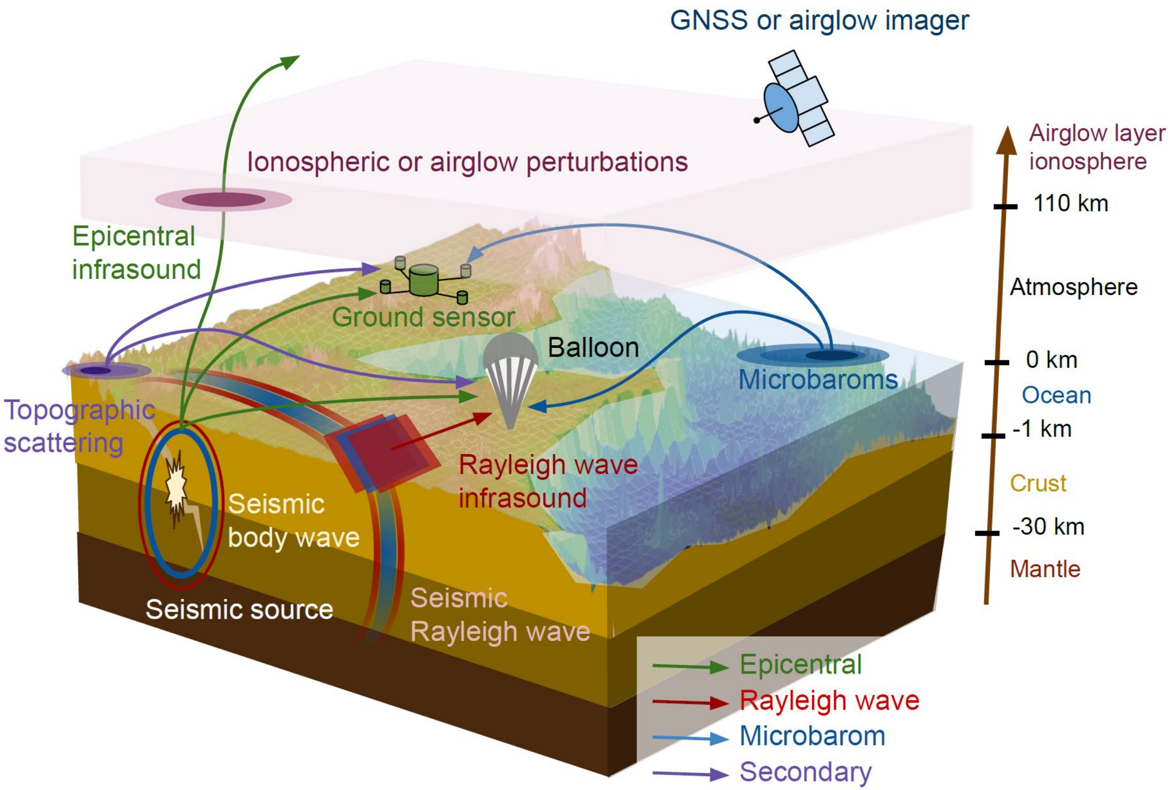
Welcome to the workshop!
Project Airborne Inversion of Rayleigh waves (AIR)

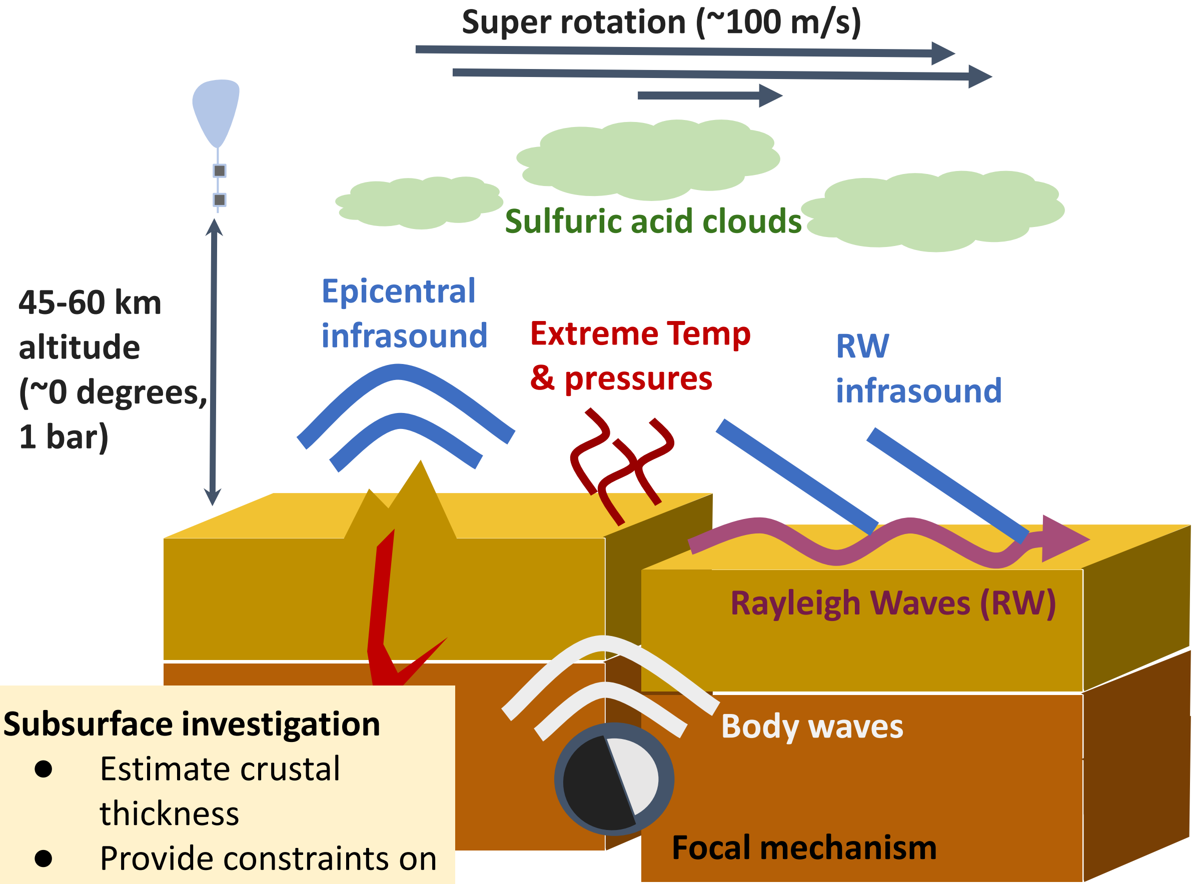
AIR workshop, 2024

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 ?



AIR: Using seismo-acoustics to explore Venus' interior



Subsurface investigation
- Estimate crustal thickness
- Provide constraints on mantle composition

Detectability
- Determine likelihood of observable magnitudes/mechanisms/ distances
- Assess detectability of seismic or direct volcanic infrasound
- Assess the potential of quake infrasound for subsurface and source inversion

Source characterization
- Estimate distribution of focal mechanisms and focal depths
- Estimate spatial distribution of active volcanoes

Workshop: Pushing for Venus seismology & collabs

Post-workshop document sharing
Building collaborations
within/outside the community

Presentations
Sharing recent seismo-acoustic
& Venus science results

Interactive sessions
Identifying challenges/opportunities
for future geophysical missions

Program day #1

September Monday 16th | Teams link: click here		
Time PST (Time CET)	8:00 - 8:15 (17:00 - 17:15)	Introduction
	8:15 - 8:45 (17:15 - 17:45)	Marouchka Froment: First results of the AIR project *Related presentation:* *Froment_internoise_AIR.pptx*
	8:45 - 9:15 (17:45 - 18:15)	Siddharth Krishnamoorthy: JPL balloon campaigns
	9:15 - 9:30 (18:15 - 18:30)	Break
	9:30 - 10:00 (18:30 - 19:00)	Anna Gülcher: Geodynamic modelling of Venus' tectonics and implications for seismicity *Related paper:* gulcher_coronae_simulations.pdf
	10:00 - 11:00 (19:00 - 20:00)	Interactive session #1: Discussion about instrumental challenges led by Siddharth Krishnamoorthy

Program day #2

September Friday 20th | Teams link: click here

Time PST (Time CET)	
8:00 - 8:30 (17:00 - 17:30)	Raphael Garcia & Iris Van Zelst: Results from the ISSI workshop titled “Seismicity on Venus: Prediction & Detection” *Related papers/preprints:* JGR Planets - 2024 - Zelst - Estimates on the Possible Ann… Garcia_preprint_seismoacoustic_detection_venus.pdf Maia_seismogenic_thickness_Venus.pdf
8:30 - 9:00 (17:30 - 18:00)	Solene Gerier: Analysis of post-seismic infrasound recorded by pressure sensors aboard stratospheric balloons *Related paper:* gerier_modeling_seismoacoustic.pdf *Asbtract:* Infrasound are produced by natural events such as explosion, volcanic eruptions and earthquakes ; and the infrasound analysis can provide information about the source of the low-frequency sound and about the medium in which waves propagate.
9:00 - 9:15 (18:00 - 18:15)	Break
9:15 - 10:30 (18:15 - 19:30)	Interactive session #2: Discussion about seismo-acoustic modeling and inversion challenges led by Marouchka Froment
10:30 - 11:00 (19:30 - 20:00)	Wrap up

Airborne Inversion of Rayleigh waves (AIR)
First results

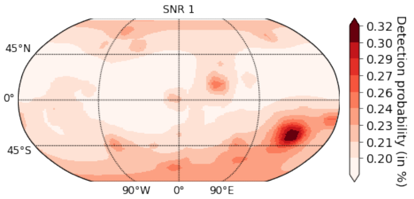
AIR workshop
September 16, 2024

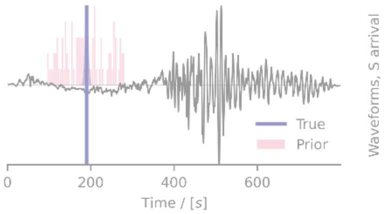
Marouchka Froment, Quentin Brissaud, Sven Peter Näsholm,
Celine M. Solberg, Tina Kaschwich and Antoine Turquet

AIR preliminary results: Detecting and inverting

Detectability

- How do seismicity estimates on Venus affect the detectability of venusquakes?
- Can volcanic processes be detected?
- How long should the balloon mission be?





Inversion

- How sensitive is the inversion to the number of balloons and phase type detected?
- What do the posterior distribution of subsurface velocity parameters look like?
- Can we validate our model on real data?

A PHSA-style detection framework

How likely are we to detect a seismo-acoustic signal with a given Signal-to-Noise Ratio (SNR) from a balloon platform?

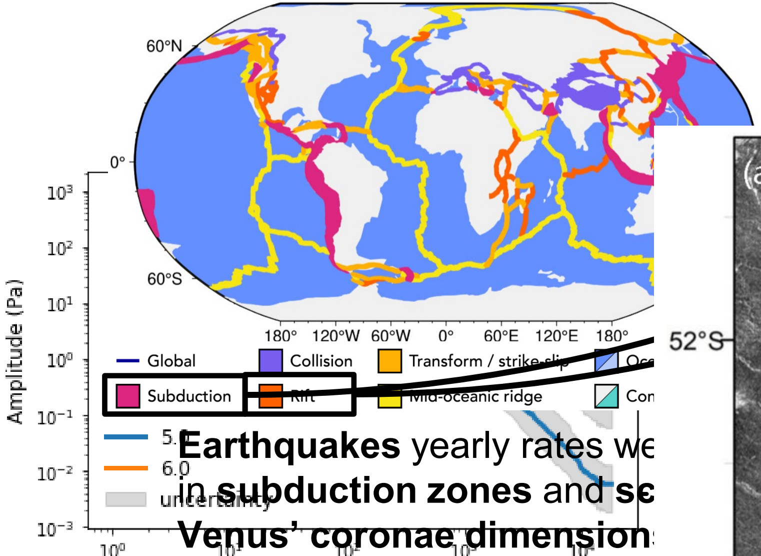
Probability of observing a signal with **SNR > d**, for a mission duration **t** from a location **x**

Rate of venusquakes with **SNR > d**

$$\boxed{\mathbb{P}(\mathrm{TL}/\sigma_n > d, M_{min}, x^{obs}_{lat,lon}, t)} = 1 - \boxed{exp[-\boxed{\lambda}(\mathrm{SNR} > d)t]}$$

Probability of **not detecting any event** from a **Poisson distribution**

Defining the rate of observable venusquakes



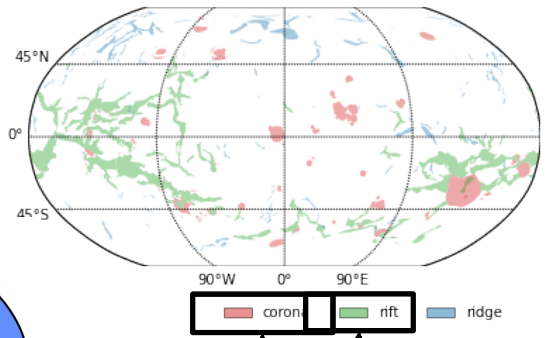
Earthquakes yearly rates we

in **subduction zones** and **se**

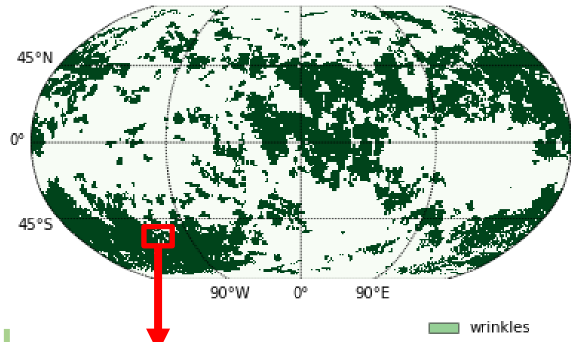
Venus' coronae dimension

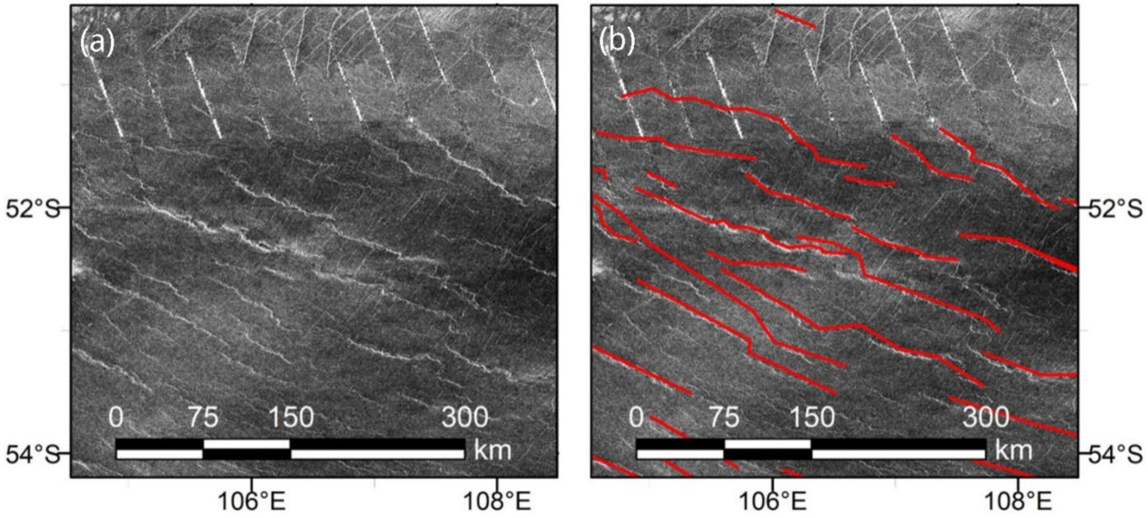
\+ seismogenic thickness

Adapted from Van Zelst, 2024



Sabbeth, 2023

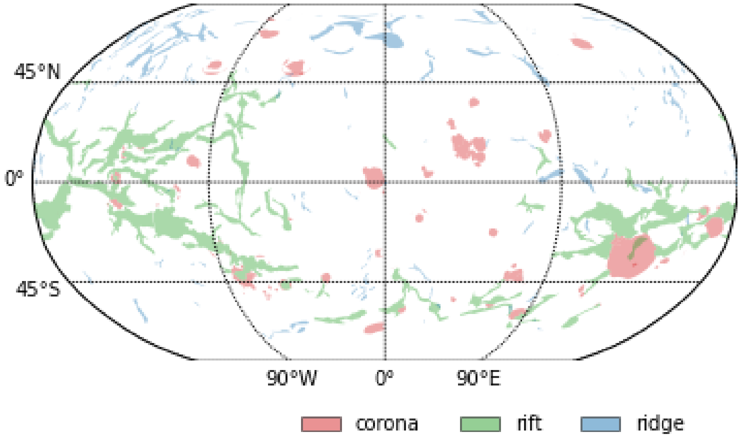




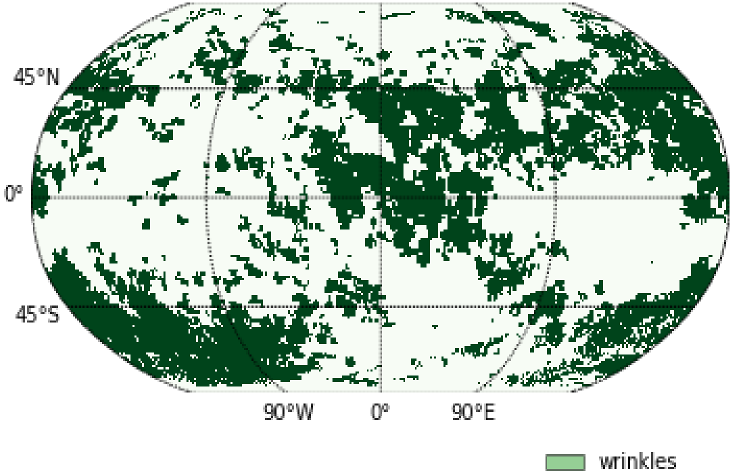
Defining the rate of observable venusquakes

