Detection and Inversion of acoustic signals on Venus

AIR Workshop #2
June 23rd, 2026

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Funded by The Research Council of Norway

FRIPRO 335903: "*Airborne Inversion of Rayleigh Waves*"

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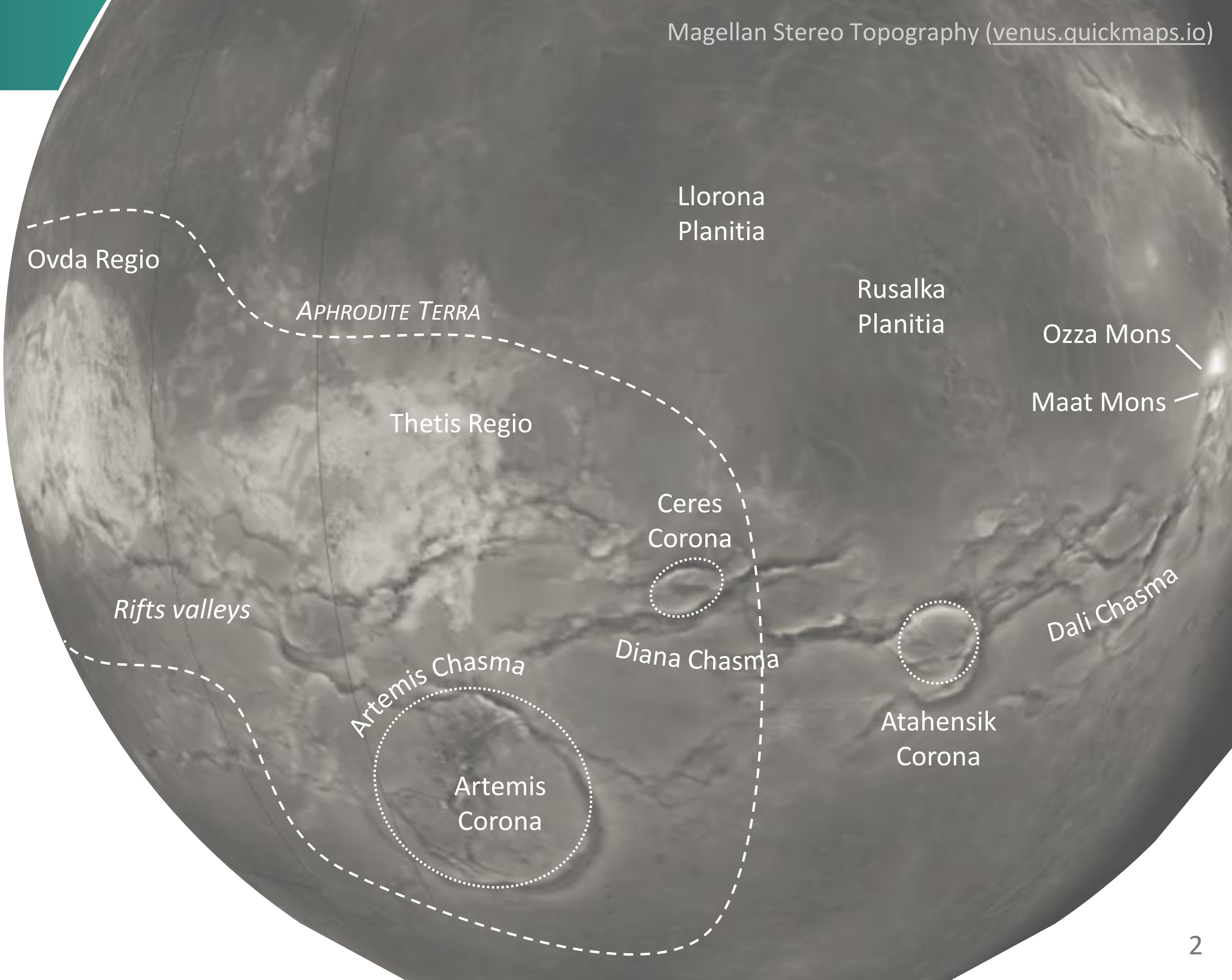
USGS science for a changing world

Venus



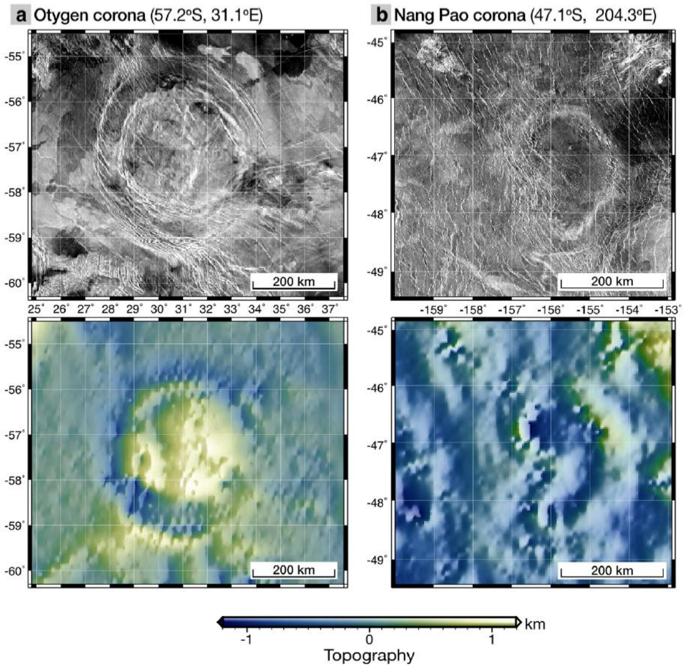
Venus

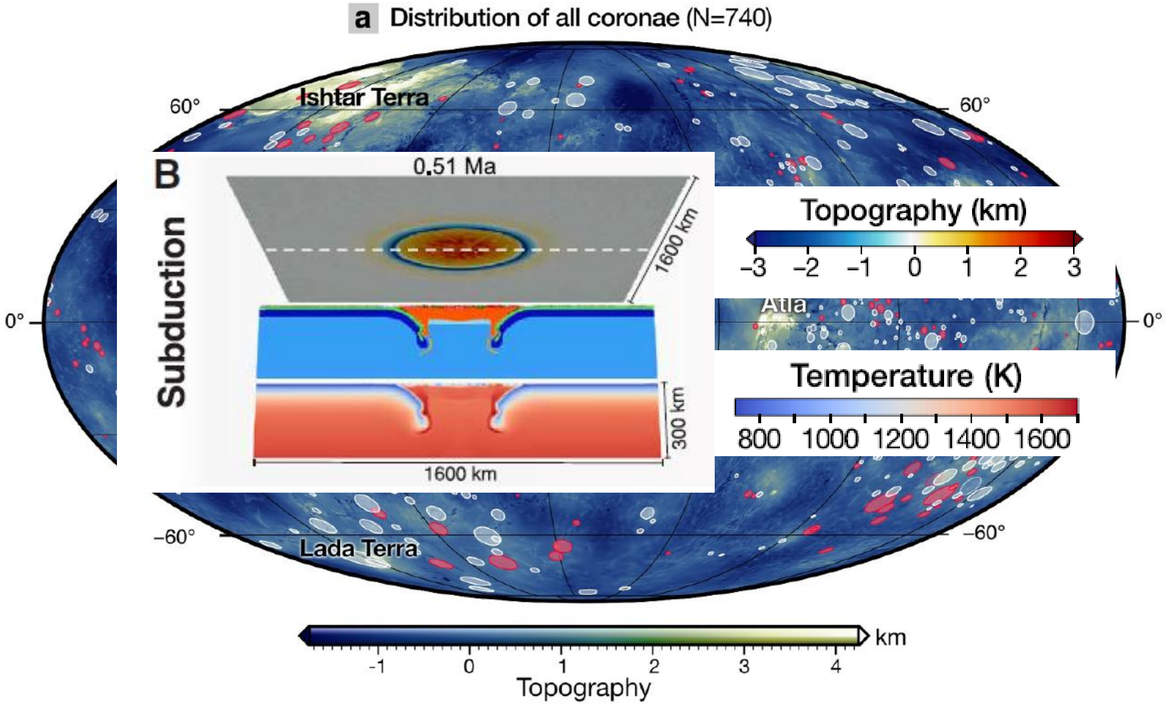
- Opaque, thick clouds
- Dry
- Slow rotation, but superrotational winds
- No magnetic field
- No *global* plate tectonics
- Young surface, intense volcanism
- Hot and dense CO_2 atmosphere

Earth's "Evil twin". What went wrong?

The enigma of Venus Coronae

Coronae: *“a quasi-circular ring of closely spaced concentric fractures, although the ring may be incomplete and deviate from fully circular”*
Currently 740 cataloged.





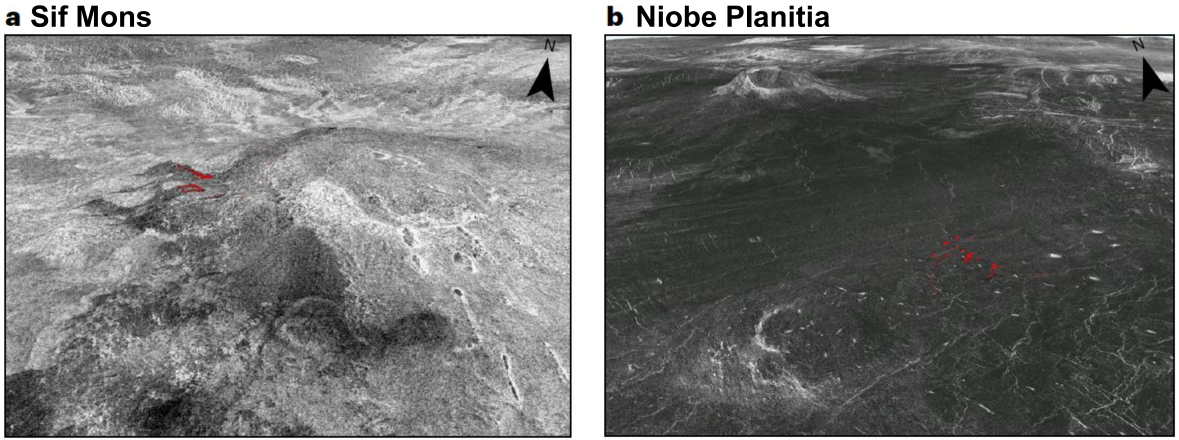
Gülcher, A.J.P., Sabbeth, L., Stofan, E., Smrekar, S.E. (2025). Coronae on Venus: An Updated Global Database and Insights Into Morphology, Spatial Distribution, Geological Setting, and Lithospheric Properties. *JGR: Planets* **130**, 10.1029/2024JE008749

Signs of ongoing volcanic activity

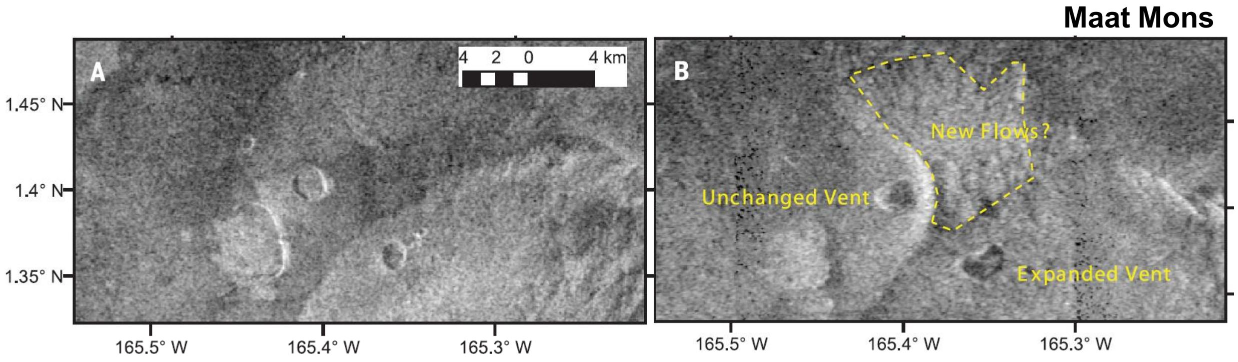
Magellan mission with a synthetic-aperture radar (SAR), conducted high-resolution mapping of 98% of Venus between 1990-1994. 42% mapped two or more times.

Changes in surface backscattering over several volcanic regions:

- **Sif Mons** (shield volcano)
- **Niobe Planitia** (shield volcanoes)
- **Maat Mons** (highest volcano)

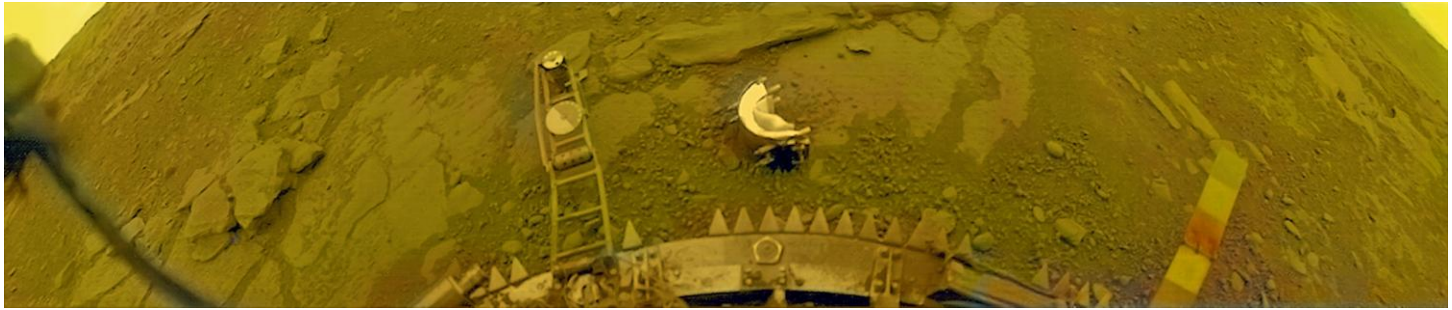


Sulcanese, D., Mitri, G., Mastrogiuseppe, M., (2024). Evidence of ongoing volcanic activity on Venus revealed by Magellan radar. *Nat Astron* **8**. 10.1038/s41550-024-02272-1



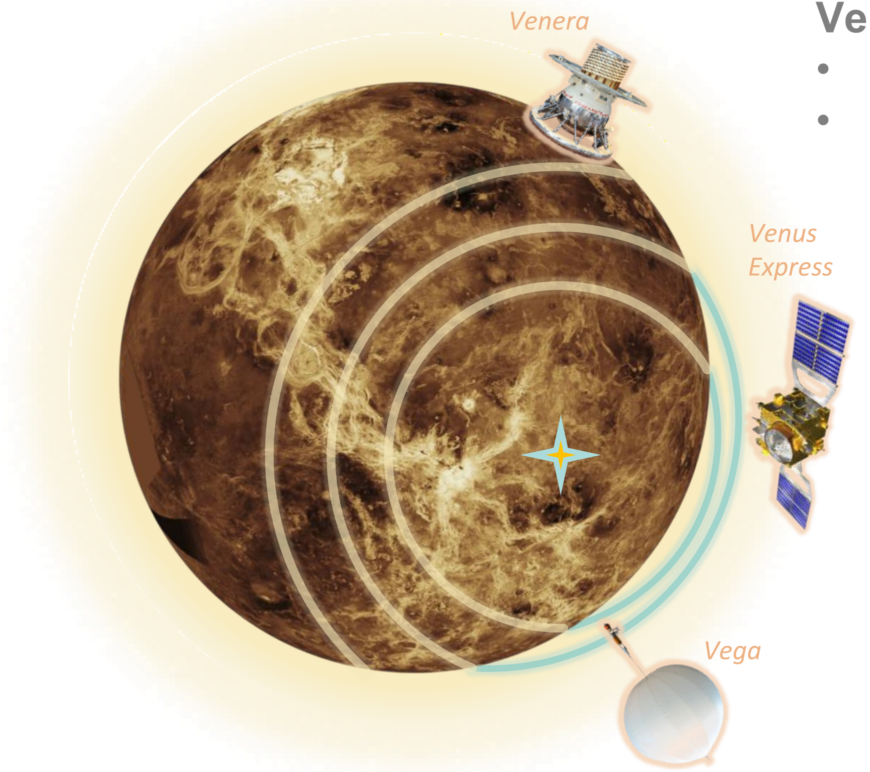
Herrick, R.R. & Hensley, S. (2023). Surface changes observed on a Venusian volcano during the Magellan mission. *Science* **379**. 10.1126/science.abm7735

Venus seismology concepts



The Soviet Union's Venera 13 probe captured two color panoramas of Venus's surface in 1982.

Venus seismology concepts



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

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

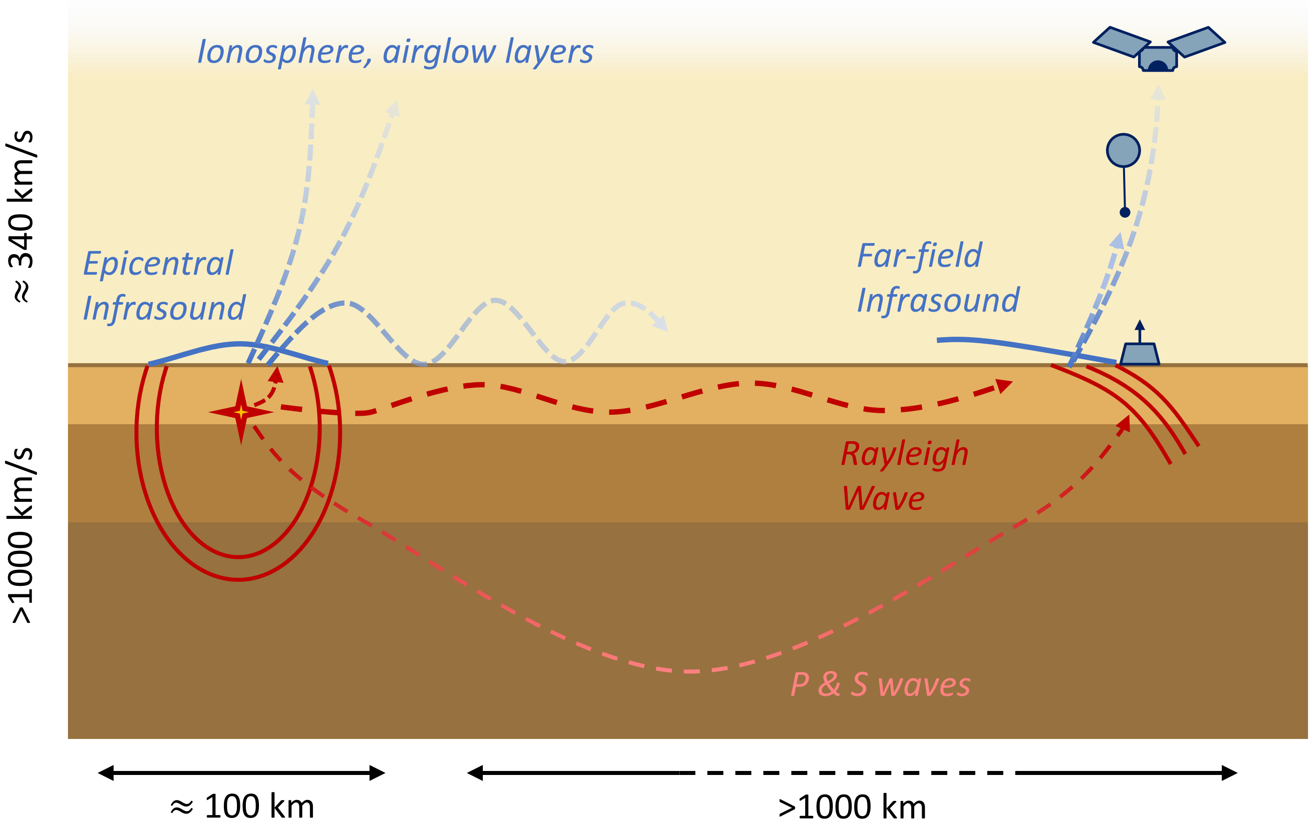
Surface sensor. Deployed seismometer. < 24 h.

