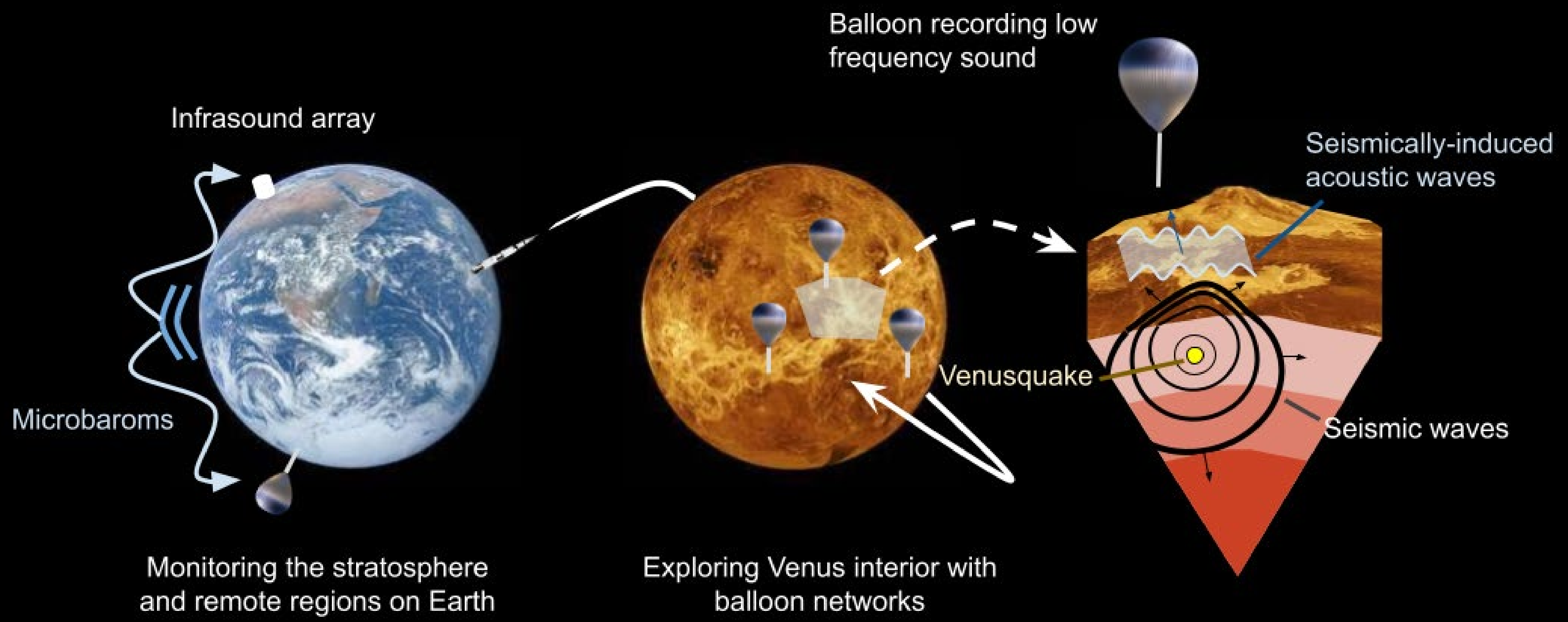
Exploring a planet with infrasound: challenges in probing the subsurface & the atmosphere

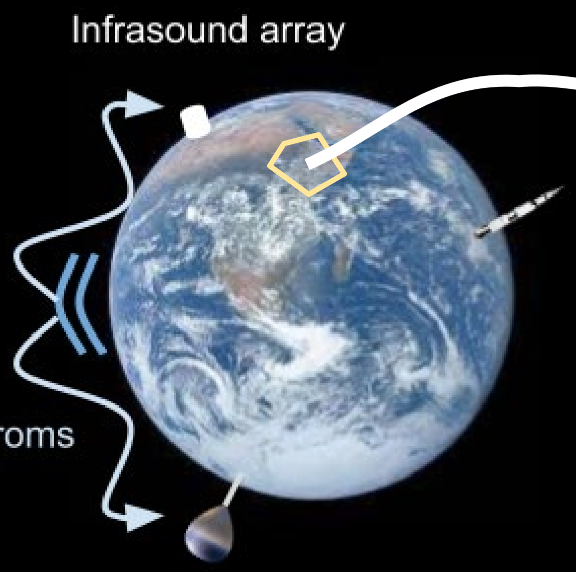
Sven Peter Näsholm, Q. Brissaud, A. Turquet, T. Kaschwich, M. Froment

186th Meeting of the Acoustical Society of America, Ottawa, Canada
Session: 1pPAb – Infrasound
Presentation: 1pPAb3 on 13 May 2024 at 1h40

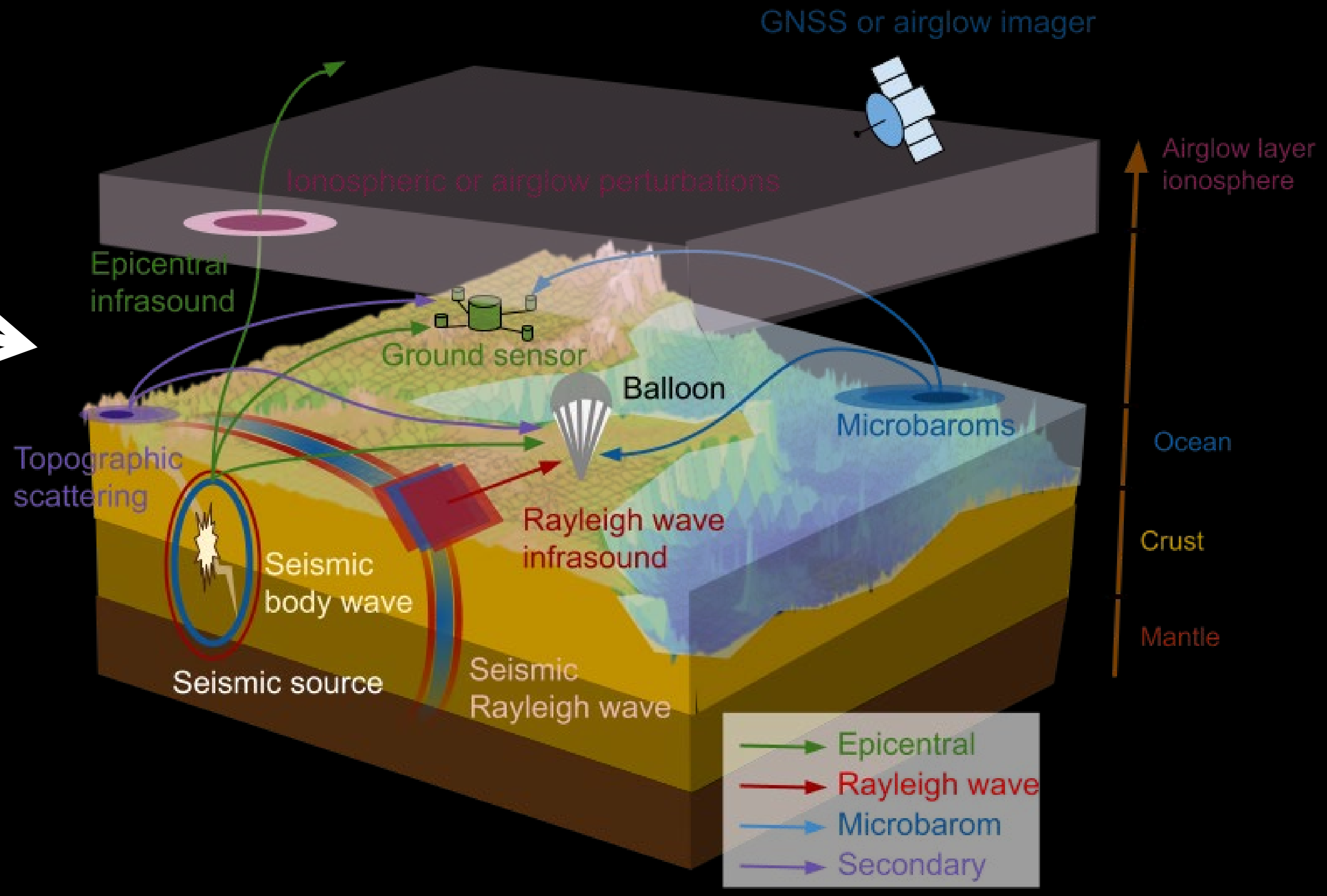
Exploring Earth & beyond



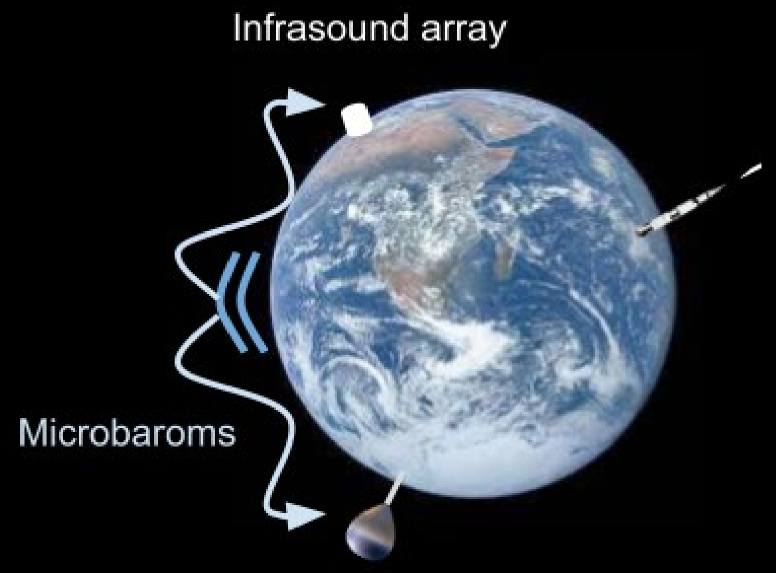
Seismoacoustics

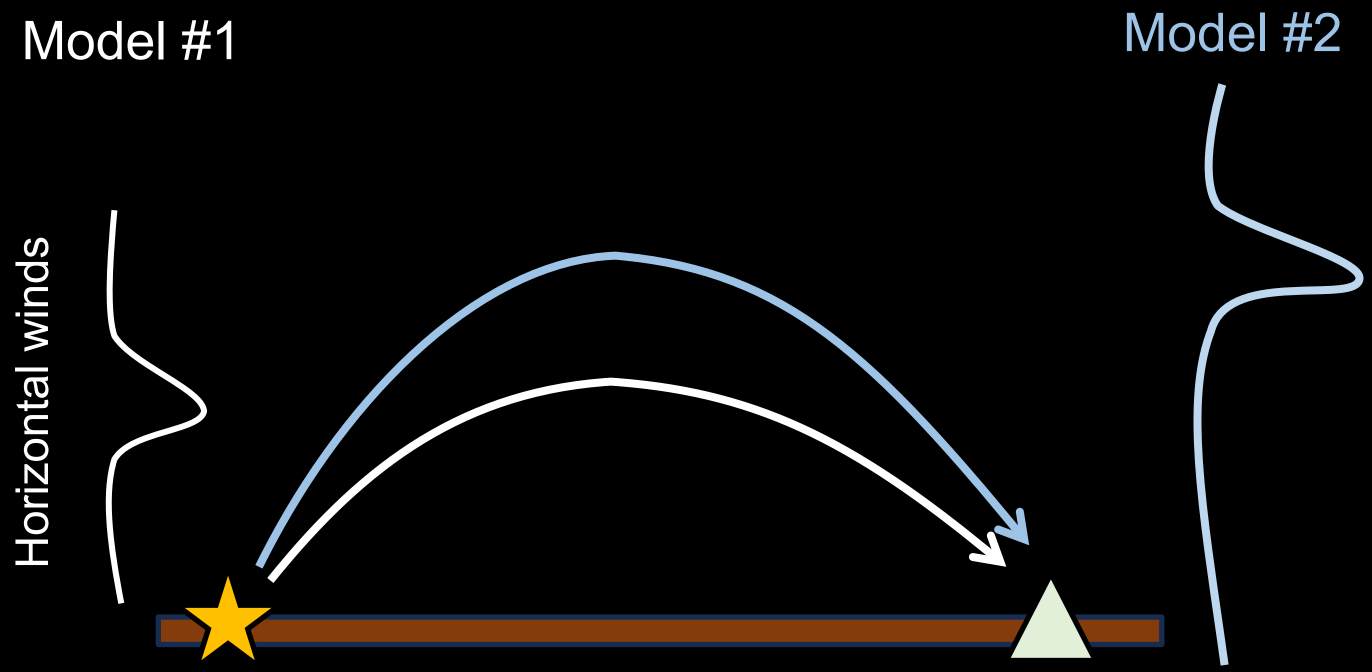


Monitoring the stratosphere
and remote regions on Earth



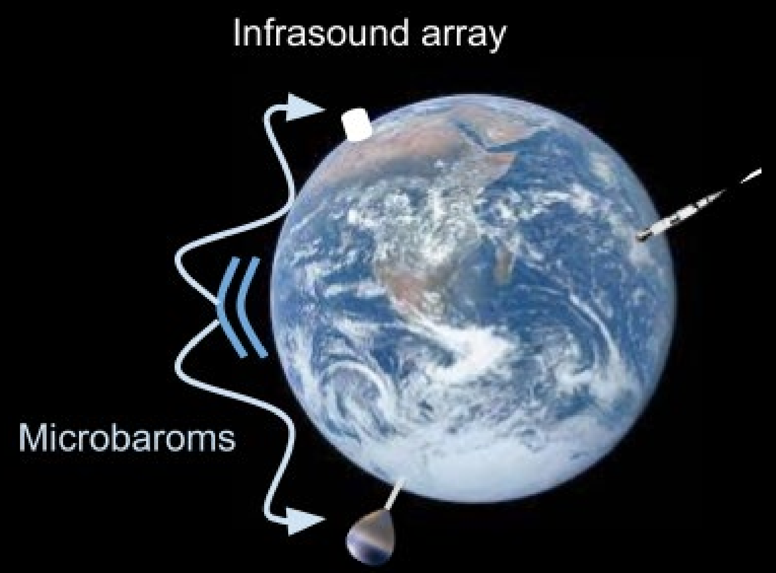
Probing Earth's stratosphere





… in practice: ill-posed inversion problem

Probing Earth's stratosphere



Infrasound from regional/global sources highly sensitive to stratospheric wind

Ambition:

- Assimilate infrasound into atmospheric & NWP models
- Enhance subseasonal / longer-range weather prediction

Need:

- Well-constrained source
- Forward model
- Uncertainty quantification
- Inversion / assimilation procedure

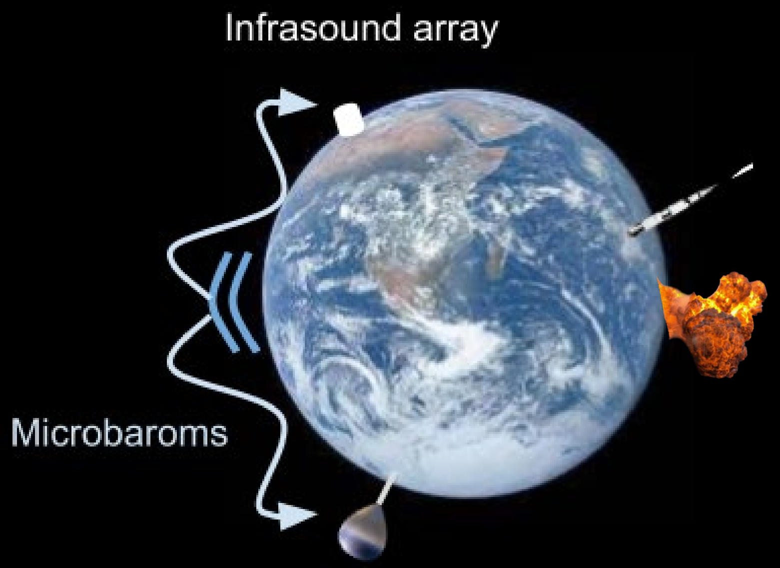
…. but maybe go fully data-driven?

Uncertainties?

- Recorded waves are footprints of **source structure**, interwoven with **atmospheric wind & temperature** effects during propagation
- Underlying hypothesis: *source & other modeling aspects better constrained than the atmospheric properties we probe*
- Uncertainty estimation as important as the data points

A well constrained source?

Ocean sources
Large-scale & global
average probing



Transient surface explosions
Fine-scale & local
snapshot probing

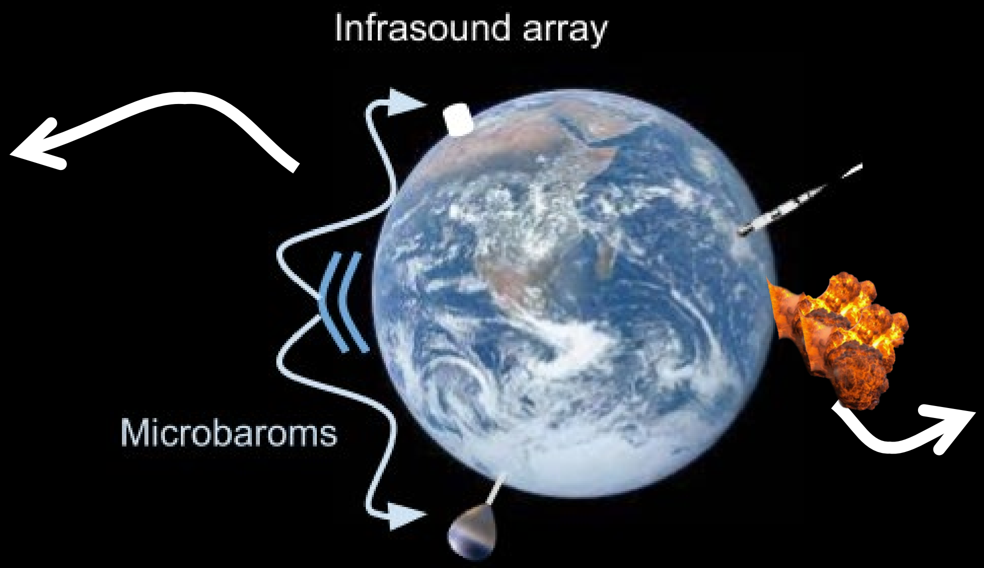
Large-scale, spatially averaged, atmospheric probing is valuable!

