



Balloon-Borne Seismology for Subsurface Exploration

AGU24, Washington D.C., USA
December 12, 2024

Marouchka Froment, Quentin Brissaud, Sven Peter Näsholm

AGU24

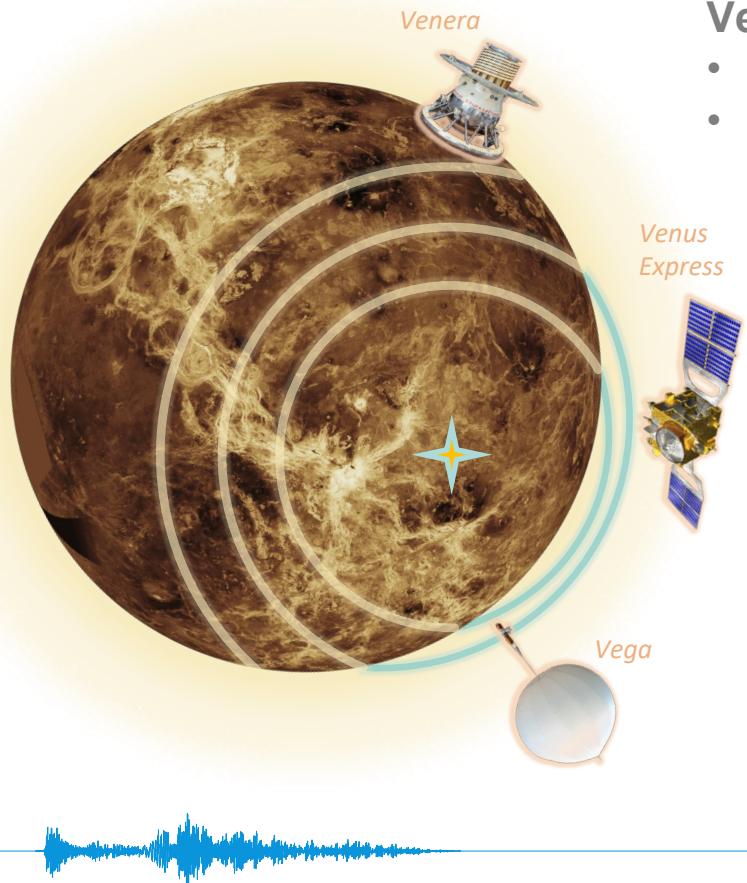


Funded by
The Research
Council of Norway



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)

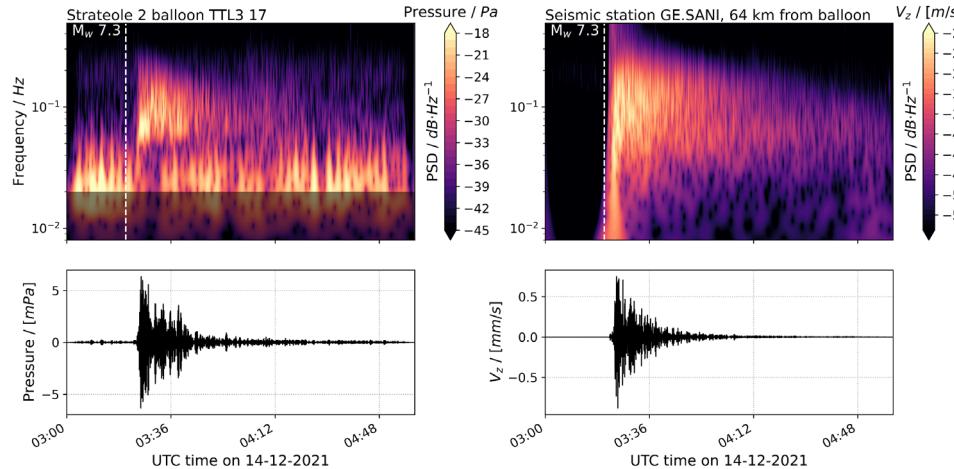
Surface sensor.

Deployed seismometer. < 24 h.

Remote sensor. Airglow modulation by acoustic perturbation. Years, $Mw > 5\text{-}6$, $f < 1 \text{ Hz}$.

Airborne sensor. Balloon-borne infrasound sensor. Months to years, $Mw > 5$, $f < 10 \text{ Hz}$.

Balloon seismology on Earth



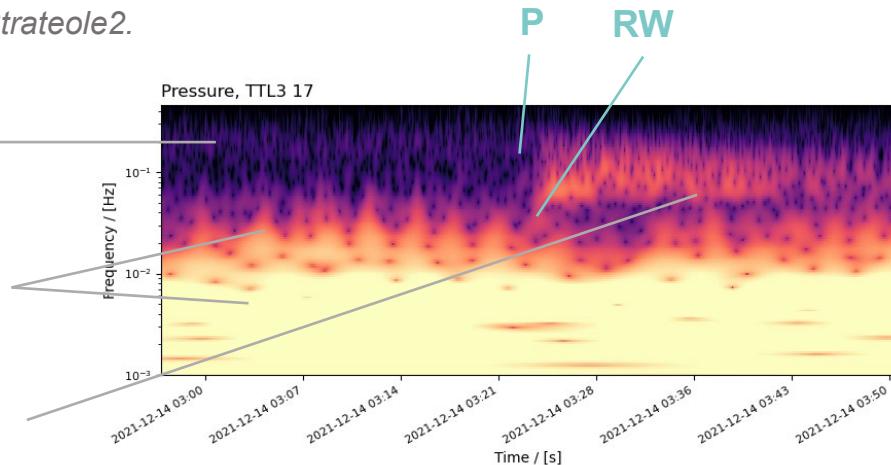
Dec. 14, 2021, Mw 7.3 Flores Sea earthquake recorded by Stratole2.

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

Microbaroms

Balloon Buoyancy oscillations

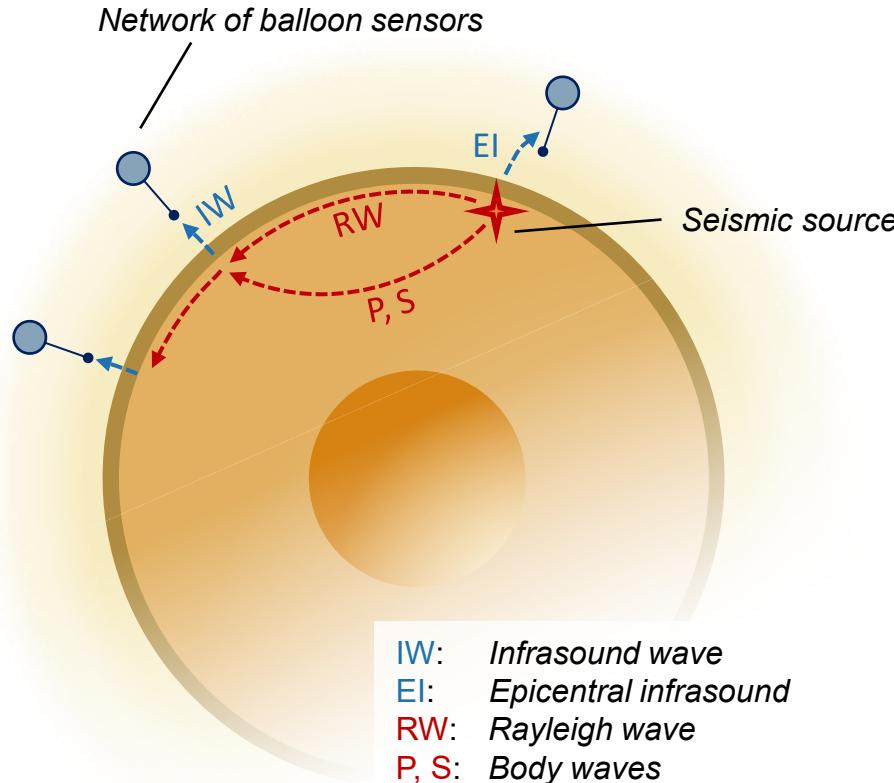
Scattering



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



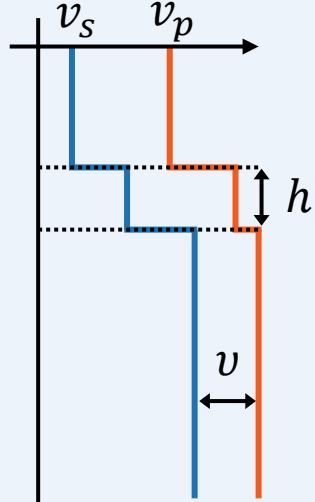
- ## Inversion challenges
- How to process seismic data of unknown origin to **simultaneously invert source & subsurface?**
 - Validation of inversion method?
 - How sensitive is the inversion to number of balloons & detected phase types?
 - What is the uncertainty of inverted source & subsurface parameters?

Source origin? Subsurface velocities?



