Venus Geophysics
Review and Outlook

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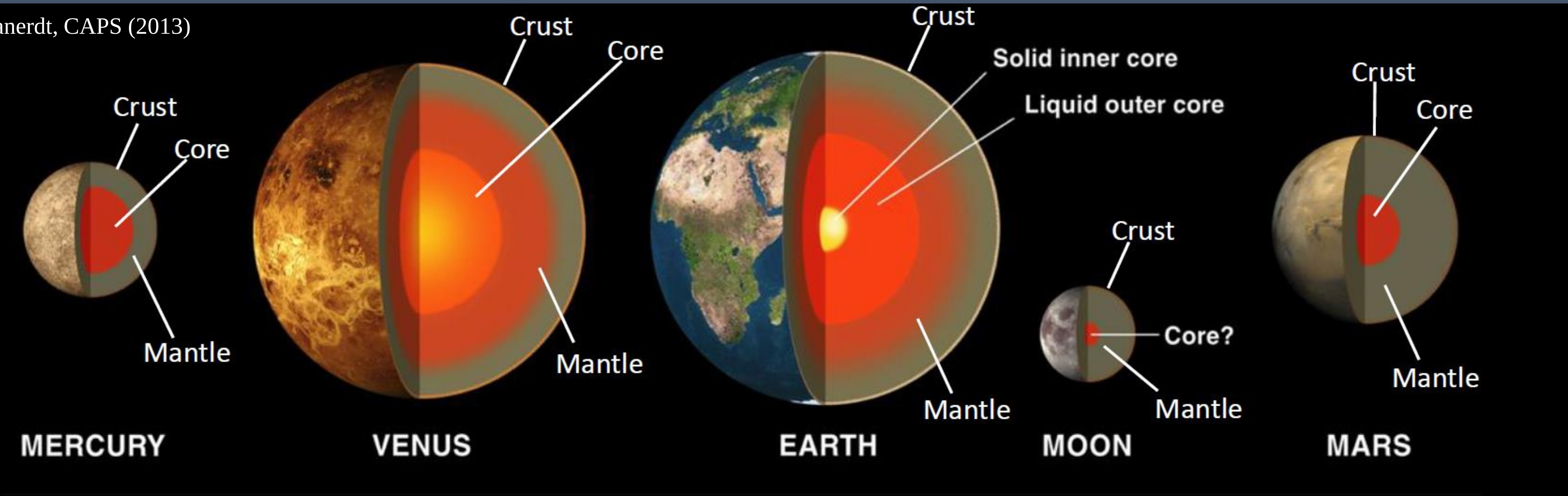
Venus Exploration and Analysis Group (VEXAG)

November 6, 2019

Geophysics

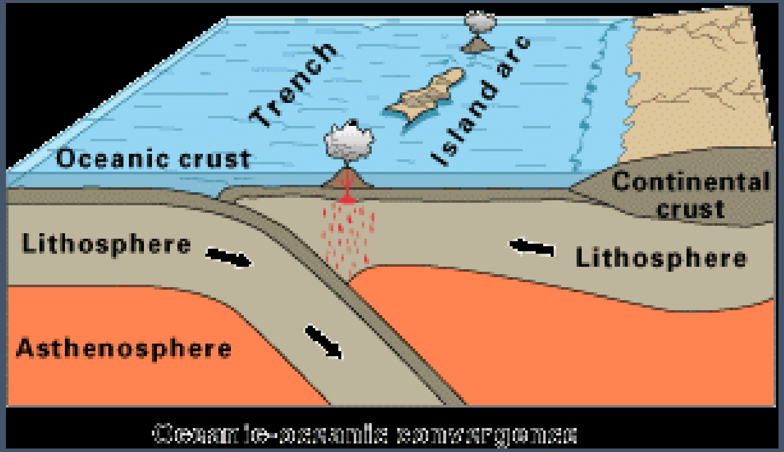
- Here, “solid-earth” geophysics.
- The physics of the Earth (interior processes).
- Using physics to image the subsurface (interior structure).

Banerdt, CAPS (2013)

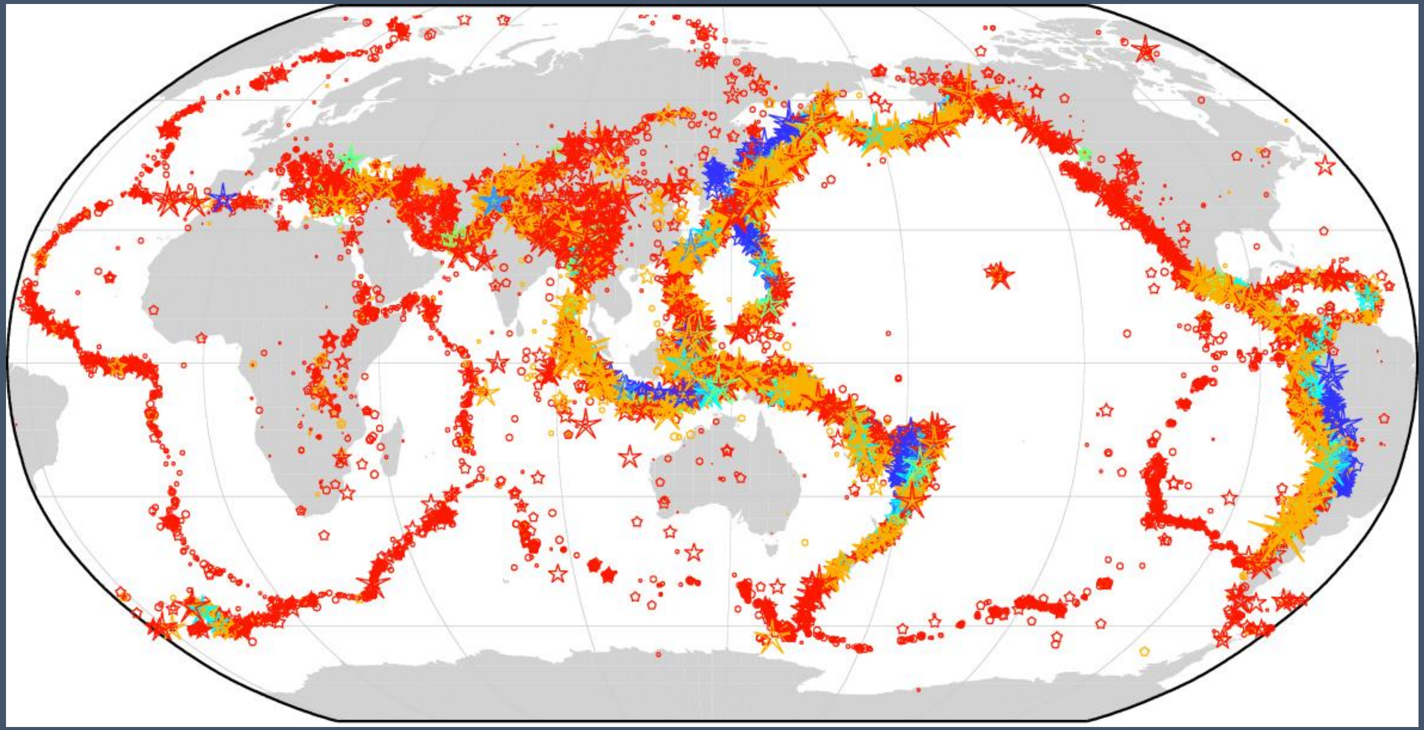


The Plate-Tectonic Revolution Was Enabled by Geophysics

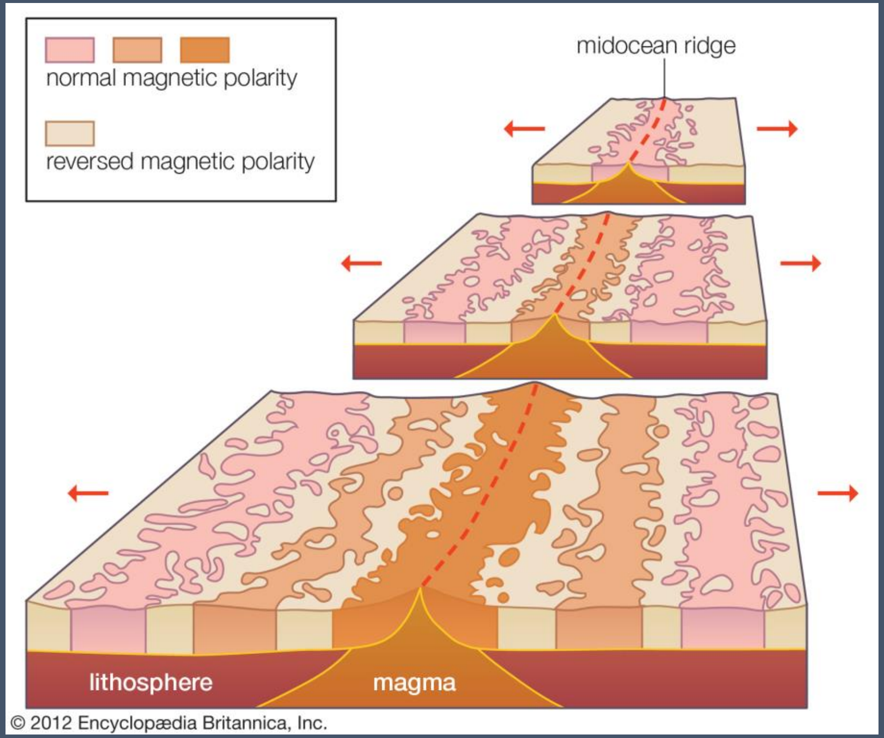
- Continental drift known but not understood.
- Global pattern of seismicity
  - Ring of Fire, mid-ocean ridges
- Linear pattern of oceanic magnetism
  - "Seafloor spreading"