Ref. satellite-based spatially averaged measurements already in operational assimilation

Modeling at local to global distances

“**Extended & low-frequency**” sources: full-waveform more appropriate

→ more expensive

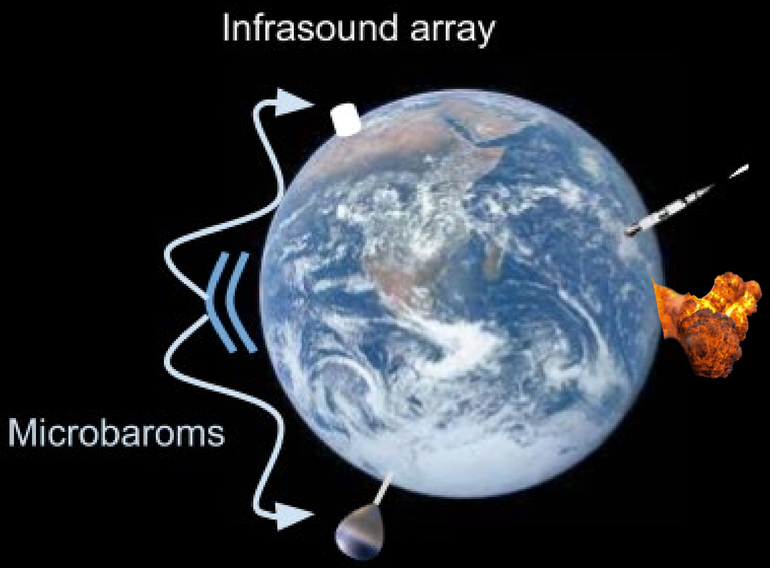


“**Small-size & high frequency**” sources in smoother models: ray tracing sometimes sufficient

… forward-modelling often fails due to non-modeled effects (small-scale structure, etc)

NORSAR

Making infrasound data relevant to atmospheric models



Sensitivity kernels

- Good convergence
- Limited to small perturbations

Geophysical Journal International
Geophys. J. Int. (2012) **190,** 687–701 doi: 10.1111/j.1365-246X.2012.05518.x

Infrasound data inversion for atmospheric sounding

J.-M. Lalande,[1,2] O. Sèbe,[1] M. Landès,[1] Ph. Blanc-Benon,[2] R. S. Matoza,[3] A. Le Pichon[1] and E. Blanc[1]

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[2] *LMFA, UMR CNRS 5509, École Centrale Lyon, Université de Lyon, 69134, Ecully Cedex, France*
[3] *IGPP, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA*

$$\frac{\partial s_x^i}{\partial m_n} = \mathcal{R}\delta q_x^i\left(\tau_{\mathrm{grd}}^i; \delta m_n\right),$$

$$\frac{\partial s_y^i}{\partial m_n} = \mathcal{R}\delta q_y^i\left(\tau_{\mathrm{grd}}^i; \delta m_n\right),$$

$$\frac{\partial T^i}{\partial m_n} = \Delta T^i\left(\tau_{\mathrm{grd}}^i; \delta m_n\right),$$

Grid search in reduced-order space

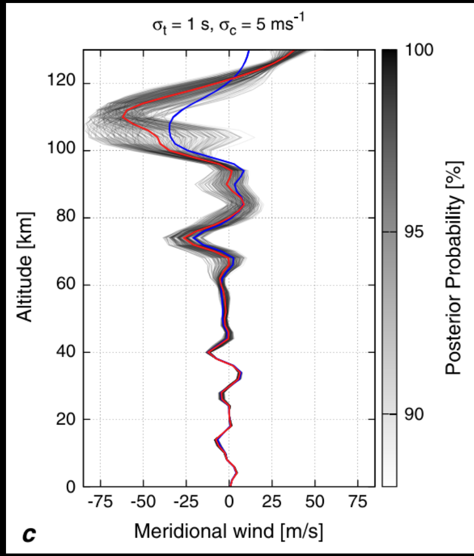
- Full posterior

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 10,707–10,724, doi:10.1002/jgrd.50833, 2013

The estimation of upper atmospheric wind model updates from infrasound data

J. D. Assink,[1] R. Waxler,[1] W. G. Frazier,[1] and J. Lonzaga[1]

Received 22 January 2013; revised 9 August 2013; accepted 10 September 2013; published 1 October 2013.



NORSAR

Translating infrasound data into atmospheric models

Highlights from our proofs-of-concept

Physics-driven model: first (off-line) infrasound data assimilation demonstration

Received: 13 September 2019 | Revised: 16 April 2020 | Accepted: 20 April 2020 | Published on: 12 May 2020

DOI: 10.1002/qj.3809

Quarterly Journal of the Royal Meteorological Society RMetS

RESEARCH ARTICLE

Assimilation of atmospheric infrasound data to constrain tropospheric and stratospheric winds

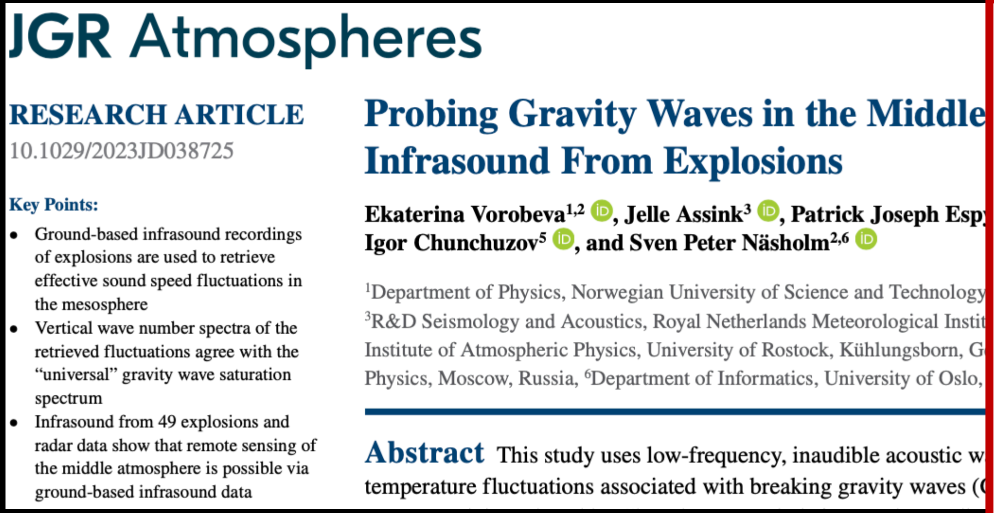
Javier Amezcua[1] | Sven Peter Näsholm[2] | Erik Mårten Blixt[2] | Andrew J. Charlton-Perez[3]

Explosion infrasound; local profile; but small model innovations due to weak stratospheric winds; still good baseline for further research [published 2020]

Translating infrasound data into atmospheric models

Highlights from our proofs-of-concept’

Physics-driven model:
retrieving small-scale effective soundspeed vertical wavenumber spectra



JGR Atmospheres

RESEARCH ARTICLE
10.1029/2023JD038725

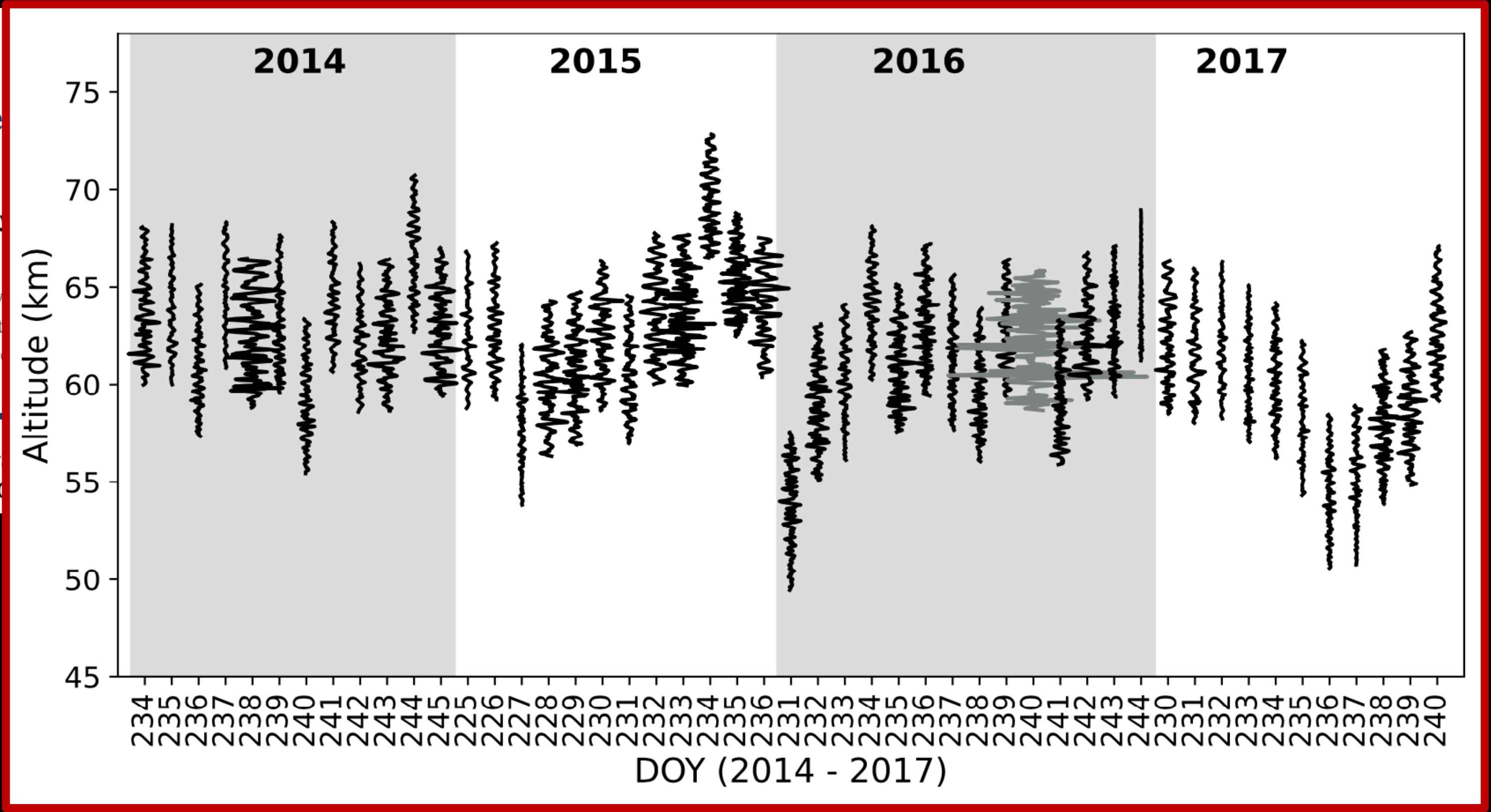
Key Points:
- Ground-based infrasound recordings of explosions are used to retrieve effective sound speed fluctuations in the mesosphere
- Vertical wave number spectra of the retrieved fluctuations agree with the “universal” gravity wave saturation spectrum
- Infrasound from 49 explosions and radar data show that remote sensing of the middle atmosphere is possible via ground-based infrasound data

**Probing Gravity Waves in the Middle
Infrasound From Explosions**

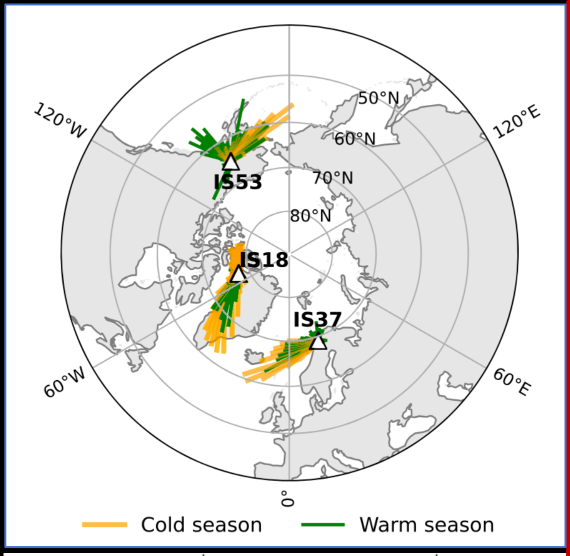
Ekaterina Vorobeva[1,2], Jelle Assink[3], Patrick Joseph Espy
Igor Chunchuzov[5], and Sven Peter Näsholm[2,6]

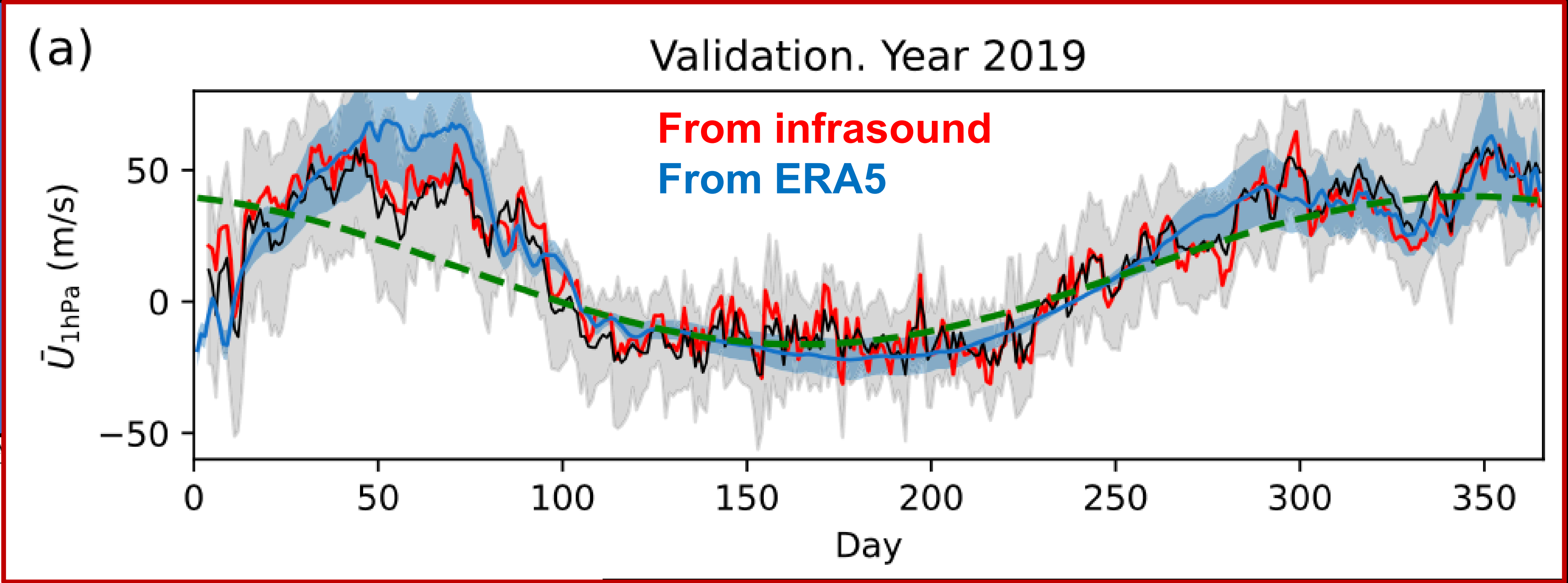
[1]Department of Physics, Norwegian University of Science and Technology
[3]R&D Seismology and Acoustics, Royal Netherlands Meteorological Instit
Institute of Atmospheric Physics, University of Rostock, Kühlungsborn, G
Physics, Moscow, Russia, [6]Department of Informatics, University of Oslo,

Abstract This study uses low-frequency, inaudible acoustic w
temperature fluctuations associated with breaking gravity waves (



Explosion infrasound; local profile;
need verification against independent measurements or models! [published 2023]





Received: 17 July 2023 | Revised: 11 January 2024 | Accepted: 27 N

DOI: 10.1002/qj.4731

RESEARCH ARTICLE

Estimating stratospheric polar vortex strength using ambient ocean-generated infrasound and stochastics-based machine learning

Ekaterina Vorobeva[1,2] | Mari Dahl Eggen[2,3] | Alise Danielle Midtfjord[3,4] | Fred Espen Benth[3] | Patrick Hupe[5] | Quentin Brissaud[2] | Yvan Orsolini[1,6] | Sven Peter Näsholm[2,7]

Microbarom sources; ERA5 as ground-truth polar cap upper stratospheric eastward wind; 5 years IMS training data;

[published two weeks abo]

Translating infrasound data into atmospheric models

Highlights from our proofs-of-concept

Physics-driven: incorporating wave-propagation modeling into the assimilation observation operator

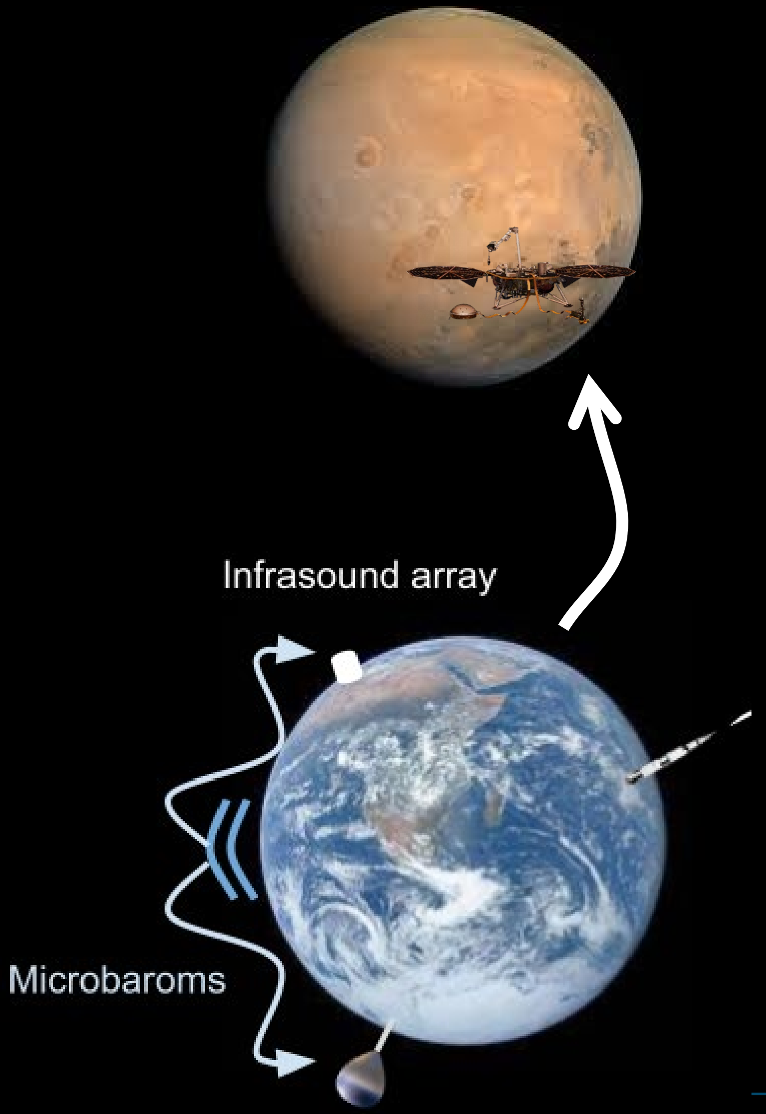
Using satellite data assimilation techniques to combine infrasound observations and a full ray-tracing model to constrain stratospheric variables