Inversion method - McMC

Subsurface model



Source location
and time

$t_s \ h_s \ lat_s \ lon_s$

Forward model

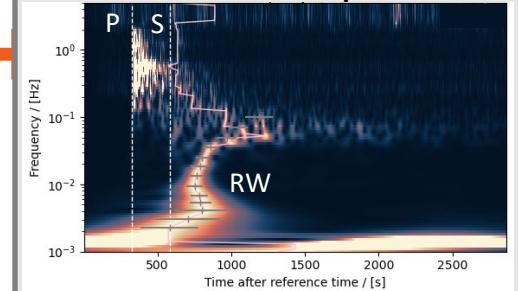
Arrival times

$$t_s + \Delta t_P + \Delta t_{RW}(f) + \Delta t_{air}$$

$\underbrace{\Delta t_P}_{\Delta t_s}$

Seismic propagation

Data: arrival picks



\neq
Misfit

+ **Priors**
(bounds on $v_s, h, r_s \dots$)

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

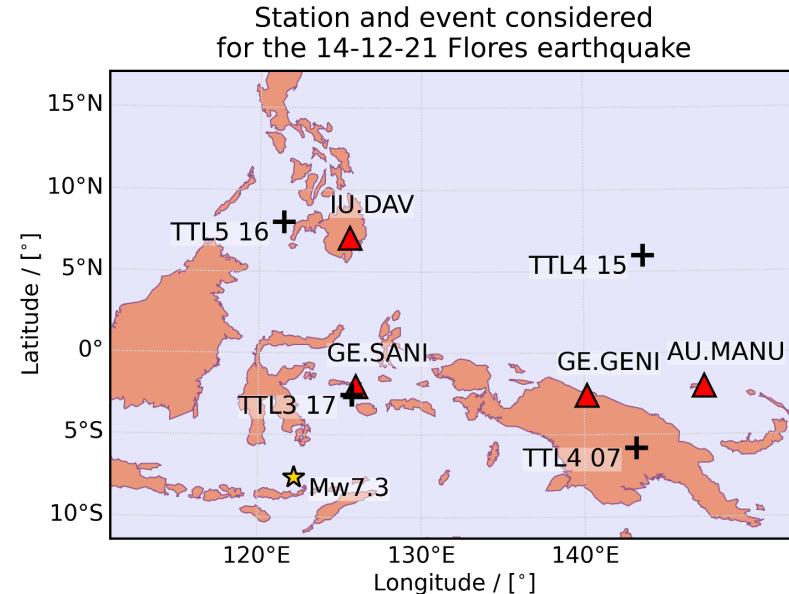
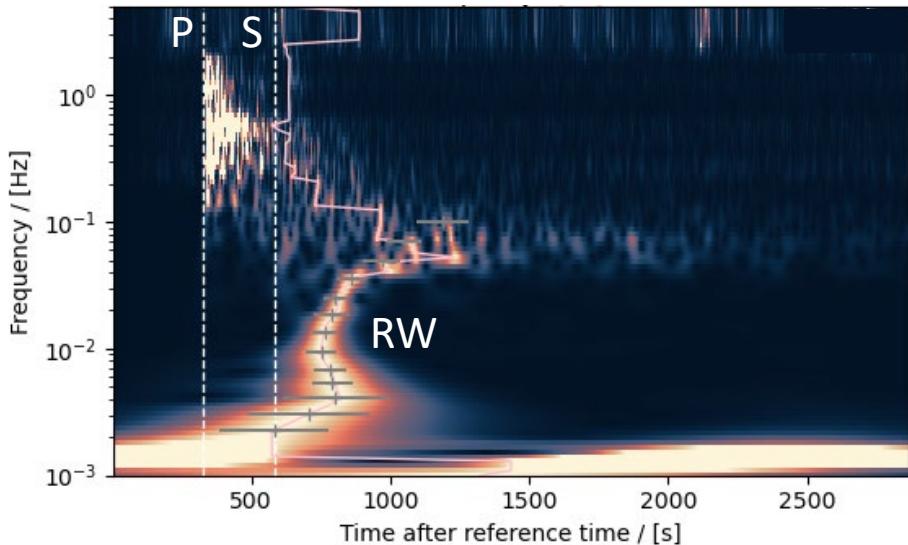
Posterior probability
($v_s, v, h, t_s, h_s, lat_s, lon_s$)

Distribution of parameters

Validating the inversion with the Flores event

Test of the inversion method with:

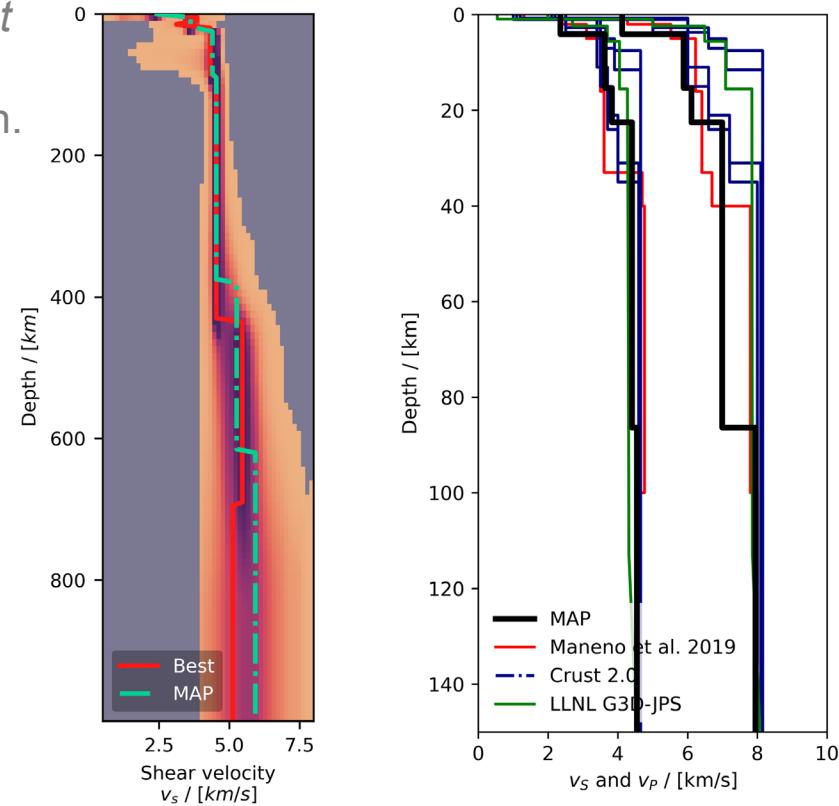
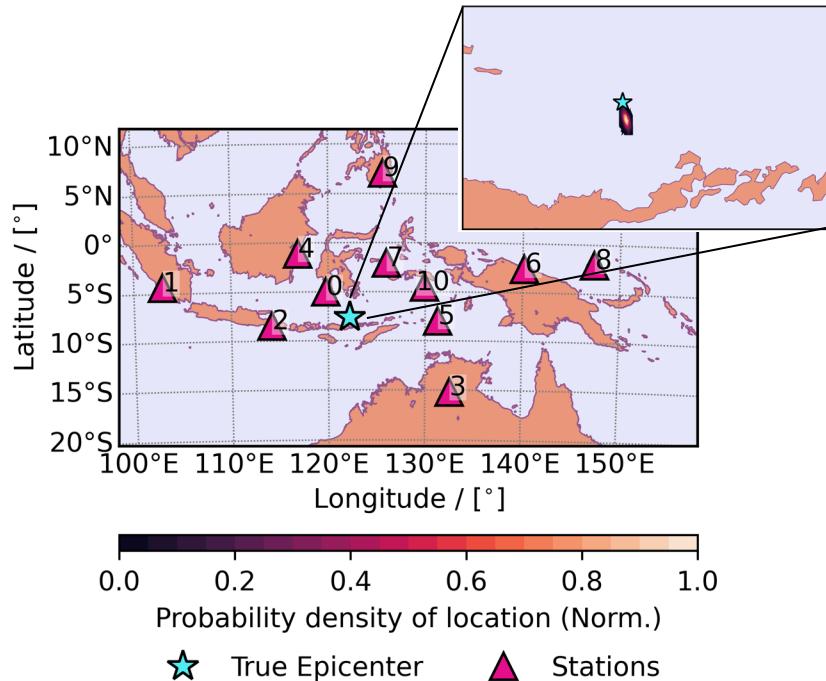
- 1) **Pure seismic data**, using only vertical component to pick P, S, RW.
- 2) **Pressure traces** from four Strateole2 balloons.



