Seismicity on Venus: Prediction & Detection

ISSI International Team Proposal 2022

Abstract

With the selection of multiple missions to Venus by NASA and ESA planned to launch in the coming decade, we will greatly improve our understanding of Venus as a planet. However, the selected missions cannot tell us anything about the seismicity on Venus, which is a crucial observable to constrain the tectonic activity and geodynamic regime of the planet, and its interior structure. We have gathered an interdisciplinary team of experts in seismology, geology, and geodynamics to assess the seismic activity on Venus from a theoretical and instrumental perspective. We aim to provide estimates of the current seismicity on Venus based on constraints from e.g., geodynamic modelling and surface fault mapping. Using these estimates, we aim to determine the associated ground motion and atmospheric perturbations that can be expected on Venus as a result of seismicity. To detect these seismic signals eventually during future missions, we will review the feasibility, advantages, and disadvantages of seismic observation techniques on the surface (e.g., broadband seismometers, distributed acoustic sensing methods), from a balloon, and from orbit. Consolidating the results from both the theoretical and instrumental parts of this proposal will make a major contribution to understanding the present-day seismicity of Venus and result in recommendations for future payload configurations for Venus missions with seismological science objectives. Hence, with this international team, we aim to advance the current state-of-the-art of Venus seismology and pave the way for future geophysical mission studies that will extend the Venus science programme beyond the current decade.

1 Scientific rationale

The coming decade has been dubbed the 'Decade of Venus' as multiple Venus missions have recently been given the green light by NASA (VERITAS, DAVINCI+; Smrekar et al., 2020) and ESA (EnVision; Ghail et al., 2016). Other space agencies such as the Russian and Indian, are also planning to target the planet in the coming years. These missions will provide a wealth of new information on Venus's atmosphere and surface and could answer the long-debated question on how geologically active Venus currently is (Glaze et al., 2018). However, the seismicity of Venus, which is a major component of its current activity, cannot be detected with the current missions. Detecting and interpreting seismic signals on Venus would have great scientific benefit, as it cannot only tell us something about Venus's current activity and tectonic regime, but it can also be used to determine the interior structure of the planet by detecting interfaces, such as the crust-mantle interface and core-mantle boundary. Indeed, measurements from the successfully deployed Apollo Lunar Surface Experiments Package on the Moon (Nakamura et al., 1982) and recent results from the InSight mission on Mars (Banerdt et al., 2020) have shown how much our understanding of terrestrial planets can be increased through data from a limited amount of seismometers. Seismic data from the Moon advanced our understanding of the lunar seismicity (Oberst, 1987) and interior structure (Nakamura, 1983), indicating the presence of a solid inner and a liquid outer core (Garcia et al., 2011; Weber et al., 2011), a sharp seismic velocity discontinuity in the mid mantle (Khan et al., 2000) and the presence of partial melt at the base of the mantle (Weber et al., 2011). Data collected by the seismometer SEIS (Lognonné et al., 2020) on board of the InSight mission have been successfully used to constrain the Martian seismicity (Giardini et al., 2020), the thickness of the crust (Knapmeyer-Endrun et al., 2021), the upper mantle structure (Khan et al., 2021), mantle seismic velocity variations (Plesa et al., 2021), and the size of the Martian core (Stähler et al., 2021).

To address the emerging science questions concerning Venus and to go beyond the coming decade of Venus to ensure a lasting programme of Venus science, we plan to explore the possibility of detecting seismicity on Venus for potential future missions. To this end, we would like to set up an international team to estimate the current seismicity on Venus and the most feasible methods to measure it.

The ultimate aim of this project is to consolidate and expand the current state-of-the-art of Venus seismology. More precisely, we have the following two objectives that are further broken down into individual work packages:

1. **Estimate the expected current level of seismicity on Venus.**
   1.1. Estimate how often we expect venusquakes globally for different moment magnitudes.

1.2. Estimate the largest possible maximum magnitude of a venusquake.
1.3. Estimate the expected seismicity associated with different structural features on Venus (e.g., wrinkle ridges, rifts, coronae, etc.).
1.4. Estimate the expected ground motions associated with Venusian seismicity.
1.5. Estimate the expected atmospheric pressure perturbations associated with Venusian seismicity.