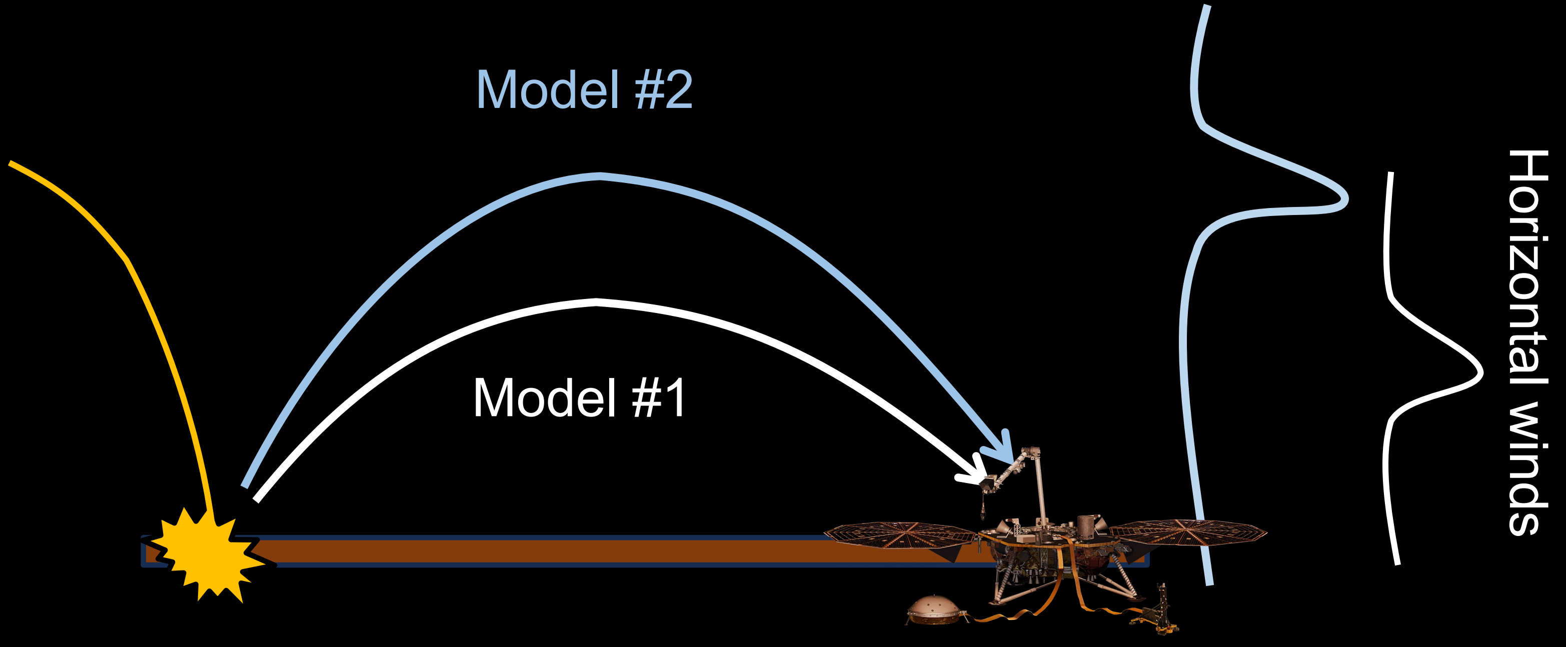
Javier Amezcua[a, b], Sven Peter Näsholm[c,d], Ismael Vera-Rodriguez[e,f]

Explosion infrasound; local profile; Modulated Ensemble Transform Kalman Filter;
This synthetic study needs data-based follow-up

[minor revision expected to soon be accepted in the AMS Monthly Weather Review, 2024]

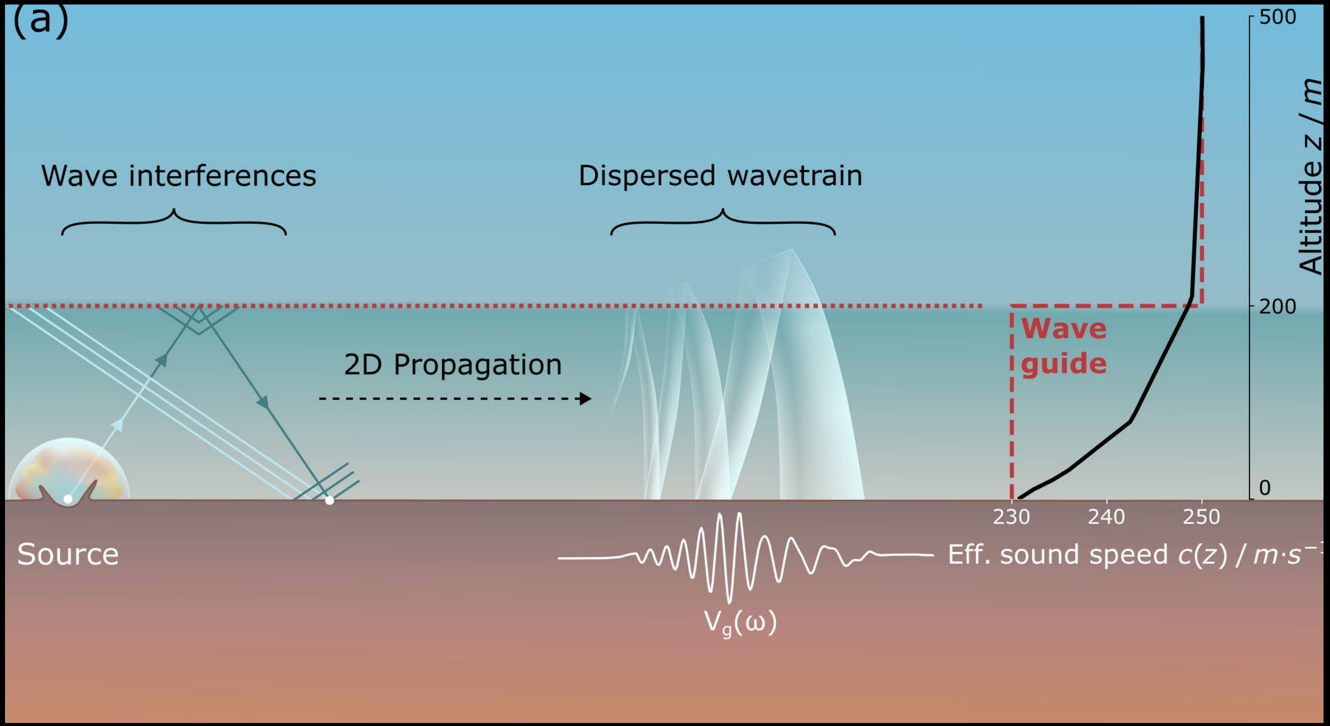
Mars

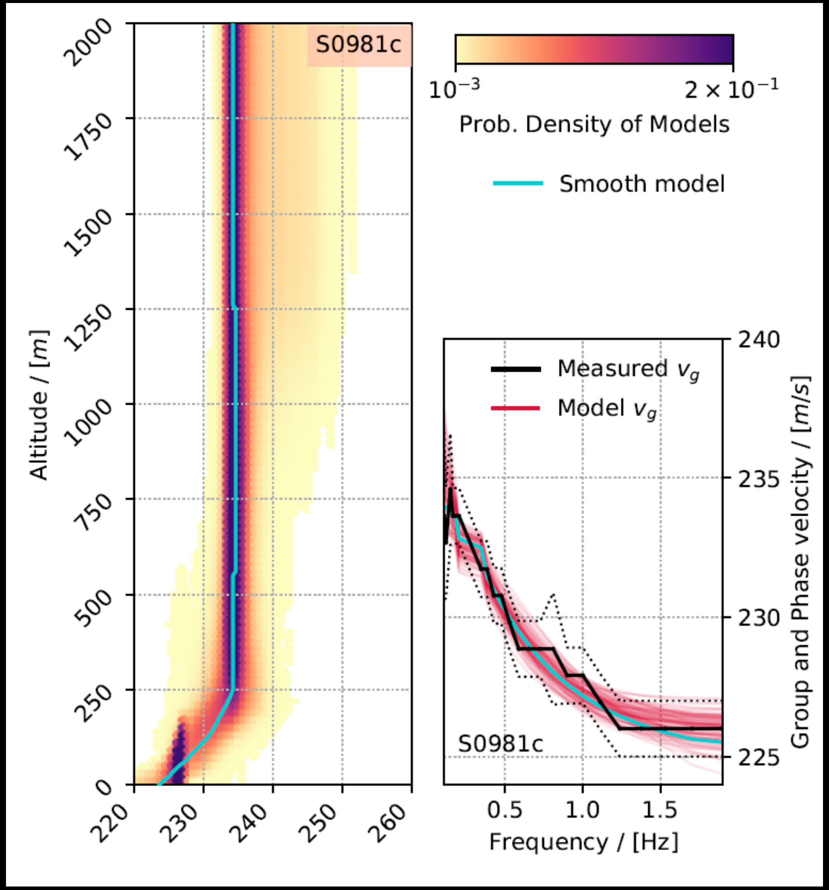




Validating low-altitude atmospheric models from meteor impact infrasound

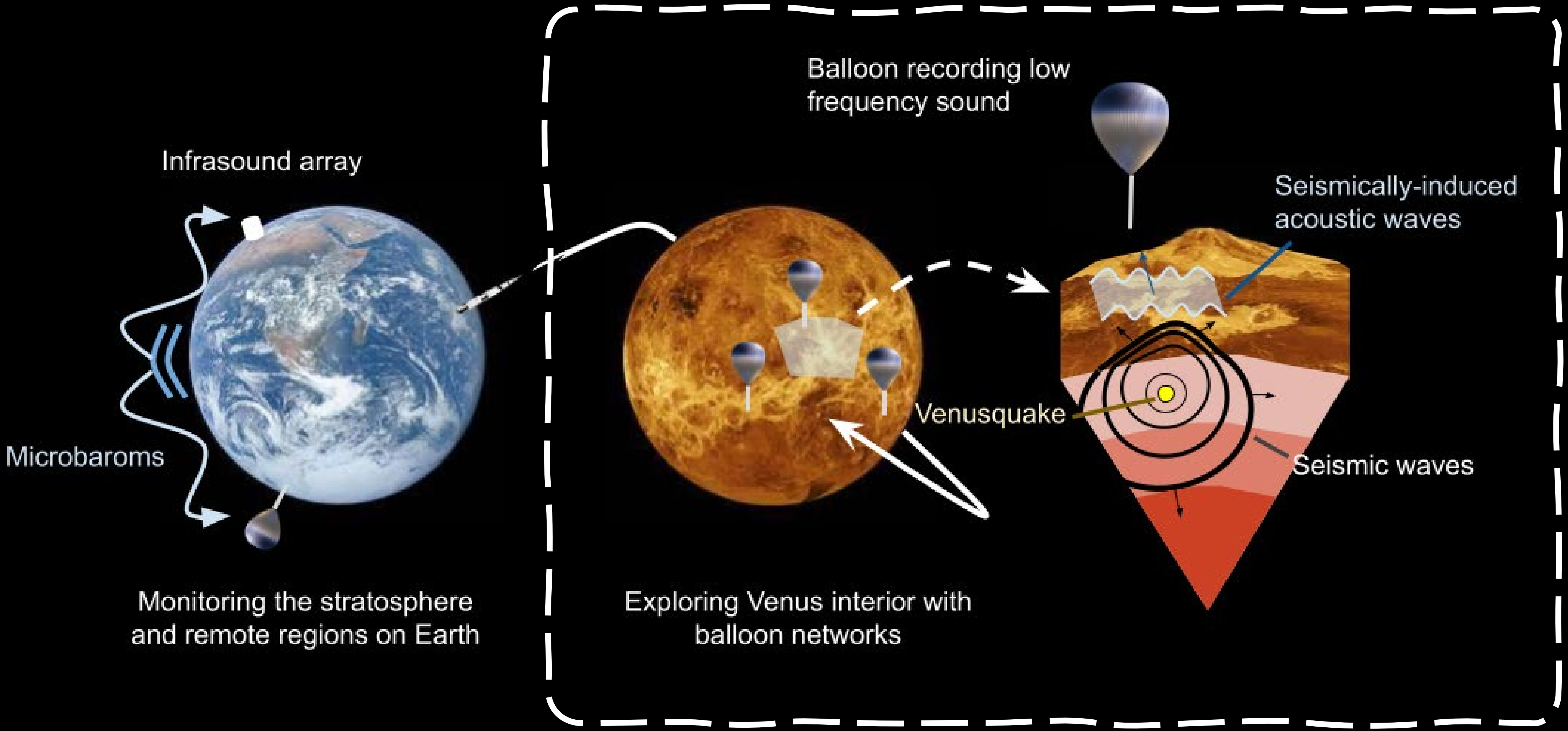
Mars





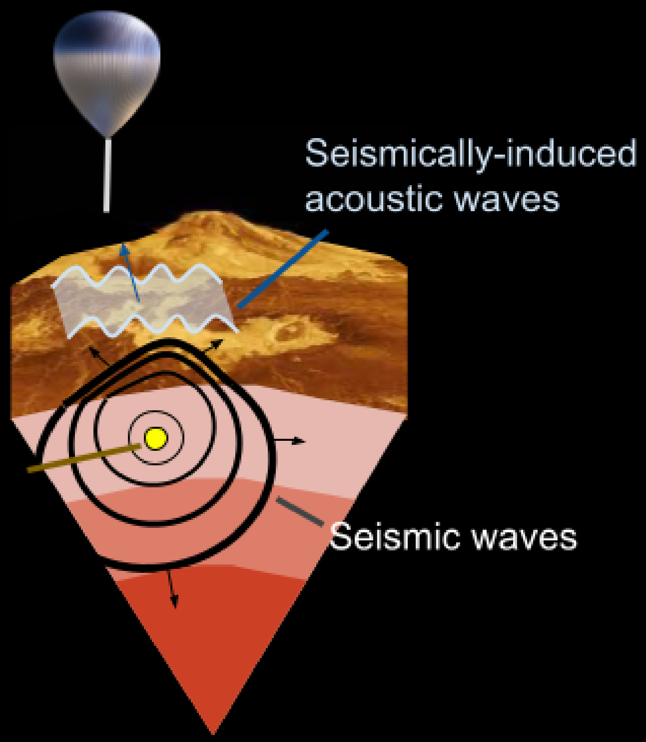
Marouchka Froment, Zongbo Xu, Philippe Lognonné, et al. Probing the Martian atmospheric boundary layer using impact-generated seismo-acoustic signals. *To appear in Geophysical Research Letters*

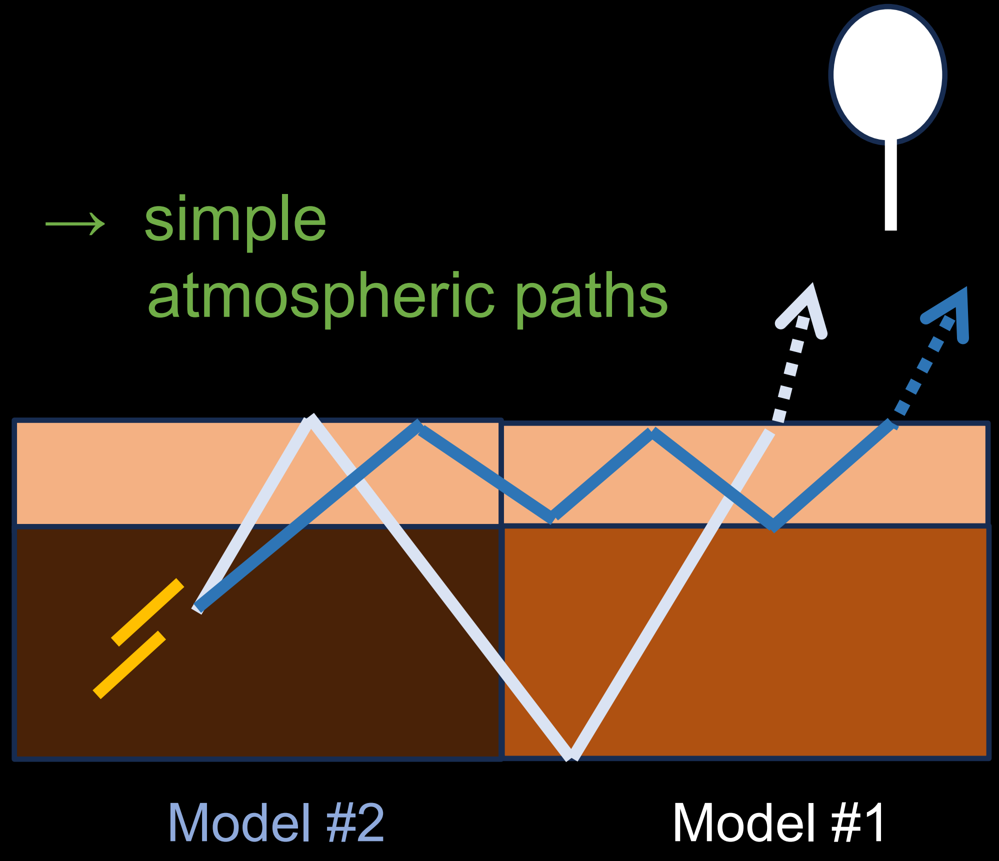
Venus



Infrasound array
Microbaroms
Monitoring the stratosphere and remote regions on Earth
Balloon recording low frequency sound
Seismically-induced acoustic waves
Venusquake
Seismic waves
Exploring Venus interior with balloon networks

