From atmospheric infrasound to the crust and mantle: demonstrating subsurface inversion using balloon data

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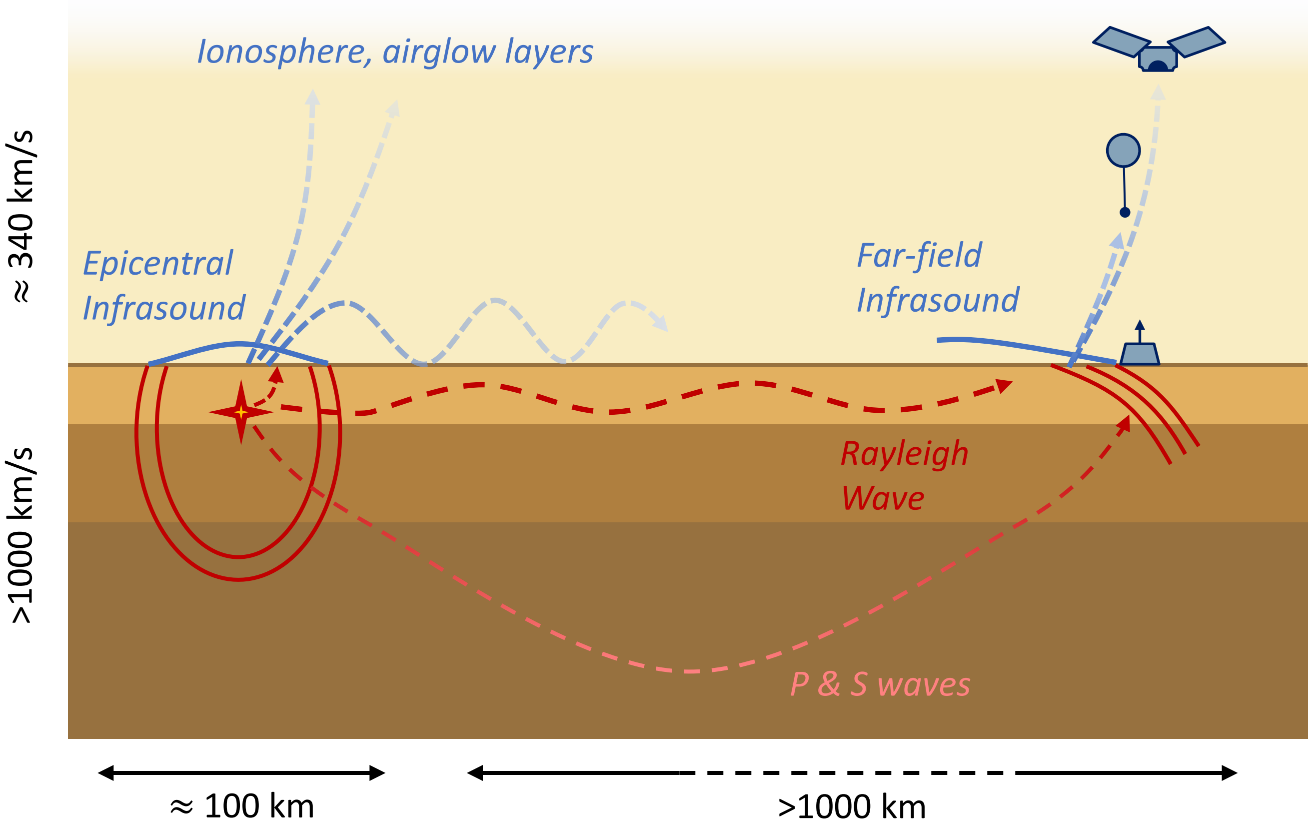
Norwegian Seismic Array (NORSAR)
University of Oslo

Funded by The Research Council of Norway

NORSAR Listening to the Earth

Earthquake Infrasound

Two types of earthquake infrasound: *epicentral* and *far-field*.



On the ground: example of Alaska recordings

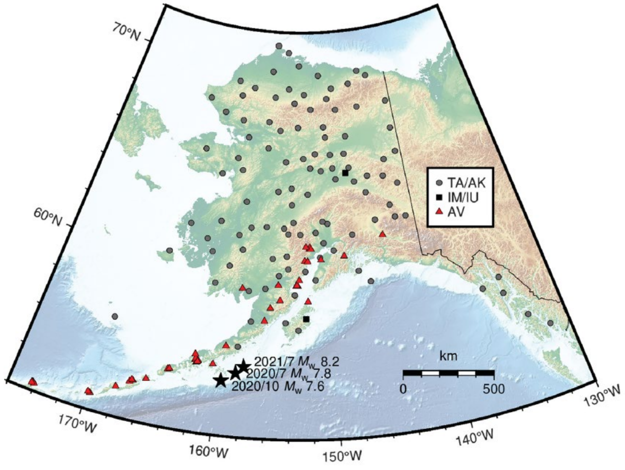
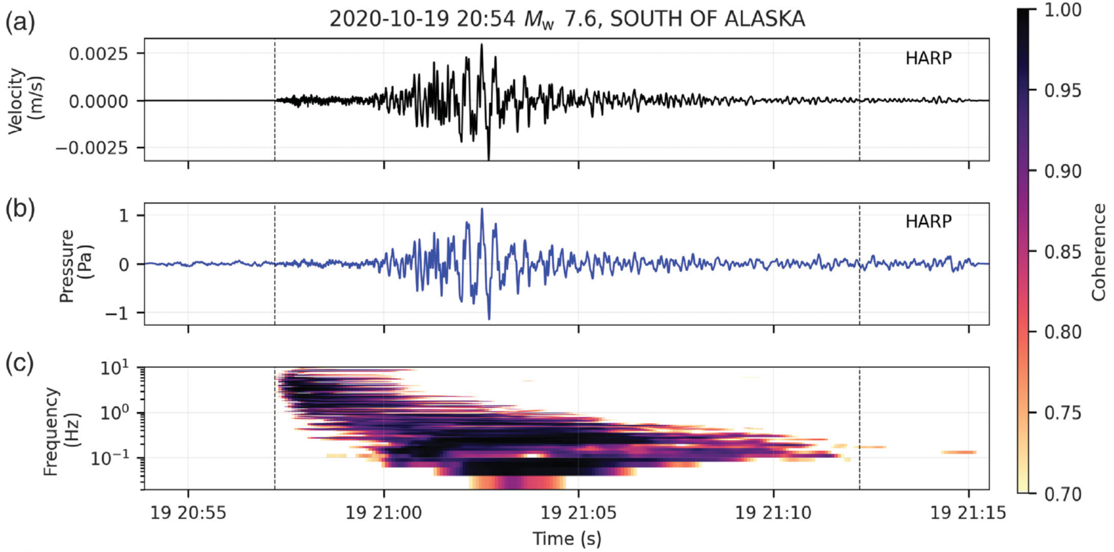


Figure 1. Map of infrasound stations in Alaska in 2020–2021. Each station's marker indicates the network: circles indicate TA/AK, squares indicate IM/IU, and triangles indicate AV. All but one station has a colocated seismometer. The locations of the three large earthquakes used in this study are plotted as stars.



Alaska network: many pressure sensors collocated with seismic sensors.
Excellent coherence between Pressure and seismic velocity following large earthquake.

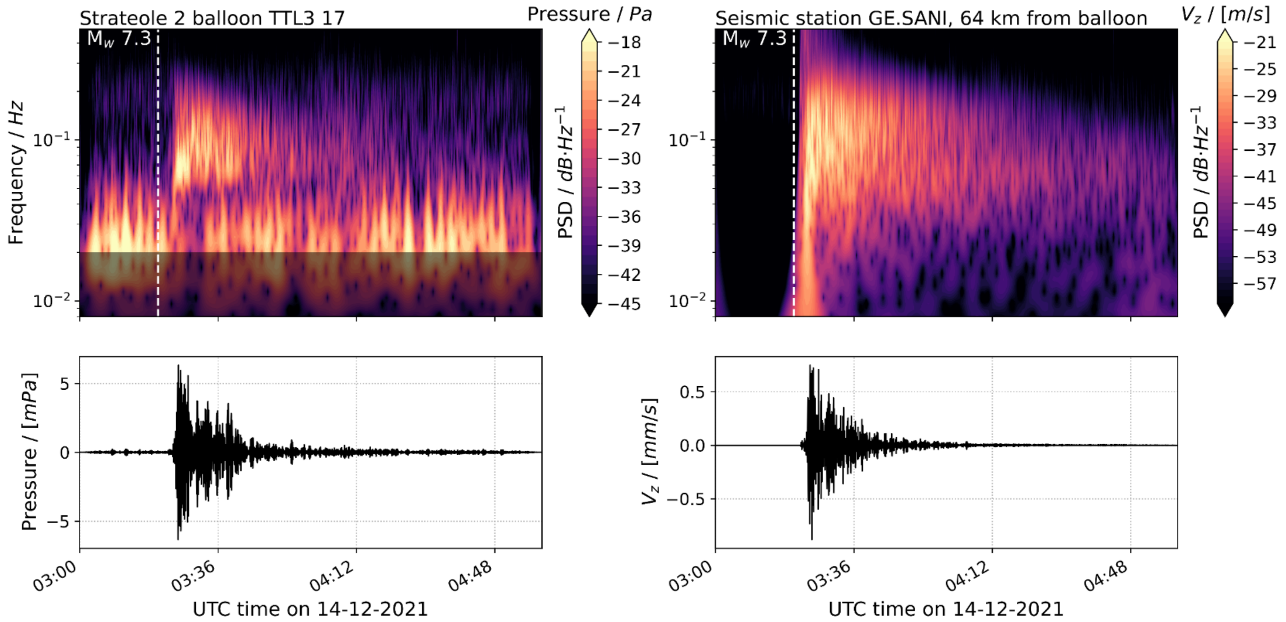
Scaling factor: $\Delta P(t) = \rho_{atm} c v_z(t)$

Figures from:
Fee, D., Macpherson, K., Gabrielson, T., (2023). *BSSA*, **113**, 1581–1595. [10.1785/0120220226](https://doi.org/10.1785/0120220226)
Macpherson, K., Fee, D., Coffey, J., Witsil, A. (2023) *BSSA*, **113**, [10.1785/0120220237](https://doi.org/10.1785/0120220237)

NORSAR

Balloon seismology on Earth

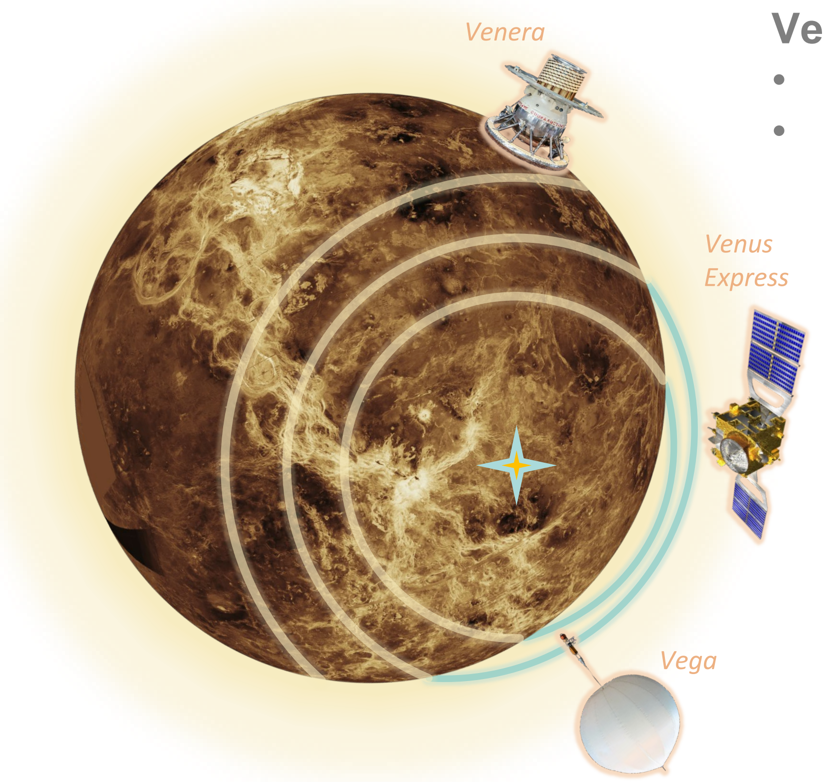
- Recording of 3 different earthquakes (Peru, California, Flores).
- Good agreement between ground seismic and airborne infrasound recordings.