2. **Determine the feasibility, advantages, and disadvantages of the different methods for detecting seismic events on Venus.**
   2.1. Determine feasibility, advantages, and disadvantages of seismic instruments that need to be placed on the surface of Venus (i.e., broadband seismometers, geophones, interrogators for distributed acoustic sensing, etc.).
   2.2. Determine feasibility, advantages, and disadvantages of seismic measurements from a balloon (i.e., barometers, inertial measurement units, etc.).
   2.3. Determine feasibility, advantages, and disadvantages of seismic measurements from orbit.
   2.4. Estimate a realistic environmental noise level on Venus taking into account the meteorological and thermal conditions.
   2.5. Recommend possible payload configurations for a future mission focusing on seismic observation of Venus.

Estimating the expected current level of seismicity on Venus

Currently, the level of seismicity on Venus is poorly known, although a few studies have been conducted into regional seismic rates (e.g., Sabbeth et al., 2021). However, local seismicity, and especially global estimates derived from seismic observations, can tell us a lot about a planet's tectonic regime and its interior structure (Nakamura, 1983; Garcia et al., 2011; Weber et al., 2011; Banerdt et al., 2020; Giardini et al., 2020; Lognonné et al., 2020). Therefore, observations on seismicity are crucial to gain an understanding of the inner workings of Venus and would also represent an important step forward in our understanding of Venus-like exoplanets and indeed our own planet Earth (Stevenson et al., 2015).

We plan to fulfil the first objective through a range of different approaches. From the geodynamical point of view, we will use three-dimensional thermal evolution models of Venus to estimate the annual seismic budget, akin to the study of Plesa et al. (2018) for Mars. From a geological point of view, we will focus on identifying potentially active faults associated with tectonic features on Venus, such as rifts, grabens, ridges, and coronae. This effectively expands previous studies such as Sabbeth et al. (2021) who determined the annual seismic moment release rates associated with faults in wrinkle ridges (Fig. 1). We also plan to explore other options of estimating the seismicity on Venus, such as scaling down Earth's seismicity rate to that of a Venus-sized planet, as was previously done to estimate the current level of volcanism on Venus (Byrne and Krishnamoorthy, 2020). In order to successfully conduct these different studies, we plan to estimate the thickness of the seismogenic zone in the lithosphere of Venus, which is effectively the brittle-ductile transition. This can be estimated through the observed fold spacing in specific regions and rheological modelling (Brown and Grimm, 1997; Resor et al., 2021) as well as through geodynamic and geophysical models constrained by estimates on the elastic lithosphere (Anderson and Smrekar, 2006; O'Rourke and