Venus

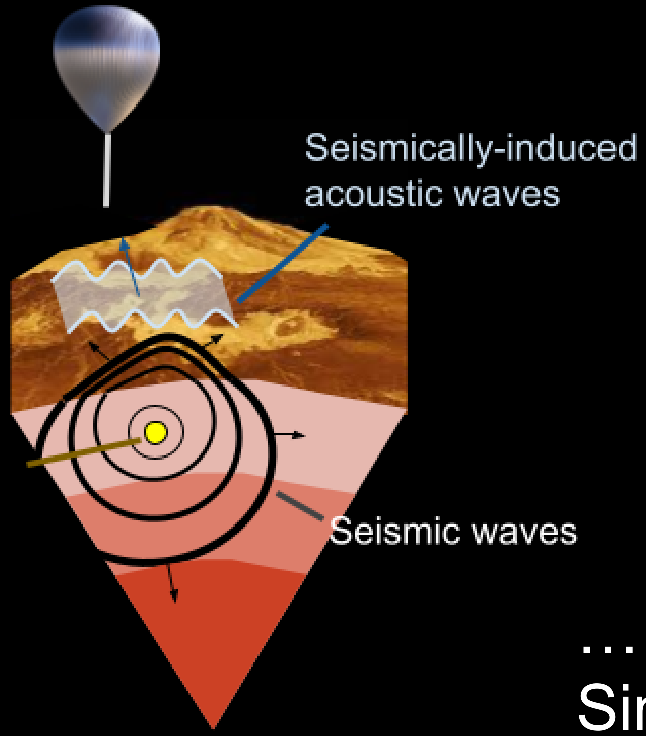


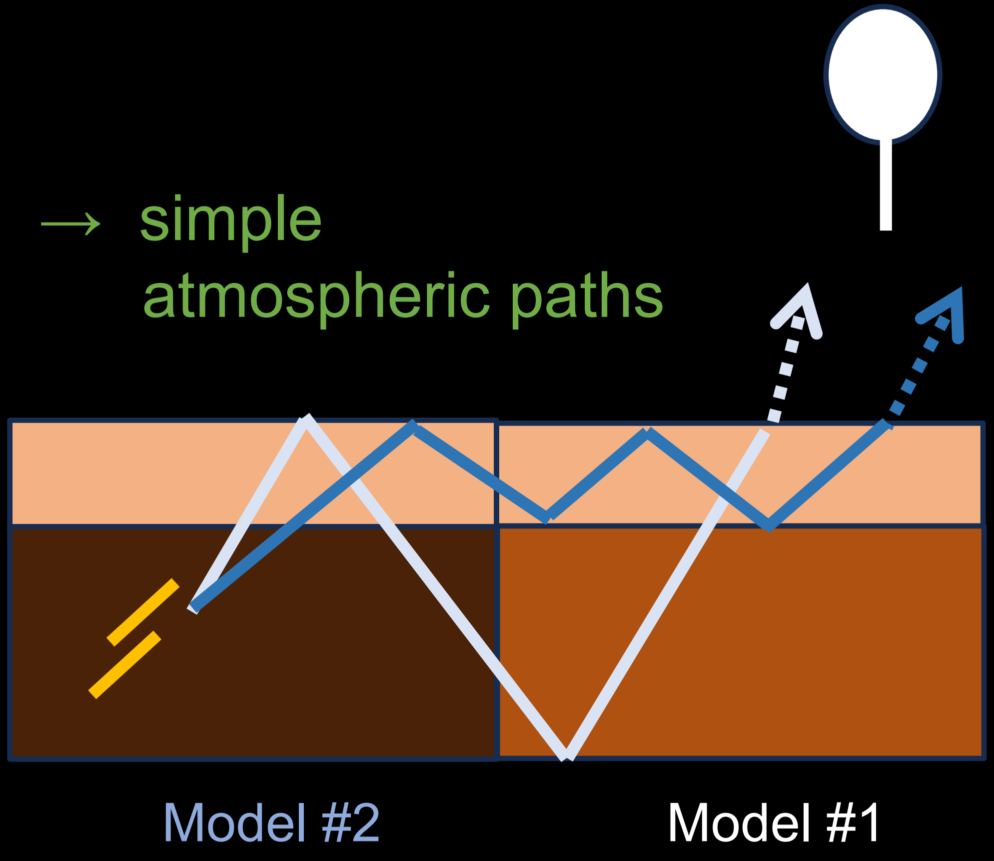


Surface too hot & too much pressure → need alternative

Utilize dispersion of surface-wave induced infrasound recorded at balloons

Venus

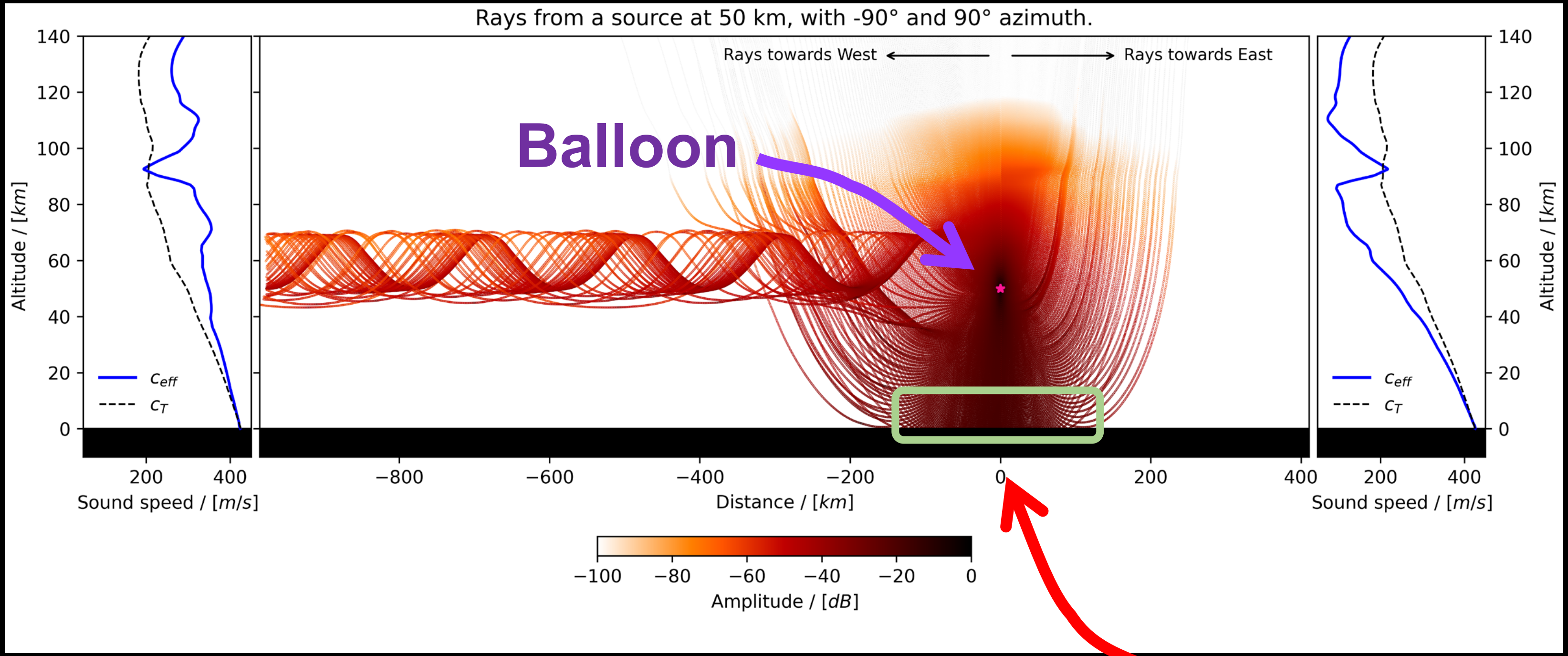




… but how well can we invert for the subsurface?
Simultaneous source & subsurface inversion

→ Partially addressed in synthetic study

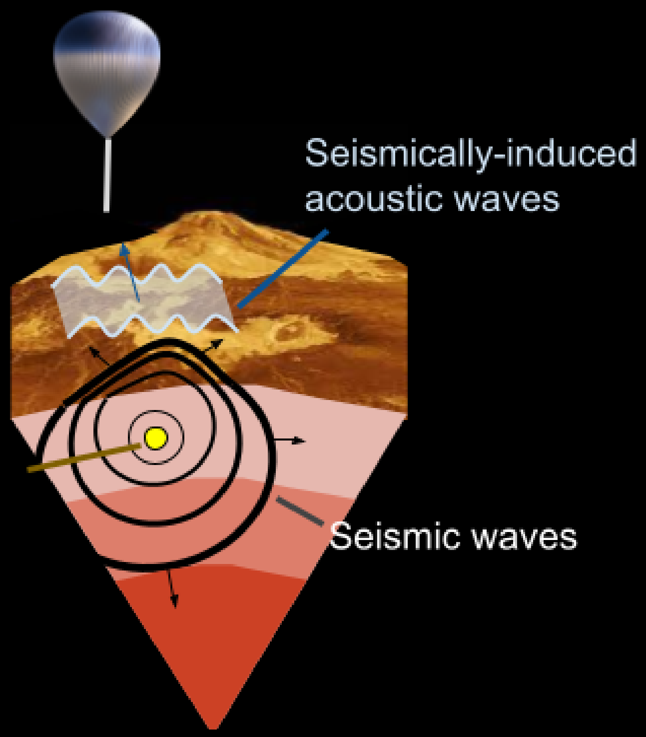
Venus reciprocal ray simulation

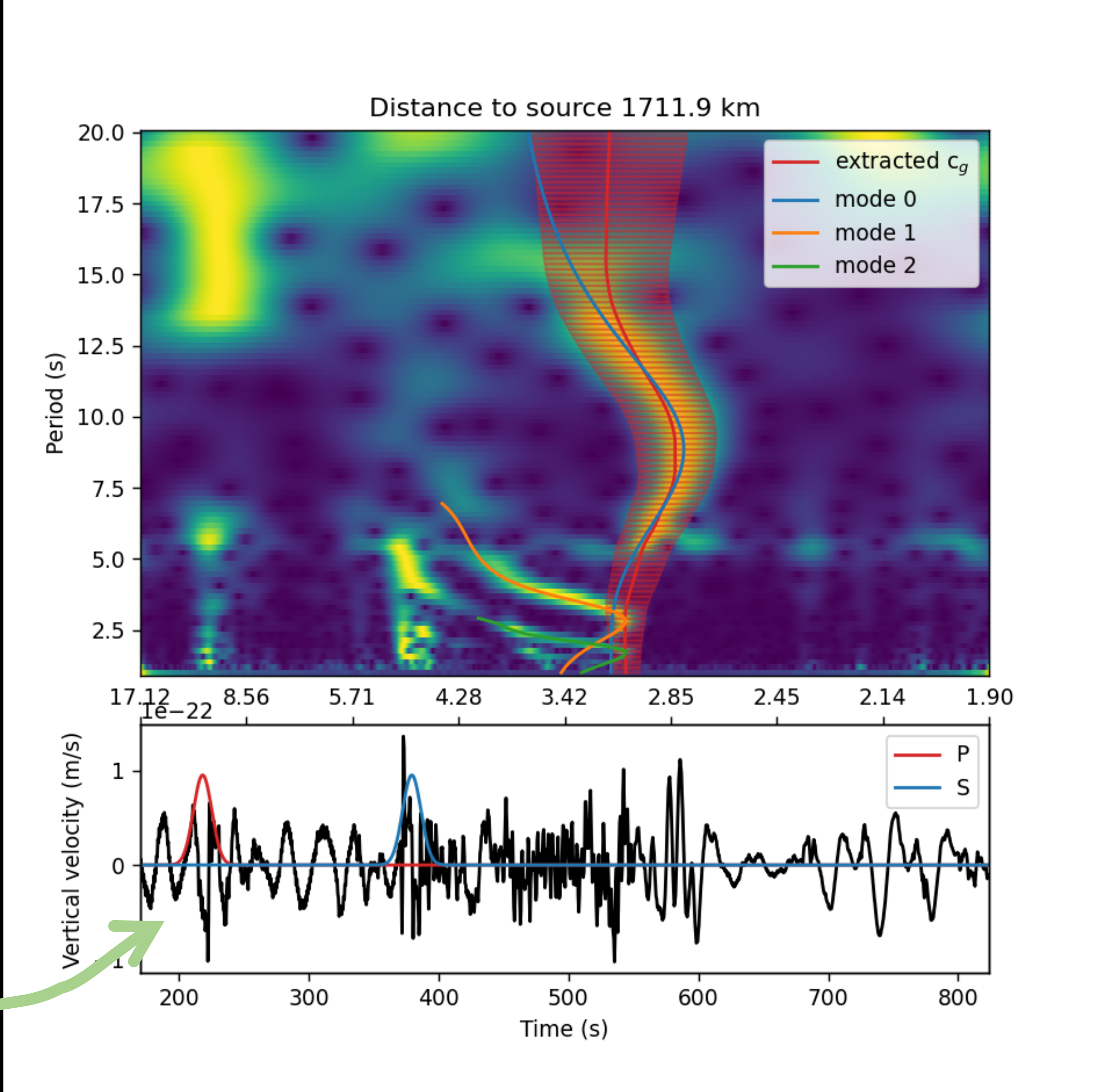


Sensitivity to coupled waves

Epicentral infrasound useful to constrain the source – especially location

Venus synthetics

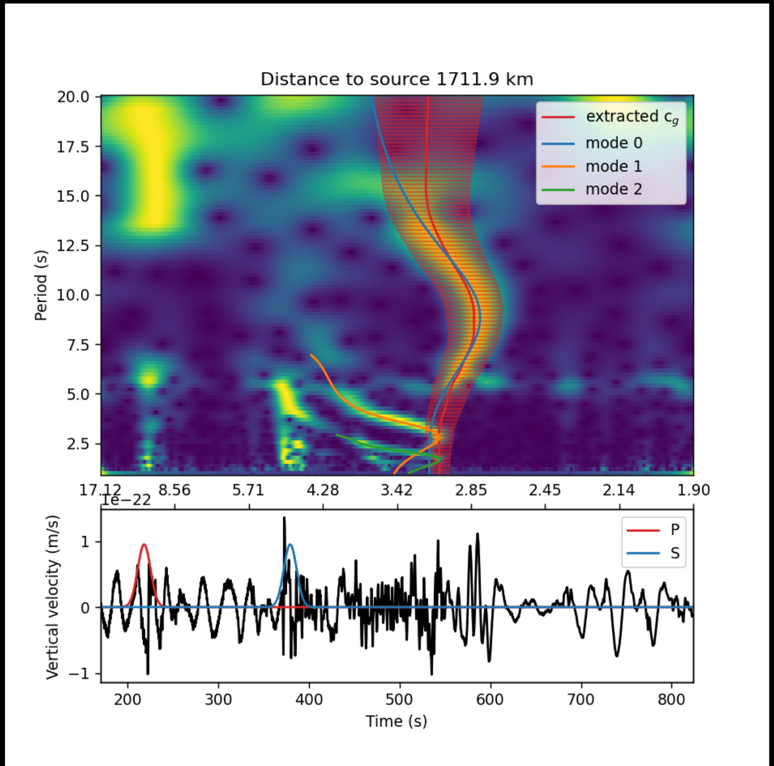


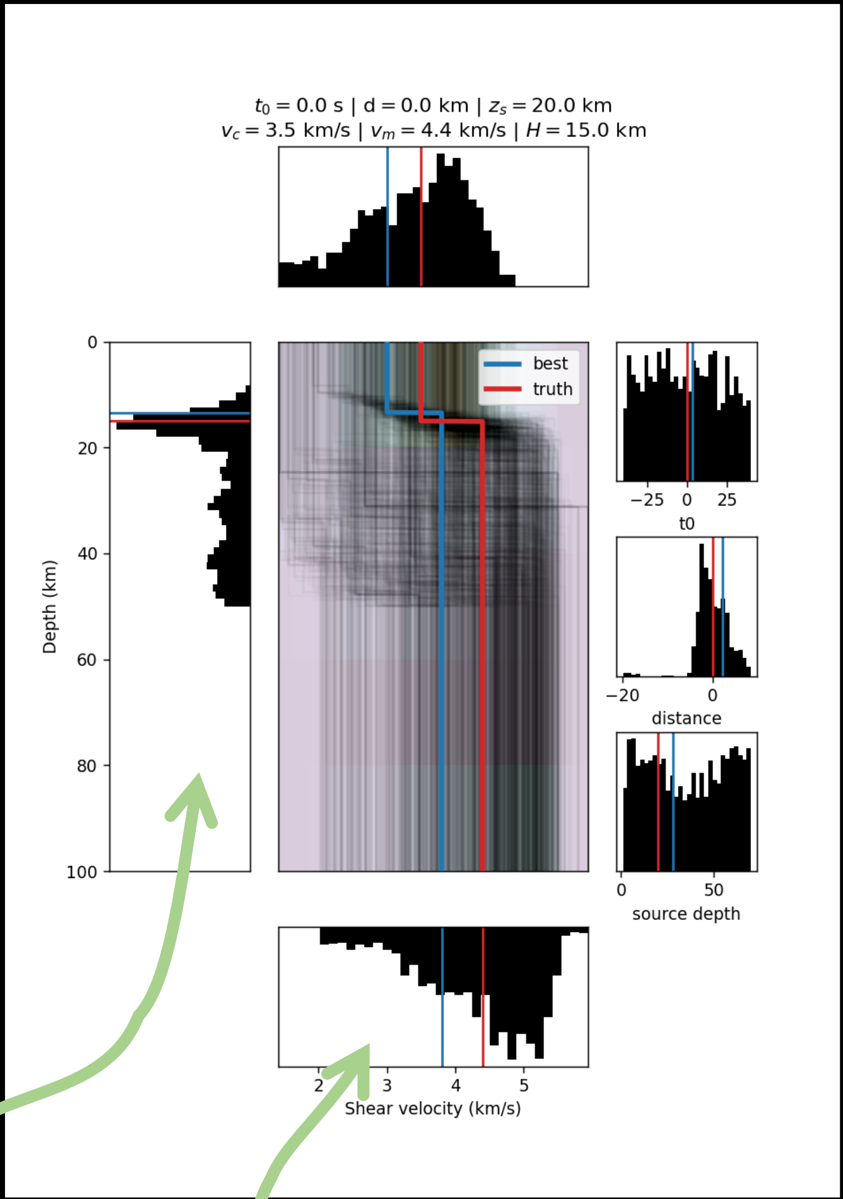


Scaled seismic Green's functions
+ real Earth balloon noise.
Crust-mantle subsurface

Preliminary Venus synthetic study

- **Output:** source location & origin time, two-layer subsurface velocities
- **Input:** Frequency-dependent S & RW infrasound arrival time
- **Sampling:** MCMC

