

What can the sound of earthquakes tell us about a planet’s interior structure?

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Abstract

Deploying seismic or infrasound arrays on the ground to probe a planet’s interior structure remains challenging in remote regions facing harsh surface conditions such as Venus with a surface temperature of 464°C. Fortunately, a fraction of the seismic energy transmits in the upper atmosphere as infrasound waves, i.e. low-frequency pressure perturbations ($< 20\text{Hz}$). On July 22, 2019, a heliotrope balloon, equipped with pressure sensors, was launched from the Johnson Valley, CA with the objective of capturing infrasound signals from the aftershock sequence of the 2019 Ridgecrest earthquake. At 16:27:36 UTC, the sound of a natural earthquake of Mw 4.2 was detected for the first time by a balloon platform. This observation offered the opportunity to attempt the first inversion of seismic velocities from the atmosphere. Shear velocities extracted by our analytical inversion method fell within a reasonable range from the values provided by regional tomographic models. While our analysis was limited by the observation’s low signal-to-noise ratio, future observations of seismic events from a network of balloons carrying multiple pressure sensors could provide excellent constraints on crustal properties. However, to build robust estimates of seismic properties, inversion procedures will have to account for uncertainties in terms of velocity models, source locations, and instrumental errors. In this contribution, we will discuss the current state of balloon-based observations, the sensitivity of the acoustic wavefield on subsurface properties, and perspectives on future inversions of seismically-induced acoustic data.

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The challenge of ground station coverage

The determination of seismic source dynamics and subsurface velocities generally relies on the analysis of seismic phases recorded networks deployed at the ground

On Venus, harsh surface conditions (> 460 C, 90 bar) prevent the deployment of seismic stations

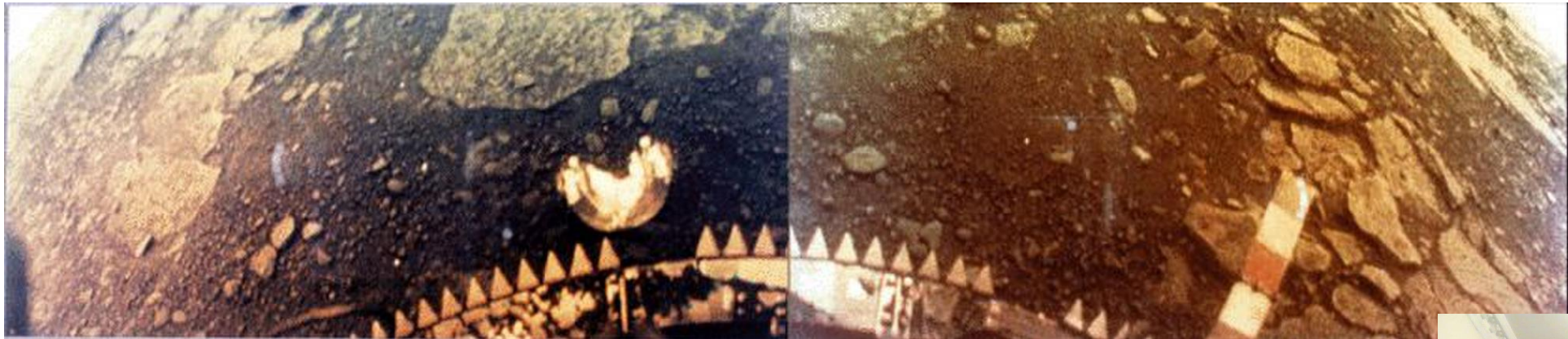


Figure: Photo of the Venusian surface by Venera 13 (1983). credit: NASA-JPL



The challenge of ground station coverage

The determination of seismic source dynamics and subsurface velocities generally relies on the analysis of seismic phases recorded networks deployed at the ground

On Venus, harsh surface conditions (> 460 C, 90 bar) prevent the deployment of seismic stations

On Earth, investigations of shallow events lack resolution to constrain accurately seismic source parameters (location, depth, moment tensor) in regions of poor station coverage such as polar regions, oceans, or volcanos

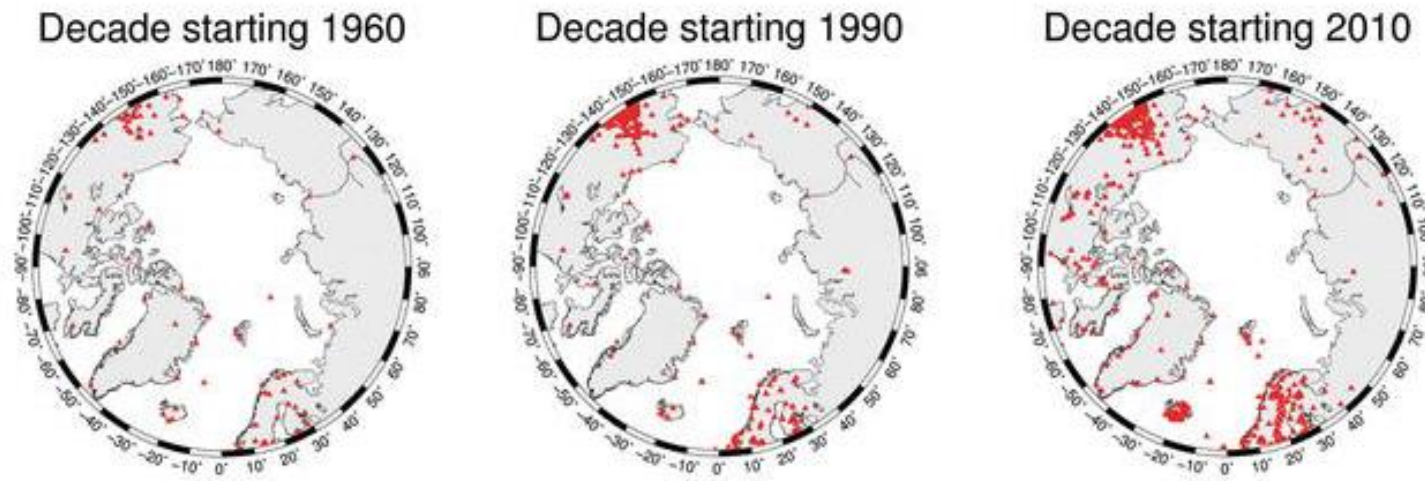
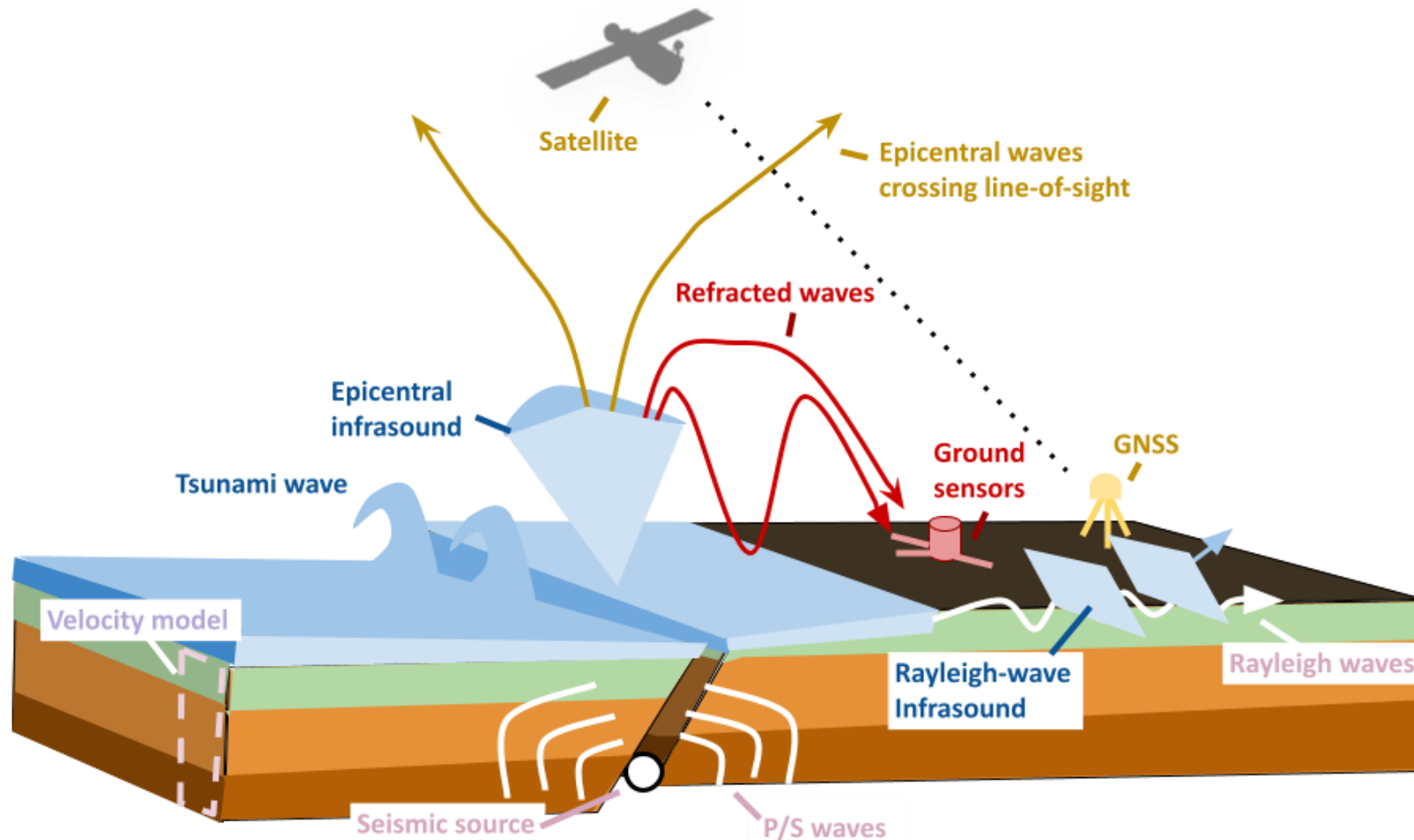


Figure: Distribution of seismic station (red triangle) in polar regions. (*Kanao, 2018*)



An answer might lie in the atmosphere

Seismic waves couple to the atmosphere and propagate over large distances as low frequency (< 20 Hz) acoustic waves, called **infrasound**, which carry information about the seismic velocities and subsurface processes

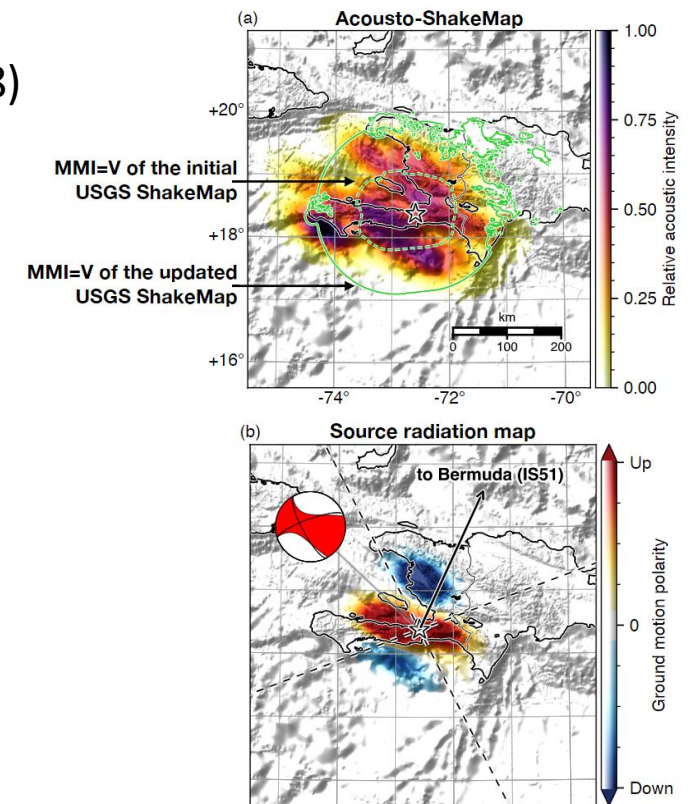
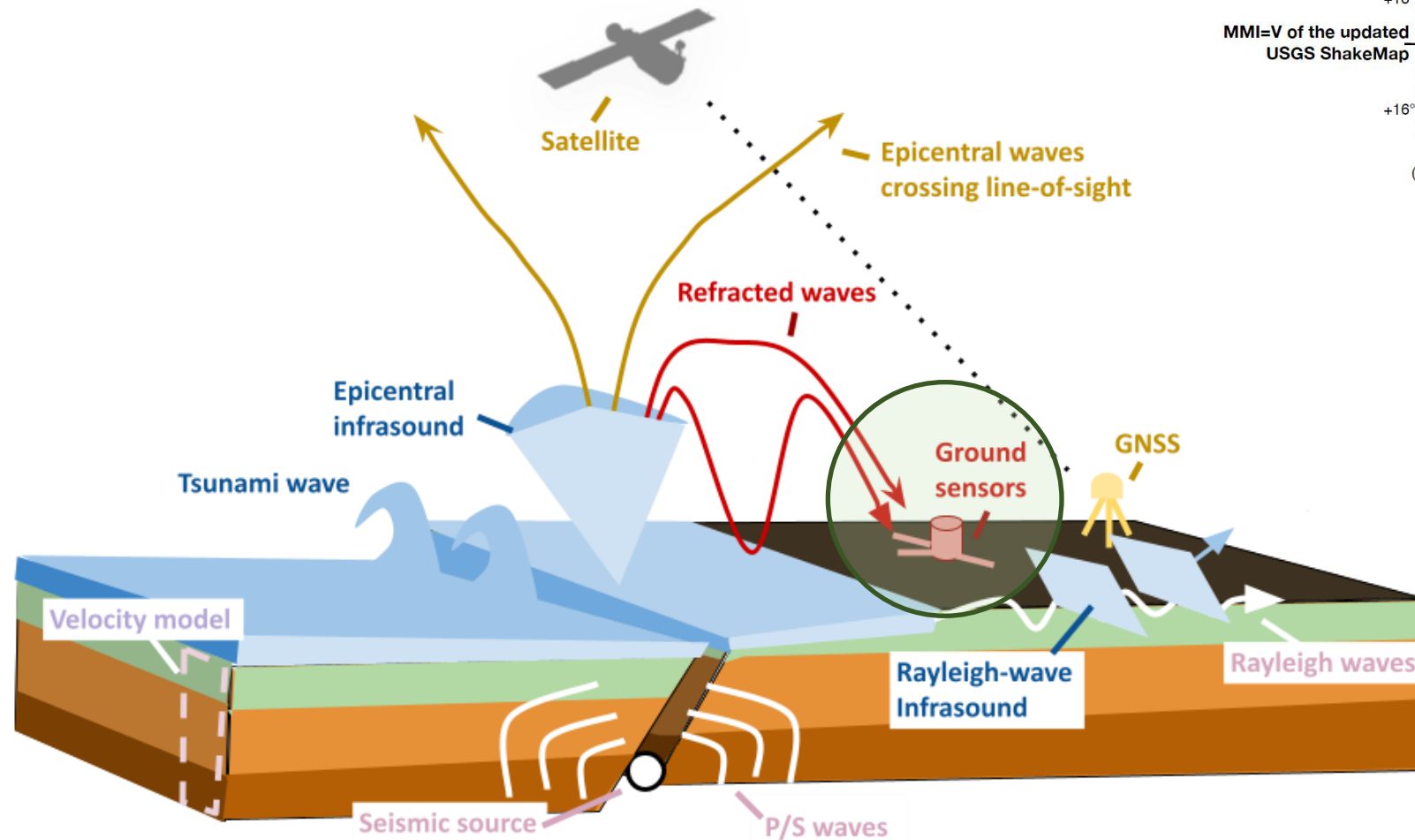


Ground observations

Figure: Reconstruction of seismic hazard maps and projected focal mechanisms after Haiti earthquake (Shani-Kadmiel, 2021)

Source characteristics

- *Amplitude + time*: Sound pressure level from seismic waves (e.g., Hernandez, 2018)
- *Relative amplitude phases + time*: Focal depth (Averbuch, 2020)
- *Amplitude + polarity + time*: Focal mechanism (Shani-Kadmiel, 2021)



Ionospheric observations

Source characteristics

- *Amplitude*: Magnitude (Astafyeva, 2013)
- *Time*: Maximum slip location (Zedek, 2021)
- *Waveform*: Fault dynamics (Inchin, 2021)

Subsurface characteristics

- *Relative amplitude*:
Basin amplification (Liu, 2021)

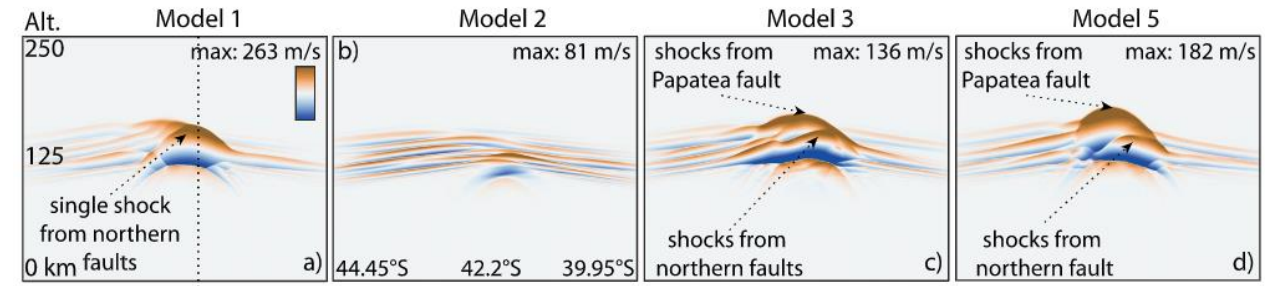
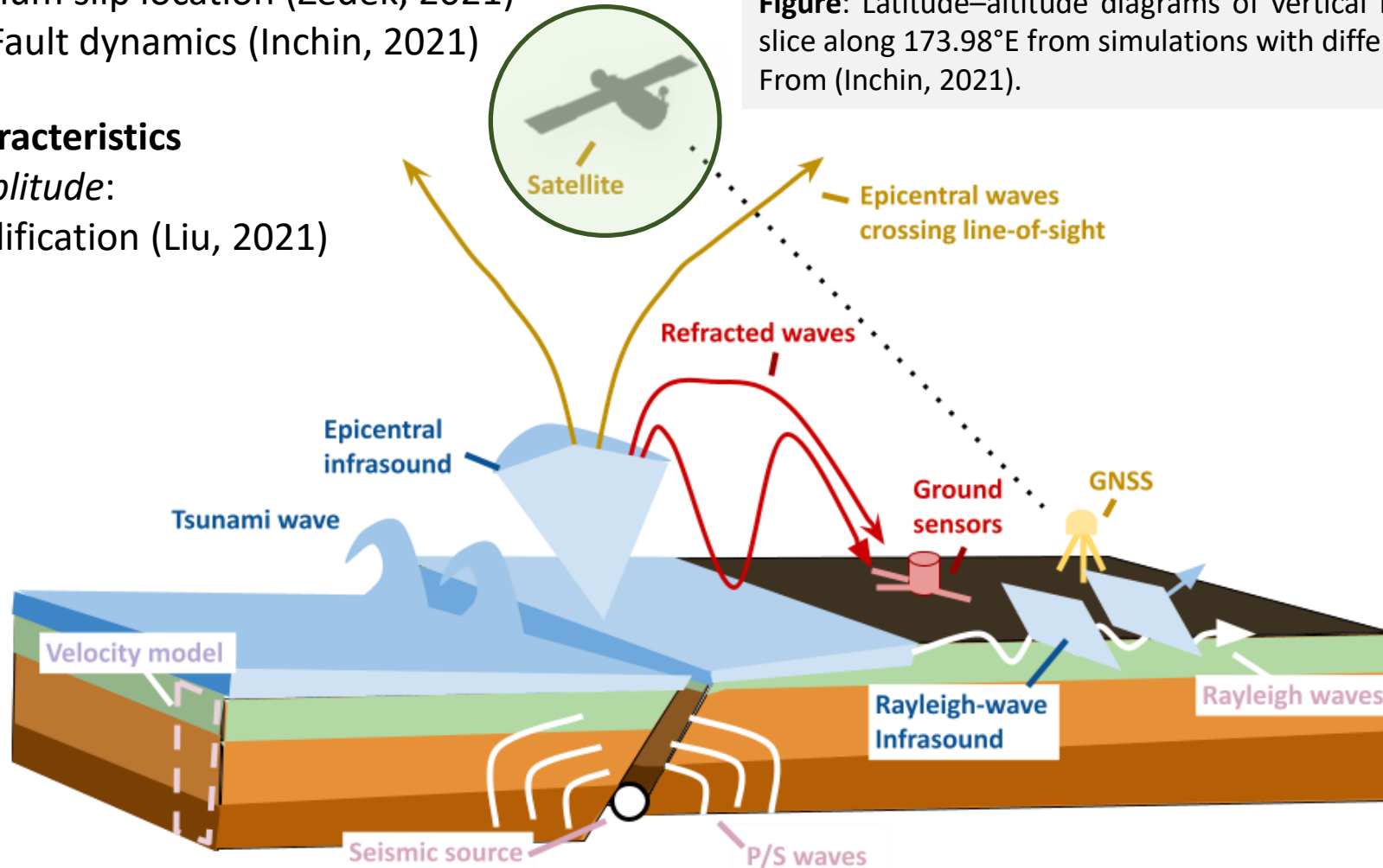