USGS



ISC.ac.uk



Brittanica

Geophysics in the VEXAG GOI

Table 1. VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.	A. Did Venus have temperate surface conditions and liquid water at early times?	**HO. Hydrous Origins (1).** Determine whether Venus shows evidence for abundant silicic igneous rocks and/or ancient sedimentary rocks.
		RE. Recycling (1). Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.
		AL. Atmospheric Losses (2). Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.
		MA. Magnetism (3). Characterize the distribution of any remanent magnetism in the crust of Venus.
	B. How does Venus elucidate possible pathways for planetary evolution in general?	**IS. Isotopes (1).** Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.
		LI. Lithosphere (1). Determine lithospheric parameters on Venus that are critical to rheology and potential geodynamic transitions, including: stress state, water content, physical structure, and elastic and mechanical thicknesses.
		HF. Heat flow (2). Determine the thermal structure of the lithosphere of Venus at present day and measure in situ heat flow.
		CO. Core (2). Measure the size of the core of Venus and determine whether it remains partially liquid.

Goal	Objective	Investigation
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**DD. Deep Dynamics (1).** Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of angular momentum.
		UD. Upper Dynamics (1). In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
		MP. Mesoscale Processes (2). Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	**RB. Radiative Balance (1).** Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
		IN. Interactions (1). Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
		AE. Aerosols (2). Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
		UA. Unknown Absorber (2). Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
		OG. Outgassing (3). Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.

Goal	Objective	Investigation
III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.	A. What geologic processes have shaped the surface of Venus?	**GH. Geologic History (1).** Develop a geologic history for Venus by characterizing the stratigraphy, modification state, and relative ages of surface units.
		GC. Geochemistry (1). Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units on Venus.
		GA. Geologic Activity (1). Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.
		CR. Crust (2). Determine the structure of the crust of Venus in three dimensions and thickness across the surface.
	B. How do the atmosphere and surface of Venus interact?	**LW. Local Weathering (1).** Evaluate the mineralogy, oxidation state, and changes in chemistry of surface-weathered rock exteriors at localities representative of global geologic units on Venus.
		GW. Global Weathering (2). Determine the causes and spatial extents of global weathering regimes on Venus.
		CI. Chemical Interactions (3). Characterize atmospheric composition and chemical gradients from the surface to the cloud base both at key locations and globally.

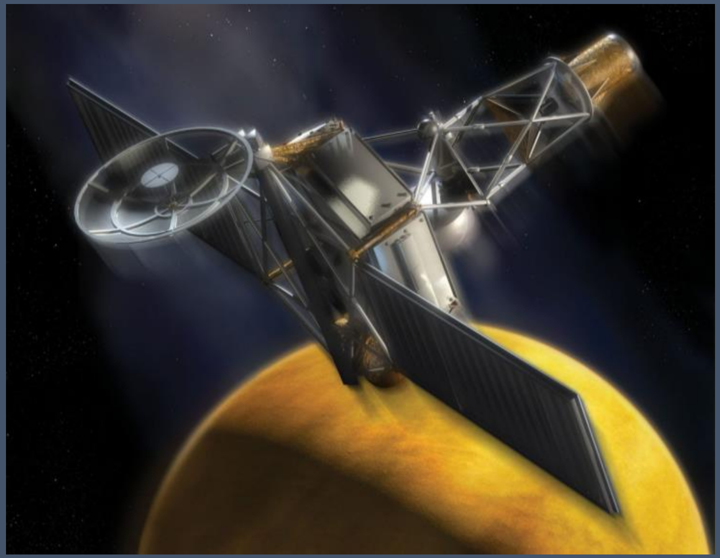
Geophysical Methods For Consideration

- Green: Some work already done at Venus
- Not treated here: InSAR Deformation

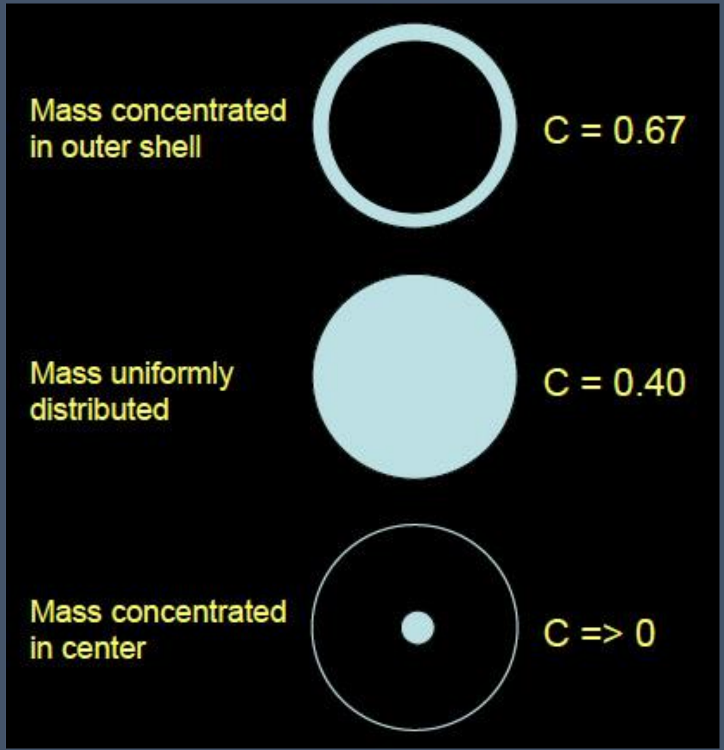
Method	Applications
Seismology	Global structure, composition, temperature, geological activity, geodynamics.
Heat Flux	Temperature, geodynamics.
Electromagnetics	Temperature, composition, geodynamics.
DC Magnetics	Core history, geological reconstruction.
Gravity	Geodynamics
Geodesy	Core, atmosphere-surface coupling
Ground-Penetrating Radar	Shallow (<1 km) structure and stratigraphy

Mass and Moment of Inertia

- Mass
  - Fundamental property of a planet
  - With size, gives mean density.
  - Accurately measured in spaceflight era
- Length of Day
  - Sensitive to balance between solid-body tides and atmospheric torques.
  - Excellent Earth-based determination (Campbell et al., 2019).
- Moment of Inertia
  - Related to radial distribution of mass, particularly core size.
  - Measure spin-axis procession variations from Earth or spacecraft (Margot et al., 2016)