The 14/12/2021 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

Venus seismology concepts



Venus:

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

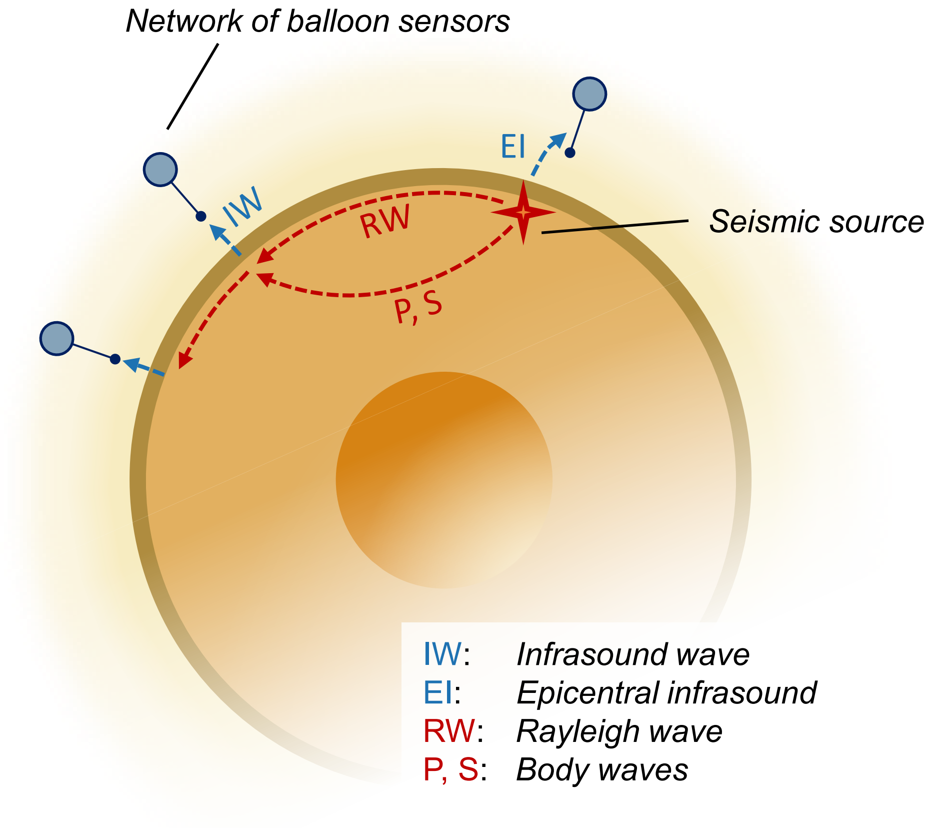
Garcia, R. F., et al. *Earth and Space Science*, **11**, (2024). 10.1029/2024EA003670

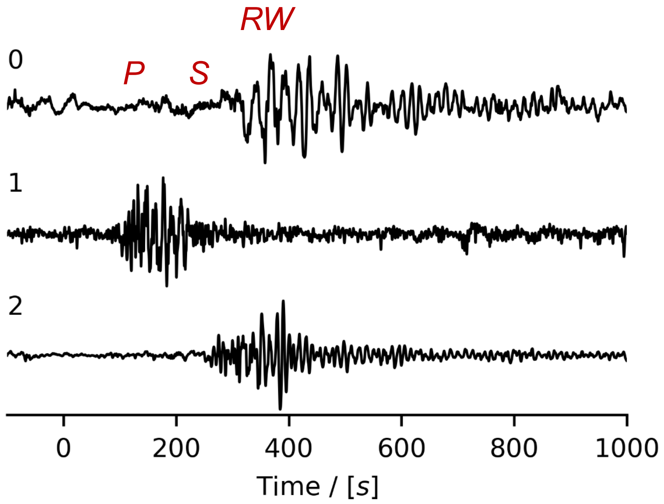
Surface sensor. Deployed seismometer. < 24 h.

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 for planetary exploration



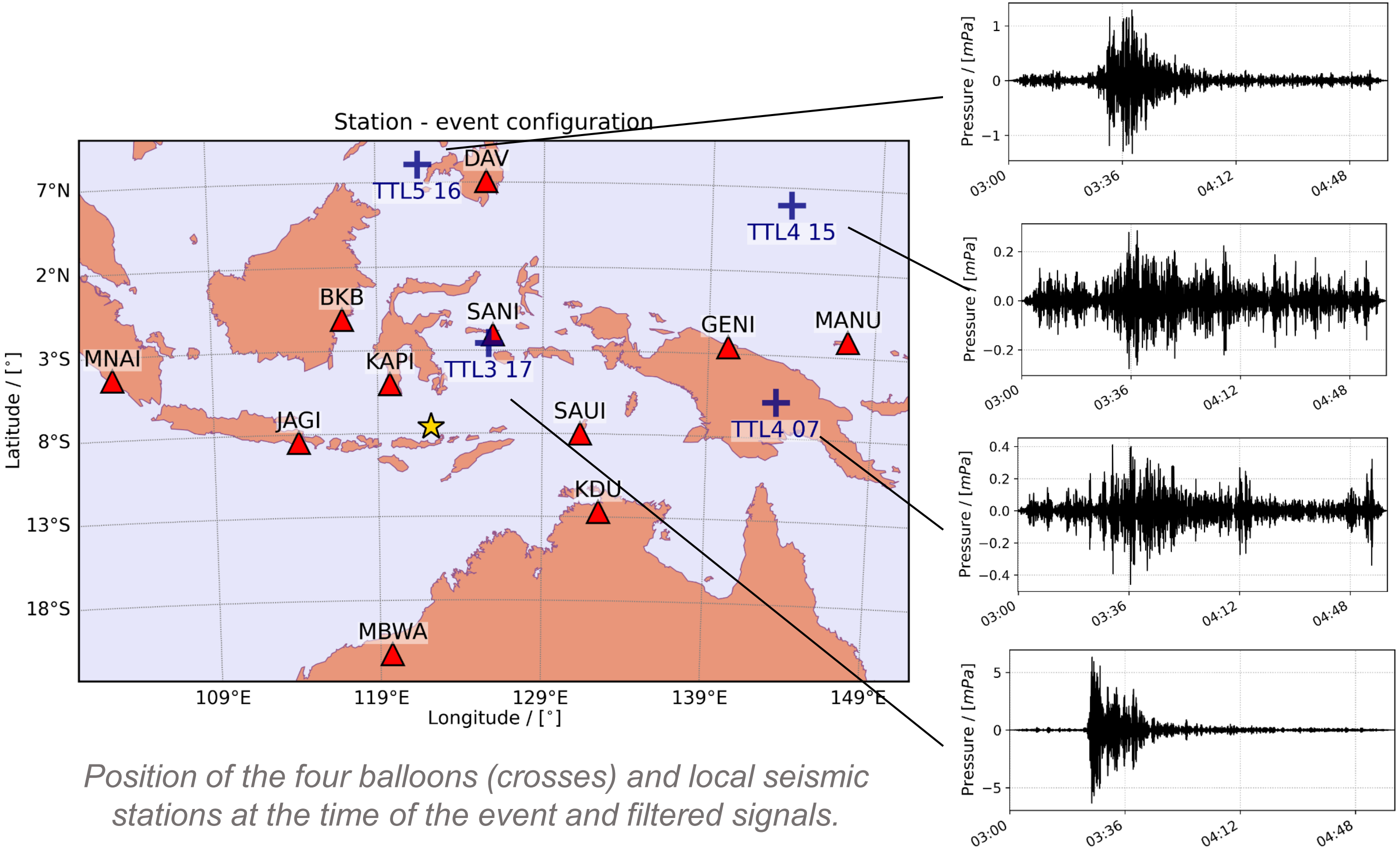


Hypothetical venusquake pressure signals recorded by three balloons, with ***unknown source origin time & distance****, but clear Rayleigh and body wave arrivals.*

Source origin? Subsurface velocities?

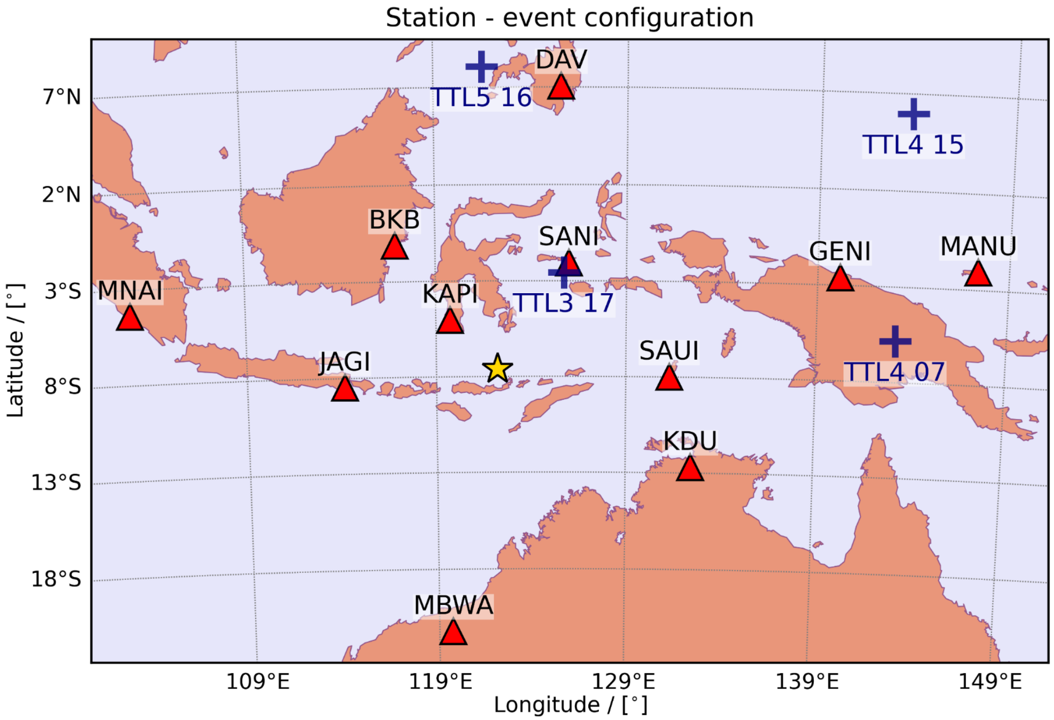
Validation: The Flores Earthquake

- 4 receivers
- High SNR
- Colocated seismic stations
- Well-characterized source



Position of the four balloons (crosses) and local seismic stations at the time of the event and filtered signals.

