Investigating the subsurface using earthquake-generated infrasound

Infrasound Technology Workshop
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CTBTO
PREPARATORY COMMISSION

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Listening to the Earth

Shameless promotion: New paper out yesterday

Given what we can assume about Venus' properties and seismicity scenarios:

What is the chance that a Venus balloon will detect a seismo-acoustically coupled quake in infrasound recordings?

(or airglow / DAS / seismometer)

Raphael F. Garcia, Iris van Zelst, Taichi Kawamura, Sven Peter Näsholm, Anna Horleston, Sara Klaasen, Maxence Lefèvre, Celine Marie Solberg, Krystyna T. Smolinski, Ana-Catalina Plesa, Quentin Brissaud, Julia S. Maia, Simon C. Stähler, Philippe Lognonné, Mark P. Panning, Anna Gülcher, Richard Ghail, Barbara De Toffoli

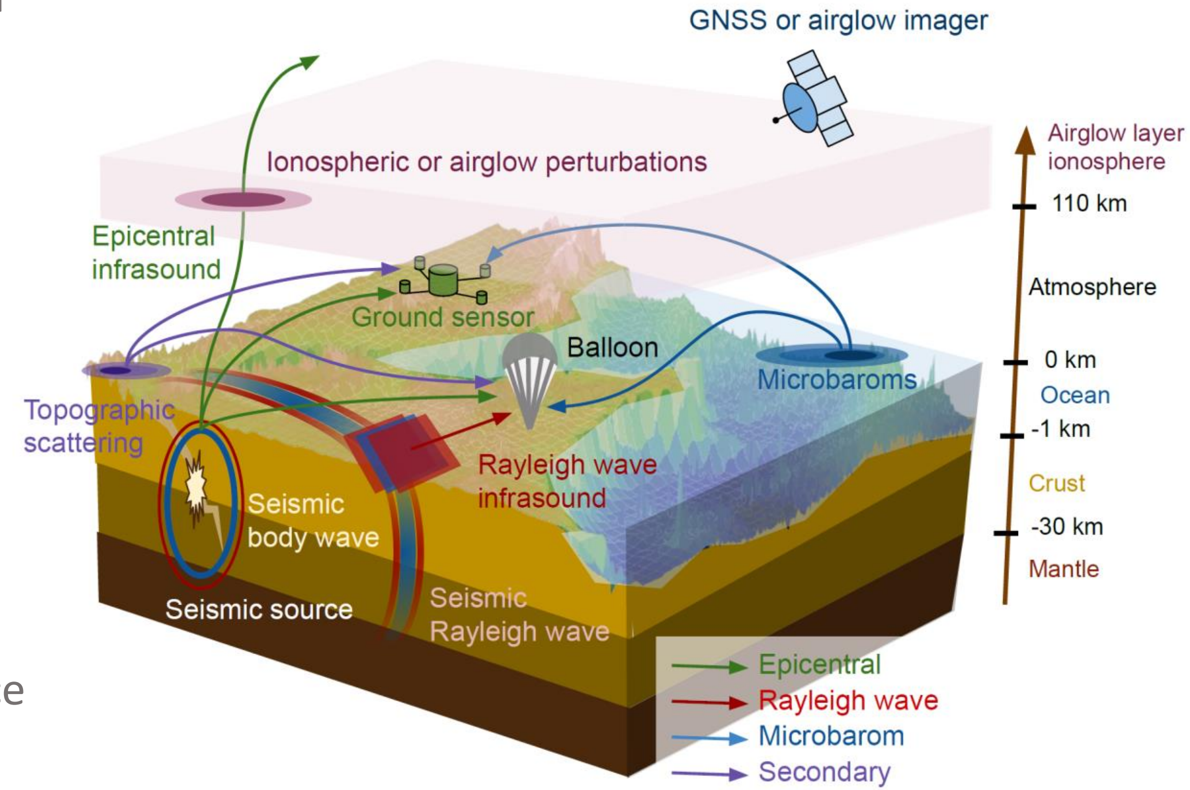
Seismic wave detectability on Venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers. *Earth and Space Science*, 11, e2024EA003670. https://doi.org/10.1029/2024EA003670

Seismo-acoustics: linking subsurface and atmosphere

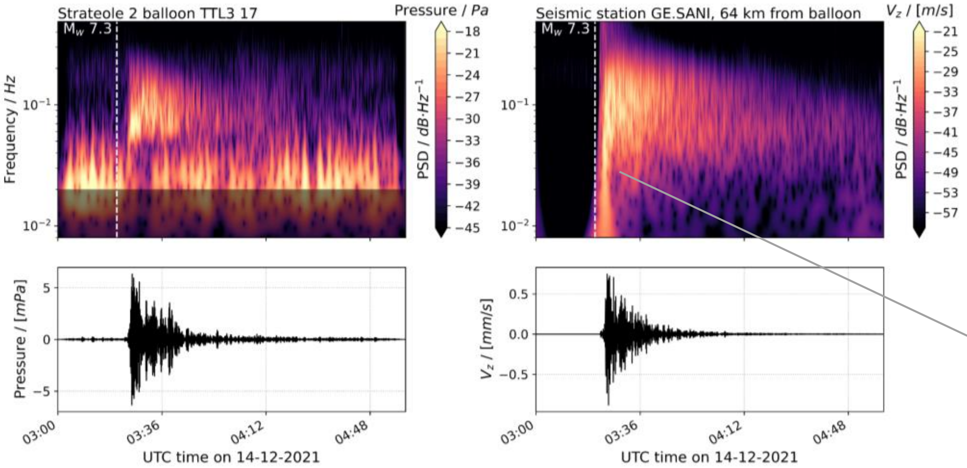
- Earthquake epicentral motion and seismic waves couple to the atmosphere

- Recording is possible through infrasound sensors on the ground, balloons, or remote sensing (GNSS, Airglow imagers)

- Can develop inversion frameworks, using balloon infrasound to study subsurface processes ?



Possible application: Balloon seismology on Earth?



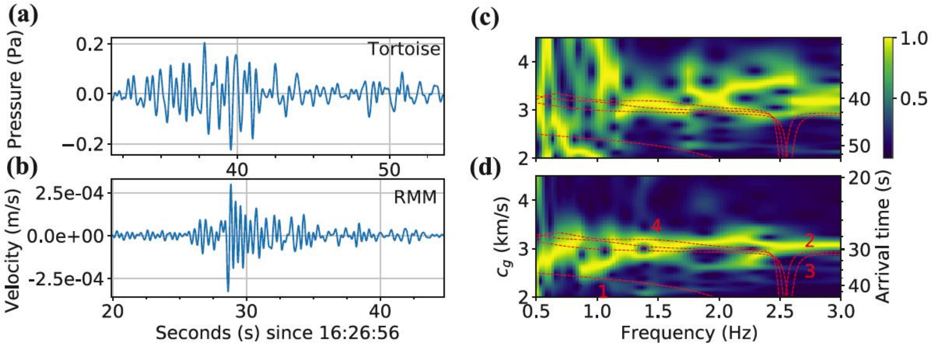
Dispersed Rayleigh Wave arrival

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

Good agreement between seismic ground-sensor and airborne infrasound recordings

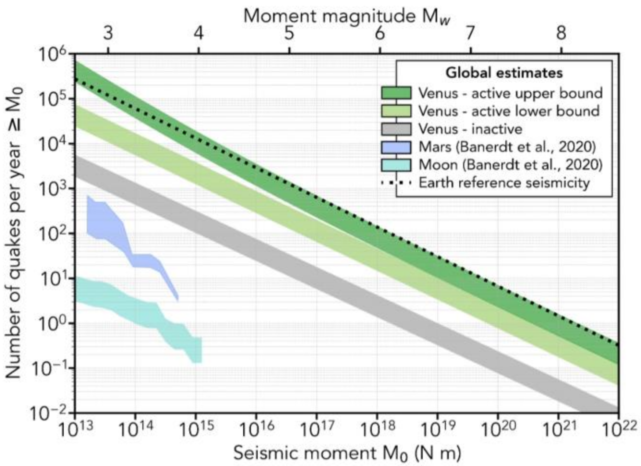
Garcia, R. F. et al. *Geophysical Research Letters* **49** (2022), 10.1029/2022GL098844

Brissaud, Q. *et al. Geophysical Research Letters* **48**, (2021), 10.1029/2021GL093013



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

Possible application: seismoacoustics on Venus?

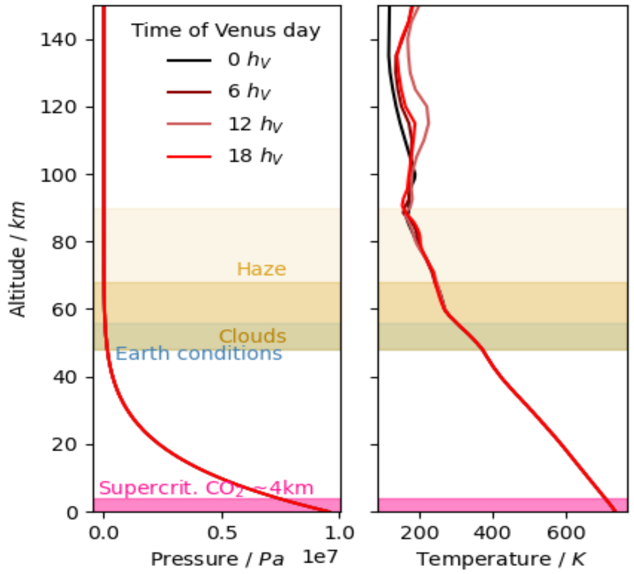


Venus does **not** have plate tectonics

But several other possible activities:
Rifts, Coronae, Volcanoes

van Zelst, I., Maia, J. S., Plesa, A.-C., Ghail, R. & Spühler, M. Estimates on the Possible Annual Seismicity of Venus. *Journal of Geophysical Research: Planets* **129**, e2023JE008048 (2024)

Garcia, R. F. *et al.* Seismic wave detectability on Venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers, *ESS*, 2024.



