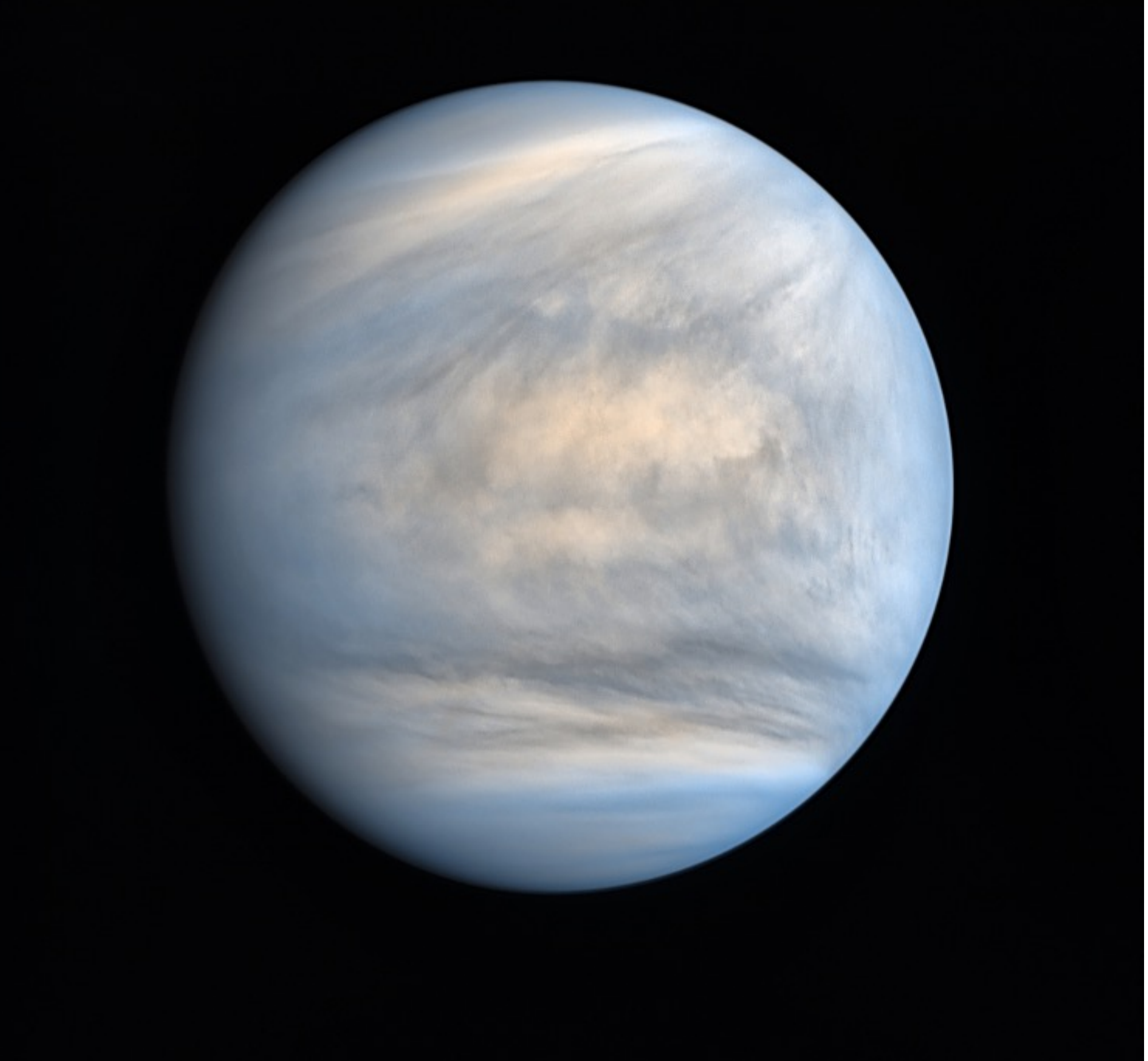
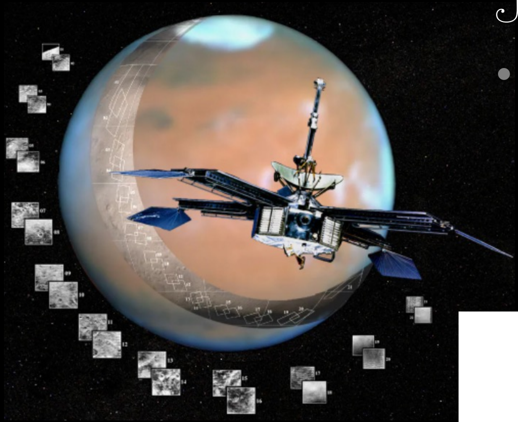