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

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

Earthquake Infrasound

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



Coupling of seismic waves into infrasound acoustic waves

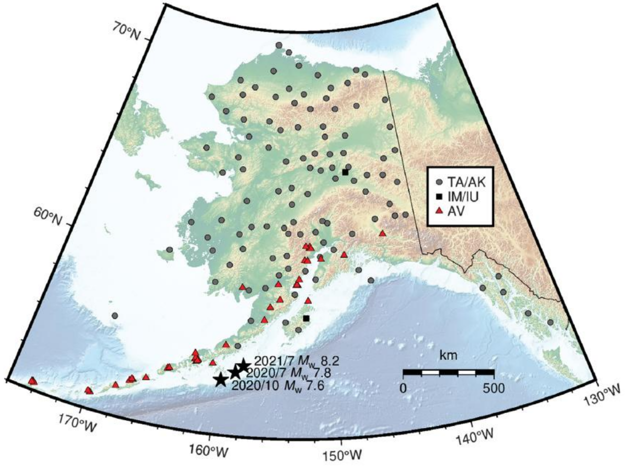
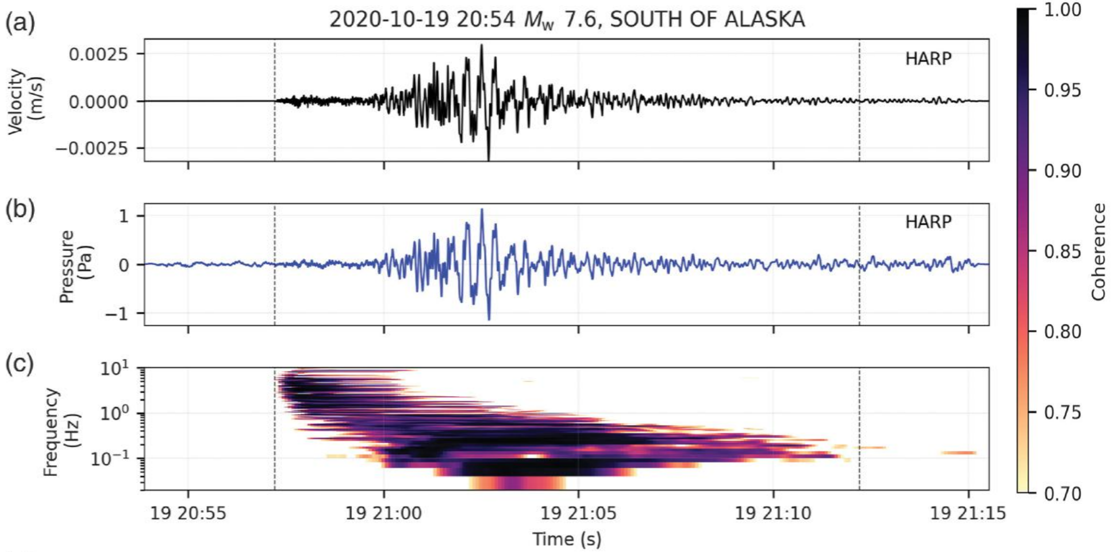


Figure 1. Map of infrasound stations in Alaska in 2020–2021. Each station's marker indicates the network: circles indicate TA/AK, squares indicate IM/IU, and triangles indicate AV. All but one station has a colocated seismometer. The locations of the three large earthquakes used in this study are plotted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



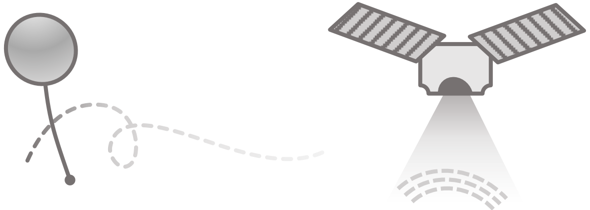
Alaska network: many pressure sensors collocated with seismic sensors.
Excellent coherence between pressure and seismic velocity following large earthquake.

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

Fee, D., Macpherson, K., Gabrielson, T., (2023). *BSSA*, **113**, 1581–1595. 10.1785/0120220226
Macpherson, K., Fee, D., Coffey, J., Witsil, A. (2023) *BSSA*, **113**, 10.1785/0120220237

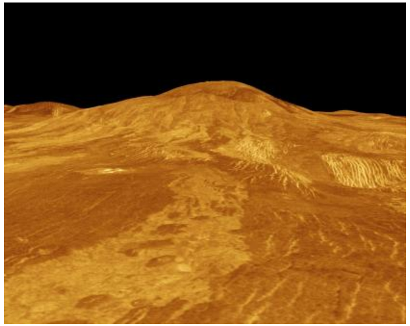
On the menu

Can venusquakes be detected from the atmosphere and from space?



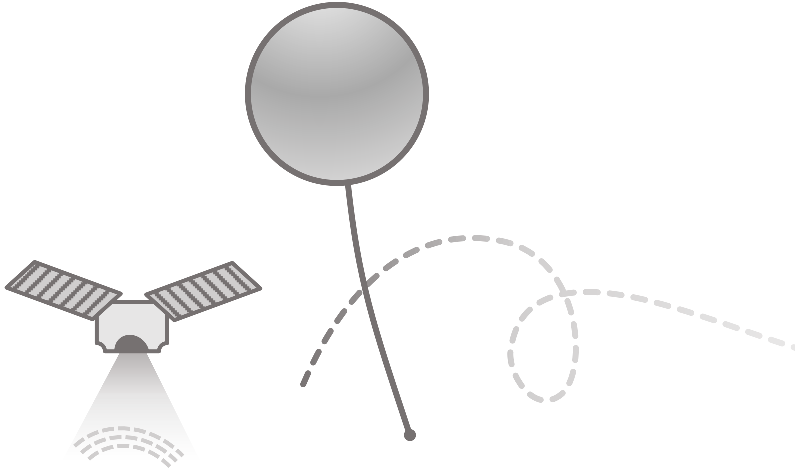
How much can balloon detections inform us about the subsurface?

Can balloons pick up on signals from Venus volcanic eruptions?



Venusquake detectability

- Could we detect venusquakes infrasound signals from balloons or airglow ?
- How does SNR, mission duration, or velocity model affect detectability?



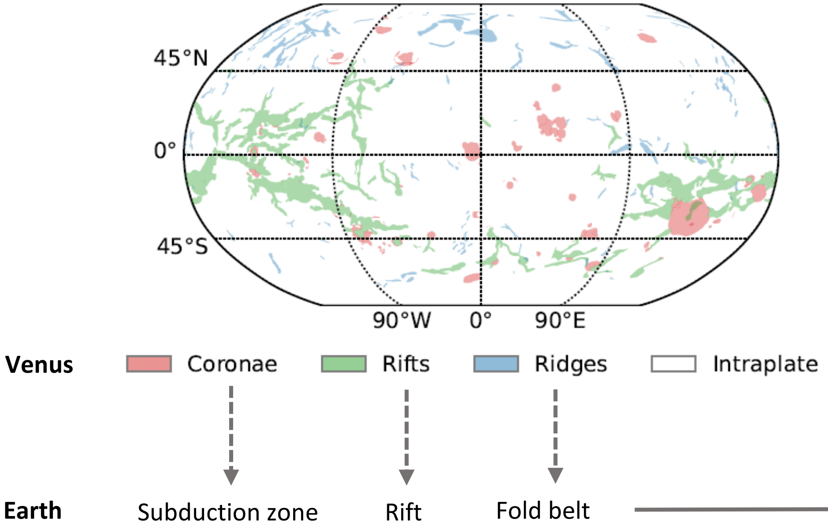
Earth and Space Science

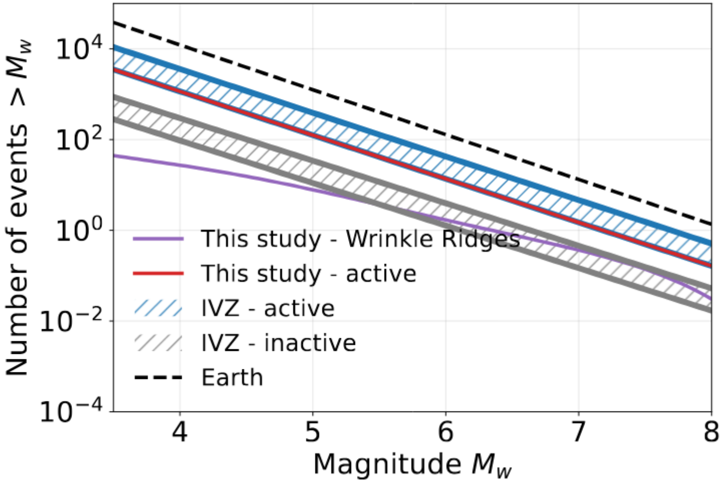
Research Article | Open Access

Aerial and Space-Borne Seismology on Venus: Viability and Design Implications for Future Missions

Quentin Brissaud, Chenxi Kong, Marouchka Froment, John Wilding, Anna J. P. Gülcher, Jennifer M. Jackson, Iris van Zelst, Raphaël F. Garci, Celine Marie Solberg, Sven Peter Näsholm

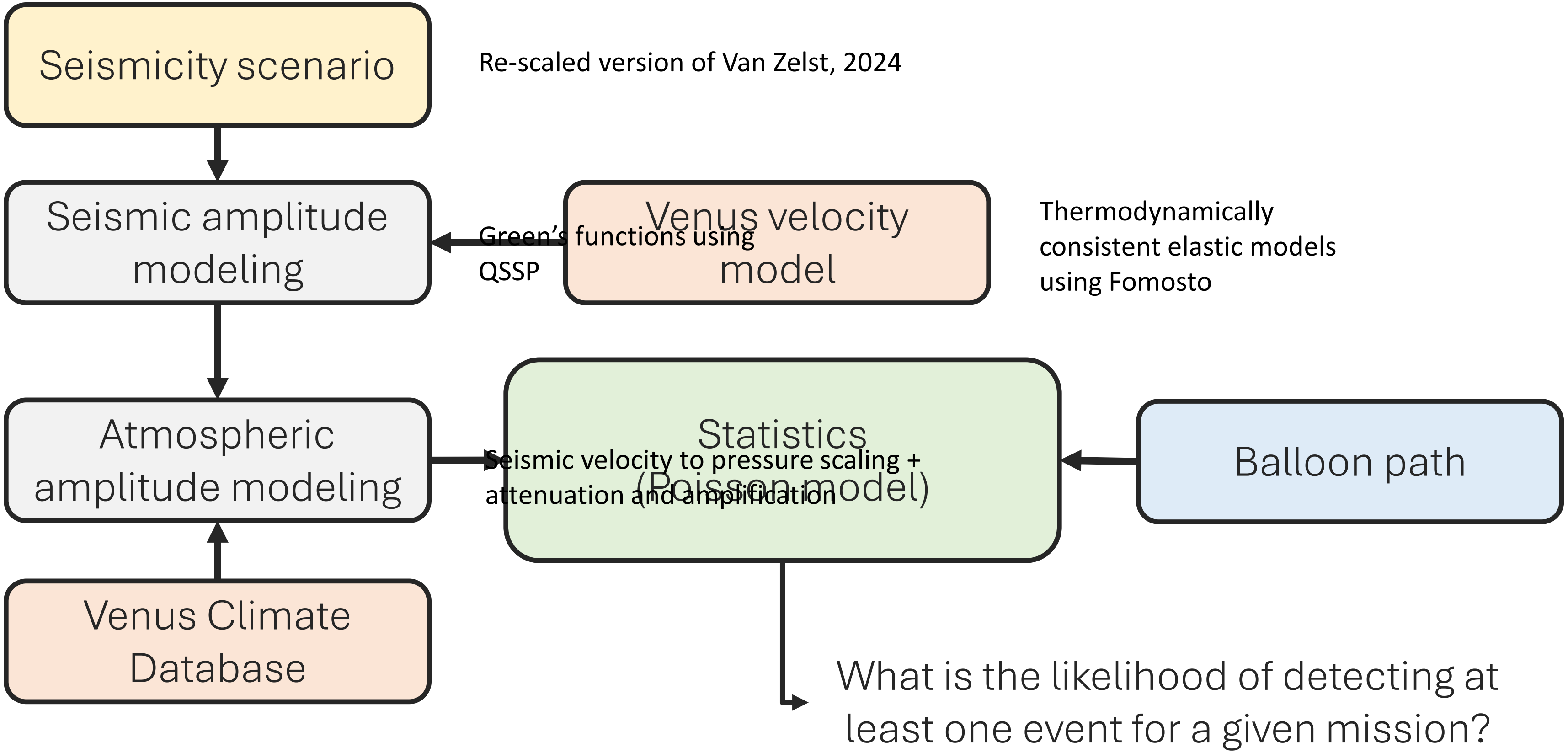
Estimated seismic activity on Venus



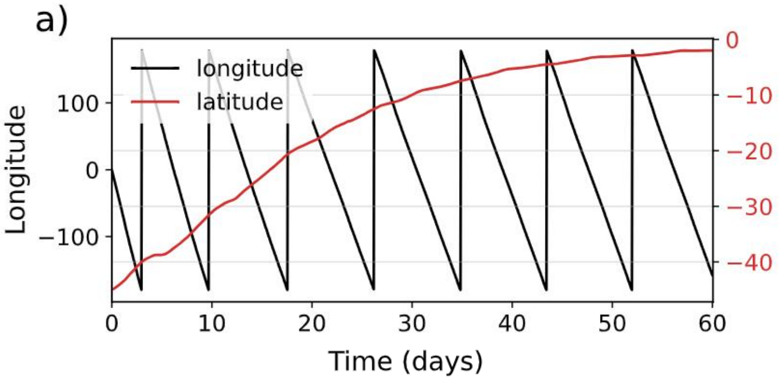


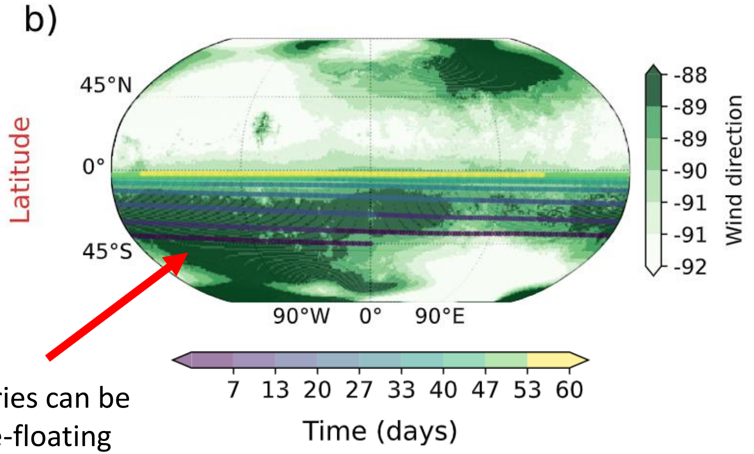
Scaling Earth catalogs to Venus seismogenic volume / area from

Methodology



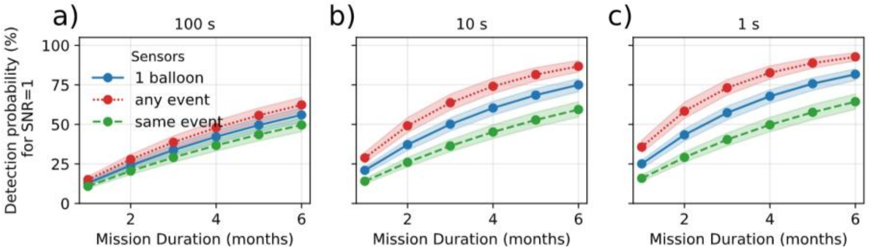
Balloon trajectory and detection probability

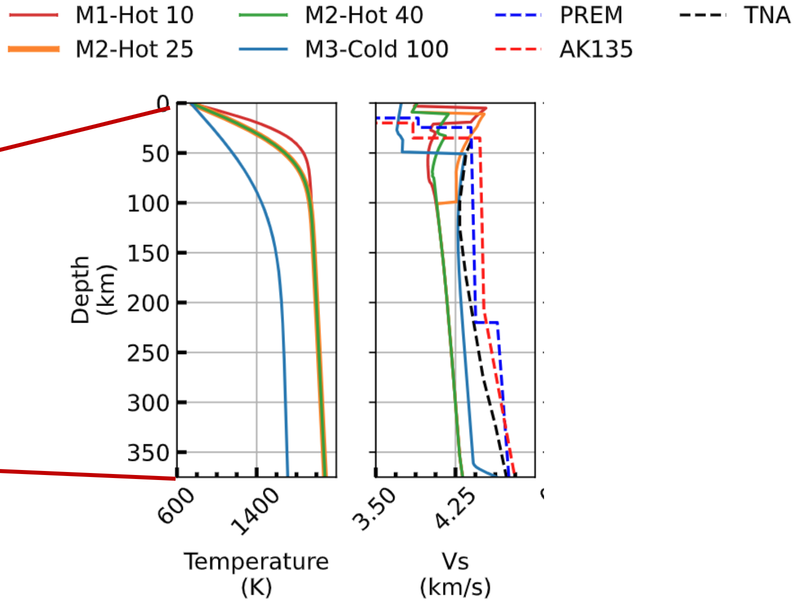




Balloon trajectories can be modelled as free-floating objects moving with horizontal winds at a constant altitude

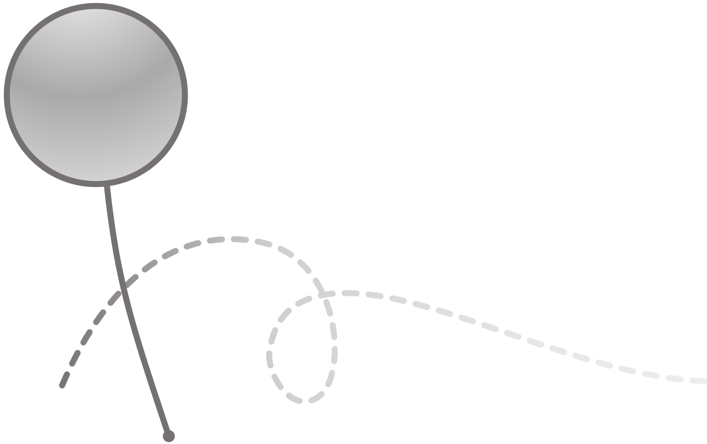
Infrasound detectability on Venus





Volcano detectability by balloons

- Could we detect infrasound signals related to volcanic eruptions on Venus ?
- How far can volcanic infrasound travel in the Venusian atmosphere?