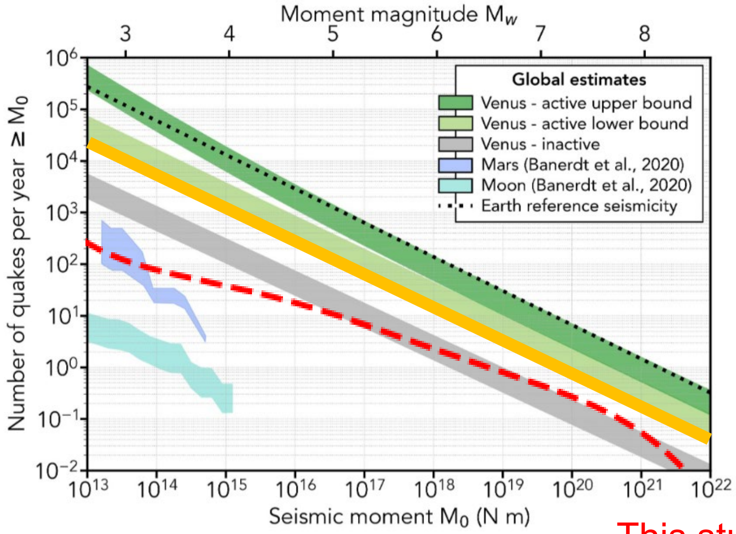
van Zelst, I., Maia, J.S., Plesa, A.-C., Ghail, R., Spühler, M., 2024. *JGR: Planets* 129, e2023JE008048. 10.1029/2023JE008048
Sabbeth, L., Smrekar, S.E., Stock, J.M., 2023. *EPSL* 619, 118308. 10.1016/j.epsl.2023.118308

Van Zelst, 2024



Sabbeth, 2023

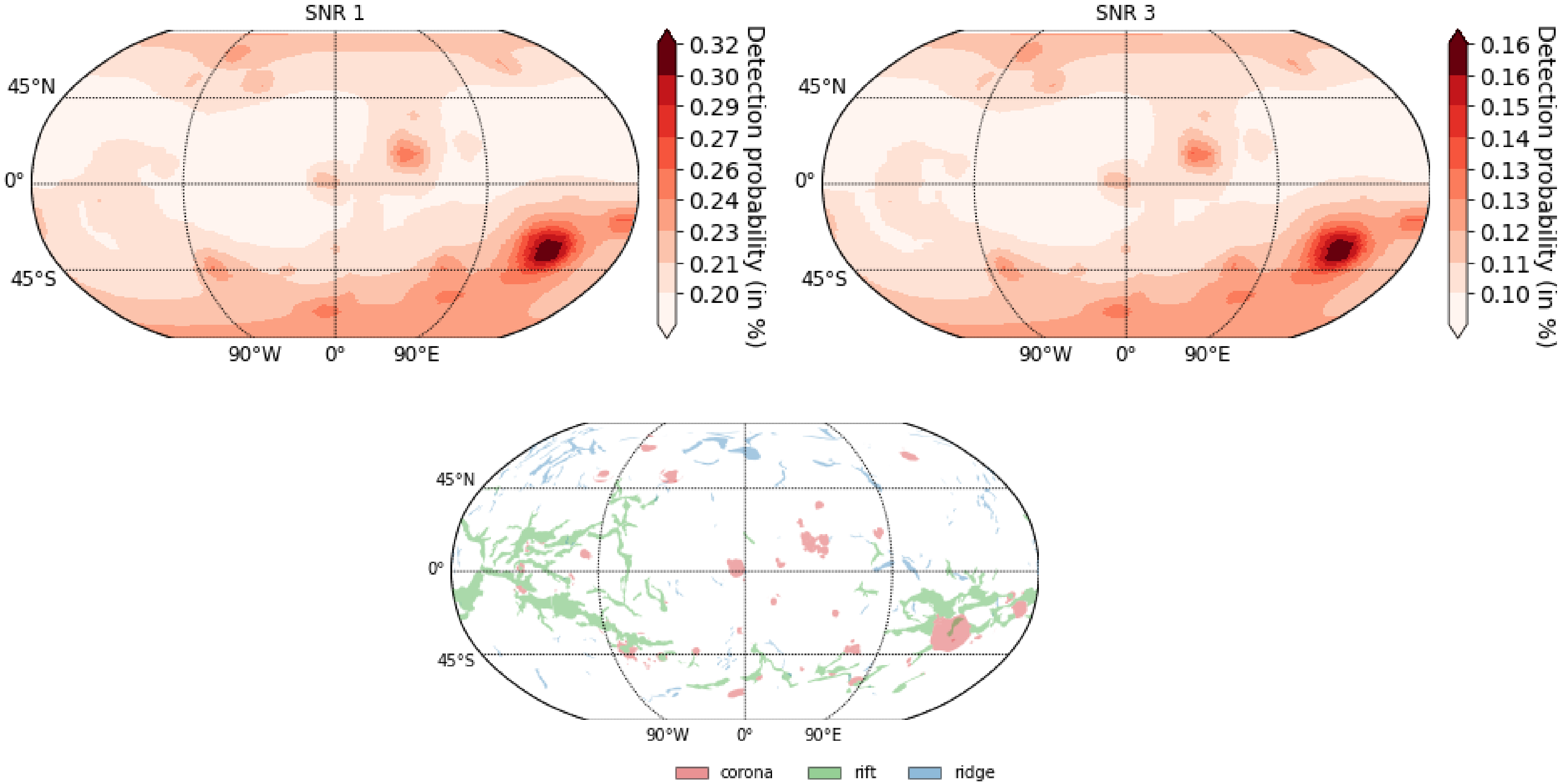




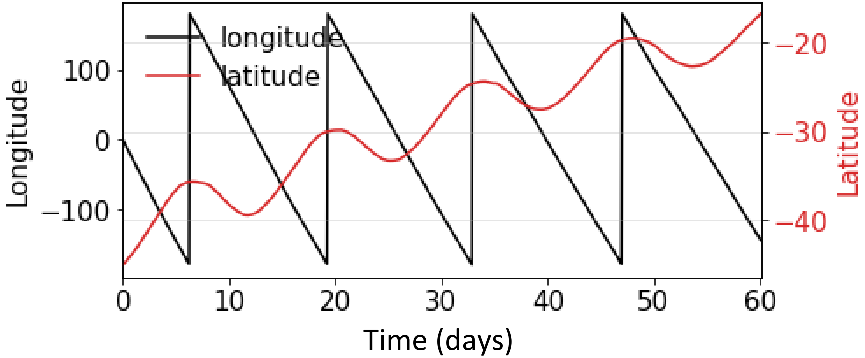
This study - Tectonic

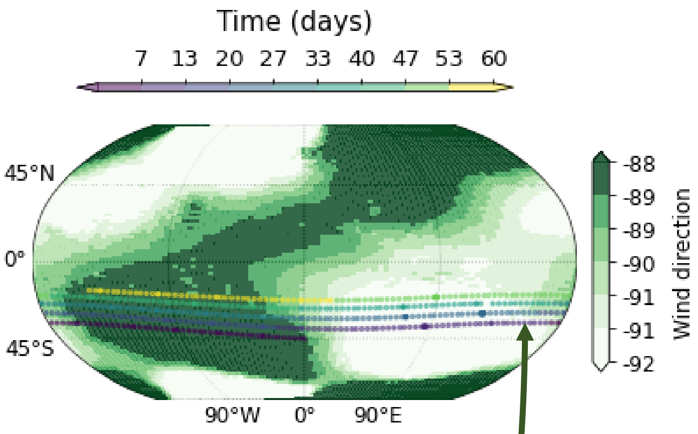
This study – Wrinkle Ridges

Detecting venusquakes – tectonic region scaling



Accounting for our flying sensor…

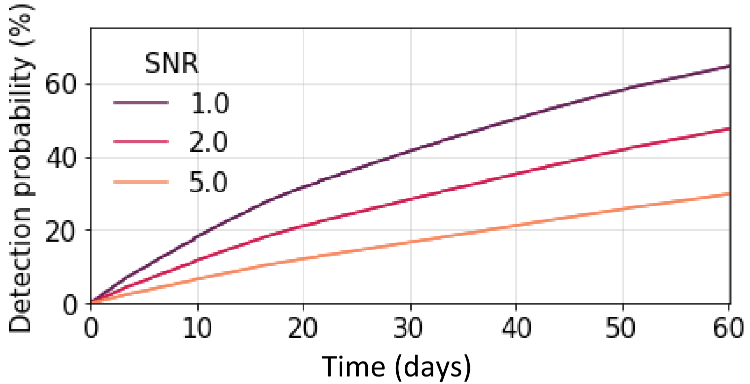


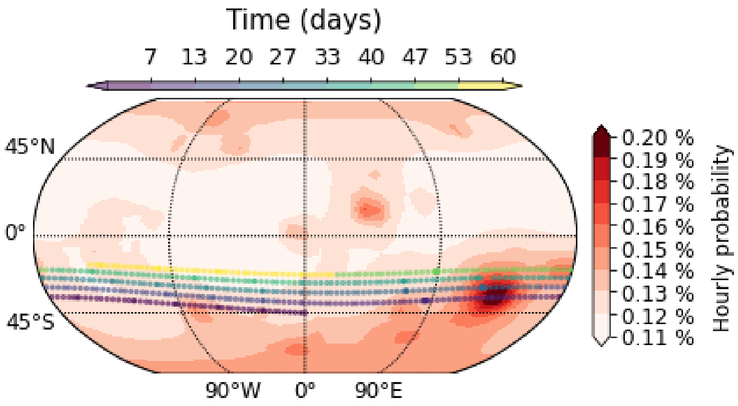


A balloon drifting at a constant altitude with horizontal winds estimated from the Venus Climate Database (VCD)

Lebonnois, S., Hourdin, F., Eymet, V., et al., 2010. *Journal of Geophysical Research: Planets 115*. 10.1029/2009JE003458
Lebonnois, S., Millour, E., Martinez, A., et al., 2021. *European Planetary Science Congress*. EPSC 2021. 10.5194/epsc2021-234
Martinez, A., Lebonnois, S., Millour, E., et al., 2023. *Icarus* 389, 115272. 10.1016/j.icarus.2022.115272

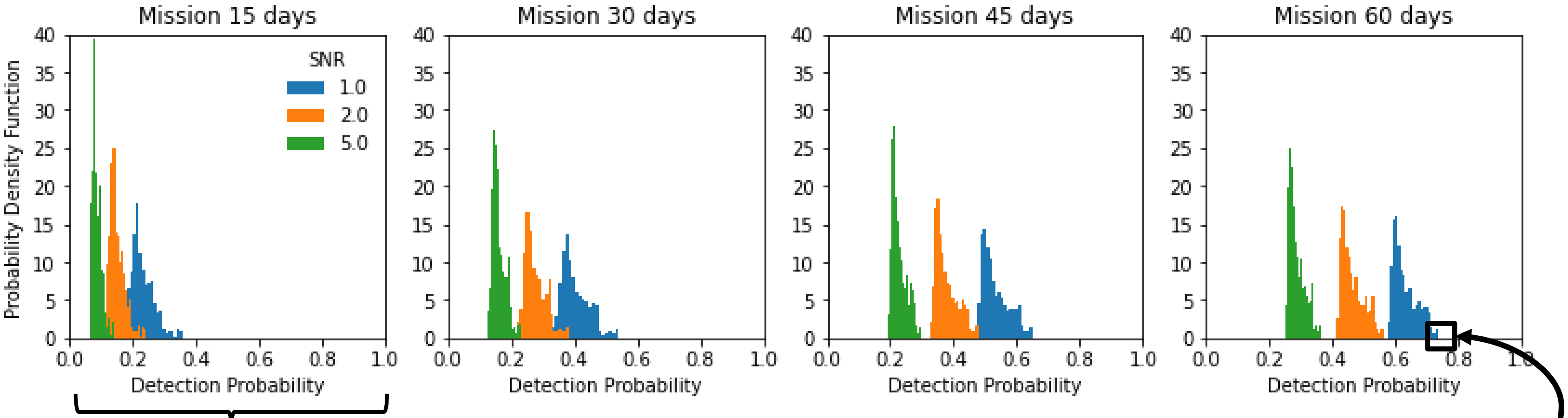
Accounting for our flying sensor…





Let’s simulate a lot of balloon flights!