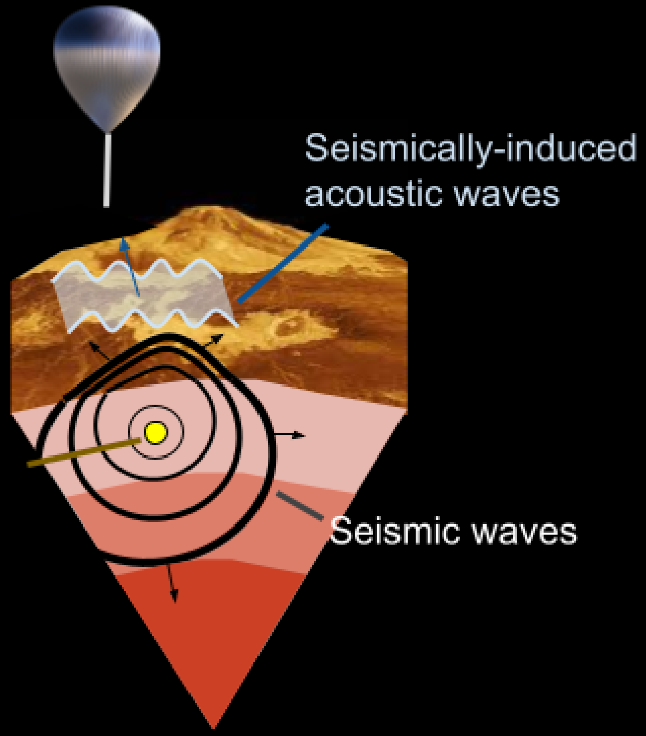


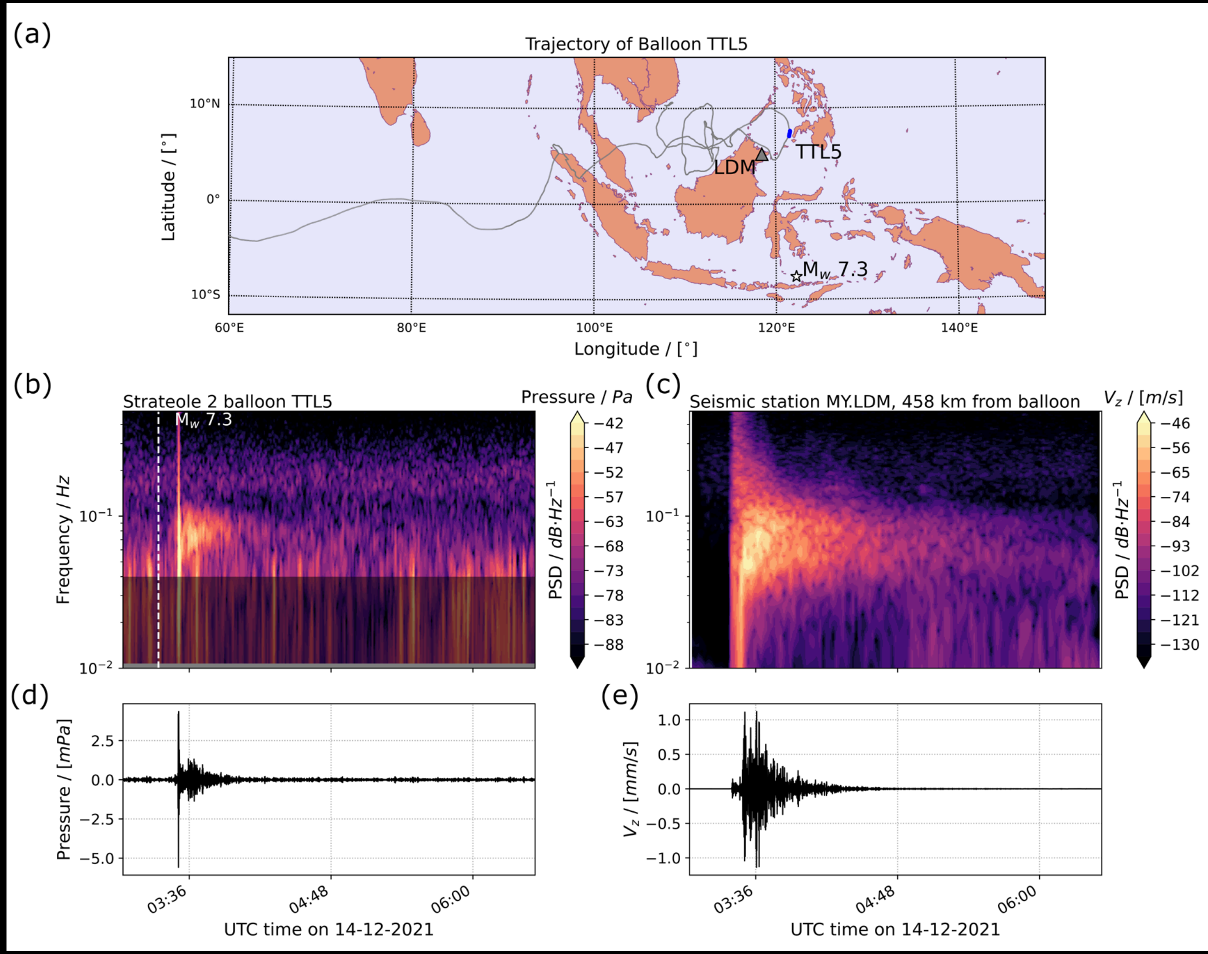


Crustal thickness well-constrained

Poor seismic velocity constraints

We have (a few) clear detections on Earth





Future?

Earth

- Must provide data / products with **added value** in context of all **other probing technologies**
- Forward-modeling verification ↦ Model diagnostics and inter-comparison ↦ Inversion & assimilation proof-of-concept ↦ Operational near-realtime diagnostics & assimilation
- Machine-learning approaches start to tackle numerical weather prediction.
  Will this replace end-to-end classical data assimilation,
  or provide speedup & bias correction, or will we mostly see hybrid approaches?

Beyond Earth

- How to maximize the benefit of Earth balloon data for proof-of-concepts?
- How to provide synthetic results that can convince mission planners?
- How to maximize the information gained from surface-wave based inversion? Beamforming? Highly efficient global modeling tools? Gradient informed MCMC sampling?

Thank you!

Happy to hear your advice & comments!

Funding from Research Council of Norway basic research programme FRIPRO:

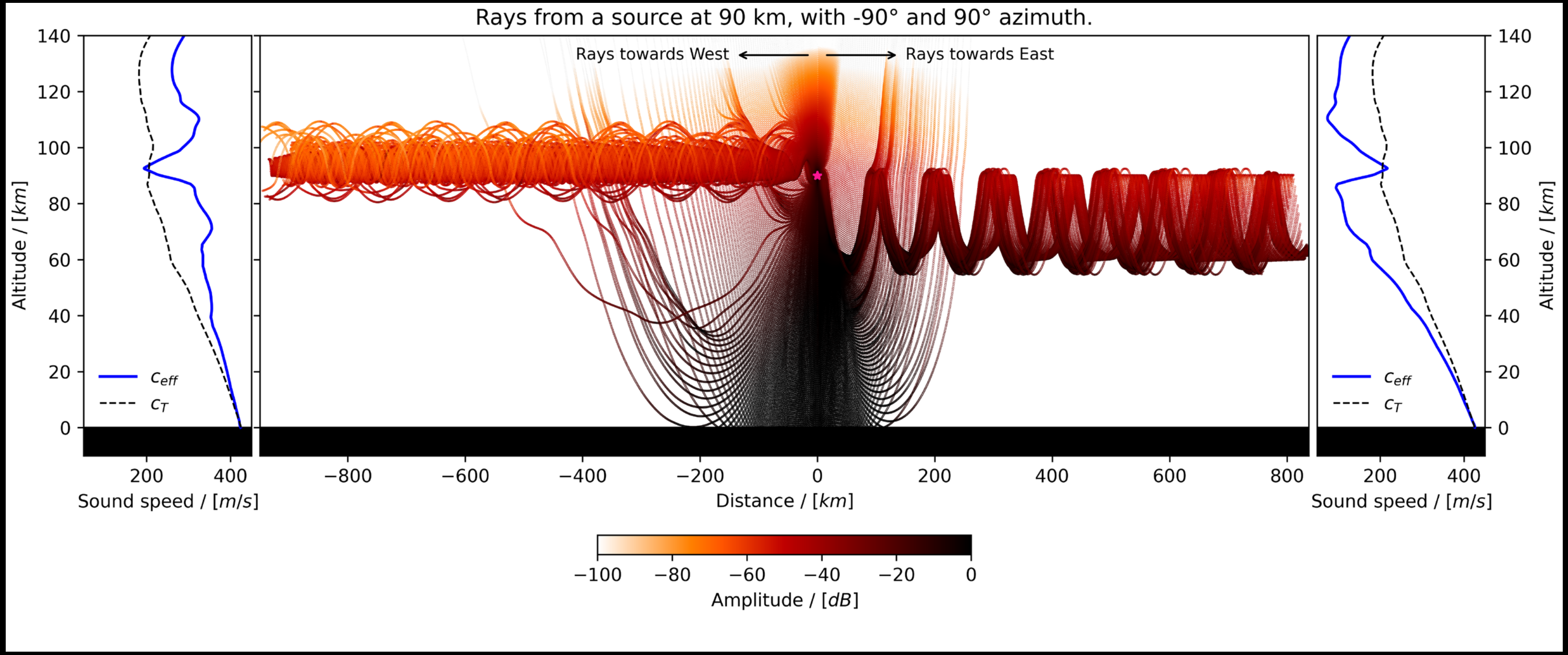
- *Airborne Inversion of Rayleigh Waves* (grant 335904)
- *Middle Atmosphere Dynamics: Exploiting Infrasound Using a Multidisciplinary Approach at High Latitudes* (grant 274377)

Supporting slides

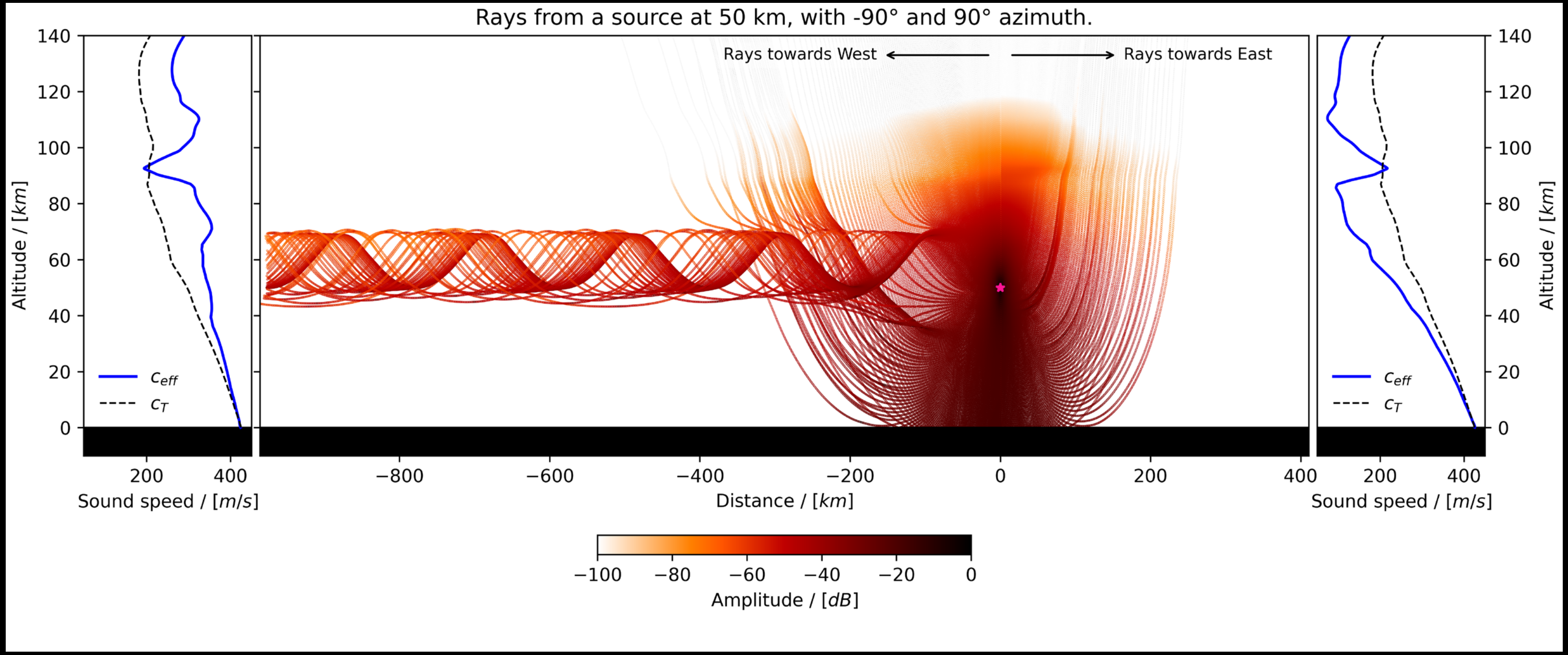
Venus

Sensitive to waves coupled ≲ 200 km epicentral radius

90 km



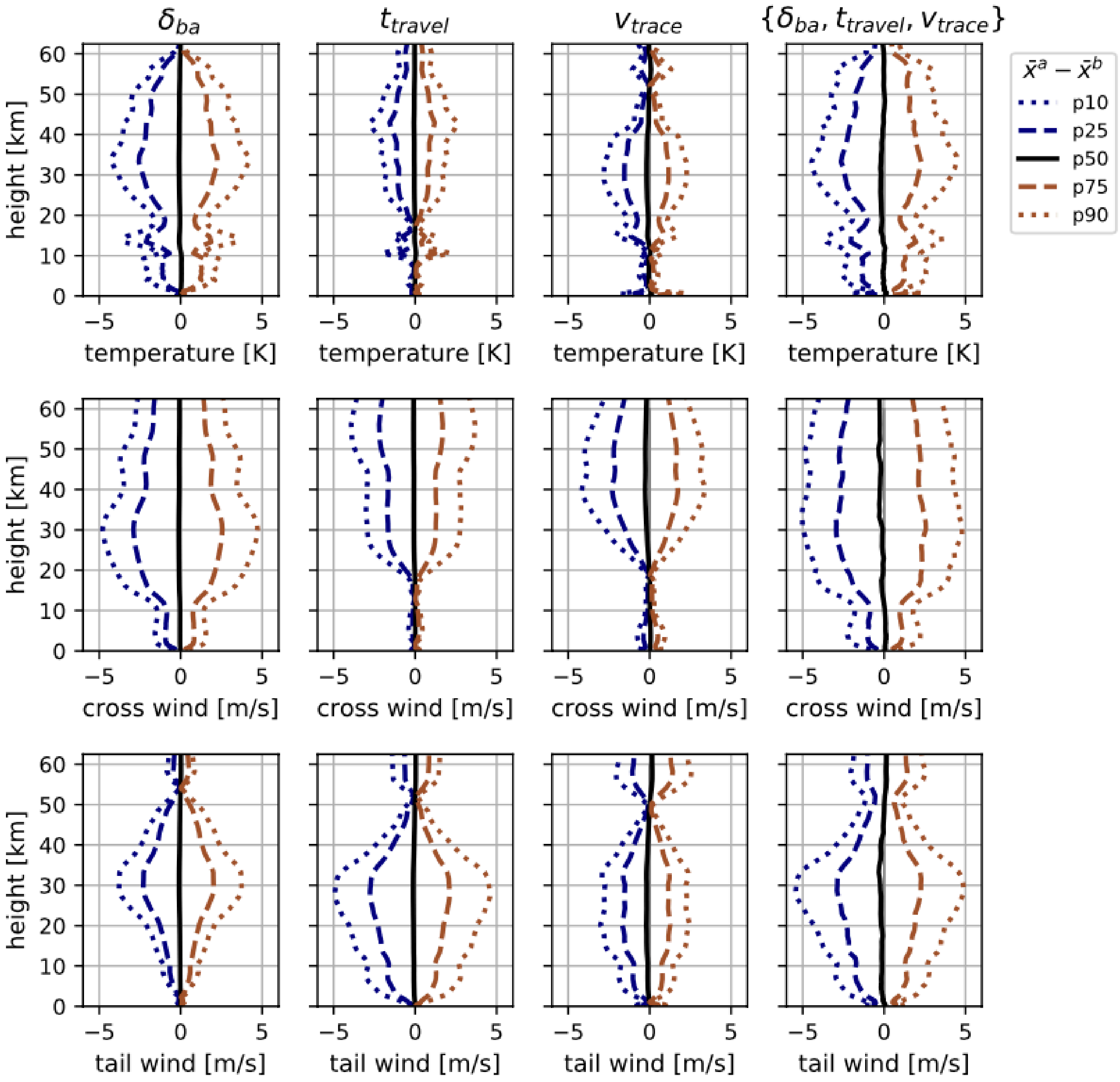
50 km

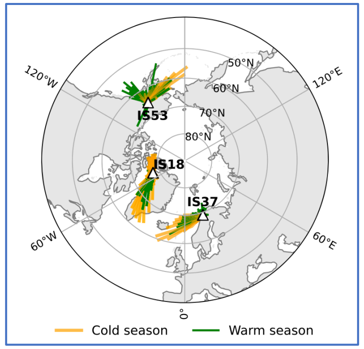


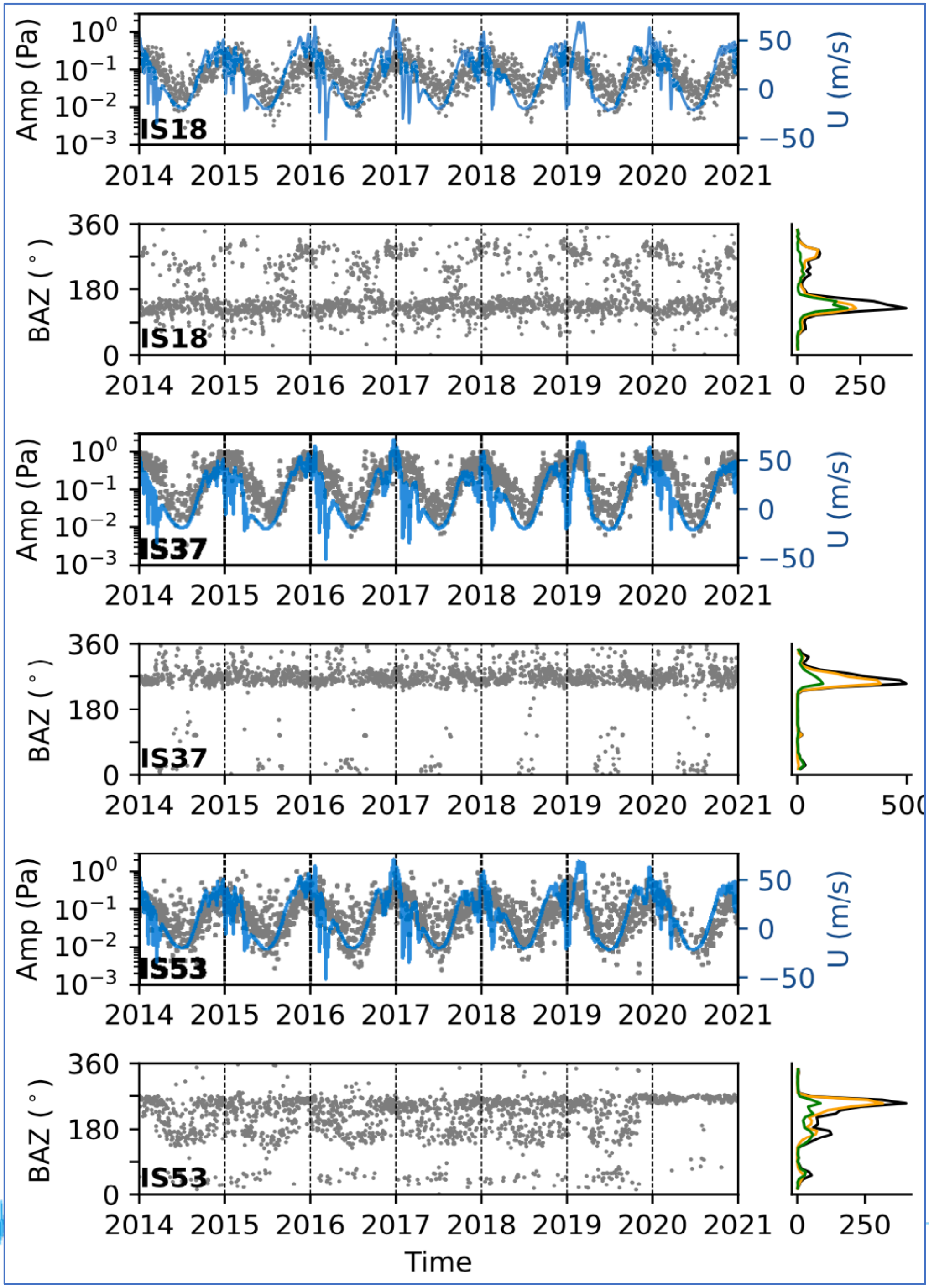
- Opportunities also for back-projection into the solid
- Building a dispersion-analysis based subsurface inversion framework