Manuscript submitted to JGR Space Physics

Infrasound waveguides on Venus could enable the detection of explosive volcanism using balloons

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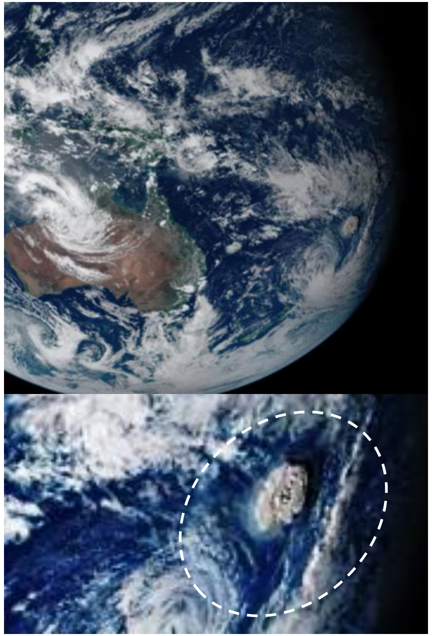
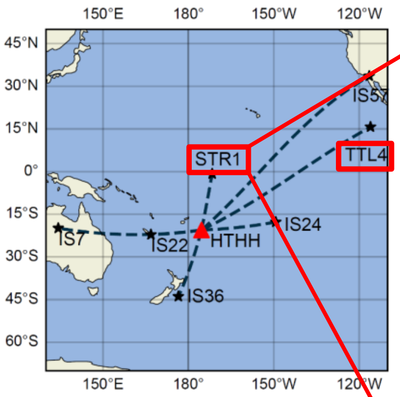
The Hunga Tonga Hunga Ha'Apai eruption (January 2022)

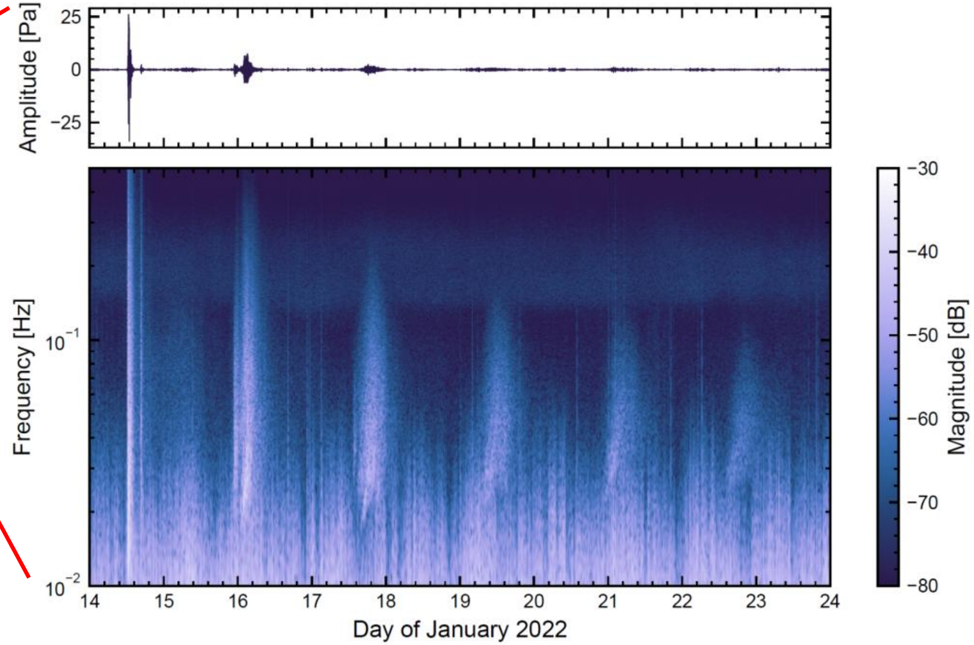
Master student project, Sophus Bredesen Gullbekk (sophusbg@uio.no)

The January 15, 2022 eruption caused a tsunami, a Mw 5.8 earthquake and shock waves detected worldwide. Can we model the infrasound recorded by balloons at long distances ?



The plume and shock wave recorded by the Himawari-8 geostationary satellite.





Methodology

VEI statistics + Active Volcano Locations

- Estimates by Byrne, 2022. Simple scaling based on planetary surface area and mass
- Dataset of large volcanoes on Venus by Hann, 2023

VEI-to-pressure mapping

VEI-to-Magnitude-to-massrate mapping + monopole pressure source

Atmospheric wave modeling

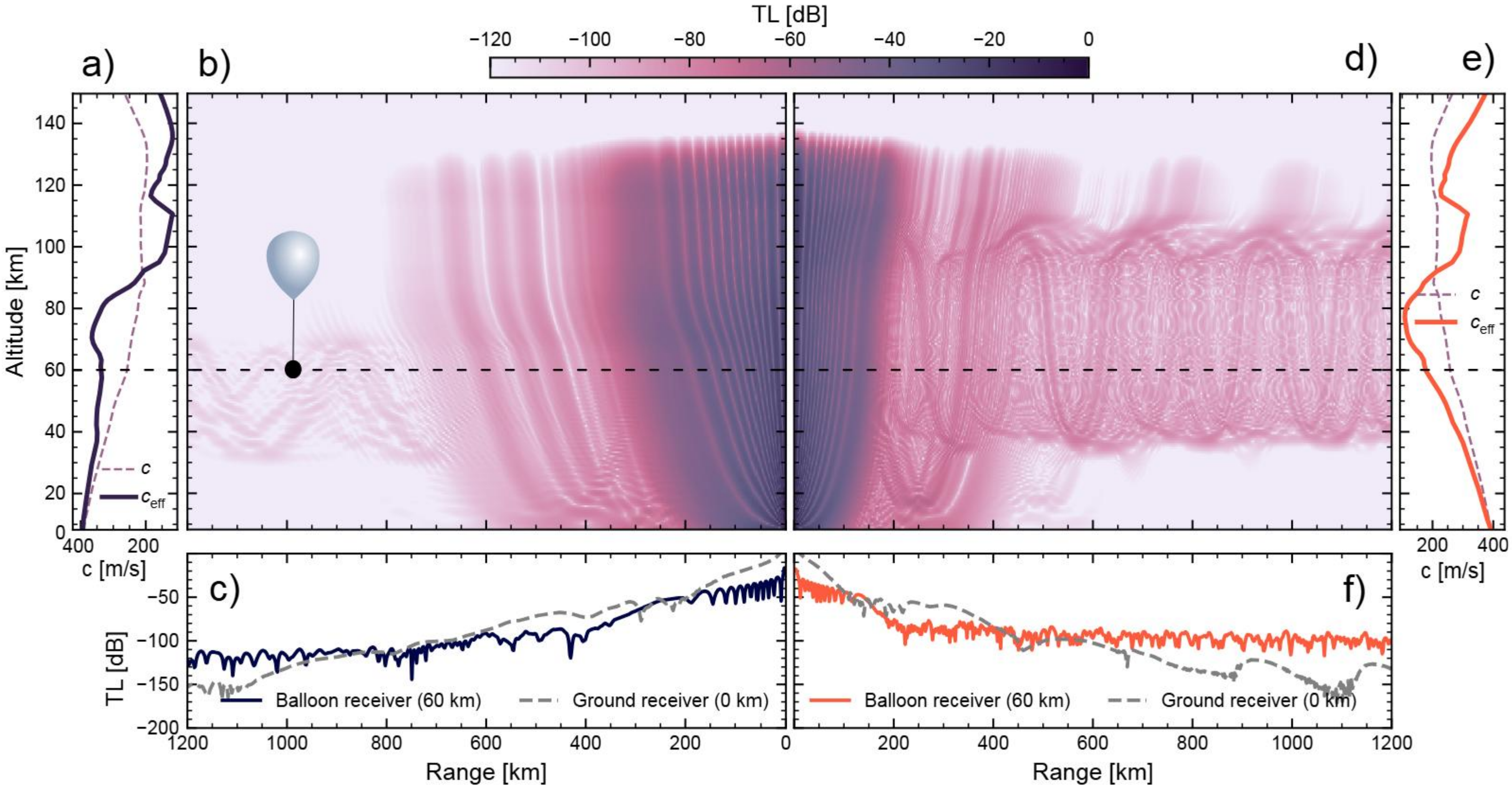
Transmission loss using NCPA's ePape range-dependent solver

Statistics (Poisson model)

Balloon path

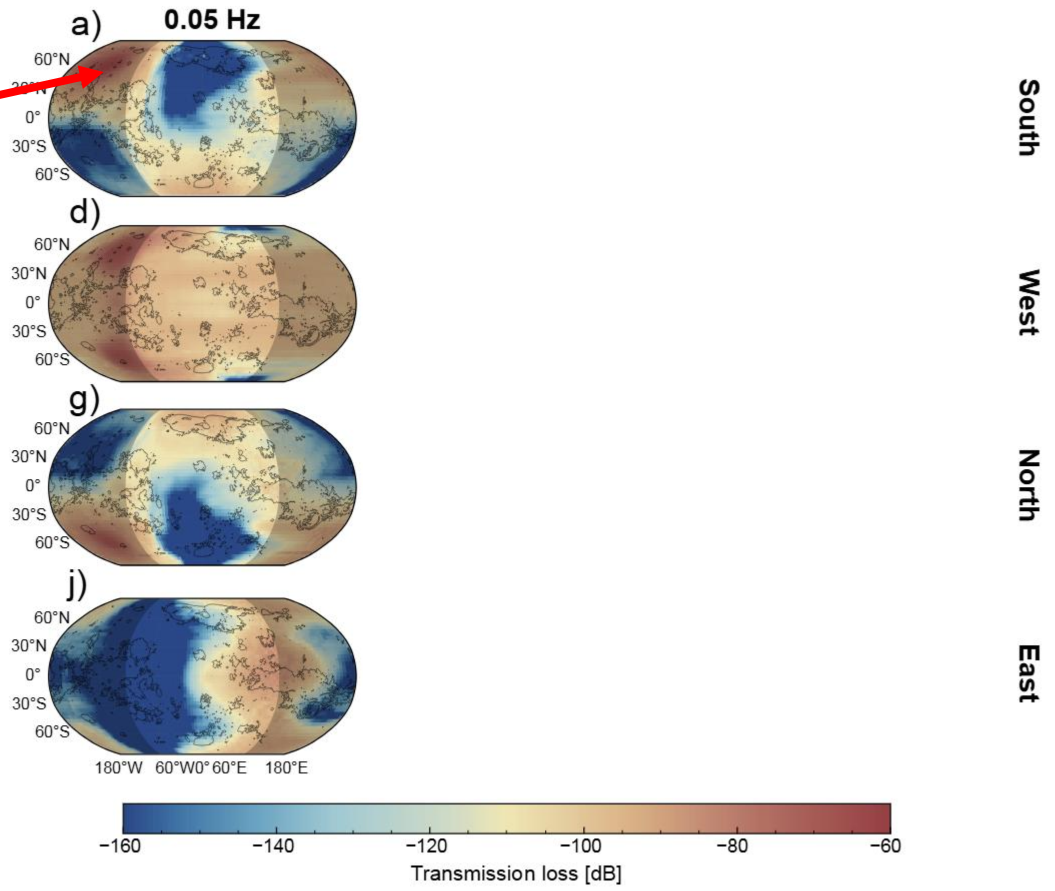
What is the likelihood of detecting at least one event for a given mission?

Infrasound propagation and volcano detectability on Venus

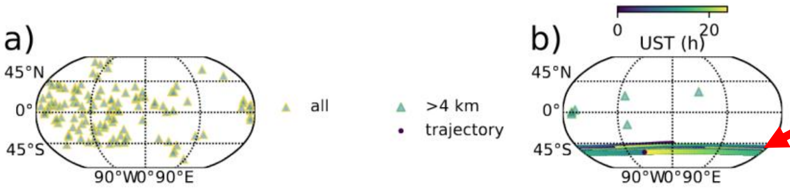


Transmission Loss Estimates

High average transmission loss from this balloon location from sources coming from the South



Infrasound propagation and volcano detectability on Venus



Balloon trajectories can be modelled as free-floating objects moving with horizontal winds at a constant altitude

Probability of detecting at least one eruption for balloon flying for 1 h over a given location

Detection probability only for the highest altitude volcanoes

Detection probability of at least one event from the highest volcanoes after a 6 months-long mission

Balloon seismology

- We have assessed that venusquakes could be detectable as infrasound from balloons
- To which extend do we constrain the subsurface structure?

communications earth & environment — **Article**

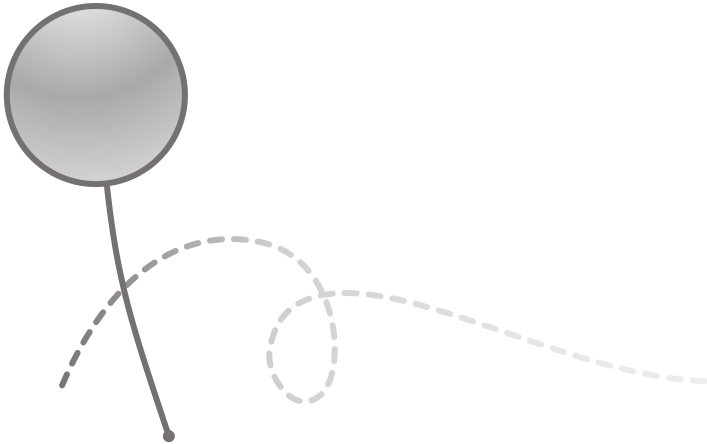
A Nature Portfolio journal

https://doi.org/10.1038/s43247-025-02917-7

Balloon seismology enables subsurface inversion without ground stations

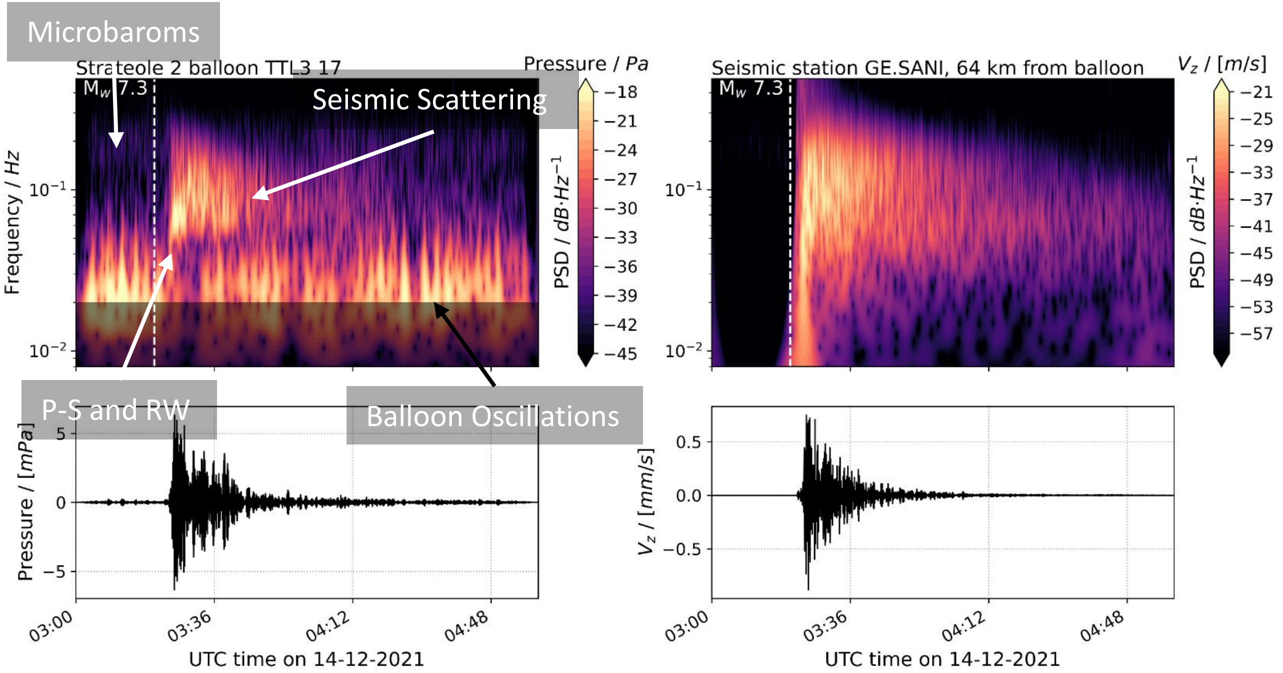
Check for updates

Marouchka Froment [1], Quentin Brissaud [1,4], Sven Peter Näsholm [1,2,4] & Johannes Schweitzer [1,3]