S. Hobbs / iaaa.org

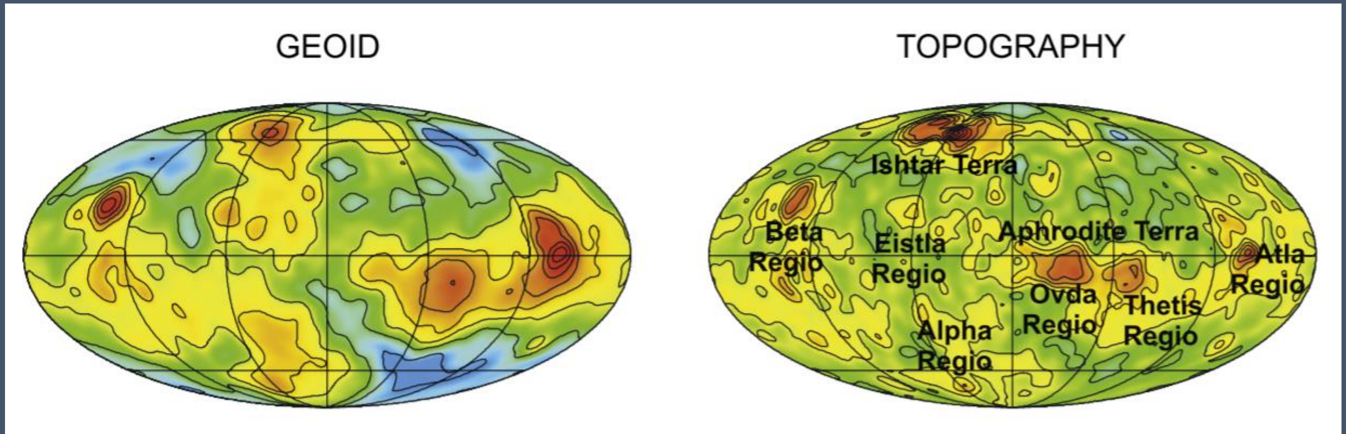


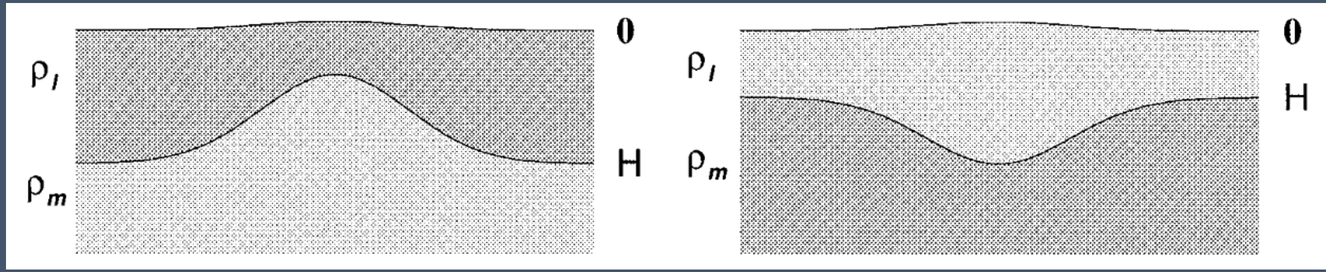
geol.umd.edu/~jmerck

Gravity & Topography

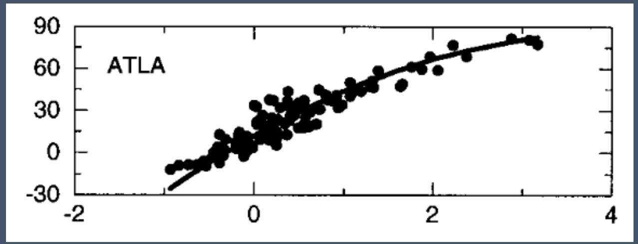
- Gravity indicates how topography is supported and illuminates interior temperature or compositional variations.
- Strong correlation, large magnitudes indicate deep thermal compensation, direct coupling of mantle to surface.
    - Largest geoid anomalies follow volcanotectonic network (Equatorial chasmata & BAT).
- Smaller signatures indicate locally thickened crust (tesserae).

Pauer et al., 2006

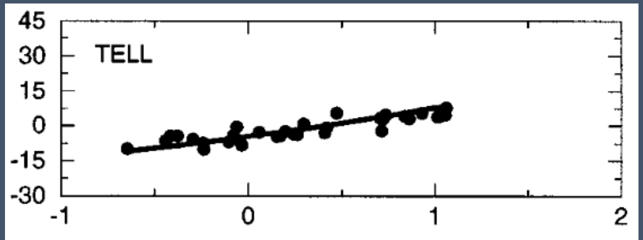




Moore and Schubert, 1999



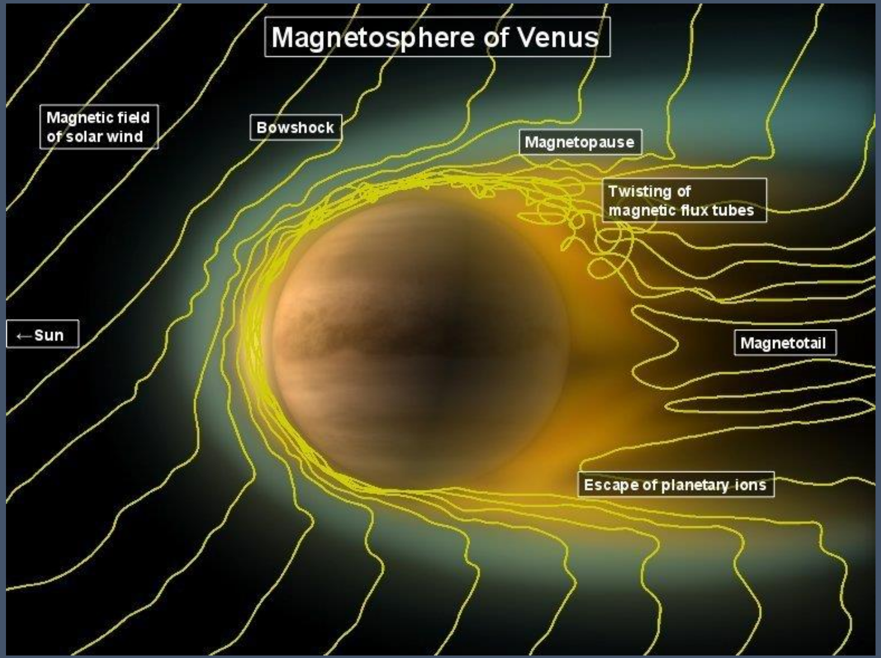
Support by hot mantle to > 300 km depth



Support by crustal root up to 75 km deep

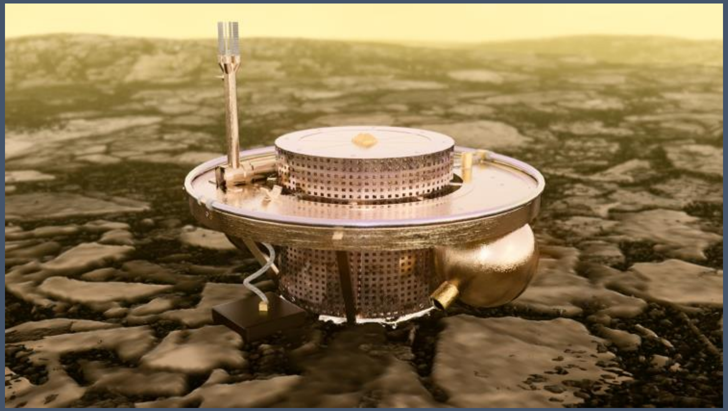
Magnetic Field

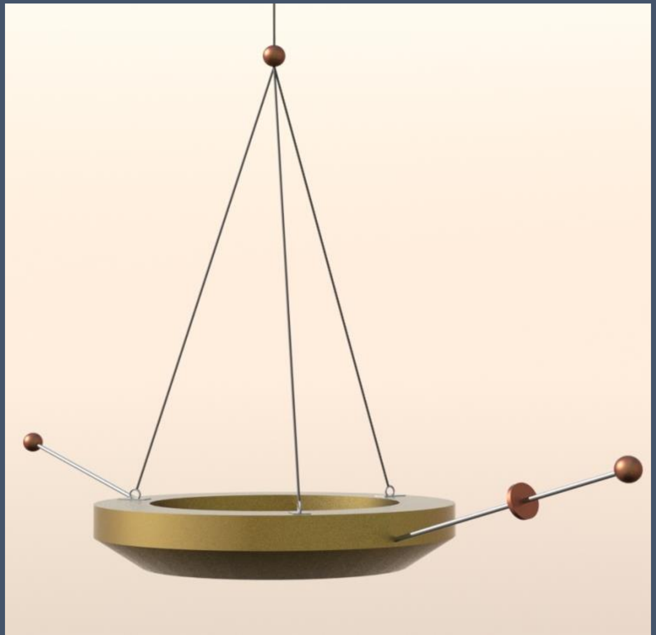
- Rich solar-wind interaction
- Upper limit to intrinsic field <10^{-5} Earth
  (Dolginov et al., 1969; Phillips and Russell, 1987)
- Variety of explanatory models
  - Core dynamo activity variable (O'Rourke et al 2018).