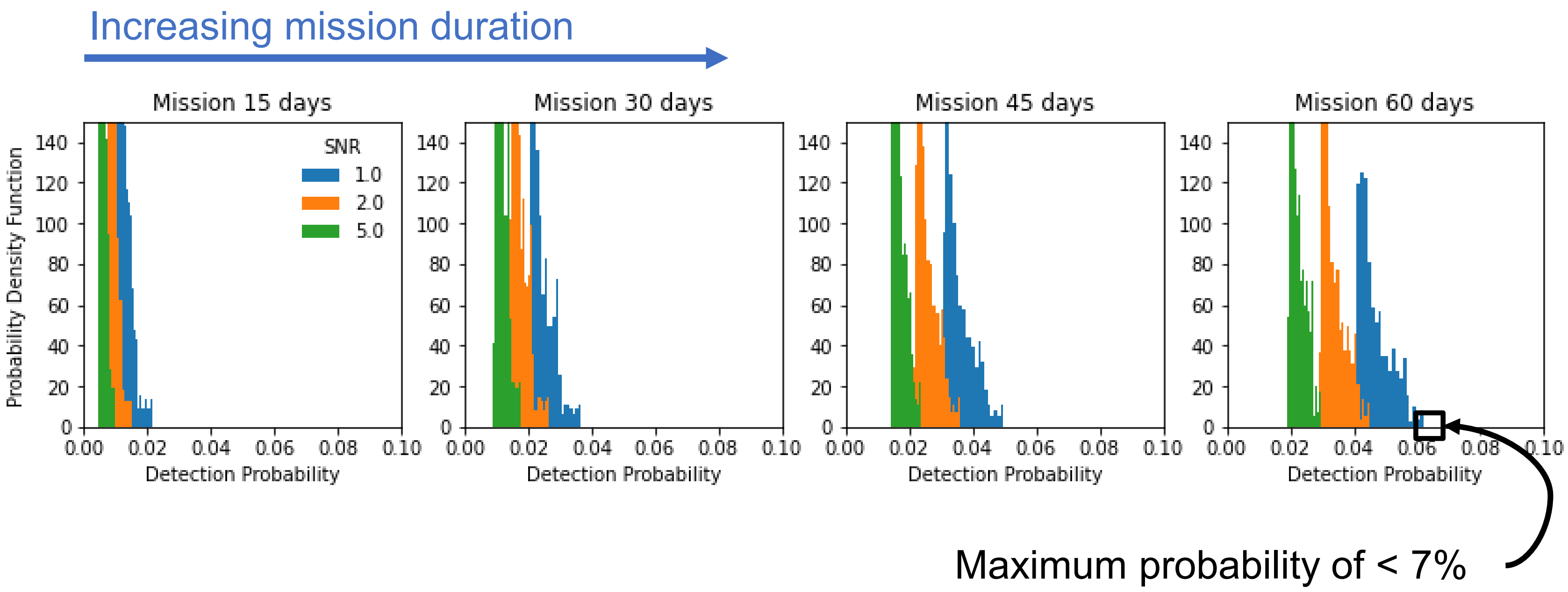
Increasing mission duration



Simulation of hundreds of flights for different drop off locations

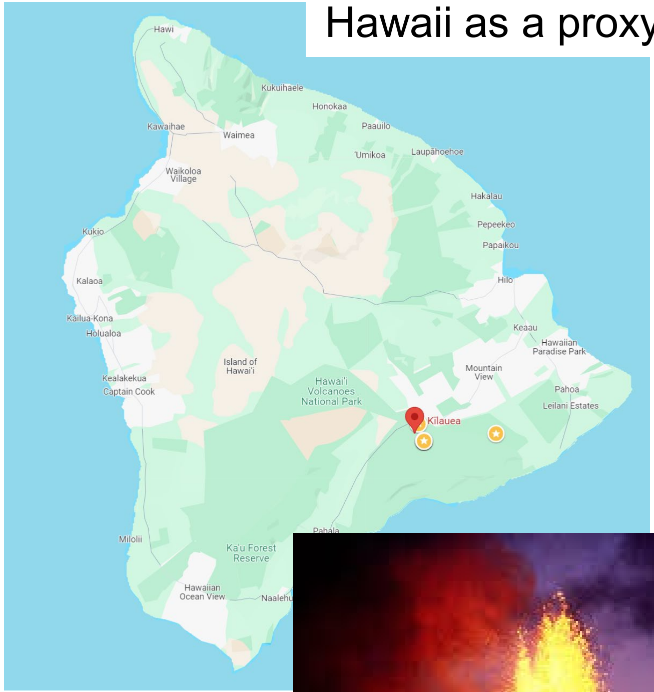
Maximum probability of < 80%

What about wrinkle ridges?

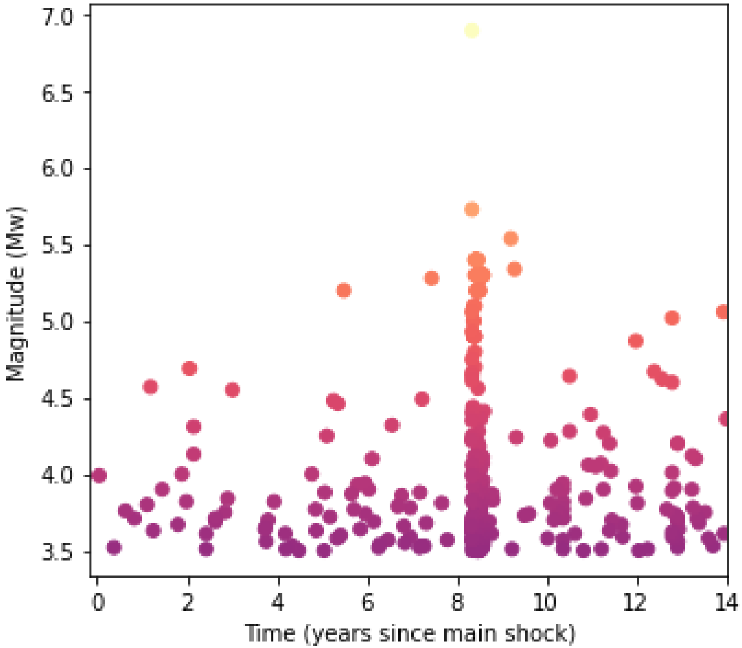


How to account for the volcanic activity?

Hawaii as a proxy

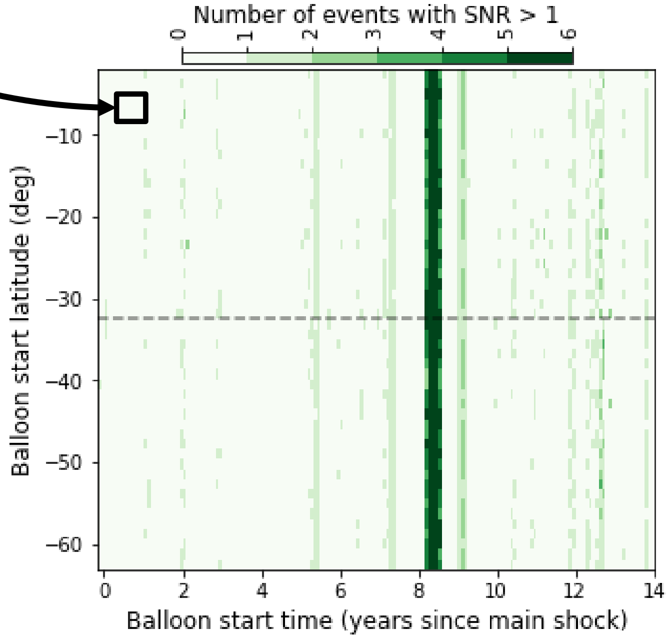


Wilding, J.D., Zhu, W., Ross, Z.E., Jackson, J.M., 2023. The magmatic web beneath Hawai‘i. *Science* 379, 462–468. [10.1126/science.ade5755](https://doi.org/10.1126/science.ade5755)

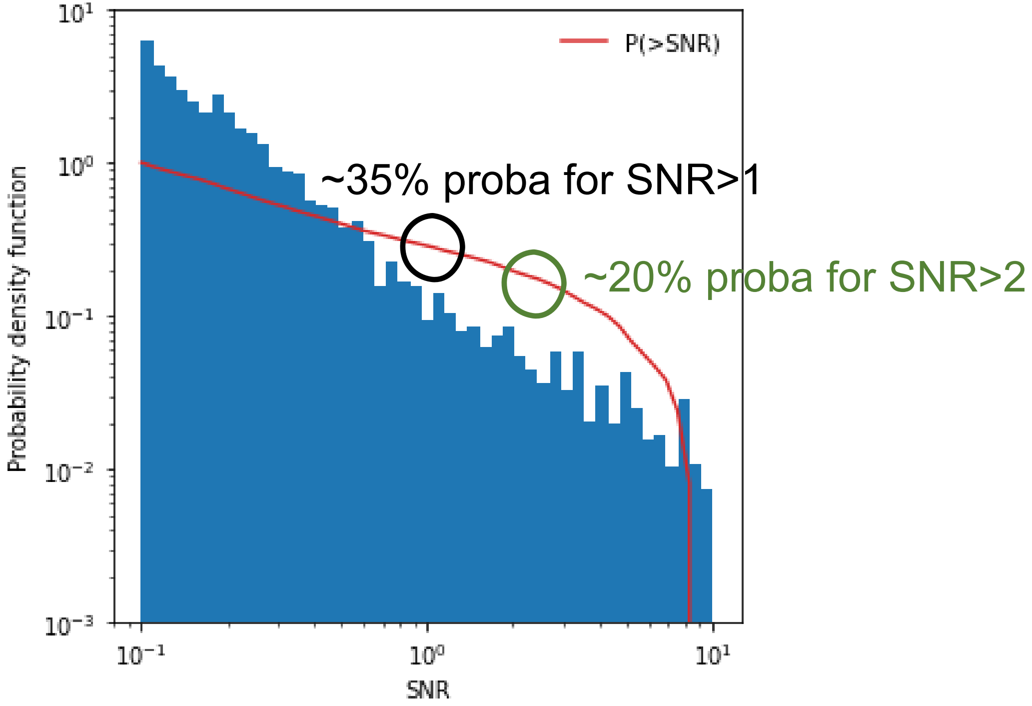


Simulating flights for varying drop off location and time

Each cell corresponds to a flight with a **unique combination of drop off location and time**



Simulating flights for varying drop off location and time

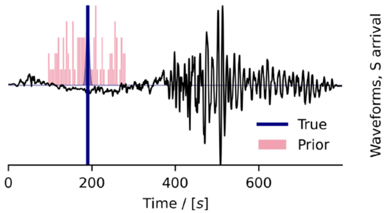


Conclusions

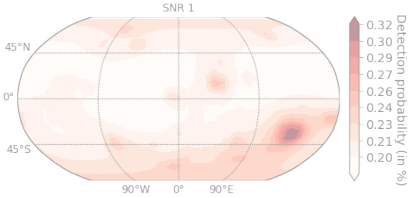
- Realistic seismicity estimates tend to produce **venusquake rates much lower than Earth.**
- **Long mission durations** (>>2 months) seem to be needed to obtain large detection likelihood of high SNR signals.
- **Seismo-volcanic events** could lead to an **increase of detection probabilities** over multiple years.

- Extra steps before publication
  - Refining **seismic velocity models** based on expected composition.
  - Modeling infrasound from **volcanic explosion and collapse** events.
  - Assessing the **impact of topography** on seismo-acoustic coupling.

AIR preliminary results: Detecting and inverting

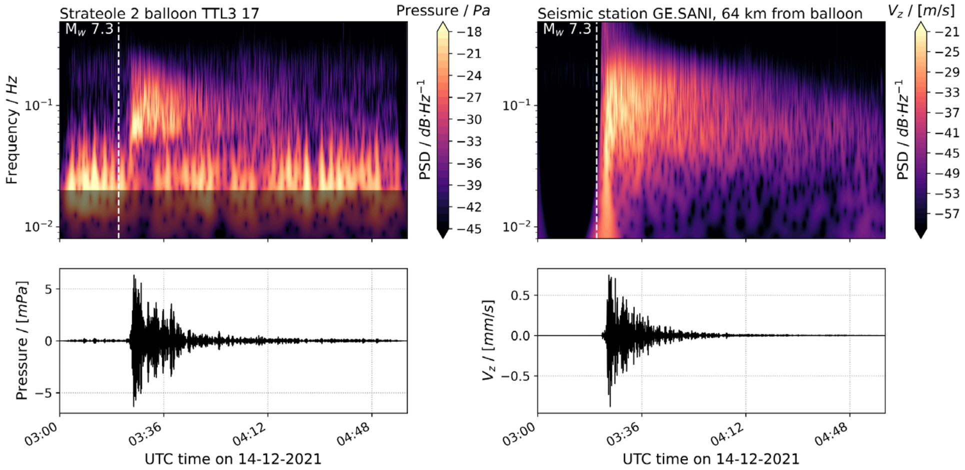


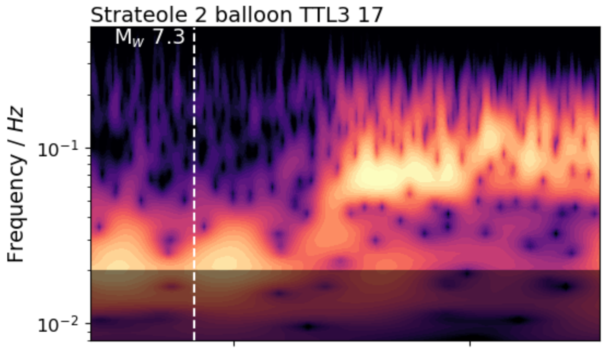
Detectability
- How do seismicity estimates on Venus affect the detectability of venusquakes?
- Can volcanic processes be detected?
- How long should the balloon mission be?



Inversion
- How sensitive is the inversion to the number of balloons and phase type detected?
- What do the posterior distribution of subsurface velocity parameters look like?
- Can we validate our model on real data?

What is the data : balloon seismology on Earth

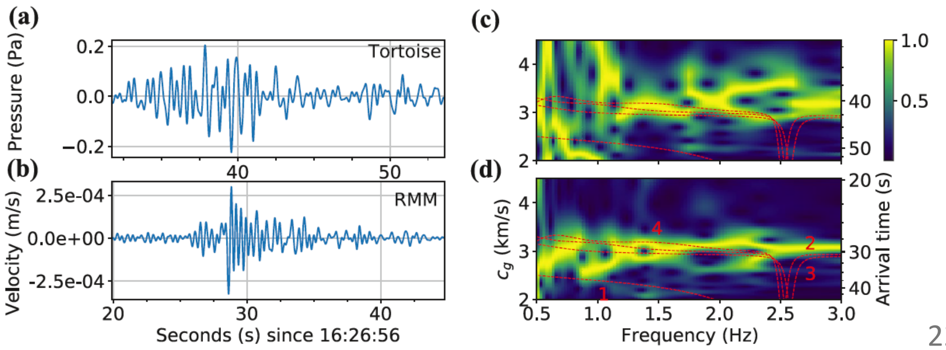




Zoom on the Rayleigh Wave arrival.

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

Good agreement between ground seismic and airborne infrasound recordings.



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)

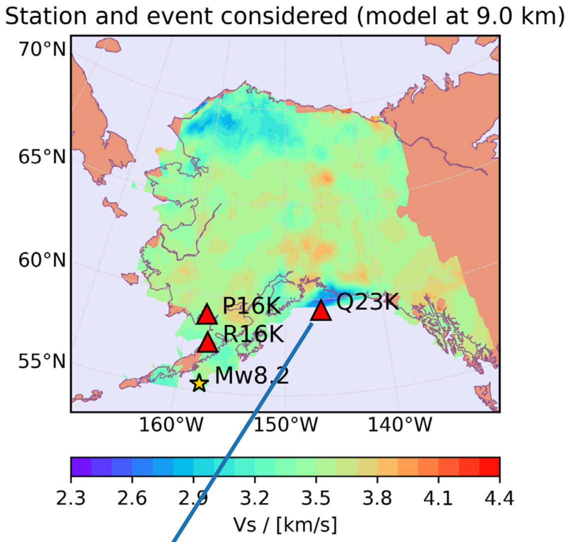
Event R1b of the 2019 Ridgecrest sequence recorded by Tortoise balloon.