Phase matching method for inversion of radio occultation experiments on Venus

Tatiana Bocanegra-Bahamon,
Chi Ao, Kuo-Nung Wang and
Panagiotis Vergados

Jet Propulsion Laboratory
California Institute of Technology

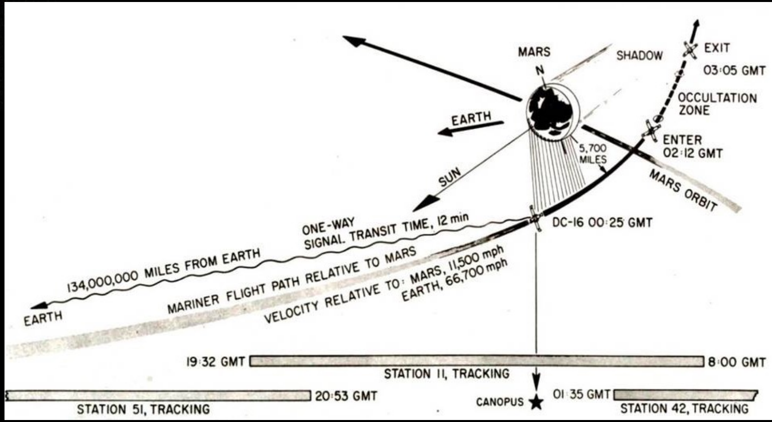
First planetary radio occultation



JPL's Mariner IV

- First radio occultation measurement of a planetary body made on July 15 1965.

Kliore et al., 1966



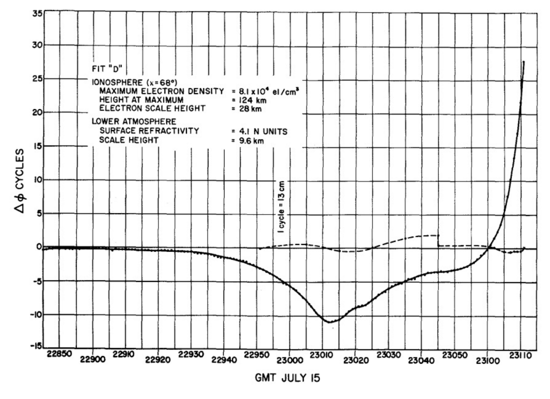


Figure 3: Difference, observed minus computed data, in cycles.

Overview

Planetary RO measurements

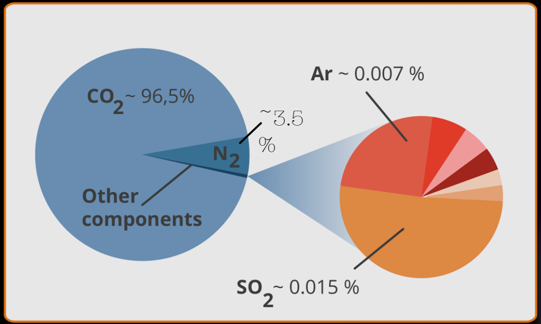
- Voyager 2: Jupiter, Saturn, Uranus, Neptune, Triton
- Voyager 1: Jupiter, Saturn, Titan, Saturn's rings
- PVO: Venus
- Magellan: Venus
- Galileo: Jupiter, Io, Europa, Ganymede and Callisto
- MGS: Mars
- Cassini: Saturn, Titan
- MRO: Mars
- Mars Express (ESA): Mars
- MESSENGER: Mercury
- Venus Express (ESA): Venus
- New Horizons: Pluto
- Akatsuki (JAXA): Venus
- Juno: Io, Ganymede
- MAVEN: Mars
- MarCO: Mars