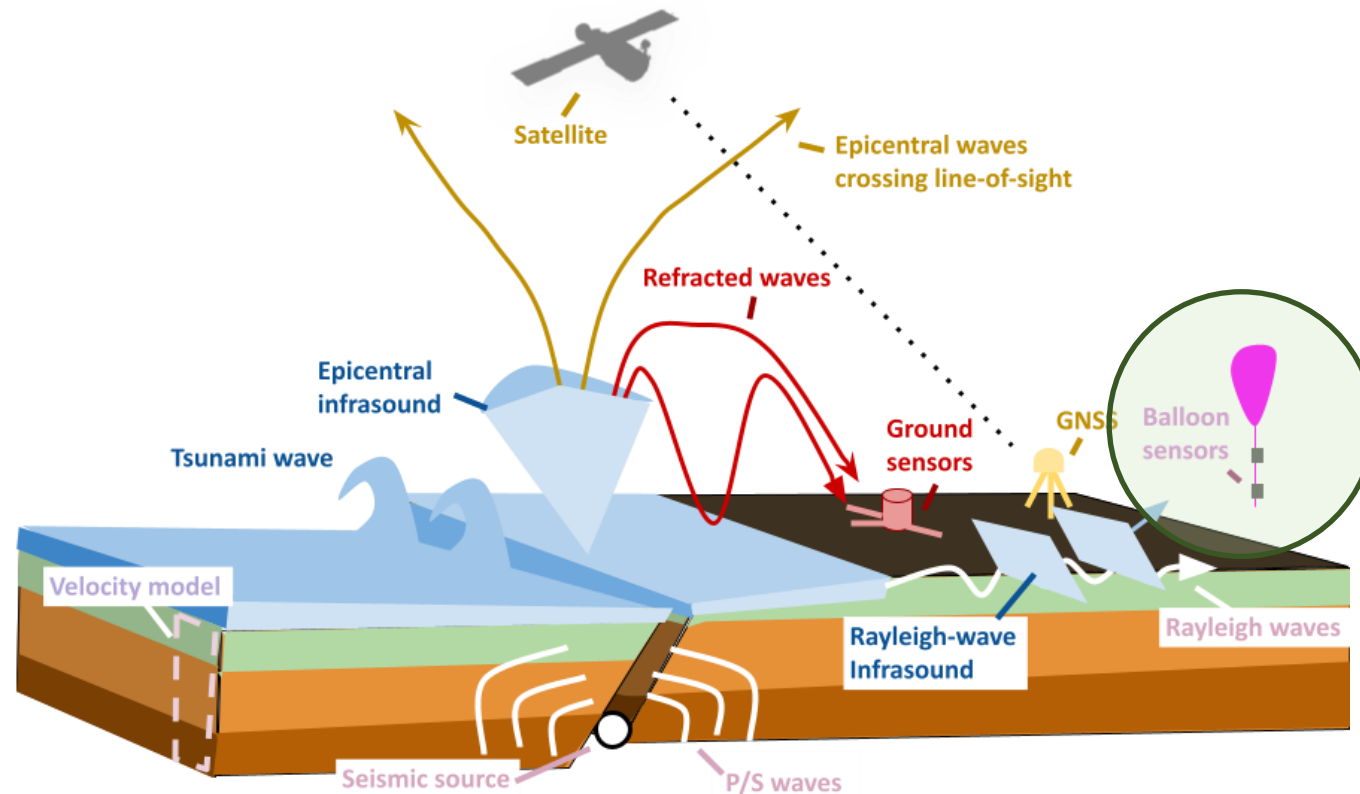
Figure: Latitude–altitude diagrams of vertical fluid velocity for the meridional slice along 173.98°E from simulations with different rupture models at $T = 500$ s. From (Inchin, 2021).



Balloons as flying seismometers?

At low altitudes, the atmosphere is non-dispersive and infrasound waves can be considered “copies” of their seismic counterparts

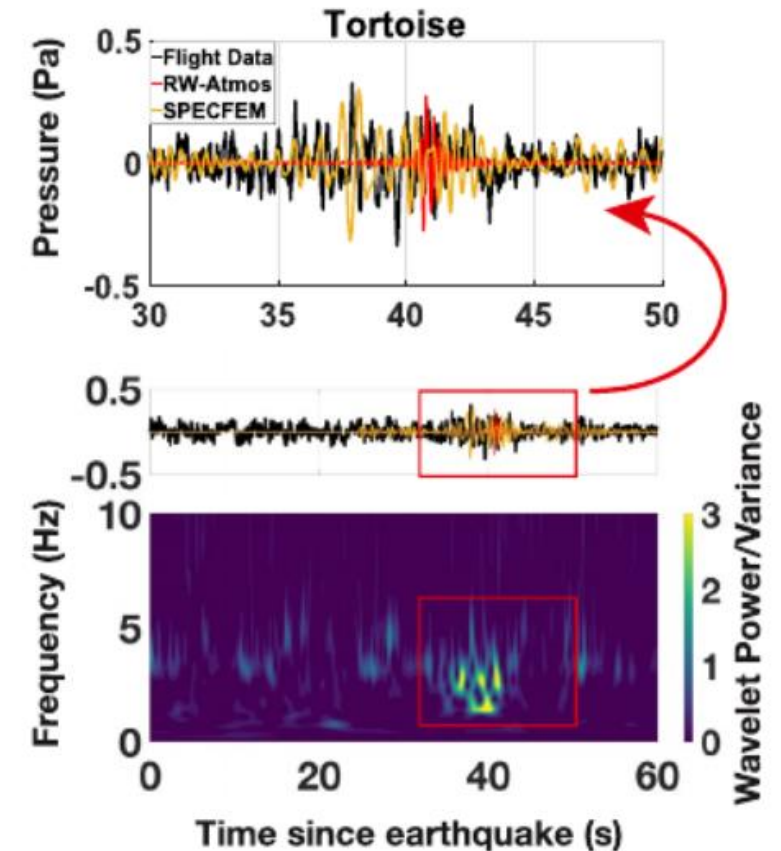
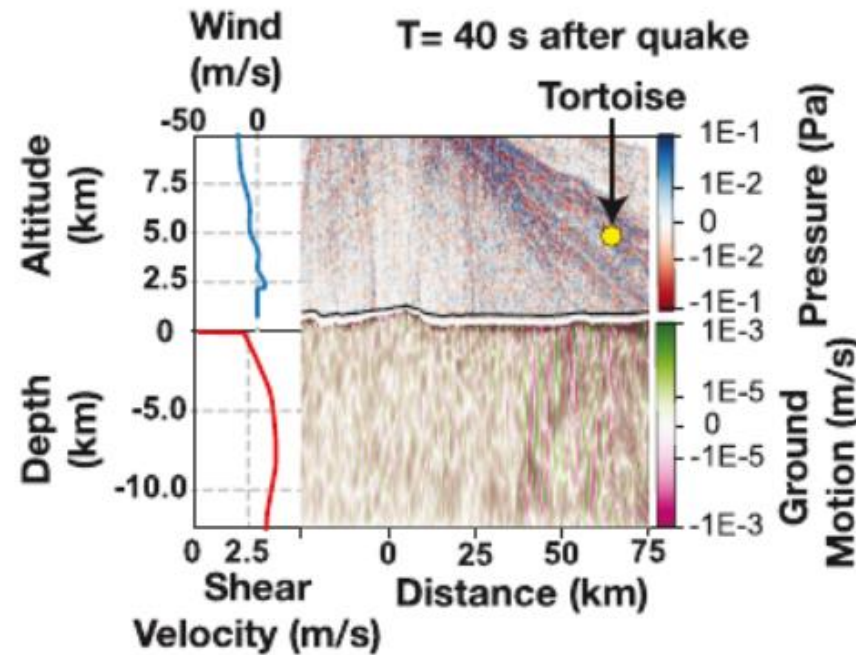
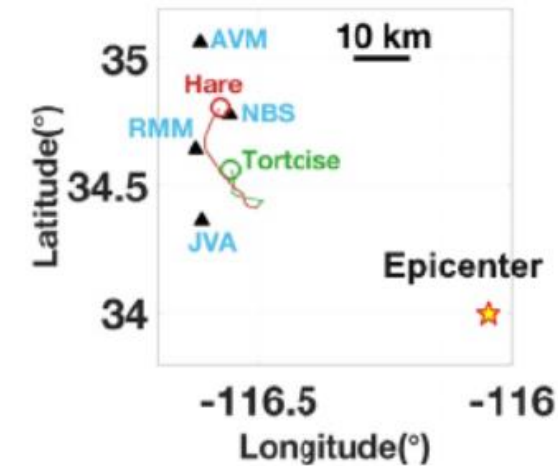
Balloons provide an inexpensive alternative to ground stations and satellite-based techniques for seismic monitoring and surface source investigations



July 22nd 2019, 16:26:56 (Brissaud et al, 2021)

In July 2019, JPL, Caltech, and Sandia deployed a free-floating balloon equipped with pressure sensors near the Ridgecrest earthquake epicenter to detect potential aftershocks

On July 22nd, pressure waveforms recorded at the balloon showed high correlation with seismic arrivals and good match with numerical simulations



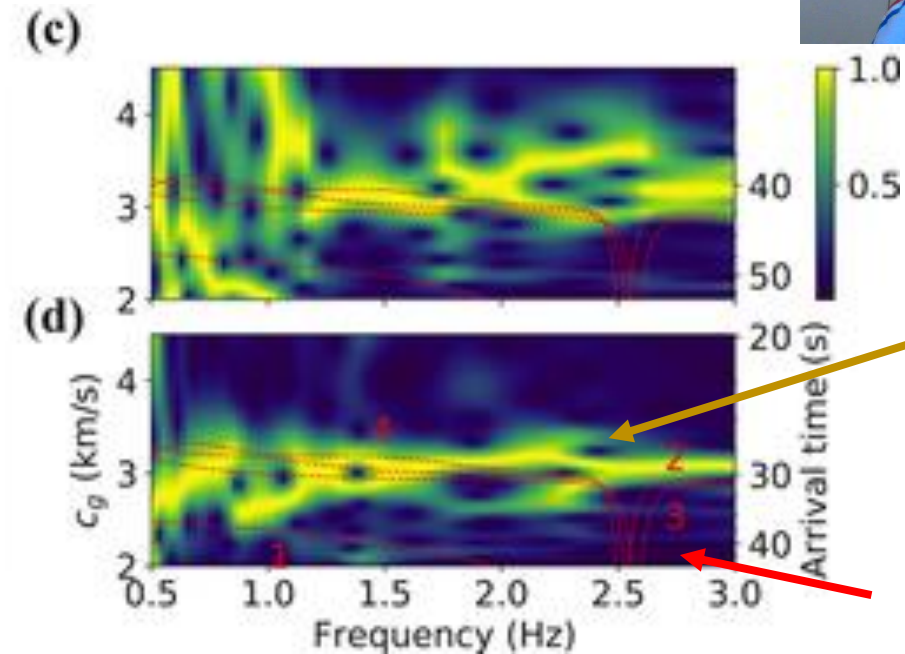
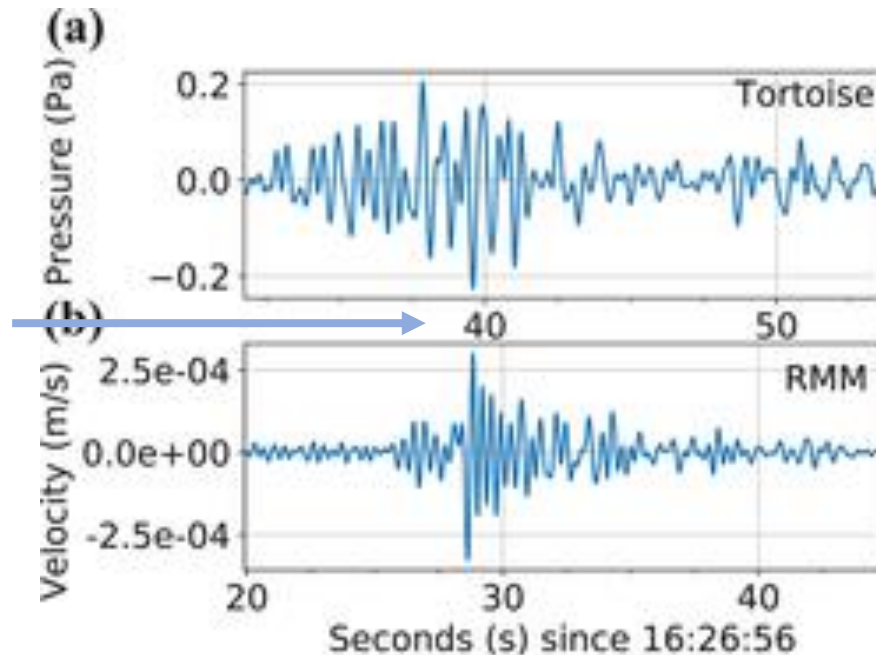
Infrasound as a *shifted-in-time* copy of seismic motion

The Frequency-Time ANalysis (FTAN) enables us to investigate the dispersion properties of both infrasound and seismic signals

Similarities in terms of higher-order Rayleigh-wave (RW) group velocity values in the frequency range of interest 1-2.5 Hz



Shifted time
accounting for
infrasound
travel time



Flat group velocity
curve typical of Lg
phases, i.e.,
constructive
interference
of higher-order RW
modes

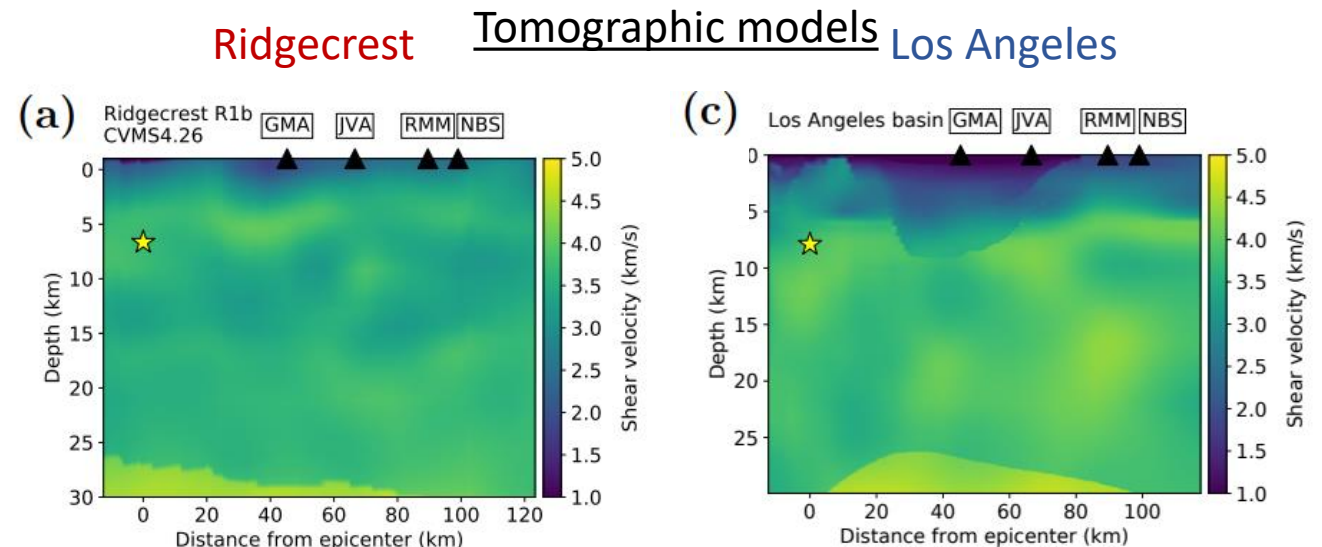
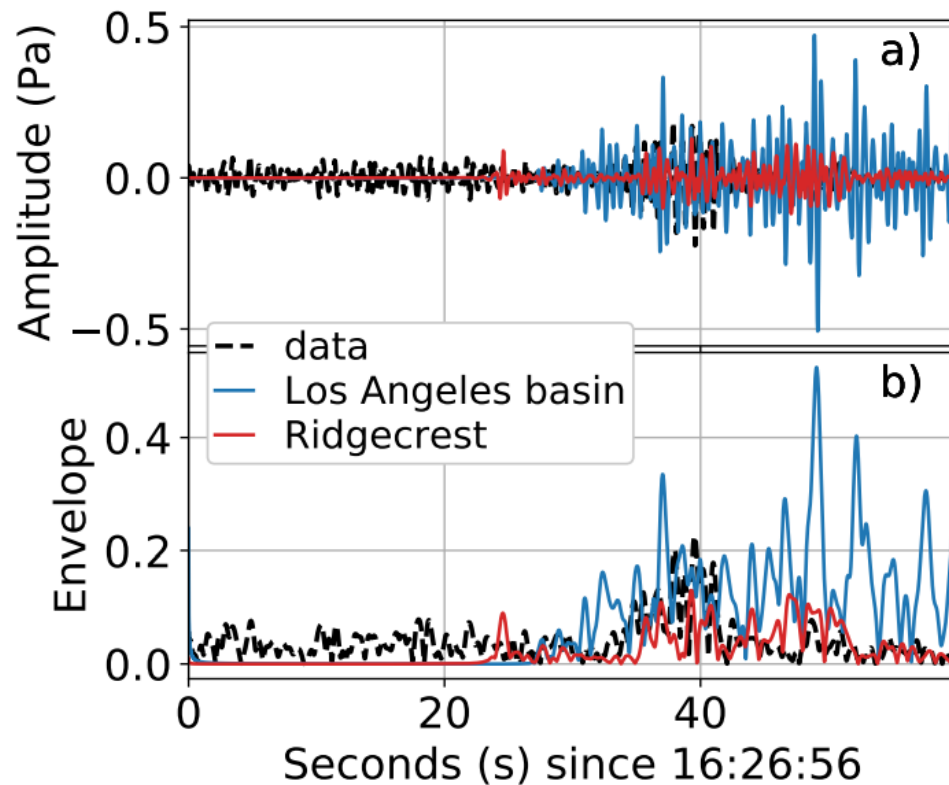
Theoretical
group-velocity
curves

Considering the peak sensitivity of RWs $d(m, \lambda) = \frac{1}{2}m\lambda$, the range of extracted group velocity values give a depth $\approx 2.4 \pm 0.6\text{km}$.

Inversions are challenging at high-frequency...