Inverting the subsurface from coupled earthquake signals

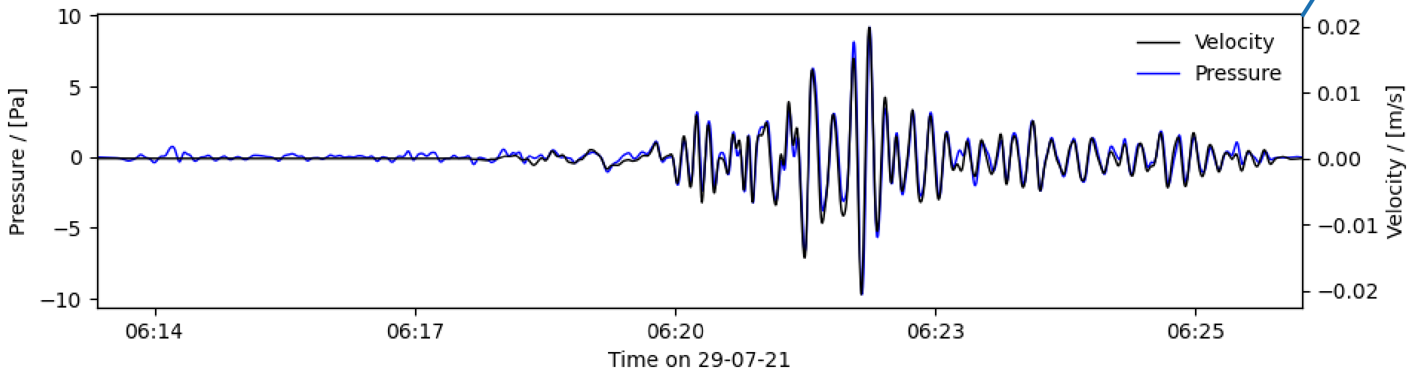
Hypotheses: Propagation of RW from ground to balloon brings no distortion.
Venus signals shall have higher SNR than Earth's

Alaska pressure recordings of earthquakes are a good proxy to test the inversion framework.

Data: Mw8.2 event on 29/07/21.
The "true" model: 4-layer model simplification of Berg et al. (2019) at the three stations.

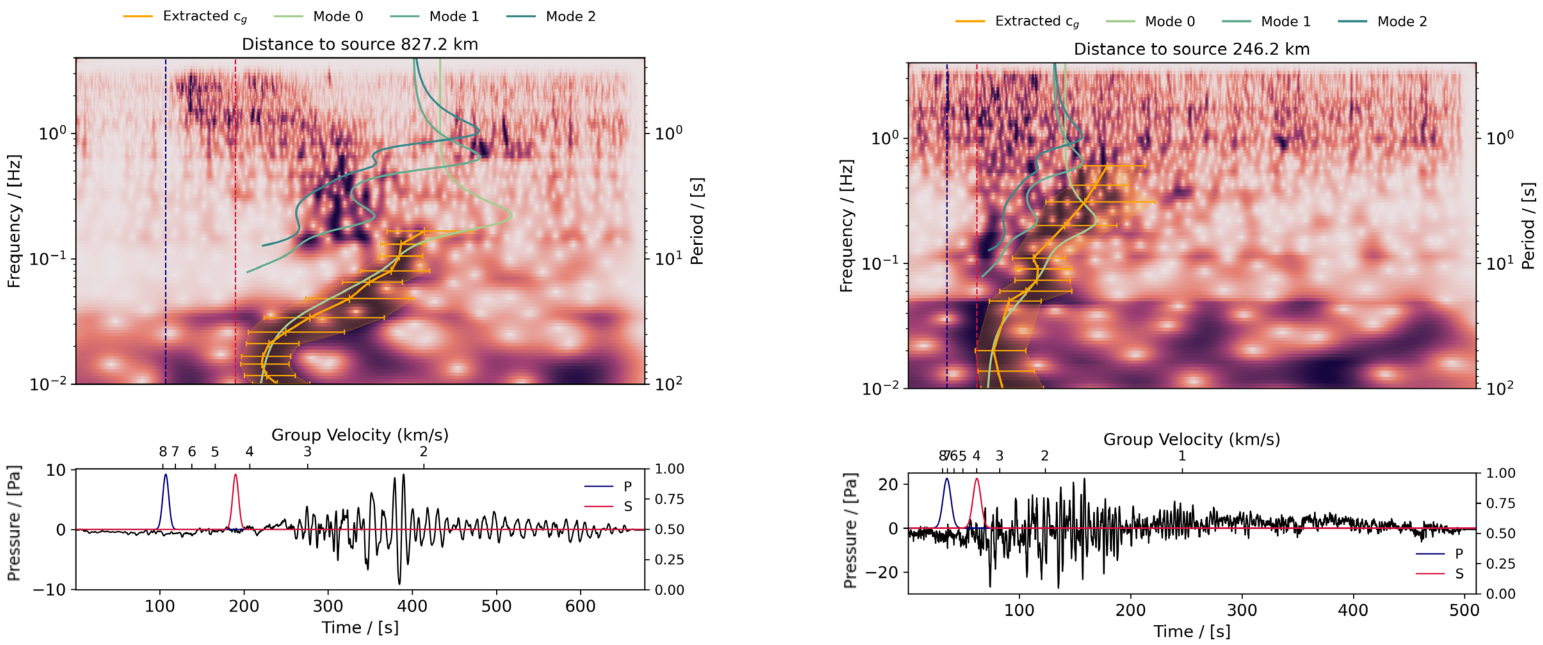


Berg, E. M. et al (2020) *JGR: Solid Earth* **125**, [10.1029/2019JB018582](https://doi.org/10.1029/2019JB018582)
Macpherson et al. 2023 (2023) *BSSA*, **113**, [10.1785/0120220237](https://doi.org/10.1785/0120220237)



NORSAR

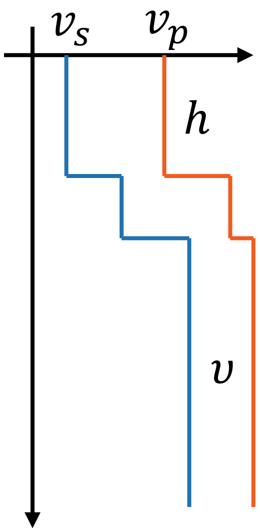
Picking the Rayleigh and S waves



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

$t_{RW}(f_i)$

t_S

Data (RW and S picks)

$\neq$

Misfit + **Priors**

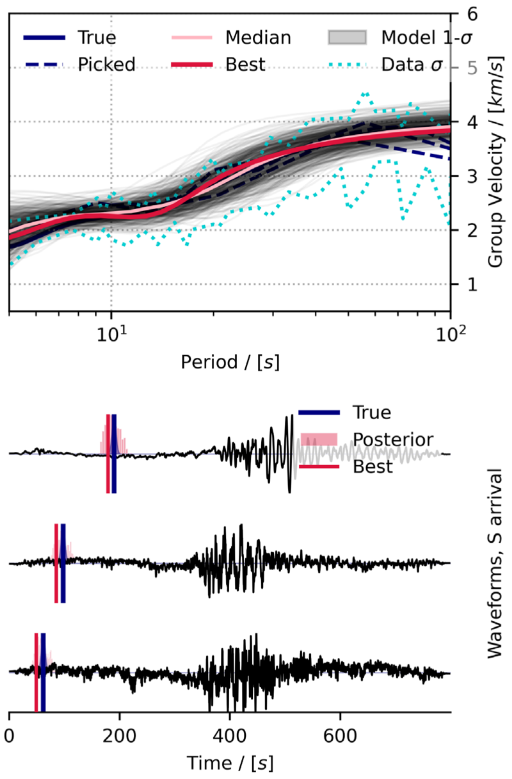
(bounds on v_s, h, r_s …)

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

Posterior probability of

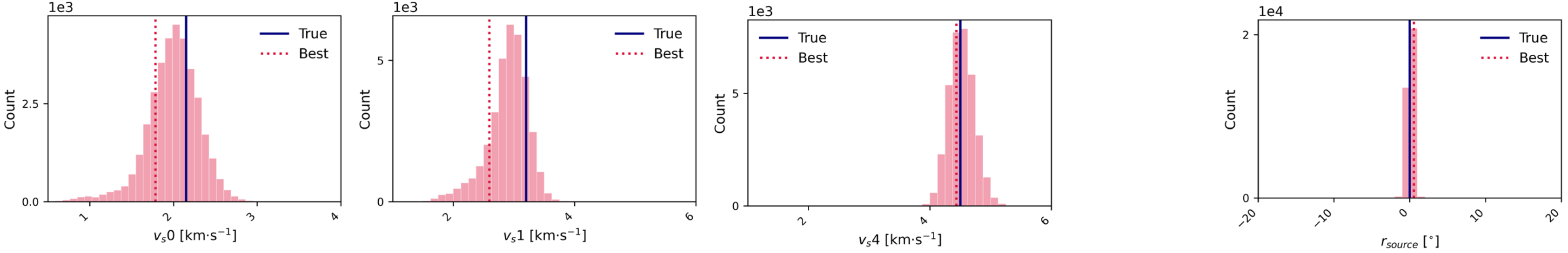
$(v_s, v, h, t_s, r_s, h_s)$

Inversion results: 3signals with S and Rayleigh waves

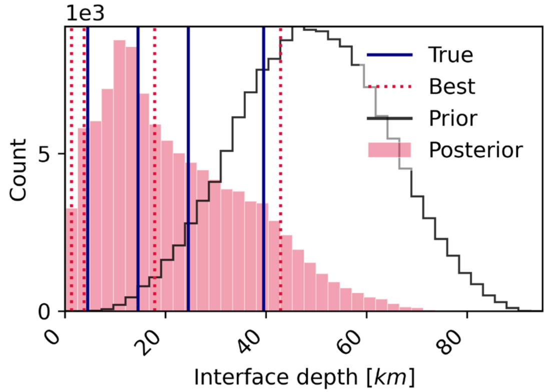


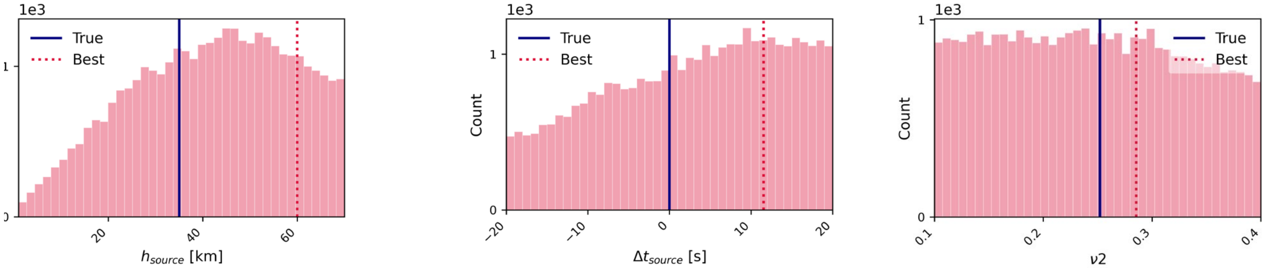
Inversion results: parameters and histograms

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



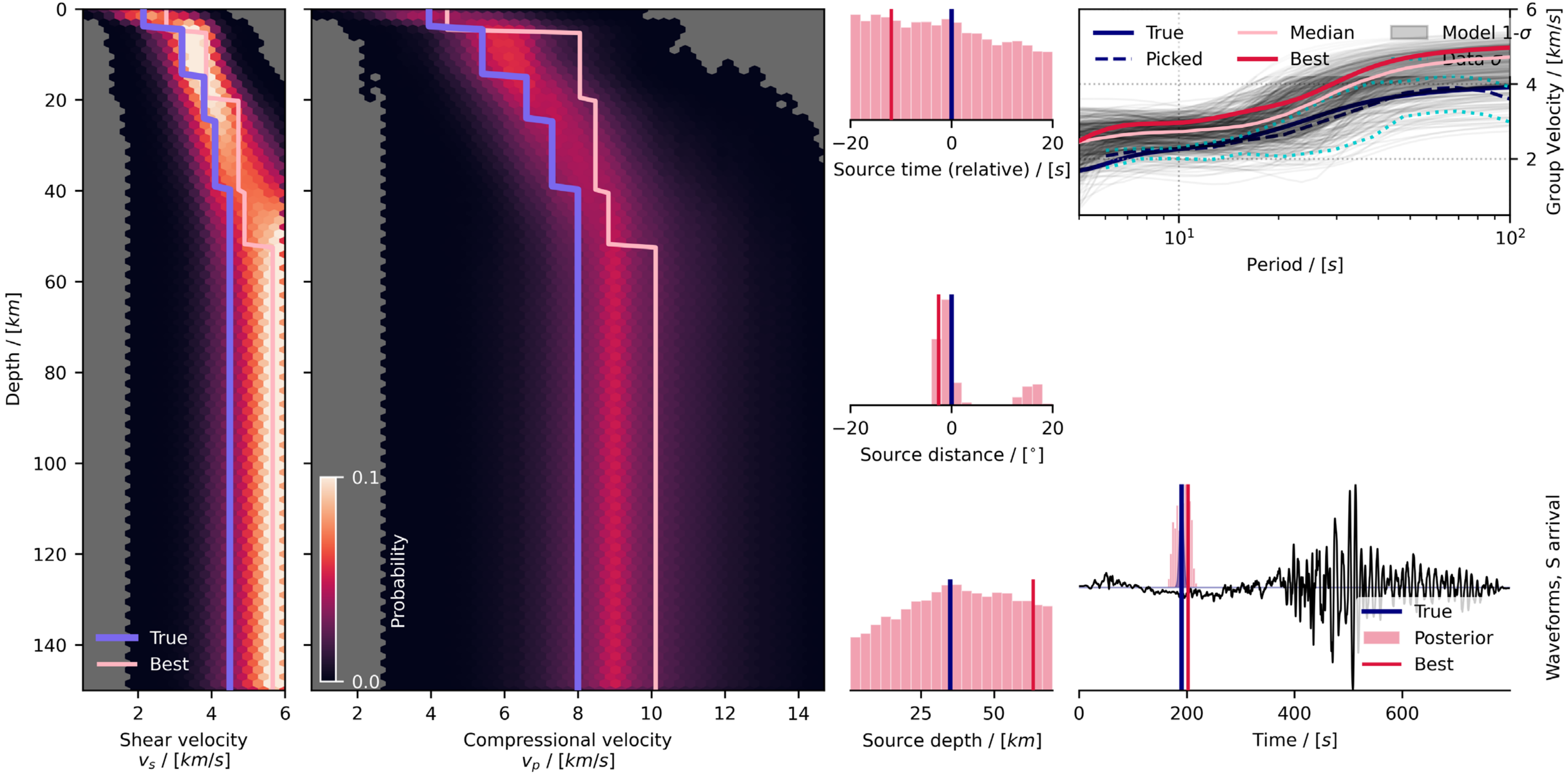
Parameters **less constrained**: Source depth, interface depth.