Venus Climate Database
Pressure & temperature near the equator

Venus is a pressure cooker under a lid of clouds, very stable over a day

Challenge for ground-based seismology, but **advantage for infrasound!**

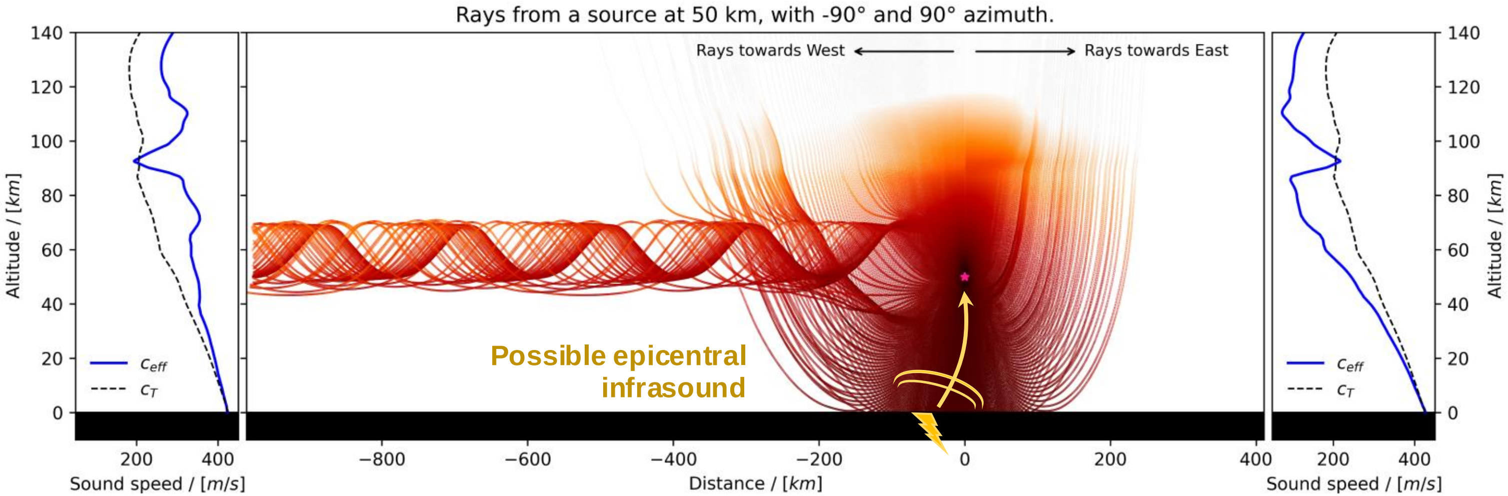
Exploring Venus interiors using balloons

Rays coupled to the atmosphere (Epicentral infrasound & coupled Rayleigh waves):

Simple propagation paths in atmosphere

Waveguides may exist at higher altitude due to the strong E → W 100 m/s winds ("*superrotation*").

Soviet missions have sent balloons to Venus Vega 1 & 2, 1985



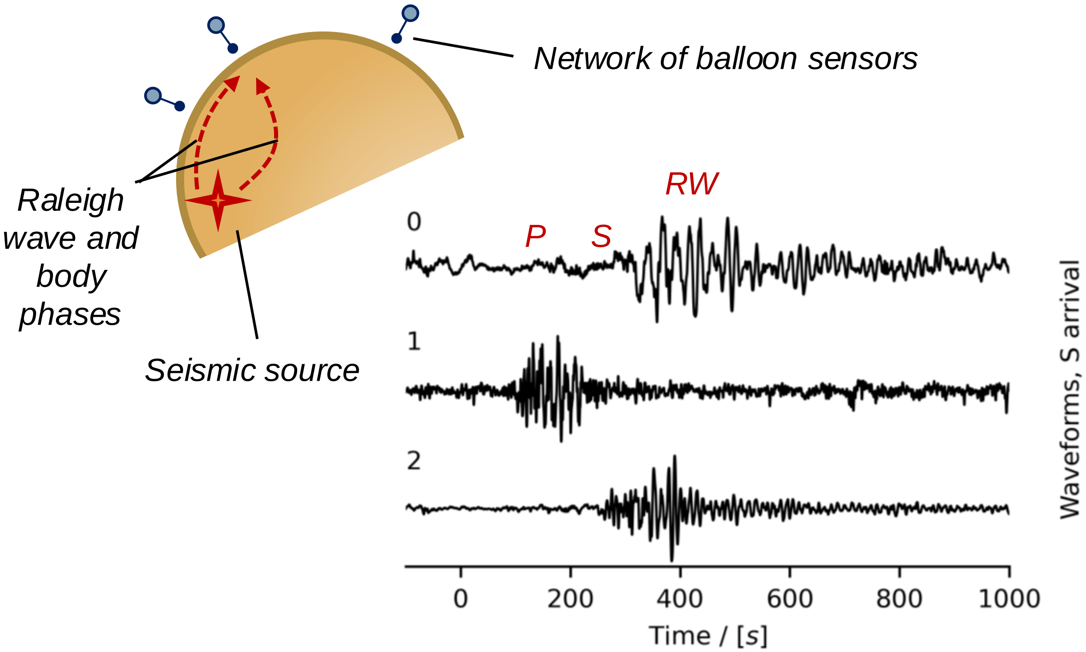
Hypothesis: Earthquake infrasound suffer little from propagating vertically

→ What information can be inferred about source & subsurface ?

Goals of the AIR project: Inversion of the subsurface

Inversion challenges

- How to process seismic data of unknown origin to **simultaneously invert source & subsurface?**
- Can the inversion method be validated with real data?
- How sensitive is the inversion to number of balloons & detected phase types?
- What is the uncertainty of inverted source & subsurface parameters?



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

Inverting the subsurface from coupled earthquake signals

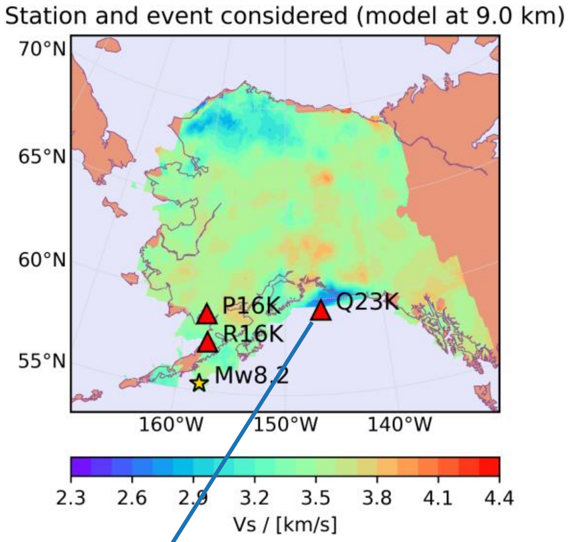
Hypotheses:

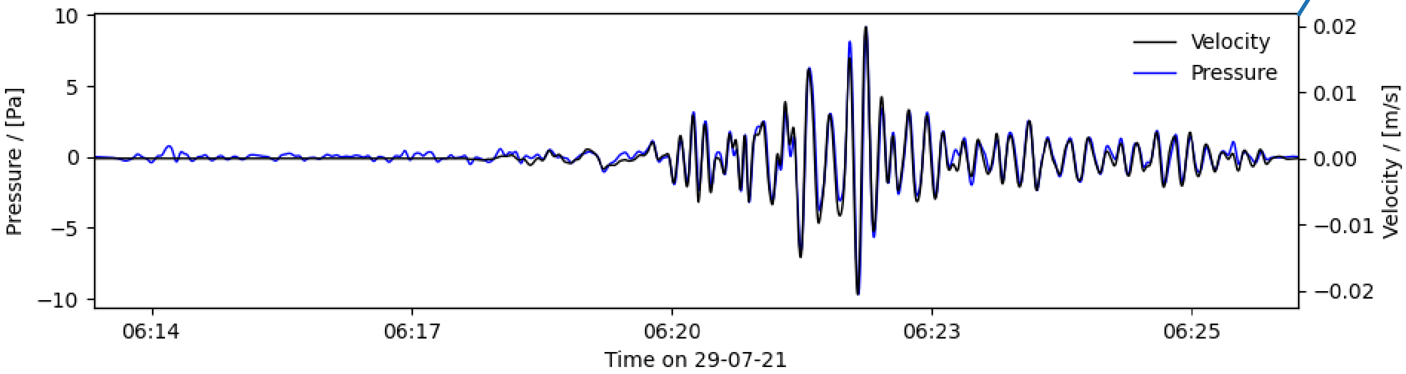
- Propagation of RW ground-to-balloon has **insignificant effect**
- Higher SNR on Venus than on Earth

Alaska infrasound recordings of earthquakes:
Good proxy to assess an inversion framework!