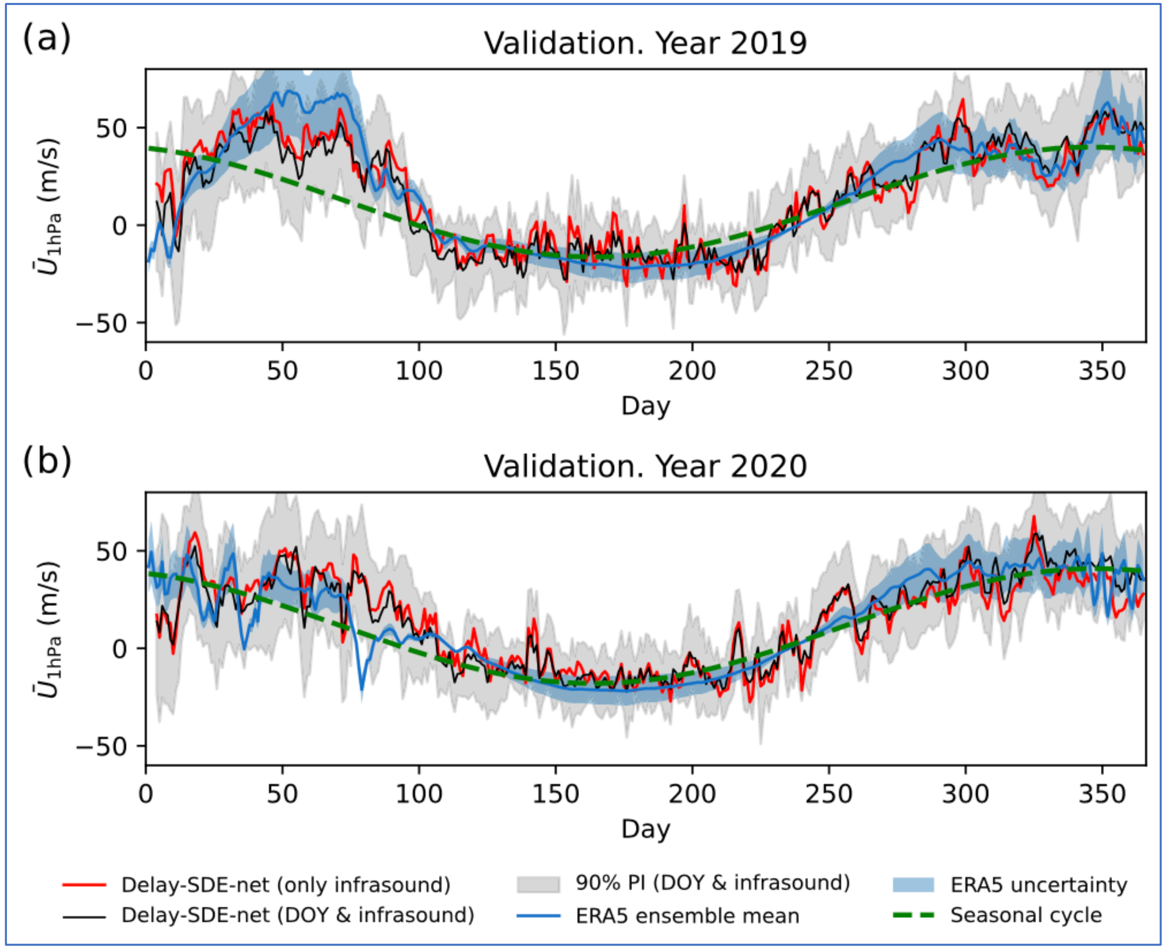
Using satellite data assimilation techniques to combine infrasound observations and a full ray-tracing model to constrain stratospheric variables

Javier Amezcua[a, b] , Sven Peter Näsholm[c,d] , Ismael Vera-Rodriguez[e,f]




120°W
50°N
60°N
120°E
70°N
80°N
IS53
IS18
IS37
60°W
60°E
0°
Cold season
Warm season

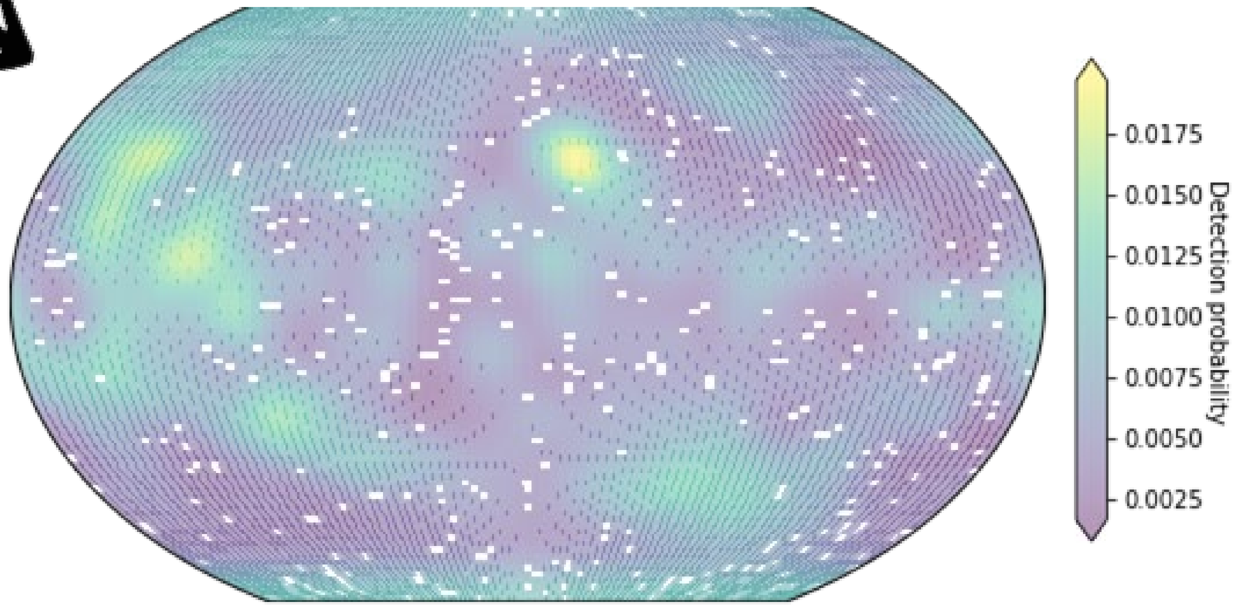

Amp (Pa)
U (m/s)
IS18
BAZ (°)
IS37
IS53
2014 2015 2016 2017 2018 2019 2020 2021
Time


(a)
Validation. Year 2019
(b)
Validation. Year 2020
$\bar{U}_{1hPa}$ (m/s)
Day
Delay-SDE-net (only infrasound)
Delay-SDE-net (DOY & infrasound)
90% PI (DOY & infrasound)
ERA5 ensemble mean
ERA5 uncertainty
Seasonal cycle

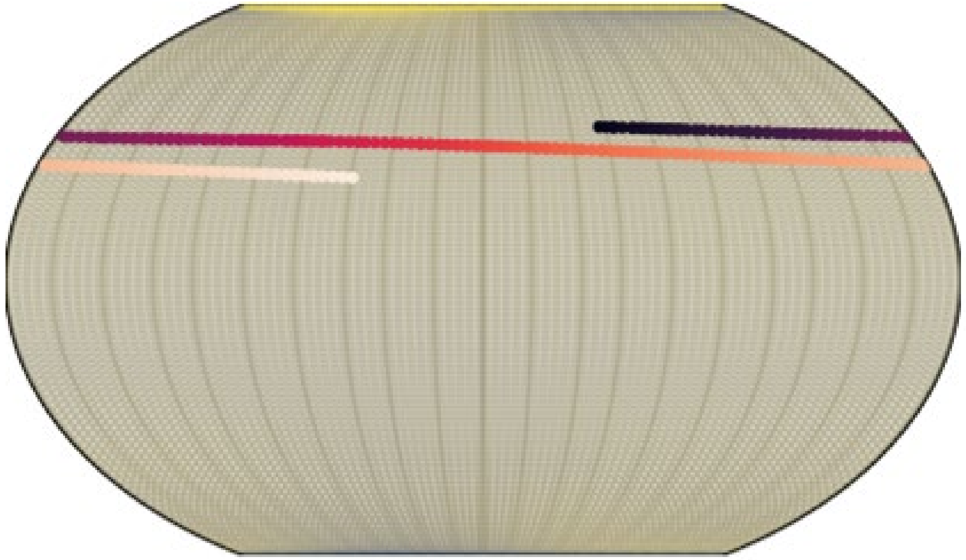
Current goal: Estimating detectability at a global scale

We want to address a first basic question: **How likely would a temporary balloon mission detect an event over a given magnitude?**

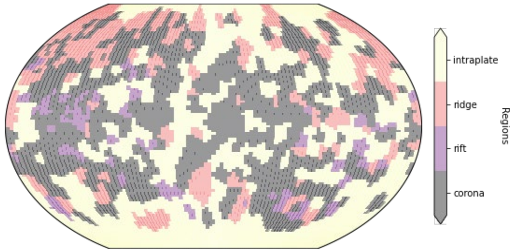
Detection probability of any event at a given location



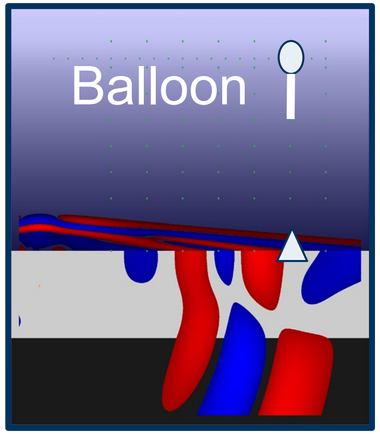
Balloon flight trajectory



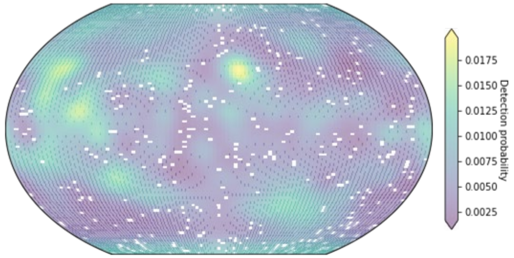
Estimating detectability: What do we need?



Seismicity estimates
Time and spatial distribution of venusquakes in different tectonic regions

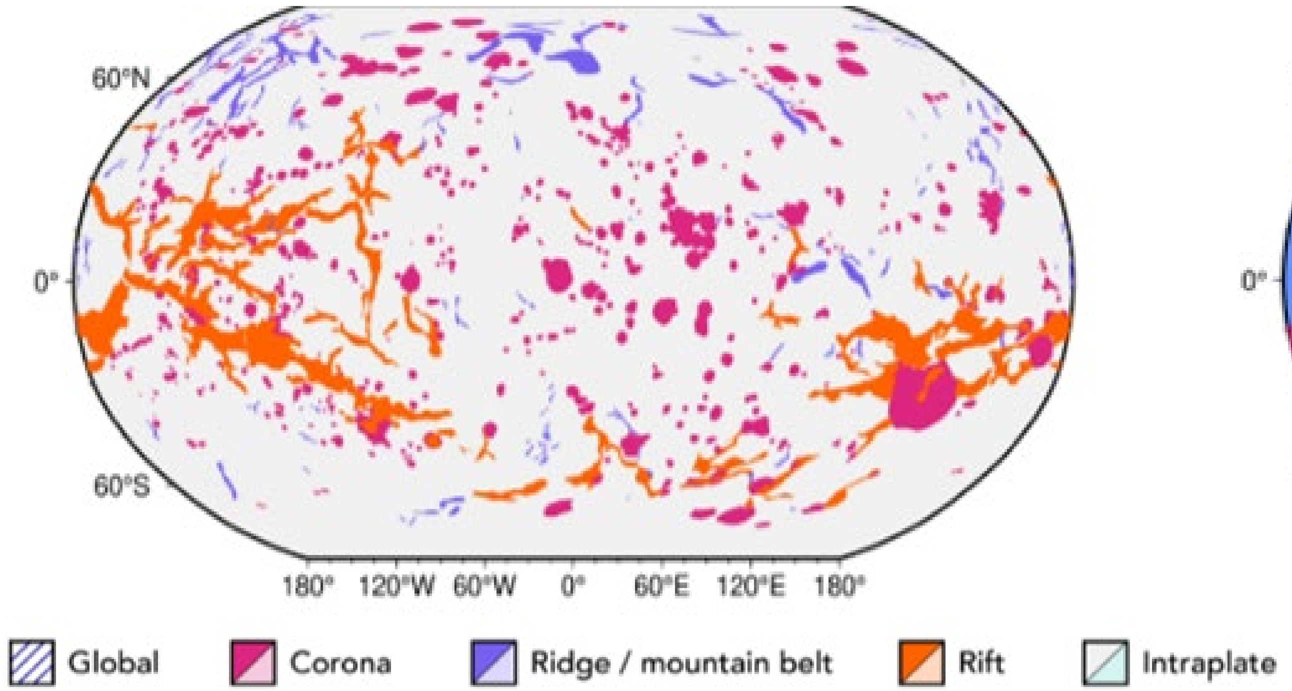


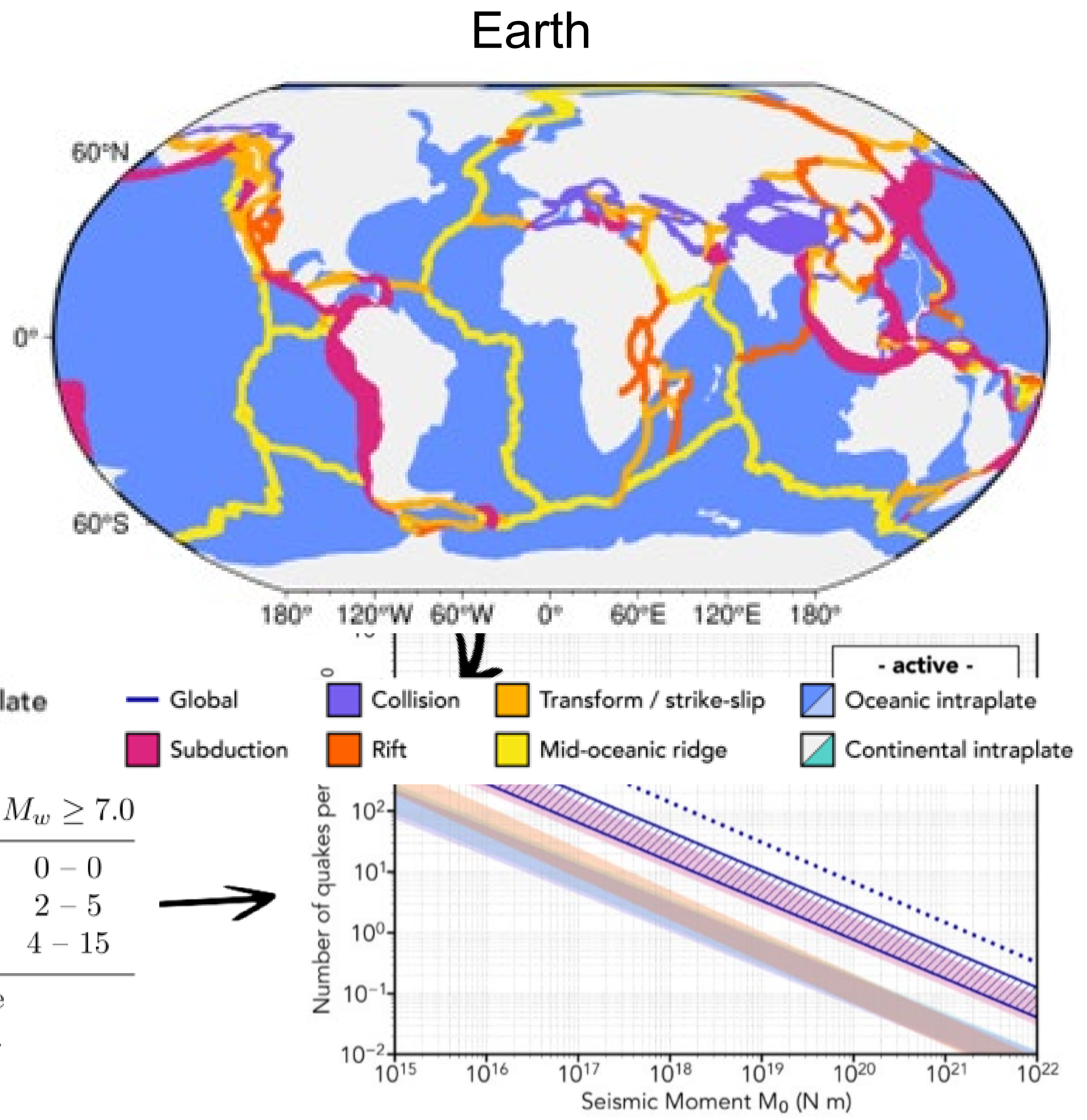
Wave simulator
Seismoacoustic simulations with SPECFEM-DG



Detection probability model
Compute likelihood of detecting any event over a given time period and at a given location

Constraining seismicity (from Van Zelst, 2023)





Estimate	$M_w \geq 3.0$	$M_w \geq 4.0$	$M_w \geq 5.0$	$M_w \geq 6.0$	$M_w \geq 7.0$
Inactive Venus	826 - 2568	95 – 296	11 – 34	1 – 4	0 – 0
Active Venus - lower bound	10760 - 33460	1161 – 3609	126 – 391	14 – 42	2 – 5
Active Venus - upper bound	84263 - 262023	5715 – 17773	465 – 1446	44 – 136	4 – 15

Table 1. Number of venusquakes per year equal to or larger than a certain moment magnitude for our three possible Venus scenarios. A range is provided based on the uncertainties in the chosen scaling factor for the seismogenic thickness.