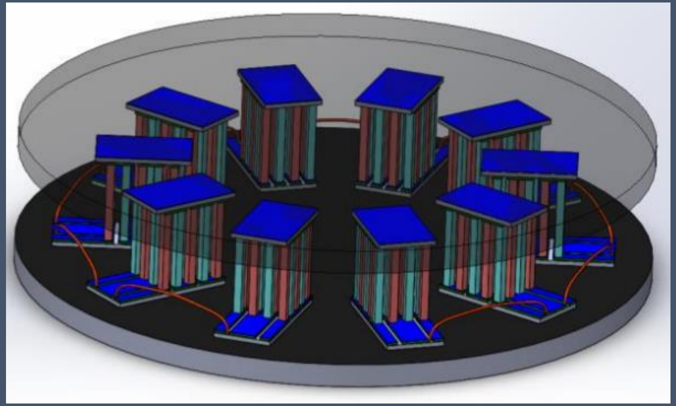


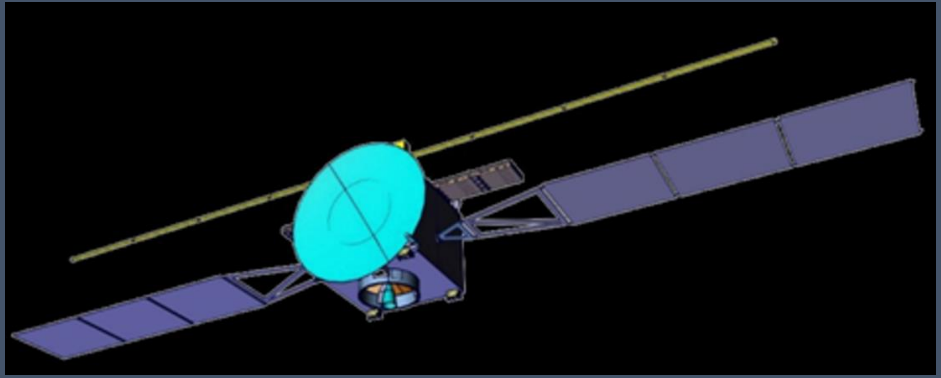
Earthsci.org (Australia)

Future Geophysics at Venus





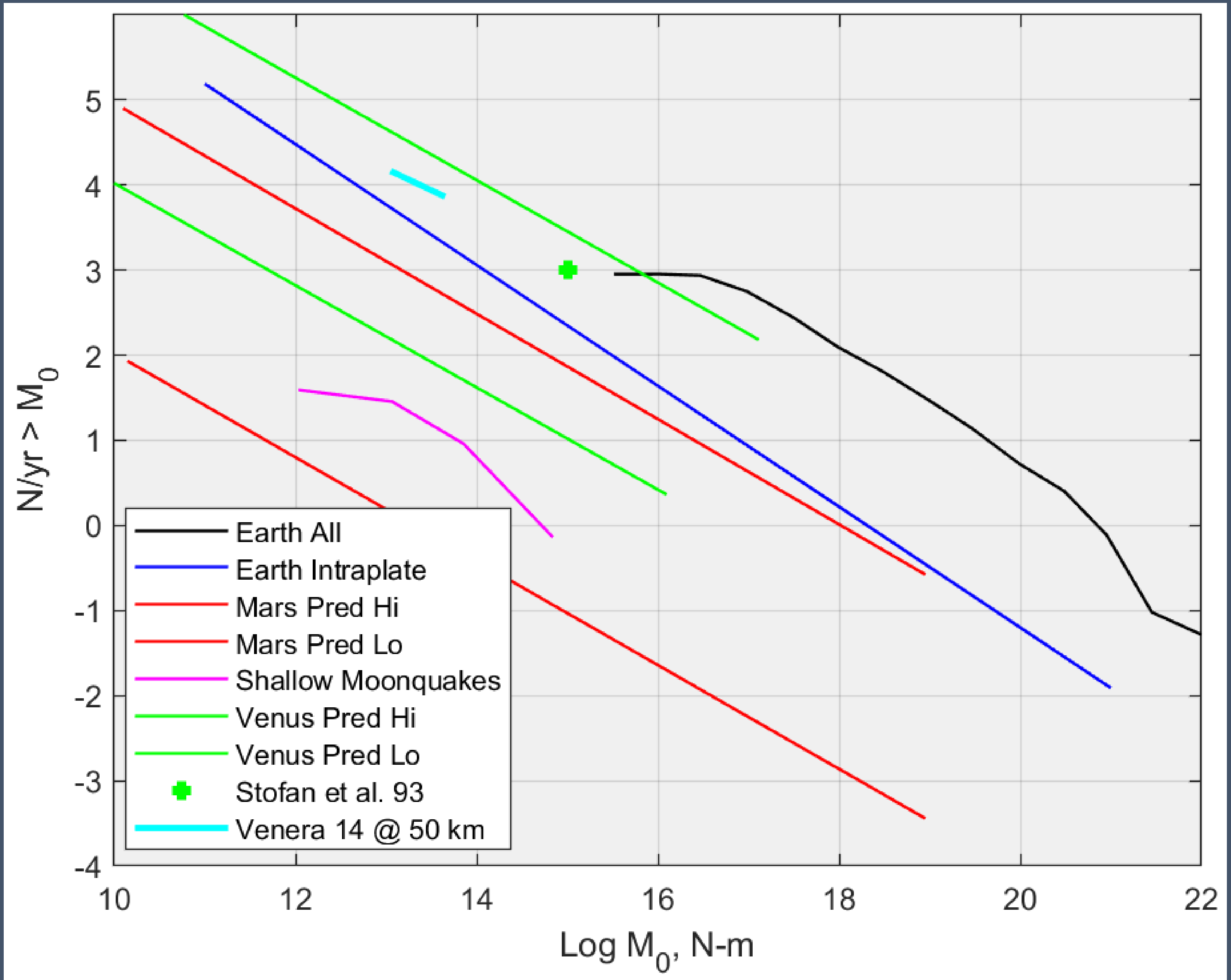




Seismicity of Venus

Lognonné & Johnson, 2007; Banerdt, 2013;Ksanfomality et al., 1983;

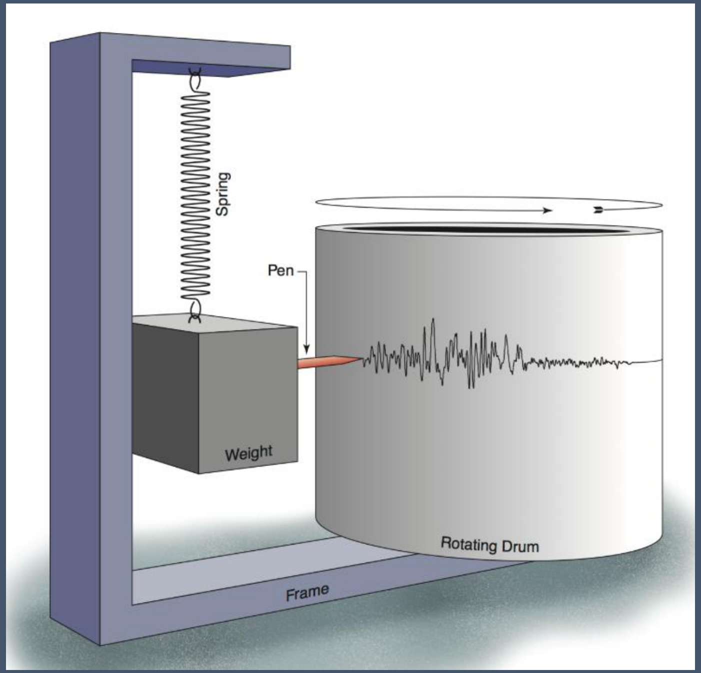
- Seismology is the backbone of geophysics.
- Orders of magnitude uncertainty in predictions.
- 2 events observed by Venera 14 (Ksanfomality et al., 1983)
  - Low spatial probability if high recurrence rate.
  - Low temporal probability if large, distant.
  - Likely, is wind noise.



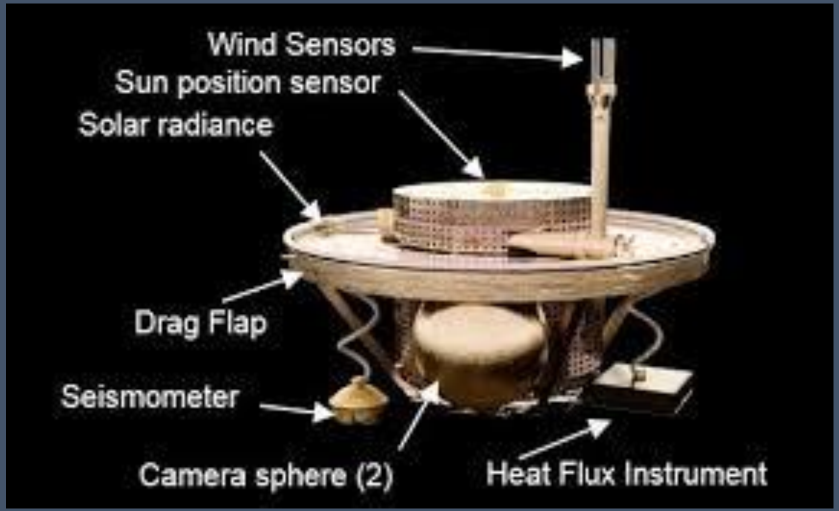
iris.edu

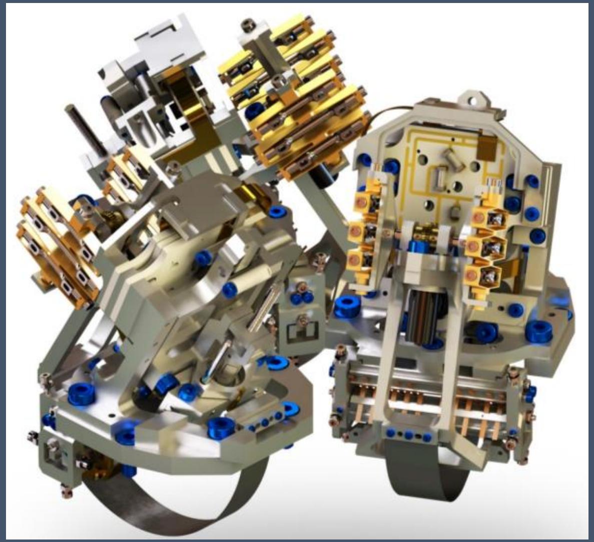
Landed Seismology

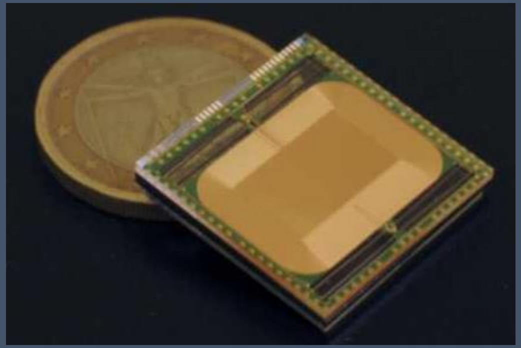
- Classical transducer is large mass on spring.
  - MEMS (e.g., Insight SP) less mass but less sensitivity.
- Adaptation to Venus is challenging.
- GRC baselined Insight SP derivative for SAEVe.
  - Limited observation time requires triggered transmission during comm relay flyover.
  - Further assessment & testing planned.