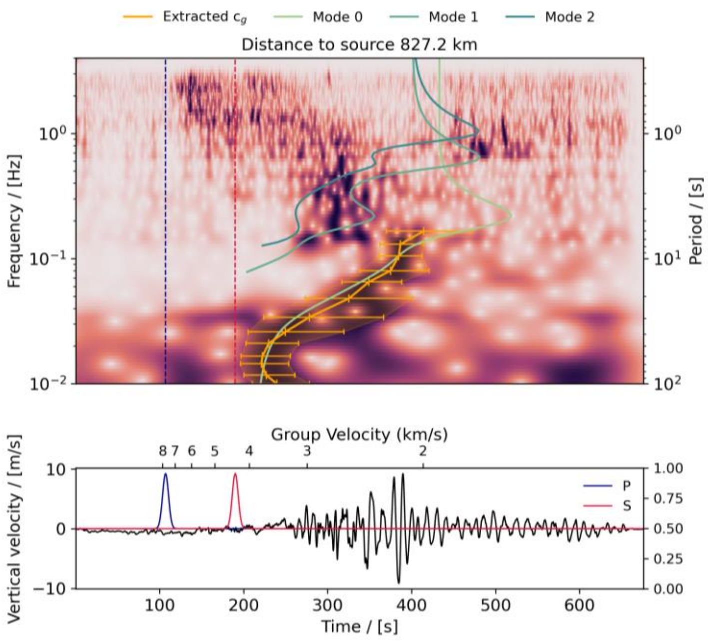
Quake: Mw 8.2, 29 July 2021
Assumed "true" model: 4-layer simplification of Berg et al. (2019) at different stations

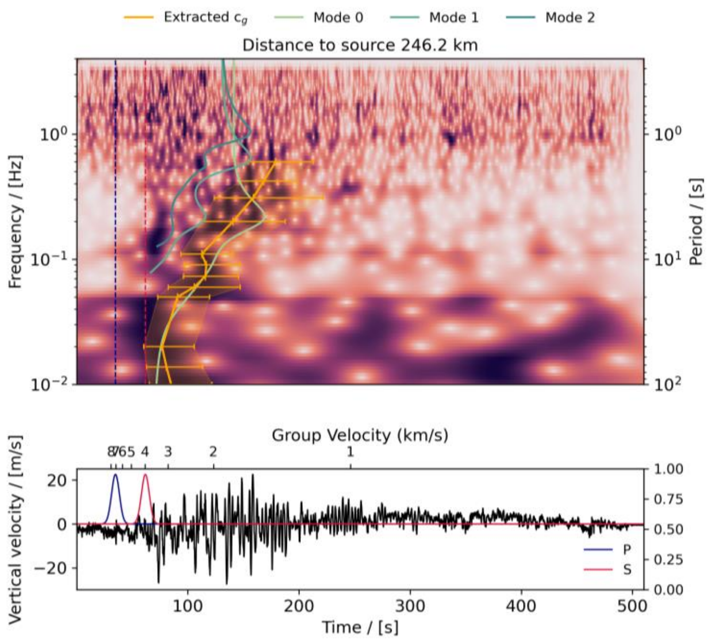
Berg, E. M. et al (2020) *JGR: Solid Earth* **125**, 10.1029/2019JB018582
Macpherson et al. 2023 (2023) *BSSA*, **113**, 10.1785/0120220237





Picking the Rayleigh and S waves

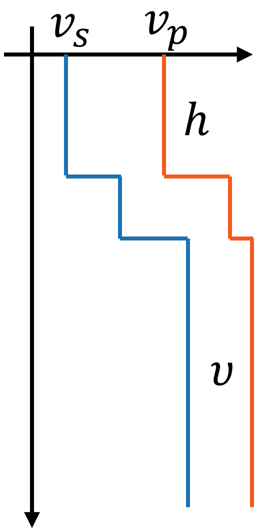




Unfiltered signals at two different distances & Frequency-Time ANalysis
to pick the RW. S picks are predicted from 1D model, associated with 5 s uncertainty

Inversion method

Subsurface model



Source location and time

t_s h_s r_s

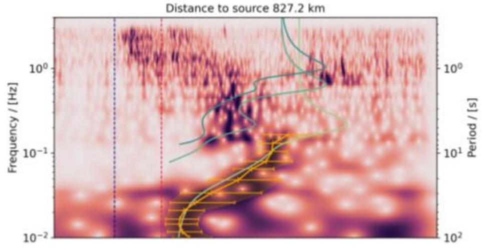
Distribution of parameters

Forward model

Arrival times

$\boldsymbol{t_{RW}(f_i)}$
$\boldsymbol{t_S}$

Data (RW and S picks)



$\neq$

Misfit + **Priors**
(bounds on v_s, h, r_s ...)

Bayesian approach

MCMC parameter space exploration

Posterior probability of
$(v_s, v, h, t_s, r_s, h_s)$

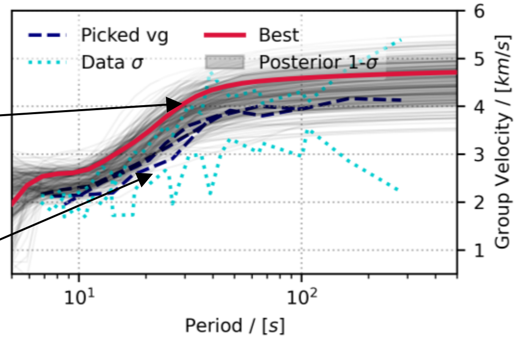
Inversion results: 3 stations with S & Rayleigh arrivals

With 3 stations:
Inversion matches the shape of the Rayleigh waves & the group velocities within 1 km/s

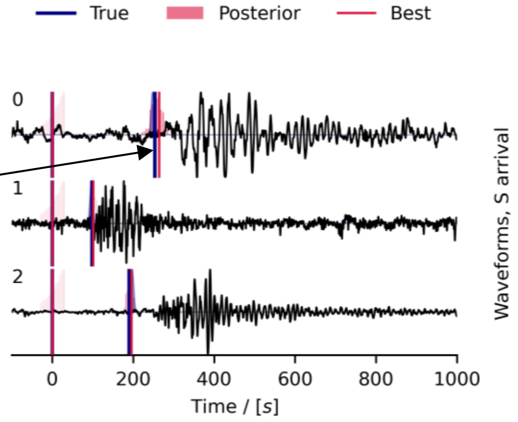
Inverted model also matches the S wave arrival time

Group velocities calculated from the posterior

Picked data



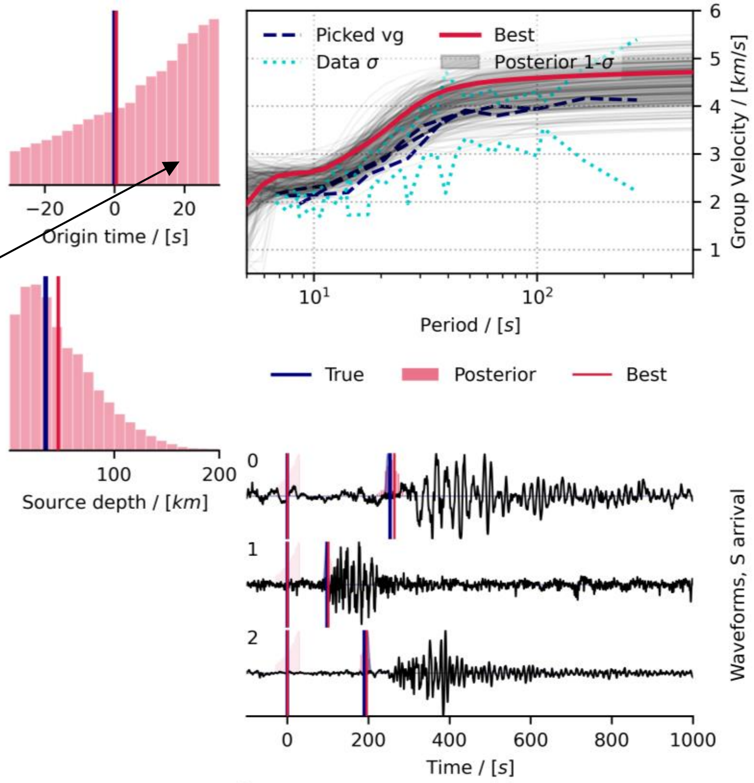
Picked and posterior S wave



Inversion results: 3 stations with S & Rayleigh arrivals

Source depth is close to the truth

Origin time biased towards positive values
⇔ shorter travel time by at least 30 s



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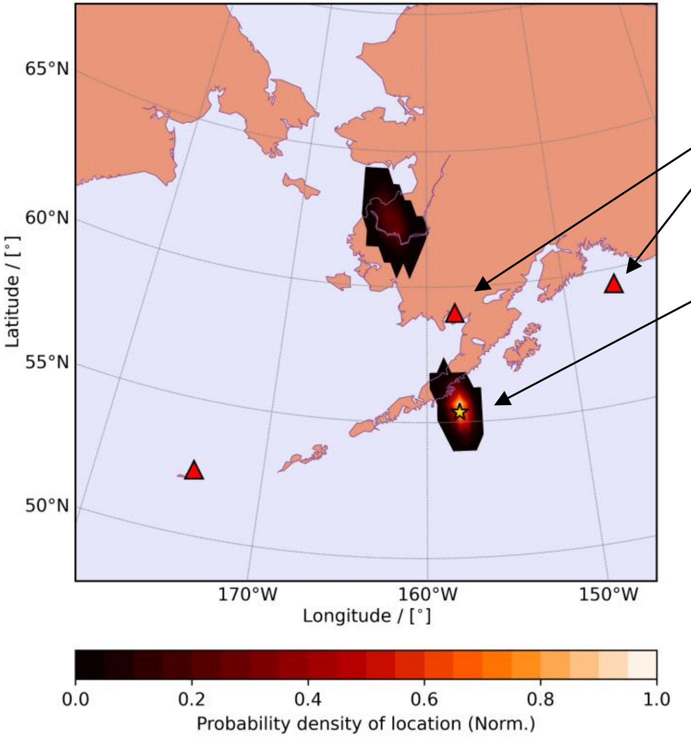
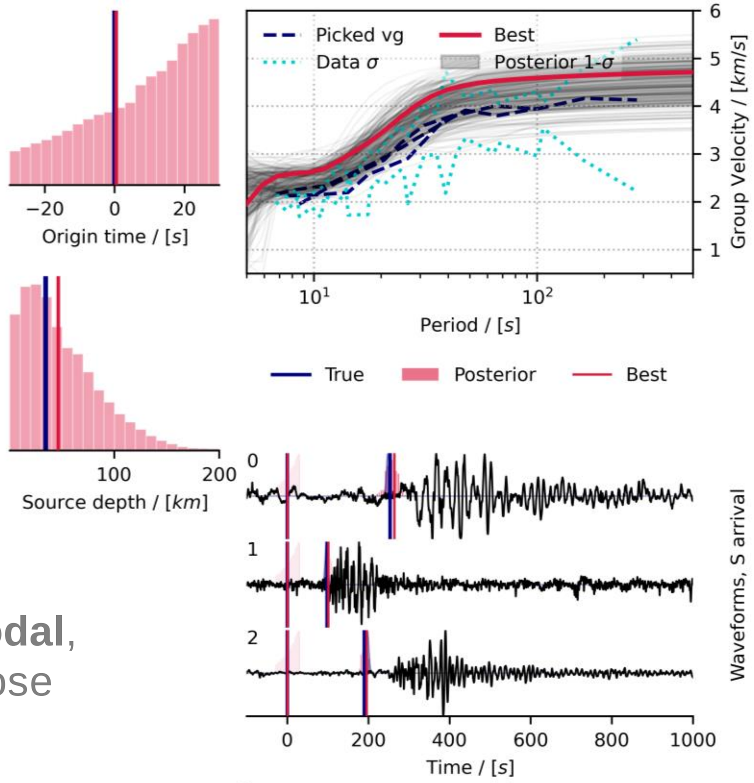
Inversion results: 3 stations with S & Rayleigh arrivals