Flores, pure seismic inversion with 11 stations

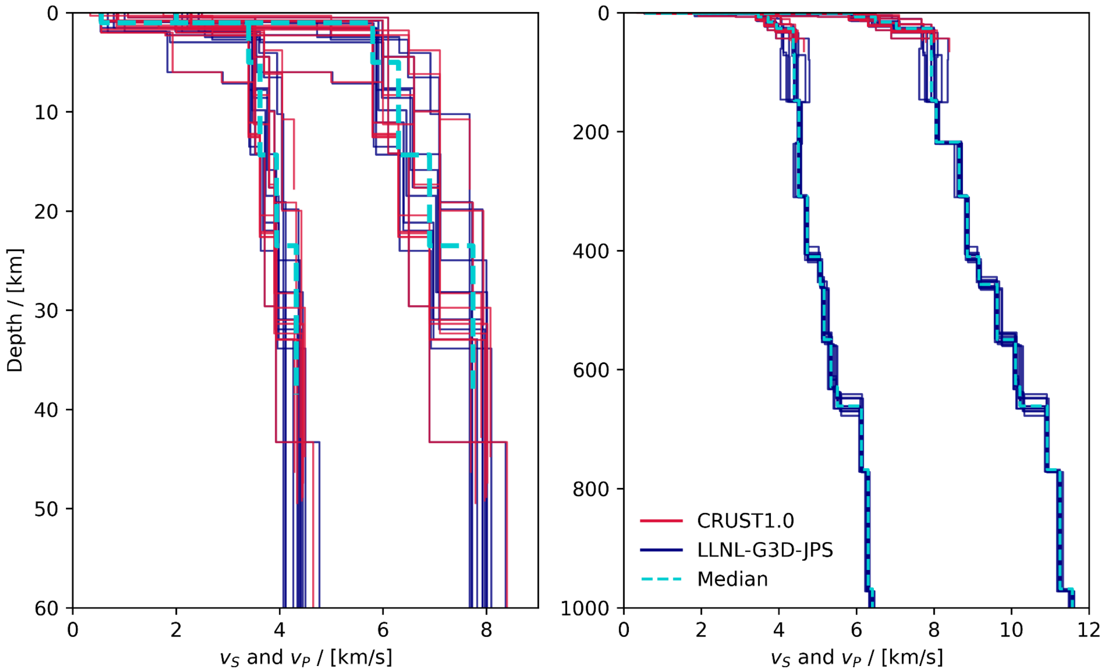


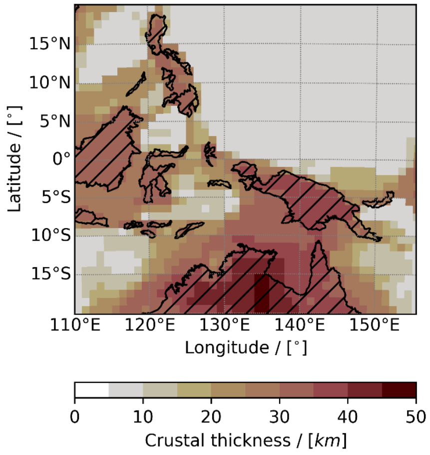
Three different inversions using P, S and RW arrivals from:

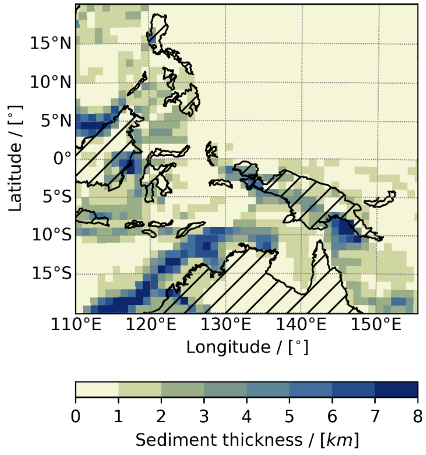
- The *vertical velocity component* of 11 seismic stations.
- A subset of seismic stations closest to the balloon.
- The 4 Strateole2 balloons.

Seismic inversion in the Flores region

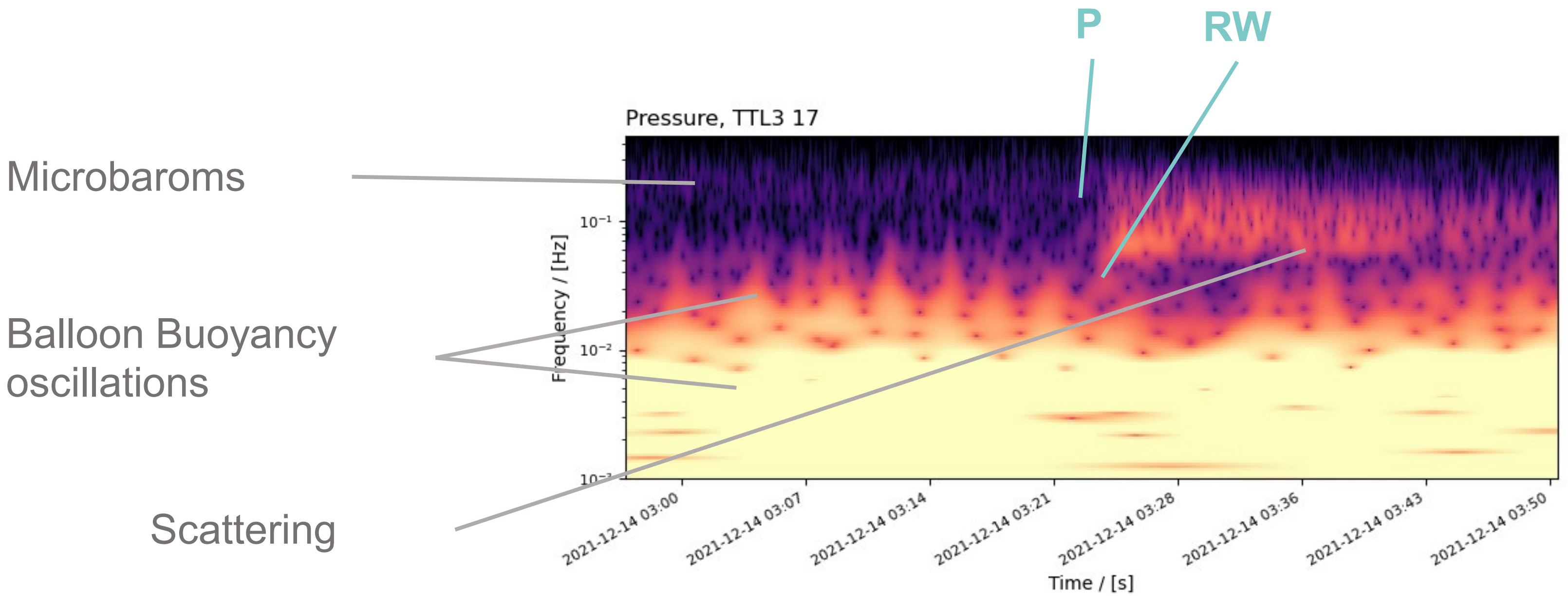
A lot of variety in crustal thickness and sediment deposits around the event.
We construct a “Median model” as our baseline for assessing our inversion results.





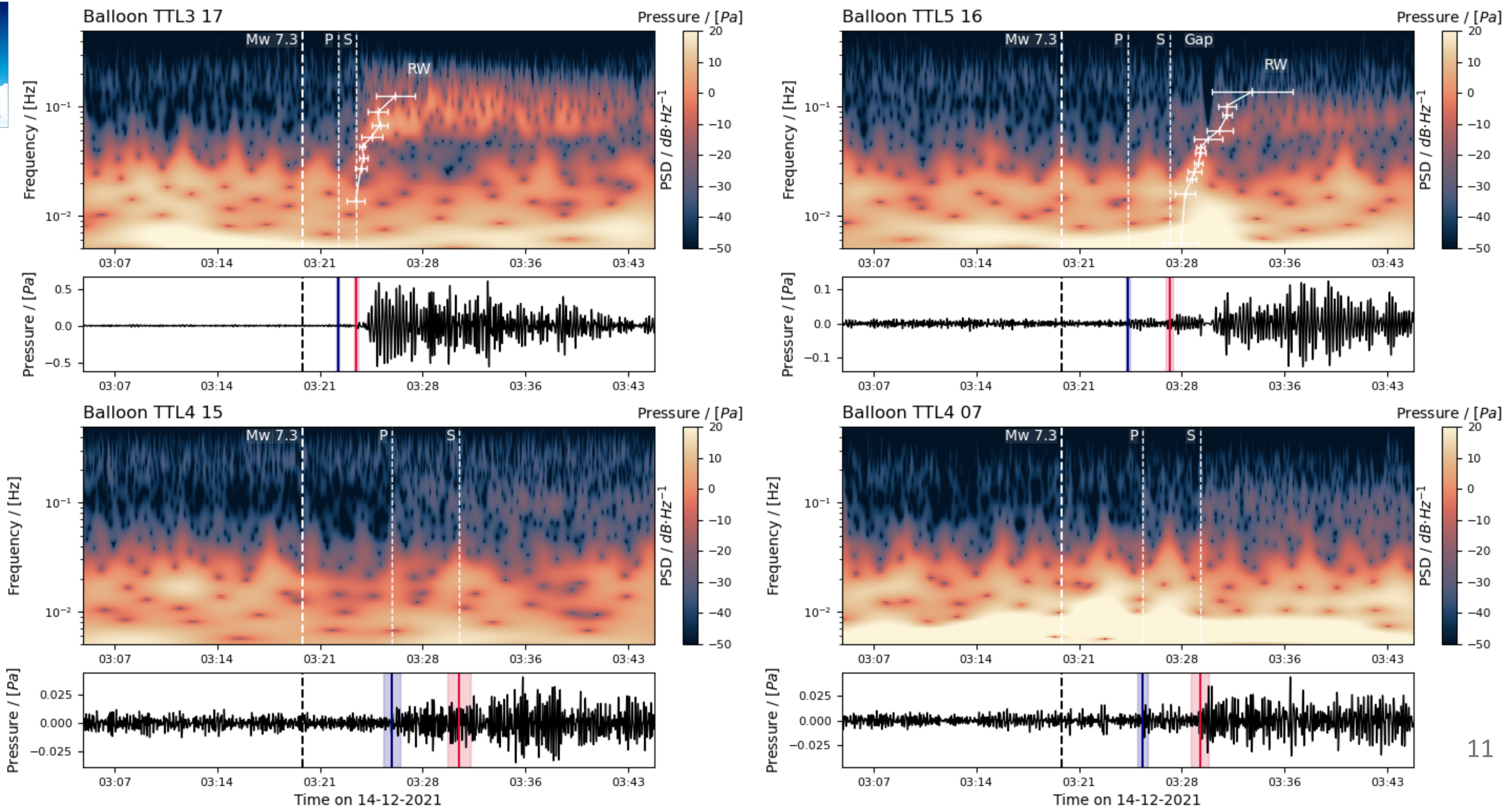


Noise in balloon pressure data



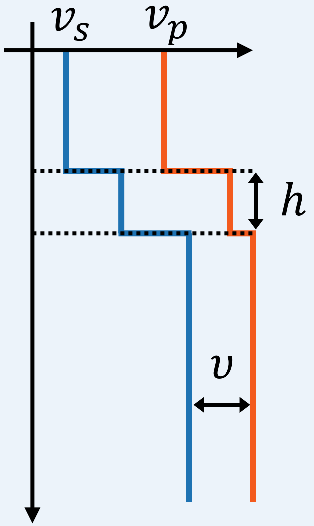
Potential noise: Balloon buoyancy attenuation, microbaroms, generation of earthquake infrasound by topographic features…