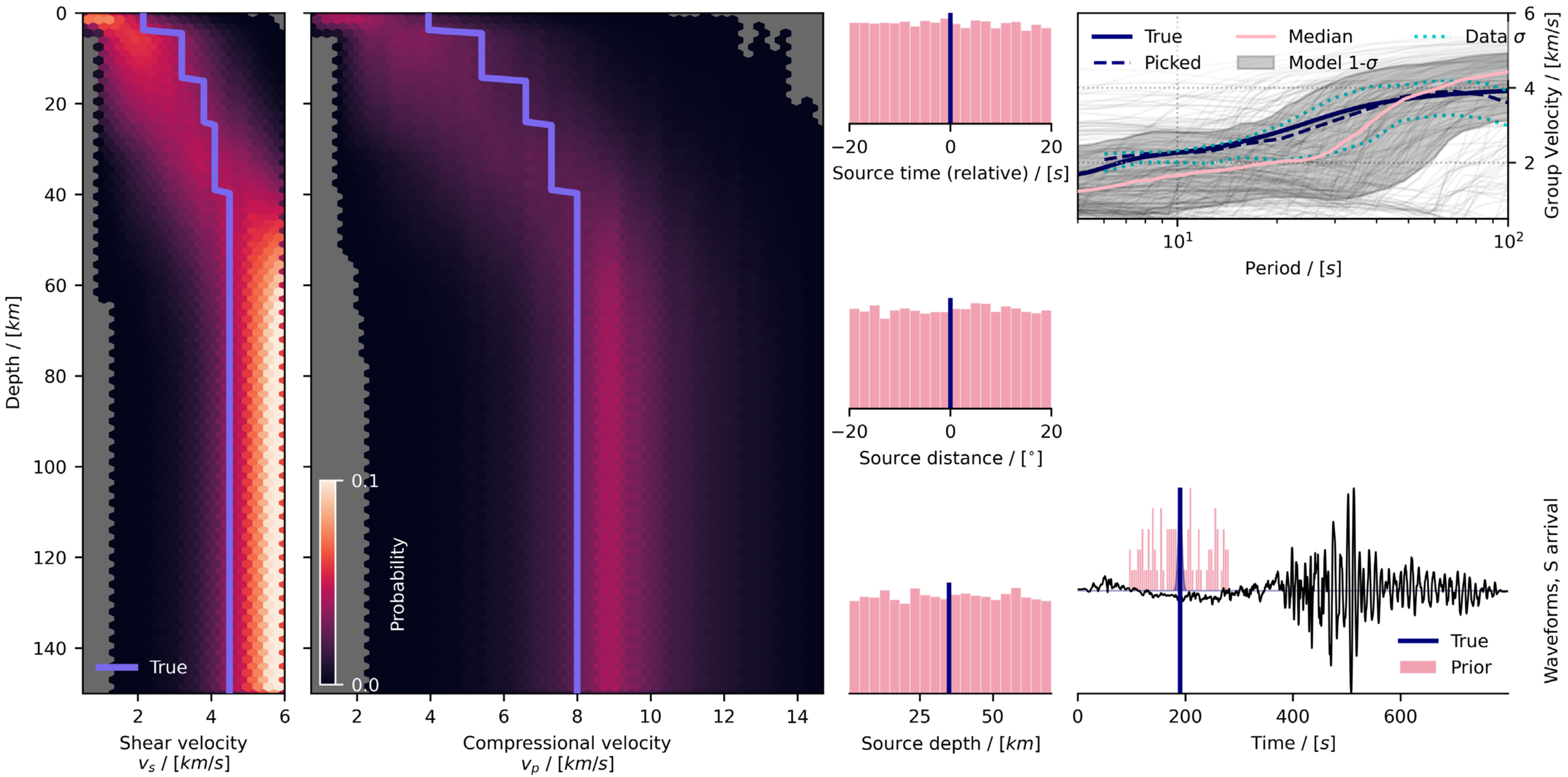


Parameters **unconstrained**:
Poisson ratio, origin time.

Inversion with a single balloon



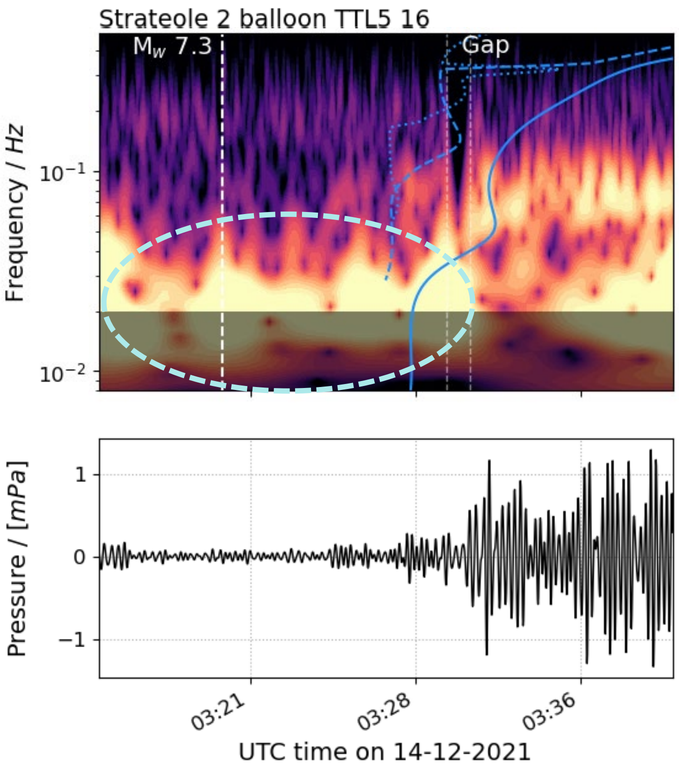
For comparison: Priors for a single balloon

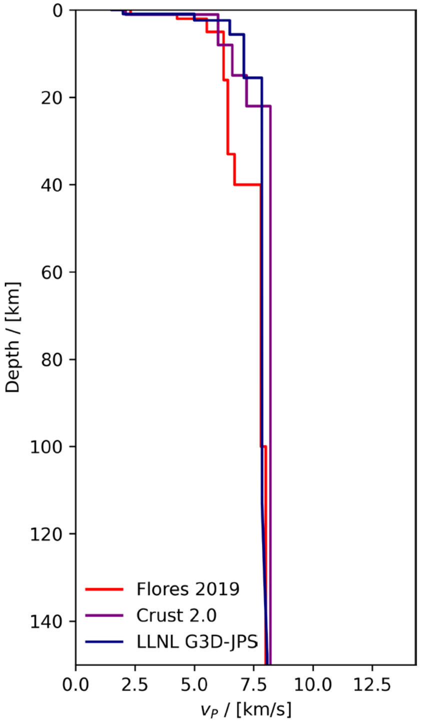


The next steps: a fully airborne inversion

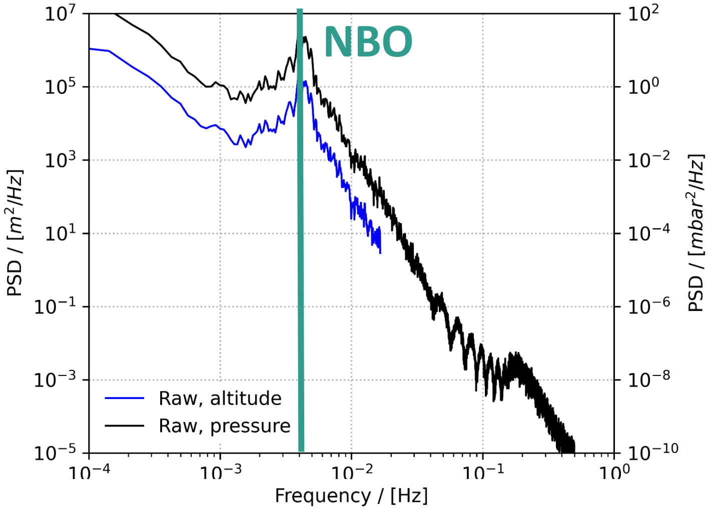
The Flores Earthquake

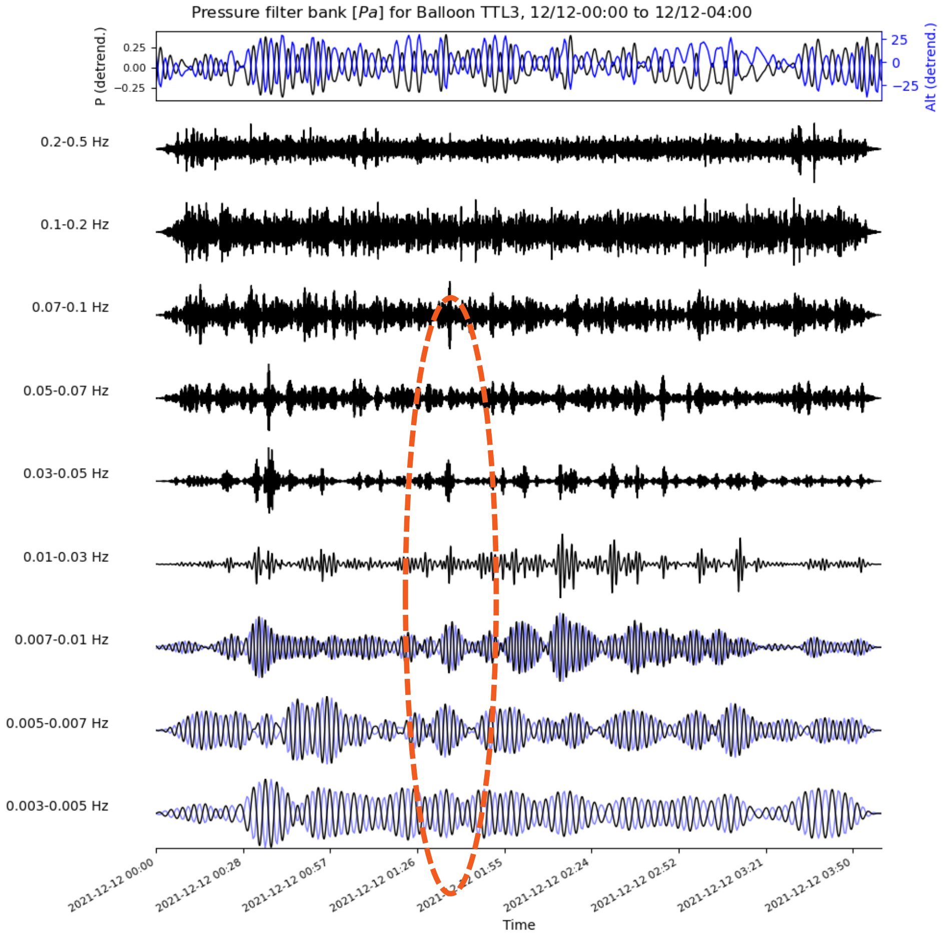
- Subsurface not well known in the region.
- A challenge in picking the RW and other picks: presence of a resonance (low velocity layers? Scattering?)
- Need better understanding of balloon oscillations at low frequency.





An unsteady sensor…





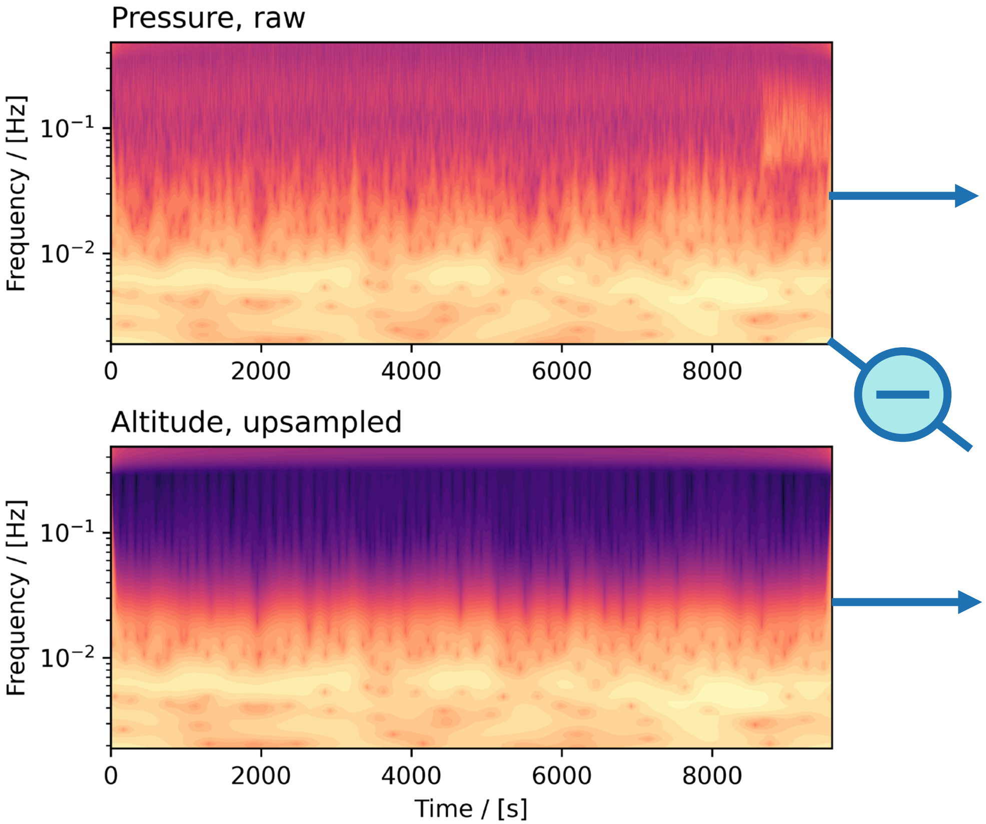
Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

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



Conclusion: Inversion

1. Inversion framework was tested with signals of the Alaska network.

2. With 3 balloons and simple RW picking, subsurface velocities can be constrained within 1 km/s.

3. One balloon cannot suffice to investigate Venus interiors, without some additional constraints on source location and time.

4. Validation coming soon with the Flores Earthquake.

5. Looking for new ways to “denoise” balloon signals and improve picking of the RW.

This workshop: Instrumental challenges

1. **Beamforming** along balloon tether: how many sensors, what geometry ?

2. Inertial Measurement Units (**IMUs**) VS mirobarometers ?

3. **Several balloons** are needed. What are operational constraints: drop-off sequence, communication, maximum number?

4. What are the **constraints in bandwidth**, and will pre-processing be needed to send lightweight data back to Earth?

5. How to correct balloon noise below 0.05 Hz ? What is the **instrument response** of the balloon + sensors system ?

6. How can we estimate the differences in **environmental noise** between Earth and Venus?

7. How much does **corrosion** by the environment limit mission duration in the clouds?

This workshop: Inversion challenges

1. Which **inversion method** is best adapted for seismo-acoustic inversions ? Is Bayesian Monte Carlo a good choice?

2. Other seismo-acoustic sources are possible: **meteors, volcanoes**. Can we identify and locate them ?

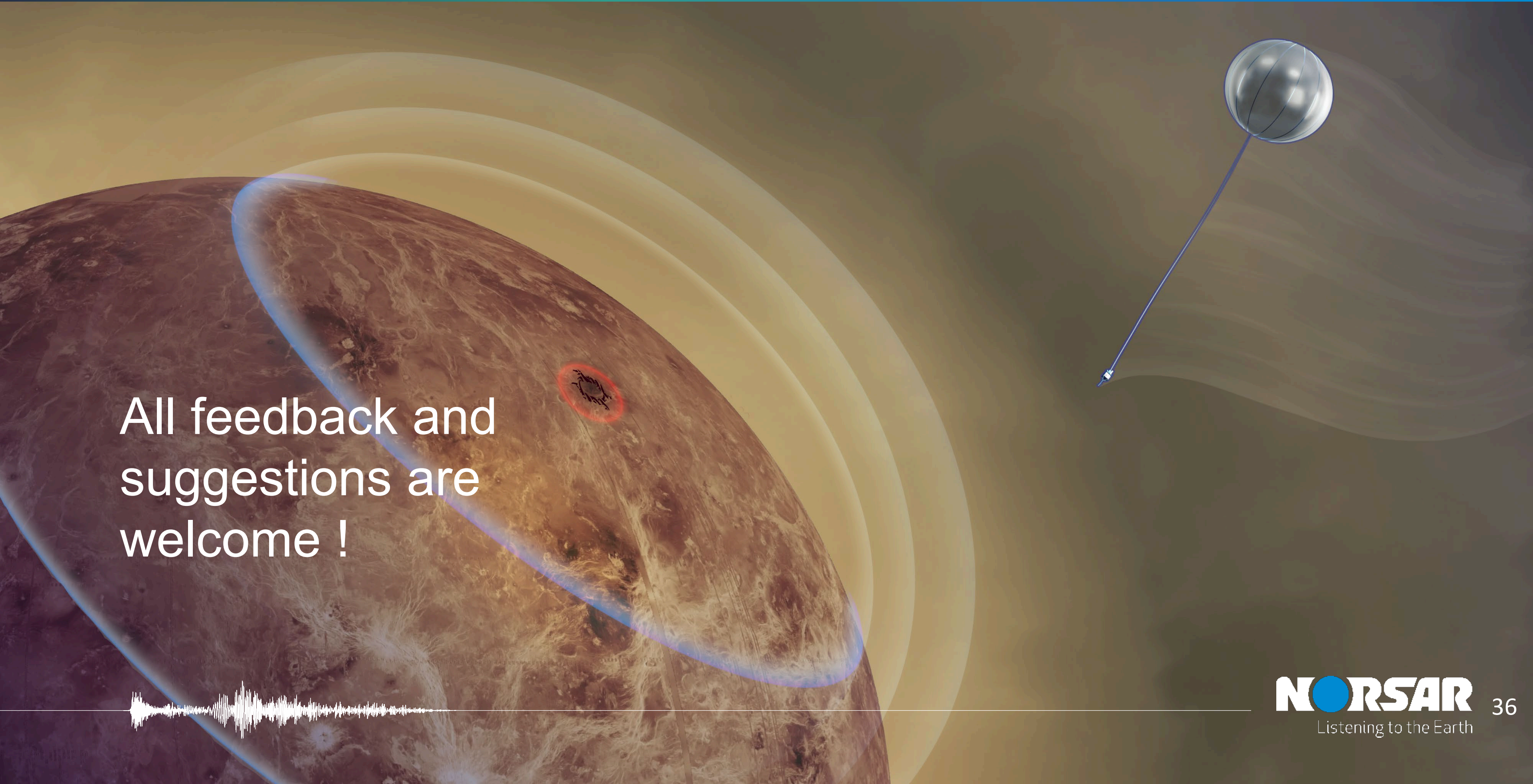
3. Modeling: are there simplifying **assumptions** on the propagation of seismo-acoustic waves that can safely be done ? Best **modeling techniques** ?