Balloon recordings of earthquakes on Earth

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

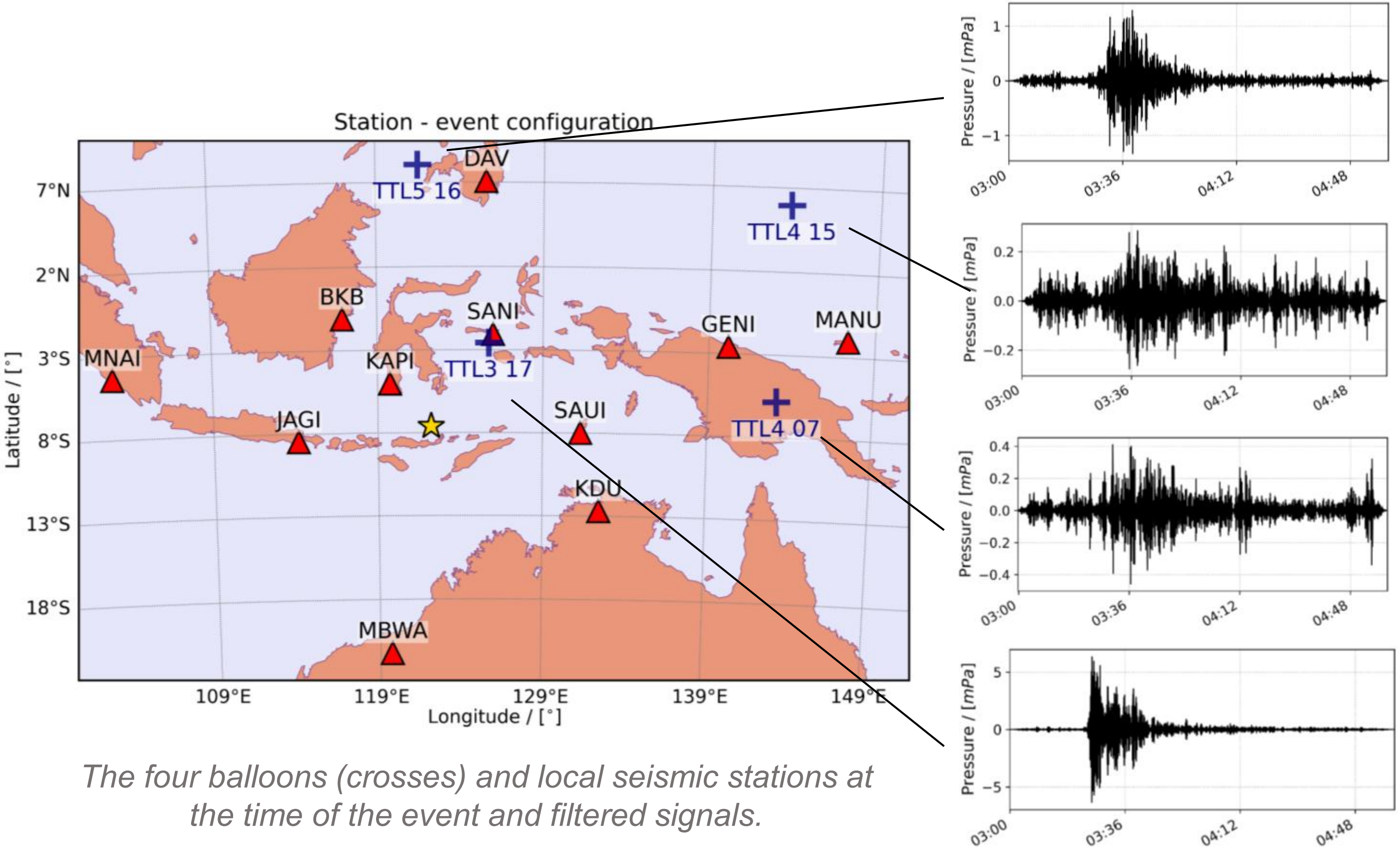


Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), 10.1029/2022GL098844
Brissaud, Q. *et al. Geophysical Research Letters* **48**, (2021), 10.1029/2021GL093013

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

Validation: The Flores Earthquake

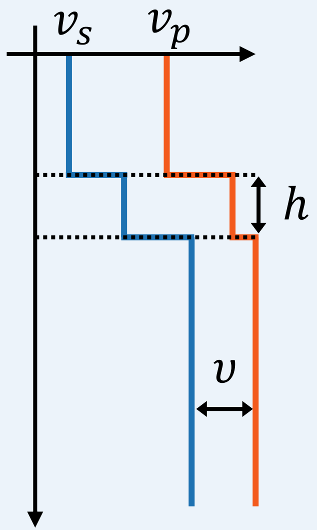
- 4 receivers
- High SNR
- Colocated seismic stations
- Well-characterized source



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

Inversion method - McMC

Subsurface model



Source location and time

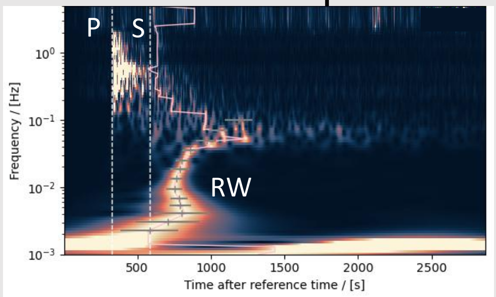
t_s h_s lat_s lon_s

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* $v_s, h, t_s \ldots$)

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

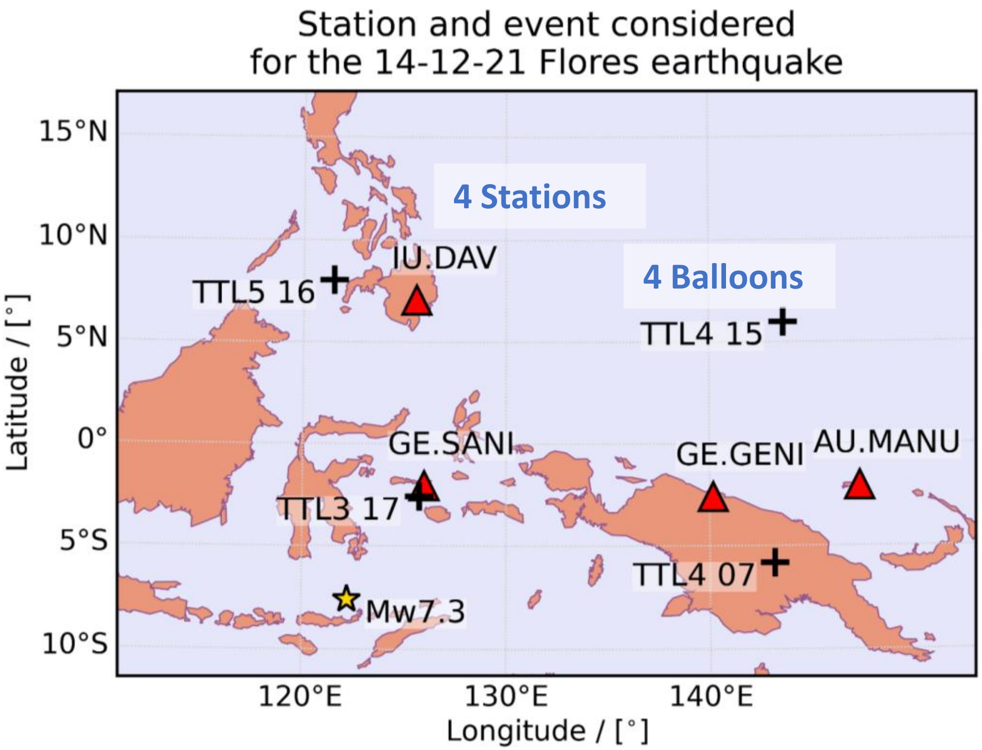
`Python module emcee`

Posterior probability

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

Distribution of parameters

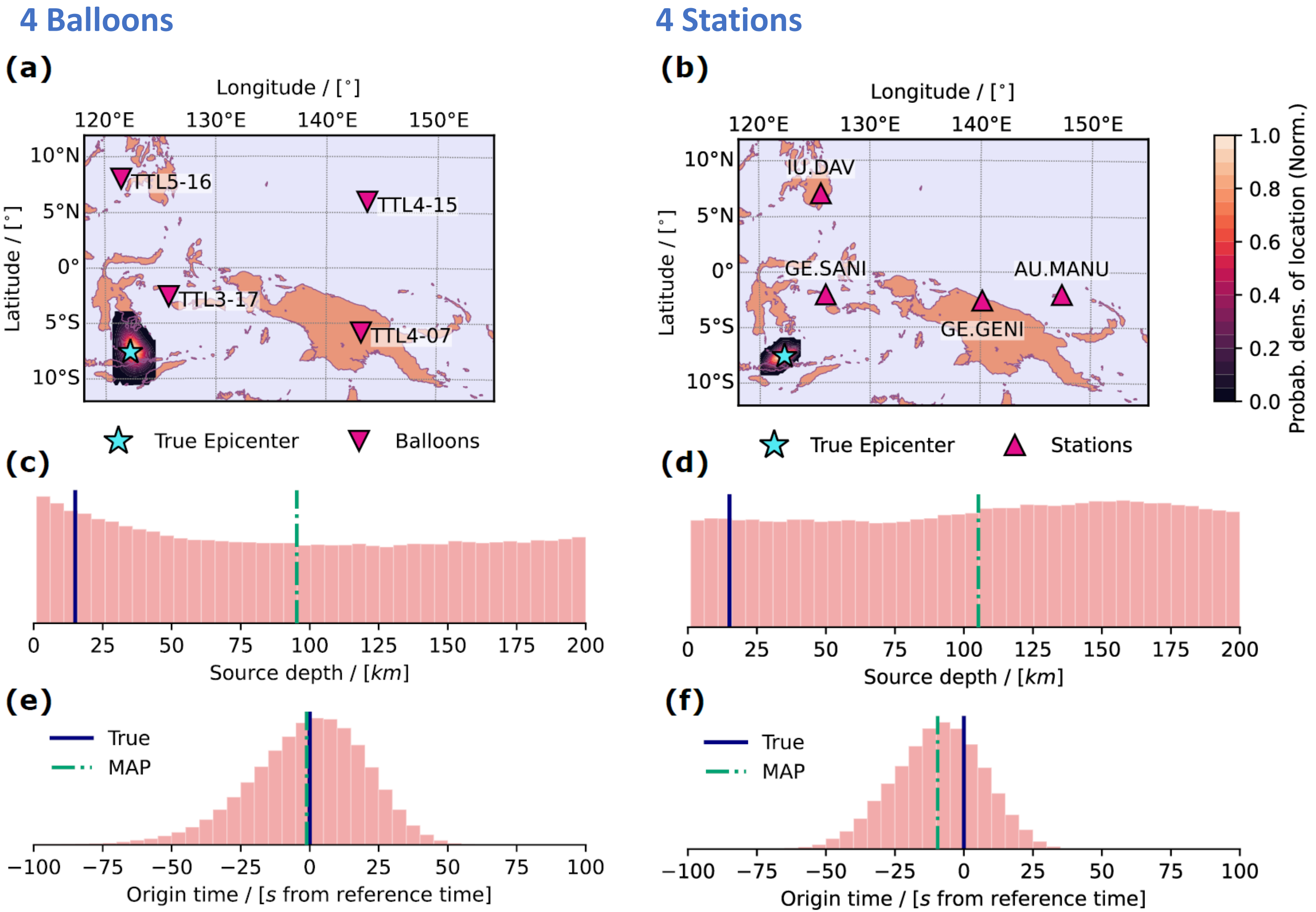
Inversion with 4 seismic stations and 4 balloons



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

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

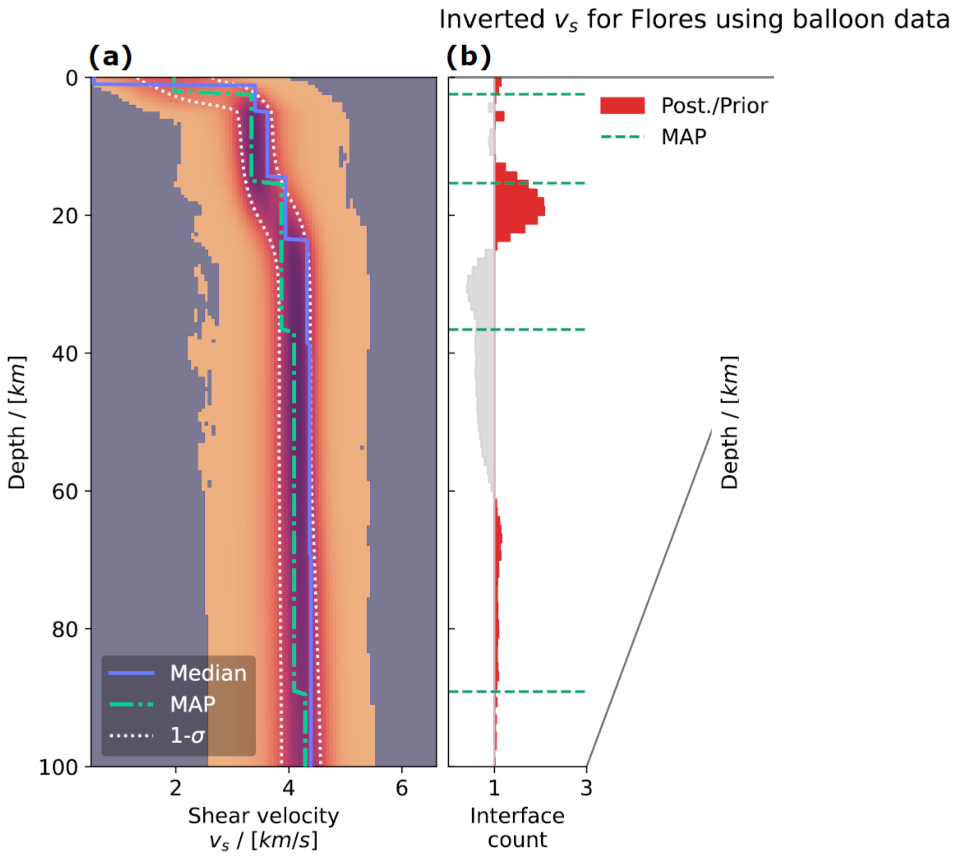
Inversion with 4 seismic stations and 4 balloons



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



Perspectives for Venus seismology

Balloons

- Very likely to capture venusquakes + volcanic signals
- Complex mission design
- Demonstrated possibility for location and subsurface inversion (<400 km)

Airglow

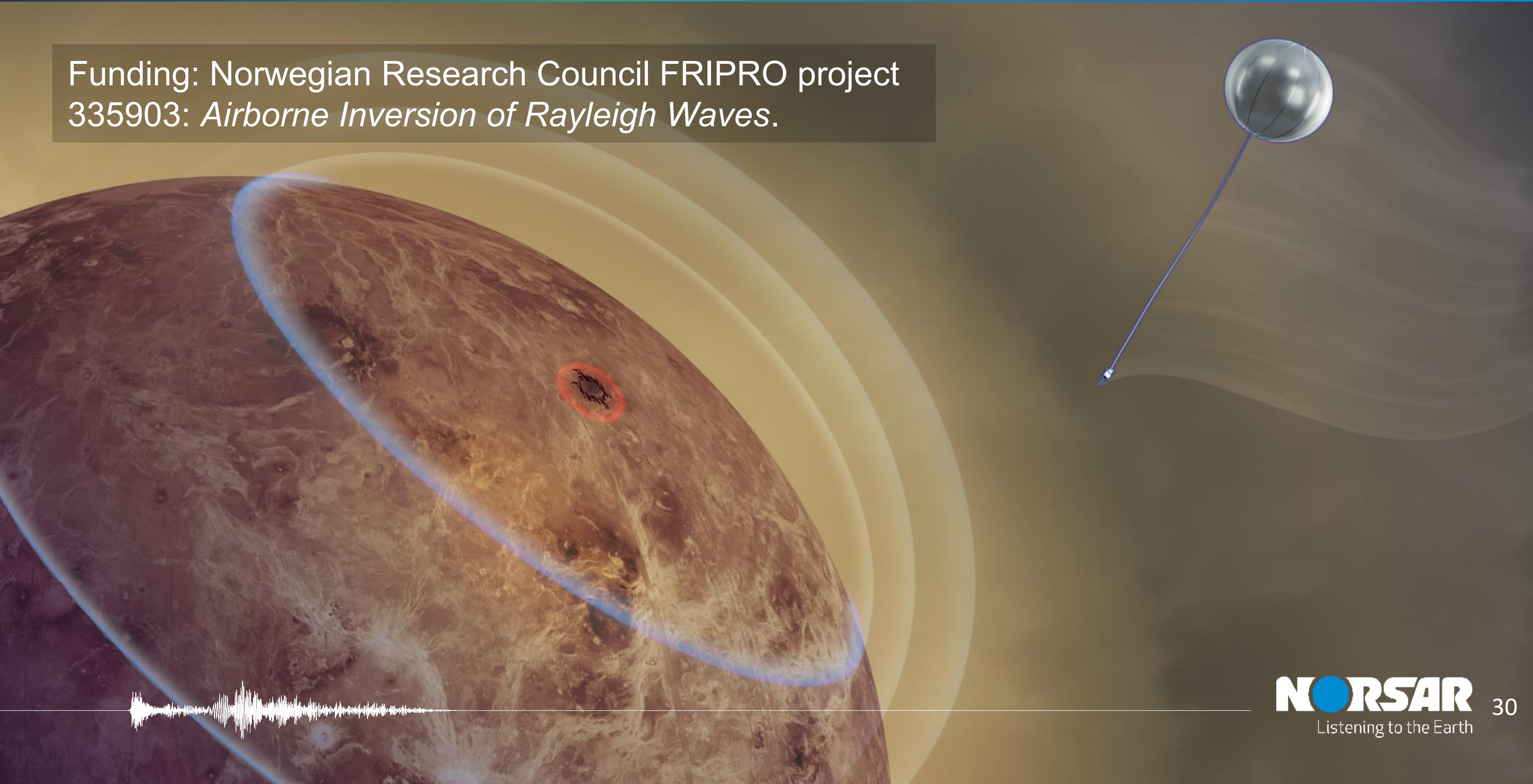
- No proof of concept for seismic signals
- More modeling required to understand the complex nLTE emissions
- Simpler mission design: an IR imager
- Very rich data for inversion and location

What about future missions?

- VERITAS (NASA), EnVision (ESA): will learn more about tectonic features and topography.
- DAVINCI (if maintained?): will provide more data on atmospheric structure, attenuation.
- **Strong community, high motivation for new Venus science !**

Thank you for your attention

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



And Venus ?

Venus

- Opaque, thick clouds
- Dry
- Slow rotation, but superrotational winds
- No magnetic field
- No *global* plate tectonics
- Young surface, intense volcanism
- Hot and dense CO2 atmosphere

- Current **geodynamic regime** of Venus?
- What processes cause its **young surface**?
- Is Venus' **lithosphere strong enough** to sustain quakes?
- Differences in **interior structure and composition** of Venus and the Earth?
- Is Venus' **interior as dry** as its atmosphere?
- Why is there **no magnetic field** on Venus?
- Why is Venus **rotation so slow**?