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

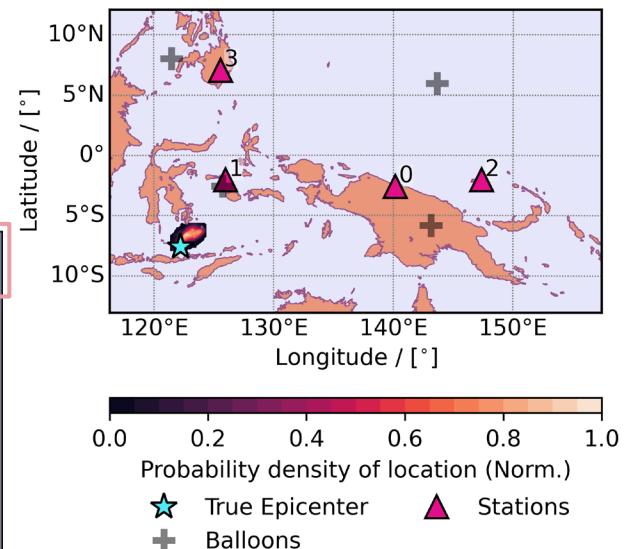
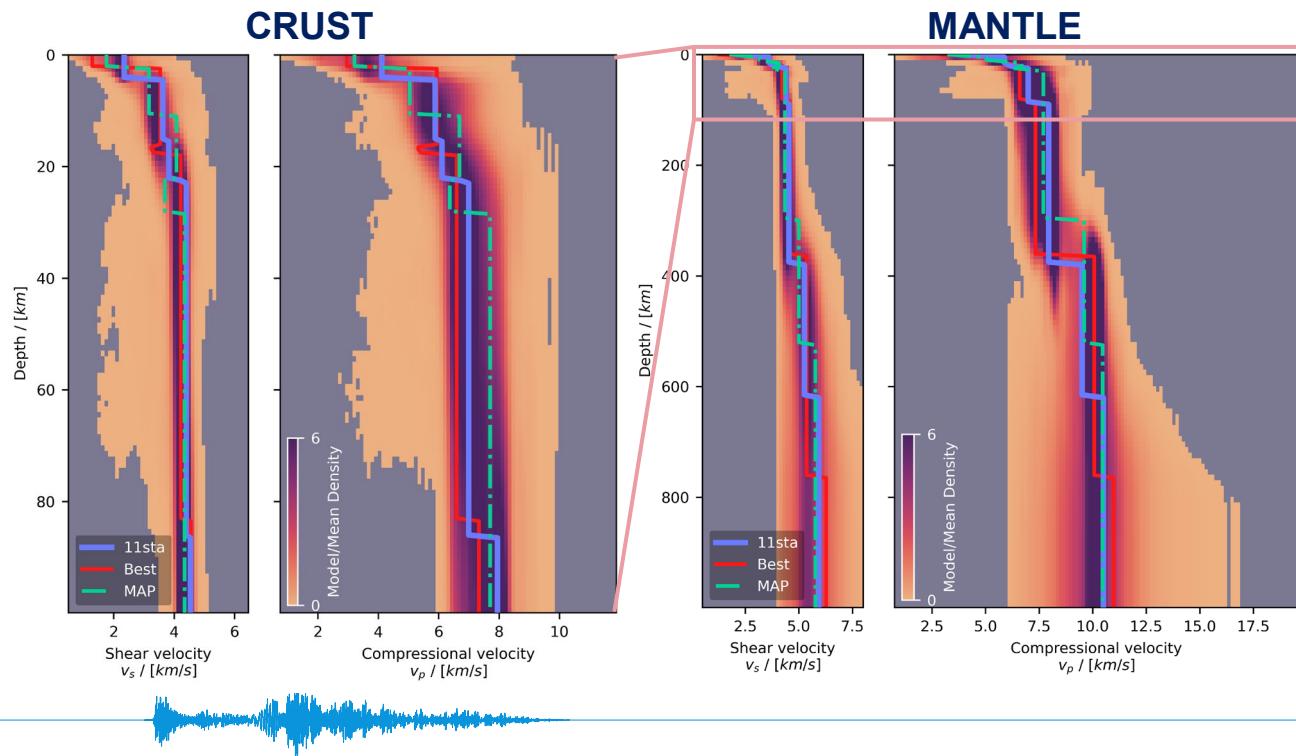
Flores, pure seismic inversion with 11 stations

- 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

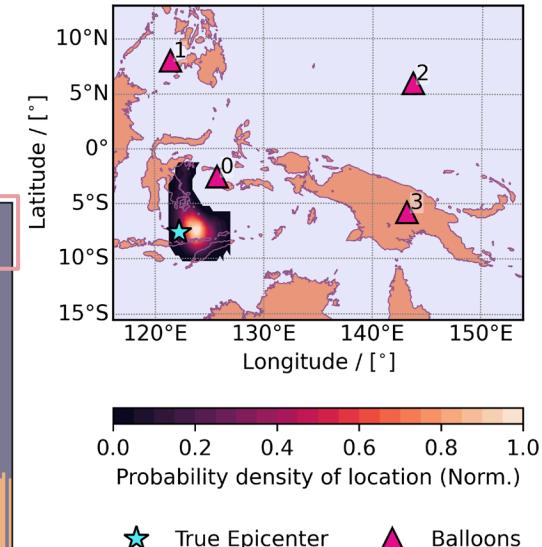
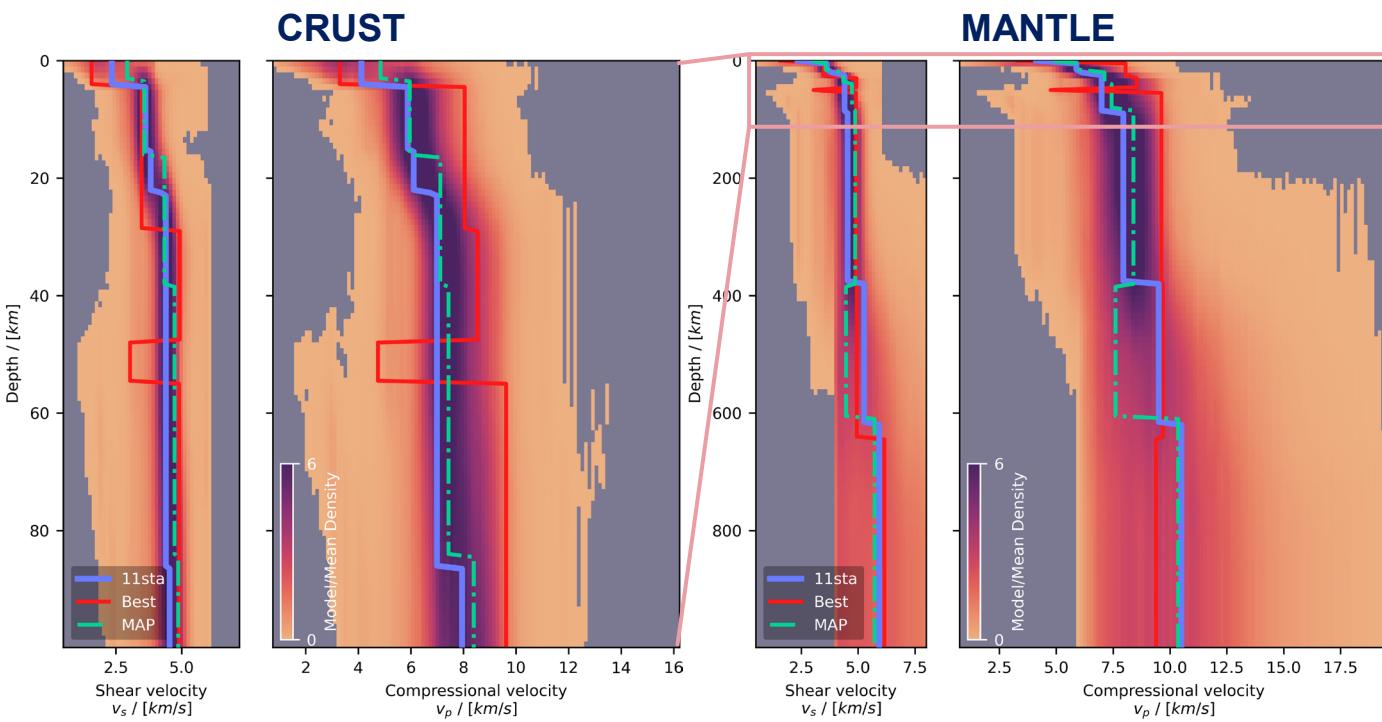
Next, we restrict ourselves to the 4 seismic stations closest to the Strateole2 stations. A similar subsurface model is retrieved, with higher uncertainty.



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

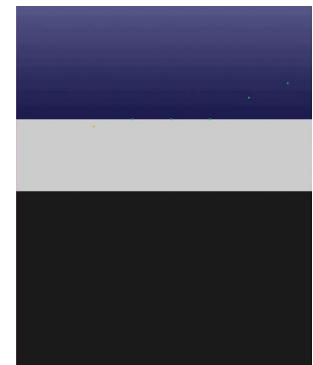
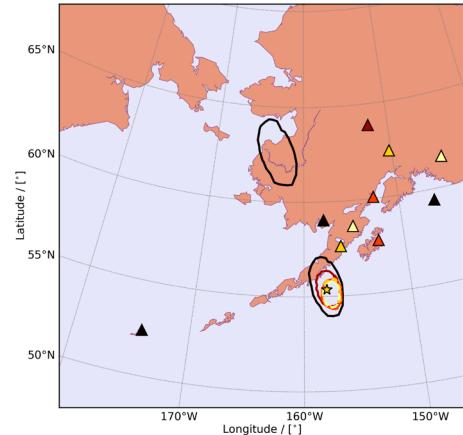
We now have a validated framework to invert source information and subsurface properties based on P, S and RW arrival times at a balloon station.