Waveforms of high-frequency phases such as Lg phases are extremely sensitive to the thickness of shallow velocity layers as well as lateral variations of crustal velocities

Extracted group velocities from Lg phases correspond to average crustal velocities and lack vertical resolution

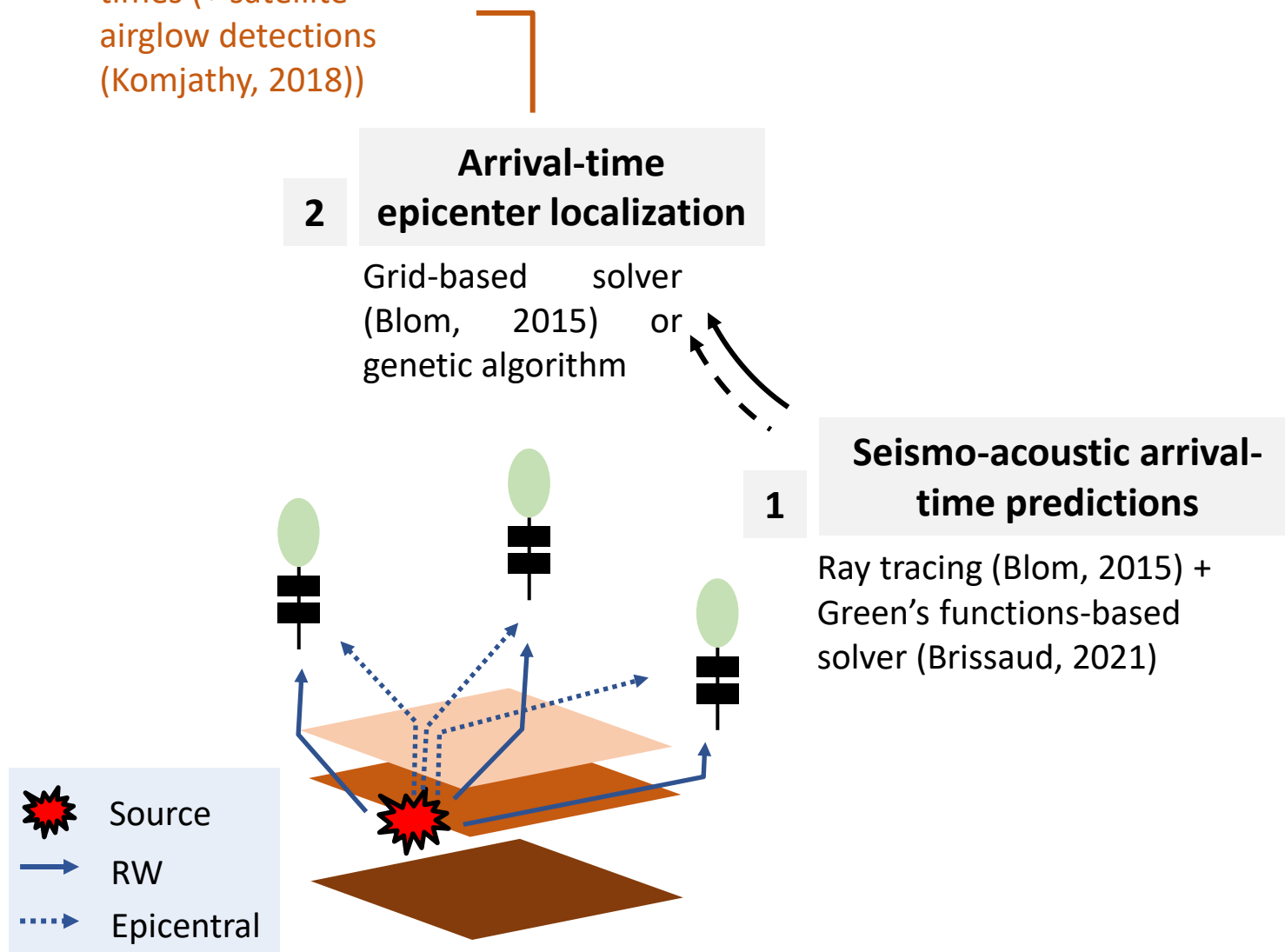


Larger-magnitude events will excite more energetic Rayleigh-wave modes and more energy at low frequency which give access to better vertical resolution and larger depths



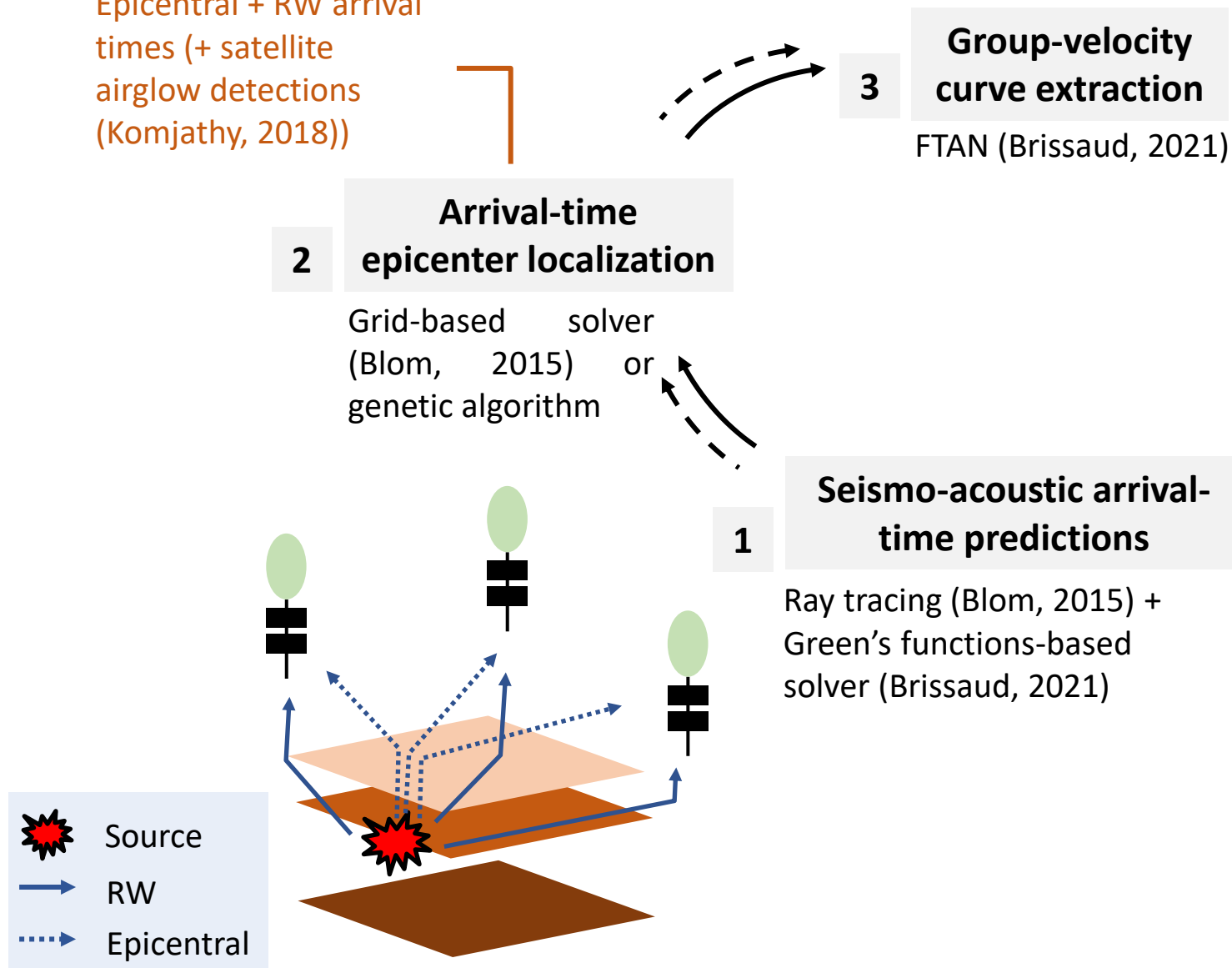
Designing an inversion framework

Epicentral + RW arrival
times (+ satellite
airglow detections
(Komjathy, 2018))

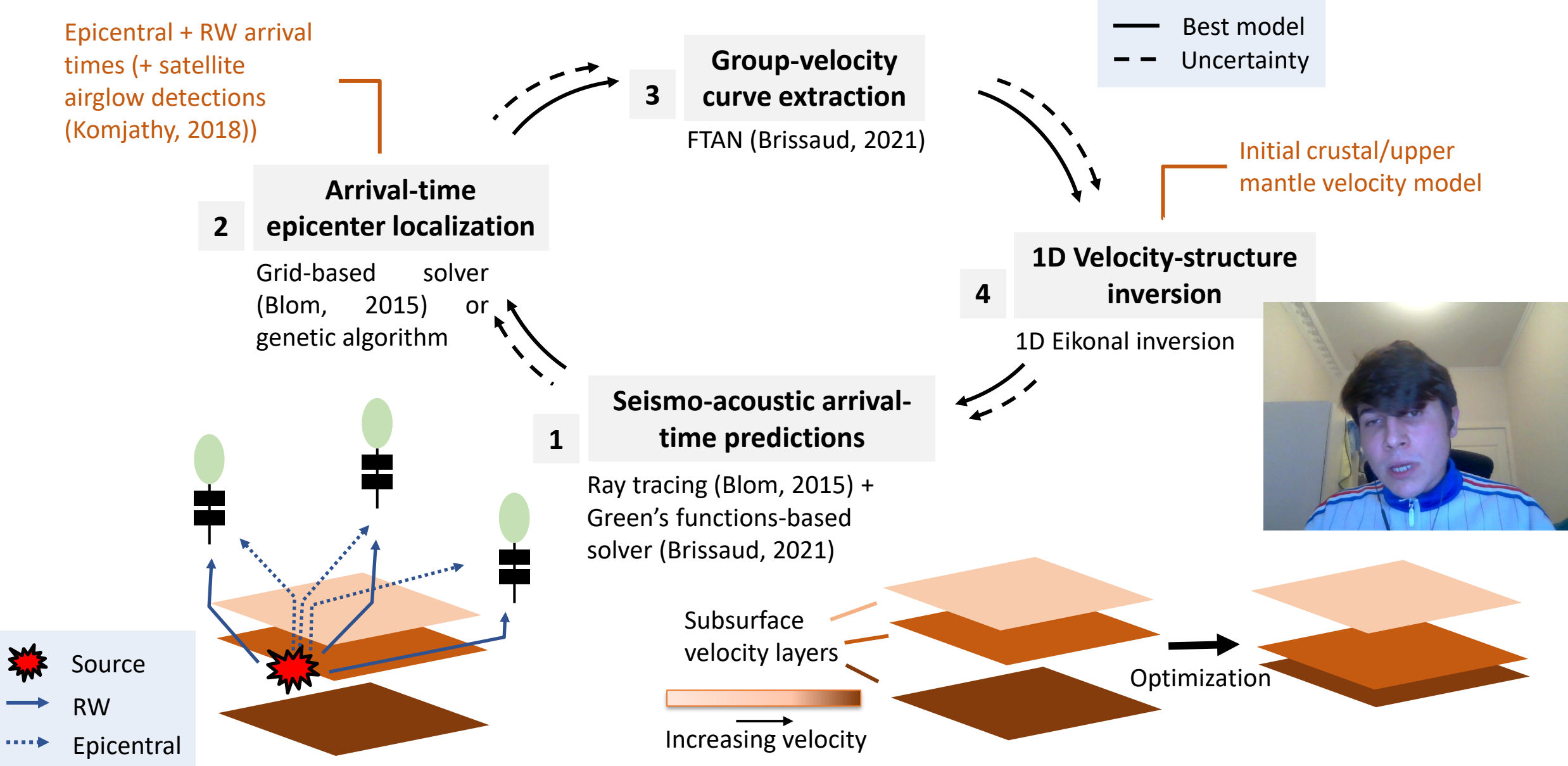


Designing an inversion framework

Epicentral + RW arrival
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(Komjathy, 2018))



Designing an inversion framework



Challenges and recommendations

Accounting for all path effects (e.g., topography, lateral seismic and atmospheric velocity variations) in arrival time predictions will require 3d range-dependent full-waveform modeling which is computationally expensive → corrections of analytical predictors (e.g., Green's functions across media with lateral discontinuities) or modeling through machine learning (see for example *S51A-04*)

Determining uncertainties during data processing, modelling, and inversions is critical. However, this process significantly increases the computational cost when using basic grid-search approaches → Iterative Bayesian algorithms?

Accurate inversions require reliable Rayleigh and Epicentral wave arrival time and dispersion extractions (potentially at very low SNR) which is time consuming and prone to inconsistencies → Building balloon detection datasets and training machine learning for binary signal-noise detection (see for example *SA11B-01*) + Cross-correlating signals across each line array on each balloon can help reducing the noise level + Using the direction-of-arrival information from each line array on each balloon can help better constraining the range of seismic group velocities

Inversion algorithms will require initial conditions which are potentially poorly constrained (or even inexistent on Venus) → Regular randomization of initial condition over a range of possible velocity structures and source location is necessary + Considering prior distribution of possible seismic source locations such as volcanoes could help facilitating the convergence



Future directions

This detection shows (1) **low-magnitude earthquakes can be detected below the stratosphere**, and (2) high signal-to-noise ratio signals provide insights into the subsurface velocity structure

Simulations indicate that competing path effects might lead to some potential misinterpretations of observed signals

And one low SNR detection is not enough to assess the full potential of balloon-based investigations...

Therefore, JPL, Caltech, and Sandia are currently funded to deploy balloons in Oklahoma, USA to monitor the low-magnitude earthquake activity



Figure: Deployment of heliotrope balloons in July 2021. Credit Brian R. Elbing





Thank you! Questions?

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Ground observations

Epicentral infrasound provide an insight on the ground deformations near the epicenter

Backprojection of acoustic energy along observed backazimuth and celerities enables the **reconstructions of ground motion maps & retrieve focal mechanisms** with a station > 1700 km away from the epicenter

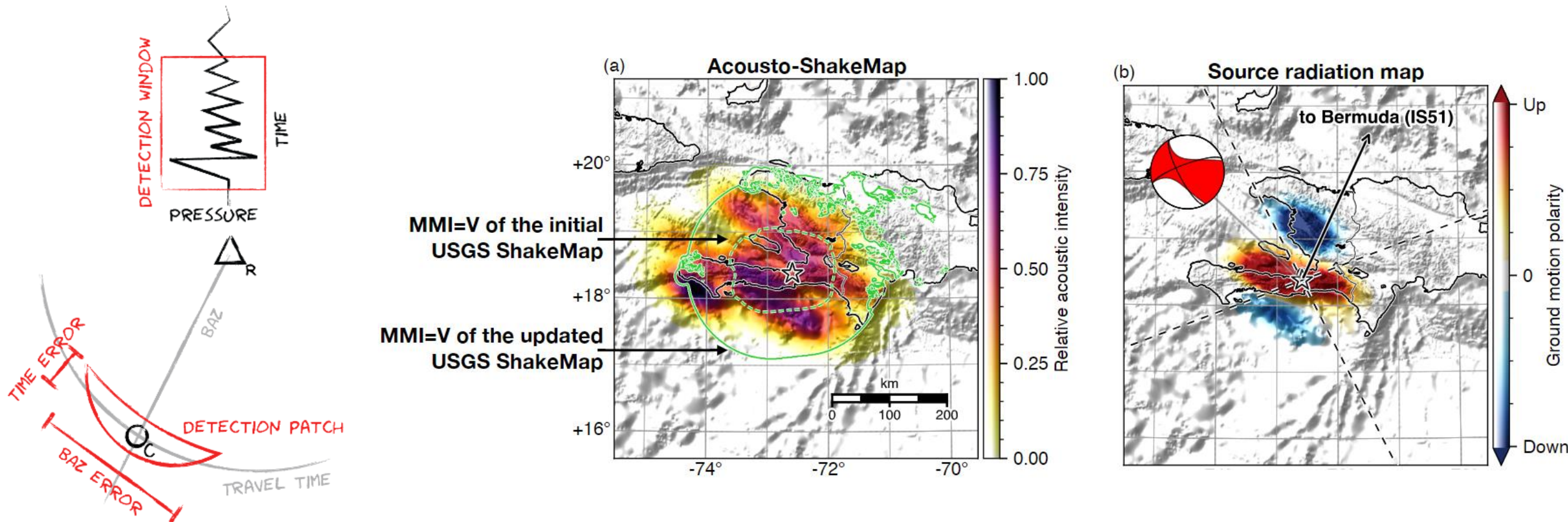


Figure: Reconstruction of seismic hazard maps and projected focal mechanisms after Haiti earthquake (Shani-Kadmiel, 2021)

Ionospheric observations

On Earth, large earthquakes have often been observed through GPS ionospheric sounding or airglow response

Ionospheric observations can help [locate large undersea surface deformations and constrain rupturing models](#)

However, GPS sounding relies on ground stations and both techniques have limited Signal-to-Noise Ratio (SNR)

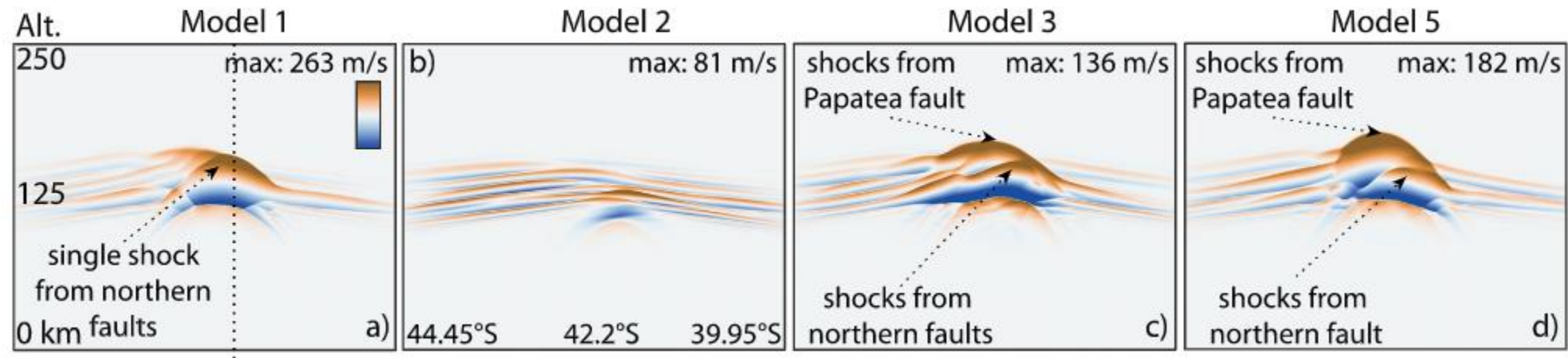


Figure: Latitude–altitude diagrams of vertical fluid velocity for the meridional slice along 173.98°E from simulations with different rupture models at $T = 500$ s

Monitoring geophysical processes with balloons

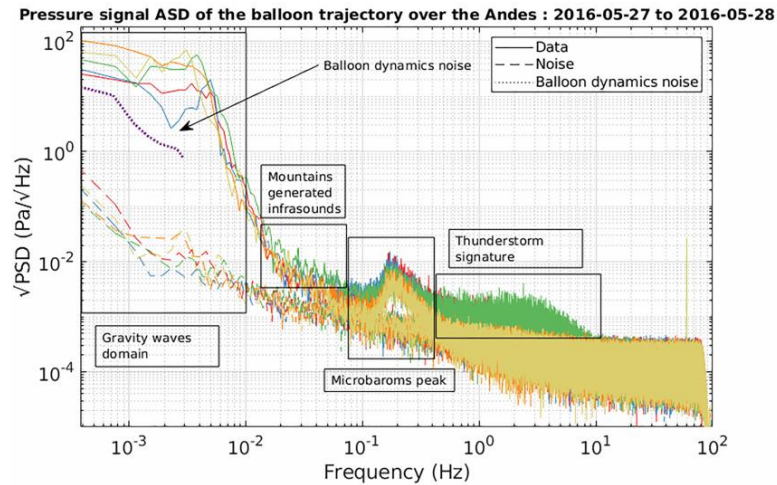


Figure: Balloon path and spectrum the acoustic wavefield generated by ocean and atmospheric processes (*Poler, 2019*)