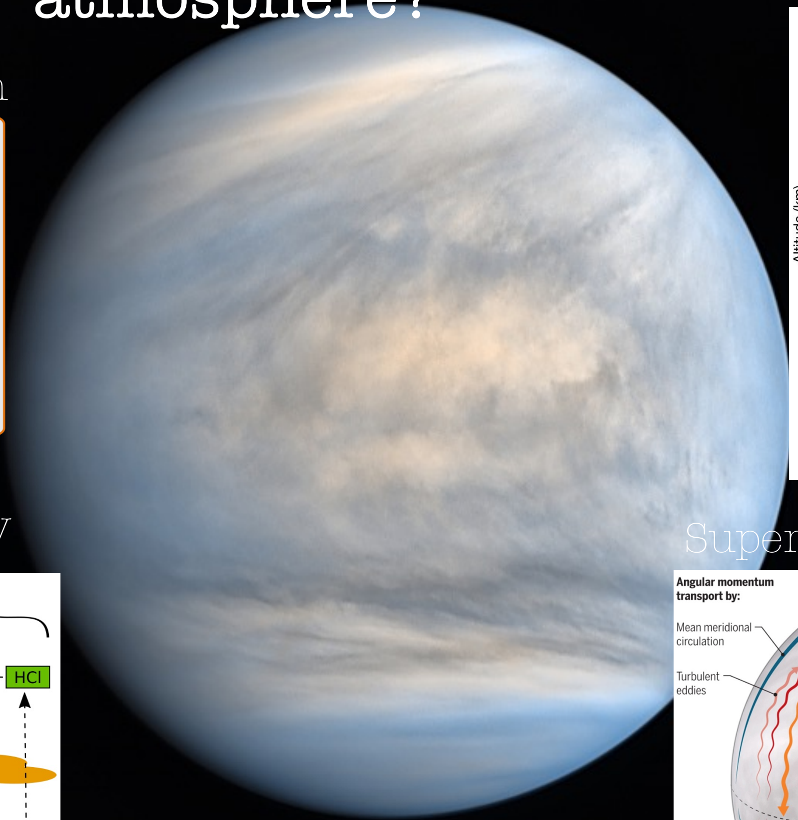
Future missions with planned RO experiments:

- JUICE (ESA): Jovian system
- Europa Clipper: Europa
- Shukrayaan-1 (ISRO): Venus
- MMX (JAXA): Mars
- VERITAS: Venus
- EnVision (ESA):Venus

Why study Venus' atmosphere?

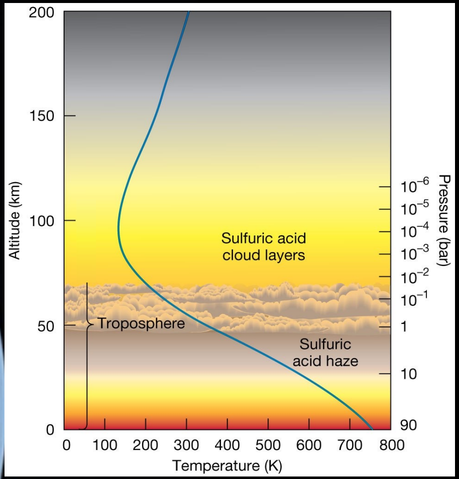
Atmospheric composition





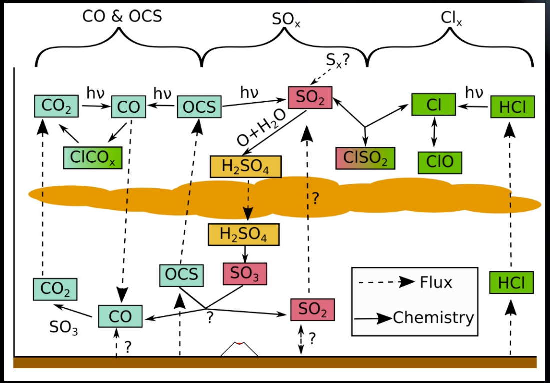
JAXA Akatsuki UV camera
Credit: Damia Bouic

Vertical temperature structure



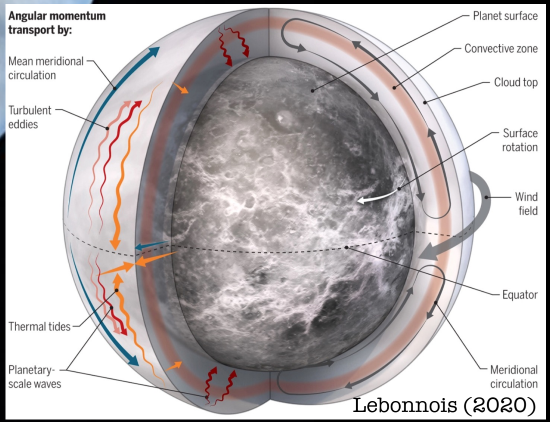
Chaisson and McMillan (2014)