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”*

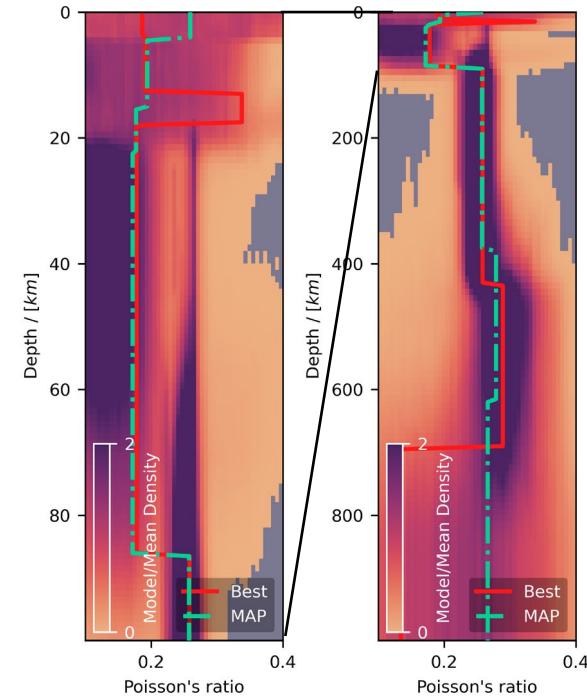


All feedback and
suggestions are
welcome !

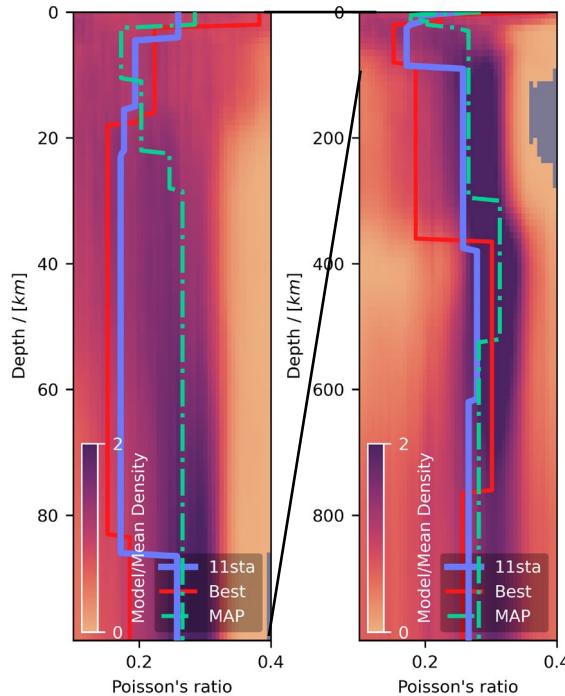
Inversion results: Poisson ratio

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

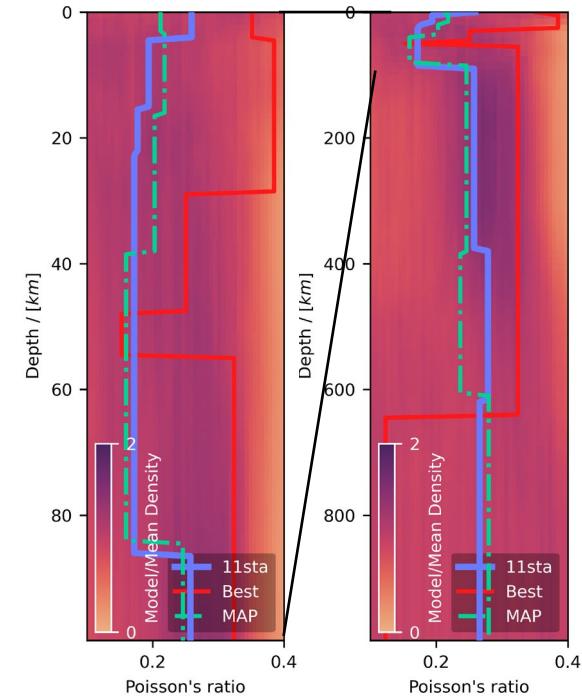
11 stations



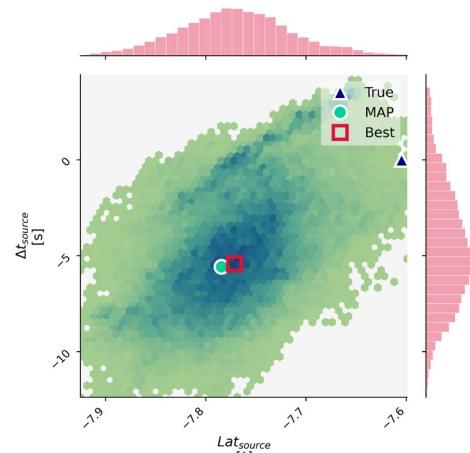
4 stations



4 balloons

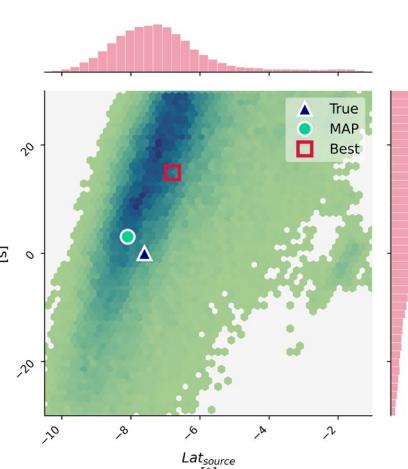
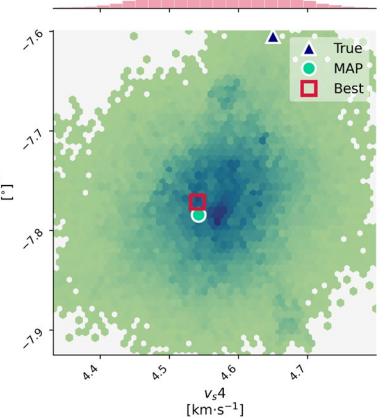
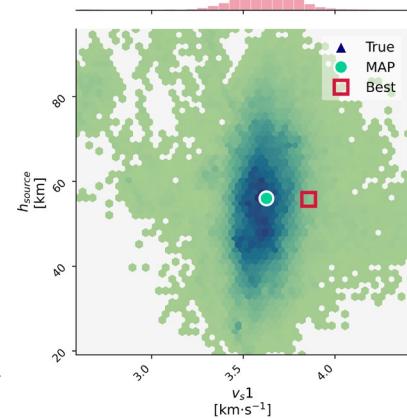


Marginal distribution of parameters



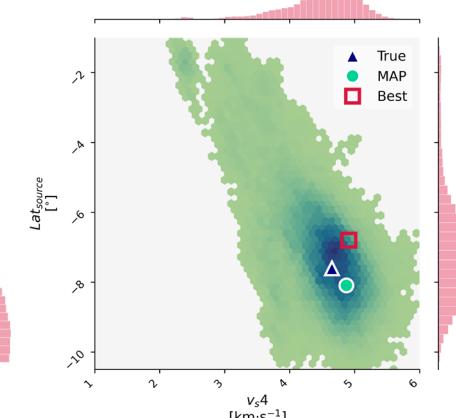
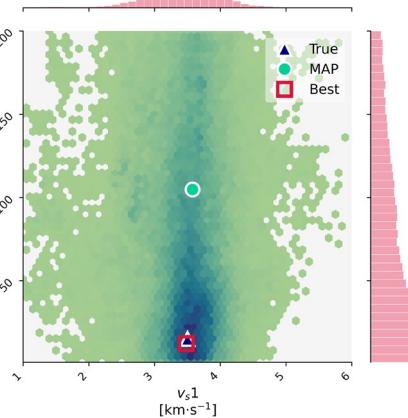
Source time vs source location.
Source depth versus v_s
Source location versus v_s