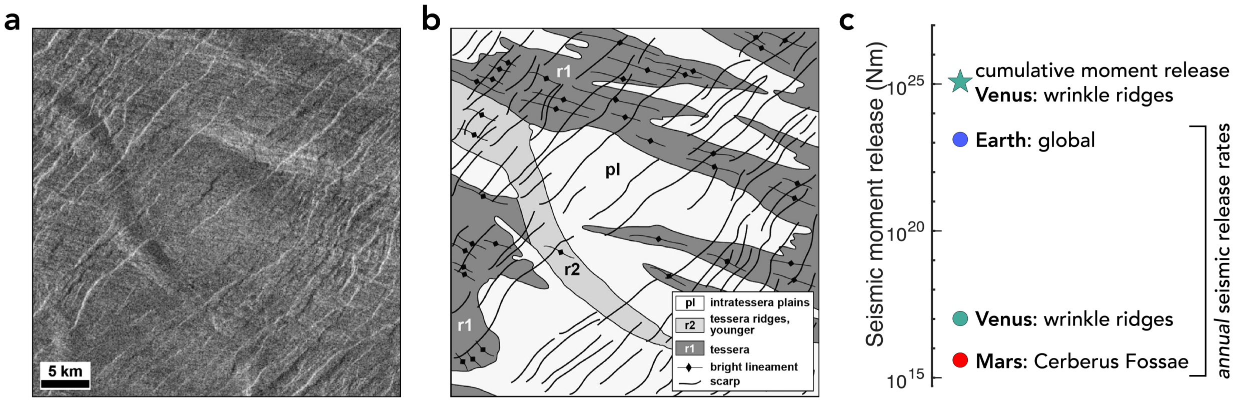

Figure 1: Estimating seismicity. (a) Radar image of the central portion of Ovda tessera on Venus with (b) stratigraphic interpretation of the unit including grabens and fault scarps (Ivanov and Head, 2015). (c) Estimate of cumulative moment release (star) and annual seismic moment release rate of wrinkle ridges on Venus (Sabbeth et al., 2021) compared to Mars (estimates constrained by InSight observations) and Earth. Note that wrinkle ridges are only one of several possible sources of seismicity on Venus.

Smrekar, 2018; Borrelli et al., 2021; Maia and Wieczorek, 2022) and crustal thickness (James et al., 2013; Maia and Wieczorek, 2022), the absence of a present-day magnetic field (Nimmo, 2002), and the moment of inertia factor (Margot et al., 2021). Comparing the resulting constraints on present-day Venusian seismicity by all these different methods will allow us to produce an estimate of the current seismicity rates on Venus with uncertainties.

When we know the seismic moment magnitude and type of faults that we might expect on Venus from the studies described above, we plan to use numerical models to estimate the level of produced ground motion and atmospheric perturbations. Constraints on these amplitudes are necessary when considering the different methods of seismic detection in our second objective.

Determining the feasibility, advantages, and disadvantages of the different methods for detecting seismic events on Venus

The first part of the project will provide estimates of the seismicity of Venus and the expected signal level. In the second part of the project, we will investigate the detectability of seismic events on Venus through further investigation on the anticipated environmental noise and a thorough review of the possible observation techniques.

Detecting seismic events on Venus is more complicated than measuring them on Mars or the Moon because of the harsh surface conditions with average temperatures of 462°C and a surface pressure of 93 bar. Still, the prospect of detecting seismic events is a promising one which can result in major scientific return. Previous studies have discussed the possibilities of detecting venusquake vibrations (Garcia et al., 2005; Stevenson et al., 2015) and suggested Venus missions that include seismometers (e.g., Kremic et al., 2018). However, a detailed comparison of the various seismic detection methods and an analysis of the applicability of individual techniques to Venus are still missing.

To determine an optimal configuration for the detection of seismic events, we will investigate multiple observation techniques including those recently established in terrestrial seismology. For example, we plan to look into the feasibility of using distributed acoustic sensing and fibre optic imaging methods that have proven to be excellent methods suitable for harsh environments on Earth (Fig. 2a; Walter et al., 2020; Klaasen et al., 2021). These optic fibres can be regarded as a small array of virtual seismometers aligned along the fibre which results in high resolution imaging of the subsurface structure (e.g., Tsuji et al., 2021; Sladen et al., 2019). This could make it an attractive option for measuring seismic events on Venus.

Classic broadband seismometers are another option to detect seismic events, with their potential clearly demonstrated by the successful InSight mission on Mars (Banerdt et al., 2020; Giardini et al., 2020; Lognonné et al., 2020; Khan et al., 2021; Knapmeyer-Endrun et al., 2021; Stähler et al., 2021). Given the harsh environment of Venus, we will look into optical seismometers where the components deployed outside the lander system can be minimised (e.g., Araya et al., 2015).

On Earth, recent studies have for the first time successfully detected an earthquake from a balloon using its acoustic signature (Brissaud et al., 2021), opening the door to balloon-based seismic observations of Venus (Fig. 2b). On Venus, the seismic signals could propagate through its thick atmosphere and lead to atmospheric perturbations that may be detectable by a balloon and even from orbit (Garcia et al., 2005; Garcia et al., 2009), as suggested by the Venus Airglow Measurements and Orbiter for Seismicity (VAMOS) mission study (Didion et al., 2018; Sutin et al., 2018). We will revisit these studies and compare them with other methods to quantify their trade-off and identify synergies between different observational techniques.