4. How could **airglow measurements** complement balloon measurements (dispersion, source localization…)

5. How can upcoming NASA/ESA missions help **constrain priors** of the interior of Venus ?

6. How to design an efficient “**Blind Test**” for Venus, as done before InSight for Mars ?

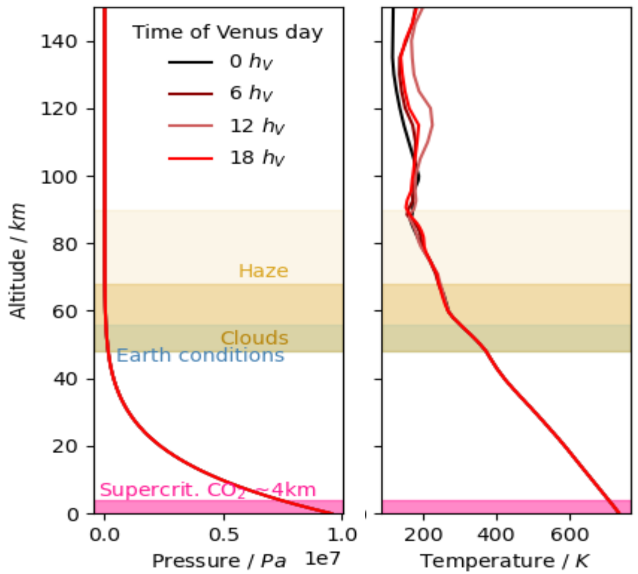
Thank you for your attention



All feedback and suggestions are welcome !

Infrasound propagation on Venus?

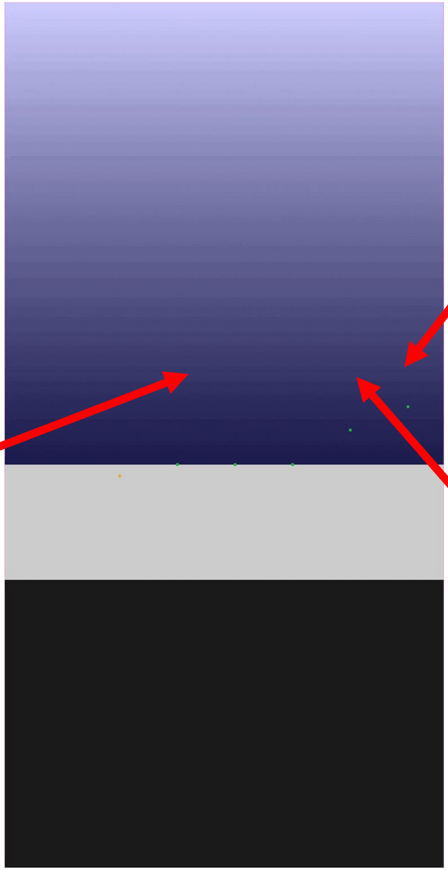
Venus is a pressure cooker under a lid of clouds, very stable throughout the day: a challenge for ground-based seismology, but an advantage for infrasound studies!



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

Infrasound modeling – SPECFEM2D-DG

Simulation of the coupling of an earthquake with the atmosphere using SPECFEM2D-DG.



Scattered body waves

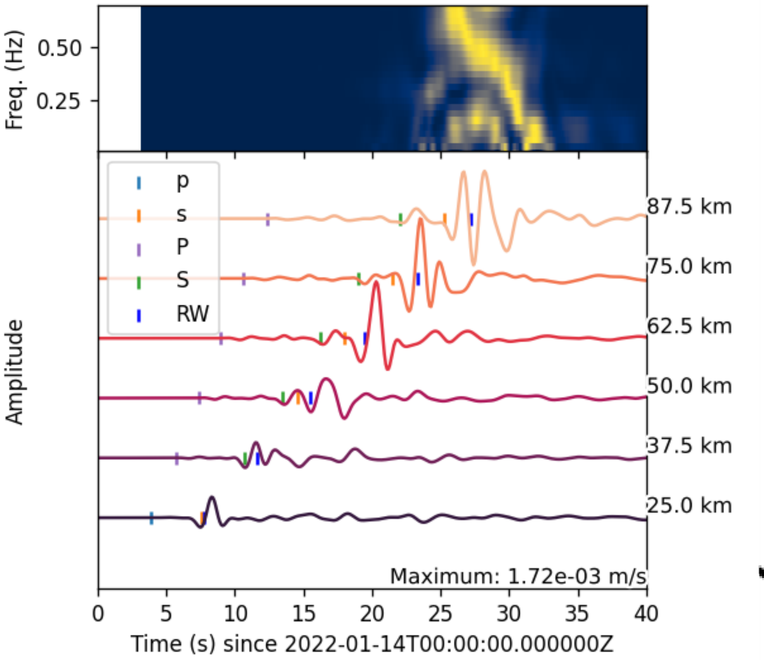
Surface waves

Epicentral Infrasound generated just above the epicenter

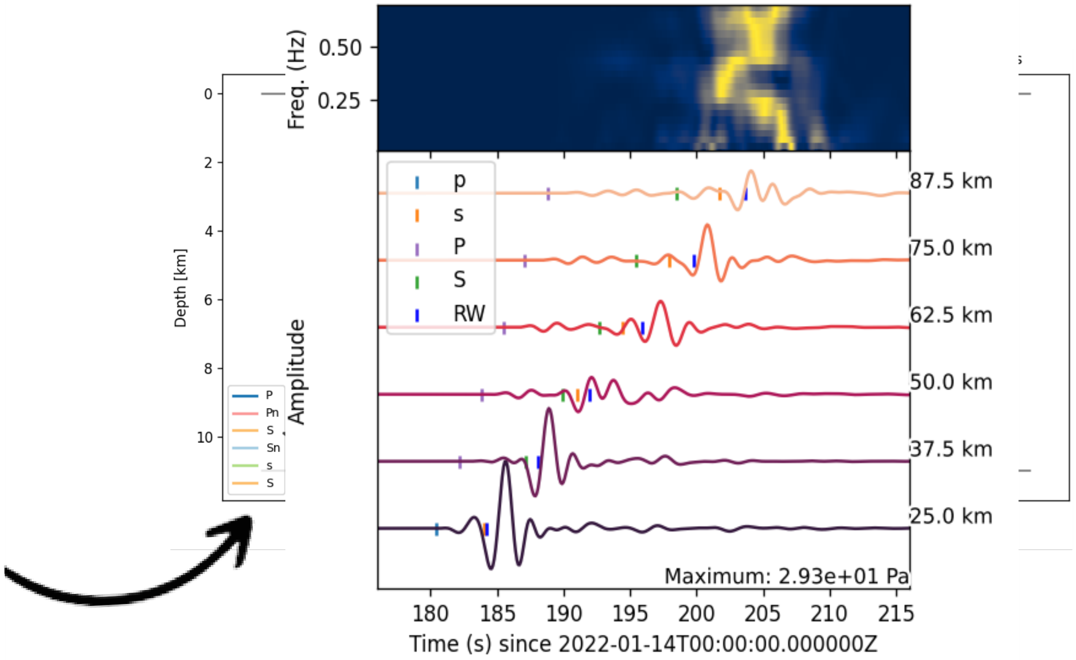
Infrasound modeling – SPECFEM2D-DG

Example of simulation outputs for a source with Mw 5 at 10 km depth and half duration 2 s.