GRC







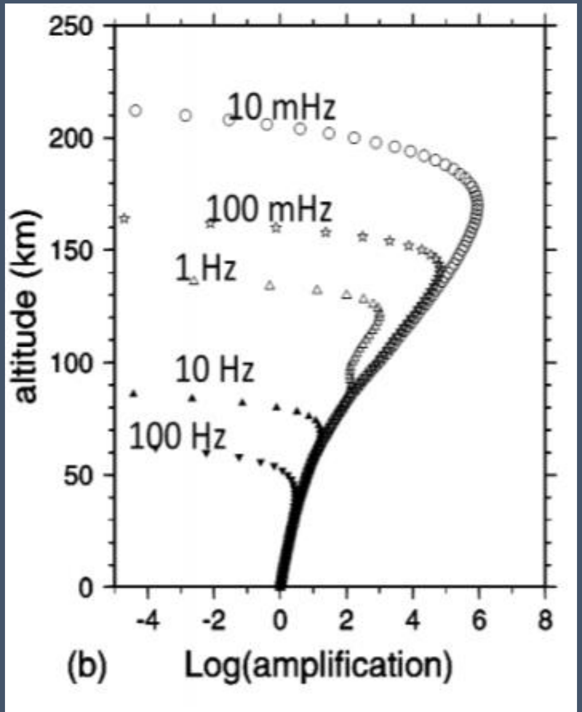
InSight VBB and SP seismometers

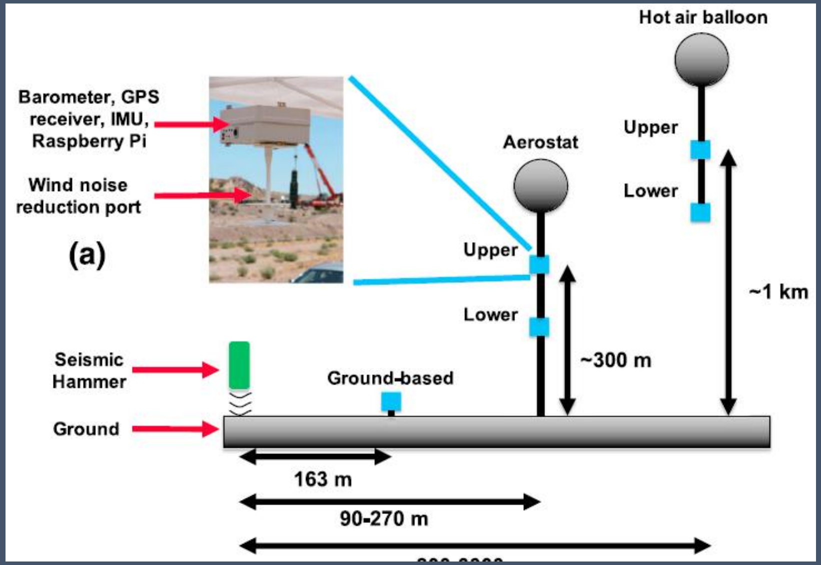
seis-insight.eu

Atmospheric & Orbital Seismology

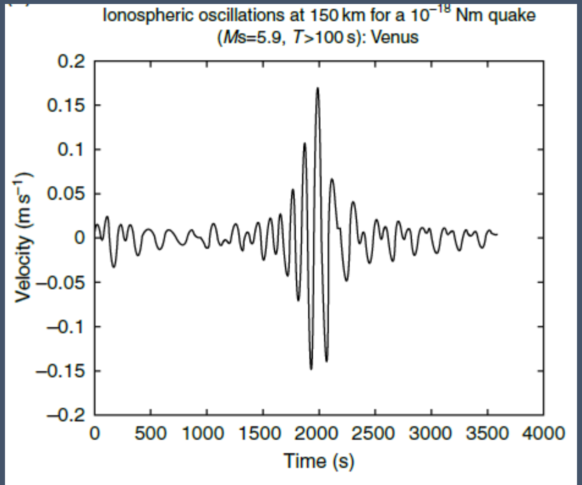
- Earthquake surface waves are strongly coupled to the thick Venus atmosphere and are amplified with altitude according to conservation of energy.
- Conceptually compelling approach to standoff seismology.
- Observe as (Lognonné & Johnson, 2007; Stevenson et al., 2015):
  - Infrasound at balloon height (50-60 km)
  - Radio sounding of the ionosphere (150 km)
  - Infrared airglow
  - Ultraviolet airglow

Garcia et al., 2005.





Krishnamoorthy et al., 2018.

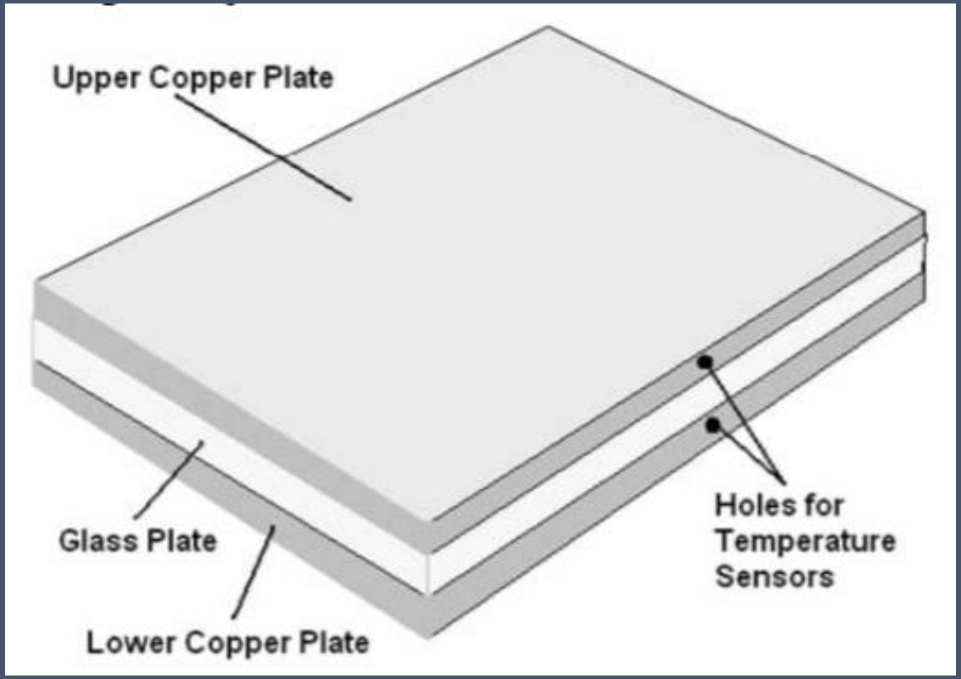


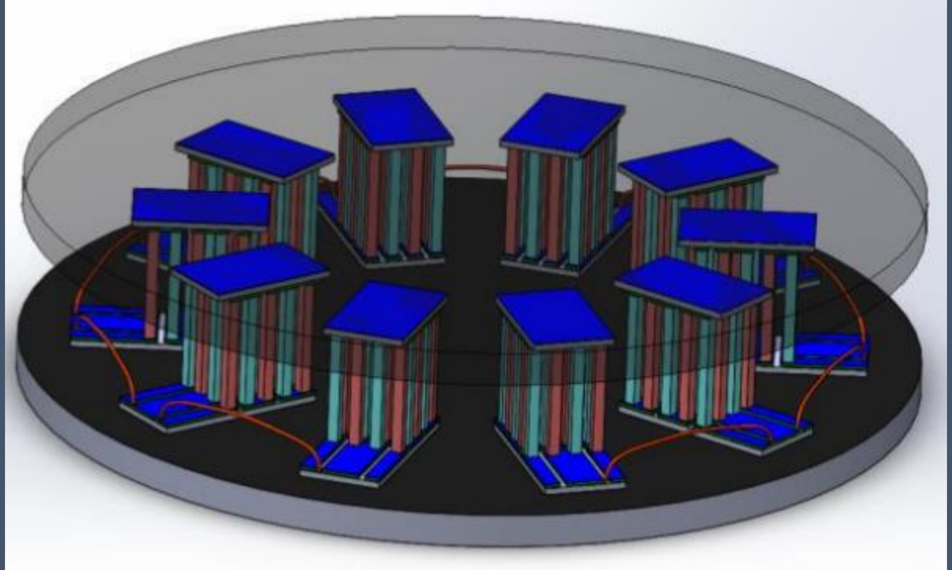
Lognonné & Johnson, 2007.