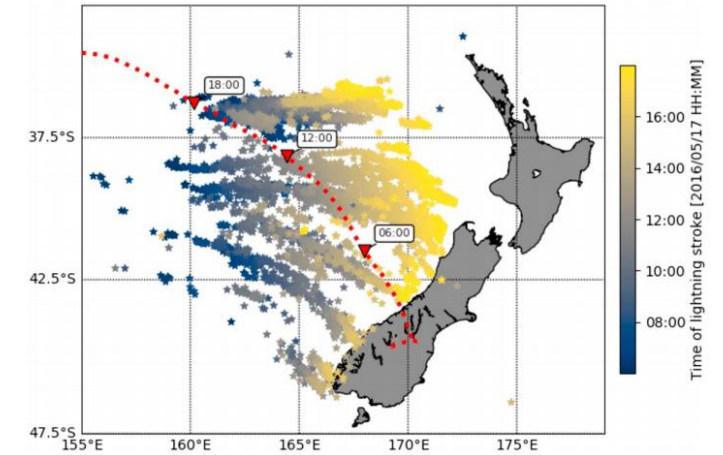


Figure: Balloon path (red) and lightning recordings at the balloon (*Lamb, 2018*)



Figure: An aerial image of the north and south craters of the Yasur Volcano with the aerostat (*Matoza, 2017*)

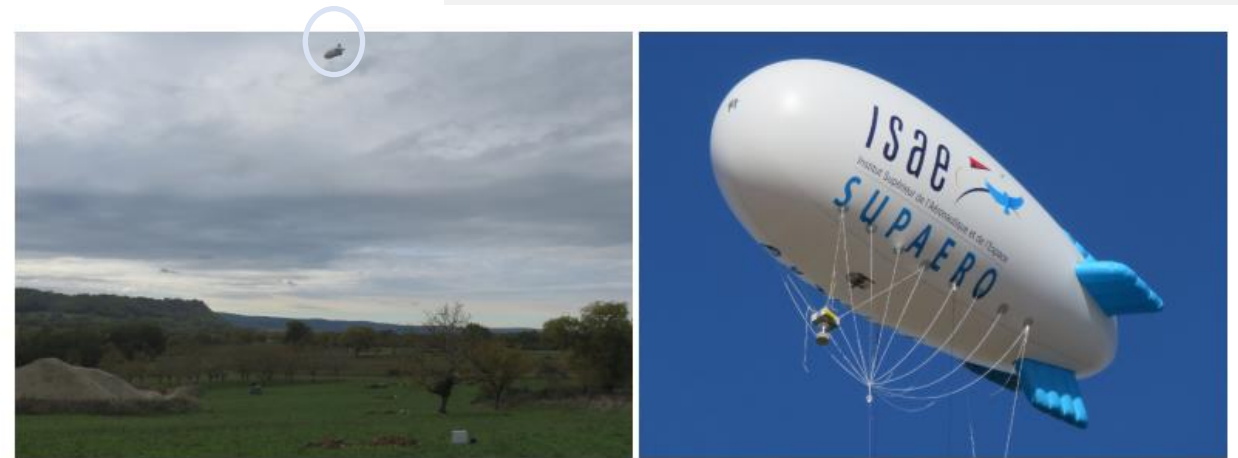


Figure: The recording of a mine blast using a tethered balloon in Southern France (*Garcia, 2020*)

What about seismic waves?

While multiple surface and atmospheric sources have been studied using free flying or tethered balloons, until recently, the acoustic signature of seismic waves had never been detected

Tremendous efforts from JPL & Caltech (Pasadena, USA) and ISAE (Toulouse, France) have demonstrated that seismic waves can be captured by pressure sensors on both tethered and free-floating balloons



Figure: Experimental setup with both free-floating (red) and tethered (white) balloons

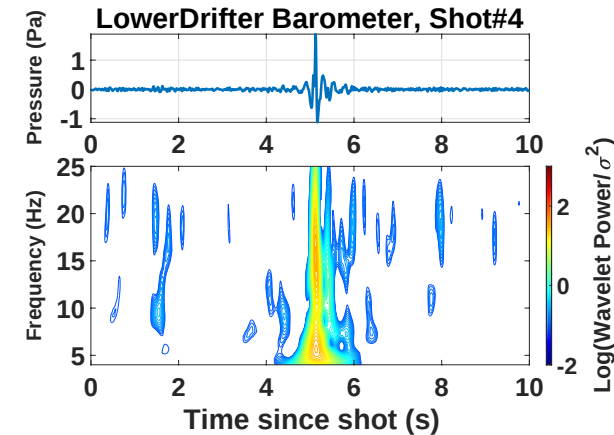


Figure: Active explosion generating both blast waves and seismic waves



What about earthquakes?

Exact timing of active sources is known, and they are located at or just below the surface which creates a strong ground-air coupling → however, the acoustic signature of natural earthquakes had never been detected with a balloon

It remained unclear if epicentral and Rayleigh-wave infrasound could be detected from the stratosphere, especially for low-magnitude earthquakes ($< M_w 5$)

Without such demonstration, the feasibility of balloon seismology on Earth or Venus is limited

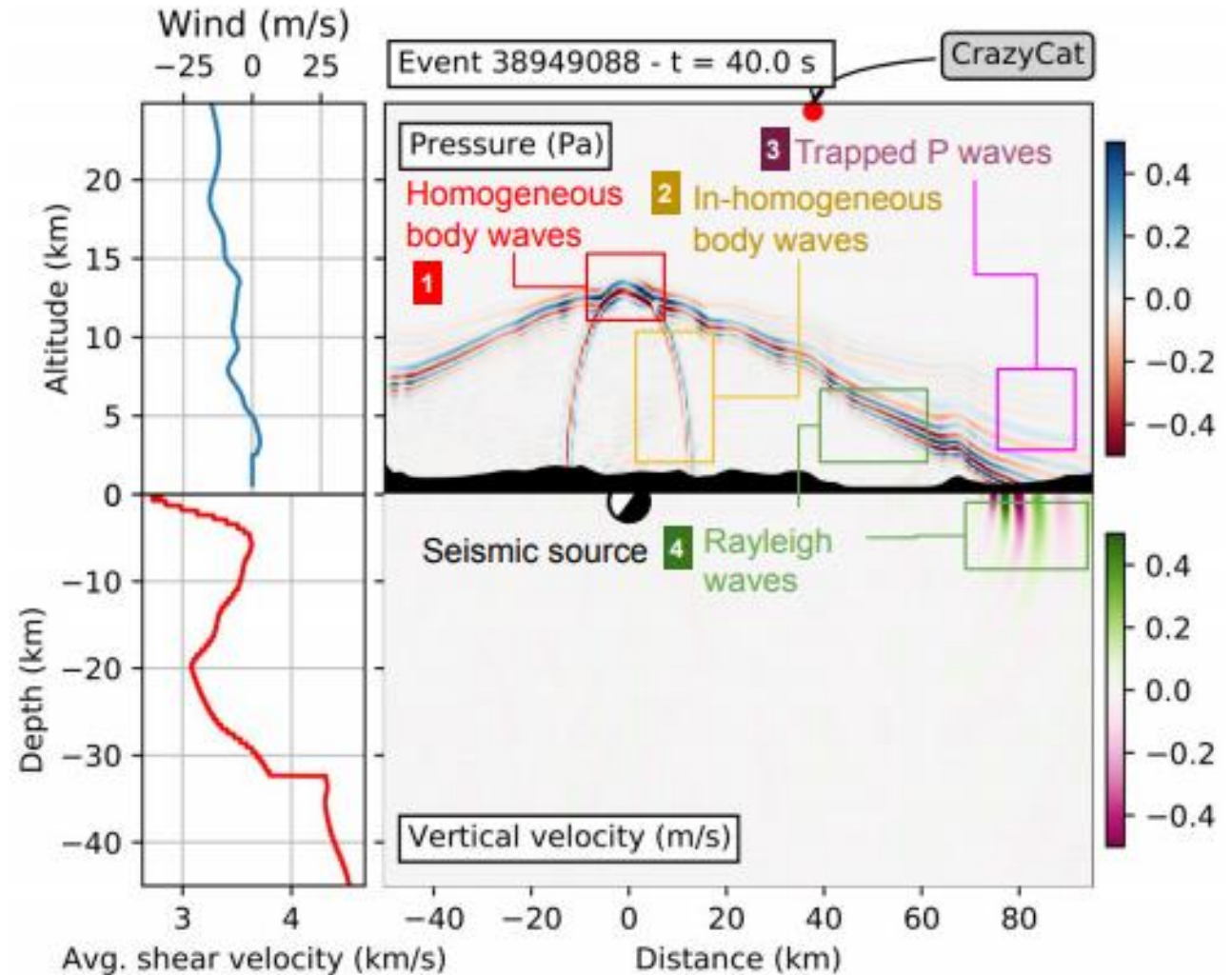


Figure: Visualization of the various seismo-acoustic contributions to the atmospheric wavefield excited by a shallow normal-faulting event

What about Venus?

Temperature and pressure at 50-60 km are Earth-like

Likely volcanic activity

Large surface pressures lead to a much more efficient energy coupling between seismic and atmospheric media

Very fast (60-150 m/s) atmospheric zonal “super-rotation”

Atmosphere is 98% CO₂, thick sulfuric acid clouds and haze from ~40-70 km

Seismicity unknown

→ High-risk high-reward planetary mission

Balloon?

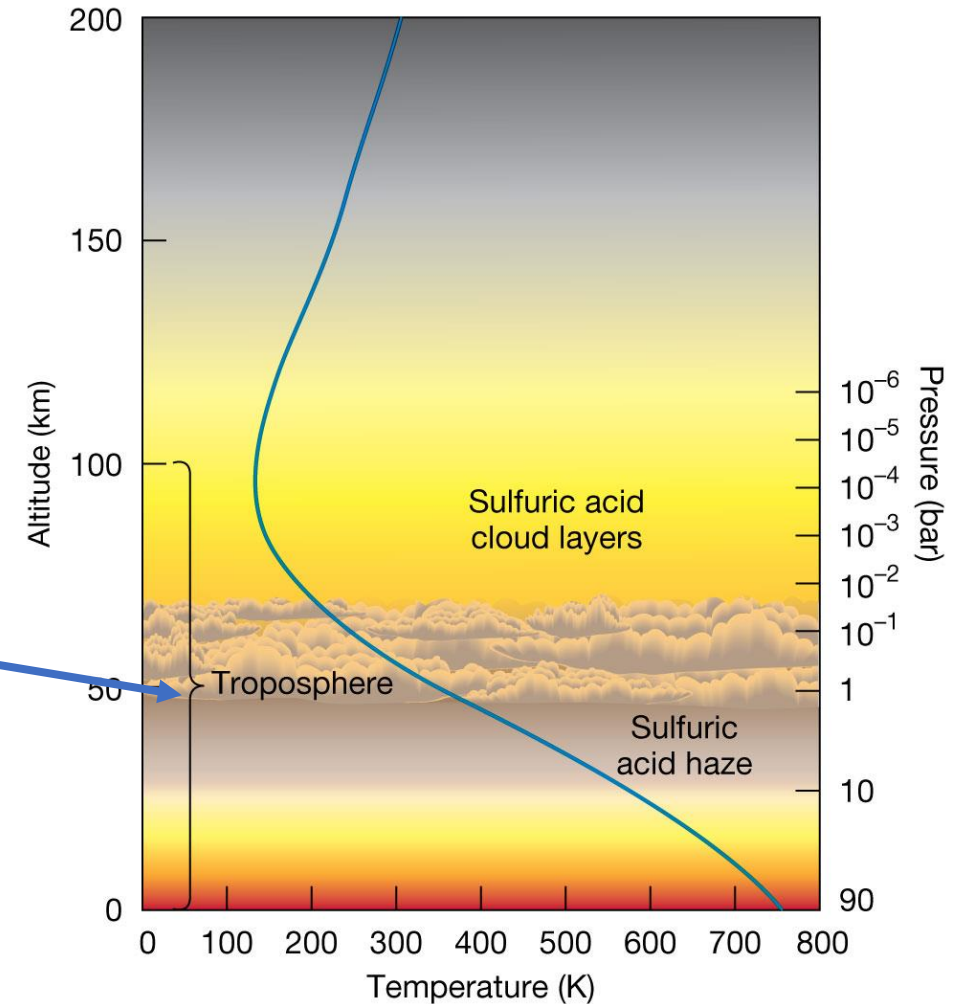
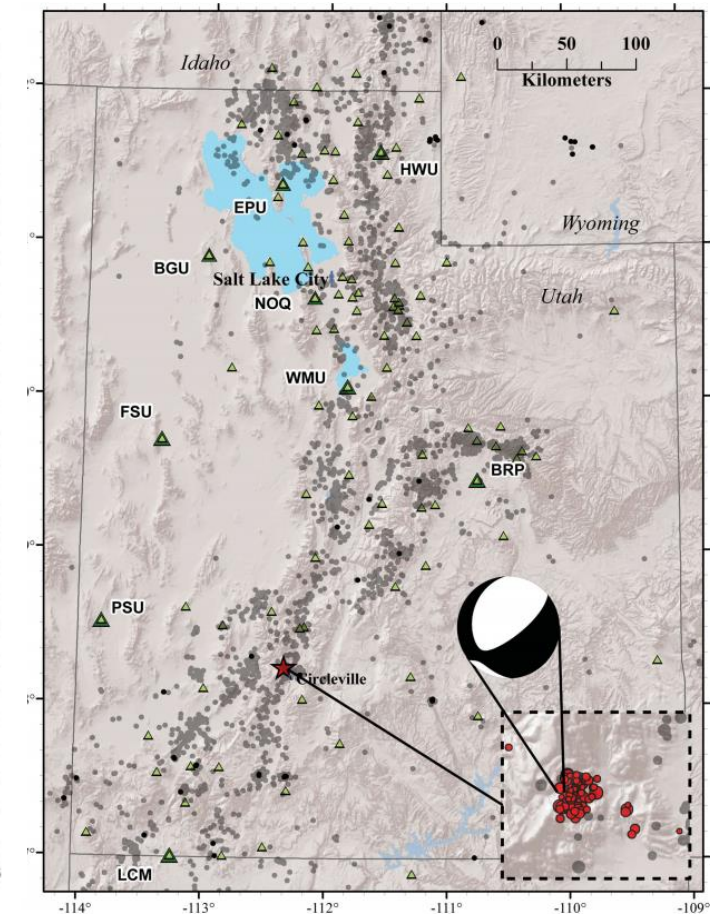
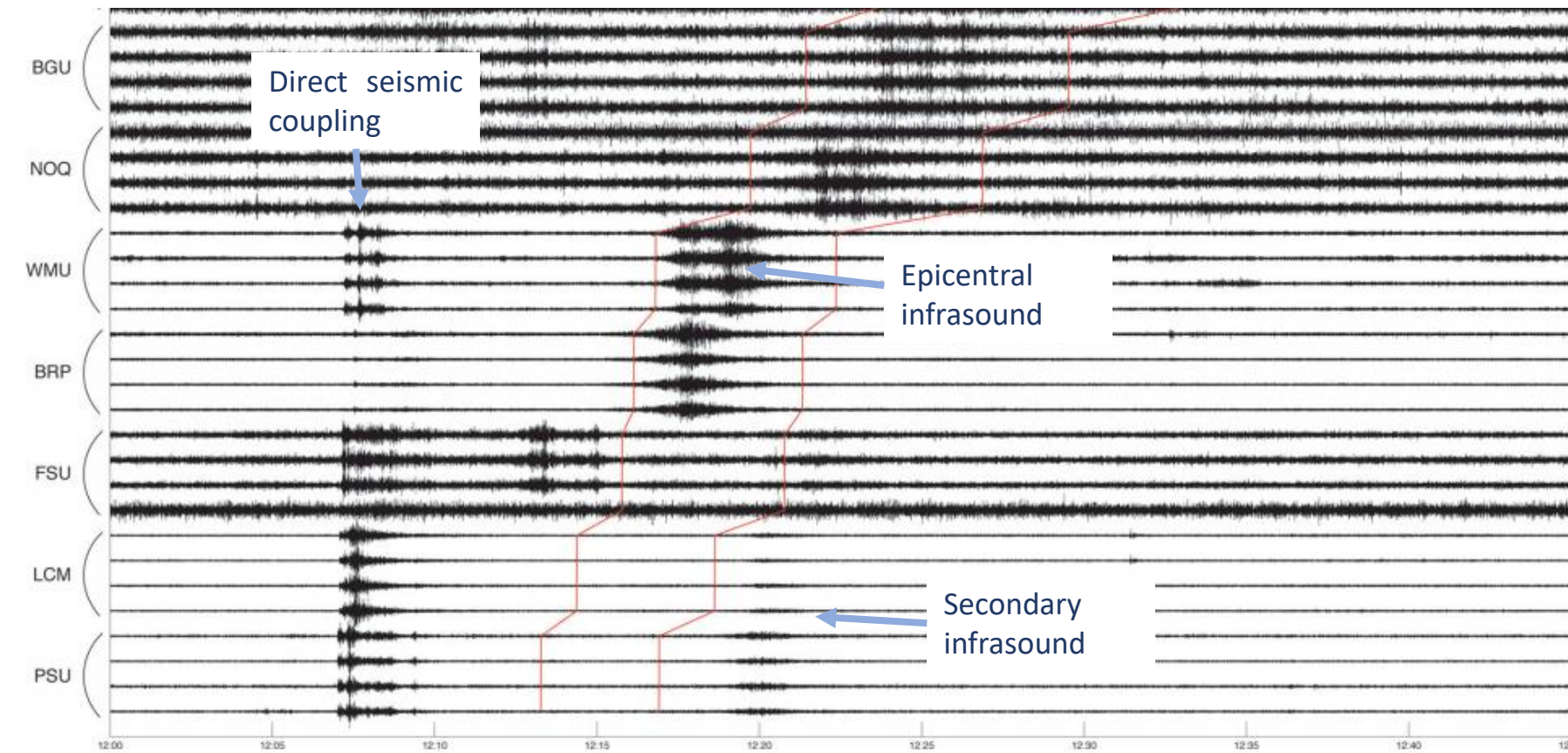


Figure: Expected temperature profile on Venus. credit: NASA

What about earthquakes?