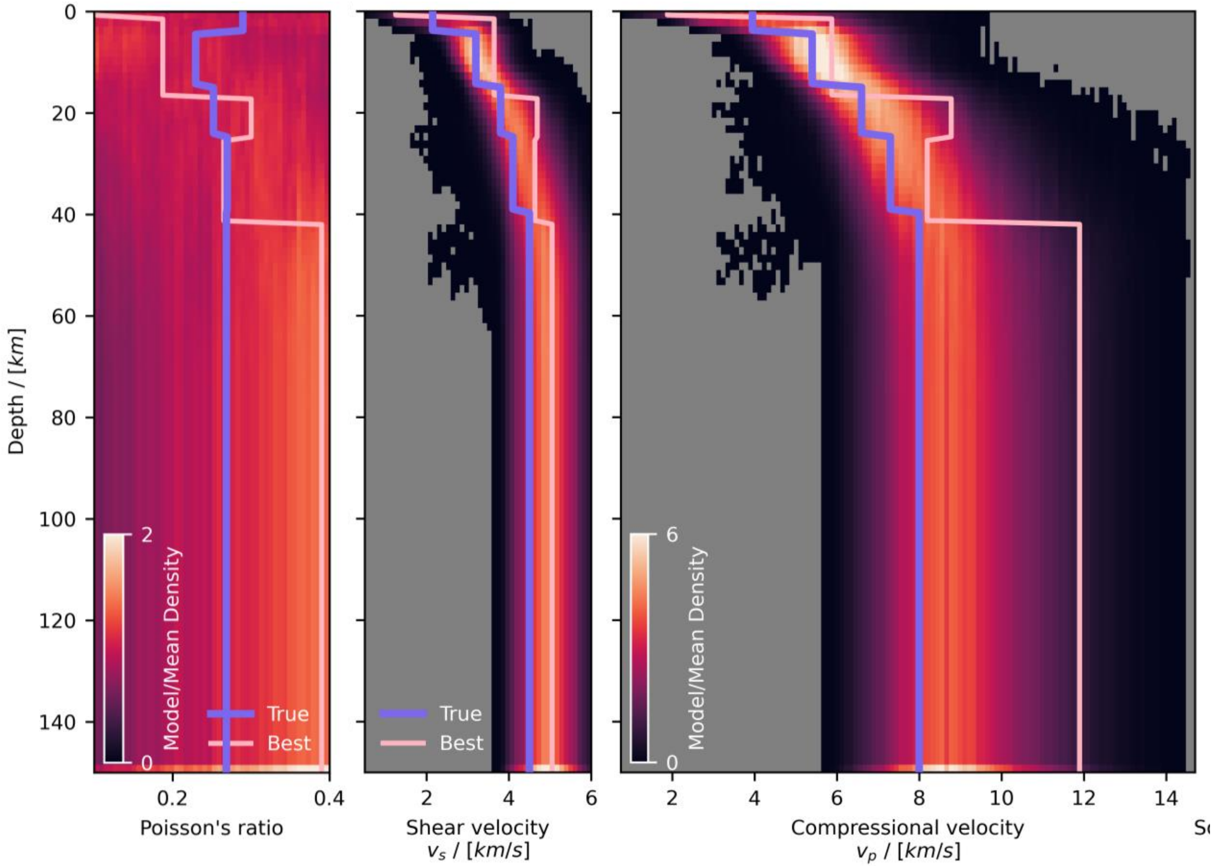
stations

event

Location is bimodal, with one mode close to truth



Inversion results: 3 stations with S & Rayleigh arrivals



The posterior distribution of models for v_s, v_p shares the same structure as the “true” model expected for Alaska, but **velocities are slightly overestimated**.

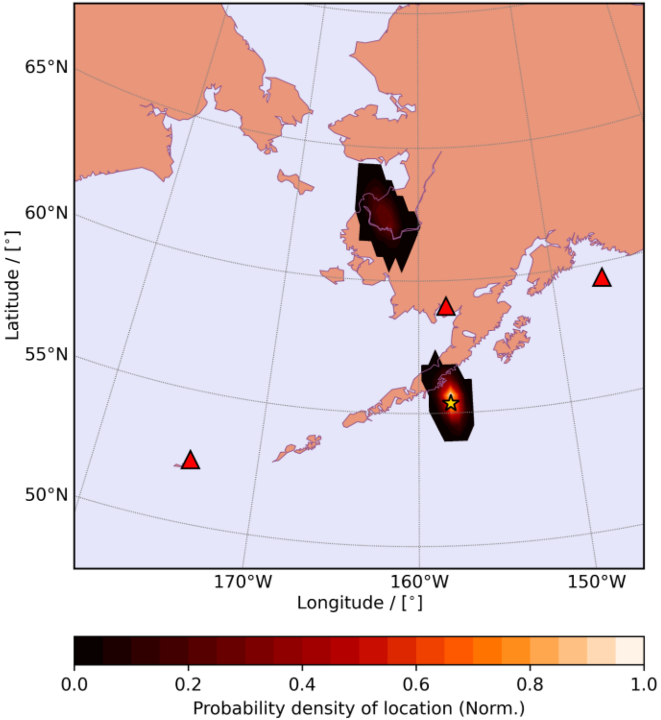
The Poisson ratio is unresolved.

Inversion results: 3 stations with S & Rayleigh arrivals

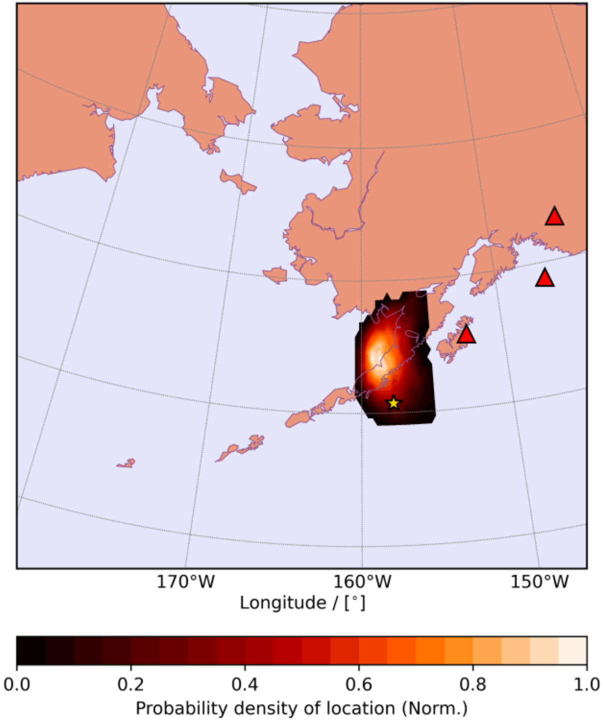
Conclusions:

Three stations/balloons only **give limited information**

A **bad azimuthal coverage or picking errors** can translate to error location error, and then to error in travel-times & subsurface velocities



Three stations with relatively good azimuthal coverage

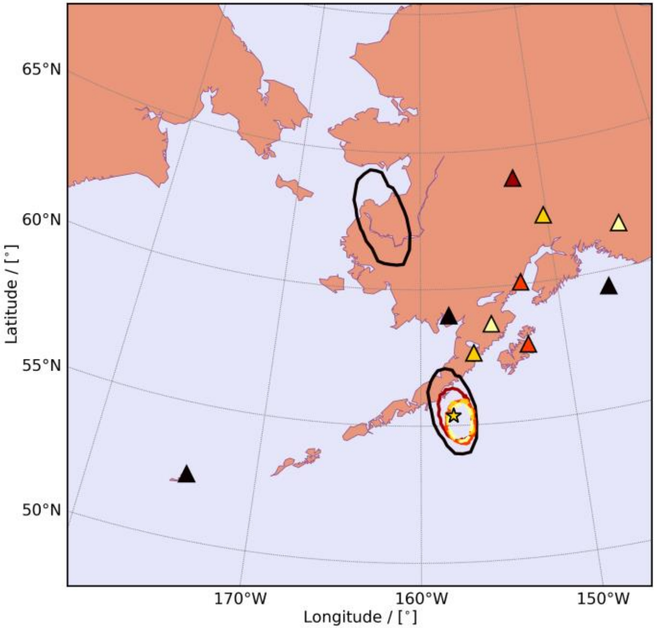


Three stations with poor azimuthal coverage

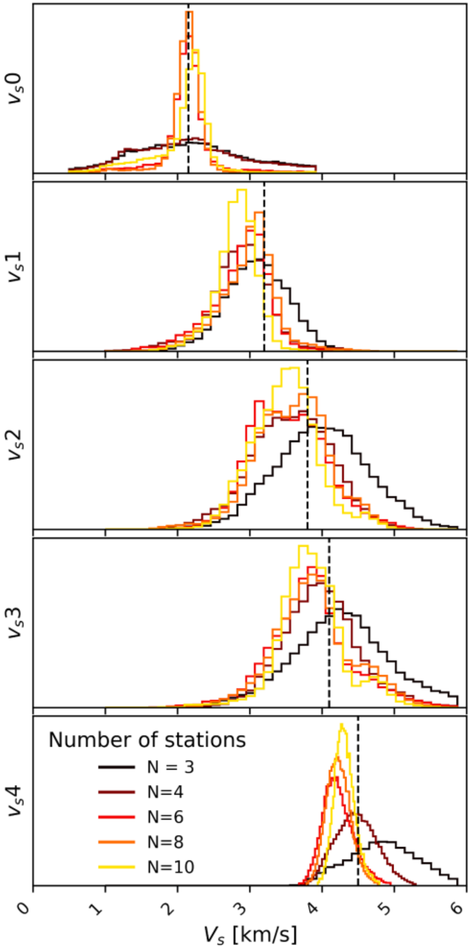
Influence of number of stations

Start the inversion with 3 stations & good azimuthal coverage, and progressively increase the number up to 10

Beyond 6 stations, the azimuthal coverage is not significantly improved.