Morgan et al., 2005

Heat Flux

- Measure temperature at multiple depths = gradient.
- Observe decay of temperature from applied heat pulse to derive thermal conductivity.
- Q = k dT/dz
- For Venus, can exploit near-isothermal surface temperature to force requilibration of thermal gradient across a plate of known conductivity.
  - Redesigned for better coupling.
  - Surface temperature variations up to 3 K require long-term monitoring.
  - SAEVe payload element (Kremic et al., 2018).

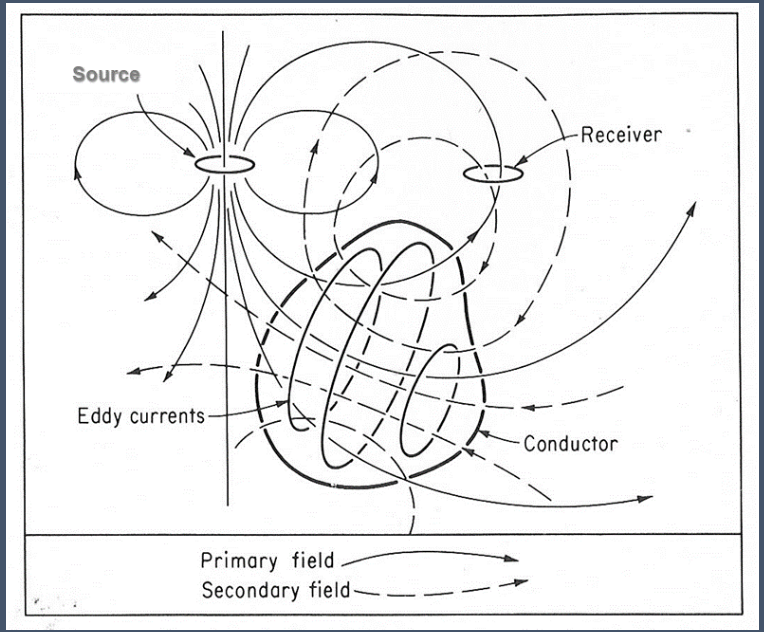




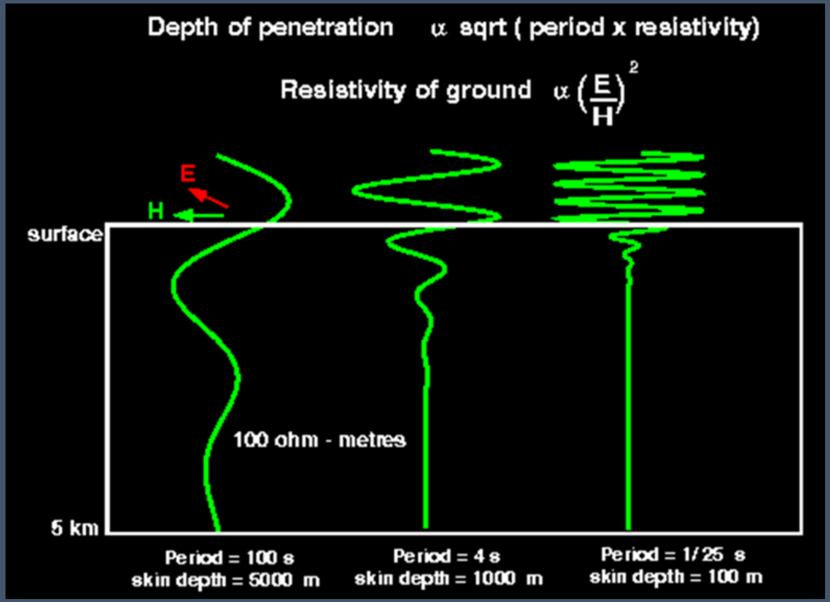
Pauken et al., 2016

Low-Frequency Electromagnetics

- Time-variable magnetic fields cause eddy currents that produce sensible secondary magnetic fields: derive electrical conductivity of the target.
- Skin depth effect: lower frequencies penetrate deeper.
- Sensitivity: 1. metal core vs rocky mantle, 2. rock temperature, 3. rock composition.
  - Close relation to heat flow and internal temperature profile.
- Transition from propagation (radar) to LFEM below ~100 kHz (?)



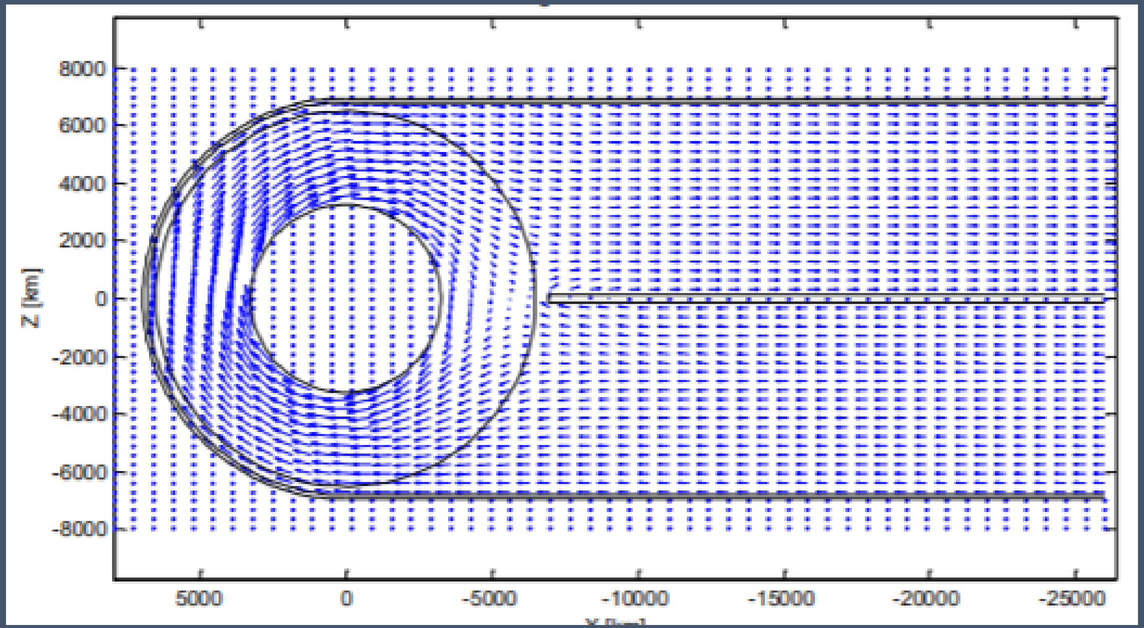
Grant & West, 1968



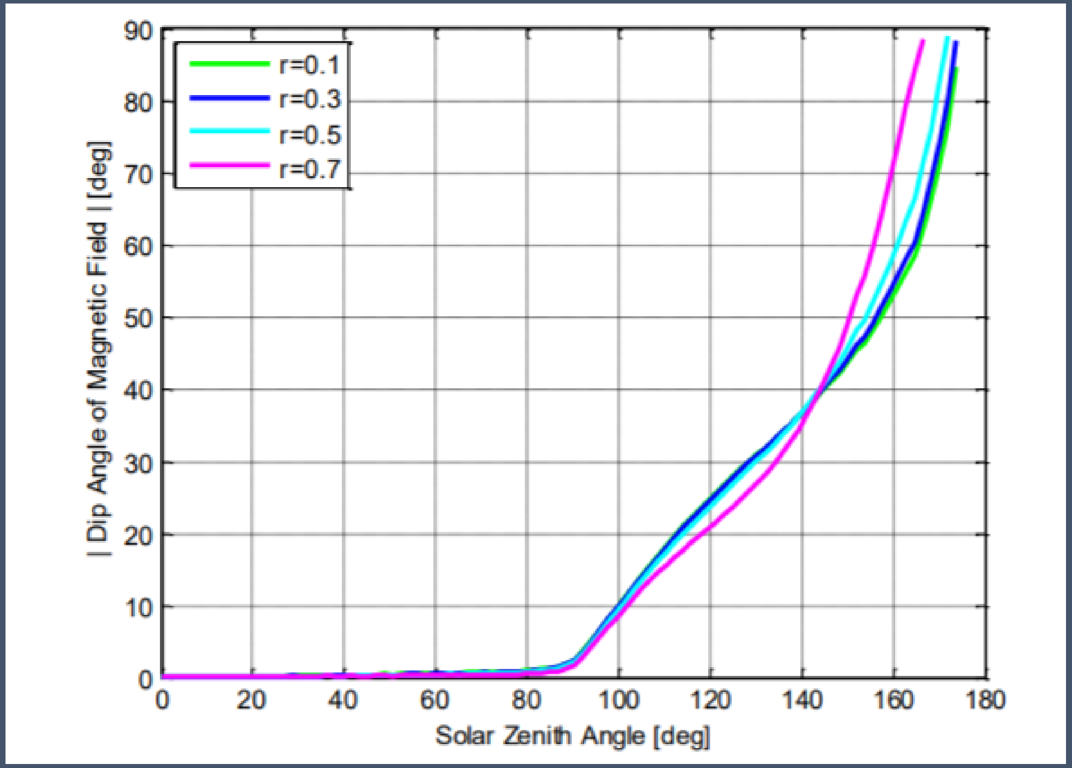
hearthweb.ess.washington.edu/booker/magnetotellurics/overview