... But observations of epicentral and secondary infrasound from small earthquakes ($M_w < 5$) exist at the ground



Figures: Infrasound records after the 2011 January 3 Circleville earthquake in Utah (Arrowsmith, 2012)

Seizing the Ridgecrest opportunity (*Brissaud et al, 2021*)

The two main 2019 Ridgecrest earthquakes on July 4 and July 7, 2019 (M_w 6.4 and 7.1) led to a long aftershock sequence

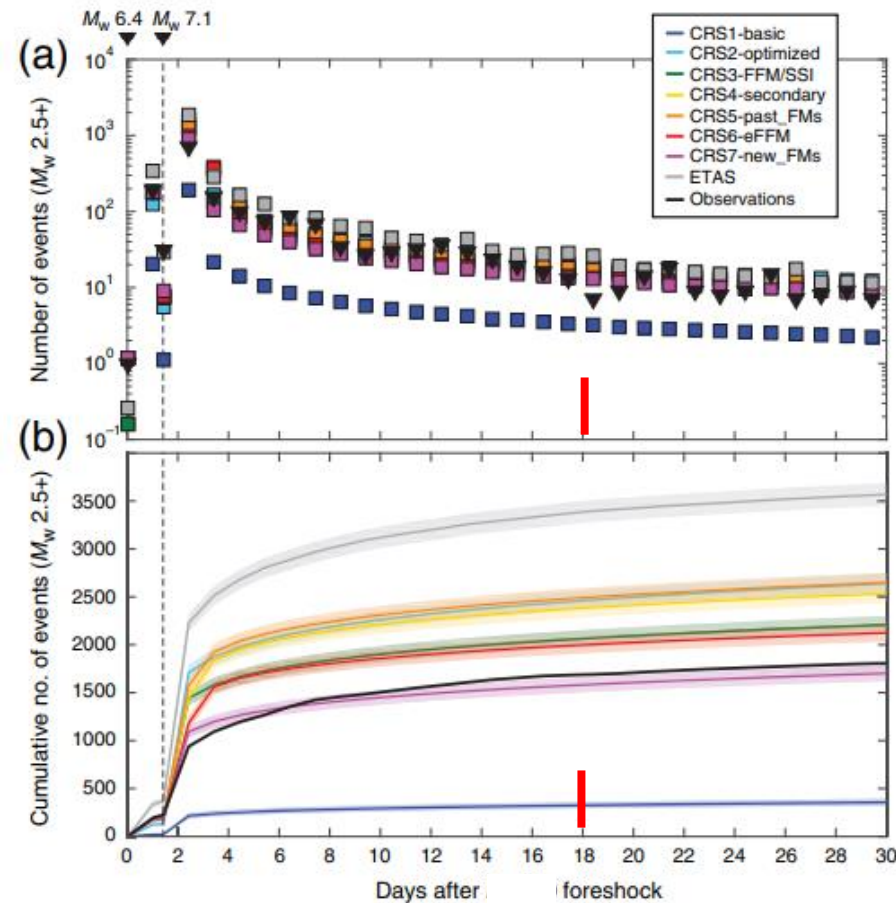


Figure: (a) number and (b) cumulative number of aftershocks given by forecast models (colors) and observations (black). (*Mancini, 2021*)

Seizing the Ridgecrest opportunity (*Brissaud et al, 2021*)

Taking advantage of the relative proximity with Ridgecrest, JPL and Caltech rushed to build, test, and deploy 4 heliotrope balloons on July 22nd and August 9th

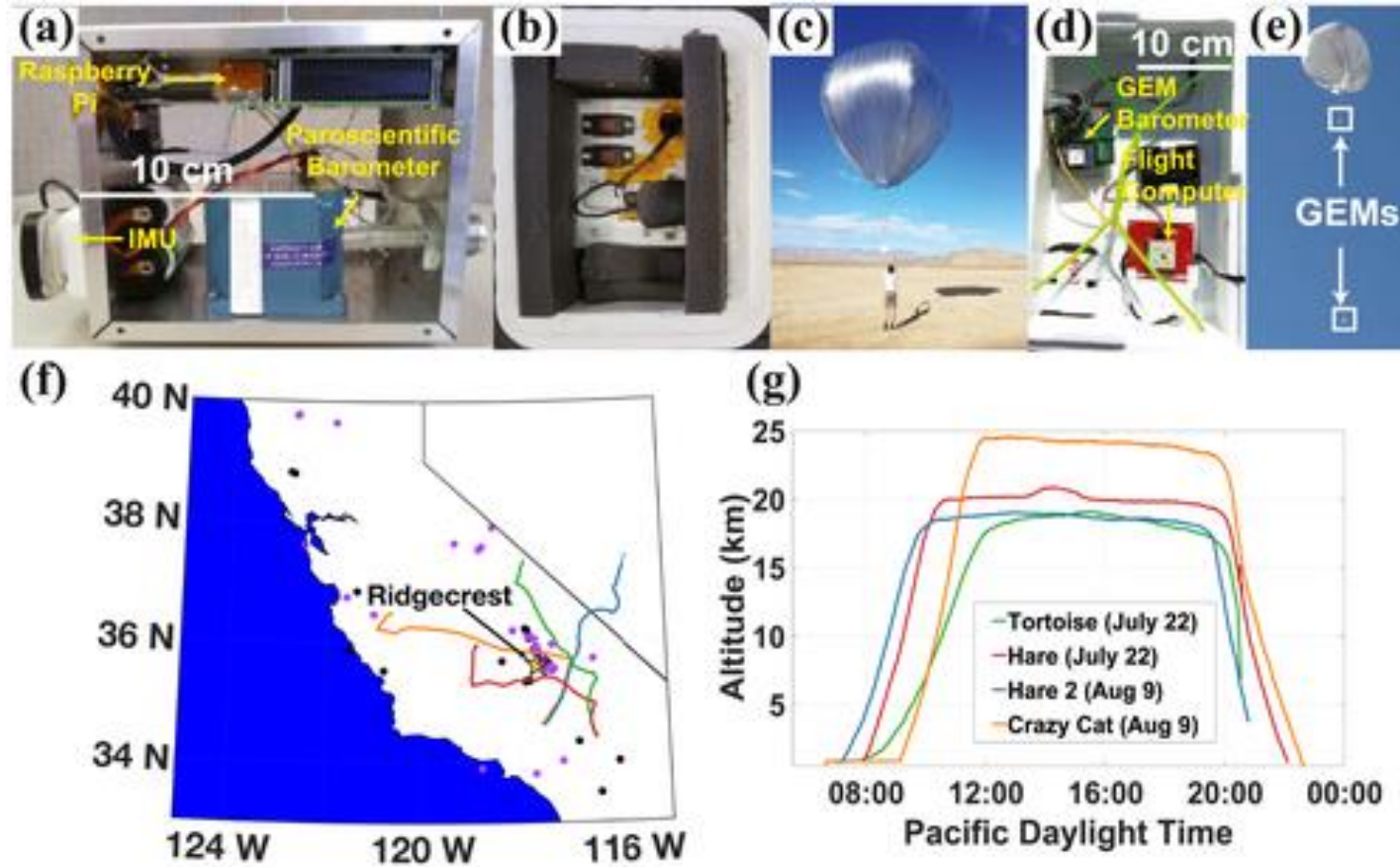


Figure: (a) Sensor package for Tortoise, Hare, and Hare 2 balloons, IMU = Inertial Measurement Unit (b) packaged sensor, (c) Launch of Hare, (d) Sensor package for the CrazyCat balloon, (e) CrazyCat with two sensor packages on a 36-m tether, (f) and (g), The trajectory and altitude profile of the balloons

Making sense of the noise

To investigate our noisy balloon dataset, we adopt a multi-step procedure:

1

Seismic catalog
SCEDC

2

Modeling epicentral
infrasound ray paths

3

Estimation of Signal-to-
Noise Ratio (SNR) at
balloon for each event

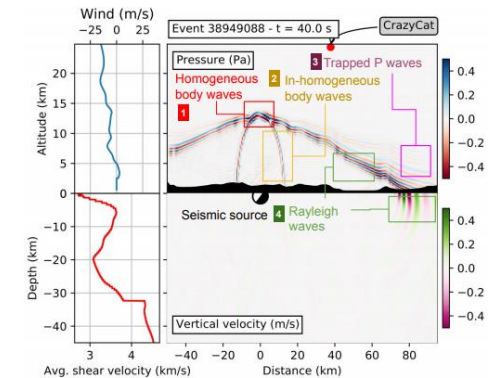
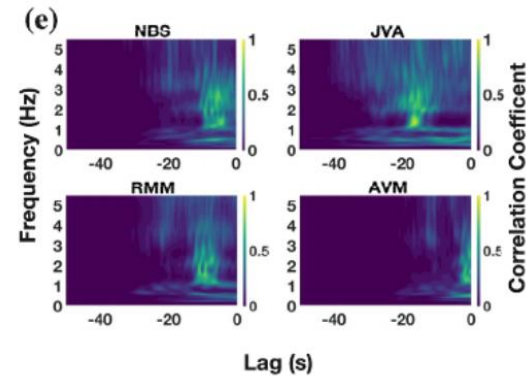
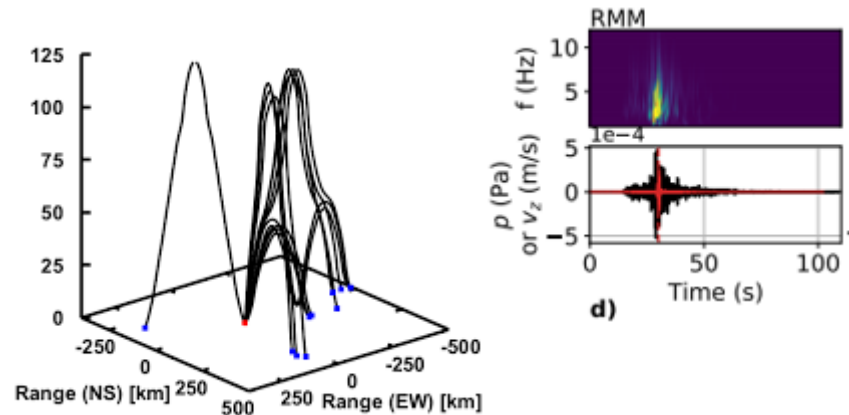
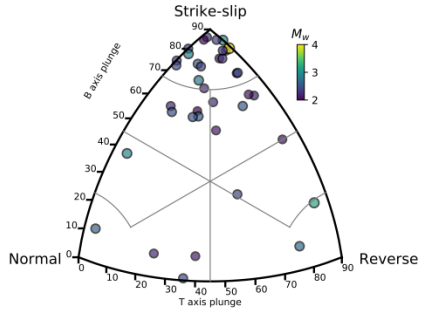
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Cross-correlations with
seismic data at the
ground

5

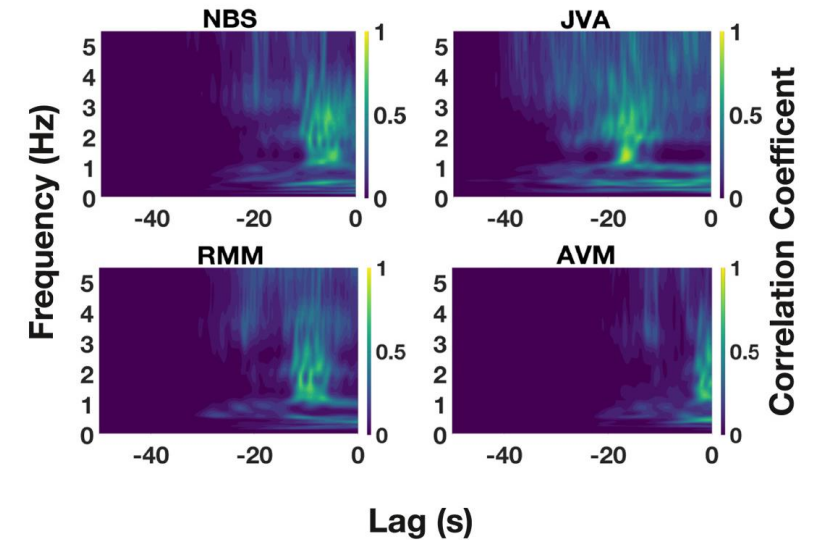
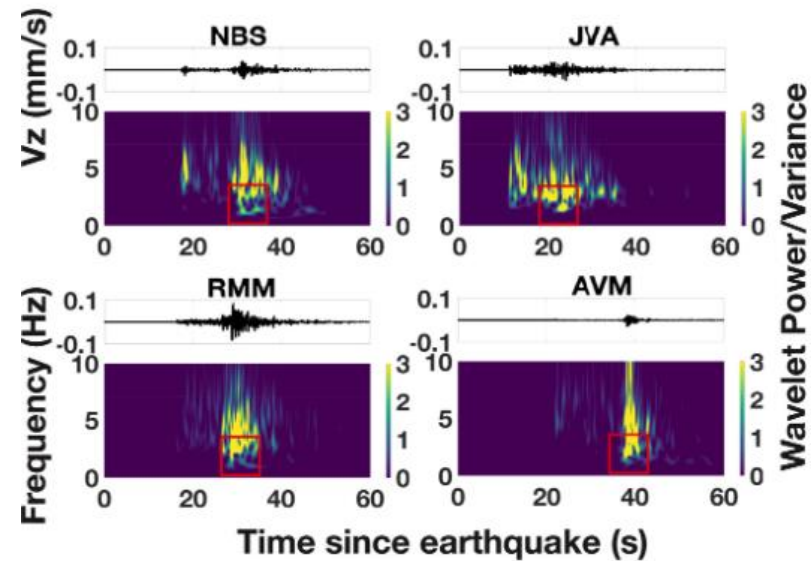
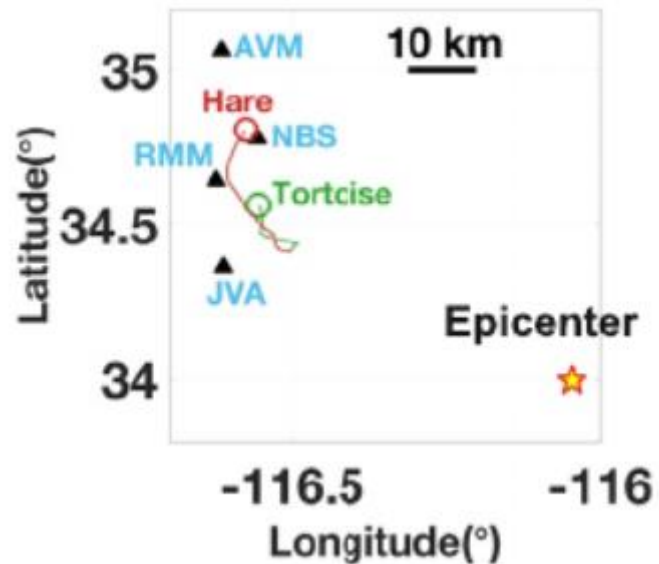
Shortlisting events with
 $\text{SNR} > 1$ and full-
waveform simulations

July 22



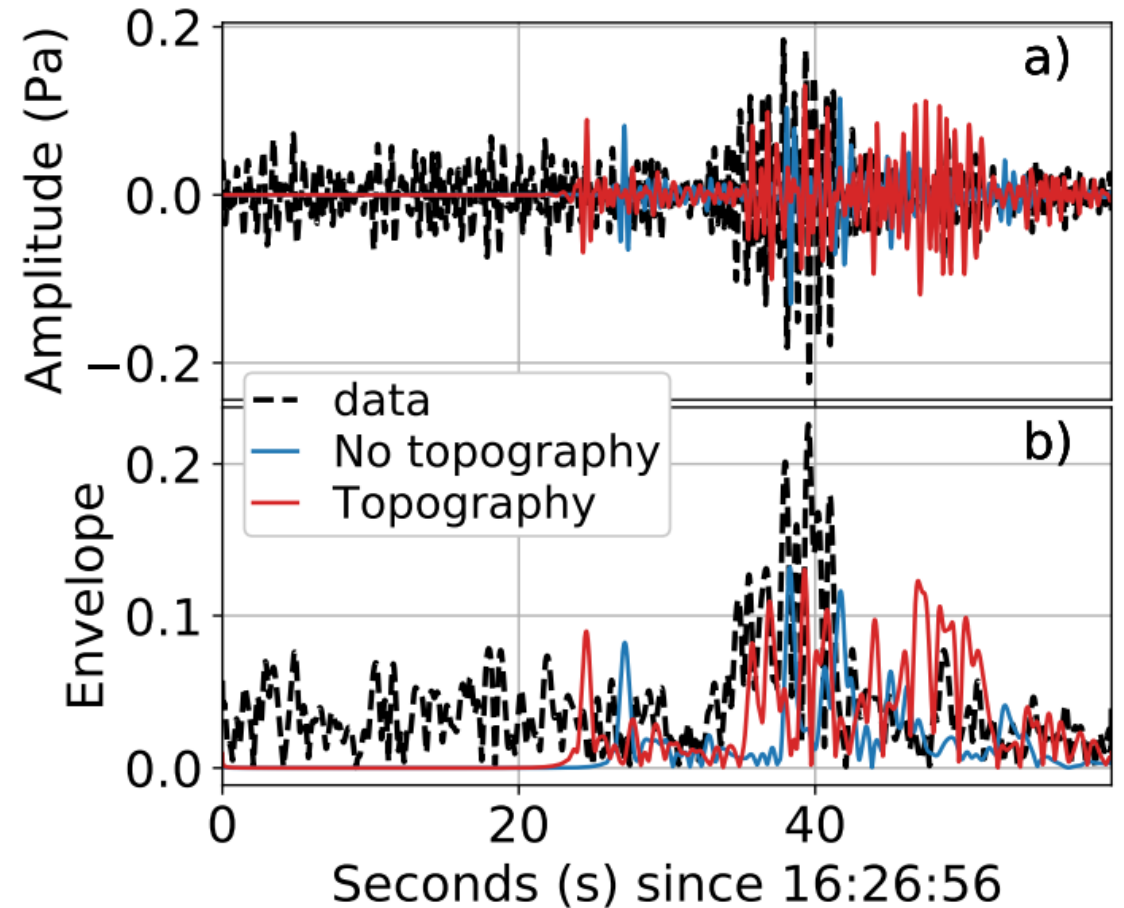
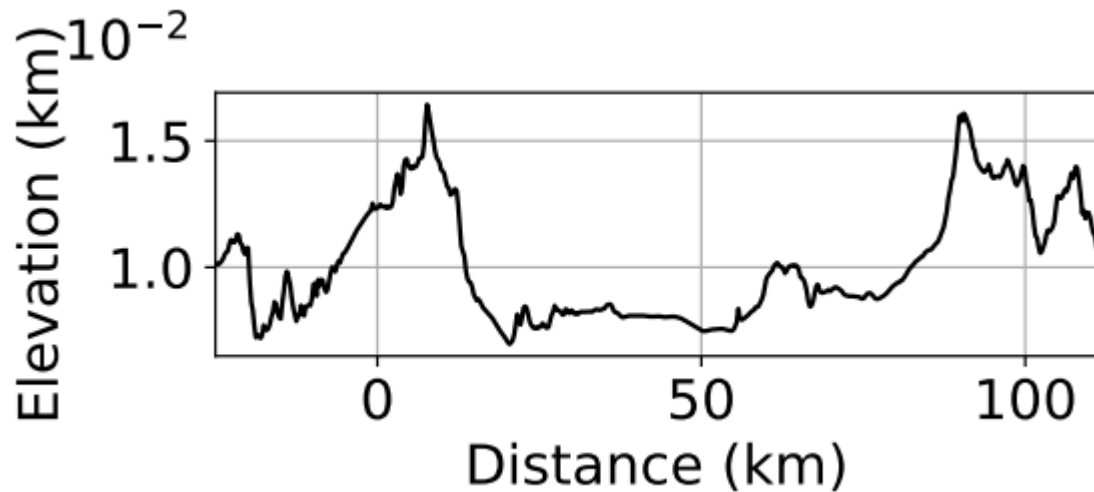
July 22nd 16:26:56

One of the shortlisted event on July 22nd showed **high correlation with seismic arrivals and good match with numerical simulations**



Seismo-acoustic path effects

Uncertainties in both topography or subsurface velocity models lead to significant variations in both amplitude and frequency content and their effects



What about Venus?

Three missions have been selected in June 2021: VERITAS, DAVINCI+, and EnVision

However, none of them include geophysical probes besides a Radio Science experiment...