10 stations

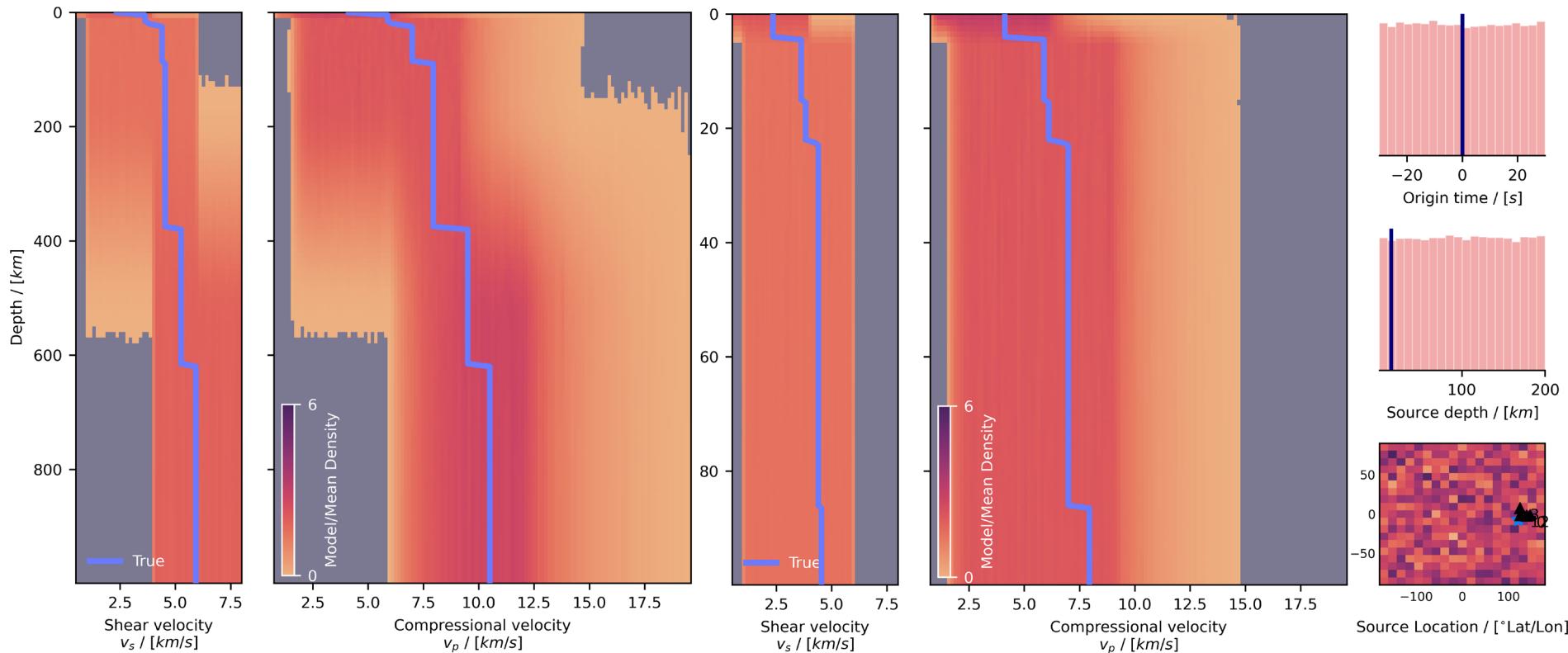


Adding information reduces trade-offs.

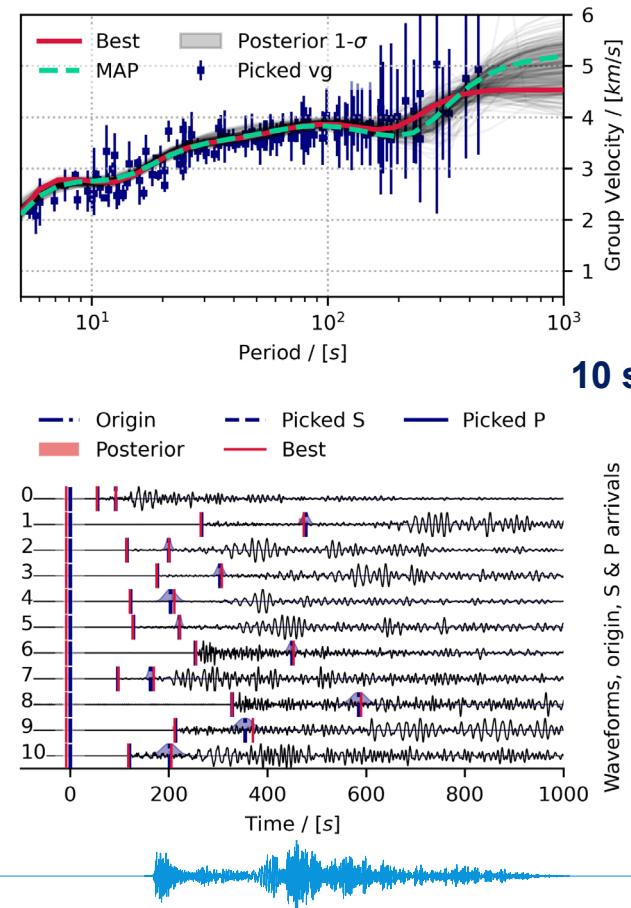
4 balloons



Prior distribution of model parameters

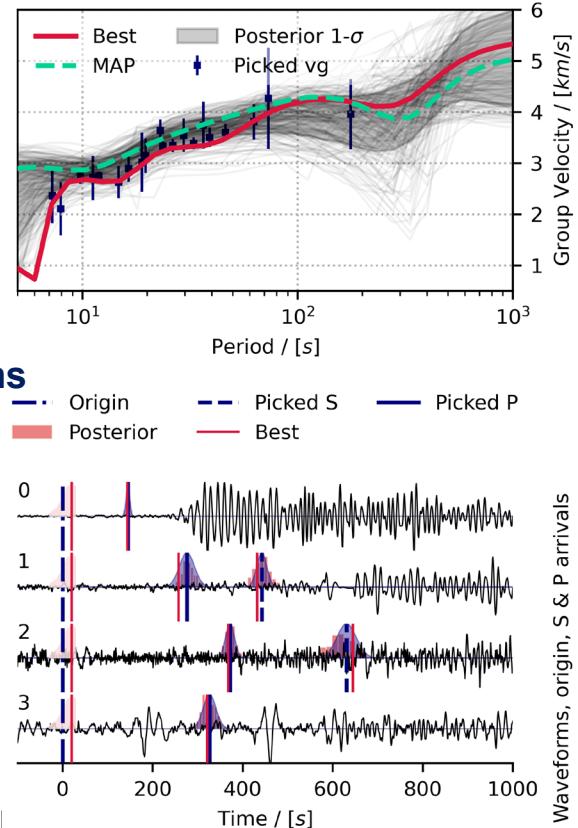


Quality of fit to the data



10 stations

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

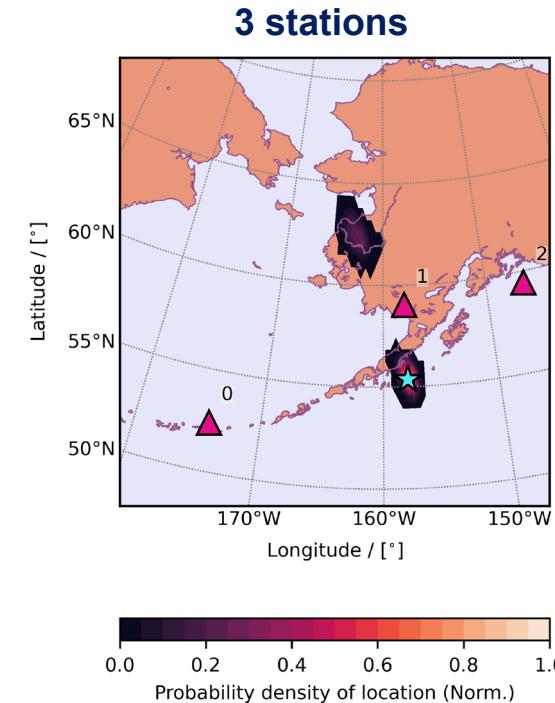
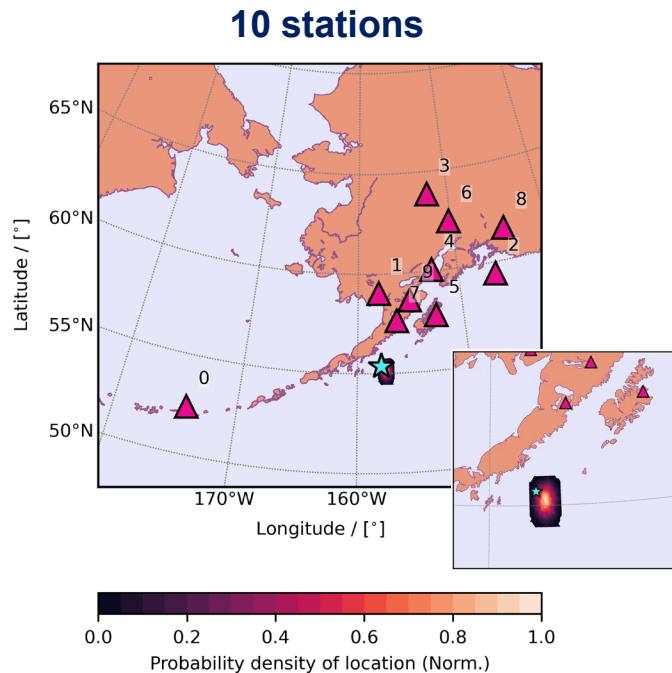