Strateole2 observations of the Flores earthquake



Inversion method - McMC

Subsurface model



Source location and time

$t_s \quad h_s \quad lat_s \quad lon_s$

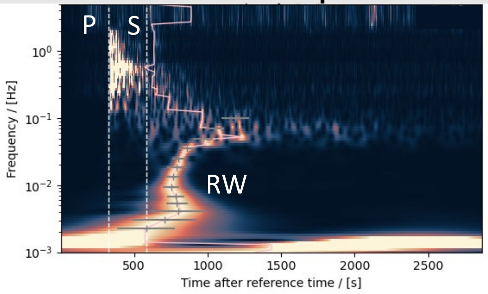
Distribution of parameters

Forward model

Arrival times

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

Data: arrival picks



$\neq$

Misfit + **Priors**

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

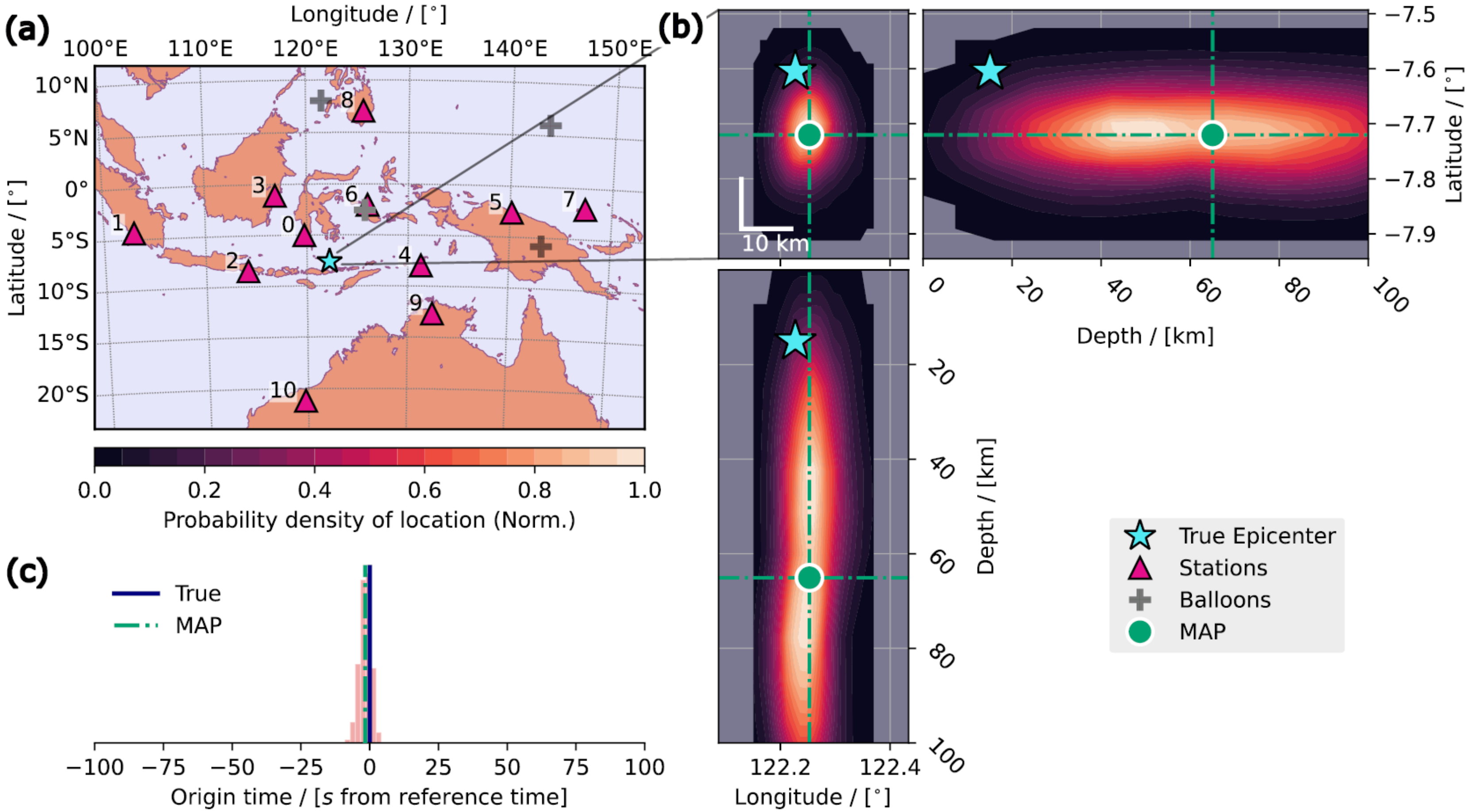
Bayesian approach: Markov chain Monte Carlo to explore the parameter space.

`Python module emcee`

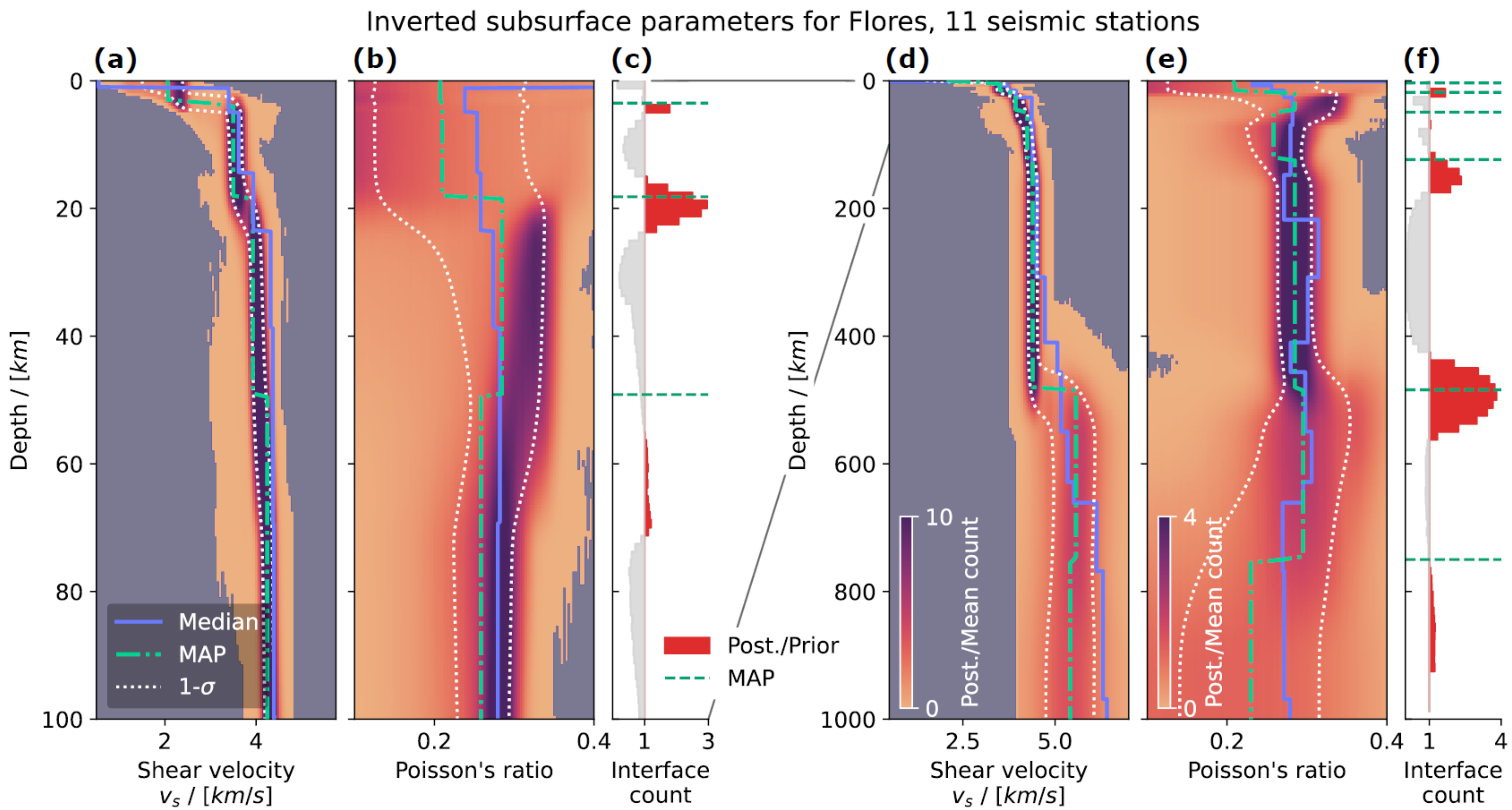
Posterior probability

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

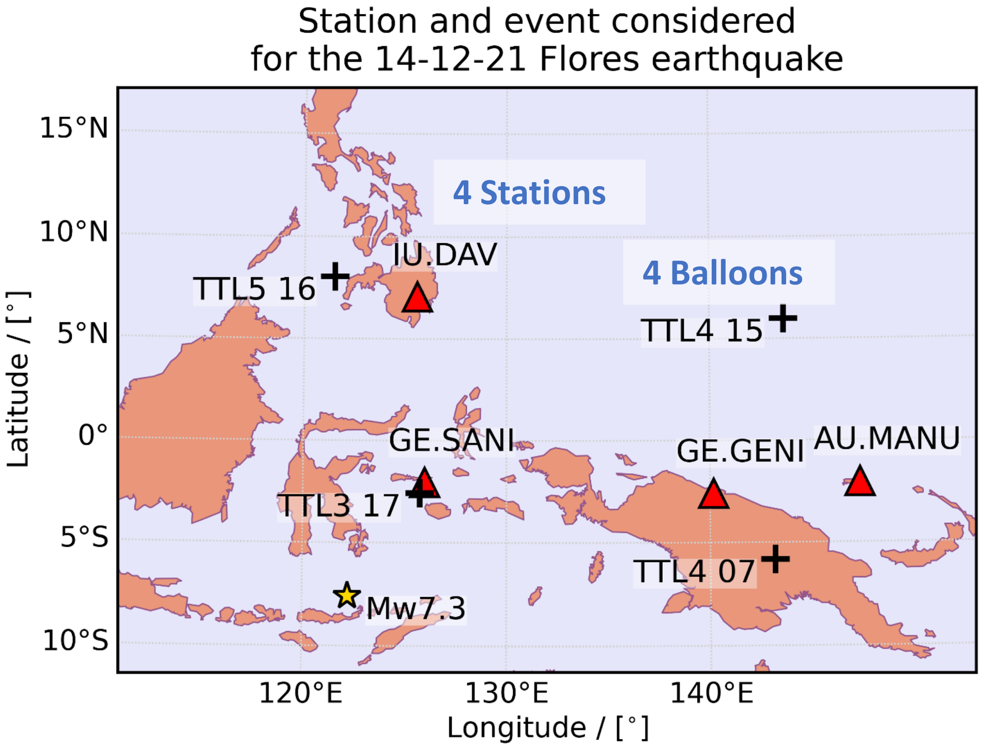
Flores, pure seismic inversion with 11 stations