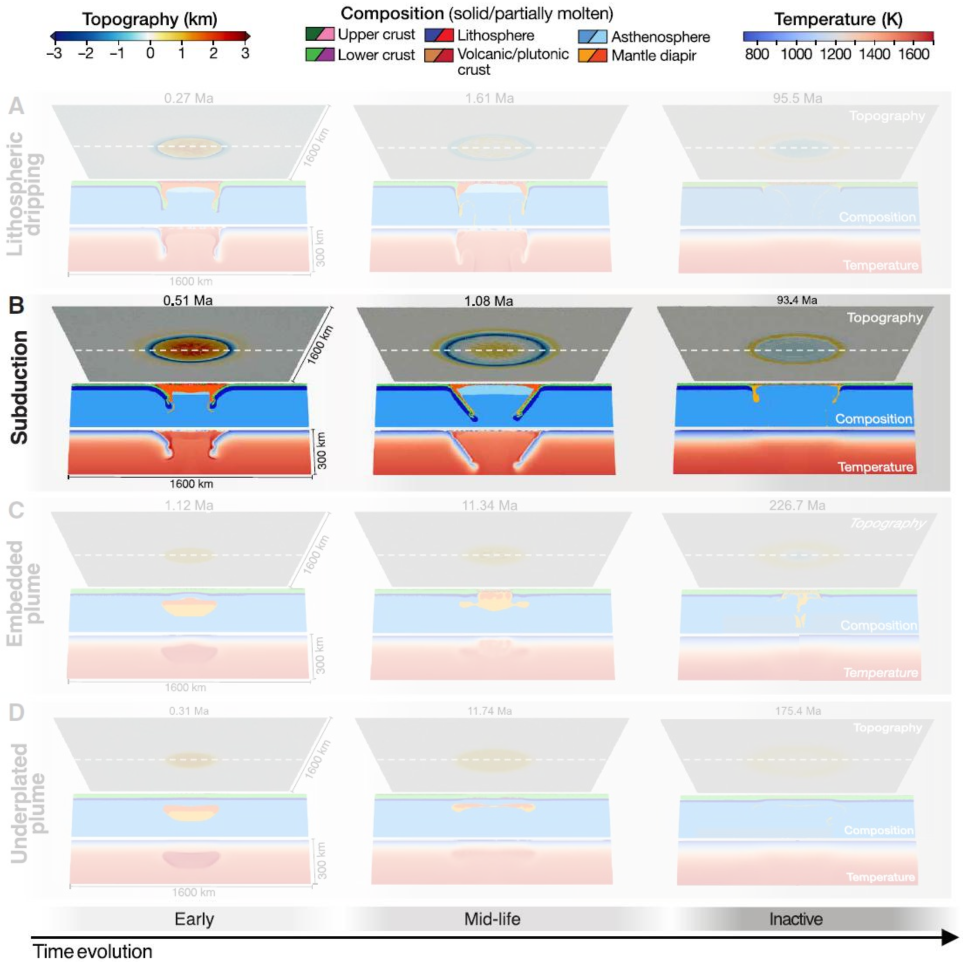
Stevenson, D.J., et al. (2015). Probing the Interior Structure of Venus. 10.26206/C1CX-EV12

Local tectonic activity ?

Thermochemical numerical simulations suggest four **geodynamic end-member scenarios for the formation and evolution of coronae**, linked to differences in topographic and gravity features.

i. Lithospheric dripping
ii. Subduction
iii. Embedded plume
iv. Underplated plume

Subduction may occur if a buoyant plume interacts with a strong lithosphere.
Ex: Unay-Ene, Atahensik

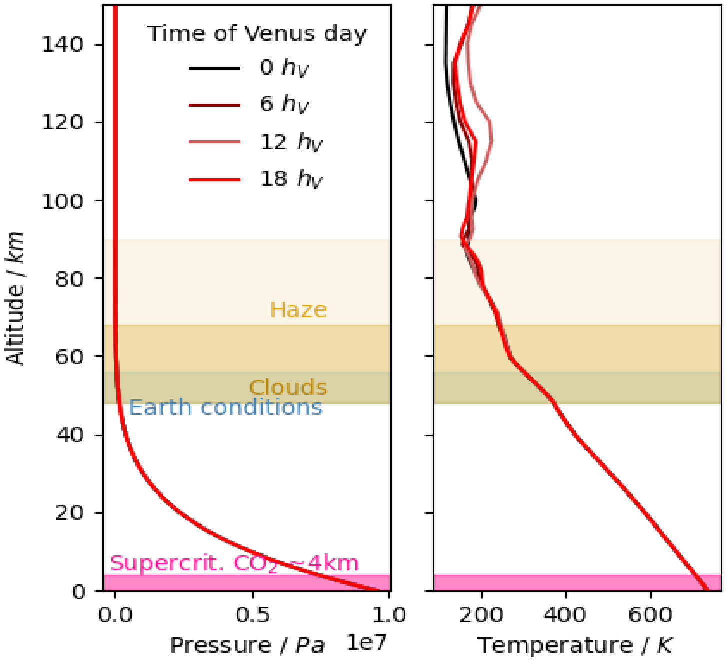


Cascioli, G., Gülcher, A.J.P., Mazarico, E., Smrekar, S.E., (2025). A spectrum of tectonic processes at coronae on Venus revealed by gravity and topography. *Science Advances* **11**, 10.1126/sciadv.adt5932

Infrasound propagation on Venus

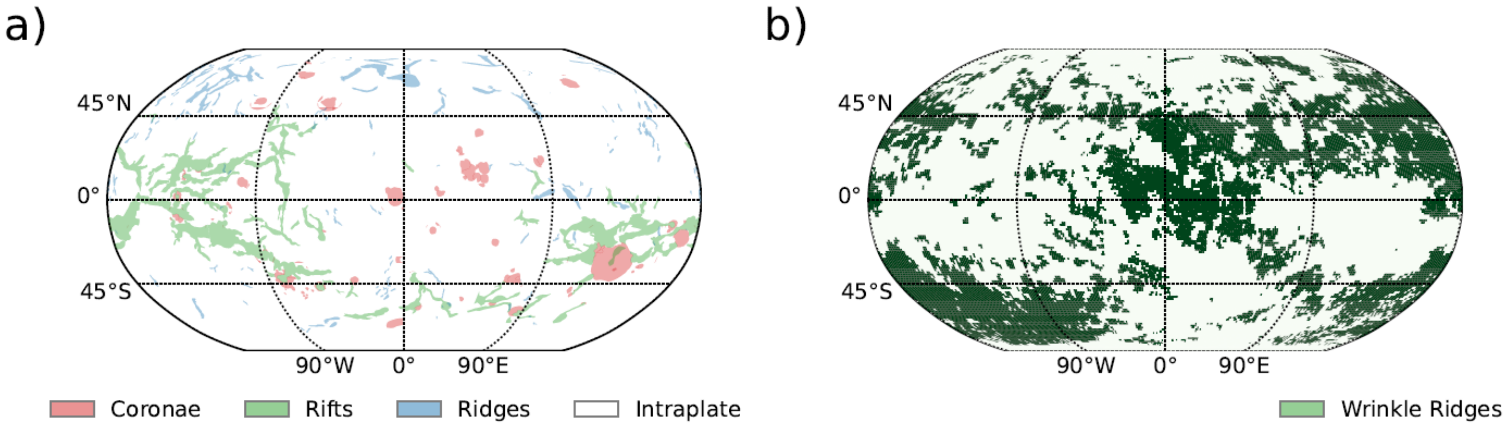
Venus is a pressure cooker under a lid of clouds, very stable throughout the day: a challenge for ground-based seismology, but an advantage for infrasound studies!

- 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?

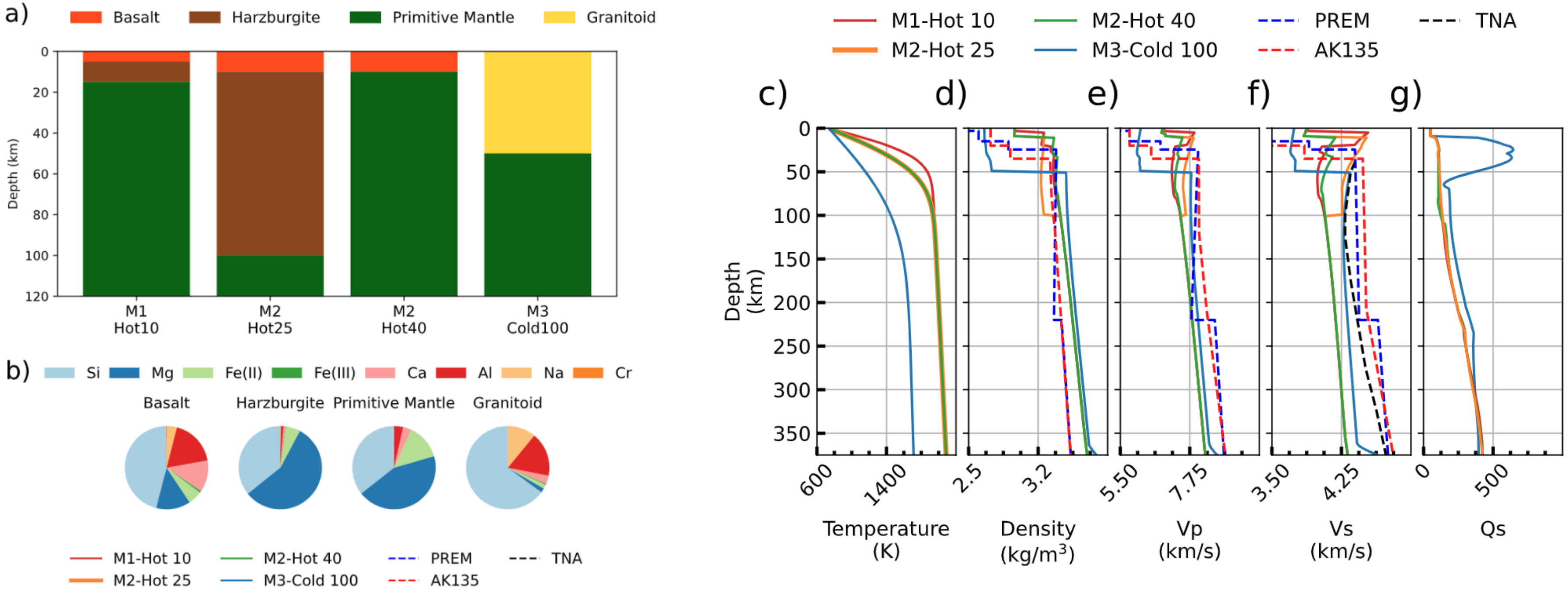


Venus Climate Database outputs for pressure and temperature near the equator.

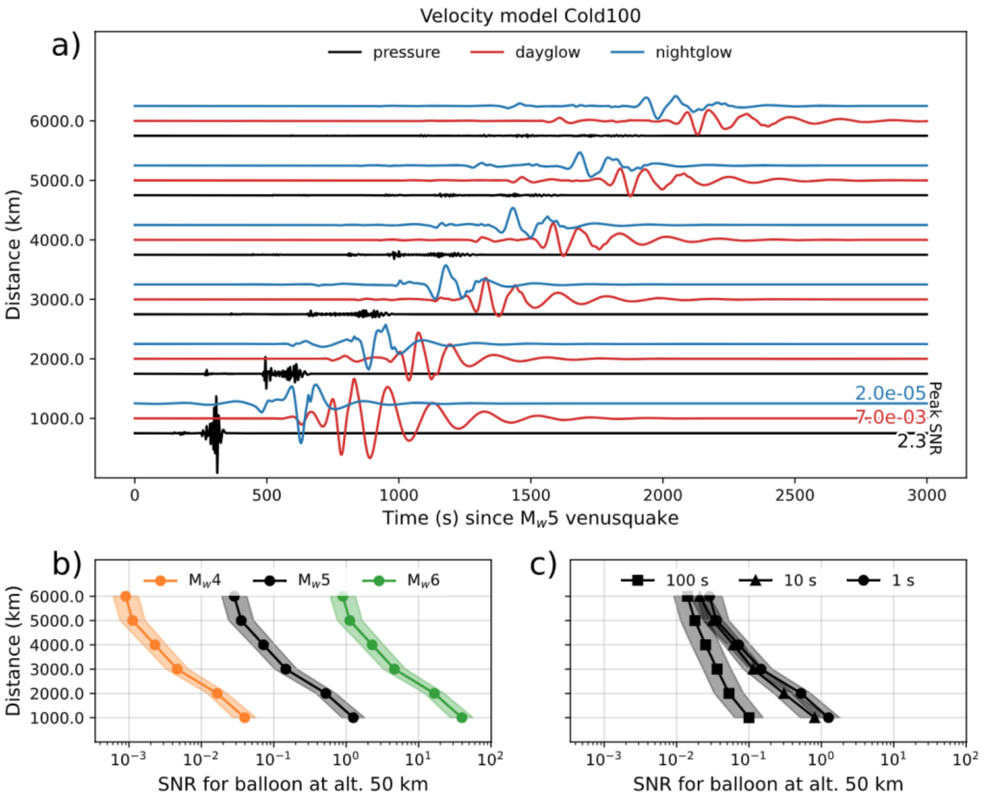
Seismogenic regions



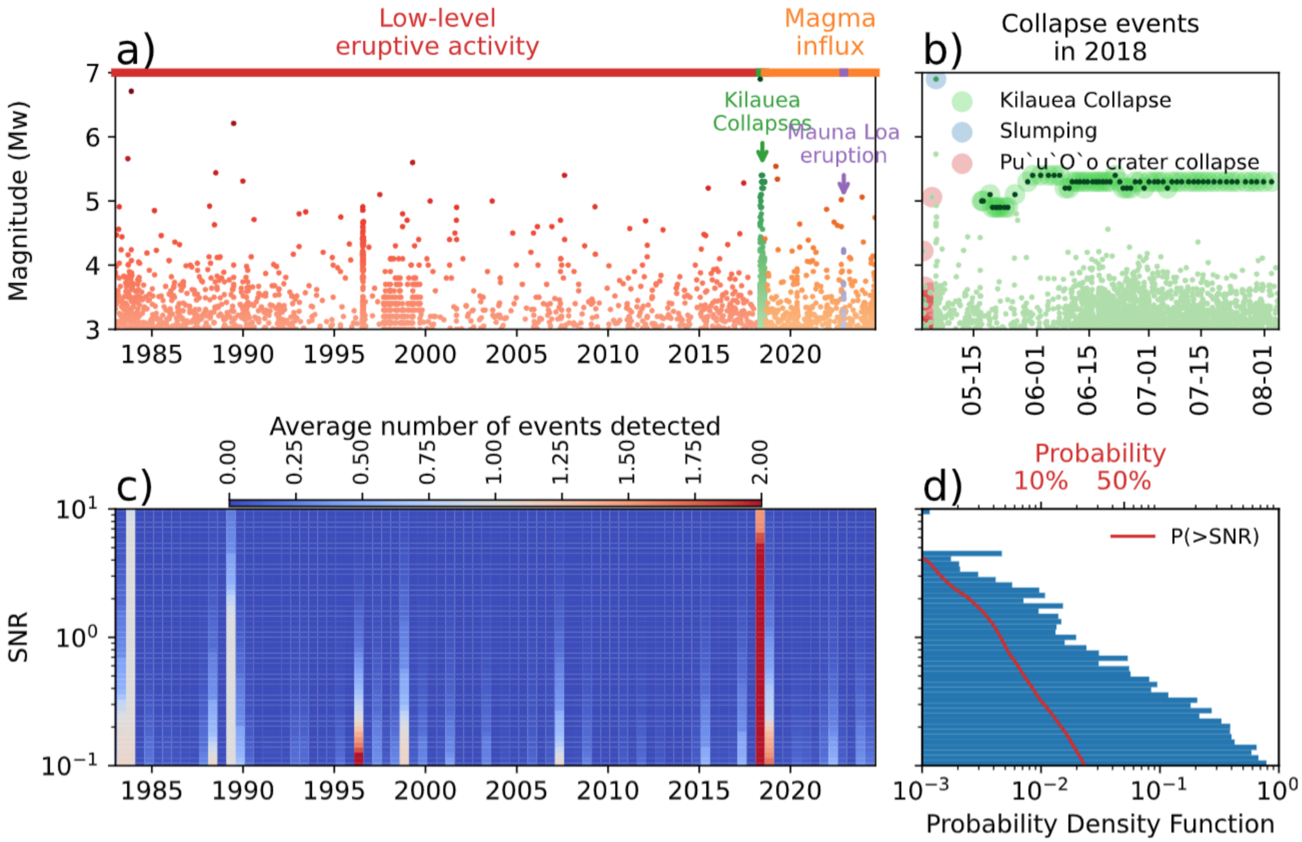
Construction of seismic velocity models



Simulated acoustic and airglow amplitudes



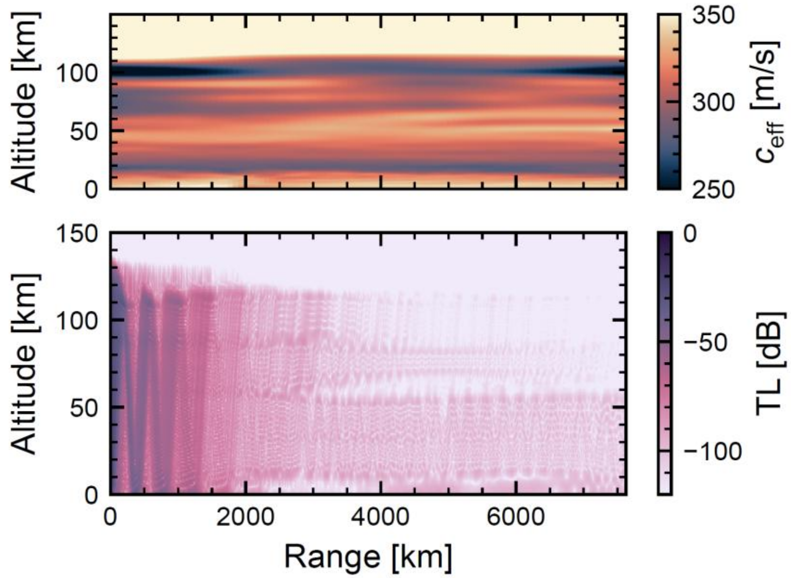
Detection of volcanic-induced seismic waves



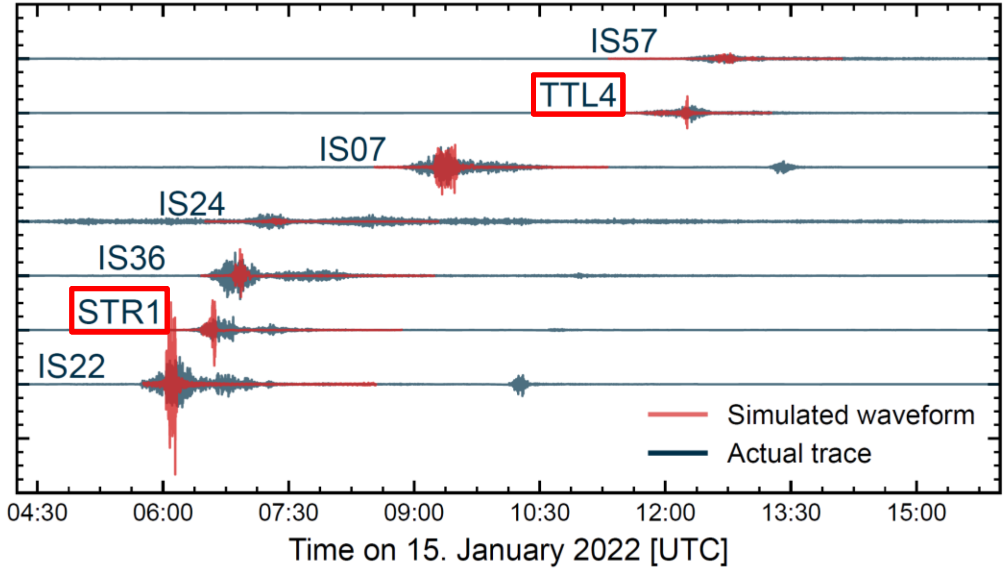
The Hunga Tonga Hunga Ha'Apai eruption (January 2022)

Master student project, Sophus Bredesen Gullbekk (sophusbg@uio.no)

We use a Parabolic Equation solver to determine the trajectory and attenuation of sound waves from HTHH towards balloons and ground infrasound stations (ncpaprop software).