4 balloons

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

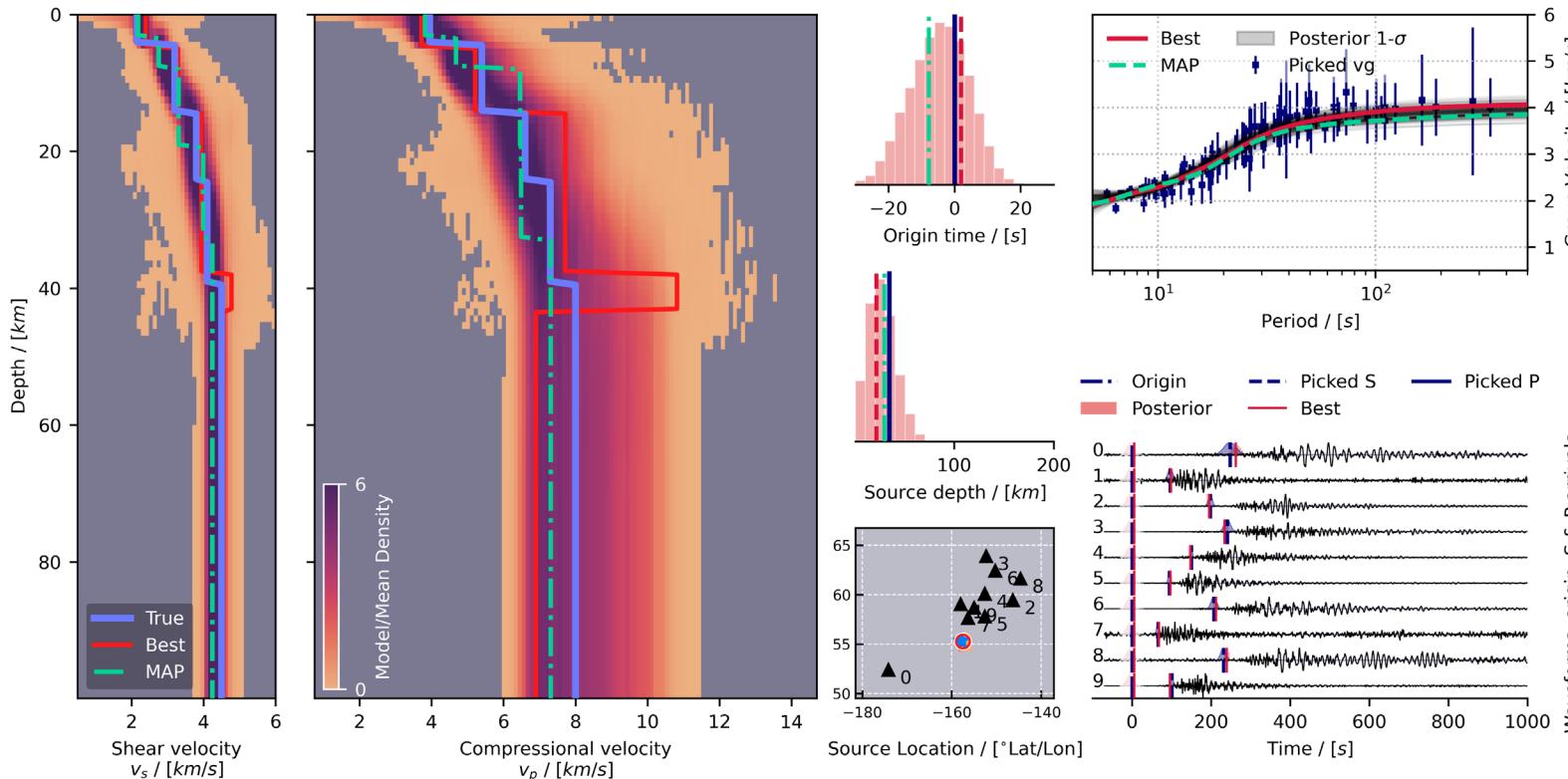
Inversion results: Alaska

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

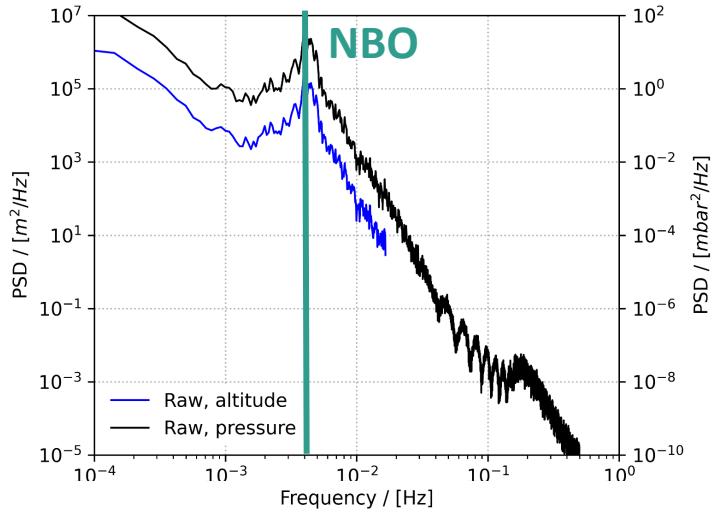


Inversion results: Alaska

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

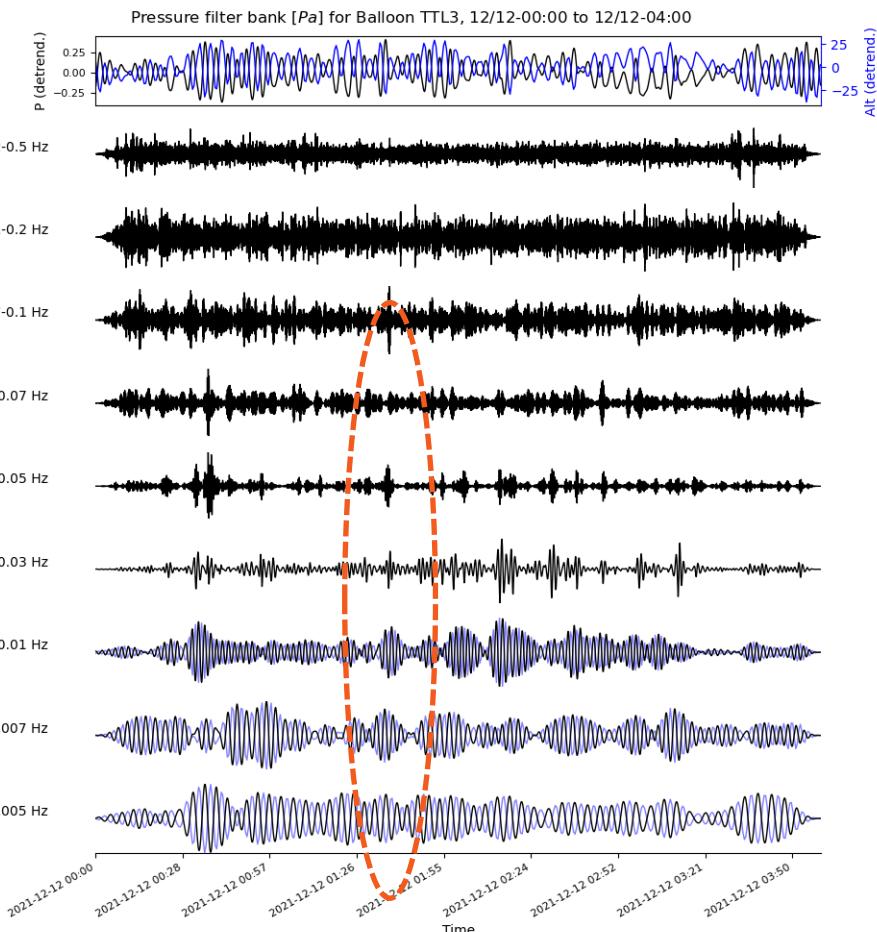


Balloon oscillation and noise



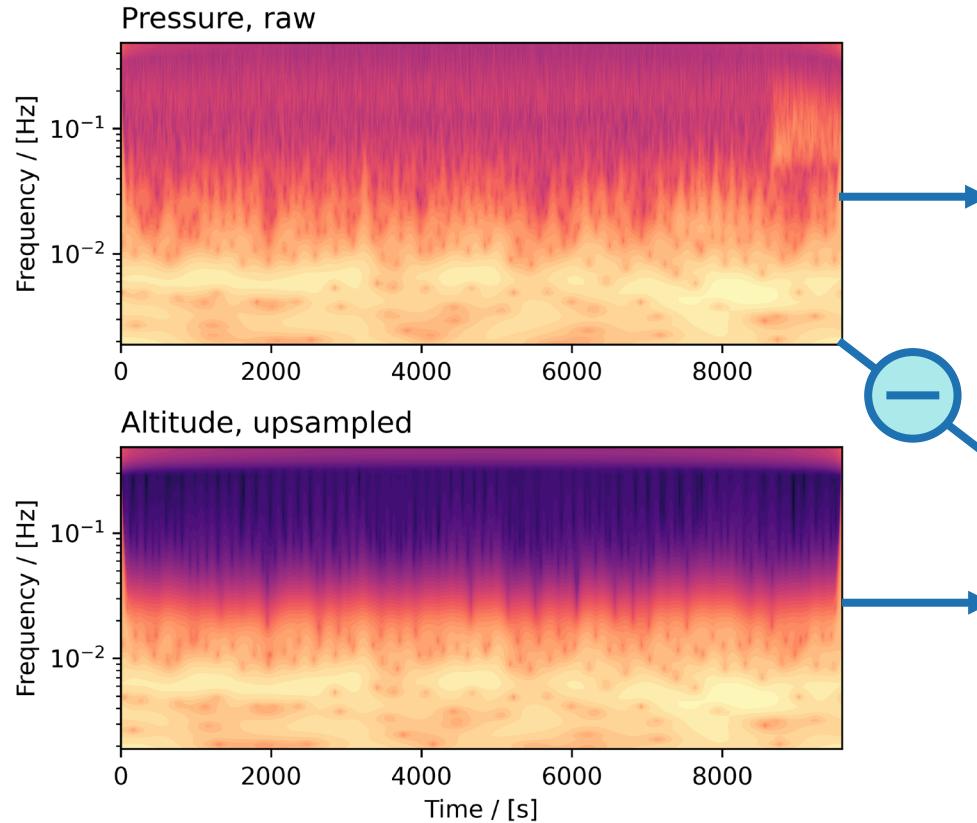
Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