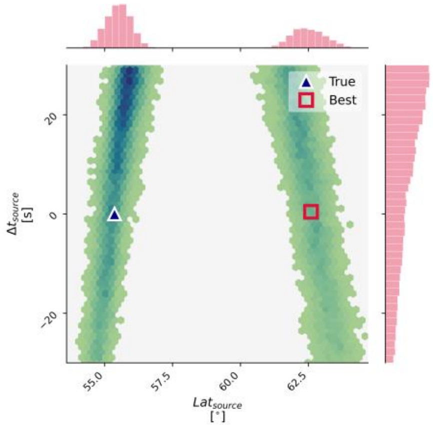


3-sigma ellipse of source location with the number of stations (black=3, yellow=10).

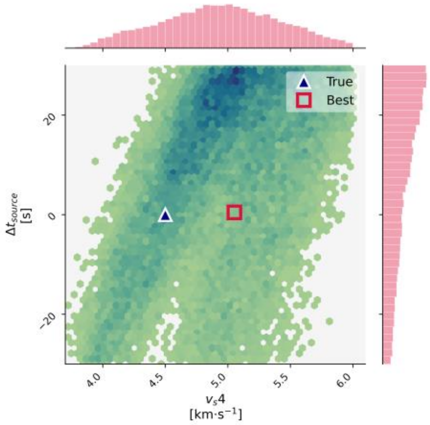


Posterior distribution of v_s in each layer from top to bottom.

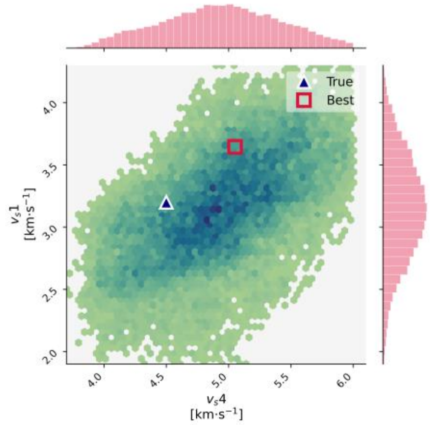
Trade-off between source location, velocity & time



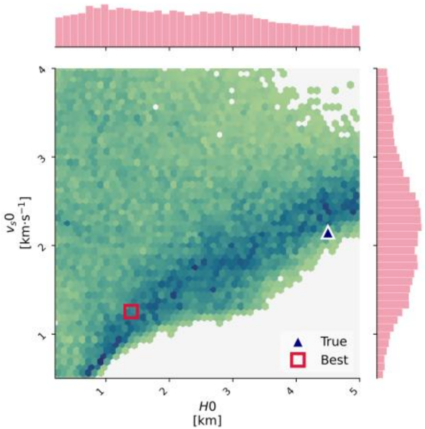
Trade-off between source time and source location



Trade-off between source time mantle velocity



Trade-off between upper crust and mantle velocities



Trade-off between upper crust velocity and layer thickness

With **3 stations:** plot marginal probability density distributions of two parameters to identify trade-offs

→

Simultaneous inversions of source and subsurface are highly non-unique

Trade-off between source location, velocity & time

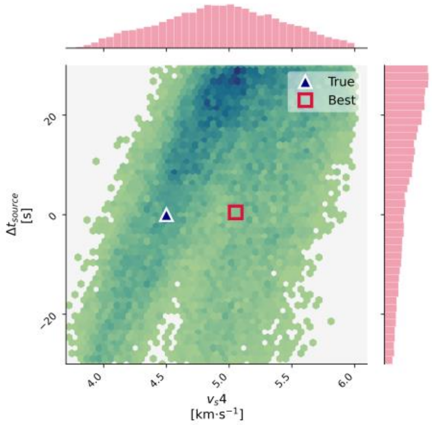
Some trade-offs are reduced by including more stations / more information

Others are linked to non-linearities in the forward problem

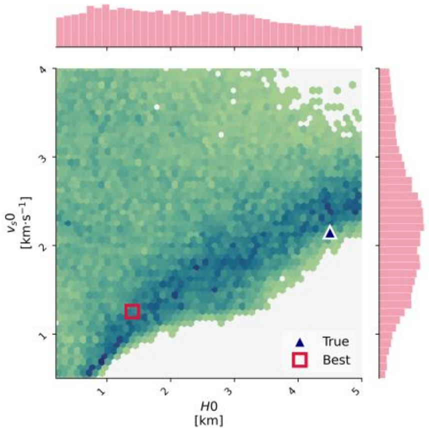
E.g., combined effect of layer thickness and layer velocity on Rayleigh Waves group velocities

3 stations

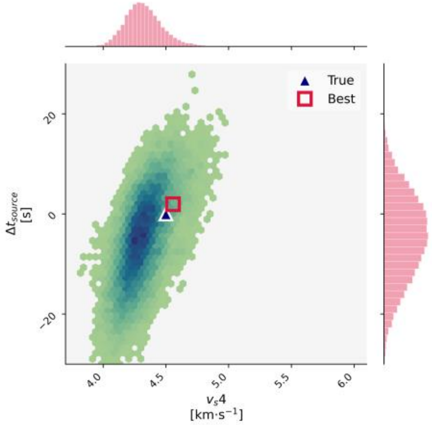
10 stations

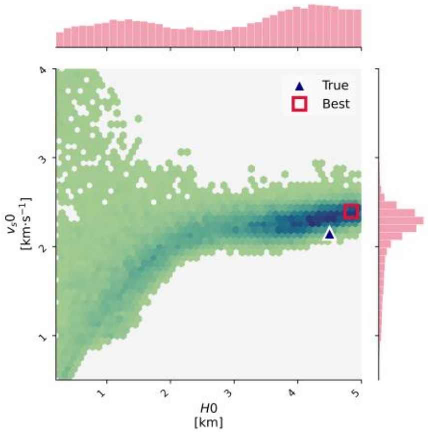


Trade-off between origin time & mantle velocity



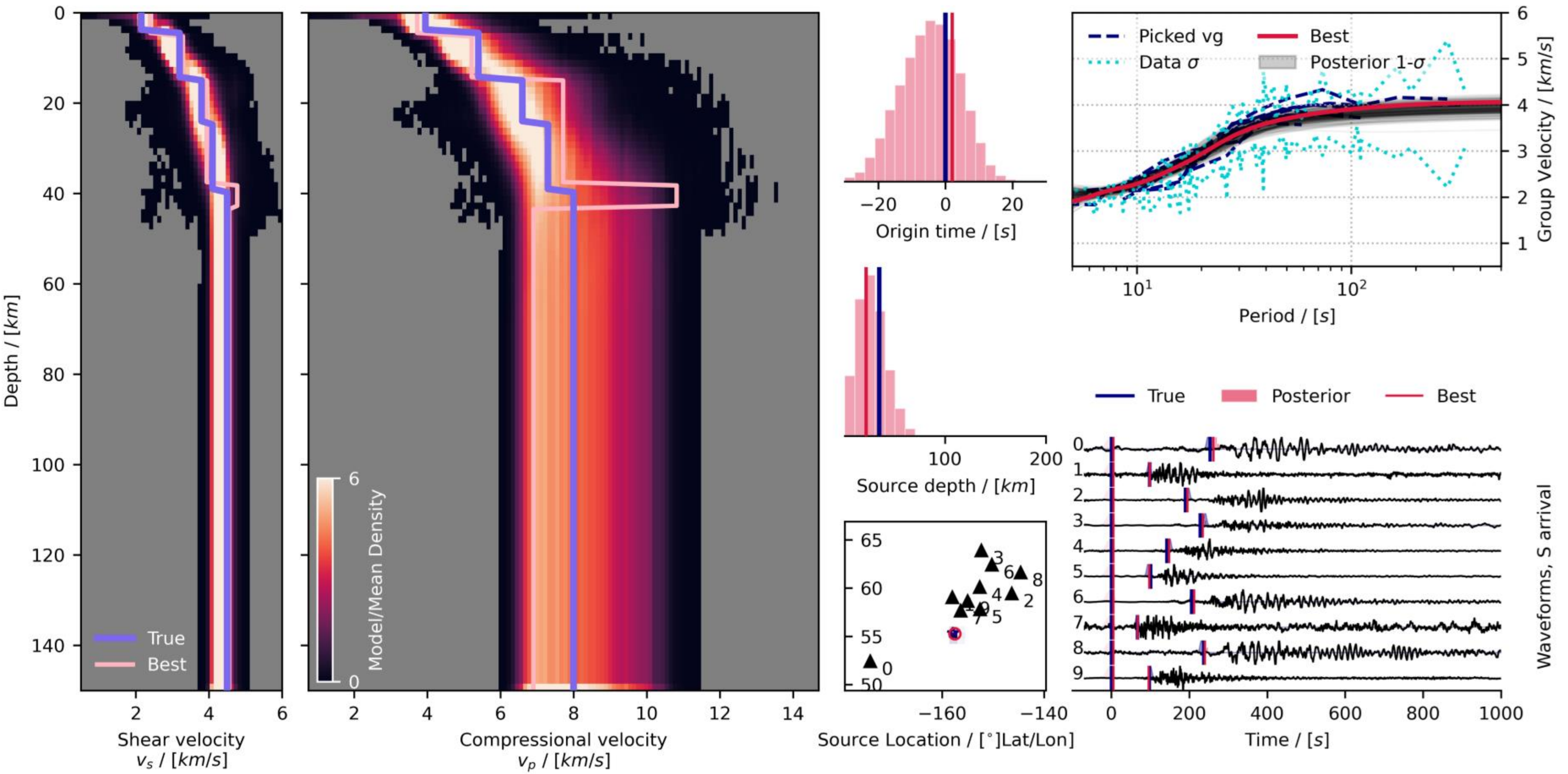
Trade-off between upper crust velocity & layer thickness