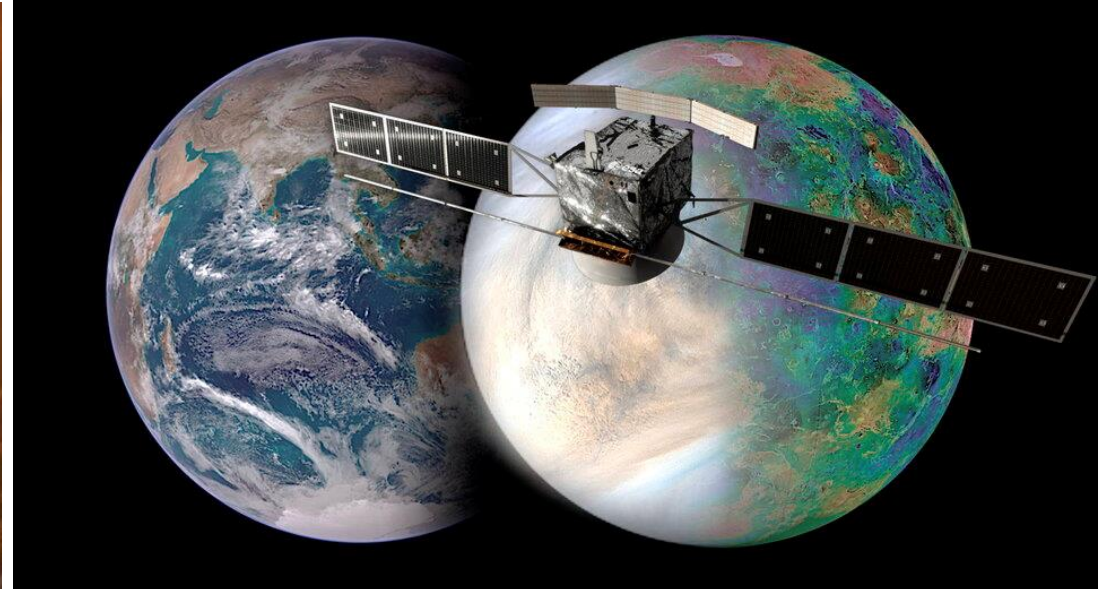
VERITAS

Surface topography & rock composition



DAVINCI+

Atmospheric composition & surface picture



EnVision

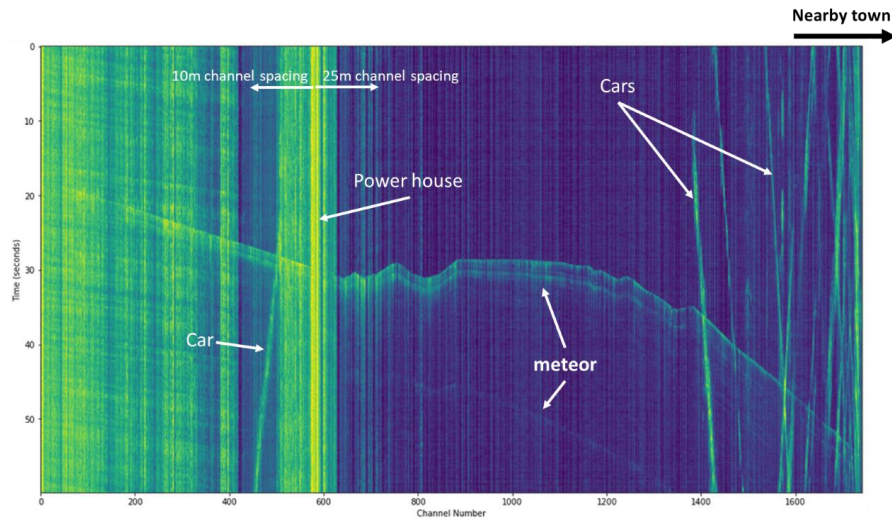
Atmospheric composition, surface thermal signature, core size

NORSAR

Research activities directly or indirectly participate towards a better understanding of seismo-acoustic couplings processes and building efficient inversion methods

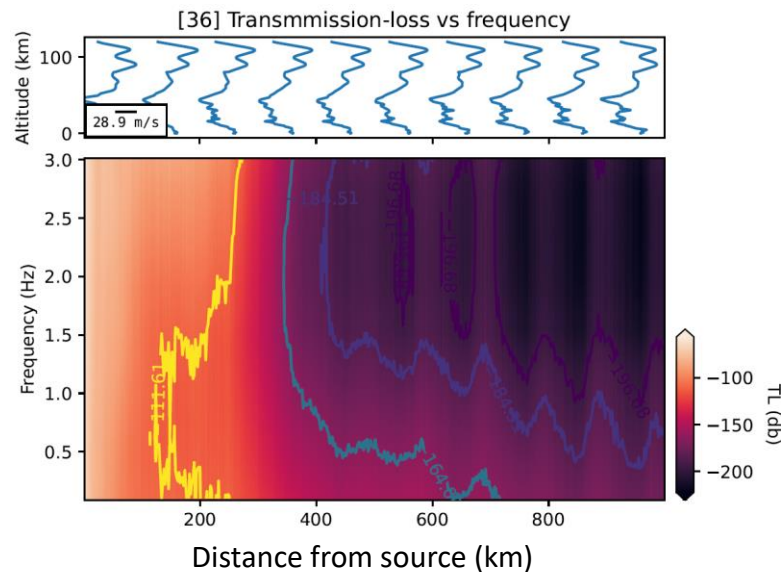
Studying infrasound propagation through DAS

Ismael Vera Rodriguez, Andreas Wuestefeld



Machine learning aided acoustic modeling

Peter Naesholm, Antoine Turquet

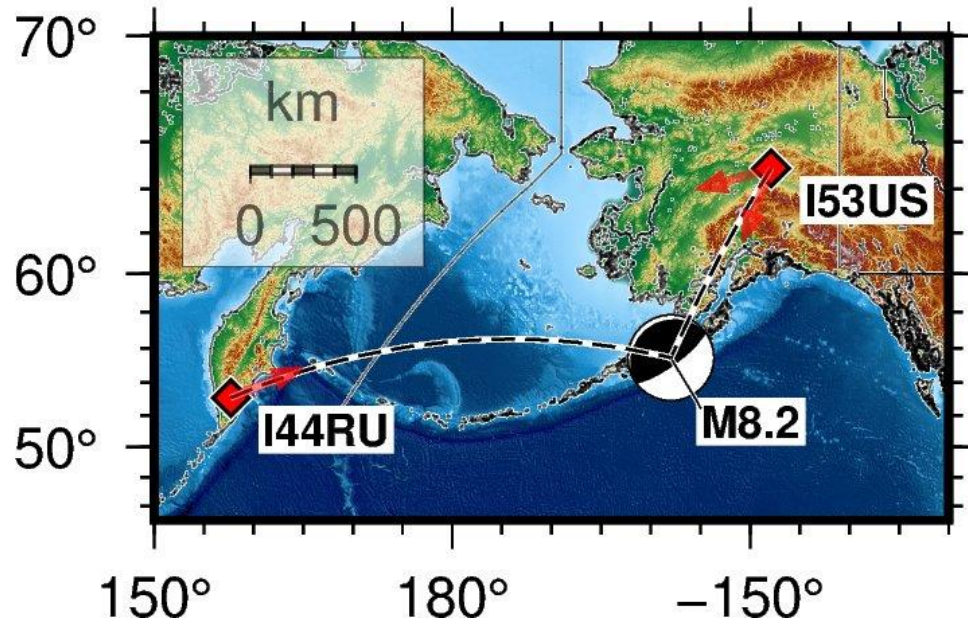


Collaborations with Swedish (miniBOOSTER) and US (PSTAR) balloon projects

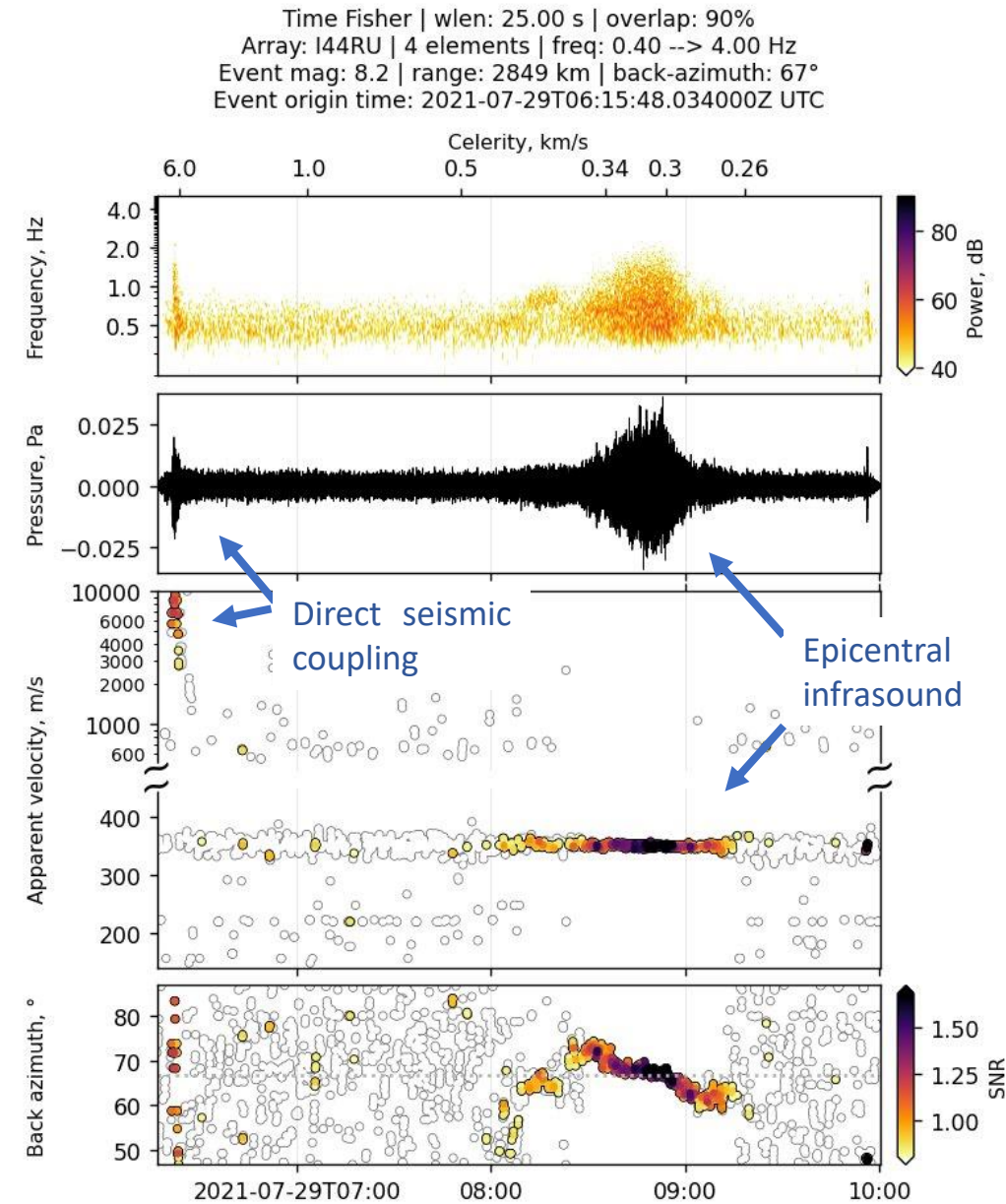
Peter Naesholm, Tormod Kvaerna



Recent seismo-acoustic records



Figures: Infrasound records after the Mw 8.2 Alaska earthquake on July 29th



Balloon deployment



Figures: (left) Inflating a 6 m heliotrope with a box fan, (center) walking the inflated envelope across an open area until it gains sufficient lift to pick up the payload, and (right) a successful launch. (*Bowman, 2020*)



Balloon landing

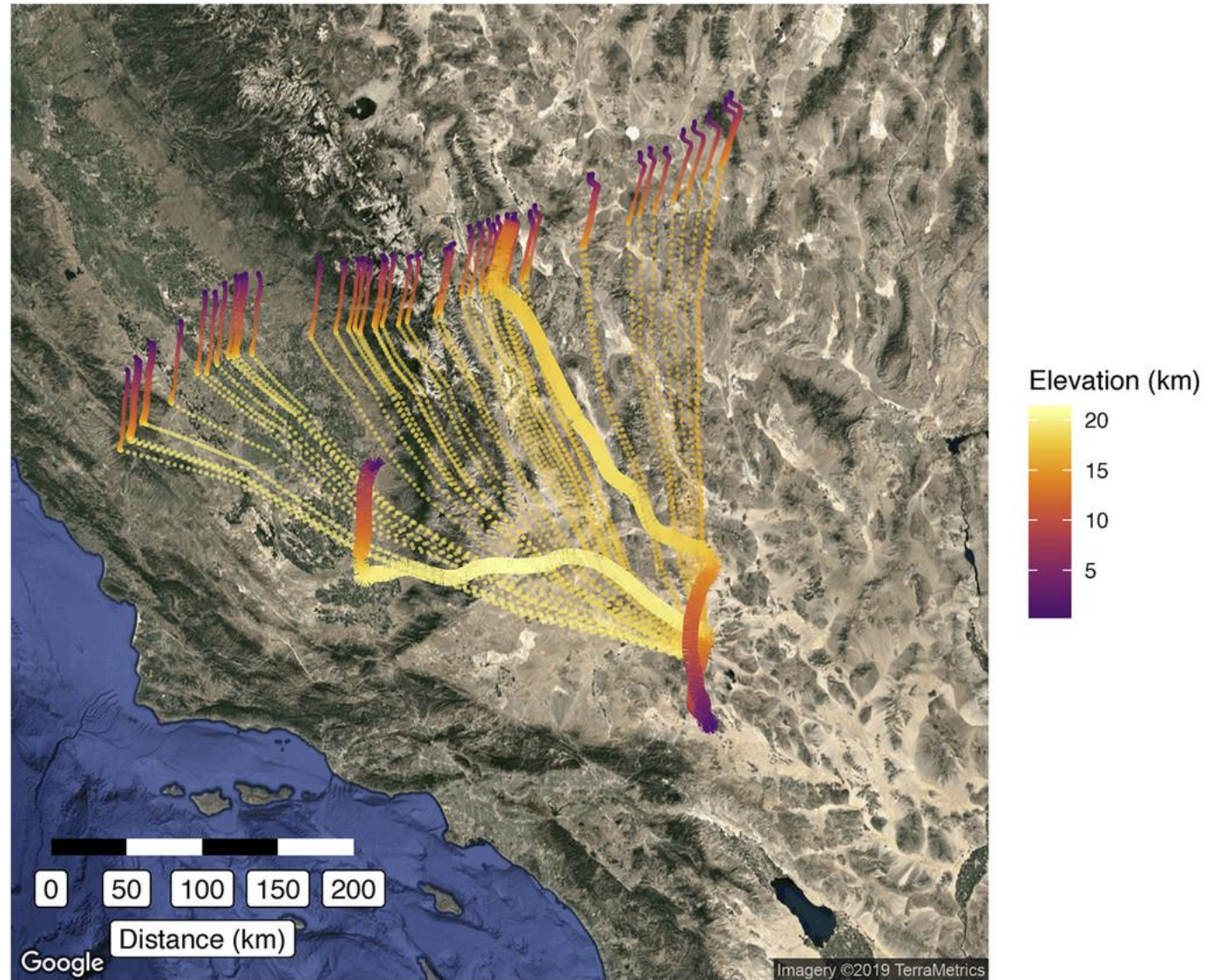


Figures: A 6 m heliotrope balloon after landing in the Arizona desert.. (*Bowman, 2020*)

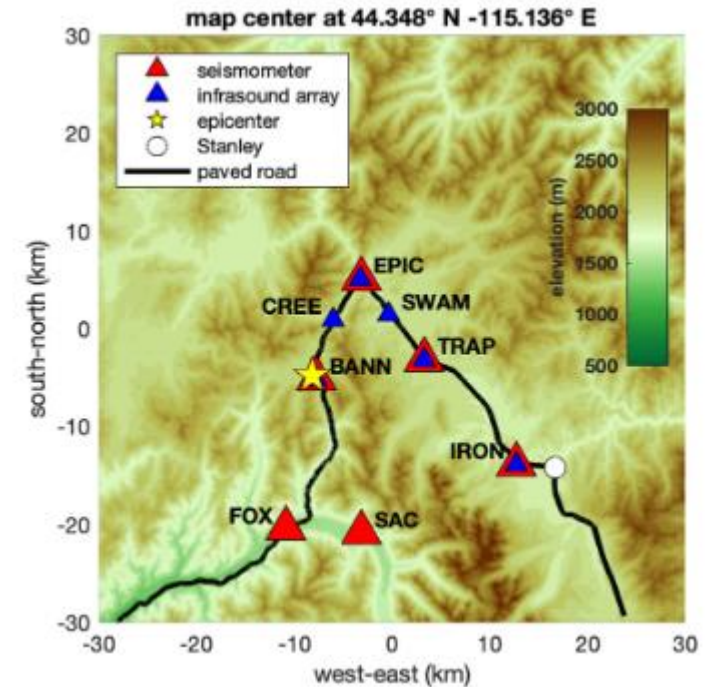
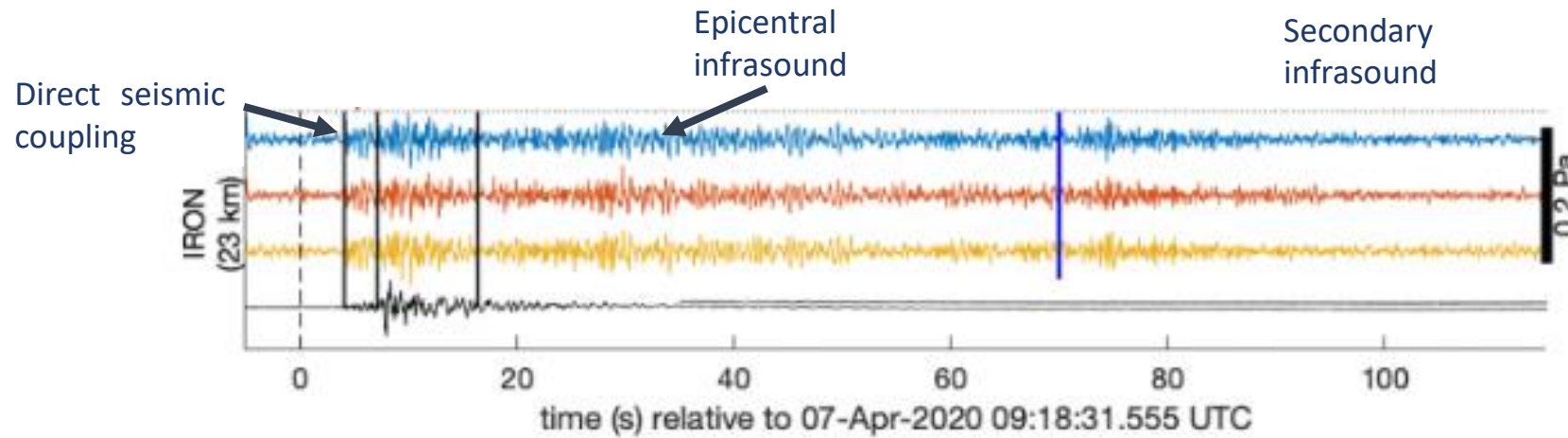