Top: Model of the sound speed in the atmosphere between HTHH and the TTL4 balloon. Bottom: Transmission Loss (TL) calculated at f=0.1 Hz with range.



Comparison of simulated and recorded waveforms at different infrasound stations, scaled to the amplitude at IS07 station.

Volcano source model

Assuming that $\dot{m}$ follows a linear ramp from 0 to $\dot{m}_{\mathrm{max}}$, with a rise time τ_r (s) and a fall time τ_f (s), the mass m reads

$$m(\mathrm{M}_g) \quad = \quad \dot{m}_{\mathrm{max}}(\mathrm{M}_g)(T_{\mathrm{dur}} + \frac{1}{2}(\tau_r + \tau_f)), \tag{10}$$

Here we will assume for simplicity $\tau_r = \tau_f$. Assuming a monopole source, the pressure at a reference distance R (m) can be approximated as

$$\tilde{p}_R(\mathrm{M}_g, t) = \frac{1}{4\pi R}\frac{\partial}{\partial t}\dot{m}(\mathrm{M}_g, t), \tag{11}$$

Peak acoustic pressure $\tilde{p}_{R,\mathrm{peak}}$ (Pa) is therefore connected to the maximum of the derivative of the mass rate $\max_t \frac{\partial}{\partial t}\dot{m}(\mathrm{M}_g, t)$. In a narrow frequency band around a frequency f, we can write $\tilde{p}_{R,\mathrm{peak}}(\mathrm{M}_g, f) \approx \mathcal{F}\left\{\frac{\partial}{\partial t}\dot{m}\right\}(\mathrm{M}_g, f)$, where $\mathcal{F}$ is the Fourier transform. We then approximate $\mathcal{F}\left\{\frac{\partial}{\partial t}\dot{m}\right\}$ with its upper envelope such that (App. A)

$$\mathcal{F}\left\{\frac{\partial}{\partial t}\dot{m}\right\}(\mathrm{M}_g, f) \approx \dot{m}_{\mathrm{max}}(\mathrm{M}_g)\left[\frac{2}{\sqrt{1+\pi f \tau_r}}\right]. \tag{12}$$

Volcano source model

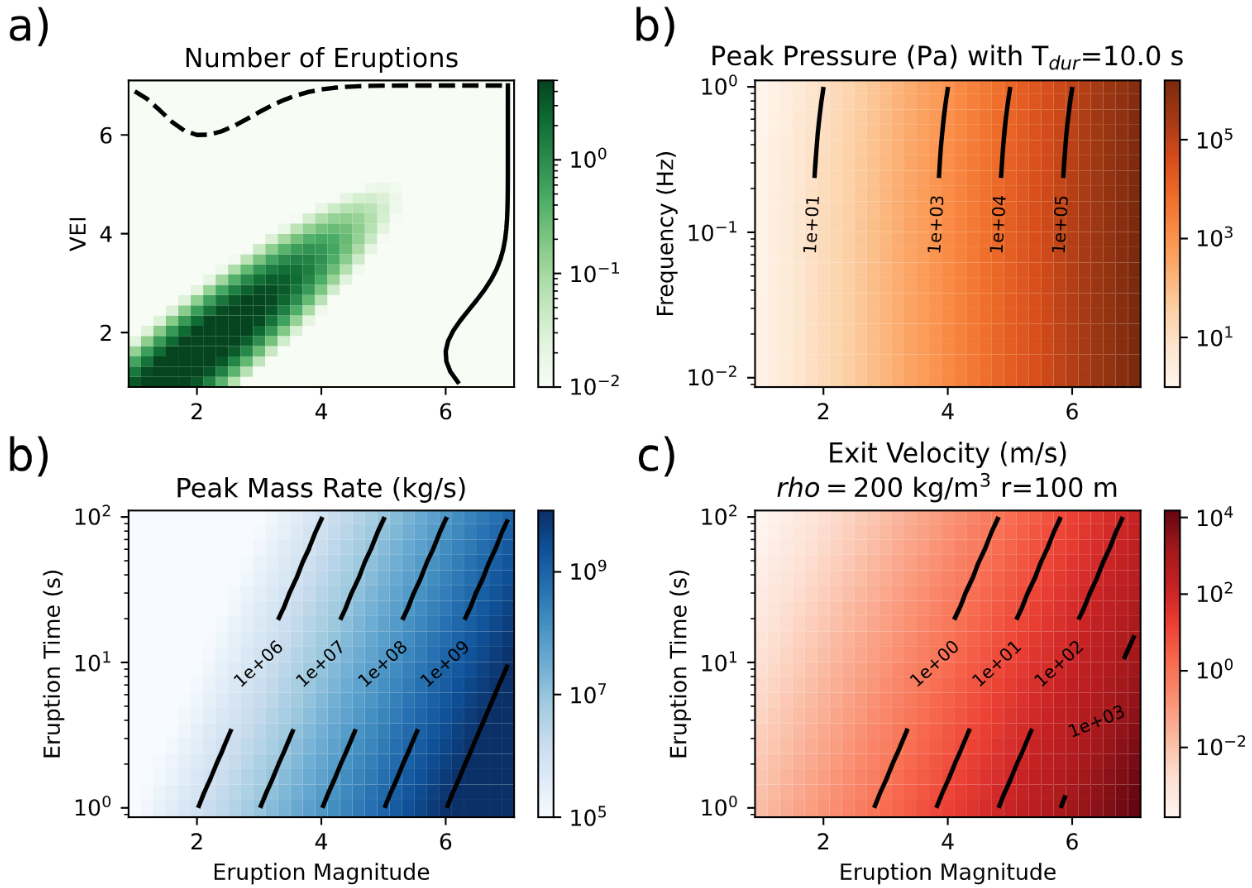
Then we can relate the peak pressure to the eruption magnitude such that

$$\begin{aligned}
\tilde{p}_{R,\mathrm{peak}}(\mathrm{M}_g, f) &\approx \frac{1}{4\pi R}\mathcal{F}\left\{\frac{\partial}{\partial t}\dot{m}\right\}(\mathrm{M}_g, f) && (13)\\
&\approx \frac{\dot{m}_{\max}(\mathrm{M}_g)}{4\pi R}\left[\frac{2}{\sqrt{1+\pi f \tau_r}}\right], \\
&= \frac{1}{4\pi R}\frac{m(\mathrm{M}_g)}{T_{\mathrm{dur}}+\tau_r}\left[\frac{2}{\sqrt{1+\pi f \tau_r}}\right], \\
&= \frac{1}{4\pi R}\frac{10^{\mathrm{M}_g+4}}{T_{\mathrm{dur}}+\tau_r}\left[\frac{2}{\sqrt{1+\pi f \tau_r}}\right]. && (14)
\end{aligned}$$

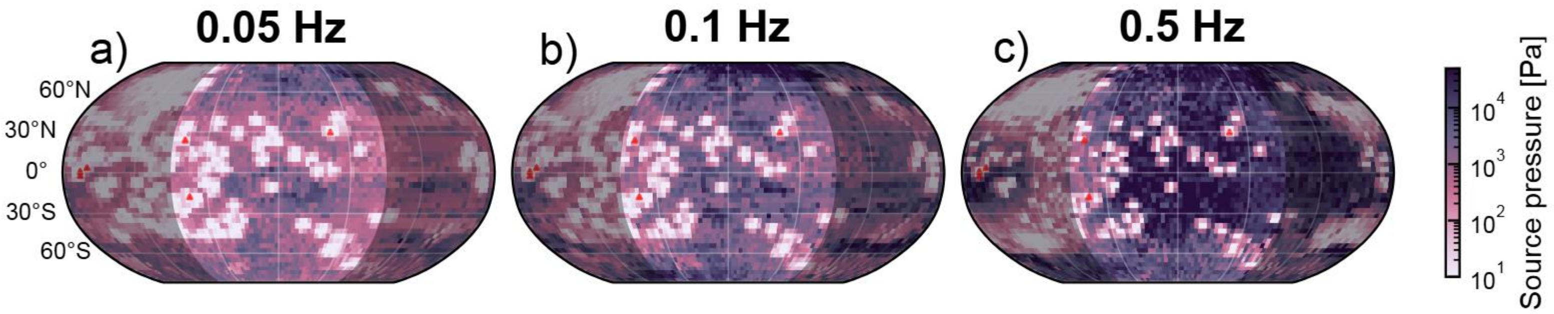
Then the VEI-derived peak pressure $p_{R,\mathrm{peak}}(\mathrm{VEI}, f)$ can be expressed in terms of magnitude-derived peak pressure $\tilde{p}_{R,\mathrm{peak}}(M_g, f)$ as

$$p_{R,\mathrm{peak}}(\mathrm{VEI}, f) = \int_{\mathrm{M}_g=1}^{7} \mathbb{P}(M_g|\mathrm{VEI})\tilde{p}_{R,\mathrm{peak}}(M_g, f)\,d\mathrm{M}_g. \quad (15)$$

Volcano source model

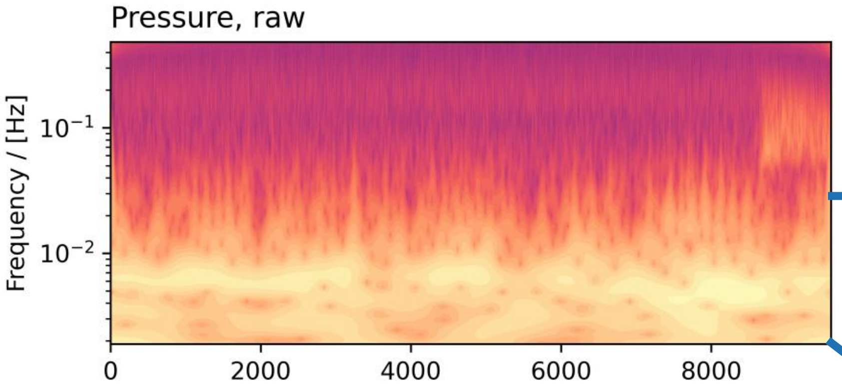


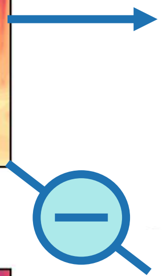
Infrasound propagation and volcano detectability on Venus

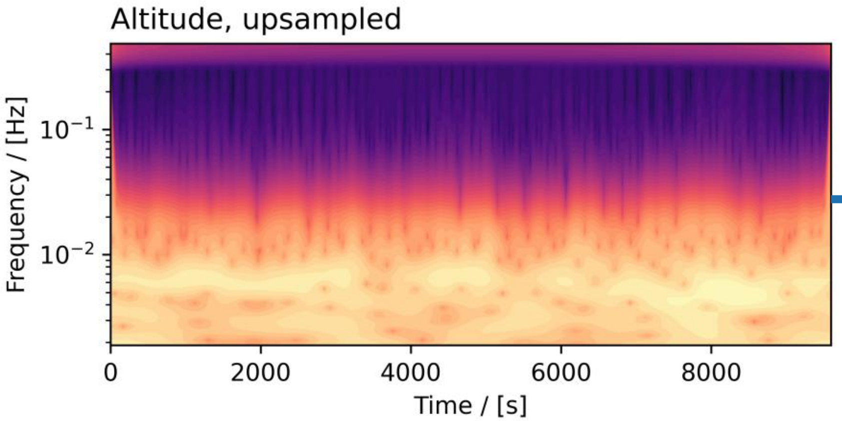


Improving the SNR at low frequency

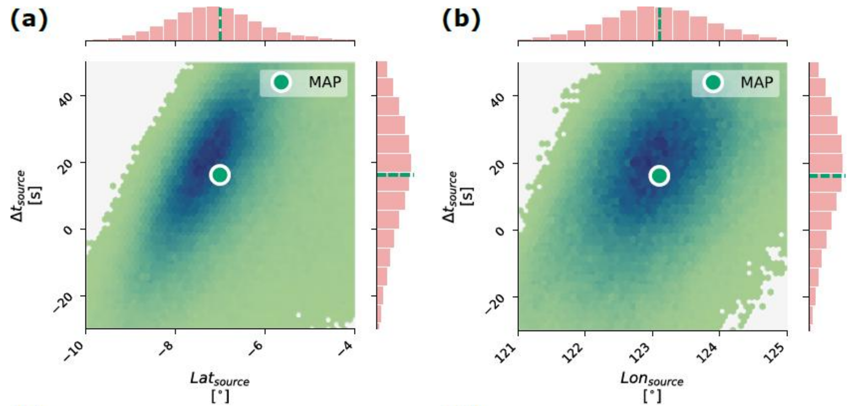
There is an exponential relation between pressure and altitude: use the low frequency GPS data to correct the pressure recordings (adapted from Podglajen, A. et al. (2022). *GRL* **49**. [10.1029/2022GL100833](https://doi.org/10.1029/2022GL100833))



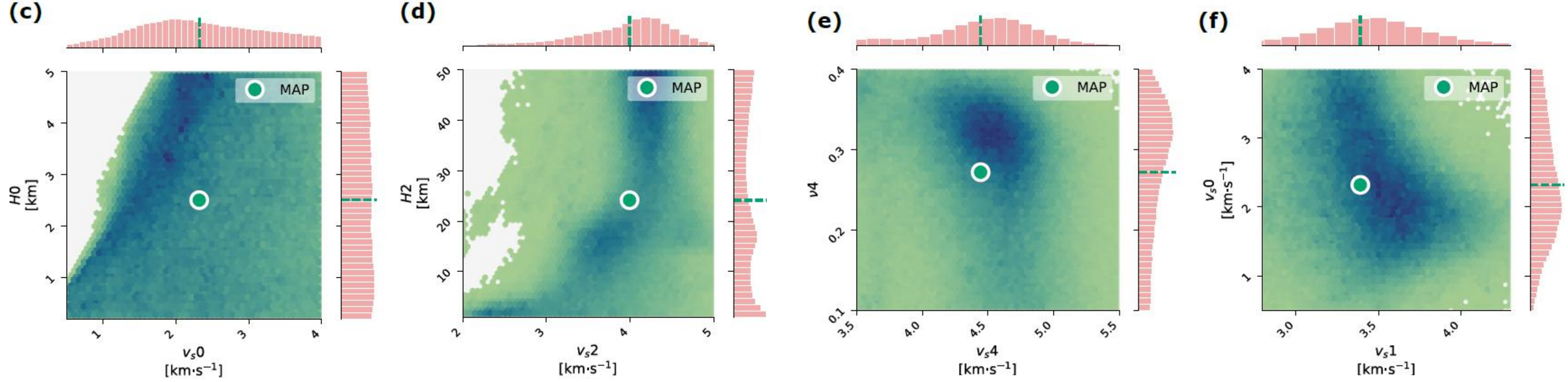




Trade-offs in the inversion

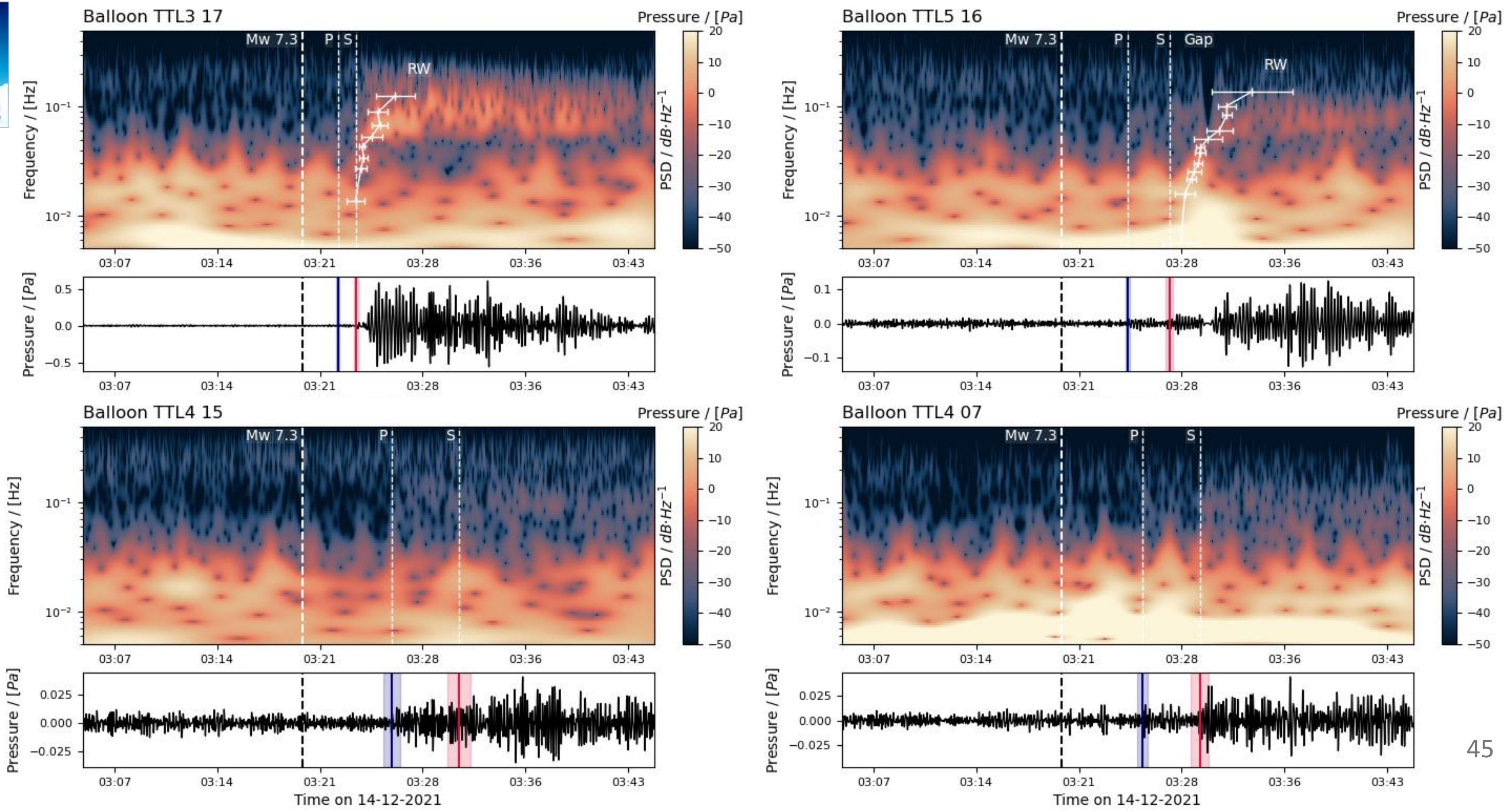


There exist trade-offs between source location and origin time, and seismic velocities.