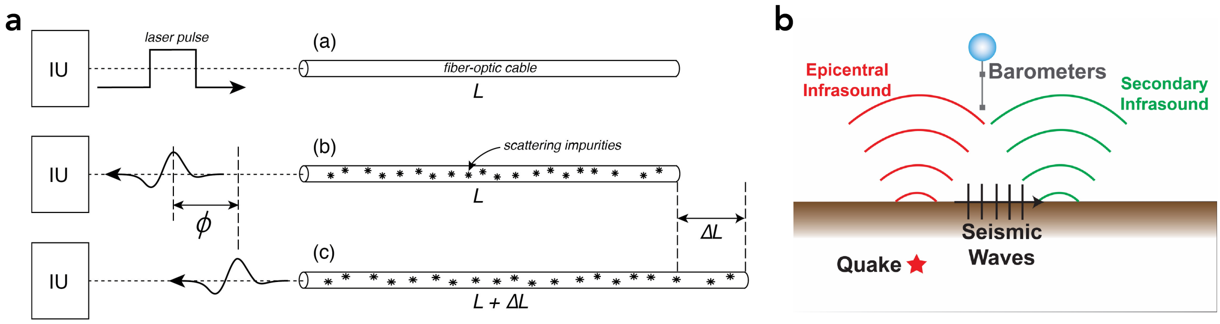

Figure 2: Detecting seismic events. (a) Distributed acoustic sensing method, where the deformation in a cable can be measured through changes in the back-scattered laser pulse (Lowrie and Fichtner, 2020). (b) Schematic showing the detection of seismic activity from balloon-borne infrasound barometers on a tether (Krishnamoorthy et al., 2020).

To quantitatively evaluate the detectability of Venusian seismicity, it is essential to have a realistic noise model. On Venus, the main noise sources are expected to be atmospheric activity and the thermal environment. While a more complete investigation of the noise environment will be required eventually, we will focus on these two main types of noise in a first effort to quantify the seismic noise level on Venus. To this end, we will take an approach similar to Mimoun et al. (2017) and Murdoch et al. (2017), who estimated noise levels on Mars ahead of the InSight mission. We will be referring to up-to-date atmospheric models of Venus to evaluate how atmospheric activity excites ground motions that contaminate the seismic signals. The thermal noise component depends on the seismic observation method. Therefore, we will consider the artificial noise levels of each method and discuss how they impact observations. Noise sources induced by the measurement system itself will also be taken into account.

Considering the recent advances in terrestrial seismology and the growing technological advances in heat-resistant technology (Venkatapathy et al., 2021), a new assessment of detection options of venusquakes is necessary and timely, and should address all these different detection methods: from orbit, on a balloon, and on a lander. For each of these methods, we aim to establish their strengths and weaknesses (e.g., what is the minimum magnitude of quakes that can be detected? on what scale can the structure of the interior be determined?) as well as their technology readiness and hence feasibility to fly on a Venus mission within the next 10–20 years.

Approaching Venus seismology from both a theoretical and engineering angle allows us to provide recommendations on possible payload configurations for future missions that aim to explore the geophysics of Venus through seismology.

2 Team

Our envisioned project requires a multi-disciplinary approach that incorporates multiple facets of seismology and disciplines like geodynamics, geophysics, and geology. Our international team will bring together people with different backgrounds in both science and engineering to study Venusian seismicity and identify strategies for the detection of venusquakes.

The proposed ISSI team consists of 12 scientists with 9 different affiliations associated with 6 countries (including 5 ESA member states) and who are of 9 different nationalities. The team is diverse with 50% of the team members being female, at least 25% identifying as non-white, ethnic minorities, and 33.3% at a career stage within 5 years of obtaining their PhD.

If the proposal is approved, we plan to involve additional early-career scientists, i.e., maximum 2 years after their PhD, including Anna Gülcher (ETH Zürich), Sara Klaasen (ETH Zürich), and Krystyna Smolinski (ETH Zürich) who have expertise on the geodynamics of coronae and the distributed acoustic sensing method.

With this team, we trust that we can carry Venus seismology into the new decade in the hopes of creating a Venus decade beyond the current one.