Core Size Determination

- Ultra low frequency (quasi-DC) variations of solar wind can reveal core. Know source-field direction, need accurate measurement of magnetic-field deflection.

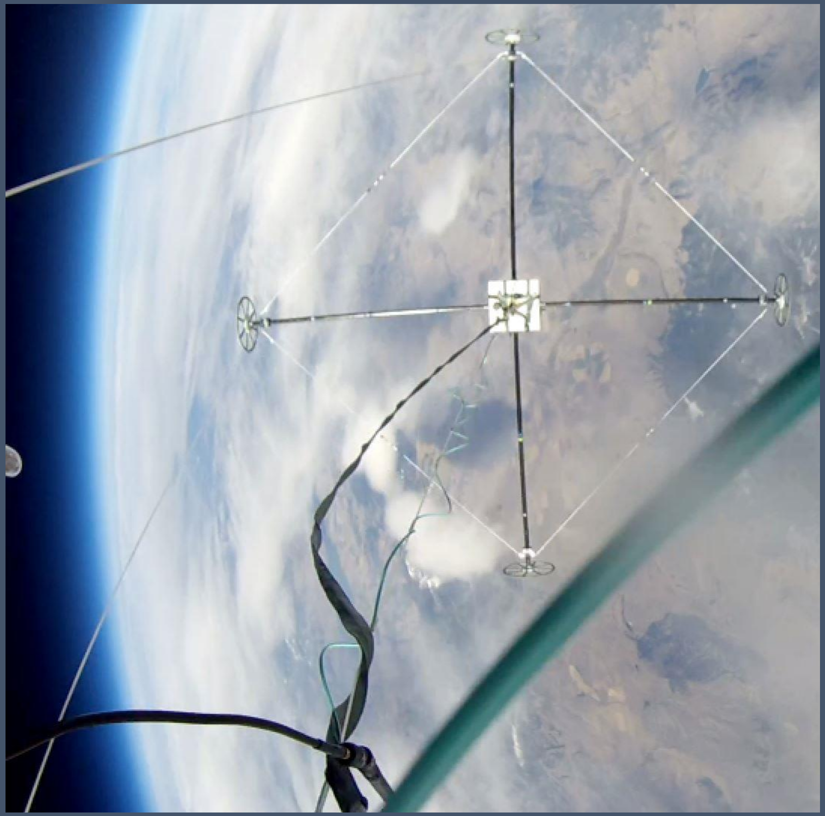


Chi et al., 2015



Low-Frequency EM at Venus

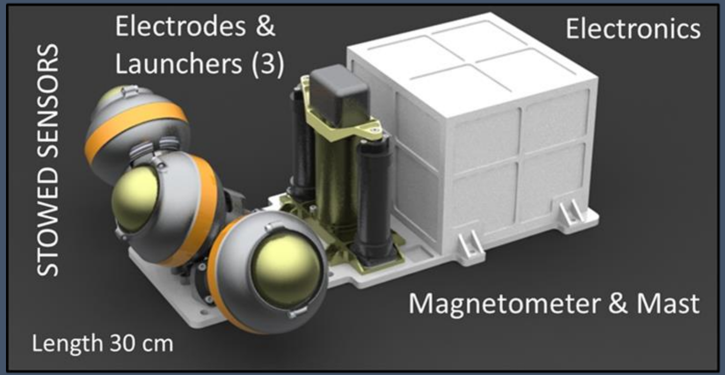
- Very low frequency signals (Hz) probe upper mantle: determine temperature/lithospheric thickness (Grimm et al., 2013).
- Requires existence of lightning on Venus (Schumann resonances) as source.



Balloon Transverse Electromagnetic Measurement (BTEM) descent from stratosphere, 2017

- Stratospheric balloon flights 2017 & 2018 demonstrated detection of ionosphere & ground.
- Require low-altitude flight to confirm ground conductivity for Earth conditions.

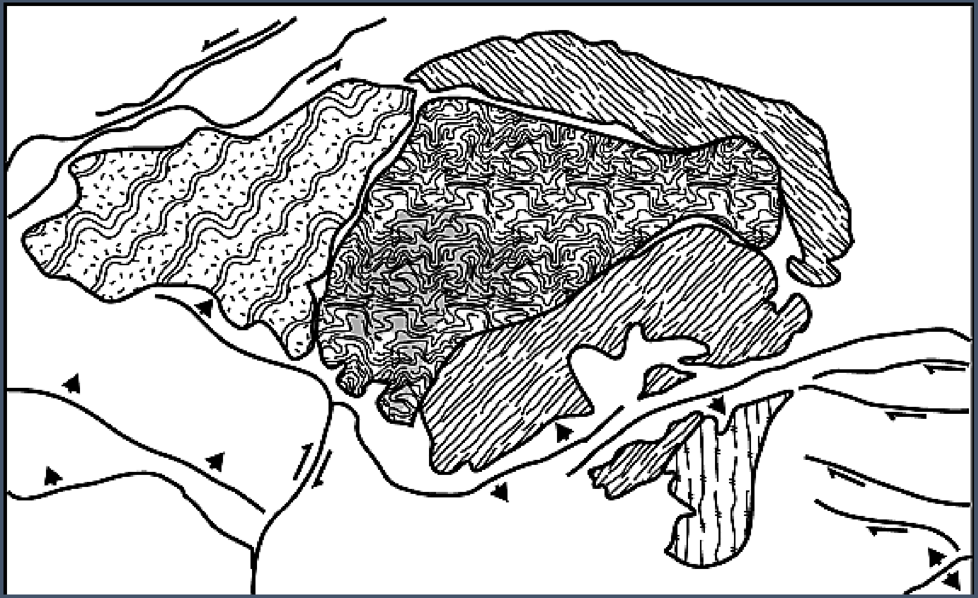
- Sensor & electronics development proceeding under Commercial Lunar Payload Services (CLPS).



Lunar Magnetotelluric Sounder (LMS), selected for 2022 lunar landing.