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

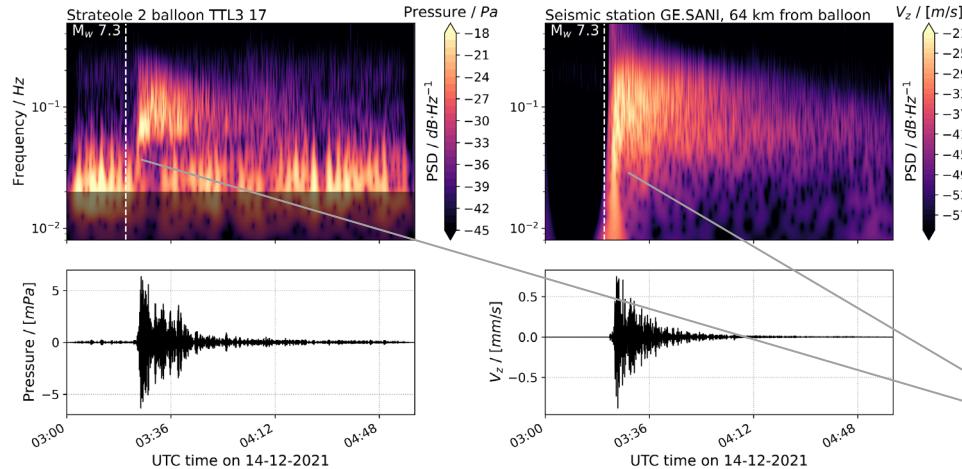


Improving the SNR at low frequency

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



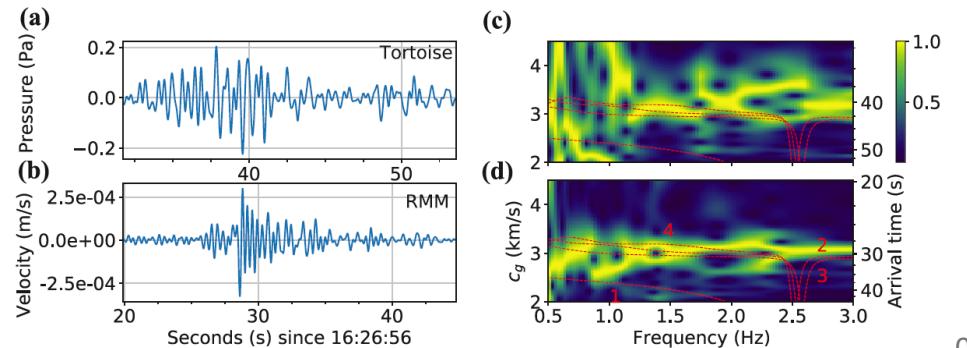
Balloon seismology on Earth



14/12/2021 Mw 7.3 Flores Sea earthquake recorded by Strato2 balloons.

Good agreement between seismic ground sensors and airborne infrasound recordings

Dispersed Rayleigh Wave arrival

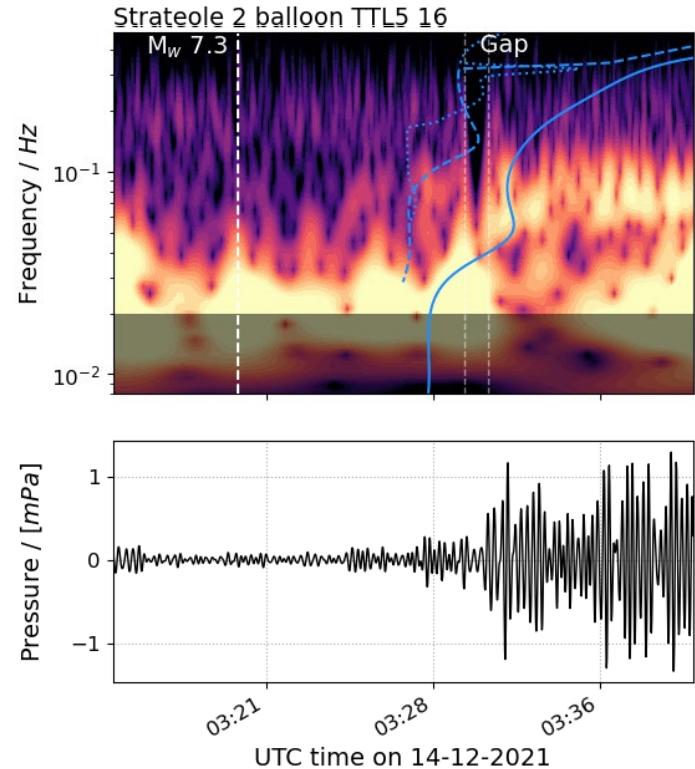
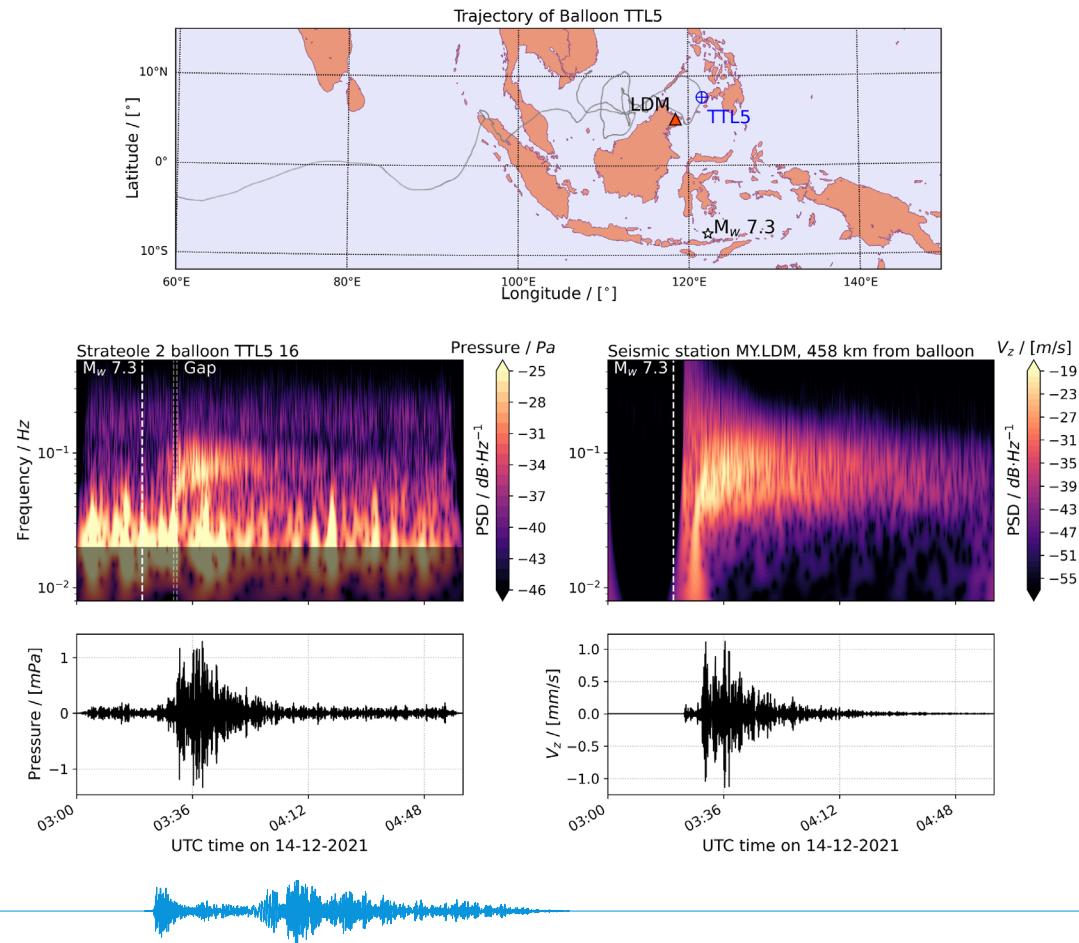


Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), [10.1029/2022GL098844](https://doi.org/10.1029/2022GL098844)