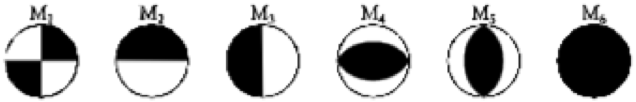
Simulating seismoacoustic signals: Strategy

Atmospheric model
Extracted from Venus Climate Database

Seismic model
Candidates for seismic models based on Earth scaling

Wave simulator
Seismoacoustic simulations with SPECFEM-DG

Focal mechanism model
Compute waveforms for fundamental moment tensors



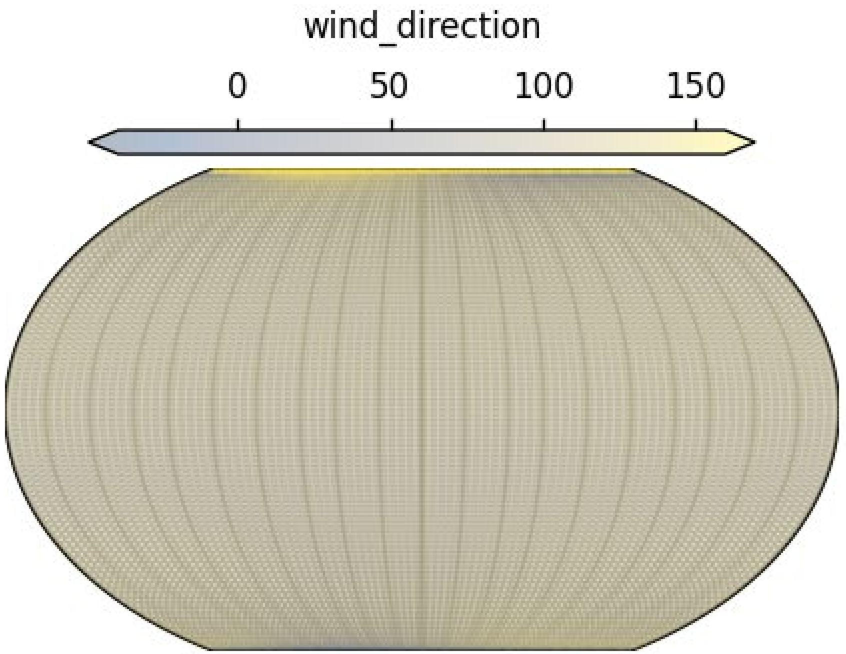
Convolution with source time function
Accounting for source time function dependence on magnitude

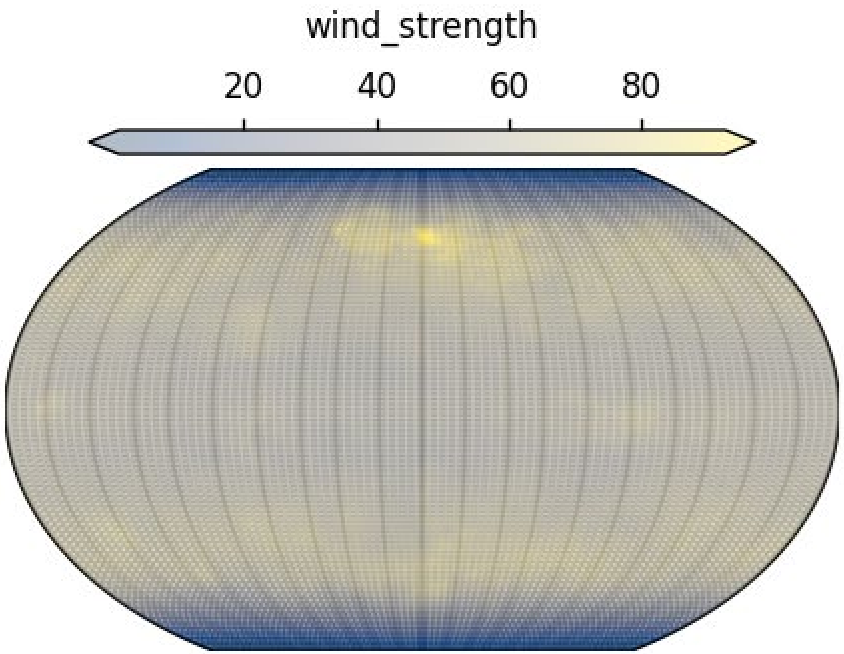
Extrapolation amplitudes to large distances
Curve fitting of amplitudes assuming asymptotic behaviour

amp(distance) **=**
a ╳ distance$^{\mathbf{b}}$
+ c ╳ distance$^{\mathbf{d}}$

Simulating seismoacoustic signals: An atmos. model

The Venus Climate Database (VCD) provides hourly predictions of winds, temperatures, and atmospheric compositions with altitude

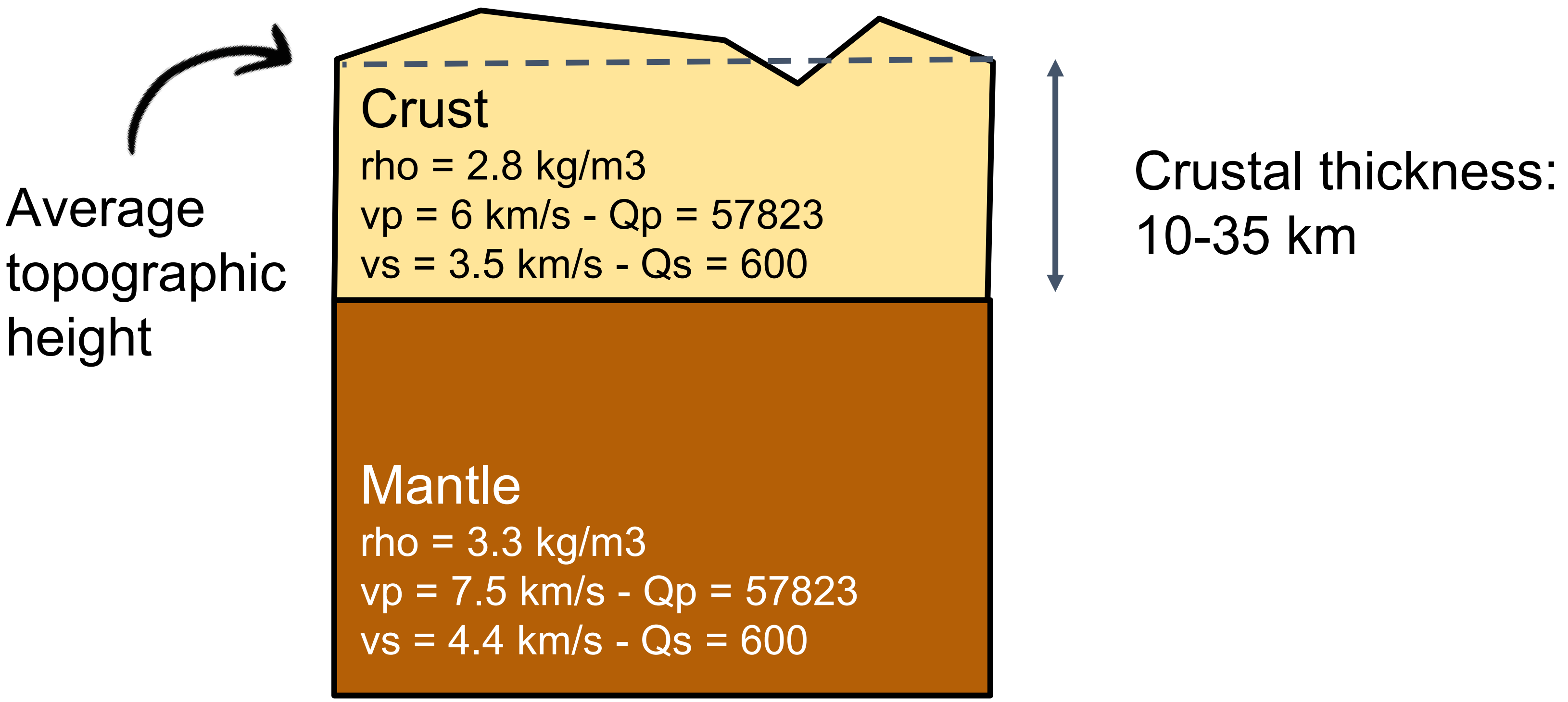




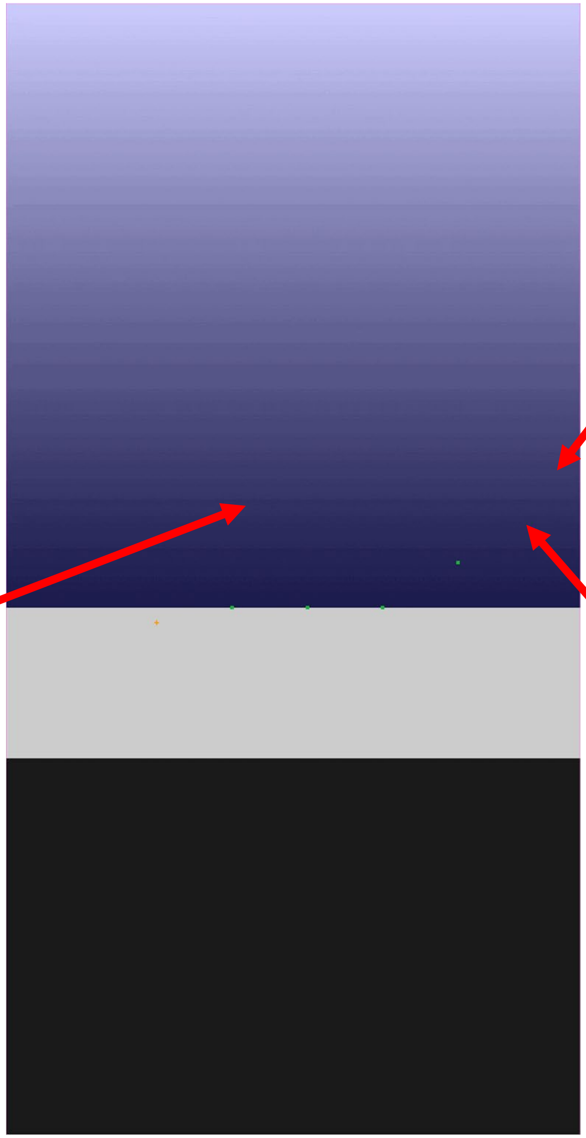
Winds at 50 km altitude

Simulating seismoacoustic signals: A seismic model

Very little constraints on the properties of the crust and mantle on Venus so we use a pressure rescaled version of the **Preliminary Reference Earth Model (PREM) as a starting point**



Simulating seismoacoustic signals



Scattered body waves

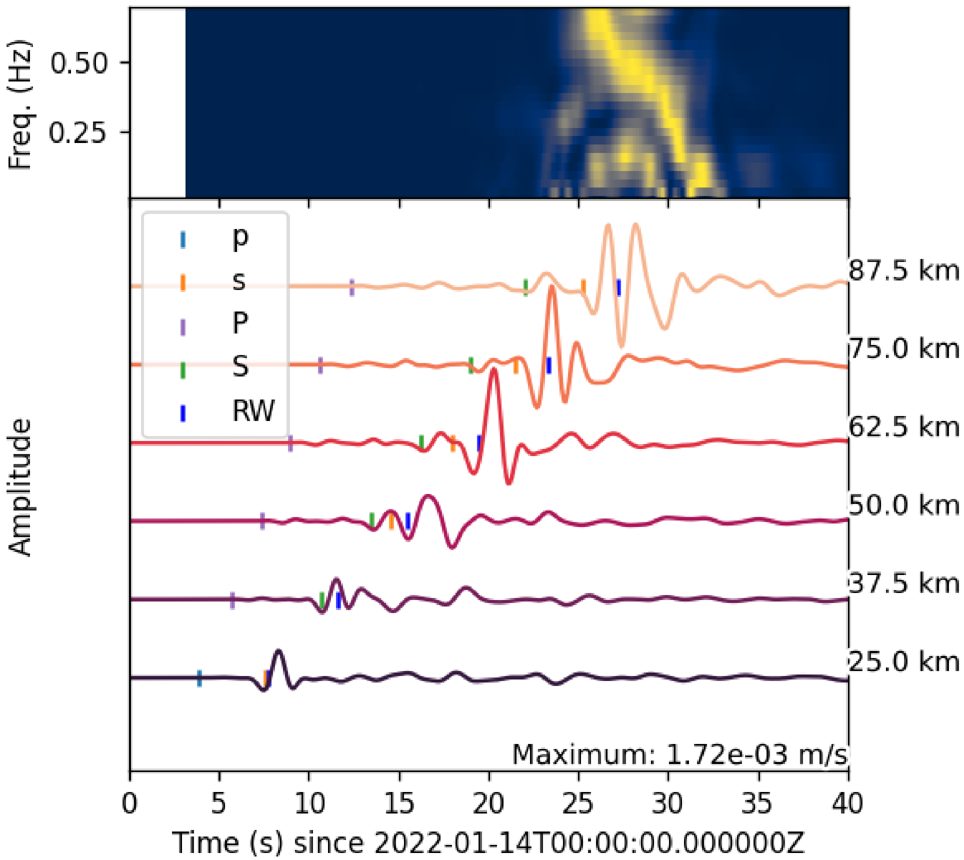
Epicentral Infrasound generated just above the epicenter

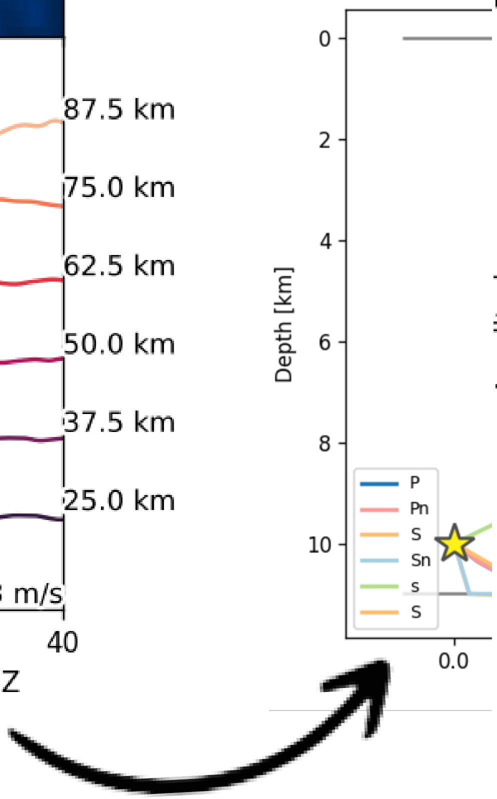
Surface waves

Simulating seismoacoustic signals

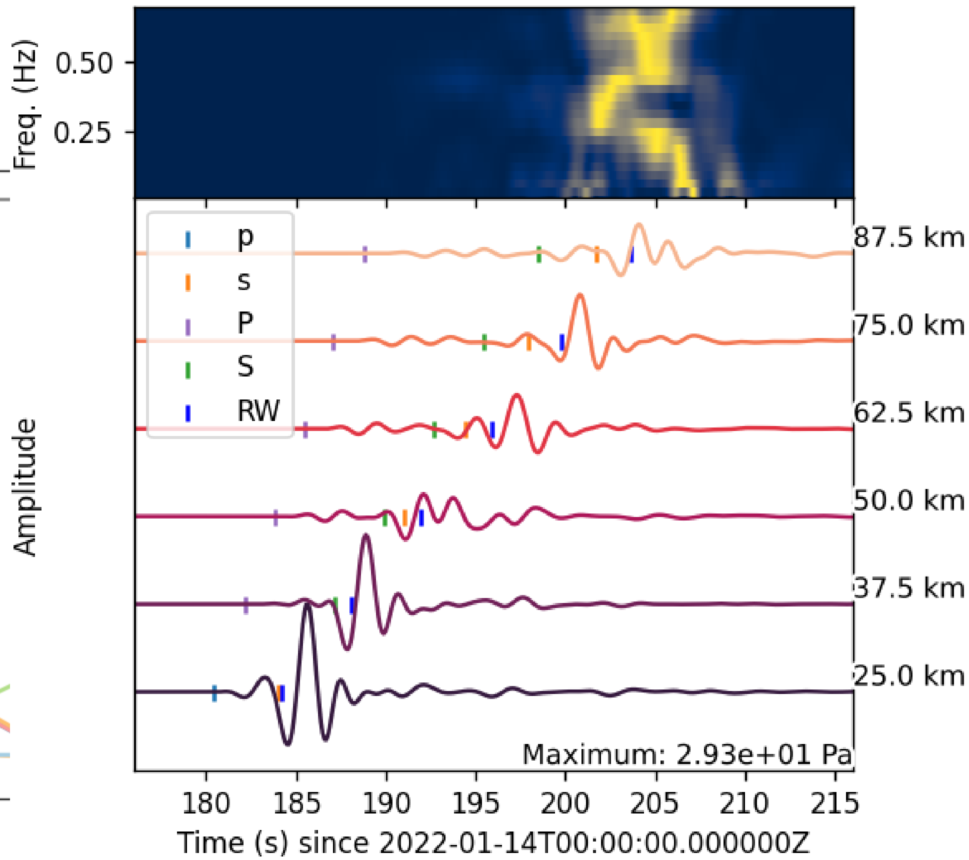
Example of simulation outputs for a source with Mw 5 at 10 km depth and half duration 2 s

Seismic sensors



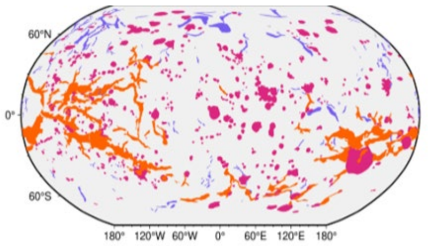


Balloon sensors at 60 km altitude



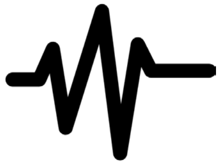
Detection probability model

Seismicity estimates



How likely is an event **e** to occur at a **given location** over a **given time** period