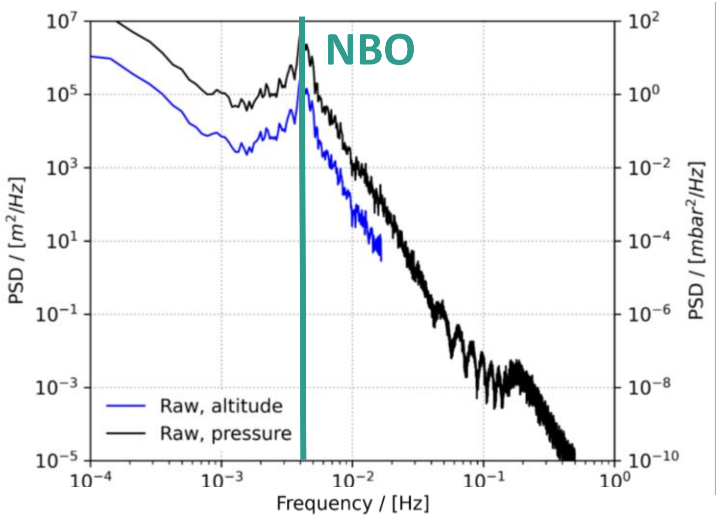


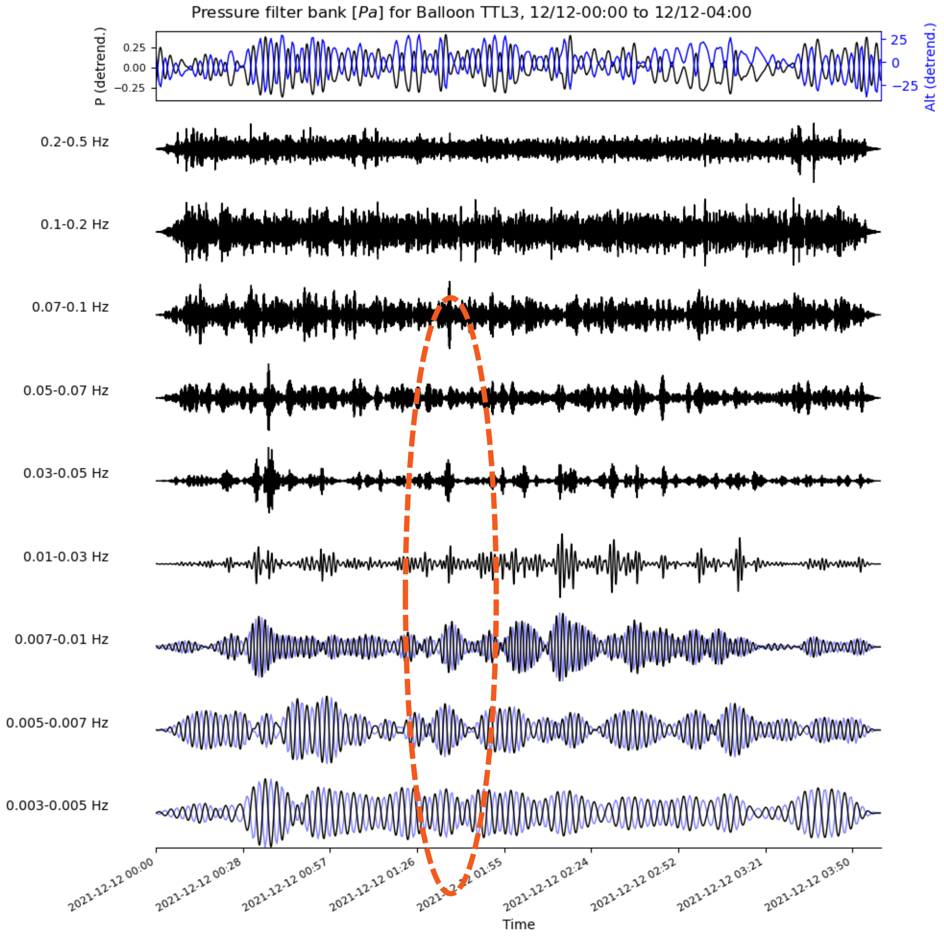
NORSAR

Strateole2 observations of the Flores earthquake



Balloon oscillation and noise



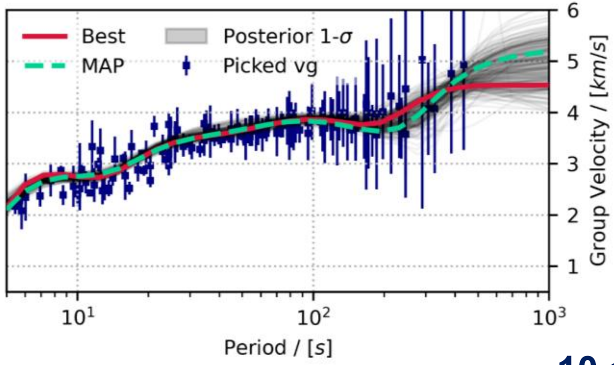


Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

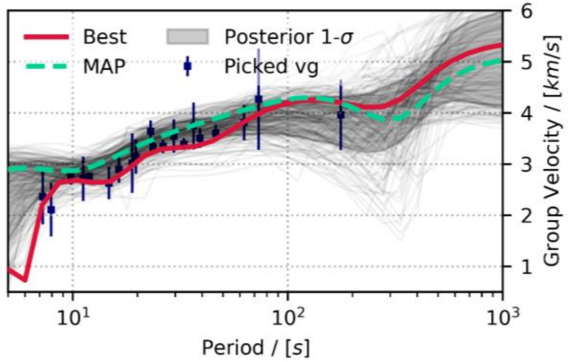
Good coherence up to GPS Nyquist frequency, perhaps even higher: **broadband energy bursts** follow altitude changes.

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

Quality of fit to the data

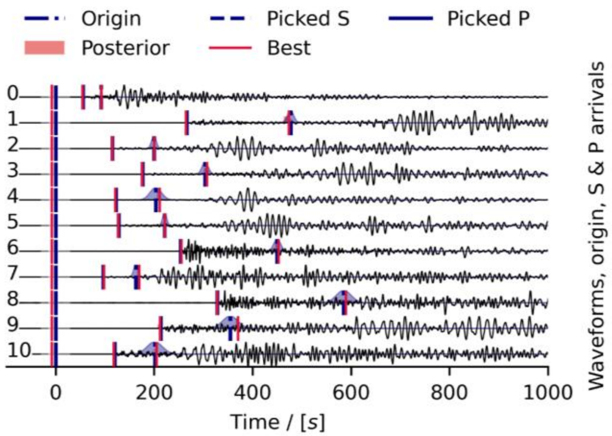


Group velocity curves from measured arrival times (blue) compared to the group velocity curves of the posterior distribution.

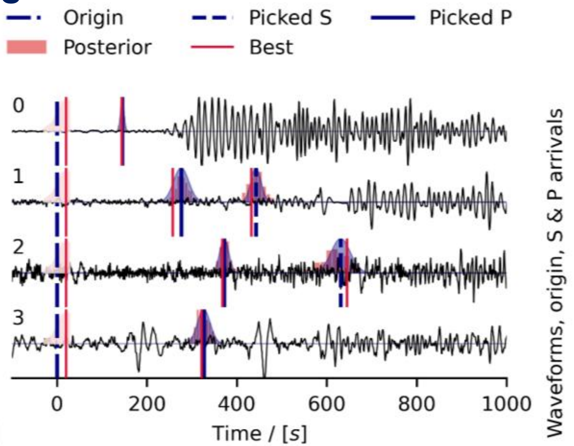


10 stations

4 balloons

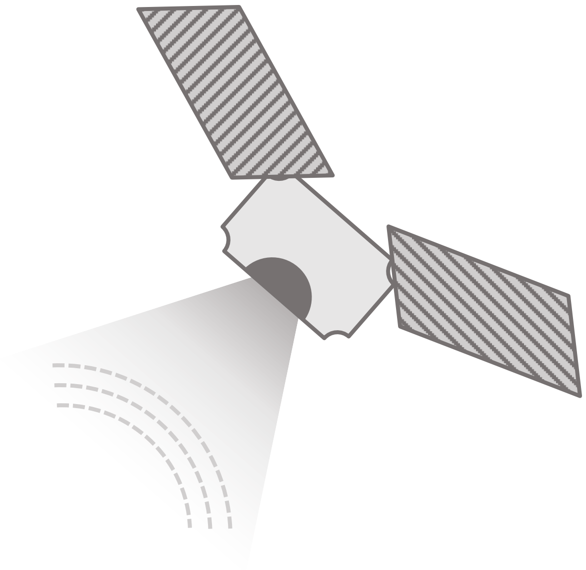


True origin time and picked S and P times, compared to the arrival time calculated from the posterior models.

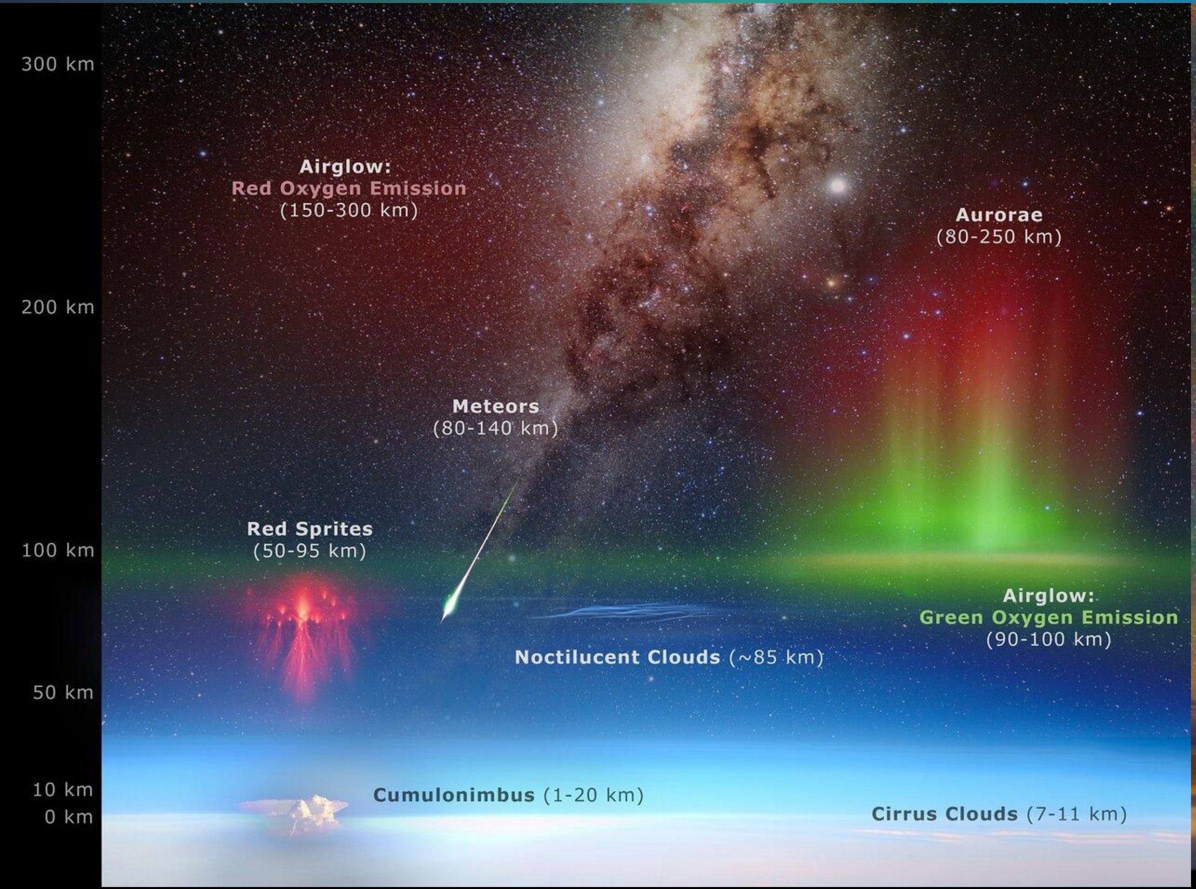


Airglow seismology

- Earthquake-generated infrasound travels to the edge of space.
- As the density of the atmosphere decreases, the wave motion is significantly amplified.
- Could we detect this perturbation in the top layers of the atmosphere?



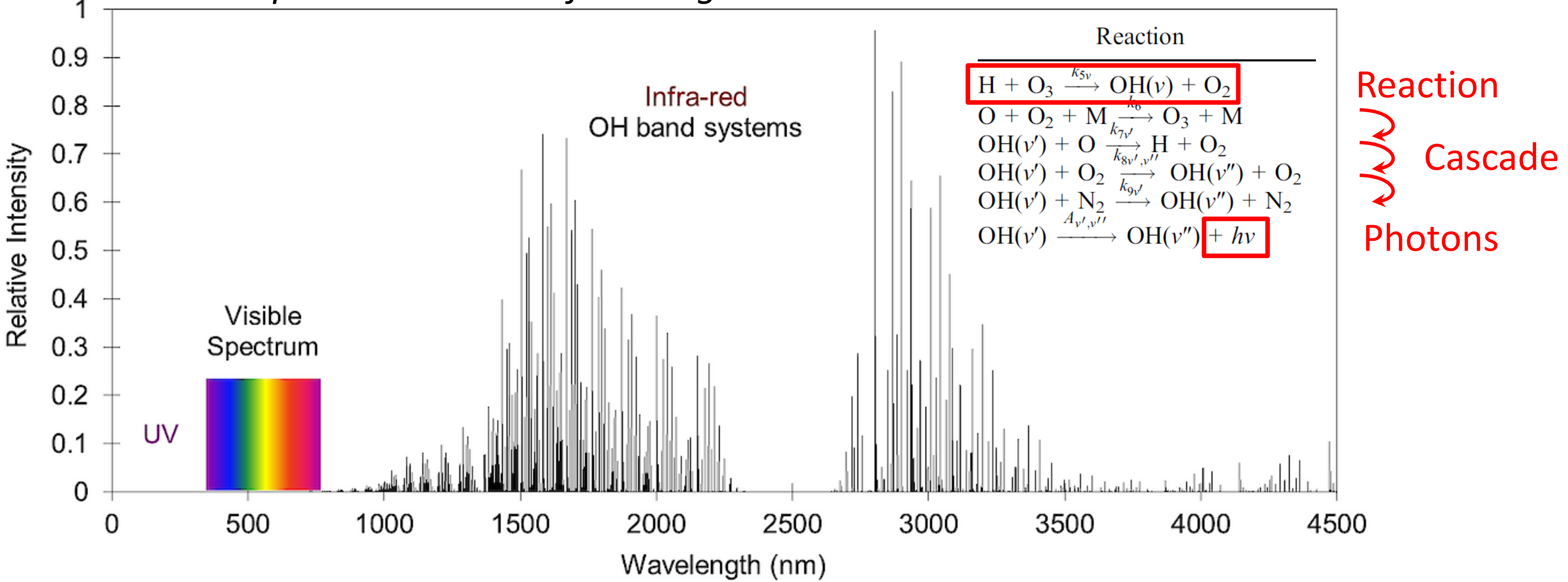
What is airglow?



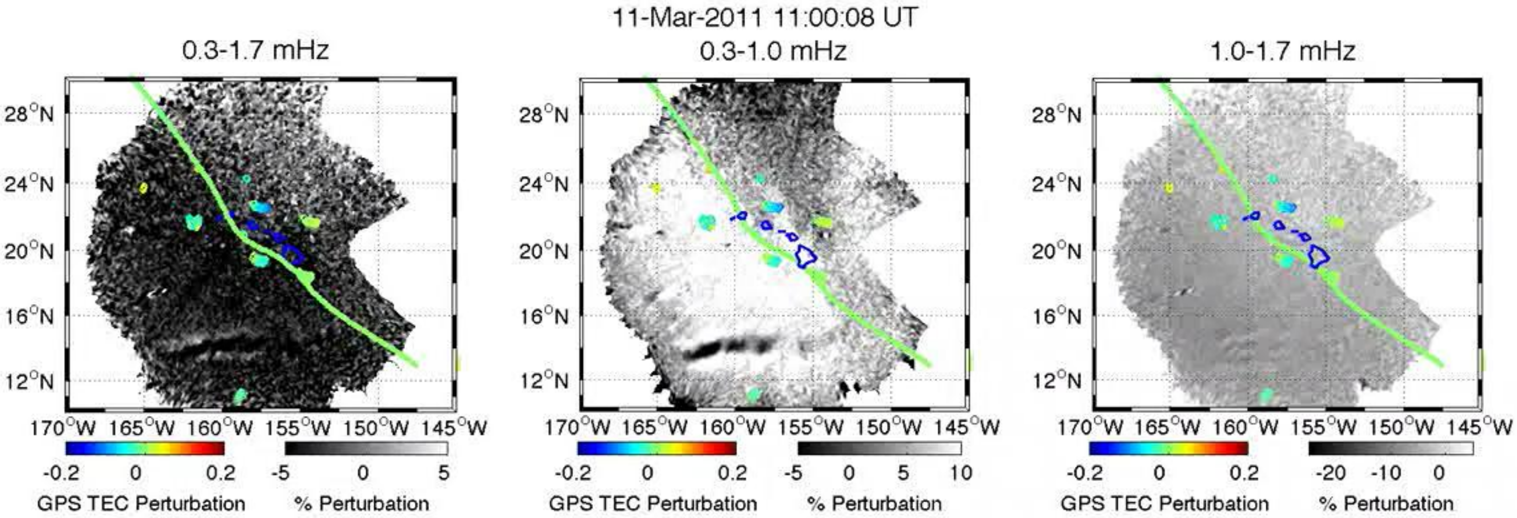
Picture: Miguel Claro, Portugal

What is airglow?

The complex mechanism of OH airglow



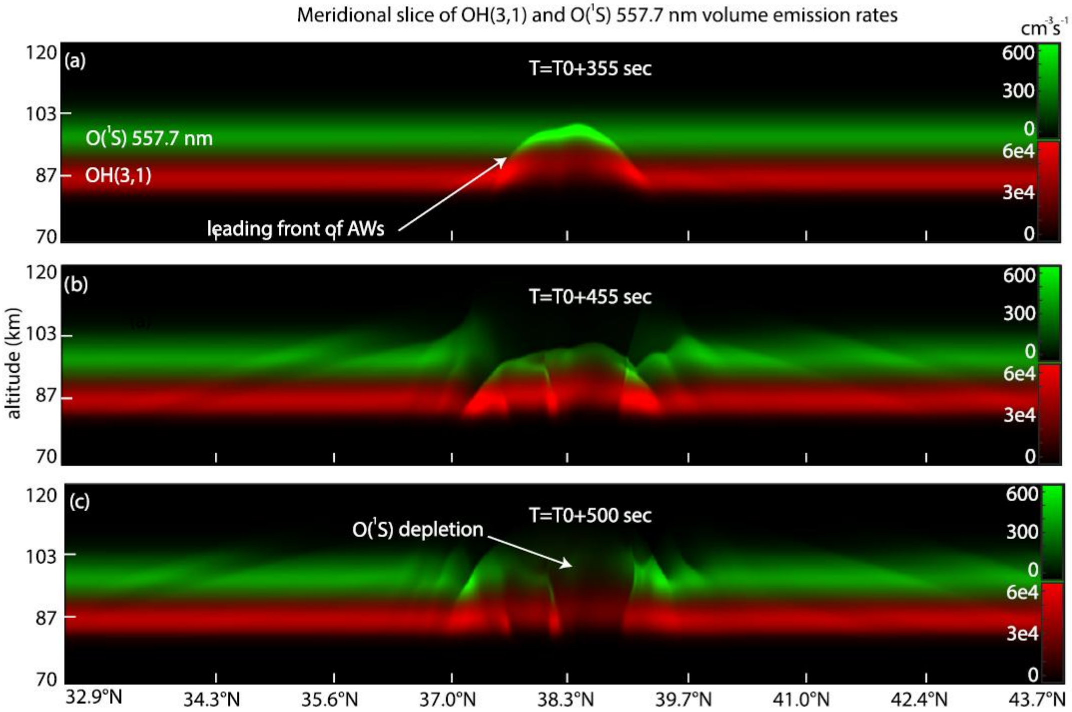
Observation: perturbation of airglow by tsunami



Perturbation of O_2^+ airglow at 250 km altitude observed following the 2011 Tohoku-Oki tsunami, filtered in different frequency bands.