Flores, pure seismic inversion with 11 stations



Inversion with 4 seismic stations and 4 balloons

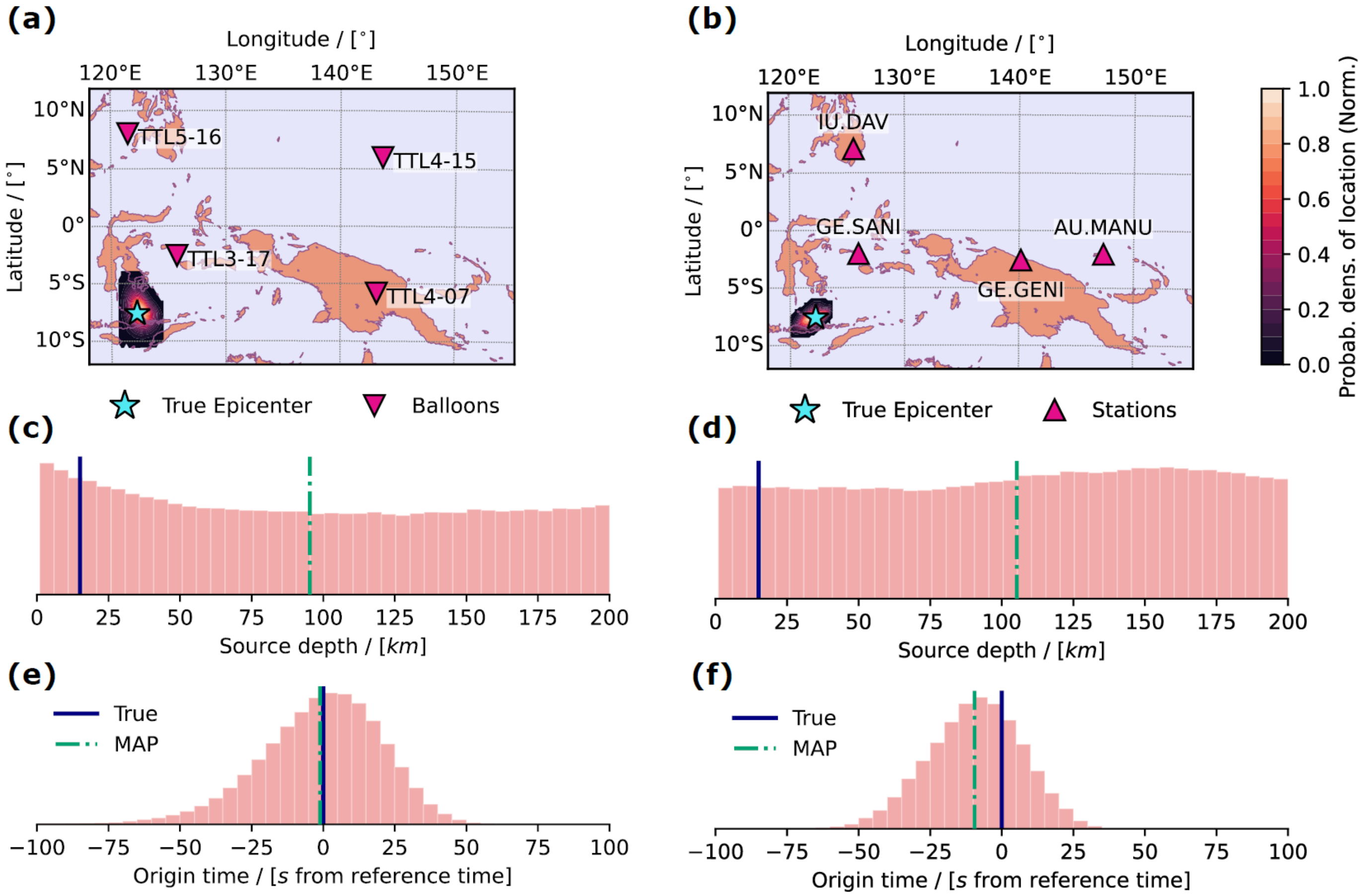


Two inversions with less information. P, S and RW arrivals from:

- Processed pressure traces of the 4 Strateole2 balloon.
- The *vertical velocity component* of 4 closest seismic stations.

Inversion with 4 seismic stations and 4 balloons

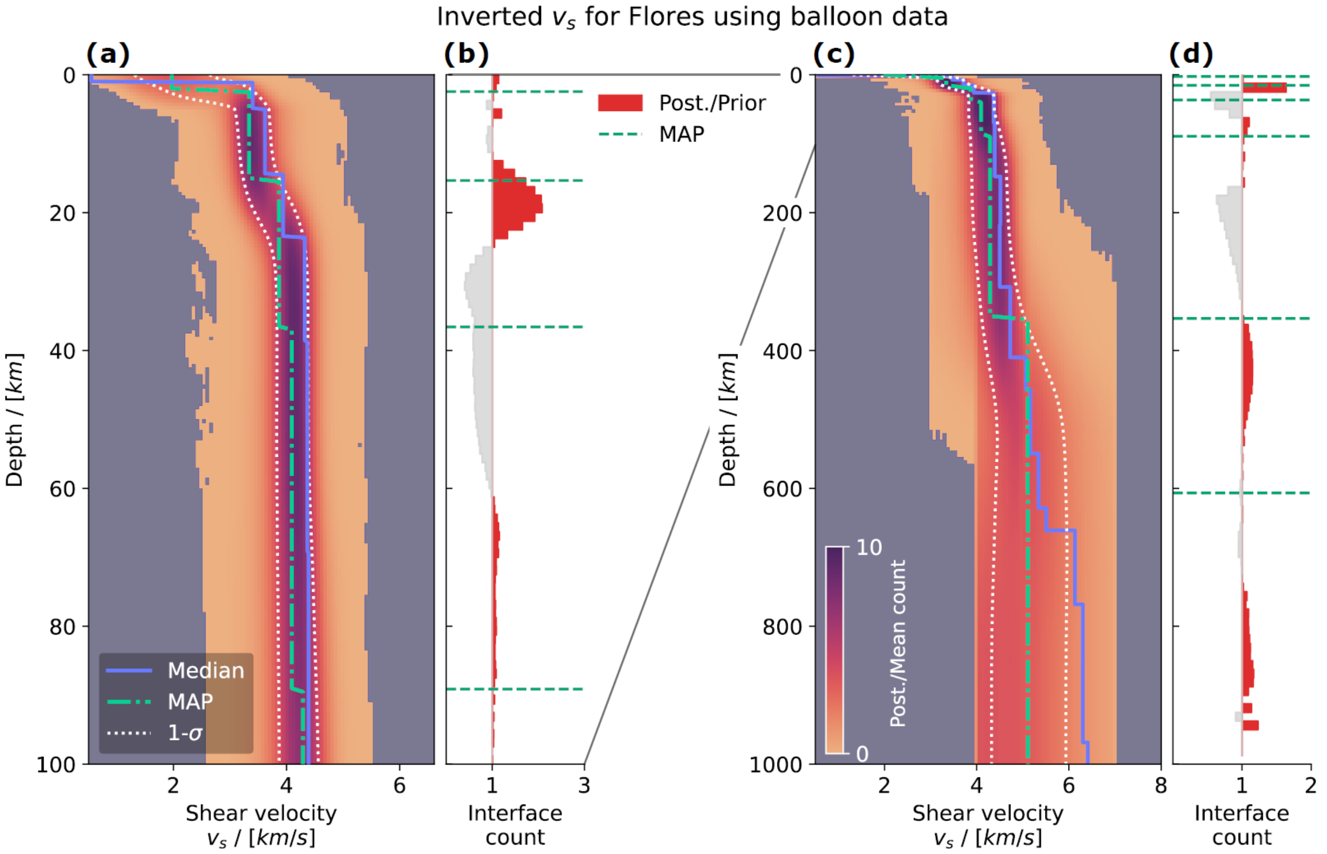
4 Balloons | **4 Stations**



P, S and RW arrivals from :

- Processing of the 4 balloon pressure traces
- the *vertical velocity component* of 4 seismic stations.

Subsurface model from 4 balloons



The same interfaces and shear-wave velocities as for the 11-station inversion are retrieved.

Conclusion – seismic inversion from Strateole2 data

Key results:

- First seismic inversion using balloon infrasound
- A joint inversion framework (source location + seismic velocities) yields satisfying results. However: only possible with a network of sensors.

Open questions / challenges:

Difficulty in picking seismic phases in single-component traces.

- Improving the LF balloon oscillation removal for better RW picking?
- Other balloon noise sources - balloon wake turbulence?
- Infrasound propagation effects - topographic scattering?

Venus seismology with balloons and airglow

Challenges on Venus:

- **How strong will the signal be ?**
  - Modeling the seismic activity
  - Modeling the detectability

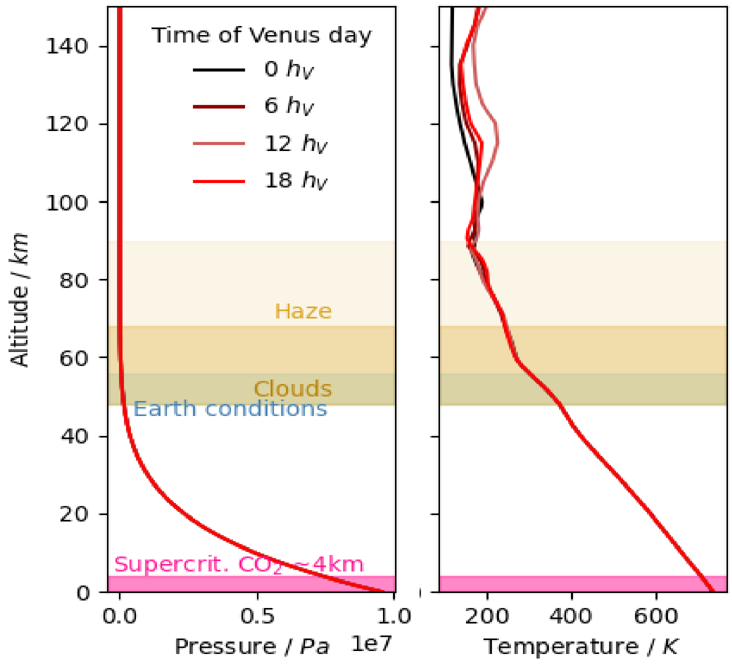
- **What will the signal look like ?**
  - Realistic model of noise: no microbaroms but turbulences / weather...
  - Improve identification of seismic phases with single-component pressure signals. Automatic, before compression!