Atmospheric chemistry



Bierson and Zhang 2020

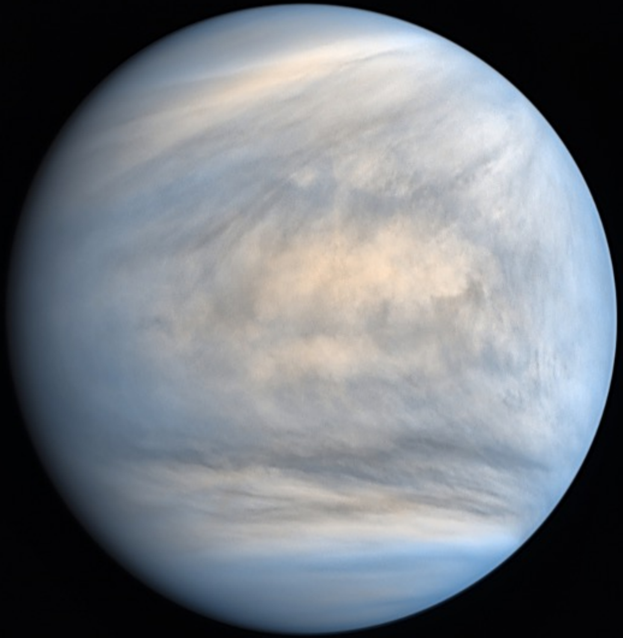
Super-rotating atmosphere



Lebonnois (2020)

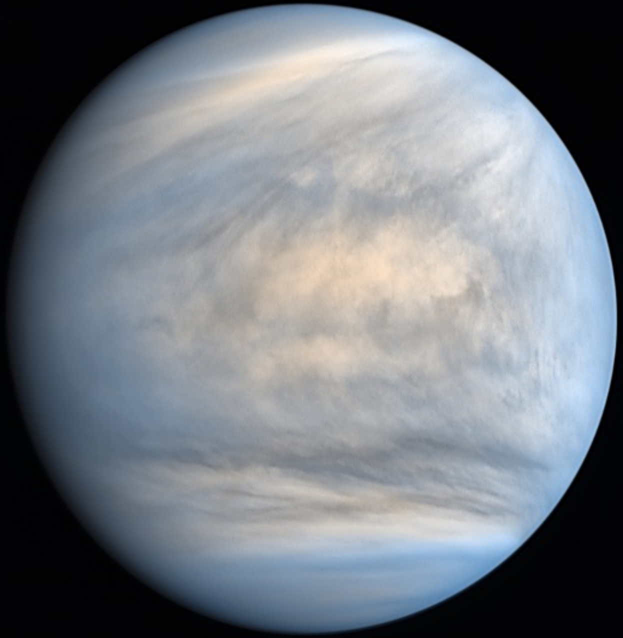
Why study Venus' atmosphere?

Priorities for Venus exploration



- What is the nature of the radiative and dynamical energy balance on Venus that defines the current climate?
  - Determine the atmospheric radiative balance and the atmospheric temperature profiles over latitude and time-of-day
- What are the morphology, chemical makeup and variability of the Venus clouds, and what is their impact on the Venus climate?
  - Analyze cloud aerosols, including their bulk composition, and vertical motions.
  - Study the abundances of their primary parent gaseous species, such as SO_2, H_2O, and H_2SO_4
- How have the interior, surface, and atmosphere interacted as a coupled climate system over time?
  - Determine the abundances and altitude profiles of reactive atmospheric species (SO_2, H_2SO_4, etc.)

What measurements are needed?