Makela, J.J., et al. (2011). Imaging and modeling the ionospheric airglow response over Hawaii to the tsunami generated by the Tohoku earthquake of 11 March 2011. *GRL* **38**. 10.1029/2011GL047860

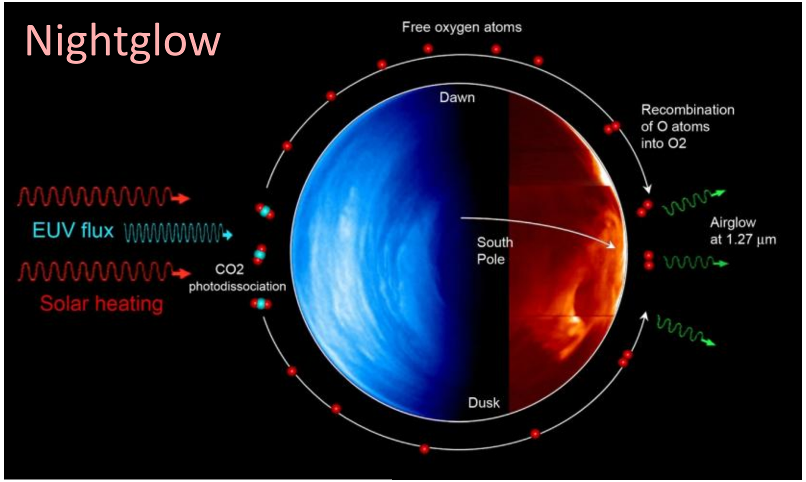
Modeling: perturbation of airglow by earthquake



Modelled perturbations of OH(3,1) -1.5 µm - and O(^{1}S) – 558 nm - volume emission rates, caused by the coupled infrasound wave of the 2011 Mw 9.1 Tohoku-Oki earthquake

Inchin, P.A., et al. (2020). Mesopause Airglow Disturbances Driven by Nonlinear Infrasonic Acoustic Waves Generated by Large Earthquakes. *JGR: Space Physics* **125**, 10.1029/2019JA027628

Venus’ infrared airglow



$$O + O + M \rightarrow O_2^* + M;\ \alpha k$$

$$O_2^* + M_i \rightarrow O_2 + M_i;\ k_i$$

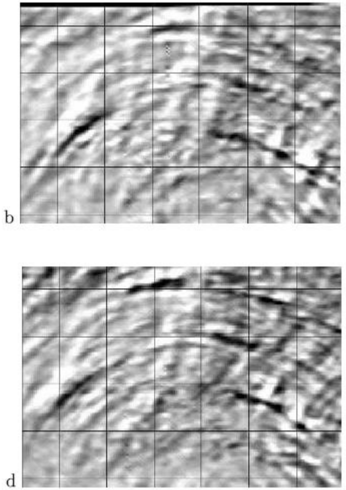
$$O_2^* \rightarrow O_2 + h\nu;\ \tau$$

Mechanism of production of infrared light at 1.27 µm by the recombination of O into O_2.

Atmospheric perturbation → Local variation of **airglow molecules concentration** → **Modulation in light intensity**

Simplification: $\Delta VER = F(\vec{v})$

ESA/VIRTIS-VenusX/IASF-INAF, Observatoire de Paris (R.Hueso, Univ. Bilbao)
Lognonné, P. et al. (2016). *JASA* **140.** 10.1121/1.4960788

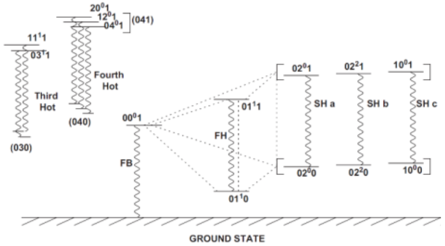


Gravity waves around the south polar vortex of Venus visible in the dayglow at 4.3 µm.

Dayglow

CO_2 molecules are excited by solar radiation. They are in non-local thermal Equilibrium (nLTE): radiative transitions (emission or absorption of photons) dominate over collisional interactions.

Very complex process leading to different light emission.

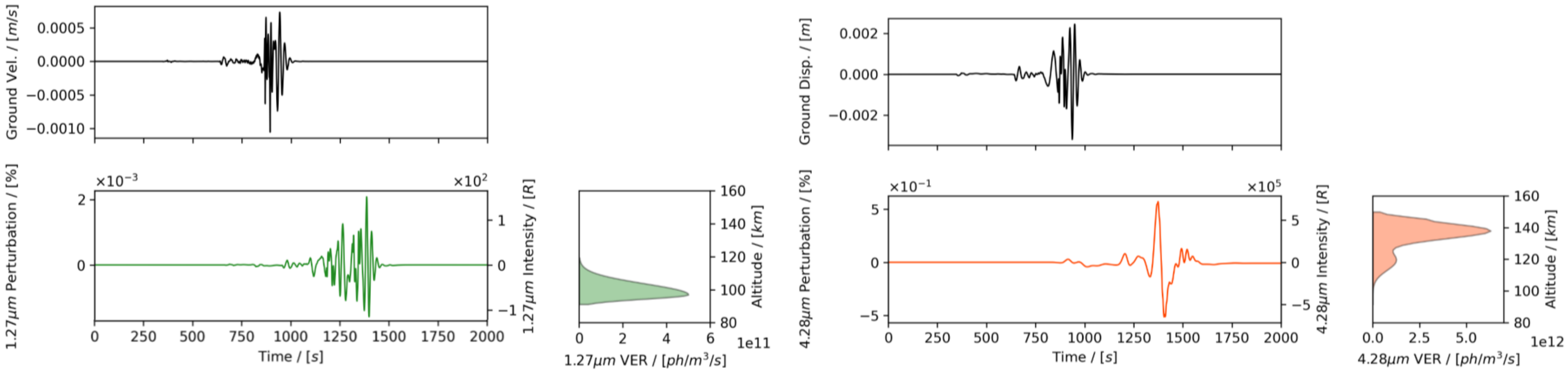


Atmospheric perturbation → Local variation in **temperature and concentration** → **Modulation in light intensity**

Simplification: $\Delta VER \propto \Delta T$

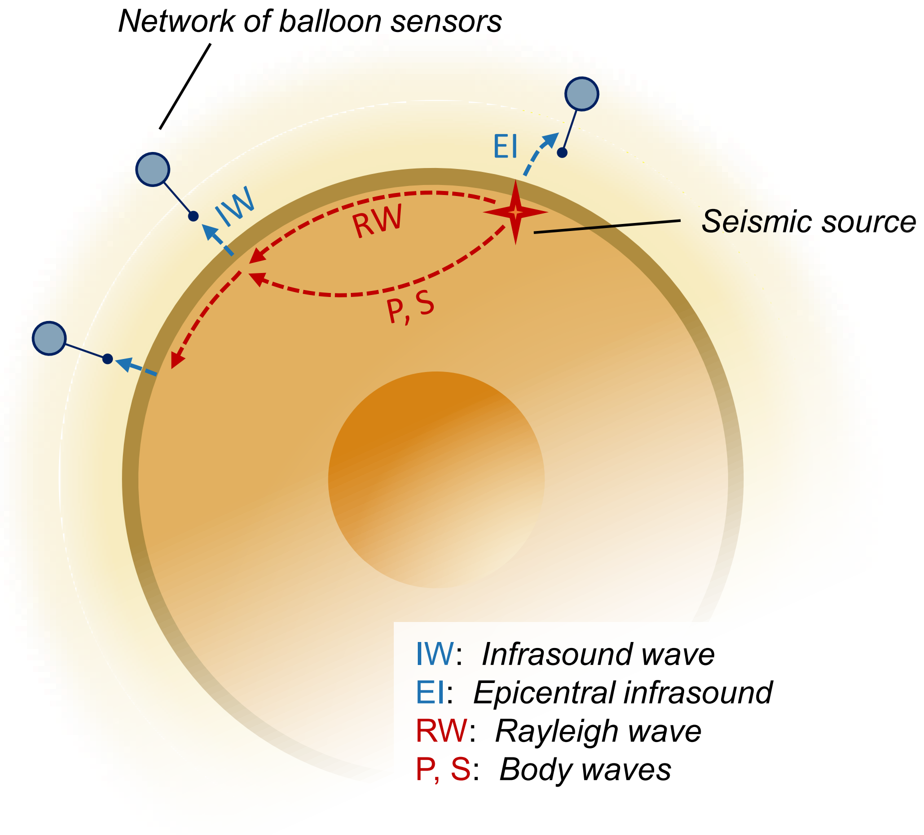
Garcia, R.F., et al. (2009). *JGR: Planets* **114**. 10.1029/2008JE003073
López-Valverde, M.A., et al. (2011). *PSS*, **59.** 10.1016/j.pss.2010.02.001

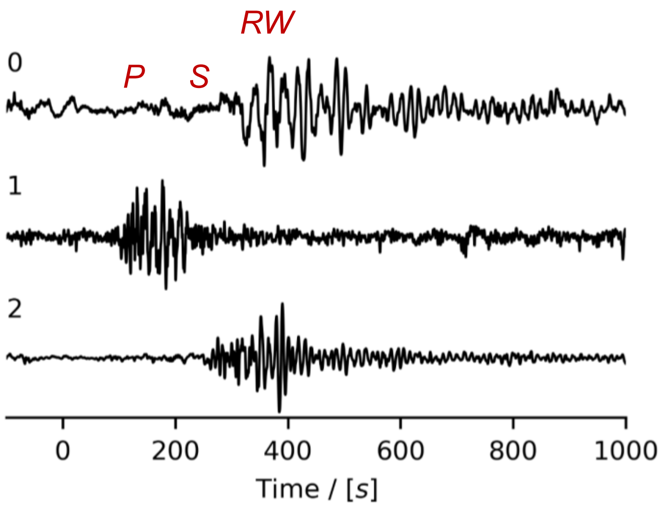
Venus' infrared airglow – modeling



Example of Nightglow (green) and Dayglow (orange) perturbations expected at 3000 km distance after a Mw 7.5 venusquake.

Balloon seismology for planetary exploration



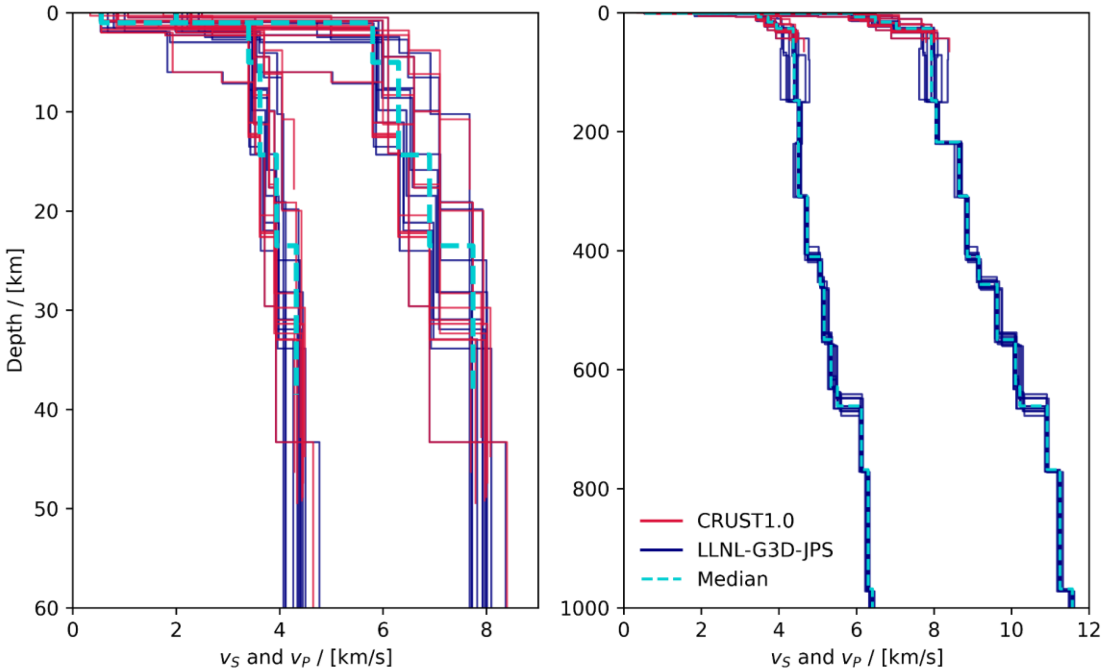


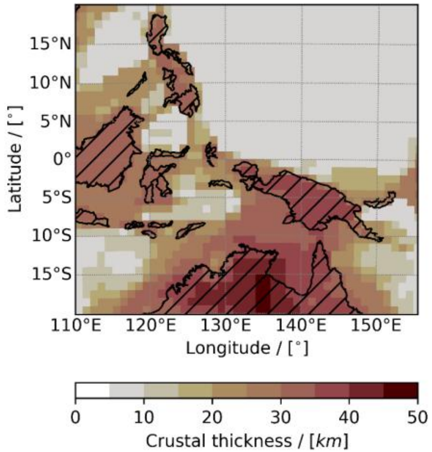
*Hypothetical venusquake pressure signals recorded by three balloons, with **unknown source origin time & distance**, but clear Rayleigh and body wave arrivals.*

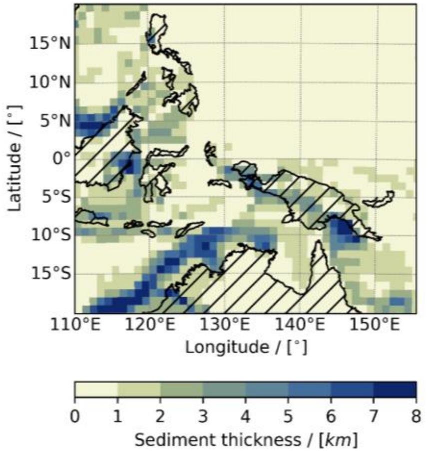
Source origin? Subsurface velocities?

Seismic inversion in the Flores region

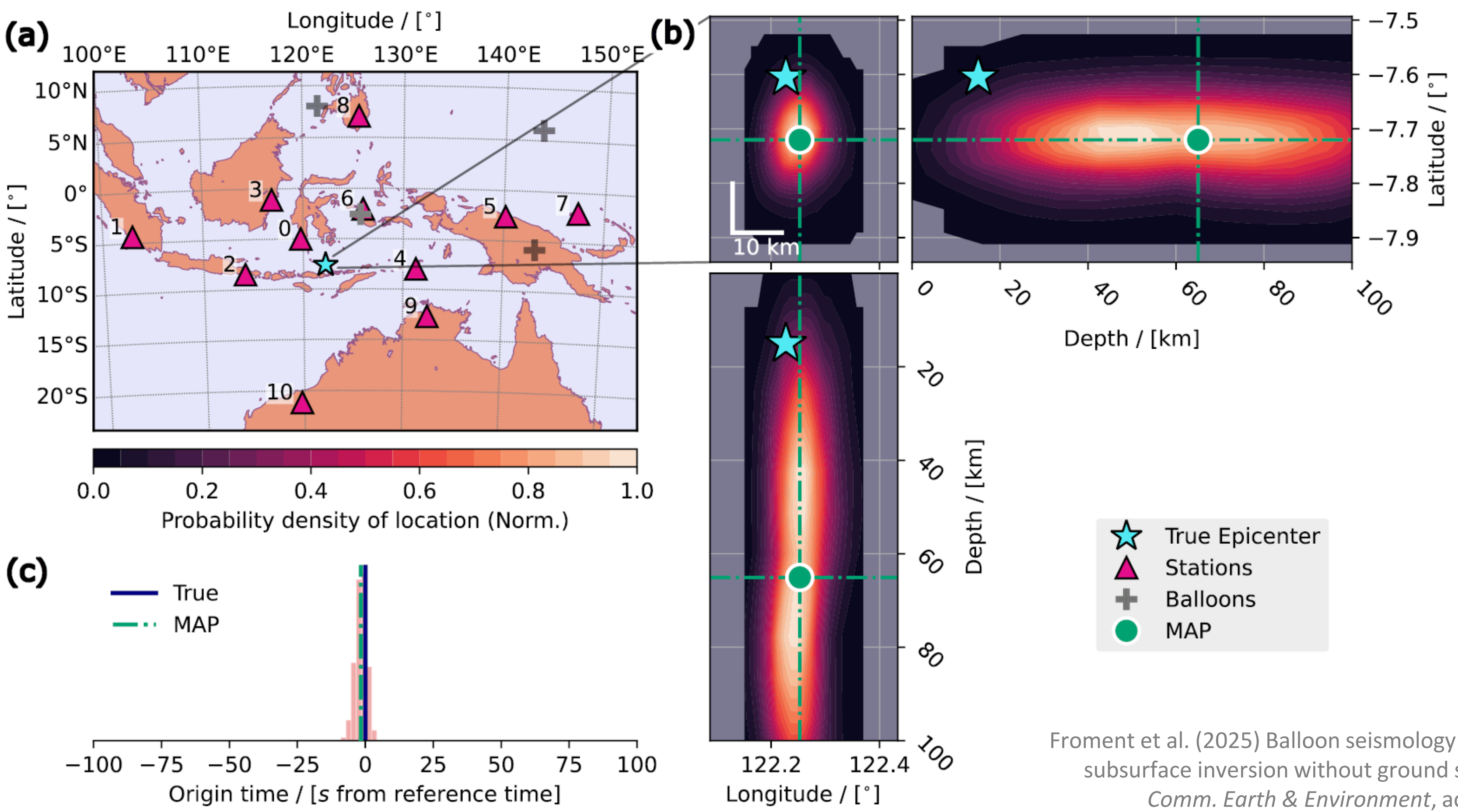
A lot of variety in crustal thickness and sediment deposits around the event.
We construct a “Median model” as our baseline for assessing our inversion results.







Flores, pure seismic inversion with 11 stations



Froment et al. (2025) Balloon seismology enables subsurface inversion without ground stations. *Comm. Earth & Environment*, accepted.

Flores, pure seismic inversion with 11 stations