- **How will balloons behave ?**
  - Balloon dynamics ?
  - Optimal location ?
  - In combination with airglow sensors?

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!

- How will the atmospheric conditions affect **infrasound propagation in different directions and local time**?
- Are there any **waveguides or refractive regions** in the Venus atmosphere?
- Does the presence of **supercritical CO_2** on the surface have any effect on seismo-acoustic coupling and absorption?

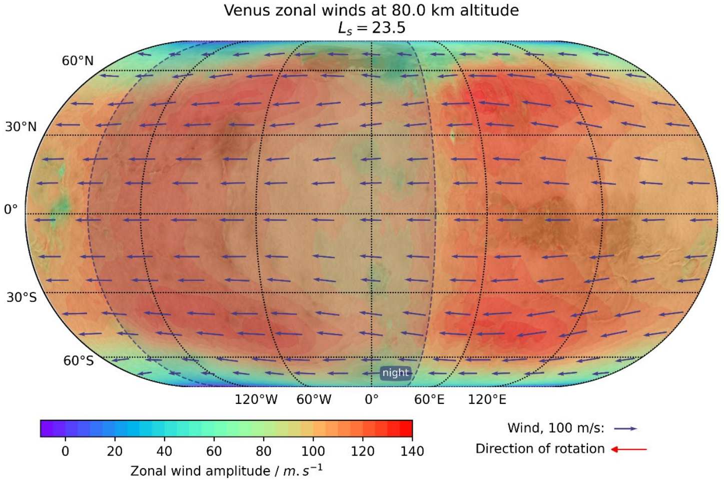


Venus Climate Database outputs for pressure and temperature near the equator.

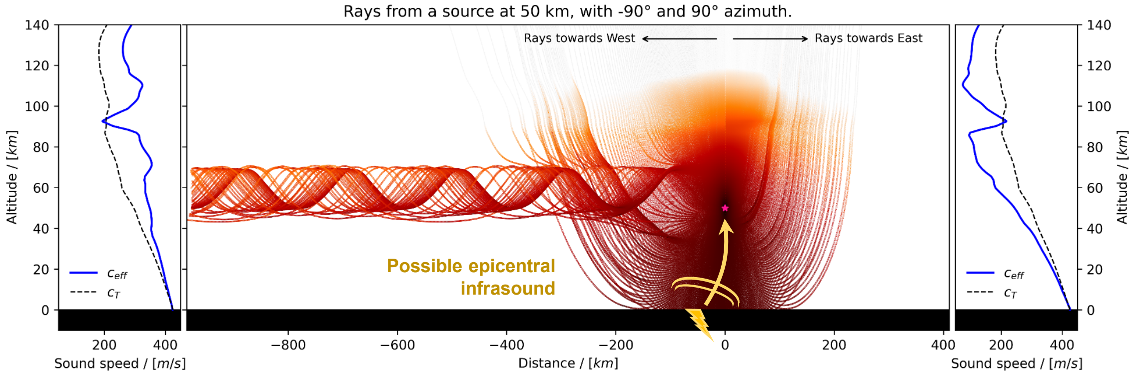
Infrasound propagation on Venus

Master student project, Sophus Bredesen Gullbekk (UiO)

Identify different geometry of propagation in the Venusian atmosphere depending on current global climate models (e.g., the Venus Climate Database) using geometric acoustics + Parabolic Equation.



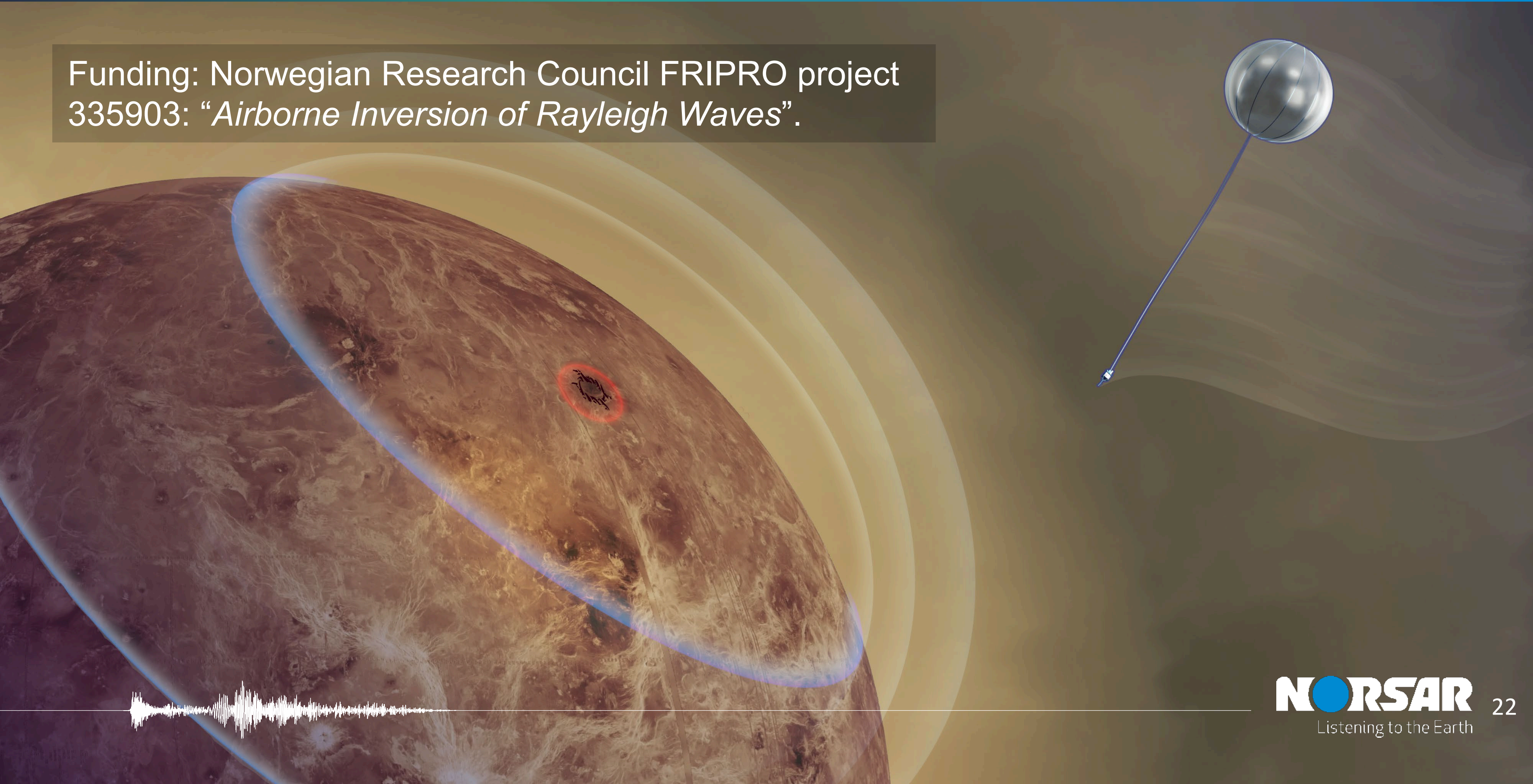
Winds at 80 km altitude predicted by the Venus Climate Database



Trajectory of rays launched from a point at 50 km altitude from the equator in the east and west direction.