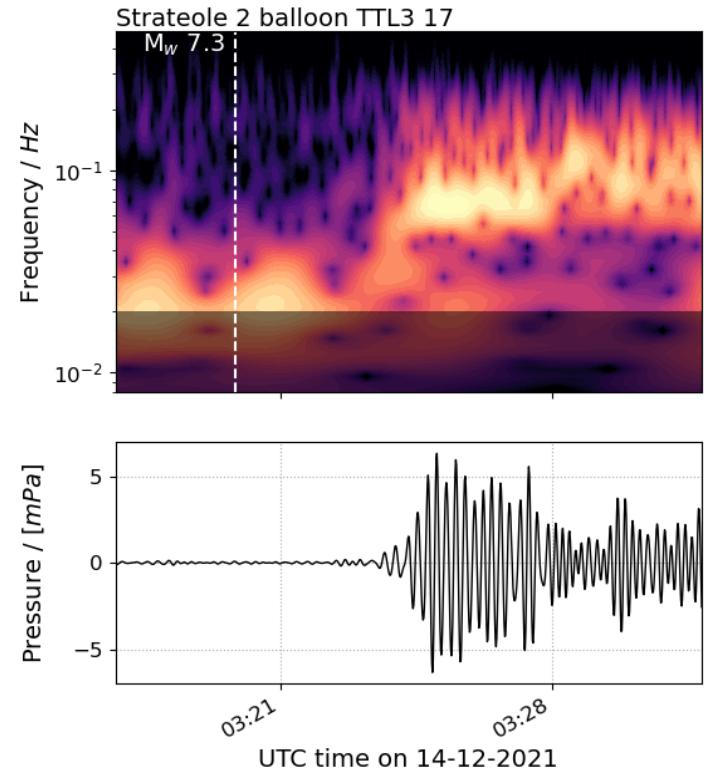
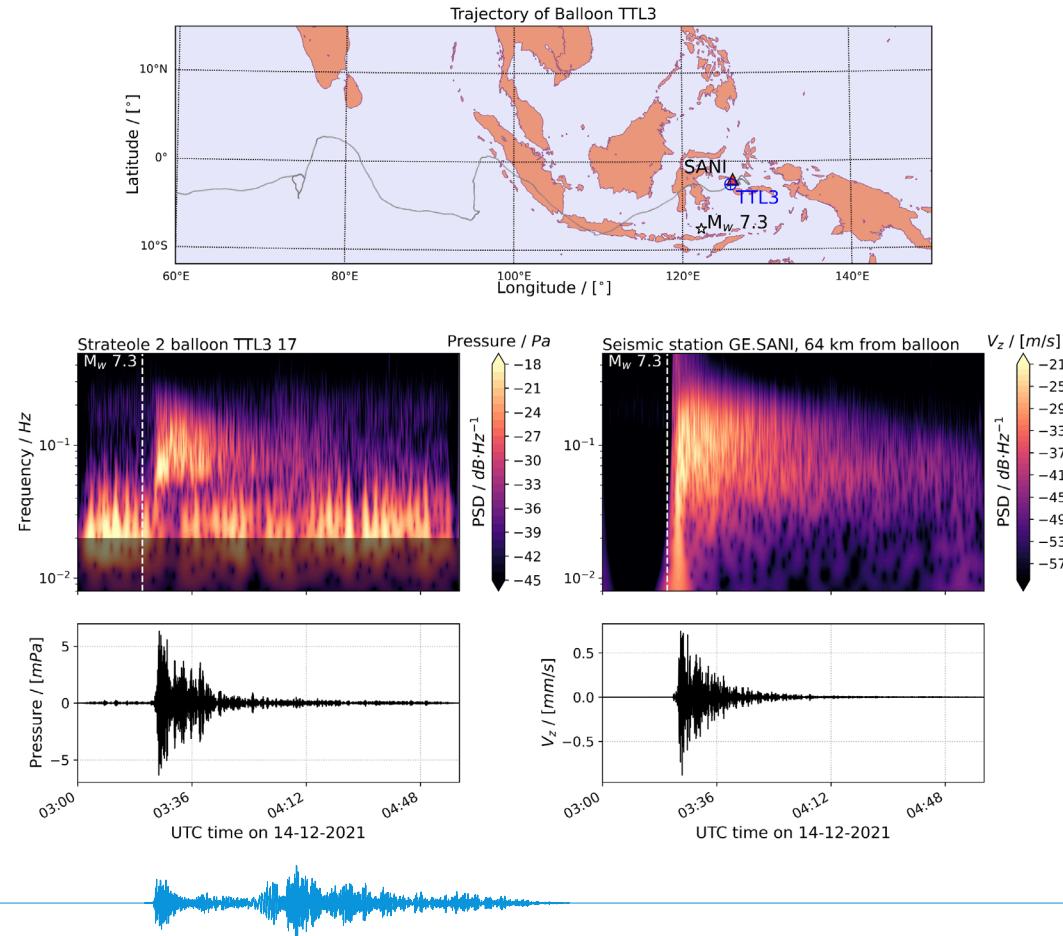
Brissaud, Q. et al. *Geophysical Research Letters* **48**, (2021), [10.1029/2021GL093013](https://doi.org/10.1029/2021GL093013)

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

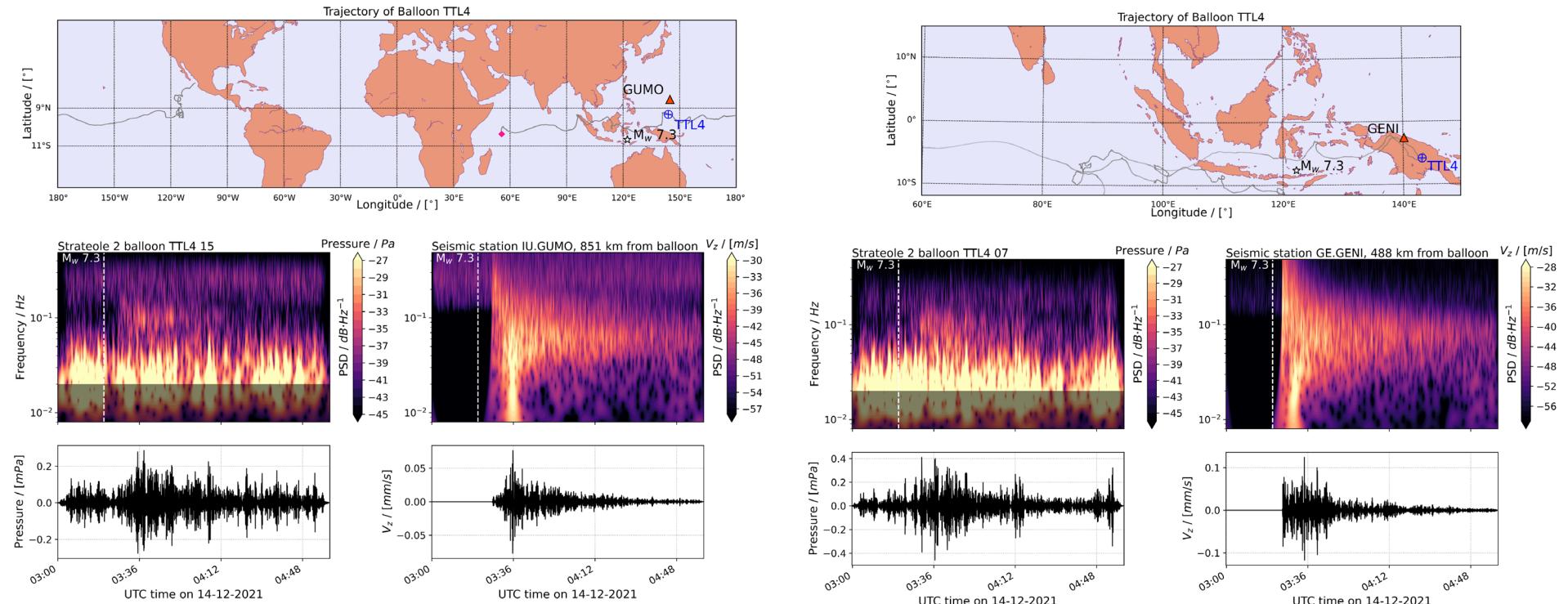
Picking the Rayleigh wave: example of balloon 16



Picking the Rayleigh wave: example of balloon 17

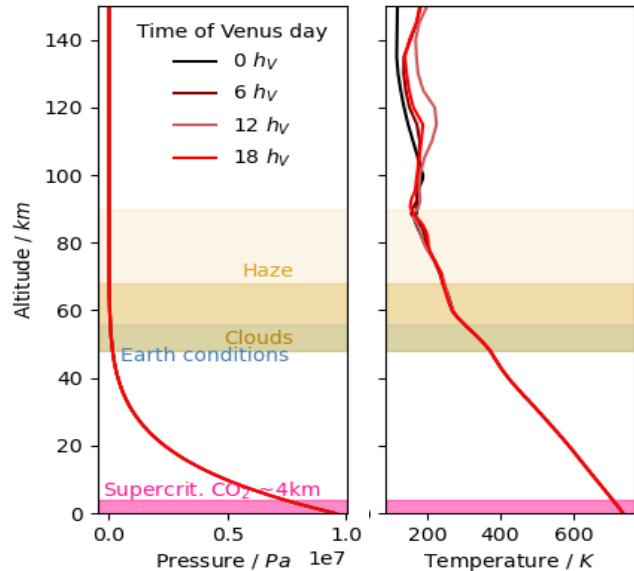


Balloon 15 and 07: a more difficult case



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