Predicted vs true trajectories

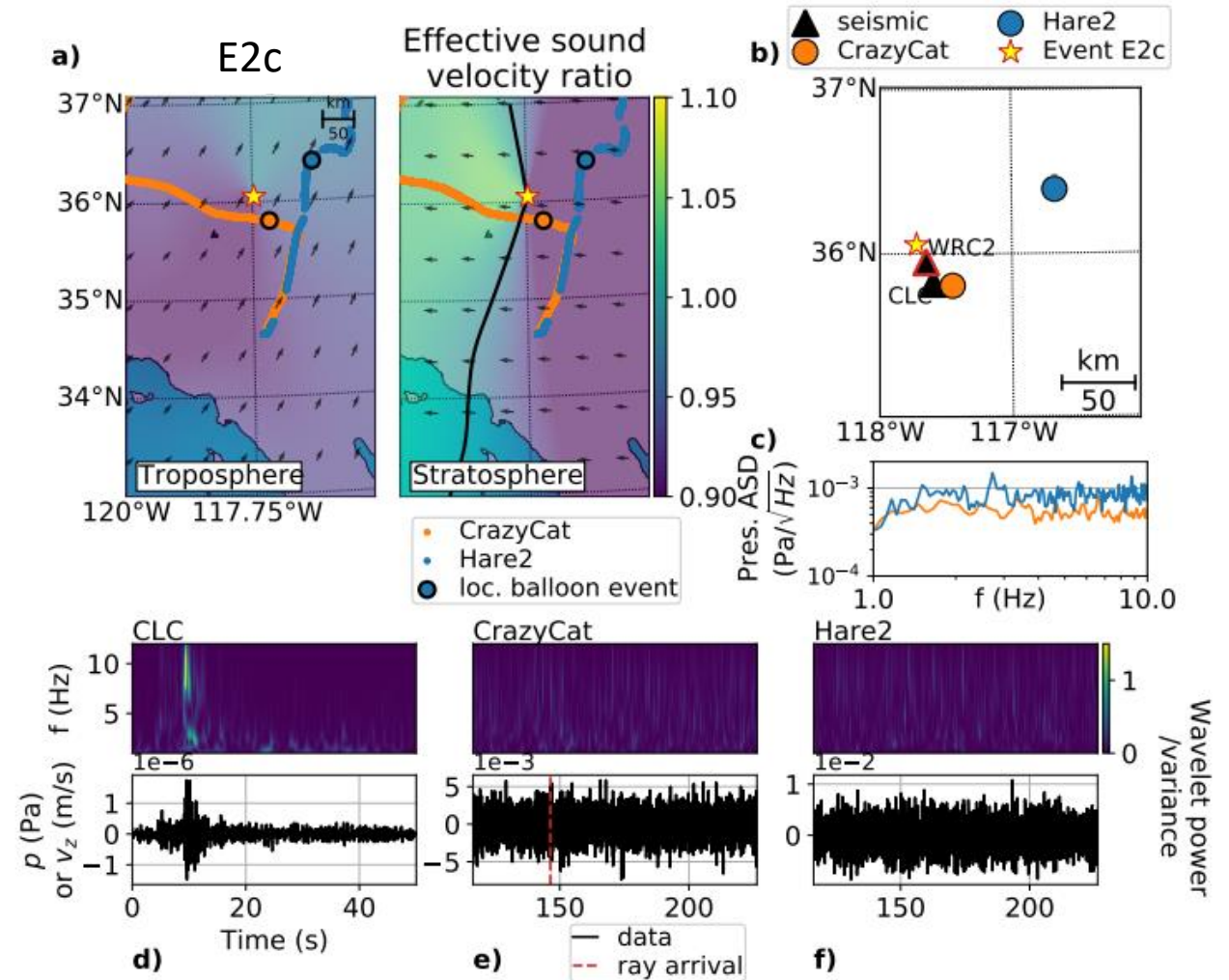
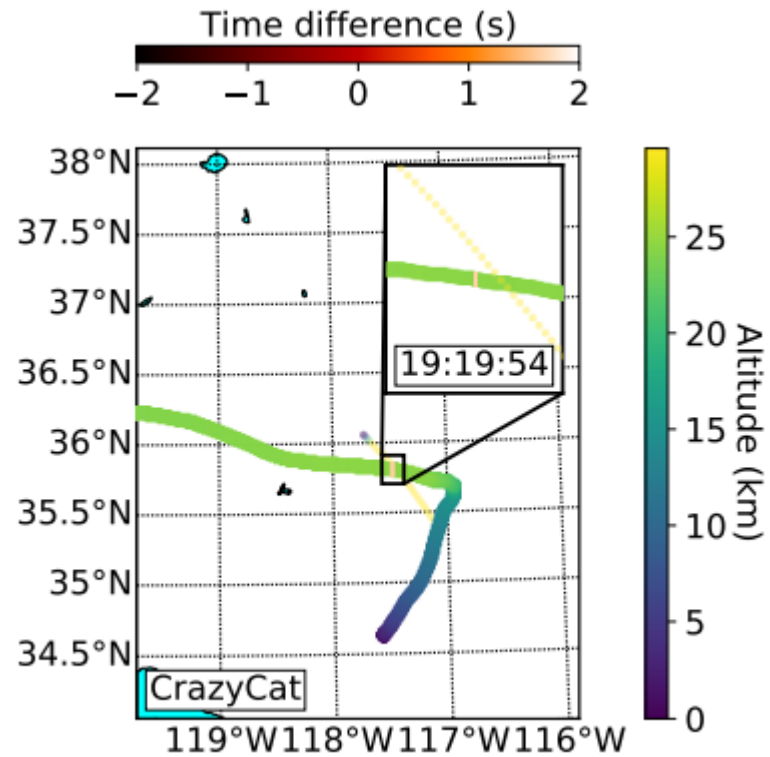
Figures: Predicted trajectories (dots) and actual trajectories (lines) for a heliotrope campaign on 22 Jul 2019. (Bowman, 2020)



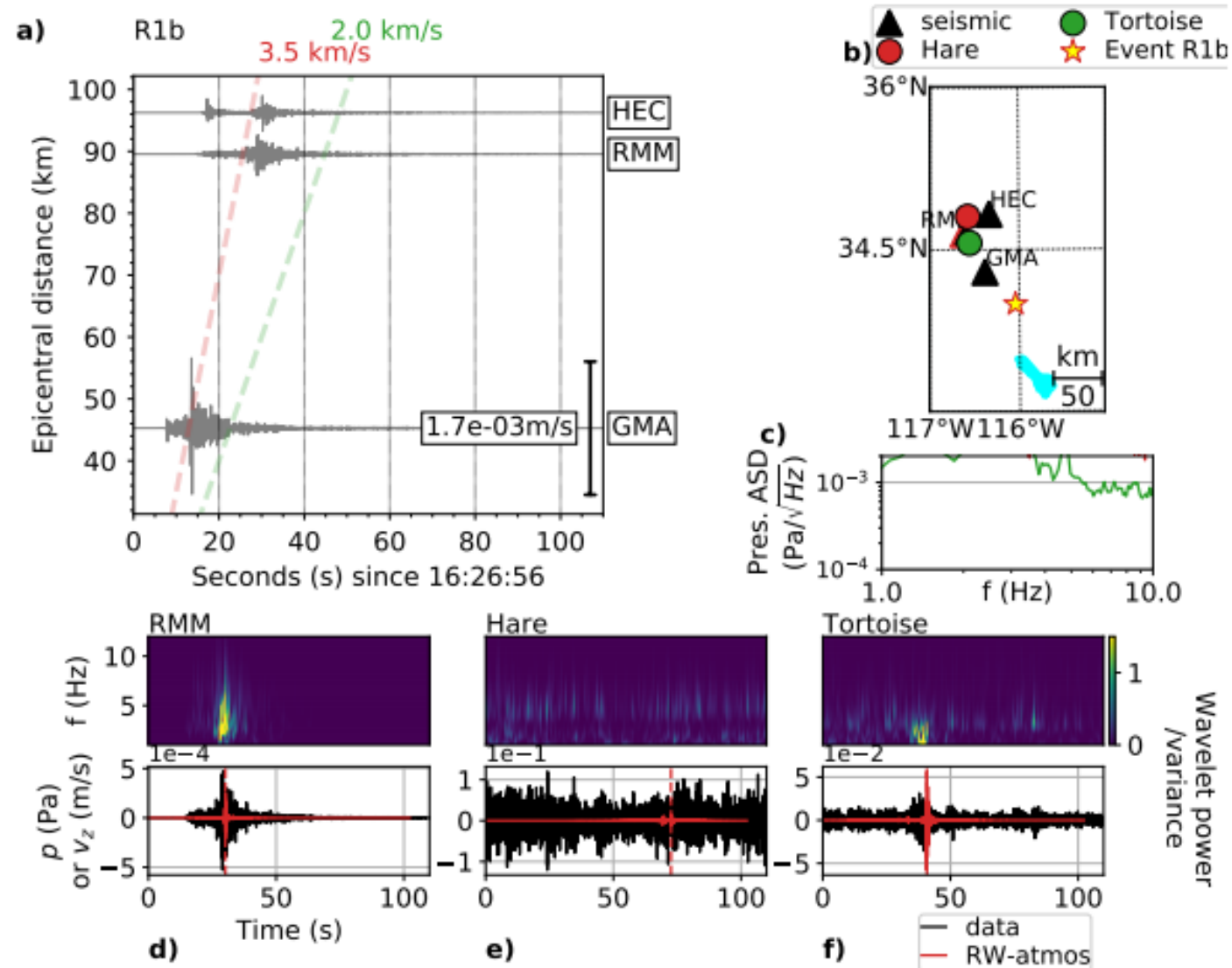
Observation of small magnitude earthquakes



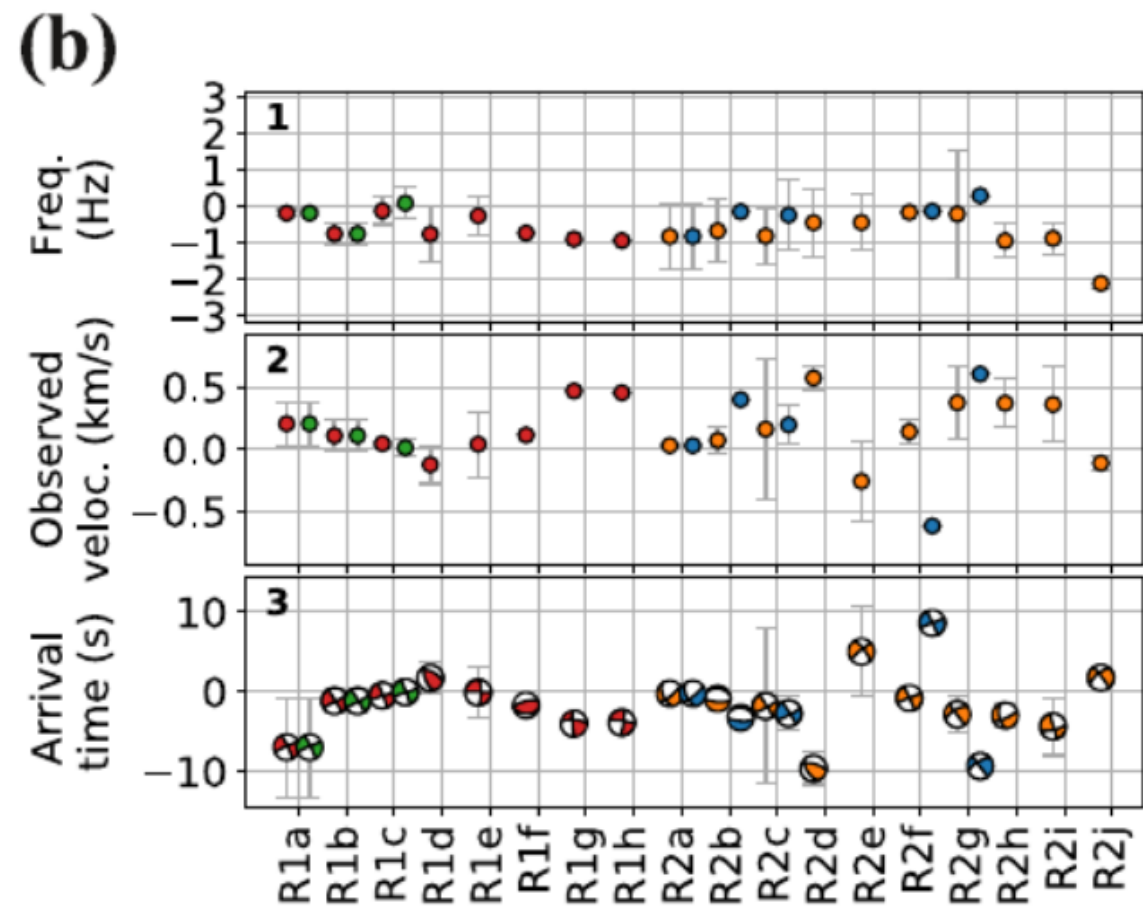
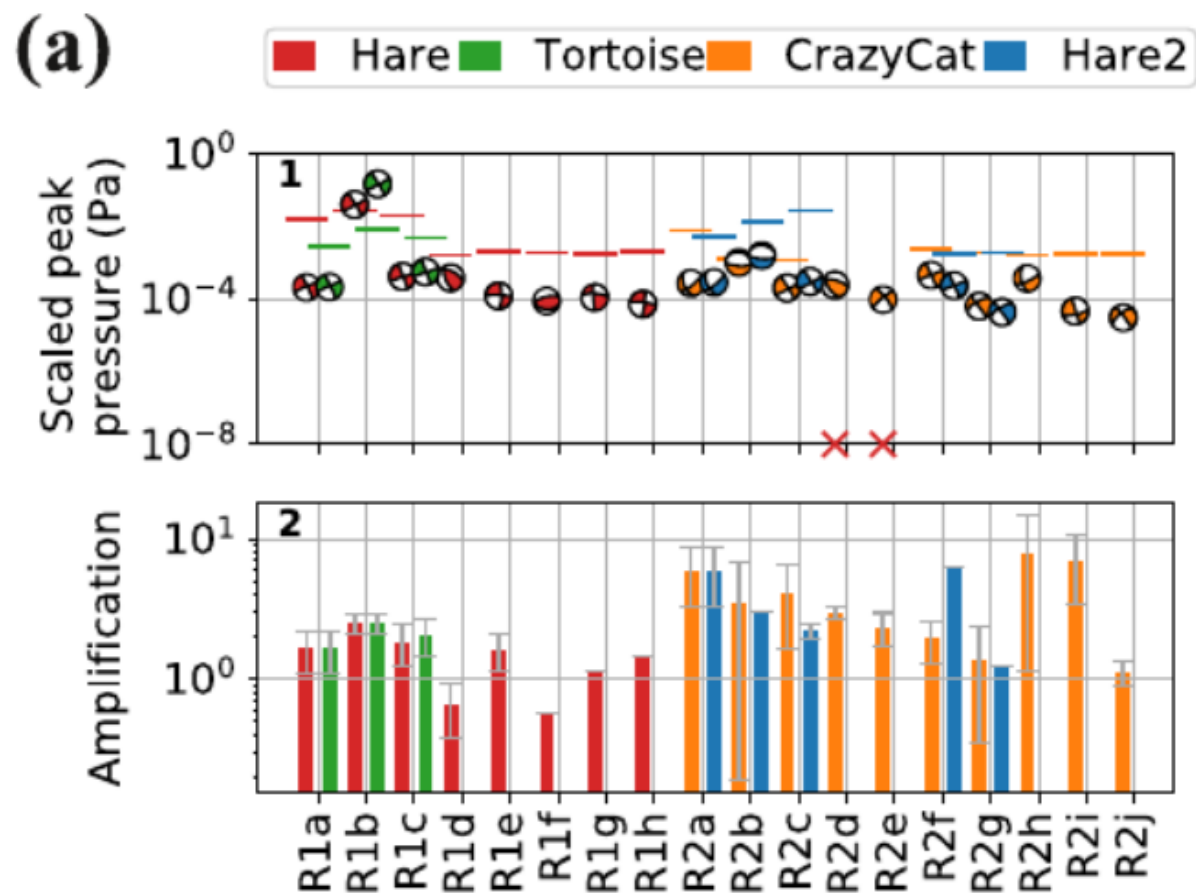
Ray tracing predictions for event E2c



RW-atmos predictions for event R1b



Estimating SNRs



Frequency Time Analysis (FTAN)

FTAN analysis corresponds to the filtering of a signal with narrowband Gaussian filters to extract the group velocity at given frequencies