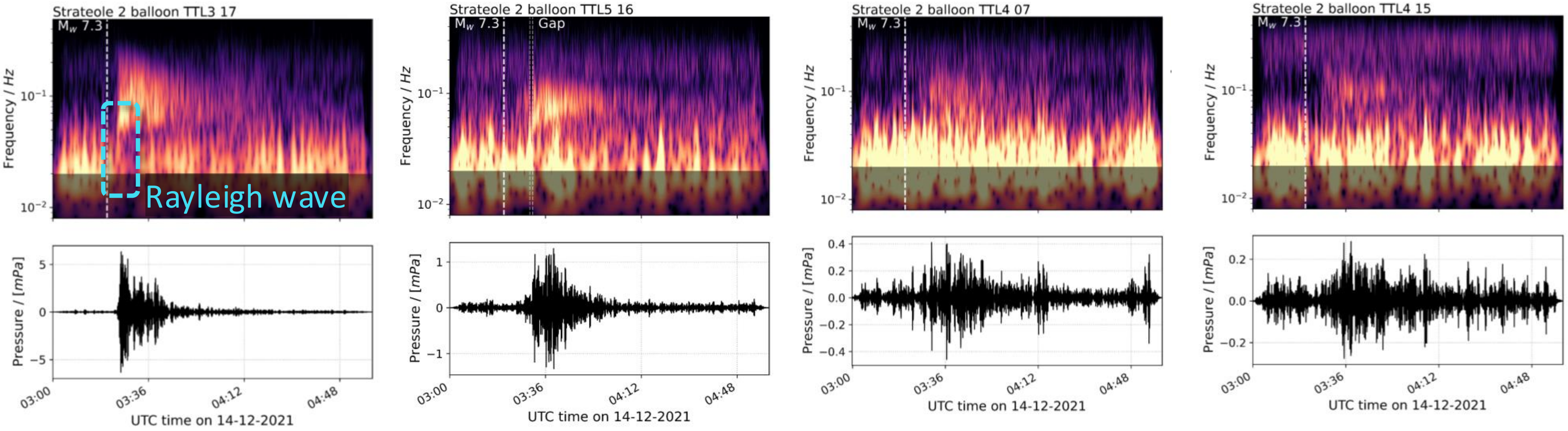


Inverted model using 10 Alaska stations

Significantly better match to true origin times, group velocities & subsurface parameters



Towards validation with balloon data

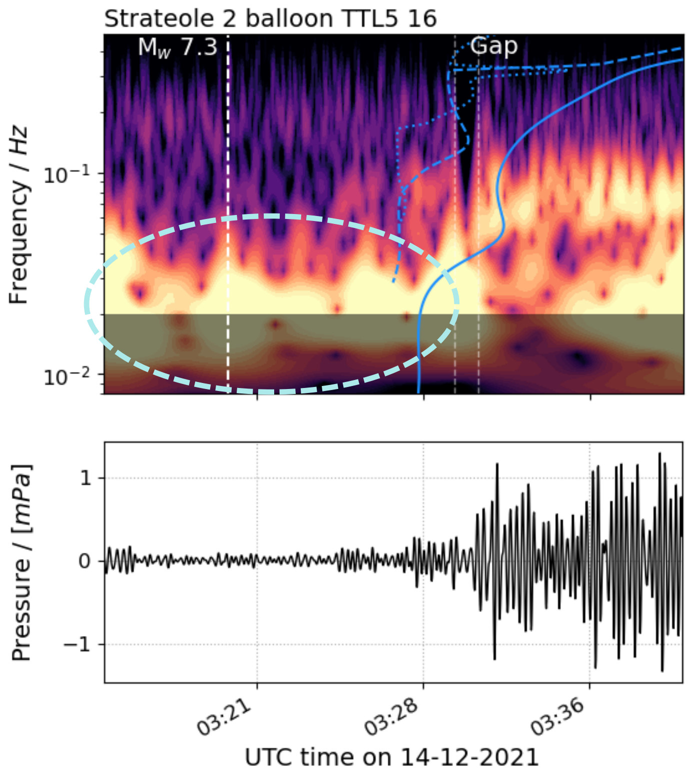


Spectrograms & time series of the four Strateole2 recordings of the Flores Sea earthquake

Can we retrieve:

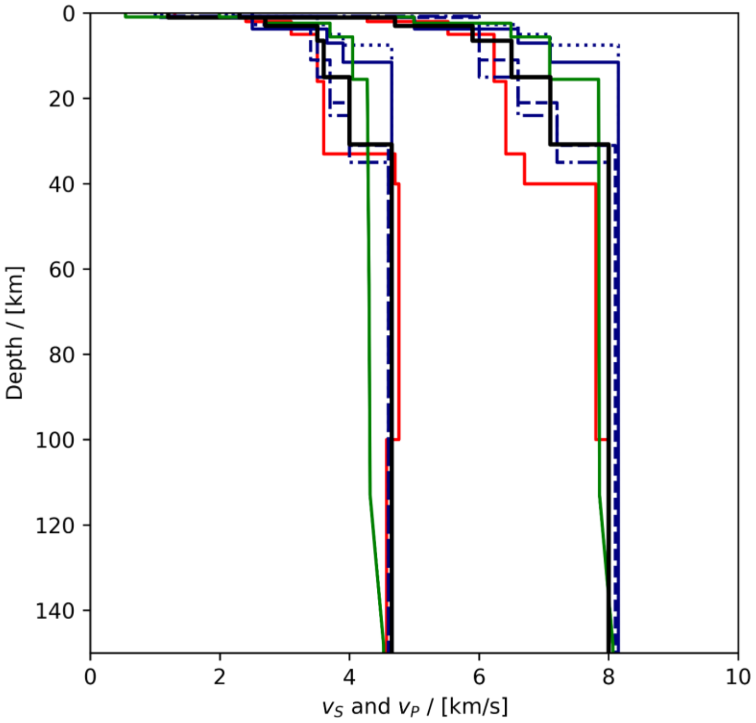
1) Flores earthquake location & origin time?
2) Subsurface model for region?

Challenges in Flores inversion

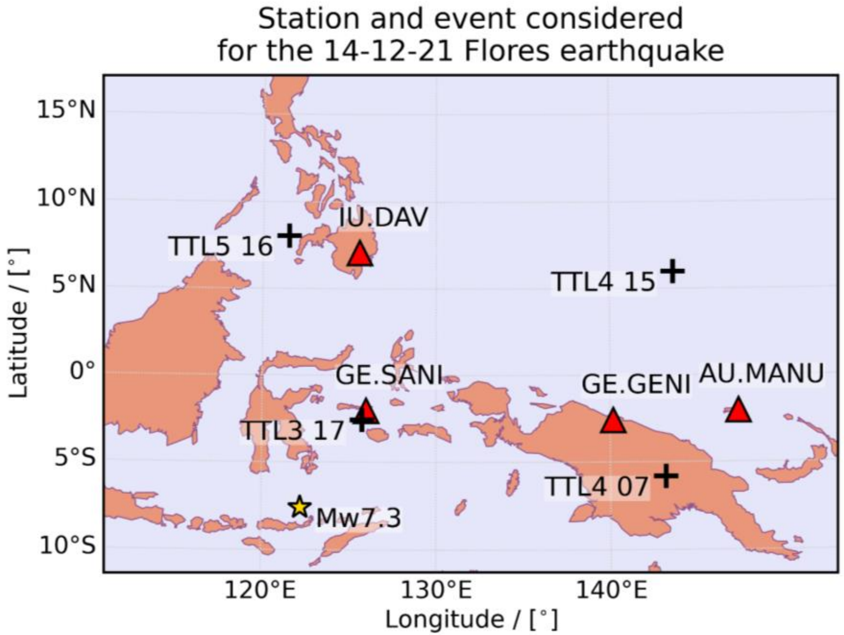


- Presence of possible mantle-going waves at the furthest locations (2000-3000 km)
- Challenge in picking RW & other arrivals: presence of resonances (low-velocity layers, scattering on heterogeneities)
- Need for processing methods to attenuate low-frequency balloon oscillations

The Flores earthquake: seismic and balloon inversion



Subsurface not well known in the region. Multiple crustal model exist



We prepare the inversion of balloon data by **first working with seismic data** using the 4 seismic stations closest to the balloons

Thank you for your attention

Funding:

