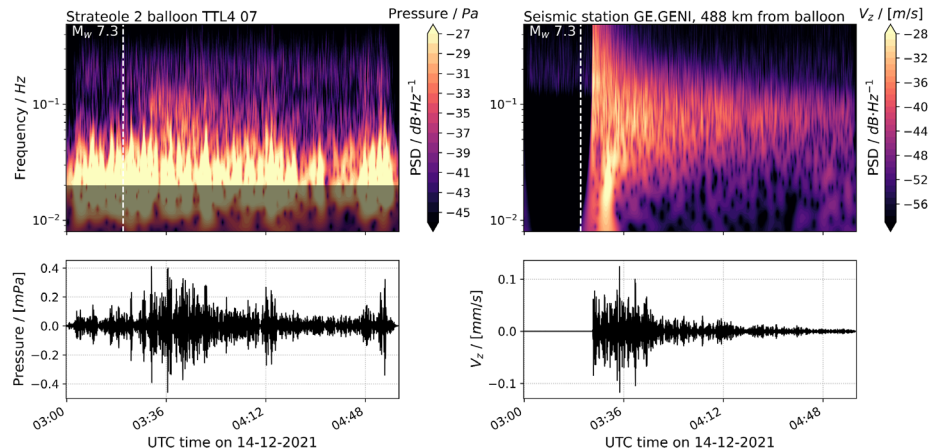
Trajectory of Balloon TTL4



Strateole 2 balloon TTL4 15

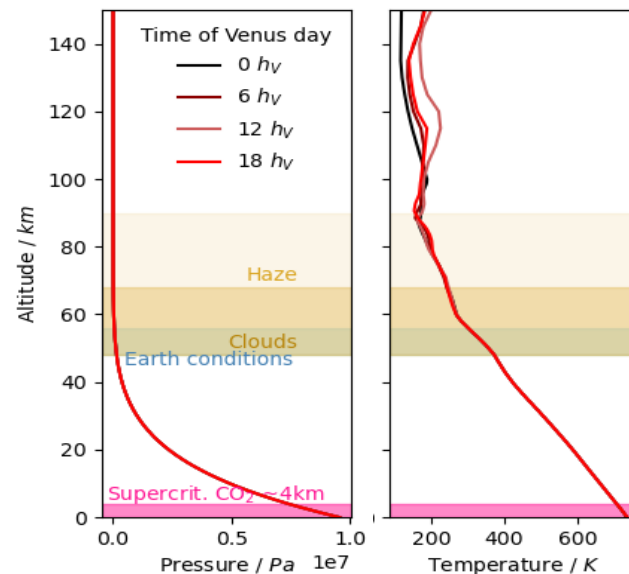


Strateole 2 balloon TTL4 07



Infrasound propagation on Venus?

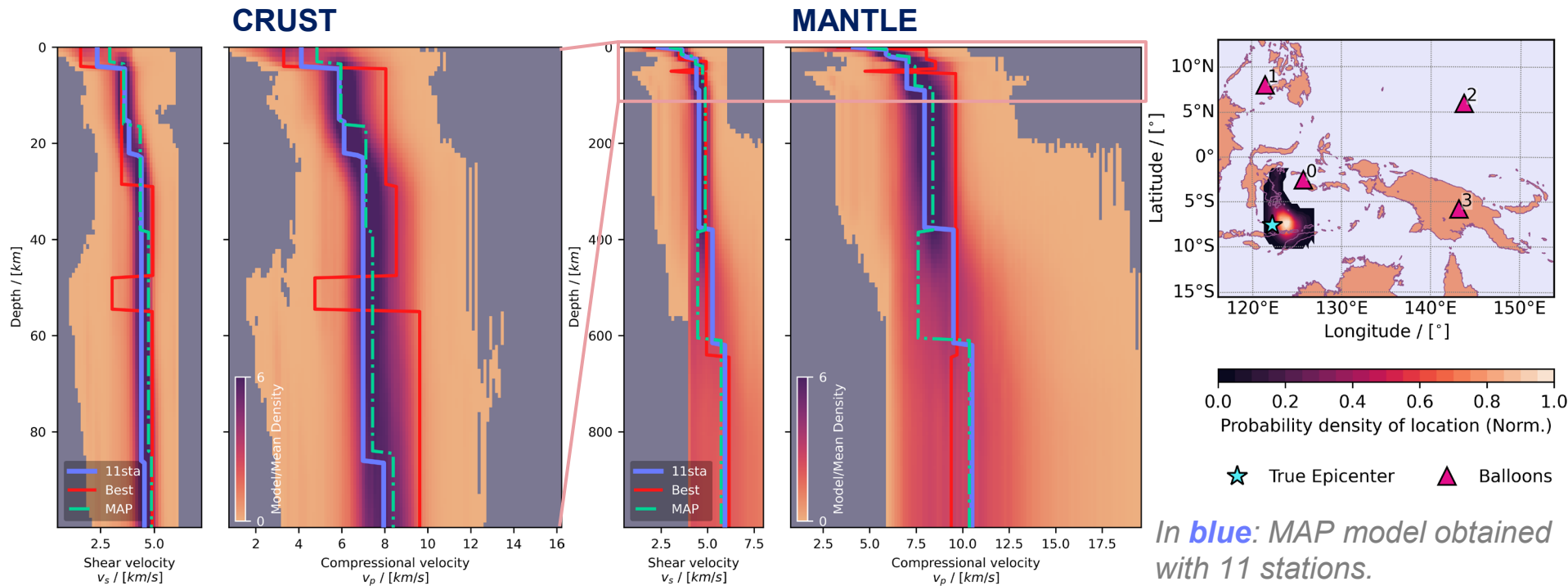
Venus is a pressure cooker under a lid of clouds, very stable throughout the day: a challenge for ground-based seismology, but an advantage for infrasound studies!



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



Flores, balloon inversion



In blue: MAP model obtained with 11 stations.