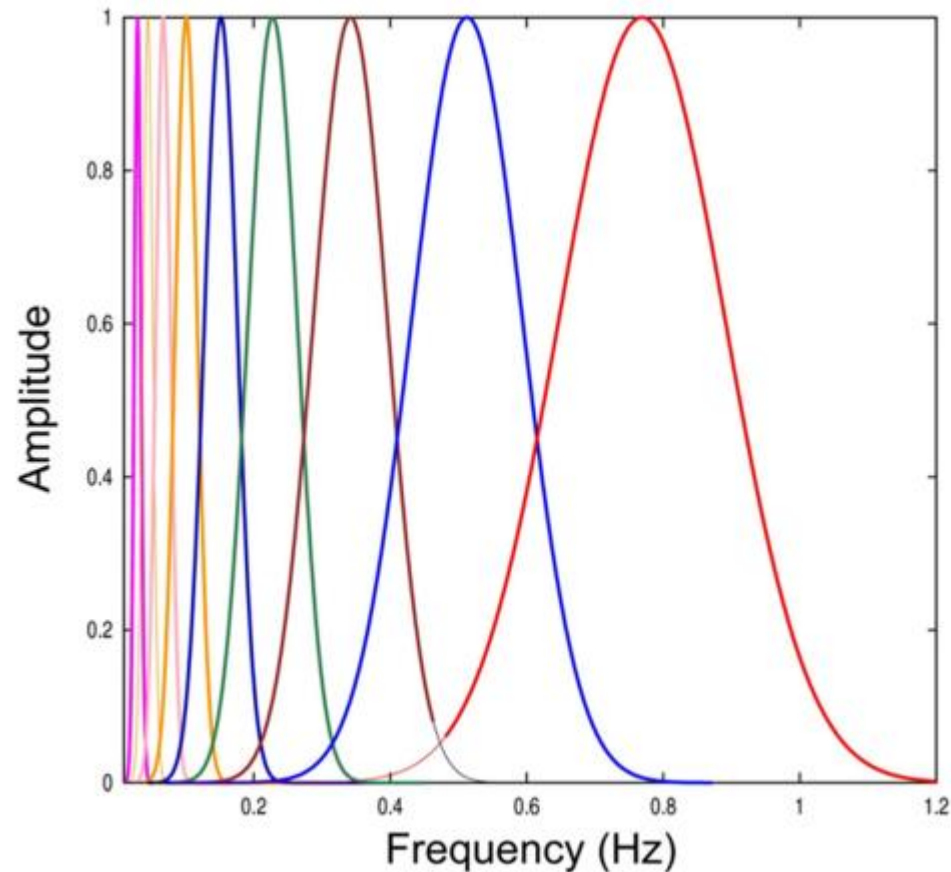


Figure: Typical FTAN Gaussian filters

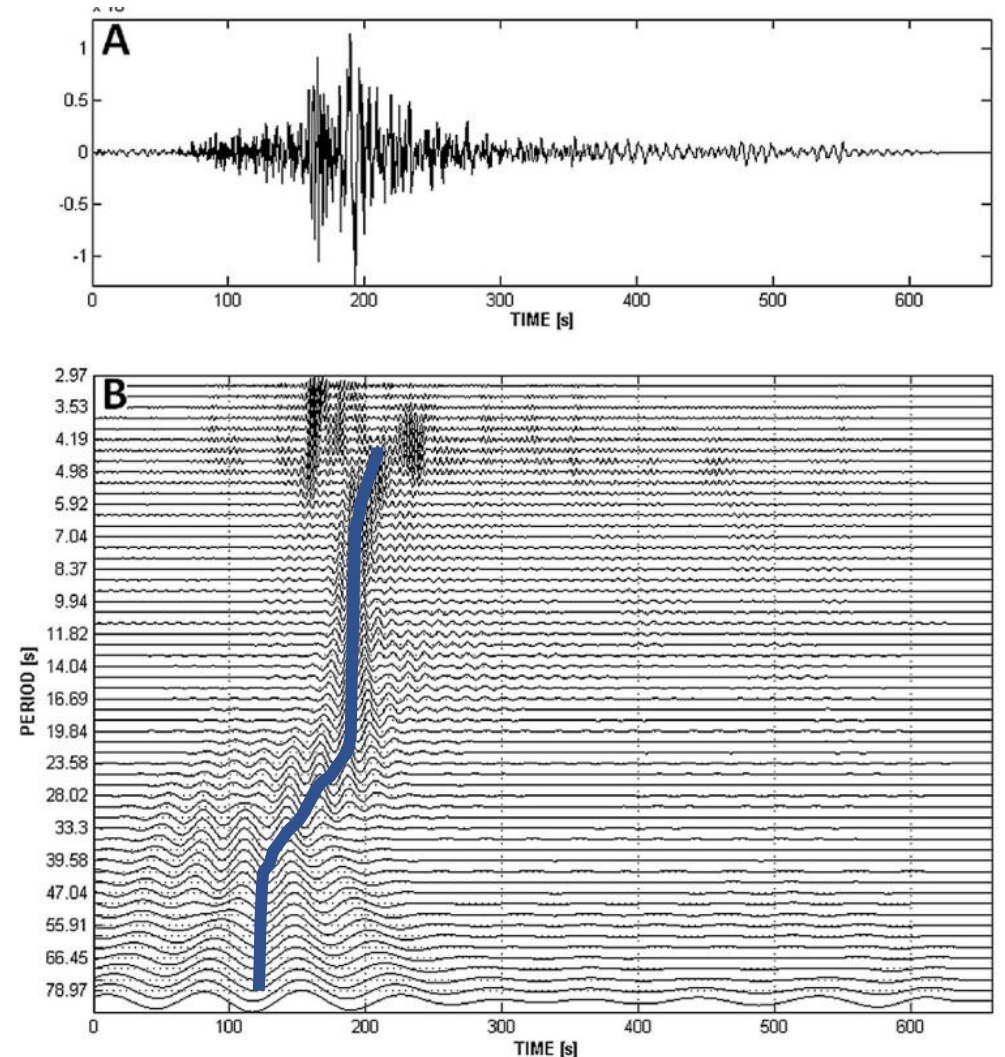
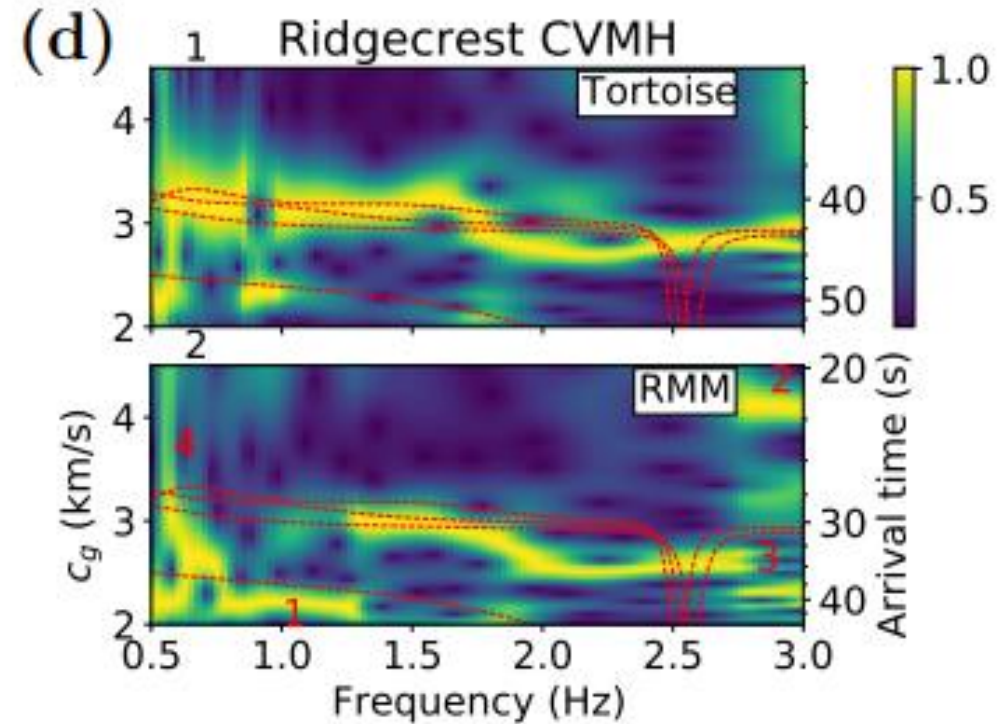
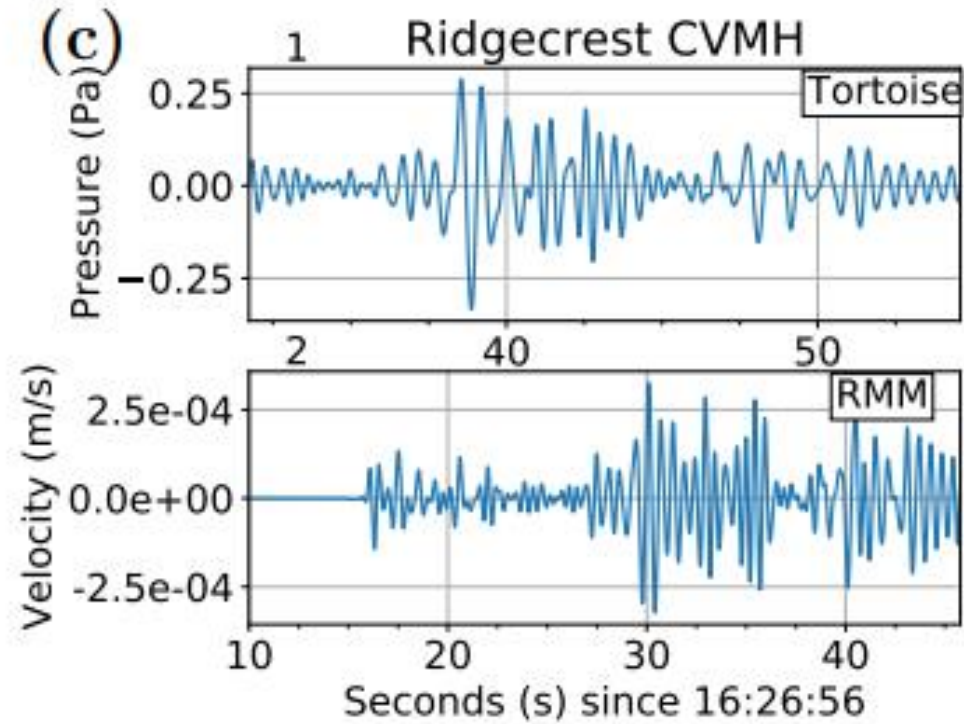


Figure: Example of FTAN results of a seismic signal (Granados, 2019)

FTAN of simulated signals



Background velocity models

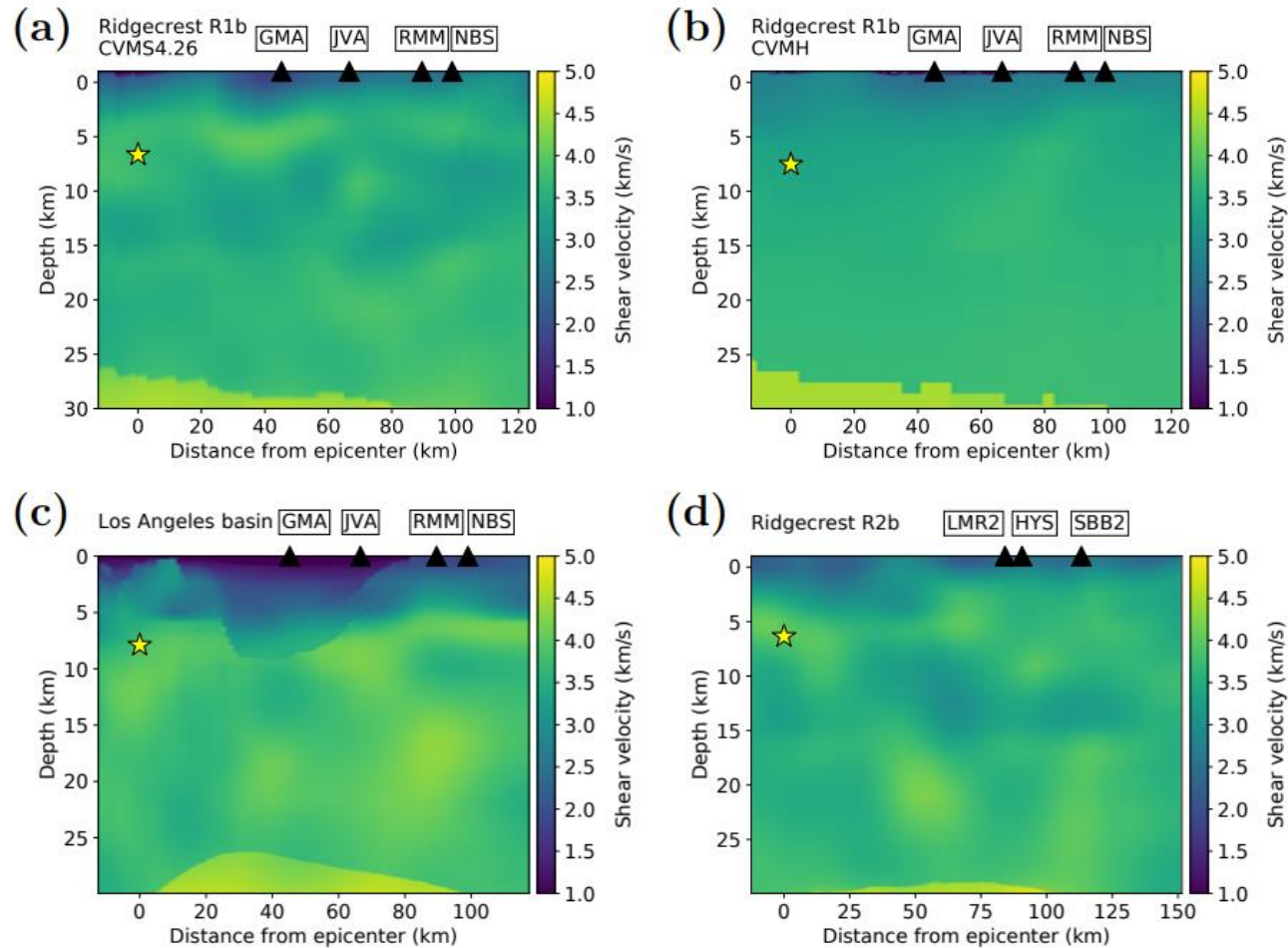
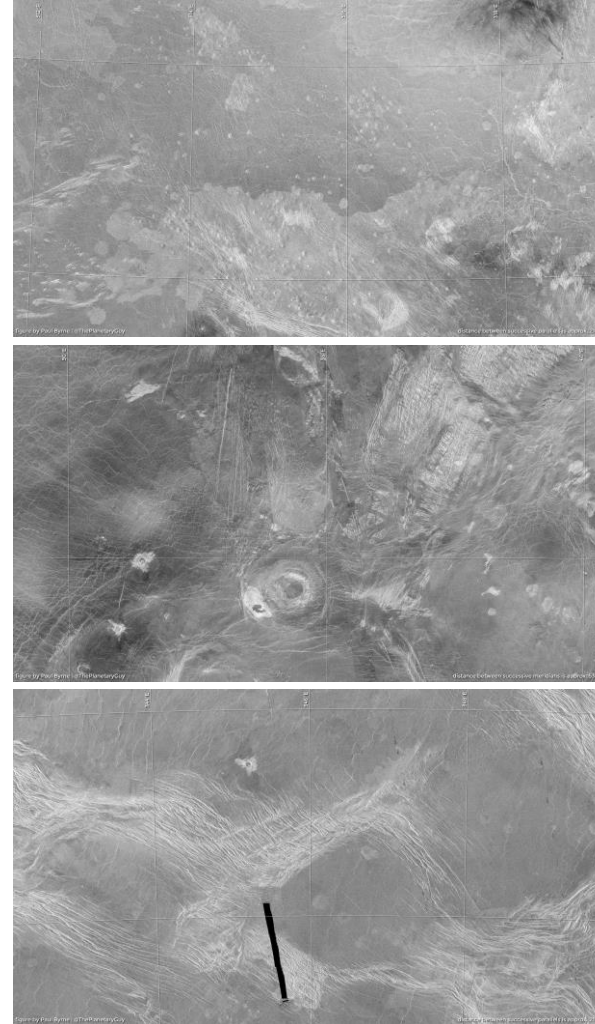


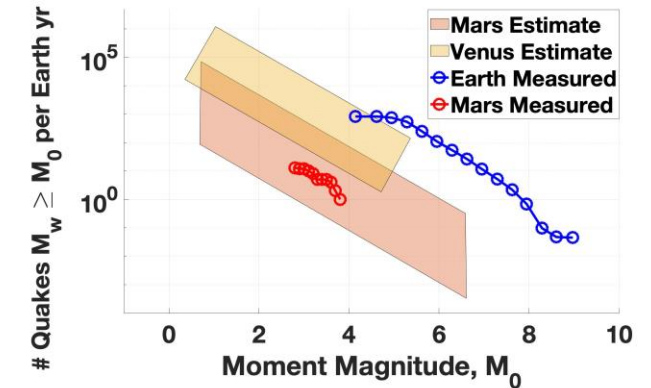
Figure S52: Shear velocity model versus depth used in SPECfEM simulations for event R1b in the Ridgecrest region extracted from the CVMS4.26 dataset (panel a), in the Ridgecrest region extracted from the CVMH dataset (panel b), event R1b in the Los-Angeles basin extracted from the CVMS4.26 dataset (panel c) and event R2b in the Ridgecrest region extracted from the CVMS4.26 dataset (panel d). The star indicates the epicentral location. Black triangle indicate the regional seismic station epicentral distance.

Venus Interior and Seismicity (courtesy of JPL)

- The surface of the planet has its own distinctive tectonic and volcanic character
- Estimates of Venus seismicity vary over a large range – no direct or indirect measurements available
- There is a lot of circumstantial evidence pointing to ongoing volcanic activity
- Detection of seismic activity can establish if tectonism is still active and can be used to probe the crust and interior of the planet
- Surface conditions are harsh, spacecraft lifetime is limited



Byrne, 2018



Data from Giardini et al., 2020 and Lognonne and Johnson, 2005



Balloon data can be traitorous

In addition to possible turbulence in the atmosphere, balloon oscillations can generate acoustic noise in the right frequency range

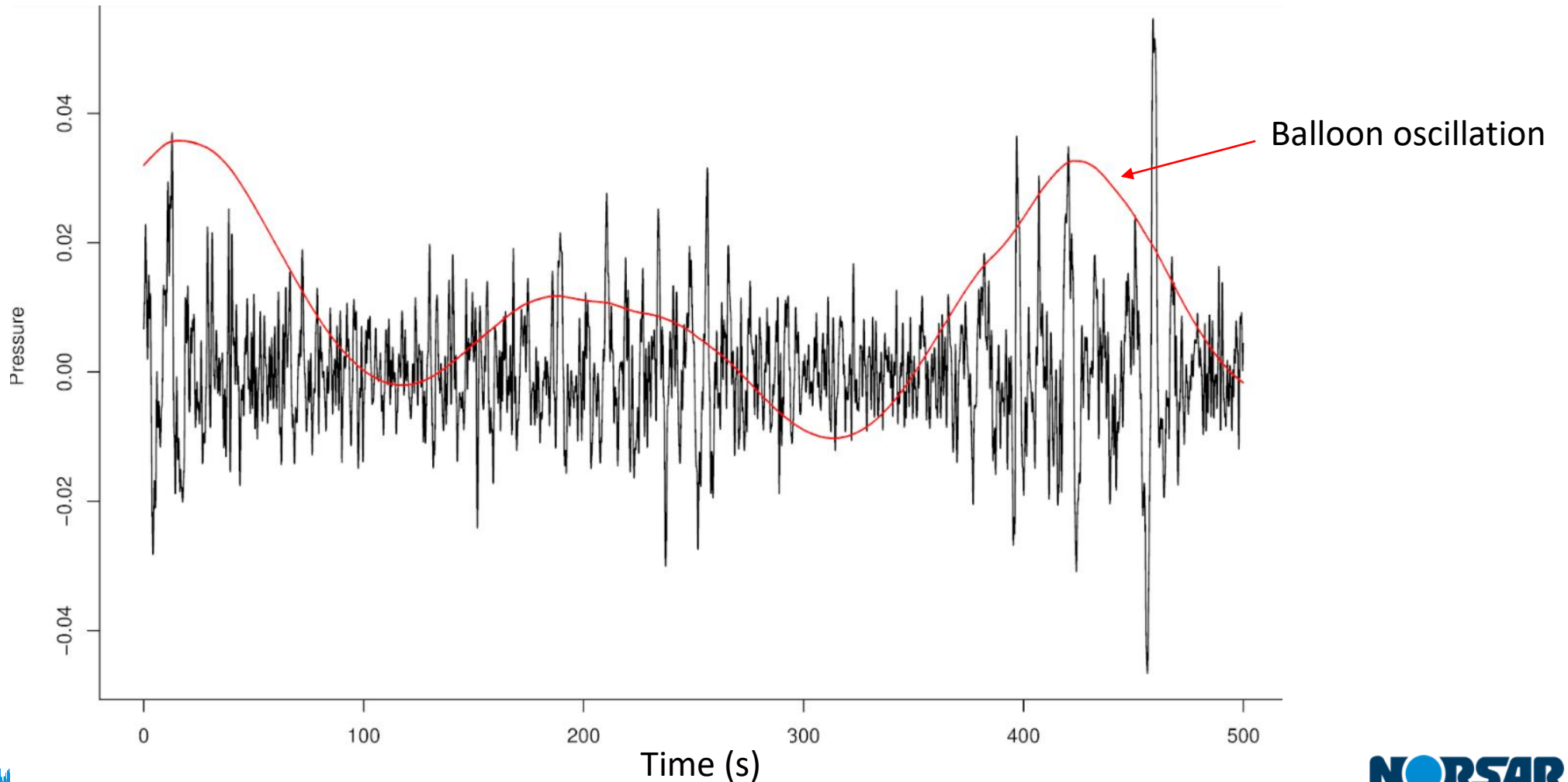
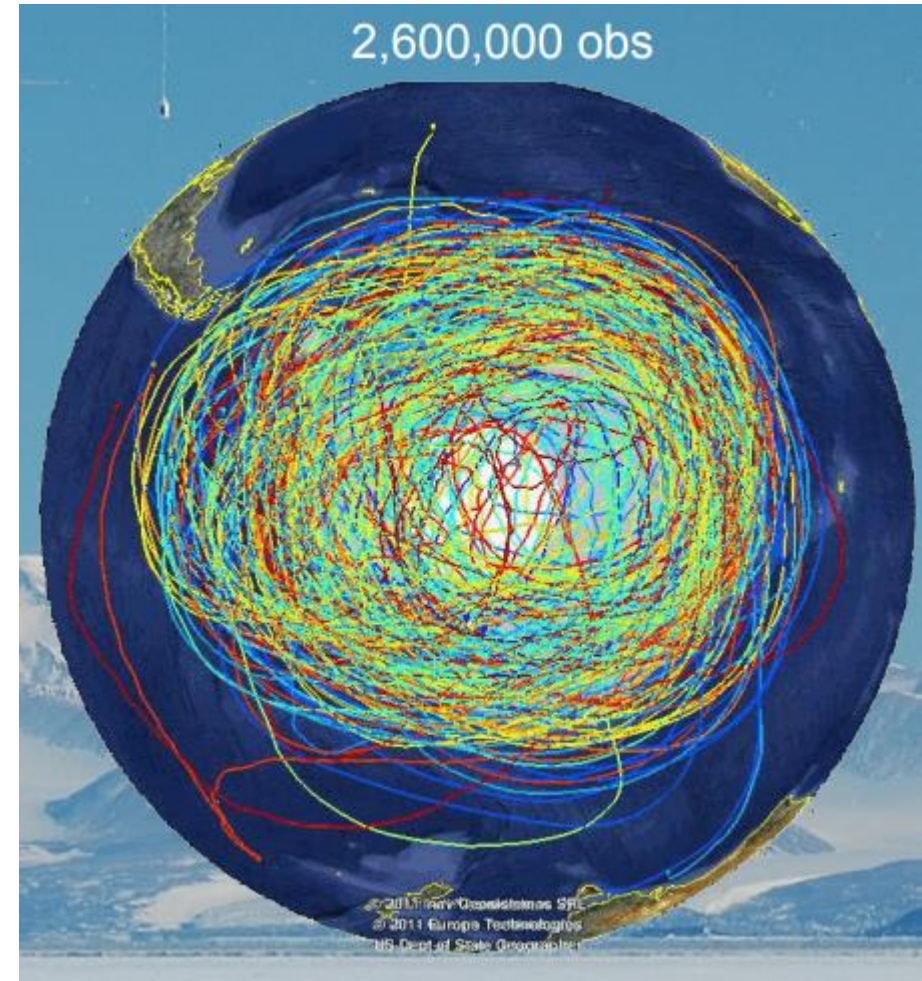


Figure: Example of pressure records (black) at balloon Hare on July 22nd along with balloon oscillations (red)

Piggybacking on long duration flights

E.g., CNES' Stratospheric balloon flying for 2-3 months about 18-20 km altitude and carrying more than 15 kg payload



Figures: Strateole-Vorcore 2005-2006 flights

Seismo-acoustic path effects

Focal mechanisms also change the structure of the infrasound wavefield