Thank you for your attention

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



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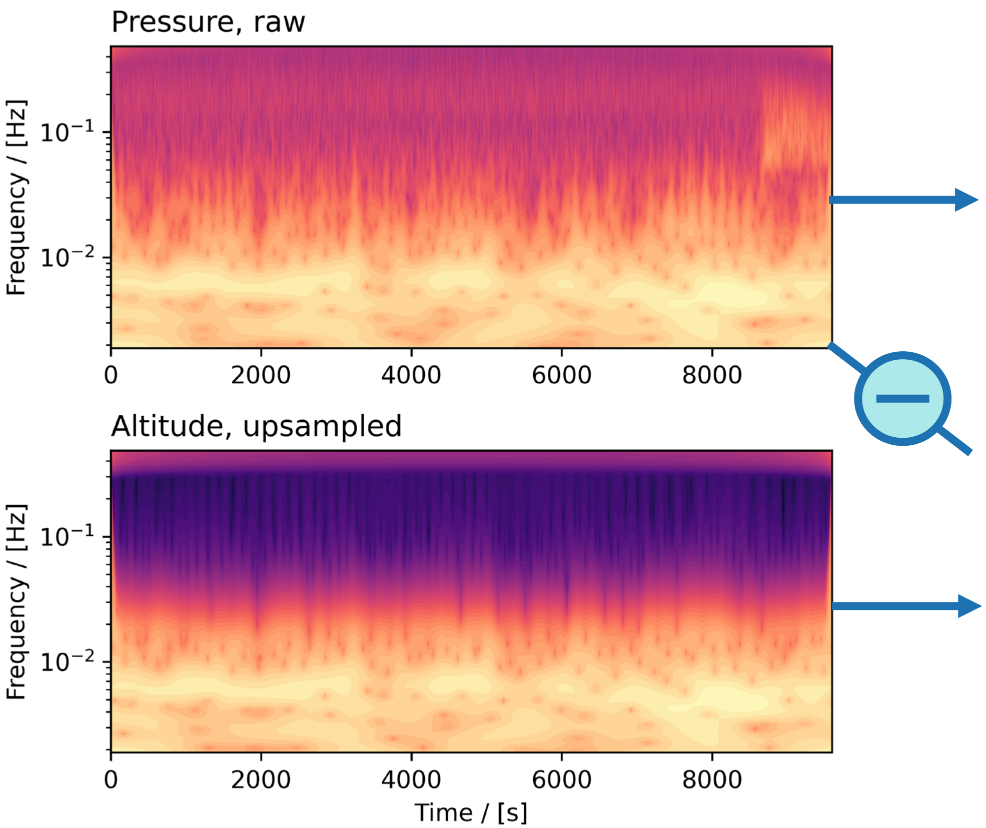
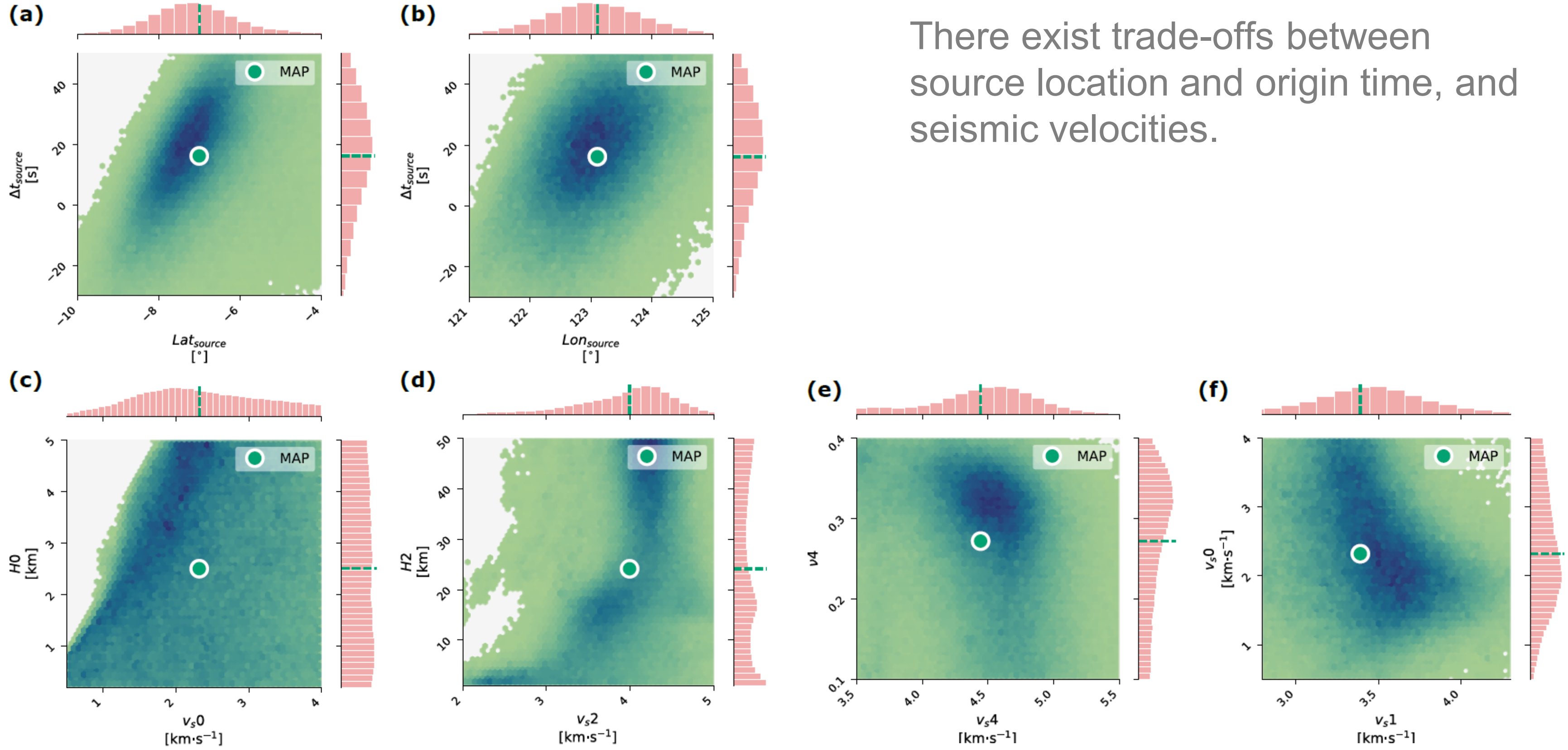
Improving the SNR at low frequency

There is an exponential relation between pressure and altitude: use the low frequency GPS data to correct the pressure recordings (adapted from Podglajen, A. et al. (2022). *GRL* **49**. 10.1029/2022GL100833)

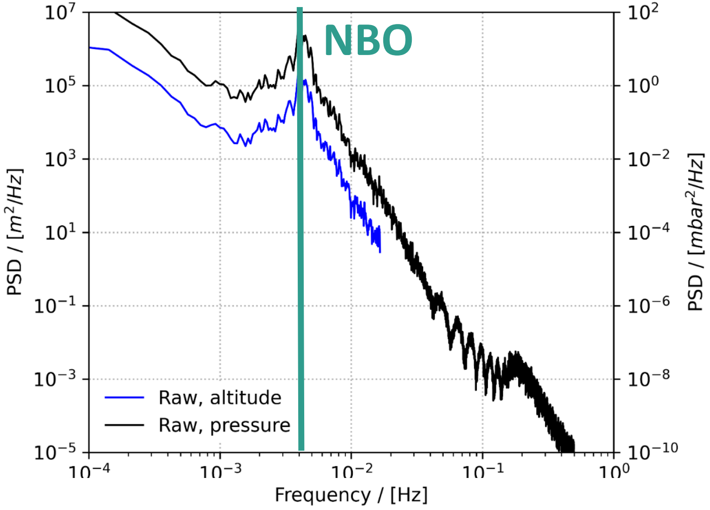


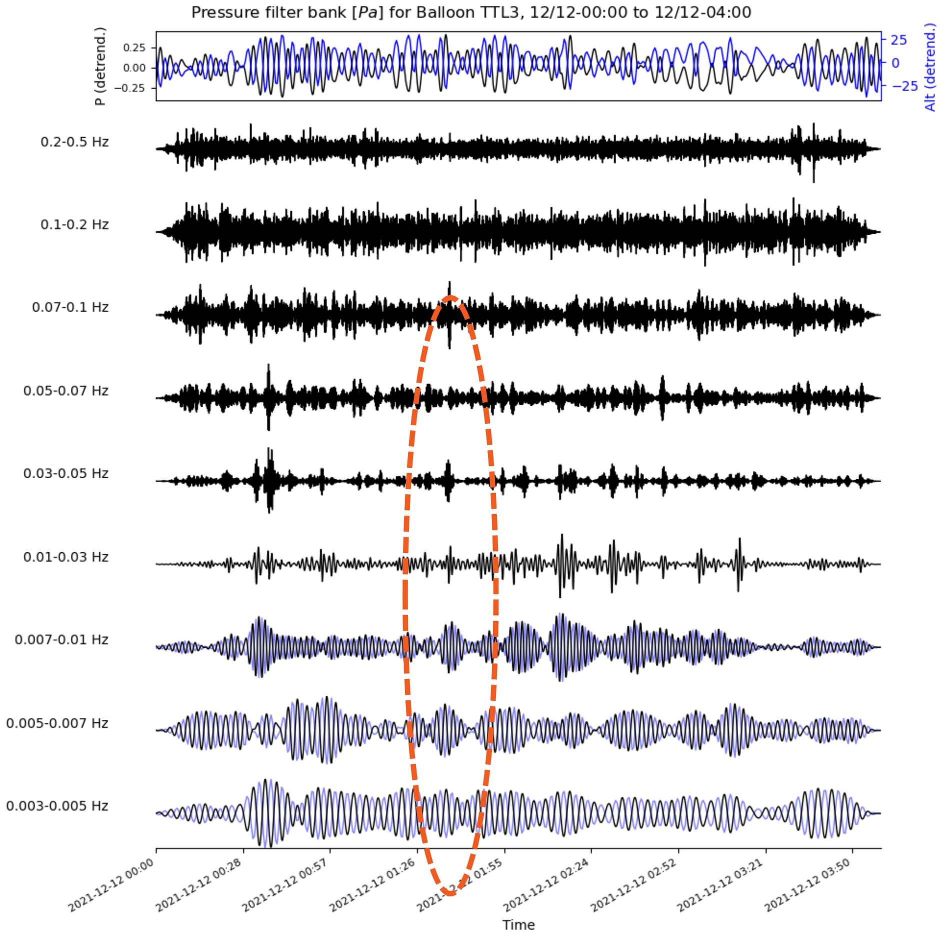
Trade-offs in the inversion



There exist trade-offs between source location and origin time, and seismic velocities.

Balloon oscillation and noise



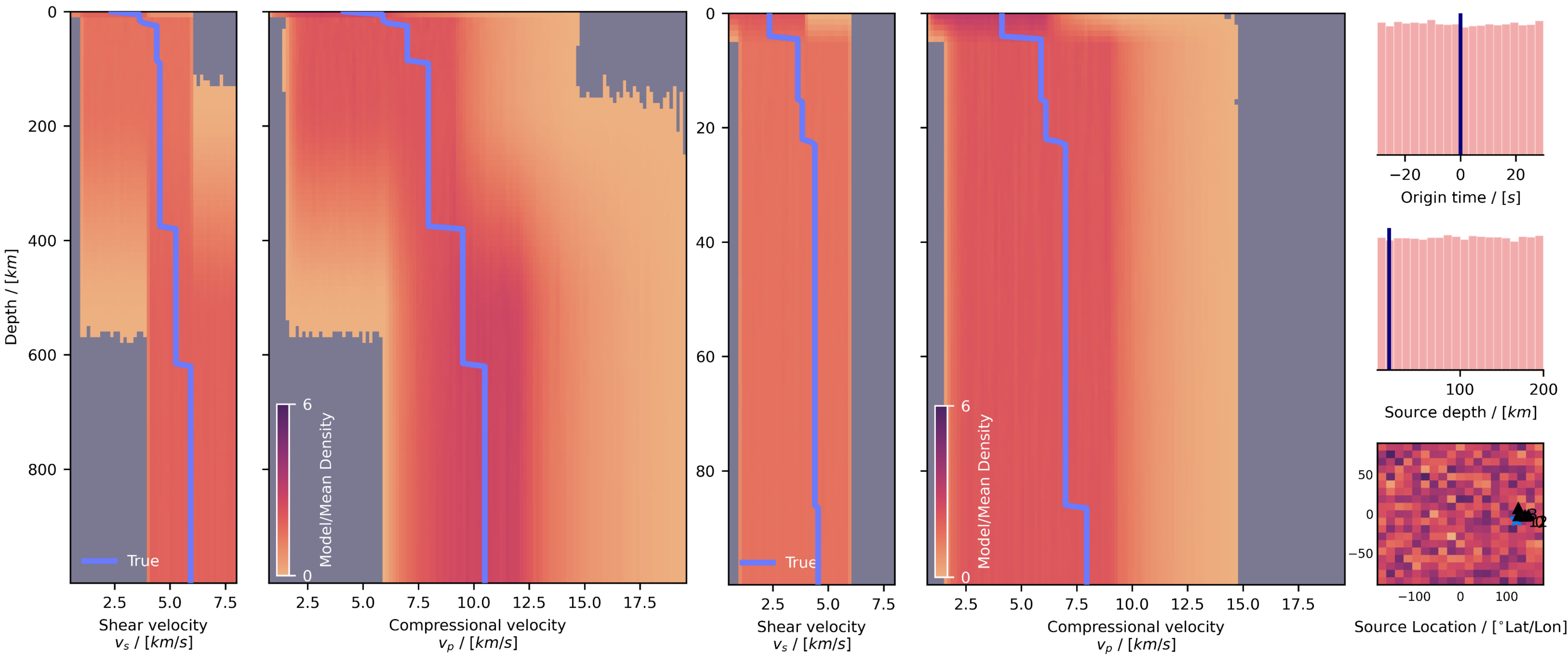


Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

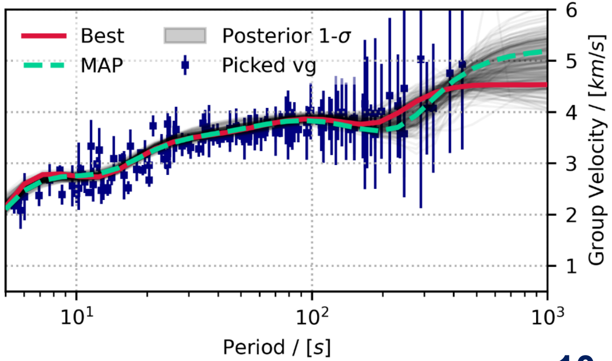
Good coherence up to GPS Nyquist frequency, perhaps even higher: **broadband energy bursts** follow altitude changes.