Name	**Expertise**	**Affiliation (Country)**
Iris van Zelst	Geodynamics & seismology	German Aerospace Center (Germany)
Andreas Fichtner	Seismology	ETH Zürich (Switzerland)
Raphaël F. Garcia	Planetary seismology	ISAE-SUPAERO (France)
Richard Ghail	Planetary geology	Royal Holloway, University of London (UK)
Anna Horleston	Planetary seismology	University of Bristol (UK)
Taichi Kawamura	Planetary seismology	IPGP / Université Paris Cité (France)
Philippe Lognonné	Planetary seismology	IPGP / Université Paris Cité (France)
Julia Maia	Geophysics	Observatoire de la Côte d'Azur (France)
Csilla Orgel	Planetary geology	ESA-ESTEC (The Netherlands)
Mark Panning	Planetary seismology	JPL / California Institute of Technology (USA)
Ana-Catalina Plesa	Geodynamics	German Aerospace Center (Germany)
Leah Sabbeth	Structural geology	JPL / California Institute of Technology (USA)

3 Expected outcomes

To share the findings of our team effort with the wider planetary science community, we aim at a minimum of two peer-reviewed publications centred around the following topics:

1. **Estimates of current seismicity on Venus**. This paper will feature the results of our seismicity estimations and will serve the community with the scientific requirements necessary for a future seismological mission to Venus. Depending on the different angles with which we approach the research question underlying this work, this paper might be split into multiple papers each focusing on the results of a distinct method or structural feature (e.g., a paper concerning an estimate of the available seismic budget from geodynamic modelling and a paper concerning the estimated seismic potential from observed faults on the surface of Venus).
2. **Seismicity detection on Venus**. This will be a review paper highlighting the different methods to detect seismic events on Venus, their technical feasibility, and their advantages and disadvantages with respect to different science objectives.

To adhere to best practices in science and research, we are committed to publishing these articles in an open-access format and we aim to make the data, results, scripts, and codes resulting from this project openly accessible wherever possible. We believe the outcomes of this project will be imperative for future Venus missions and will ignite new research on planetary seismology and the physics-based modelling thereof.

4 Projected schedule

We anticipate a maximum project duration of two years. Within that time, we plan to have two one-week in-person meetings with the possibility for remote participation to increase inclusivity of team members that may not be able to travel for various reasons. Each meeting will focus on one of our two main objectives:

- Meeting 1: **'Seismicity on Venus'** (late 2022 / early 2023): review and execute different methods of estimating the current level of seismicity on Venus.
- Meeting 2: **'Detecting seismic events on Venus'** (mid 2023): review the different techniques to detect seismic signals on Venus and assess the advantages and disadvantages of each method both in terms of technical feasibility and maximising scientific return.

In addition, we would like to organise a third fully online meeting in mid 2024 to wrap up the project and discuss its final outcomes. We also expect to hold regular (e.g., monthly) short online progress meetings to further foster collaboration and the team spirit.

Based on the timing of the meetings, we anticipate to submit the paper(s) on estimates of the current seismicity level of Venus late 2023 and the review paper on seismic detection methods on Venus mid 2024.

5 Added value of ISSI

ISSI has an outstanding reputation and track-record within the planetary and space sciences, which makes it the perfect scientific environment to inspire interdisciplinary planetary research. From a practical point of view, the location of ISSI is central and easy to access for both our European and US team members, making it ideal to host in-person meetings. Furthermore, we are keen to use ISSI's excellent facilities for online and hybrid team meetings to promote smooth international collaborations and allow team members to join in-person meetings remotely when they are unable to travel. Indeed, the infrastructure provided by ISSI for international teams, including logistics, financial support, and the opportunity to host a team website are crucial to ensure that a large international project such as this one is successful.

6 Resources requested

In order to facilitate the two planned in-person meetings, we request financial support for the living expenses of the team members in Bern for the duration of the meetings, as well as travel support for the team leader. Since we plan to accommodate remote participation of the in-person meetings, we request a room with facilities for online attendance, including audio and video, wireless internet access, a projector, and a white board. To further facilitate online collaboration and to realise our third online meeting, we request licenses for online collaboration tools, including Overleaf and Zoom. We also plan to use an ISSI hosted website for our project with an internal, access-locked area for team members that facilitates easy file sharing and communication. In addition, the public area of the website will be used to disseminate the scientific advances of our project to the wider community. Throughout the project, team members will be individually funded by their home institutions.

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