Research Council of Norway basic research program FRIPRO

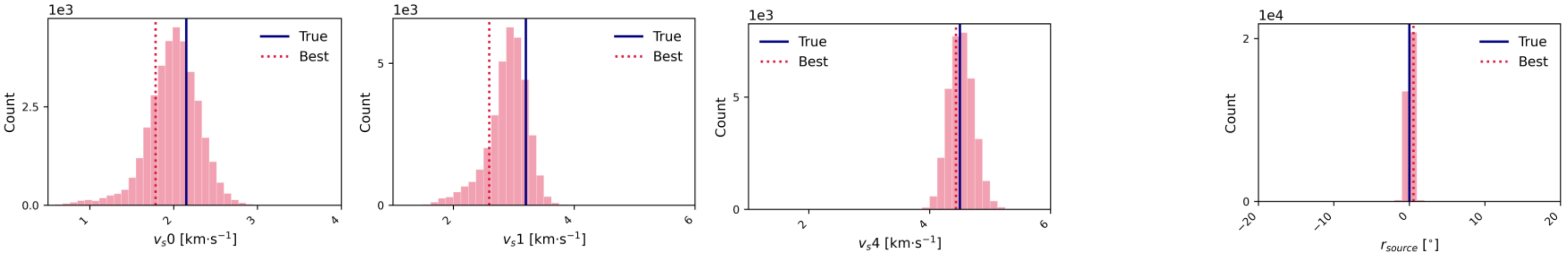
Airborne inversion of Rayleigh waves

Contract 335903

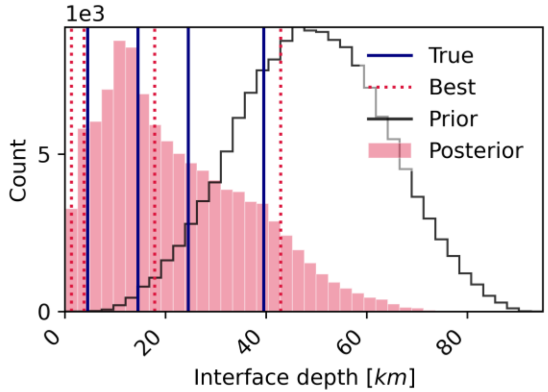
Your feedback & suggestions are welcome !

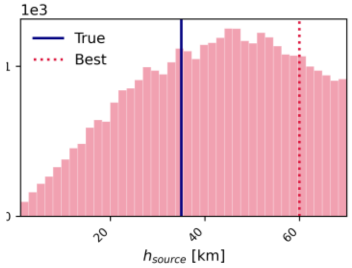
Inversion results: parameters and histograms

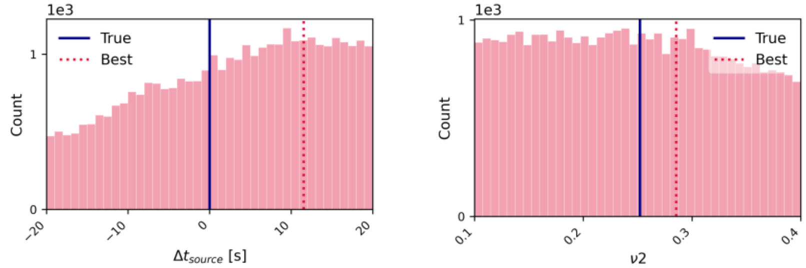
Parameters **constrained much better than the priors**: distance, shear wave velocity



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







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

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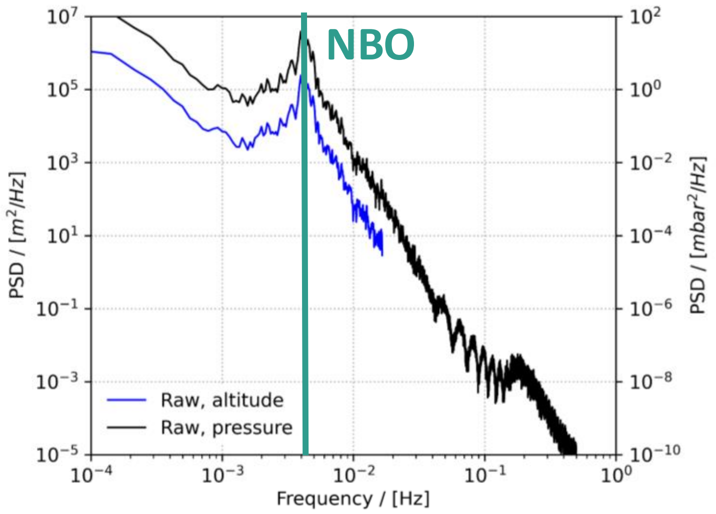
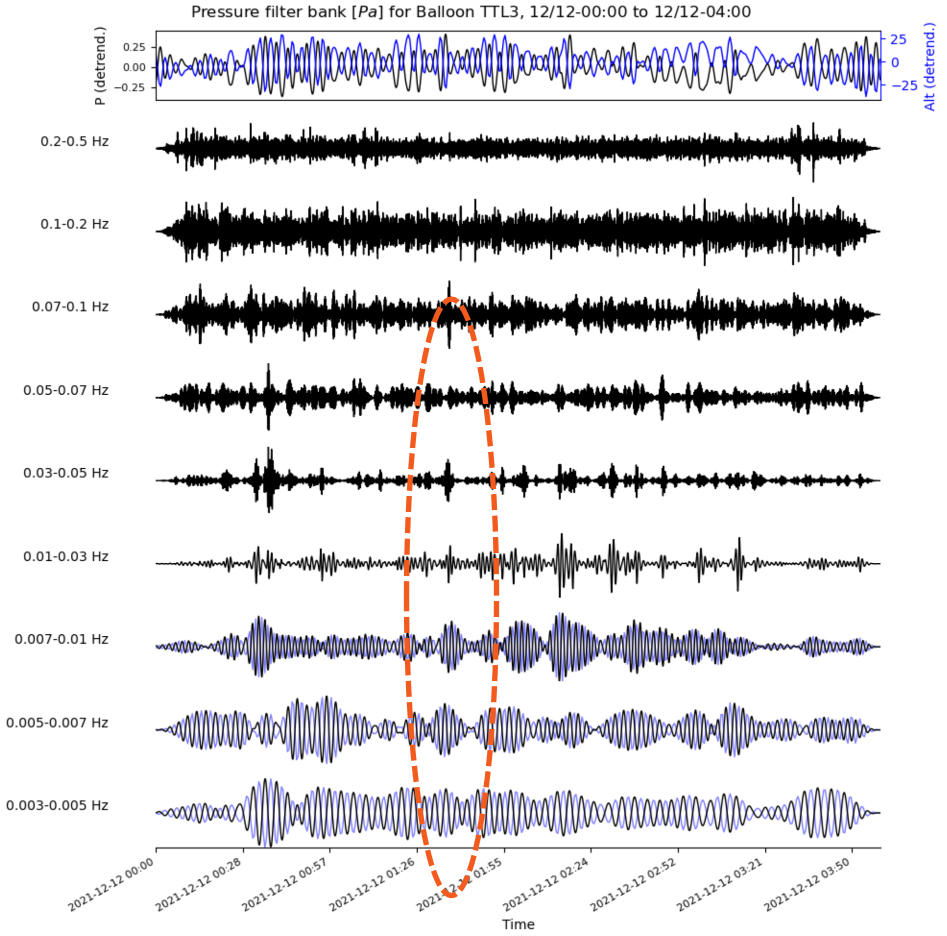
An unsteady sensor…



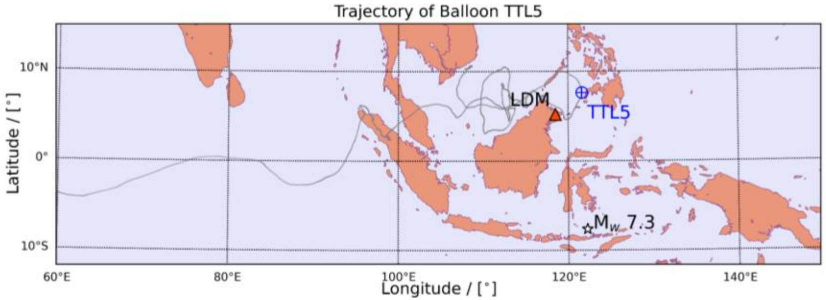


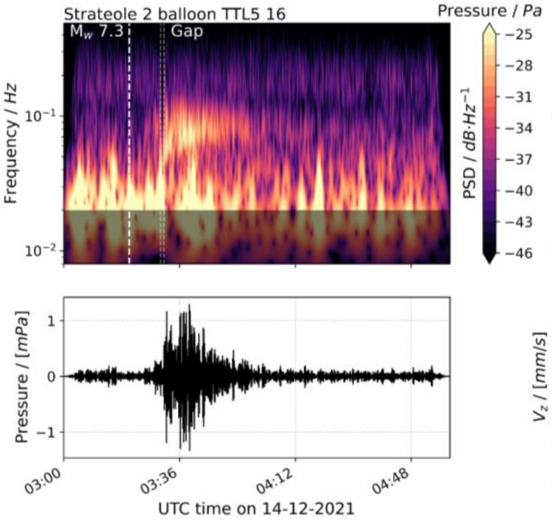
Balloons position determined by buoyancy, wind forces, gravity. Presence of a **Neutral Buoyancy Oscillation** = balloon normal mode.

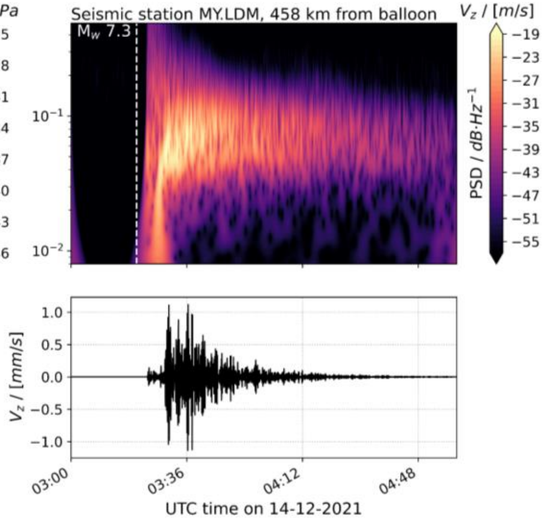
Good coherence up to GPS Nyquist frequency, perhaps even higher: **broadband energy bursts** follow altitude changes.