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

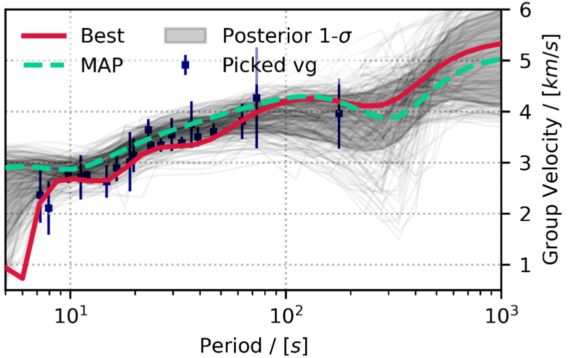
Prior distribution of model parameters



Quality of fit to the data

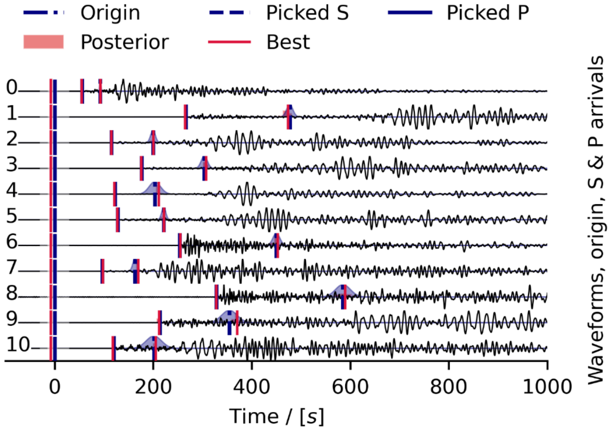


Group velocity curves from measured arrival times (blue) compared to the group velocity curves of the posterior distribution.

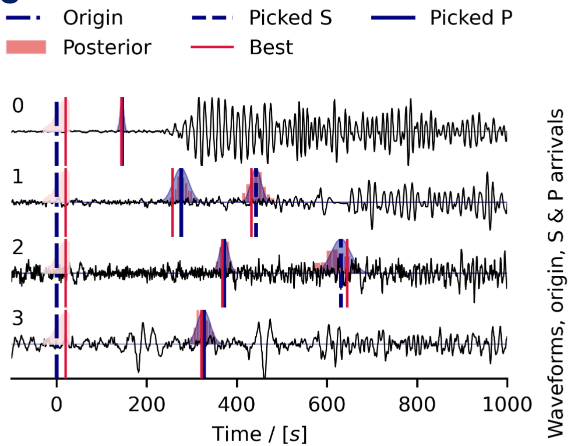


10 stations

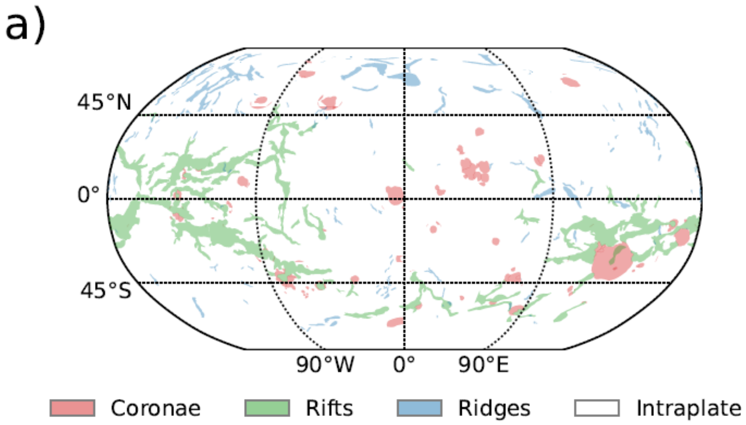
4 balloons

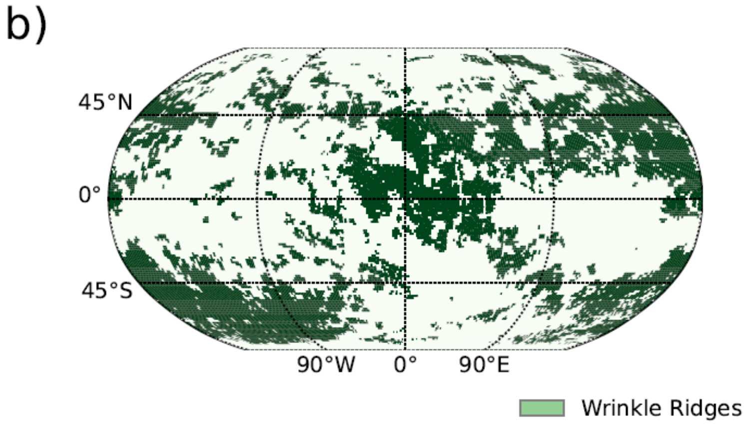


True origin time and picked S and P times, compared to the arrival time calculated from the posterior models.



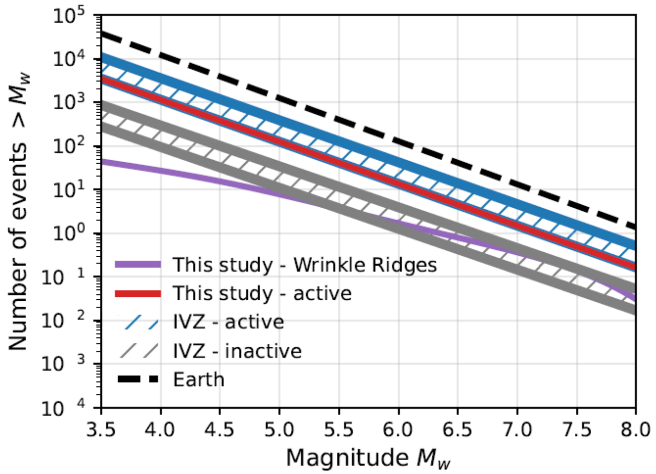
Seismic activity on Venus





Venus does **not** have plate tectonics.

But several other possible sources of activities:
Rifts, Coronae, Volcanoes.

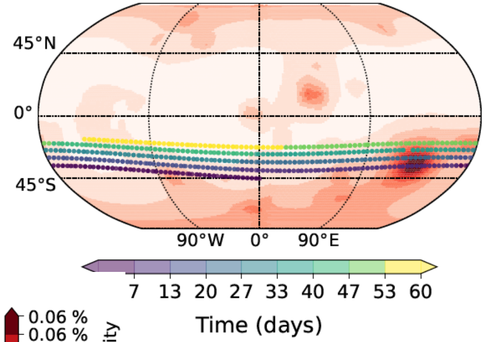


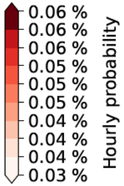
Brissaud, Q. et al. *(2025, in preparation)*
van Zelst, I., et al. (2024). *JGR: Planets* 129. 10.1029/2023JE008048
Garcia, R. F., et al. *Earth and Space Science*, **11**, (2024). 10.1029/2024EA003670

Infrasound detectability on Venus

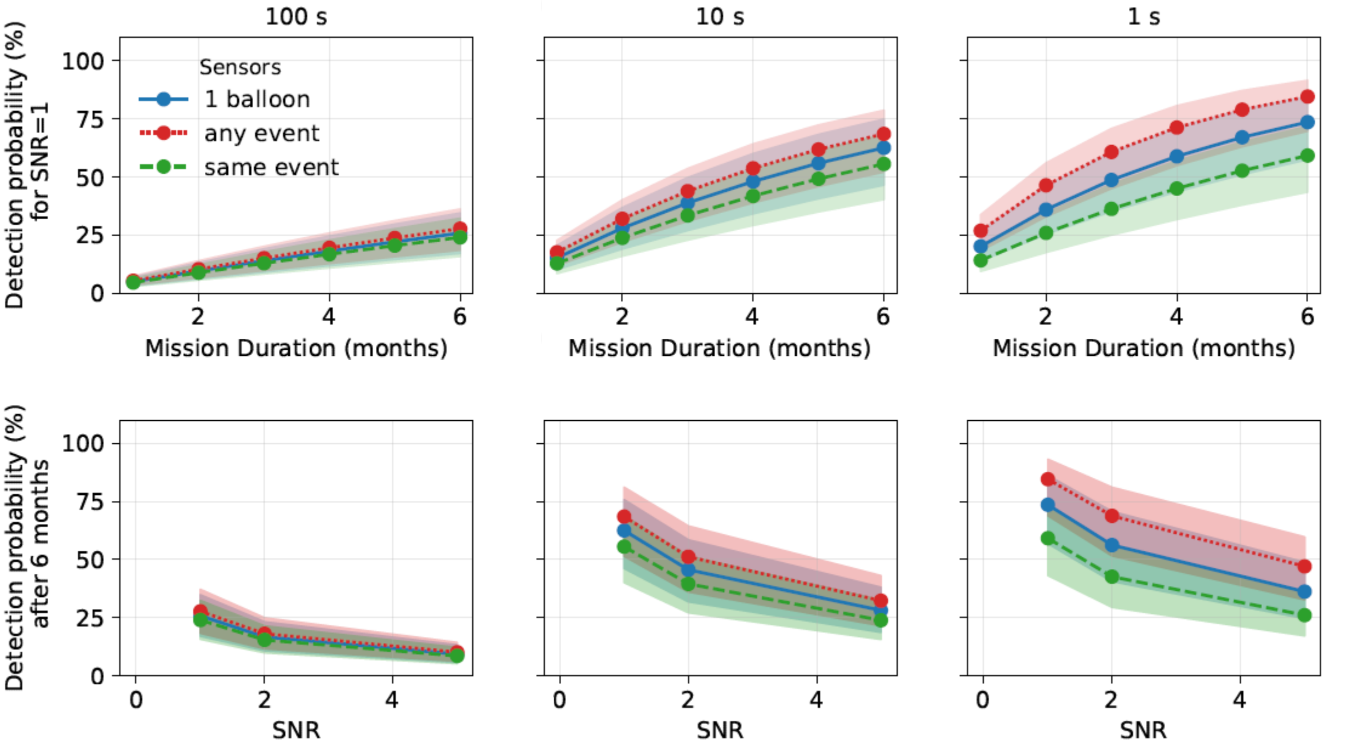
Detection probability according to:

- **Mission duration**
- **Minimum Signal-to-Noise ratio**





The typical flight path of a balloon (green-blue), and the local detectability for an hour spent above each region (red).



Brissaud, Q. et al. *(2025, in preparation)*