Simulated waveforms



How likely is a balloon to detect event **e** for a certain **noise level** and at a **given location b**

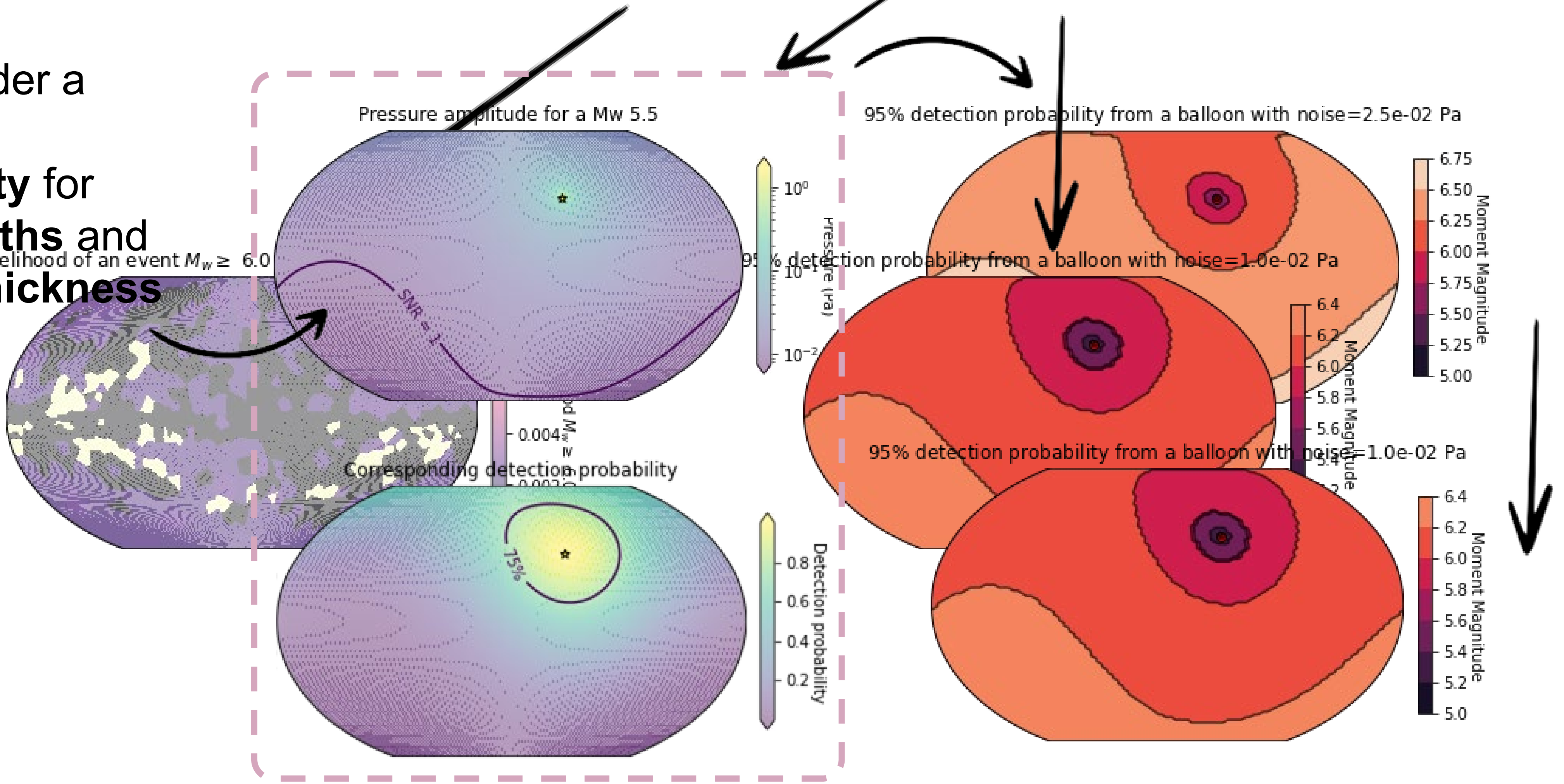
How likely is a balloon to detect **ANY** event from a **given location**

$$\mathbb{P}(b_{gh})_{gh\in\Omega} = 1 - \prod_{ijkM_0}(1 - \mathbb{P}(e_{ijkM_0})\mathbb{L}(\mathrm{amp}|e_{ijkM_0}, b_{gh}, \mathrm{noise}_{ij}))$$

A global view of detectability

$$\mathbb{P}(b_{gh})_{gh\in\Omega} = 1 - \prod_{ijkM_0}(1 - \mathbb{P}(e_{ijkM_0})\mathbb{L}(\mathrm{amp}|e_{ijkM_0}, b_{gh}, \mathrm{noise}_j))$$

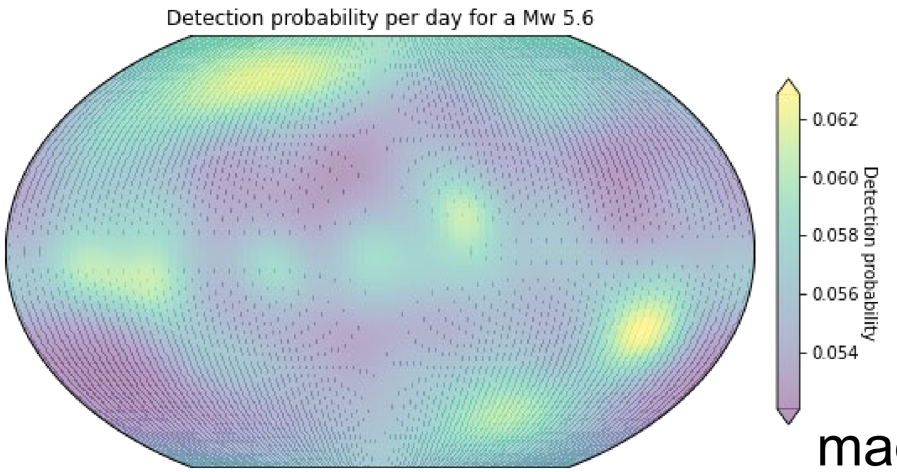
We consider a **uniform probability** for **focal depths** and **crustal thickness**



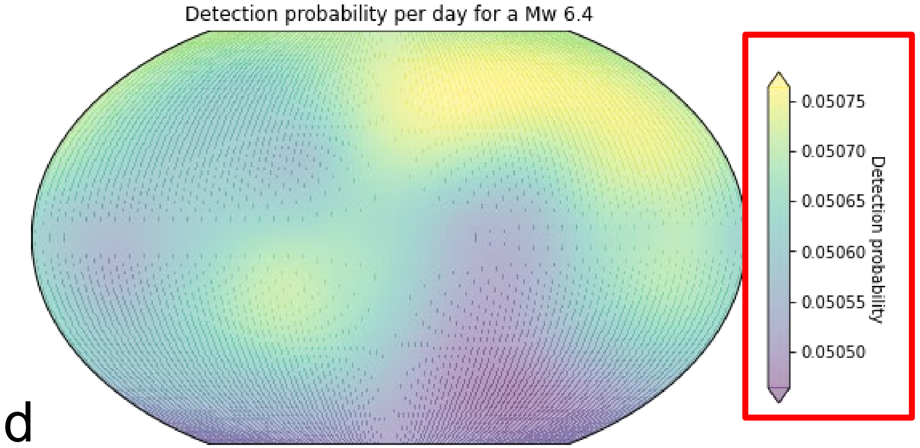
Lower noise level

A global view of detectability in an active Venus setting

Only little variations of detectability with location due to the **very strong coupling between the ground and the atmosphere** (~100 times stronger than Earth)



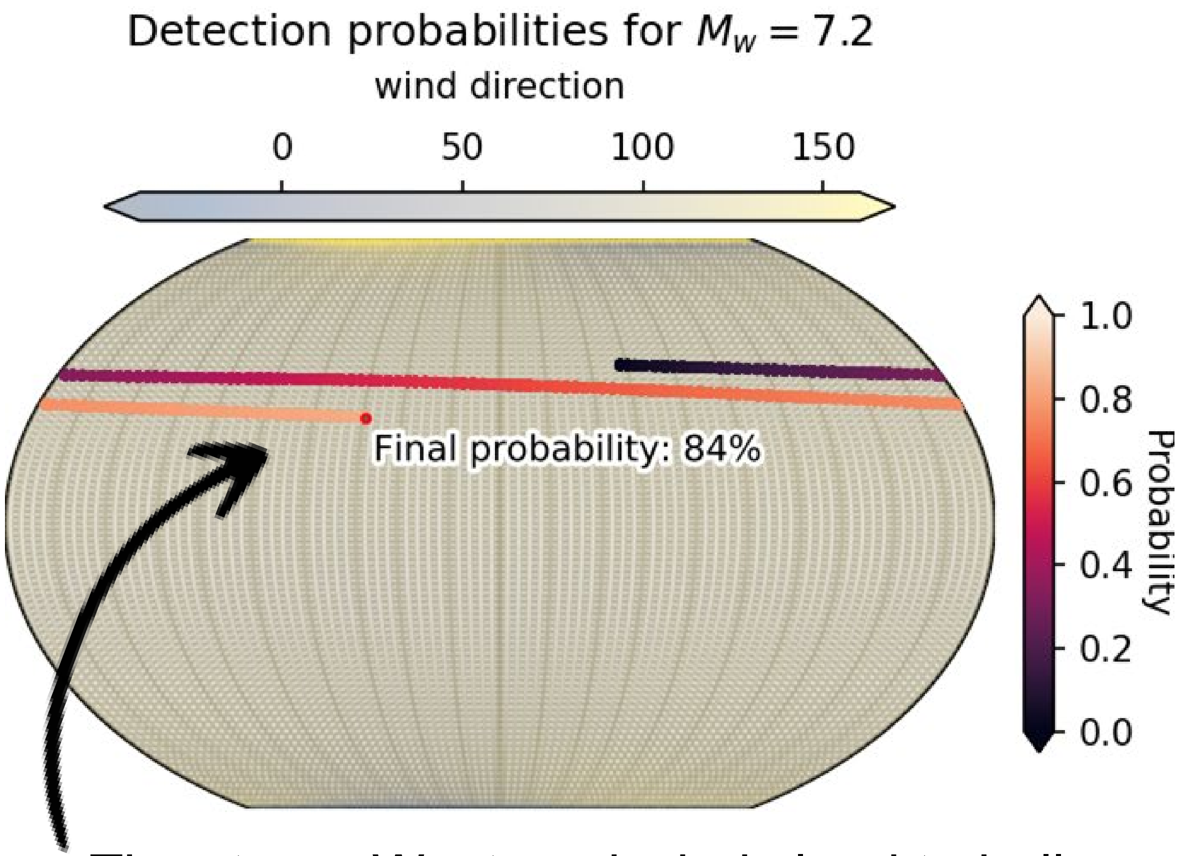
Increasing magnitude threshold

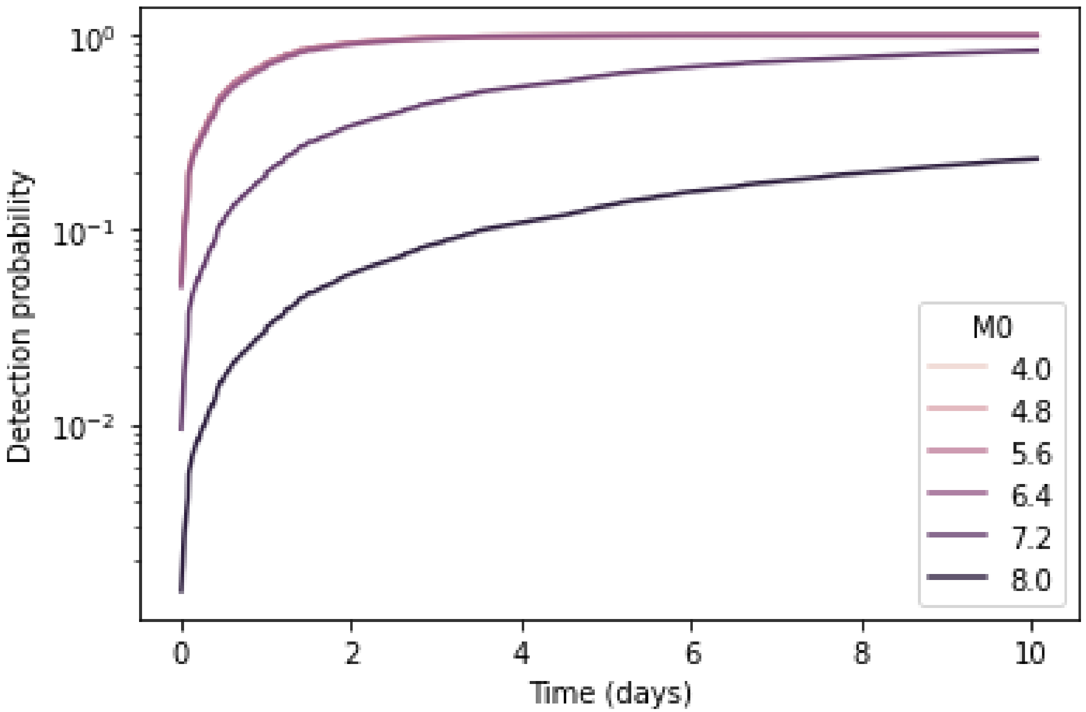


<< 1% variations

What if our sensors are moving?

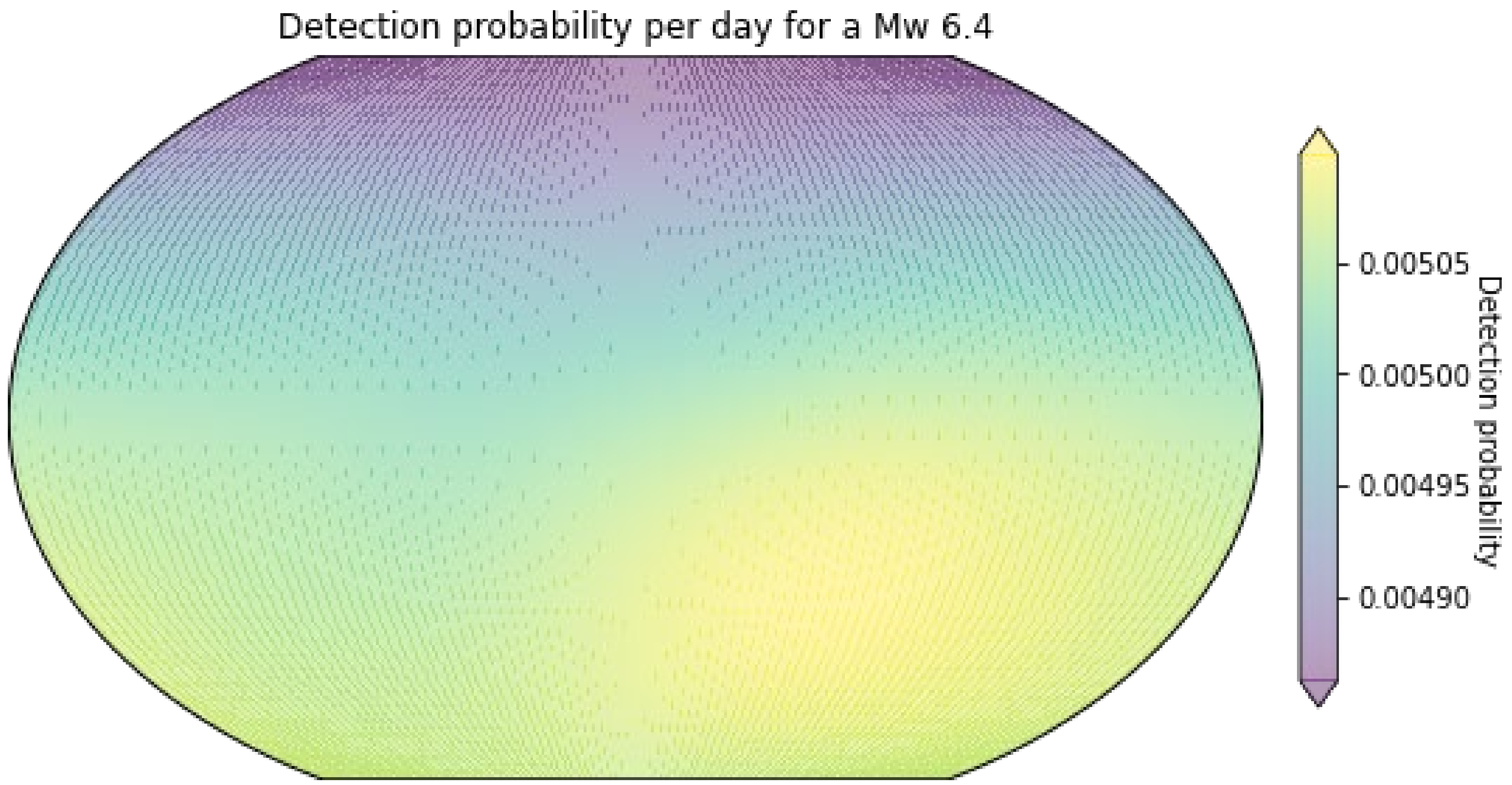
We simulate balloon trajectory by assuming a constant flight altitude of 50 km and a balloon drifting freely with the wind





The strong Westward winds lead to balloons travelling mostly along latitude lines

Inactive Venus



Resolving elementary moment tensors

Hejrani, B., & Tkalčić, H. (2020). Resolvability of the centroid-moment-tensors for shallow seismic sources and improvements from modeling high-frequency waveforms. *Journal of Geophysical Research: Solid Earth*, *125*(7), e2020JB019643. https://doi.org/10.1029/2020JB019643

G*Mm = elementary signal produced by numerical simulations

$$M_{est}=\begin{bmatrix} -a_4+a_6 & a_1 & a_2 \\ a_1 & -a_5+a_6 & -a_3 \\ a_2 & -a_3 & a_4+a_5+a_6 \end{bmatrix}.$$

$$u=\sum_{m=1}^{6}(G*M_m)a_m$$

Coefficients to build the full moment tensor $M=\sum_{m=1}^{6}M_m a_m$

Elementary moment tensors

$$M_1=\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} M_2=\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} M_3=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{bmatrix} M_4=\begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} M_5=\begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} M_6=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} Mnn & Mne & Mnd \\ Men & Mee & Med \\ Mdn & Mde & Mdd \end{pmatrix}$$