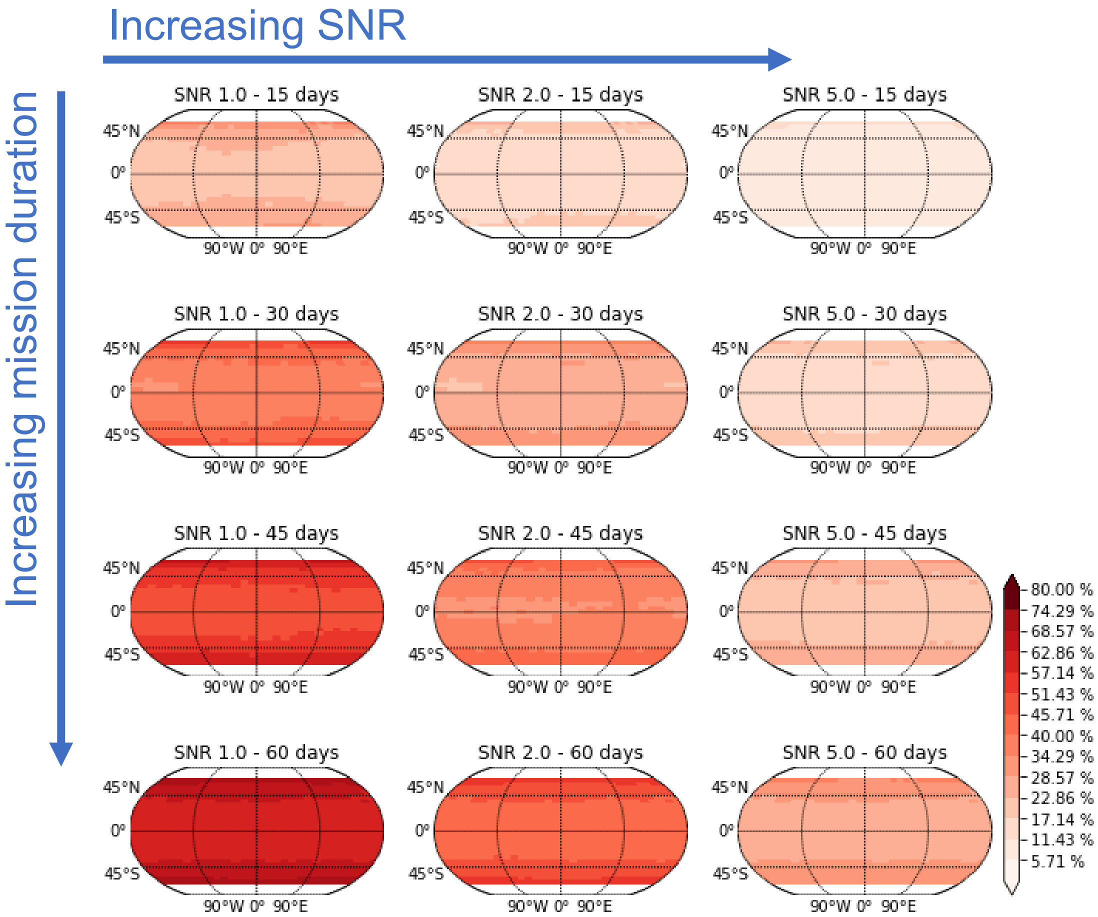
Seismic sensors



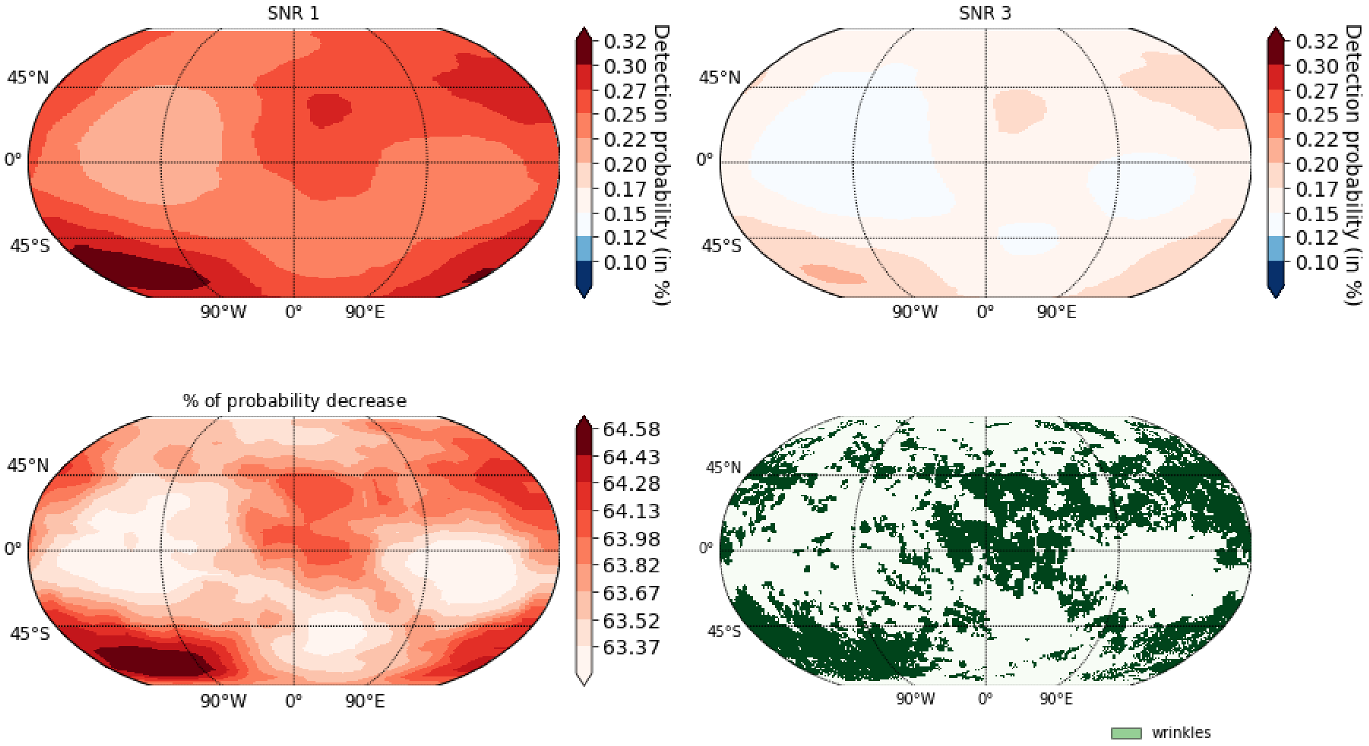
Balloon sensors at 60 km altitude



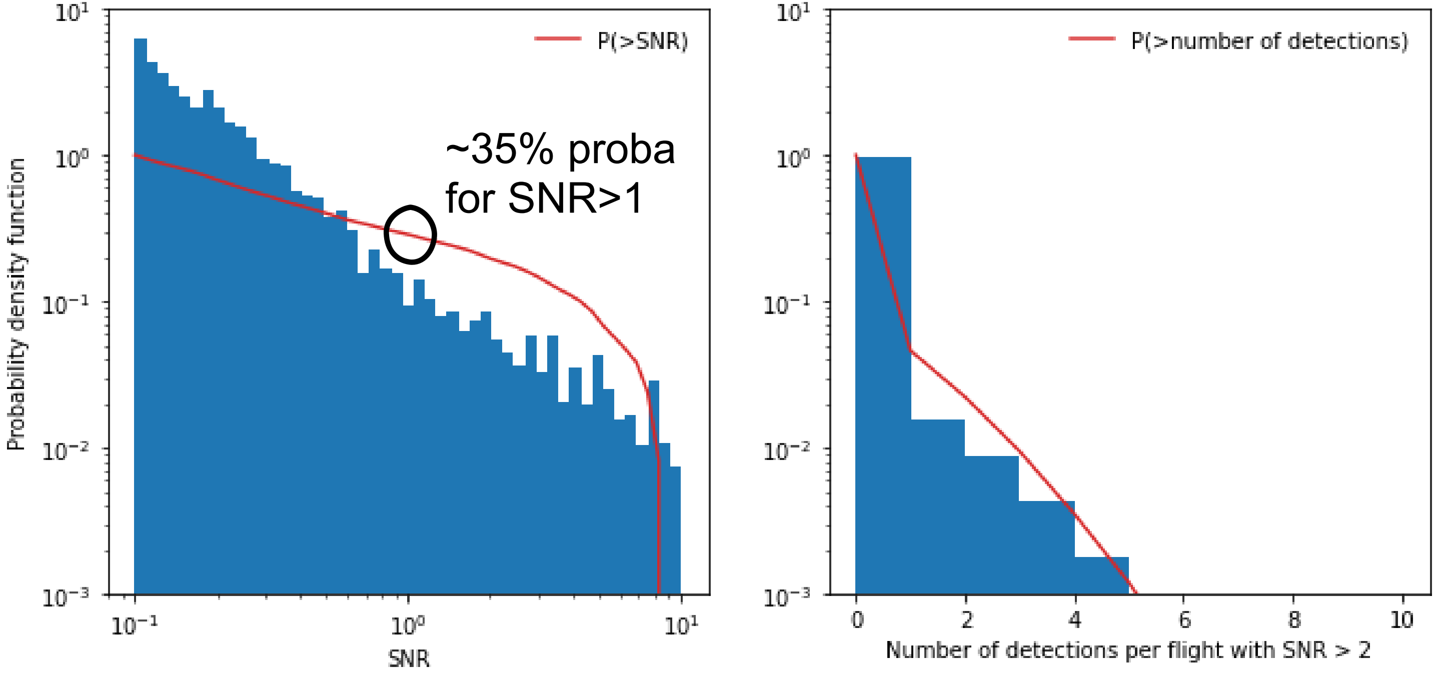
Let’s simulate a lot of balloon flights!



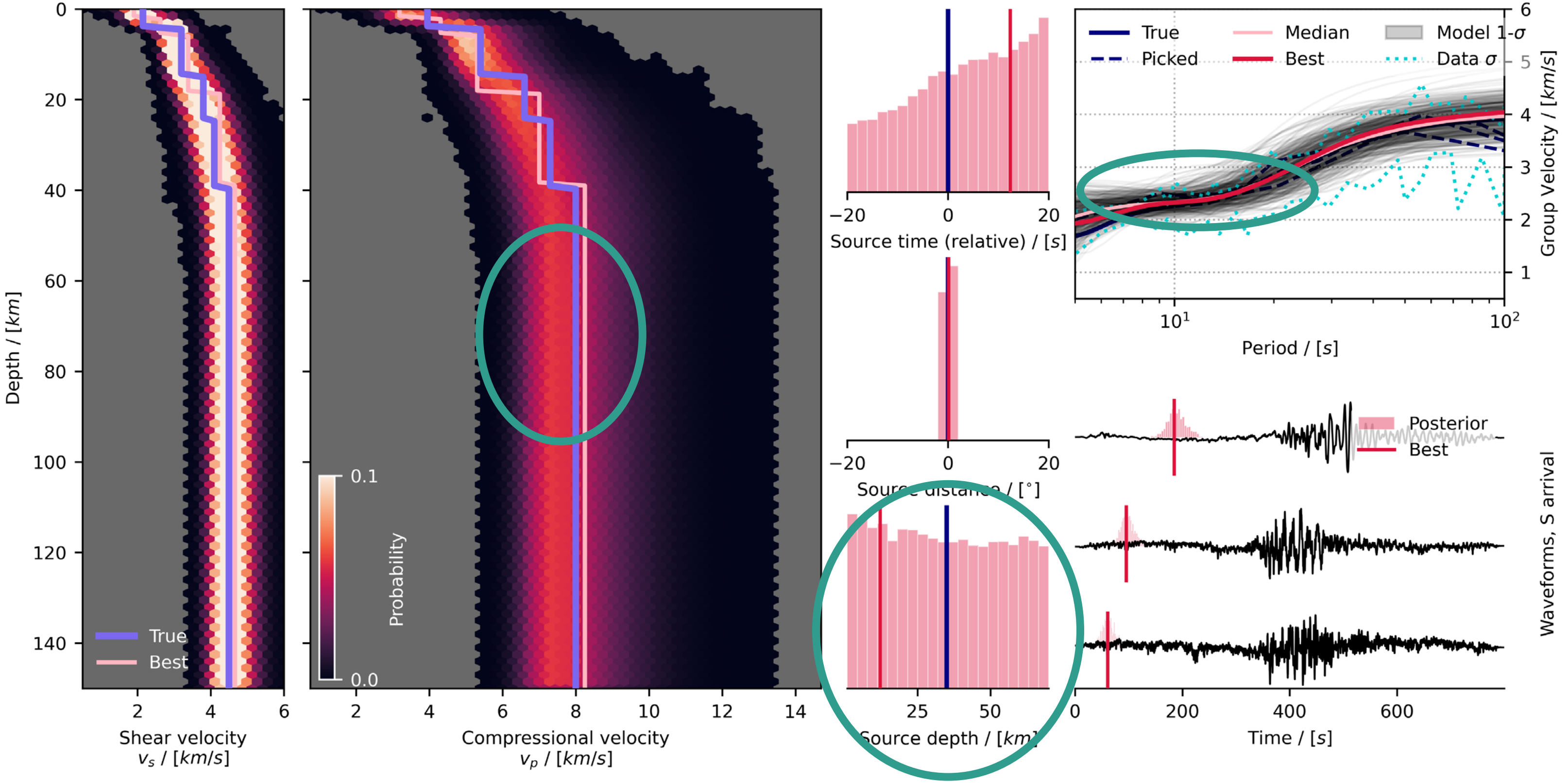
Daily probability for wrinkle ridges



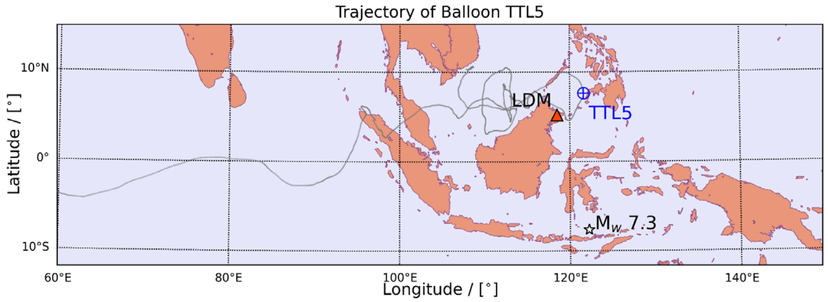
Simulating flights for varying drop off location and time

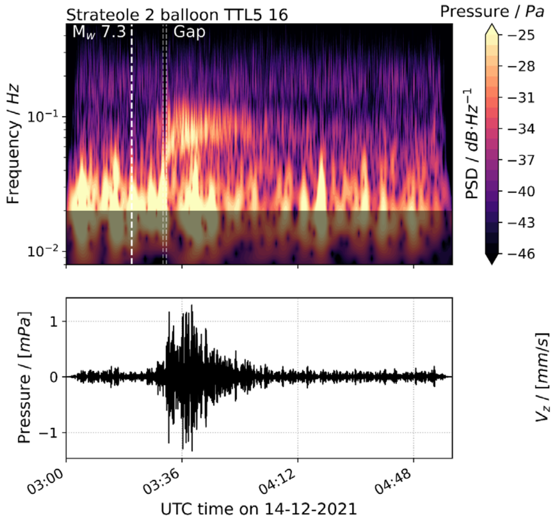


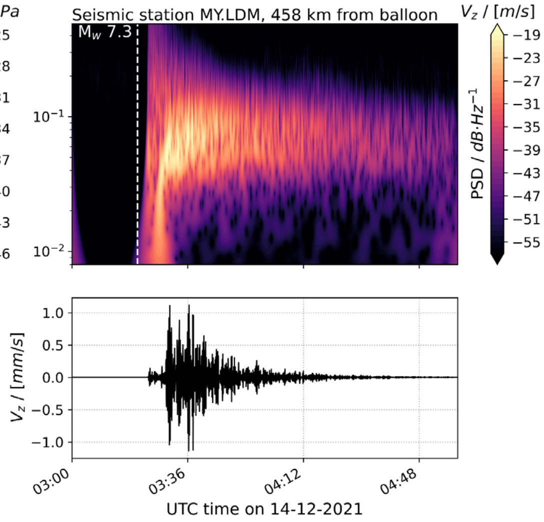
Inversion results: 3signals Rayleigh waves, no S

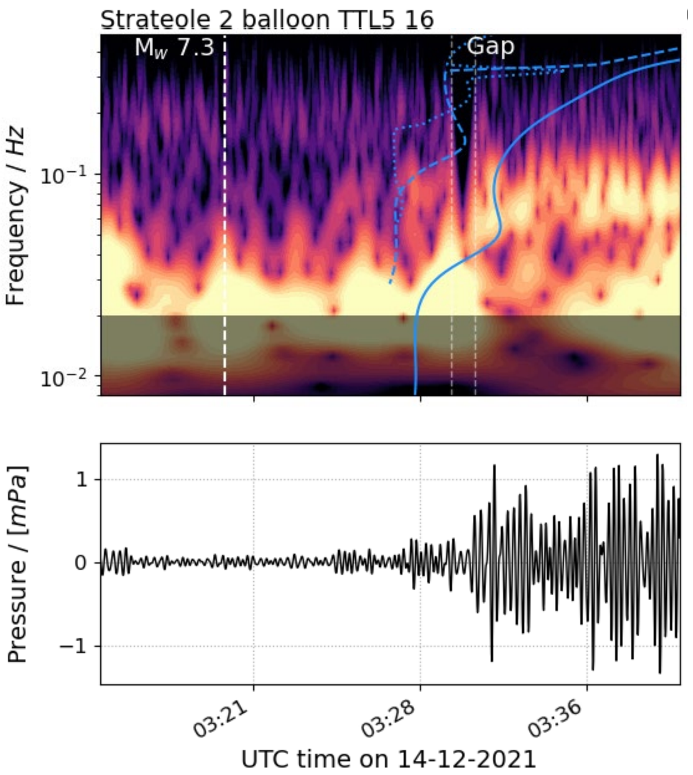


Picking the Rayleigh wave: example of balloon 16

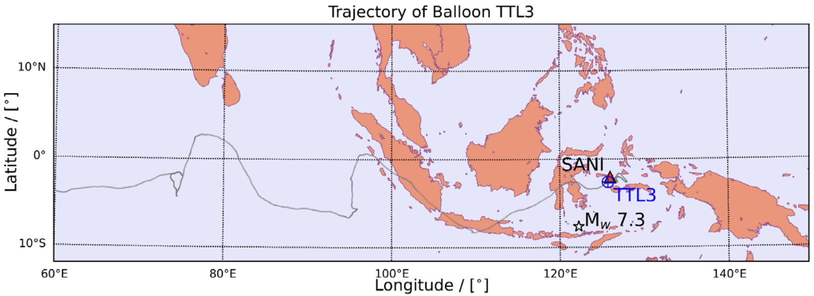


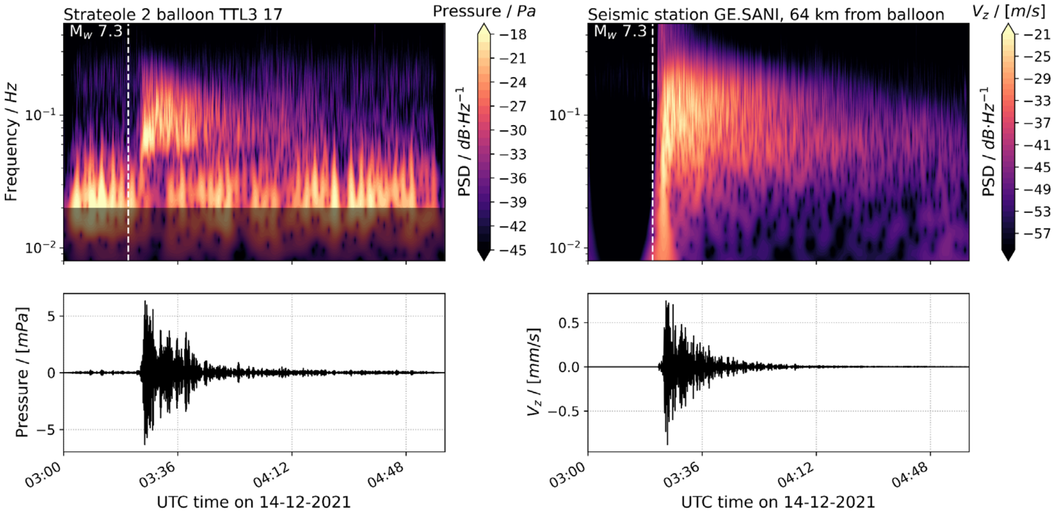


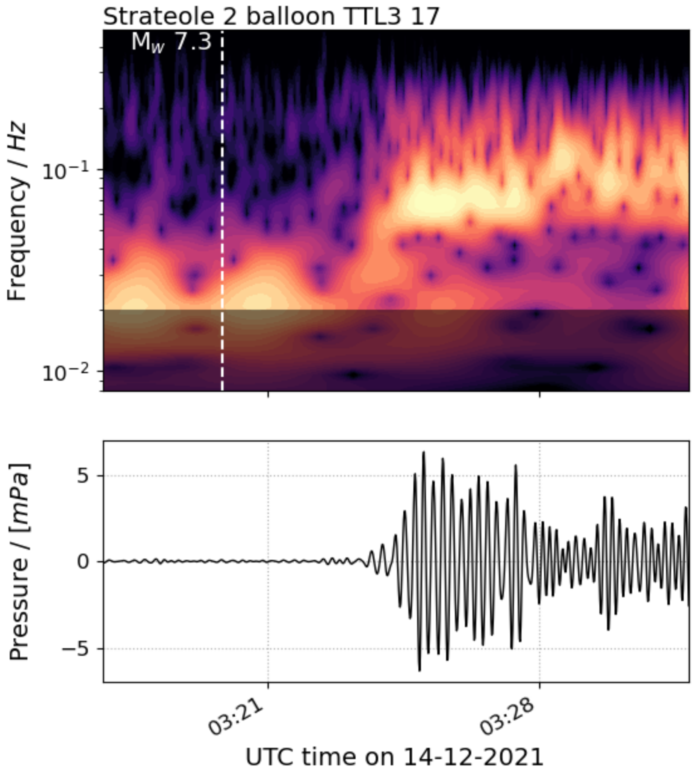




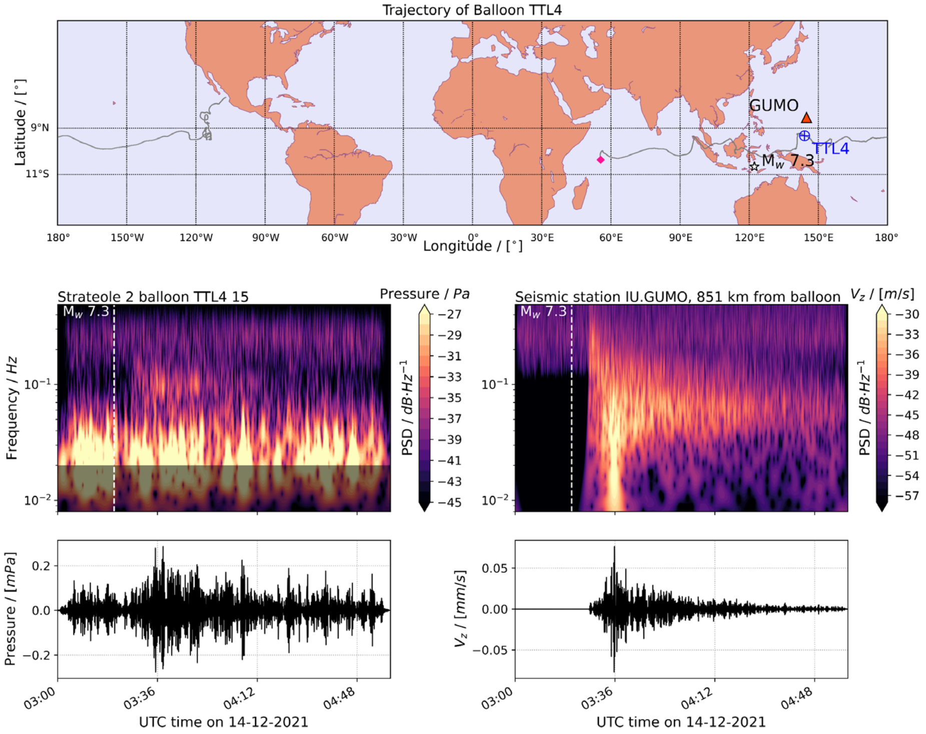
Picking the Rayleigh wave: example of balloon 17