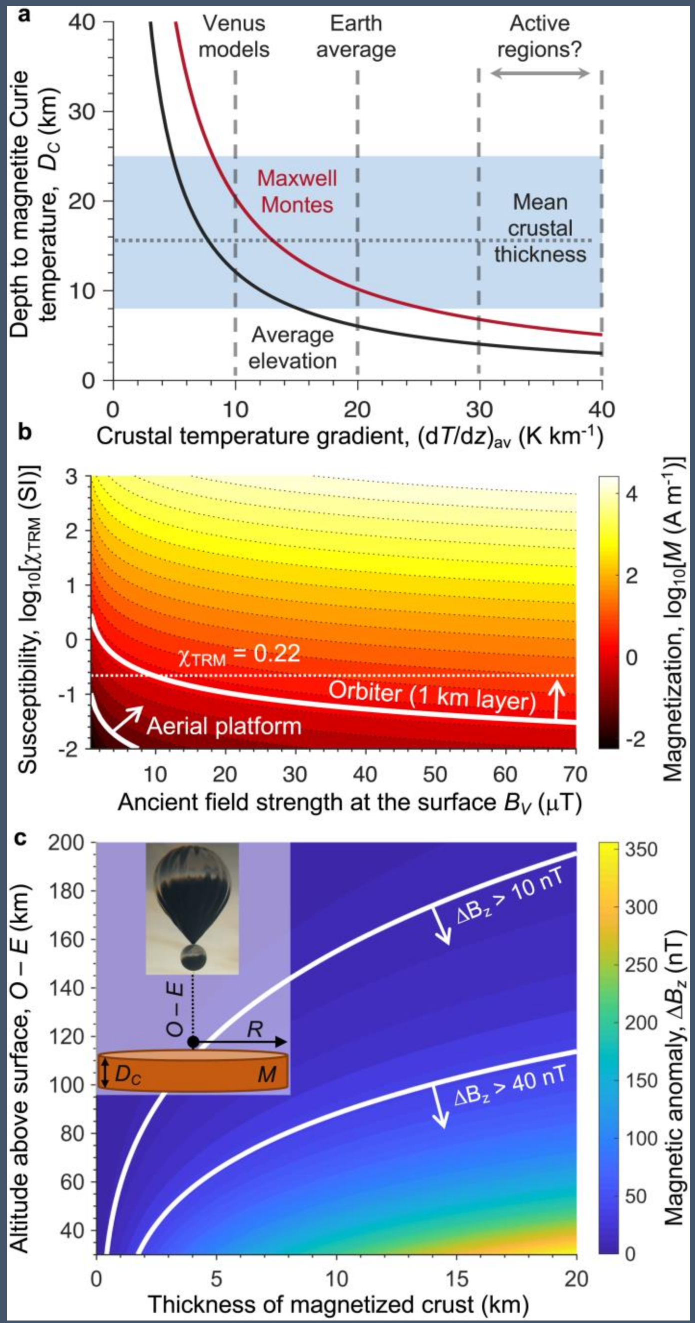
DC Magnetics

- Crust can be magnetized to kms-10s km depth, depending on temperature gradient, may survive ~Gyr.
- Requires magnetizing field: Did dynamo exist? When did it end?



Ovda Regio: Ghail, 2002

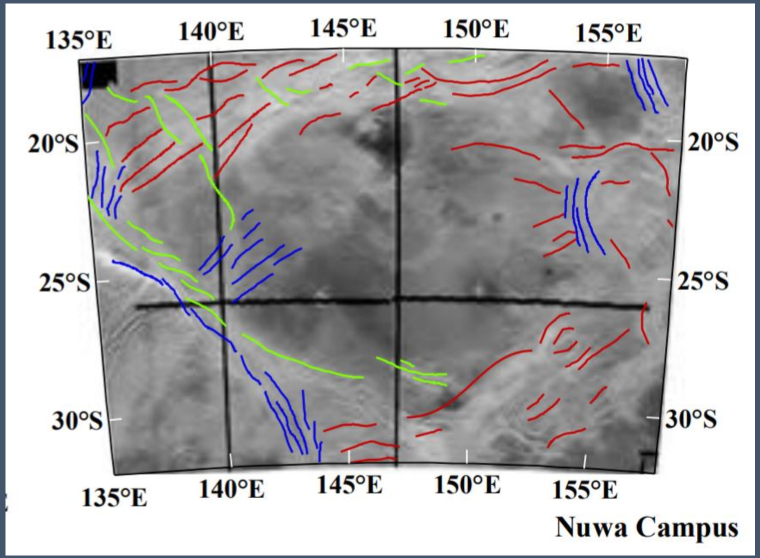
- Preserve signatures in ancient "core" of tesserae?

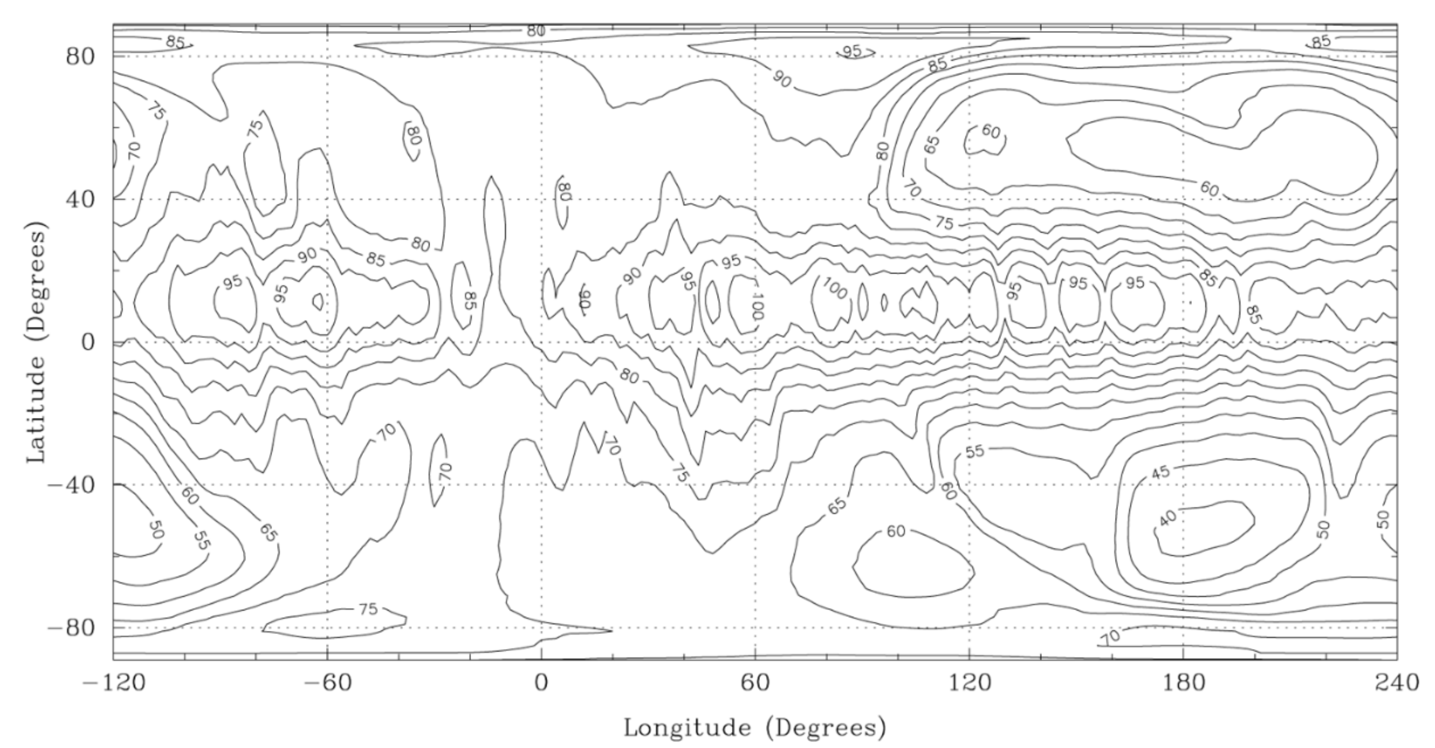


O'Rourke et al., 2019

Gravity

- Current gravity field degree 40-100 (200-450 km resolution).
- Require degree >180 for significant improvement.
  - Resolve coronae, campi, craters
- Ka-band tracking provides improved accuracy, but may require multiyear dedicated tracking.
- Alternatively, do GRACE/GRAIL.

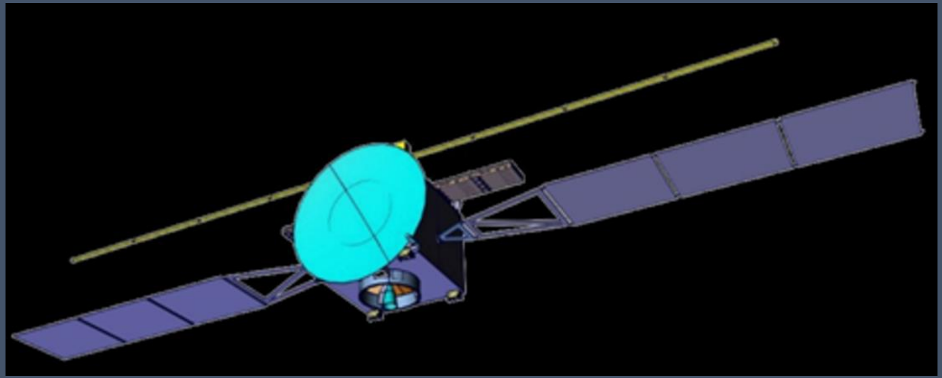




Konopliv et al., 1999

Ground-Penetrating Radar

- Shallow structure & stratigraphy to complement orbital imaging & topography.
- Proposed for EnVision (Sounder): 16 MHz based on RIME (Bruzzone et al., 2013)
- Exploration depth several hundred m, ~10 m vertical resolution.
  - Attenuation due to absorption at high temperature well-understood.



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Assessment & Conclusion

- High Readiness
  - DC Magnetics
  - Gravity & Geodesy
  - GPR
- Medium Readiness
  - Heat Flux
  - Electromagnetics
  - Airborne Seismology (Infrasound)
- Low Readiness
  - Landed Seismology
  - Orbital Seismology

- Geophysics is an integral a part of planetary exploration and contributes to many VEXAG Investigations.
- Gravity data were fundamental to our basic view of Venus as a geodynamically unique planet.
- Seismology is likely to make the strongest impact on the future, but is a long-term investment.
- Other methods can contribute significantly in the shorter-term.