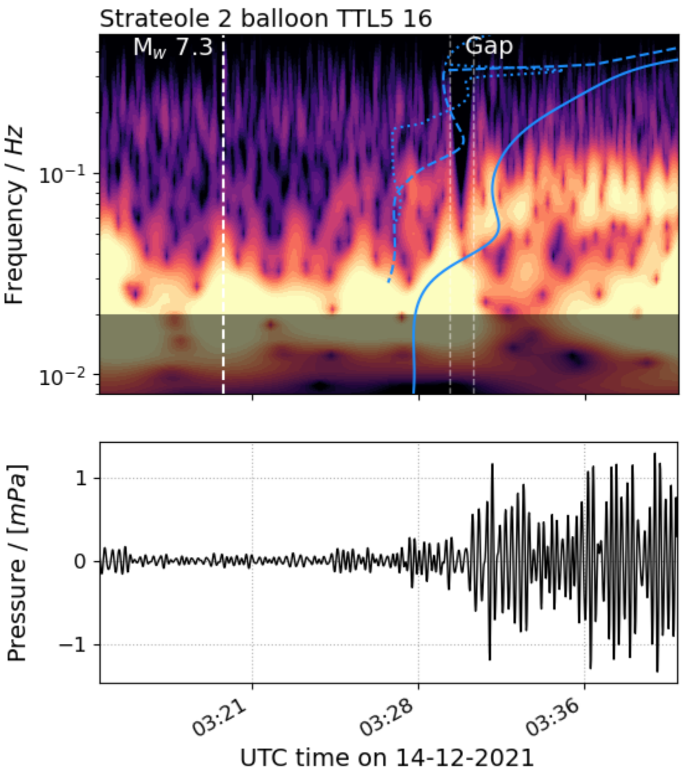
Massman, W. J. *Journal of Applied Meteorology (1962-1982)* **17**, 1351–1356 (1978).

Picking the Rayleigh wave: example of balloon 16

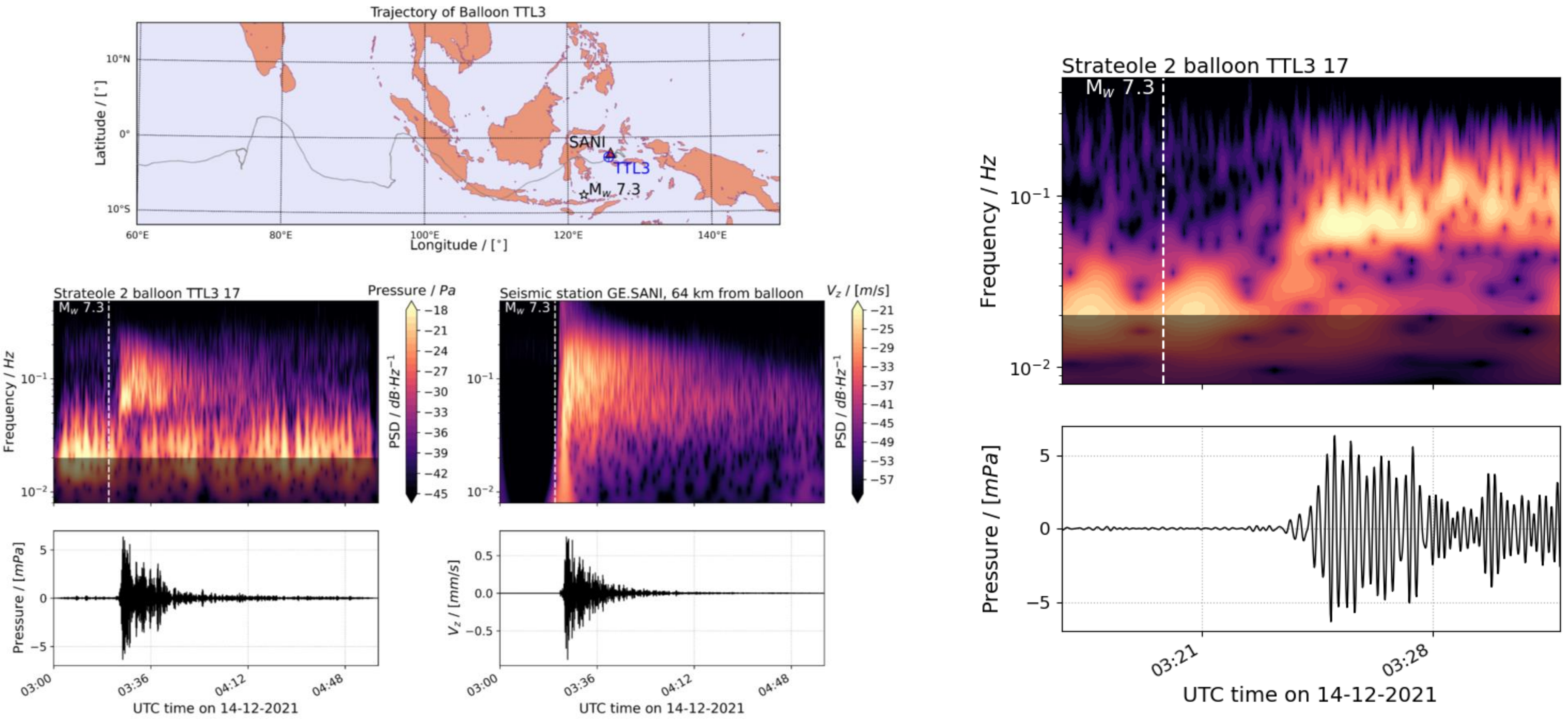




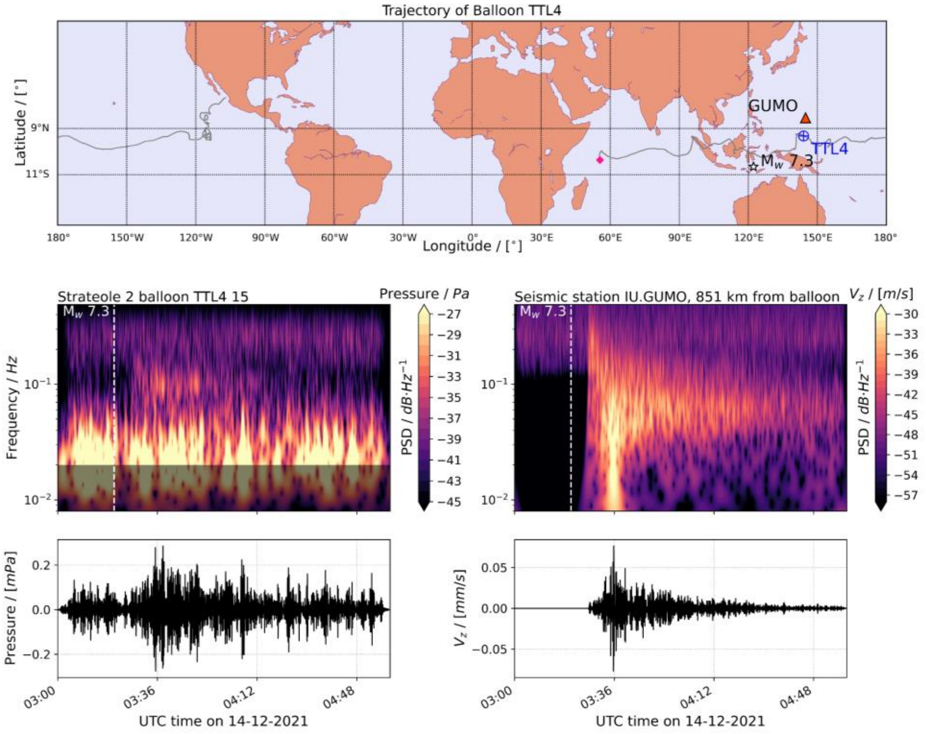


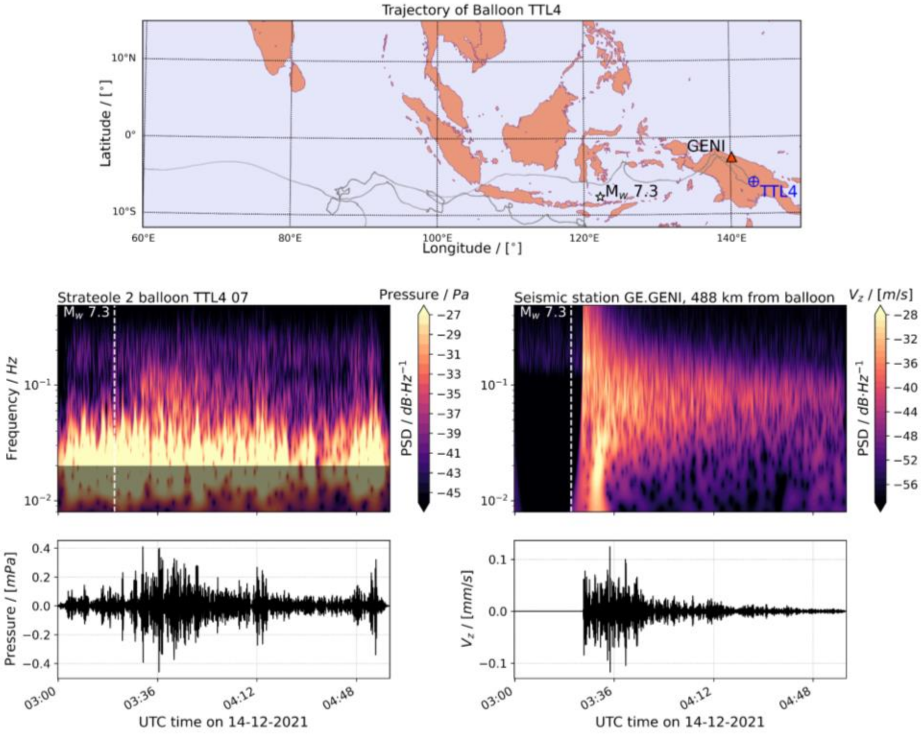


Picking the Rayleigh wave: example of balloon 17



Balloon 15 and 07: a more difficult case.





Sensitivity analysis for models of the Flores sea