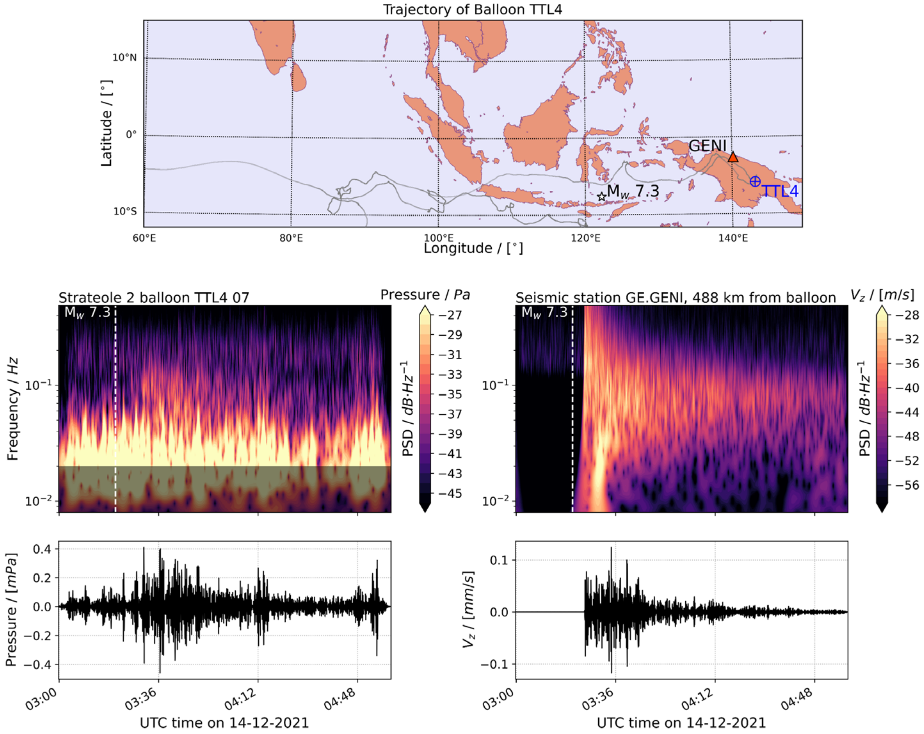






Balloon 15 and 07: a more difficult case.

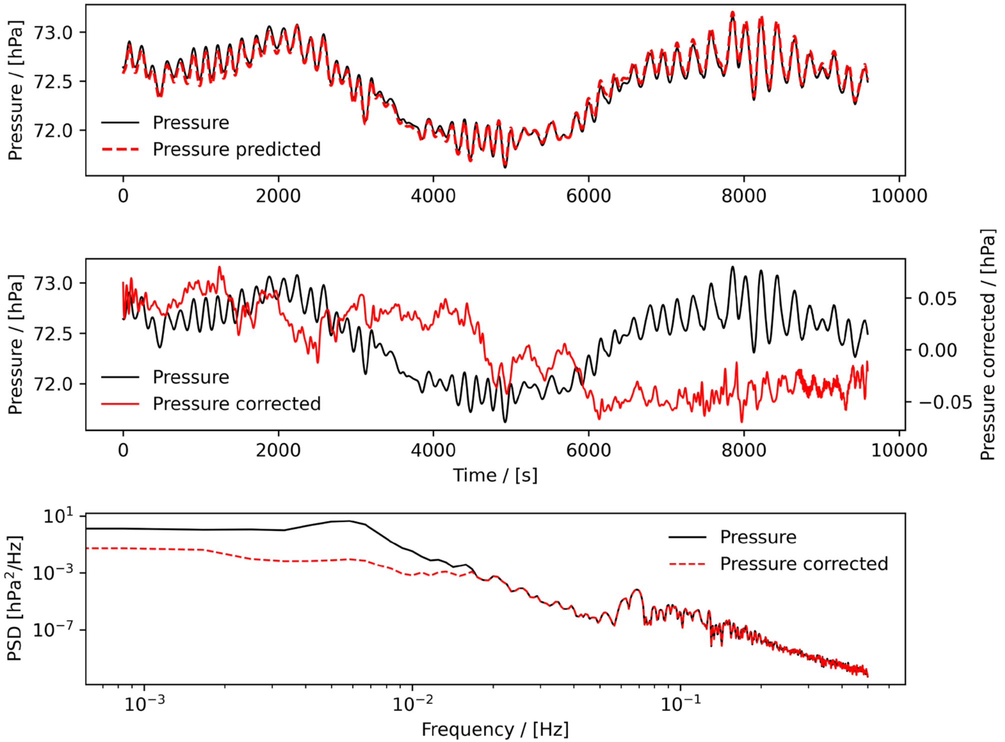




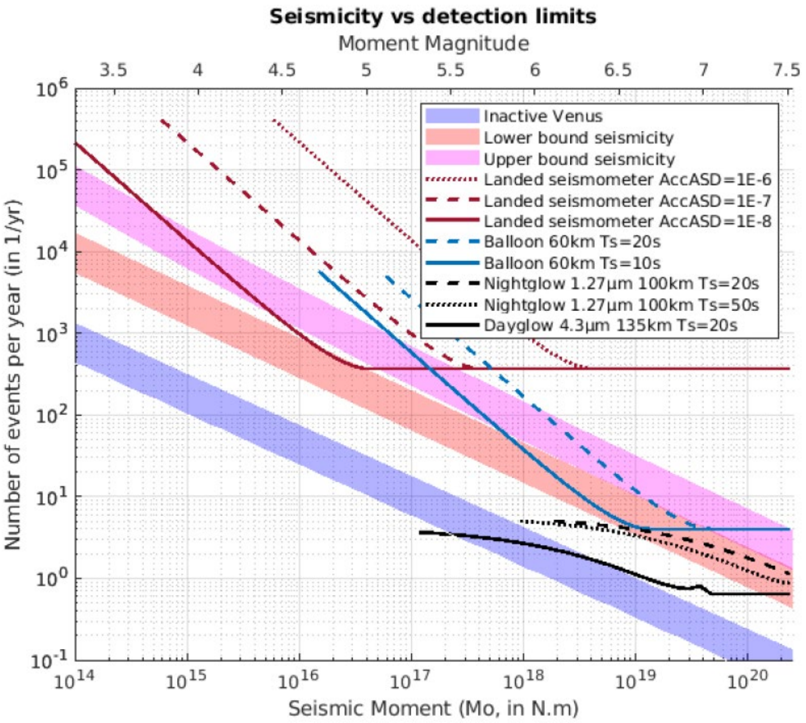
Improving the SNR at low frequency

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

The correction in the time and spectral domain.



Different mission concepts for Venus seismology

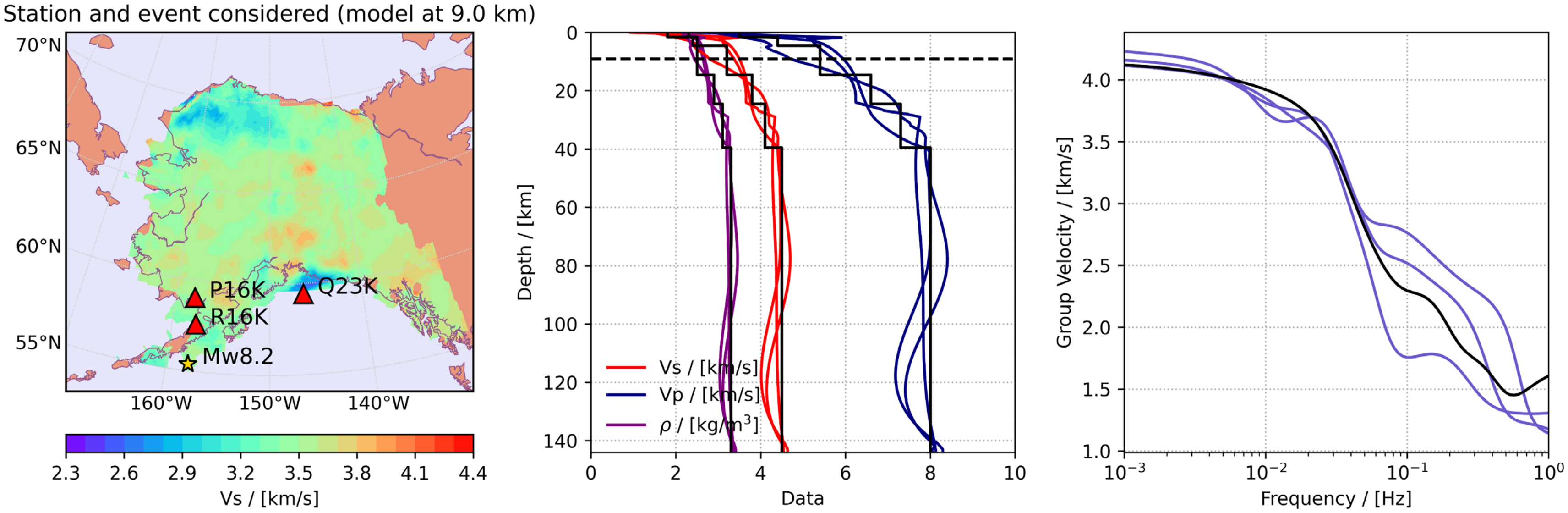


From: Garcia, R. F. *et al.* Seismic wave detectability on Venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers, *Preprint*, 2024, work of the International Space Science Institute (ISSI) team

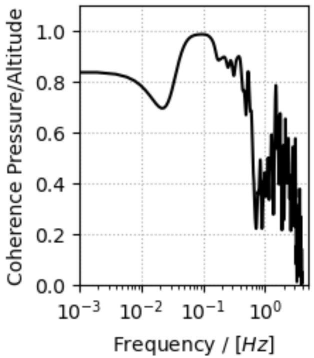
Shaded: number of events per year for different magnitudes depending on Venus activity.

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

Alaska data



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.

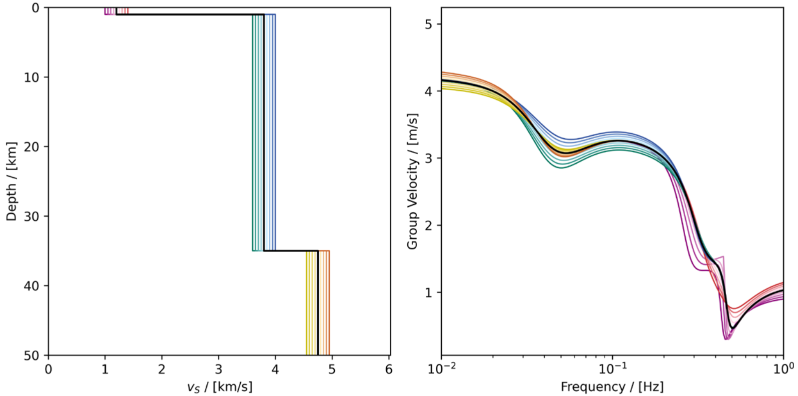


Coherence between pressure and vertical velocity traces

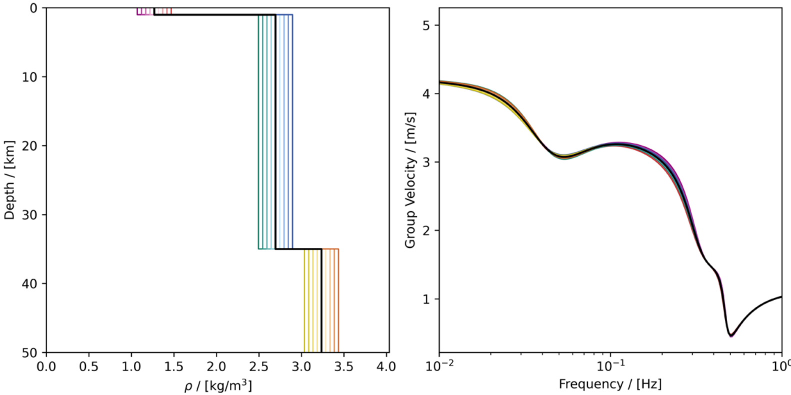
Berg, E. M. et al (2020) *JGR: Solid Earth* **125**, http://doi.org/10.1029/2019JB018582
Macpherson et al. 2023 (2023) *BSSA*, **113**, https://doi.org/10.1785/0120220237

Sensitivity analysis for models of the Flores sea

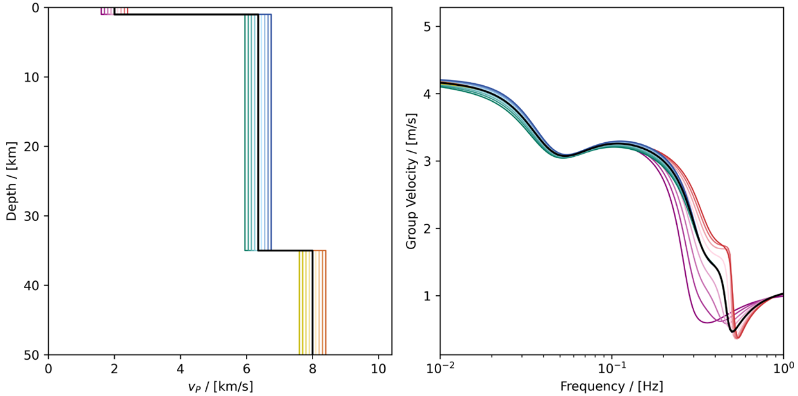
Δv_S variations from -0.2 to 0.2



Density $\Delta\rho$ variations from -0.2 to 0.2



Δv_P variations from -0.4 to 0.4



Poisson ratio ν variations from 0.2 to 0.4