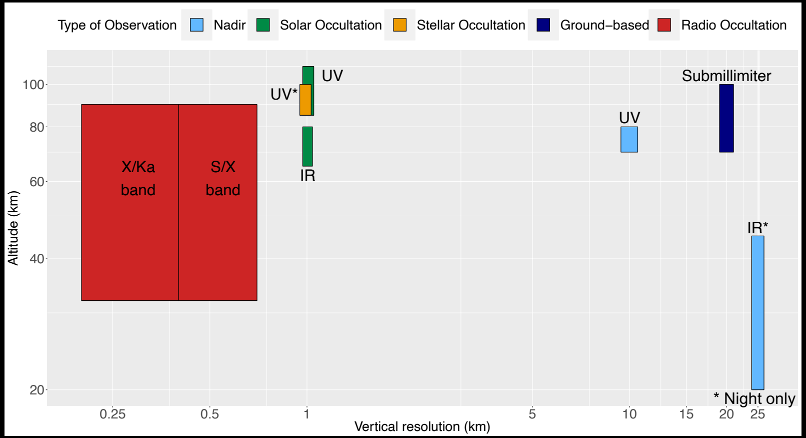


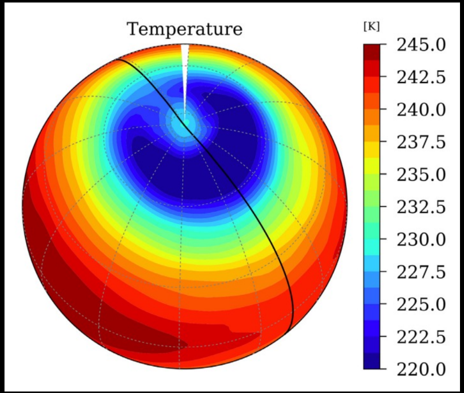
- Vertically and horizontally resolved profiles of thermal structure and atmospheric composition at and below the cloud base as a function of latitude and time of day
- Methods for accomplishing this:
    - Probes/landers
    - Narrow IR window observations
    - Radio occultation measurements
    - Ground-based microwave radiometry

Radio-holographic methods for Venus RO

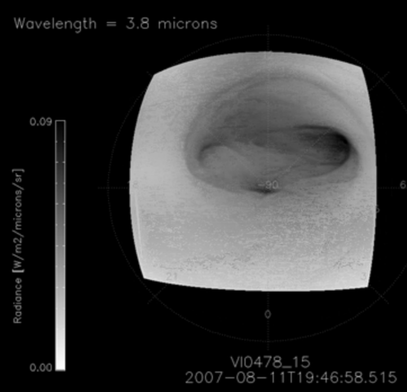
- RO is the only spacecraft remote sensing technique able to probe the atmosphere through and below the dense cloud layers (down to 33 km altitude) at high vertical resolution.
- RO is the remote sensing technique with highest vertical resolution.

- However, in order to study short-scale structures higher vertical resolutions than the ones that have been achieved with X- and S-band are needed.
- Additionally, multipath propagation had been detected at high latitudes due to the presence of the cold-collar region.





Garate-Lopez & Lebonnois (2018)



ESA/VIRTIS-VEX. G. Piccioni.

Shift towards a hybrid 'wave/optic' approach

Issues with a ray-theoretic (geometric optics) approach:

- By definition, neglects diffraction effects.
- Vertical resolution is diffraction-limited to the first Fresnel zone

$$r_{F1} = \sqrt{\lambda D|\zeta|}$$

- Multi-path interference cannot be addressed with a single-ray propagation approach.

Solution found in radio-holographic techniques:

- The formulation of the RO signal as a complex wave field is used.
- The field is presented at the receiving aperture as the sum of a complex spectral series.

$$f(t) = \sum_{j=1}^{N} A_j e^{-i\psi_j(t)}$$

Phase Matching

Complex wave field

$$f(t) = \sum_{j=1}^{N} A_j e^{-i\psi_j(t)}$$

Phase transform

$$M(a) = \int_0^T f(t) e^{-i\psi_m(a,t)} dt$$

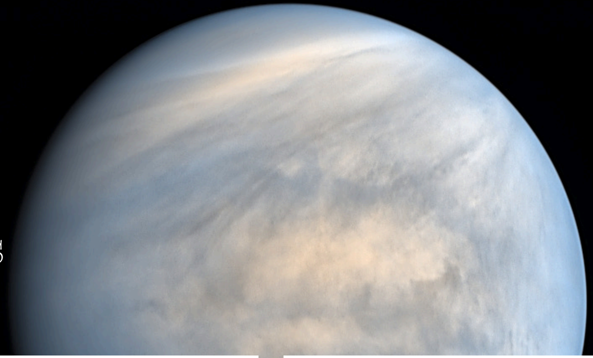
$$M(a) = \int_0^T A(t) e^{-i(\psi(t) - \psi_m(a,t))} dt$$

$$\frac{\partial(\psi - \psi_m)}{\partial a} = k\alpha$$

Implementation:

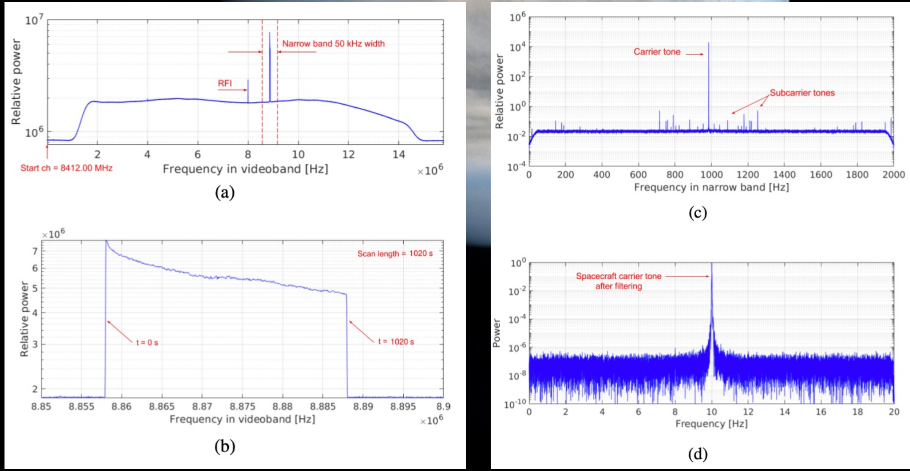
1. Obtain the phase matching function $\psi_m = kS_m$, where S_m is the expected ray-path length, given the position of the transmitter and receiver in the occultation plane.
2. Apply the phase transform to the RO signal for a desired range of impact parameters.
3. Determine the bending angle solution by differentiating the unwrapped phase of the transformed field with respect to the impact parameter.
4. Obtain refractivity by applying the inverse Abel transform

Phase Matching for Venus RO



- Demonstration of the technique with datasets from JAXA's Akatsuki and ESA's Venus Express

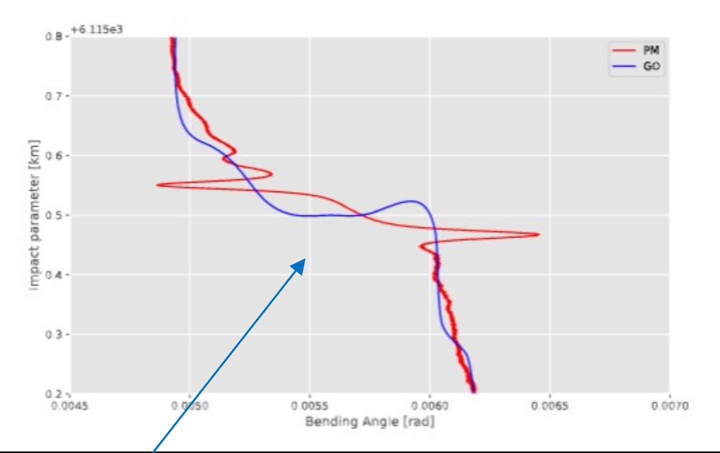
Data acquisition date and time (UTC)	S/C	Station	Antenna diameter (m)	Solar elongation (deg)	Distance to S/C (AU)	Latitude (deg)	SZA (deg)	Type
2012-04-27 05:10-06:05	VEX	Ur	25	41	0.47	83.4	170	Egress
2012-04-29 05:10-06:05	VEX	Bd	32	40	0.46	83.6	169	Egress
2012-04-30 05:10-06:05	VEX	Bd	32	40	0.45	83.7	168	Egress
2012-05-01 05:10-06:05	VEX	Bd	32	39	0.44	83.8	167	Egress
2017-05-26 21:05-21:09	VCO	Us	64	45	0.63	0.2	5	Ingress
2017-05-26 21:30-21:33	VCO	Us	64	45	0.63	-46.3	135	Egress
2017-07-20 05:06-05:10	VCO	Us	64	41	1.06	42.3	48	Ingress
2017-07-20 05:31-05:35	VCO	Us	64	41	1.06	-1.2	172	Egress



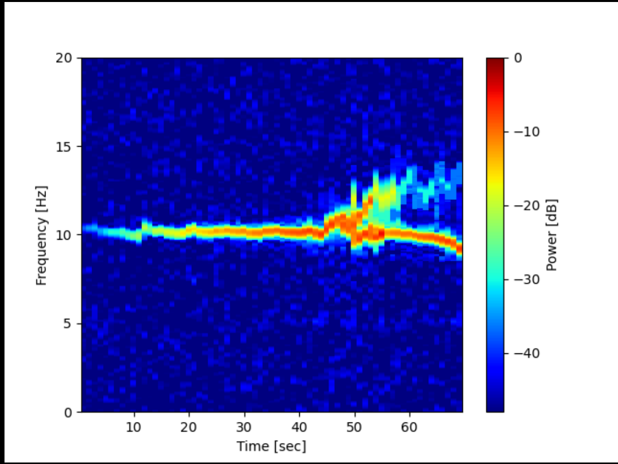
Phase Matching for Venus RO

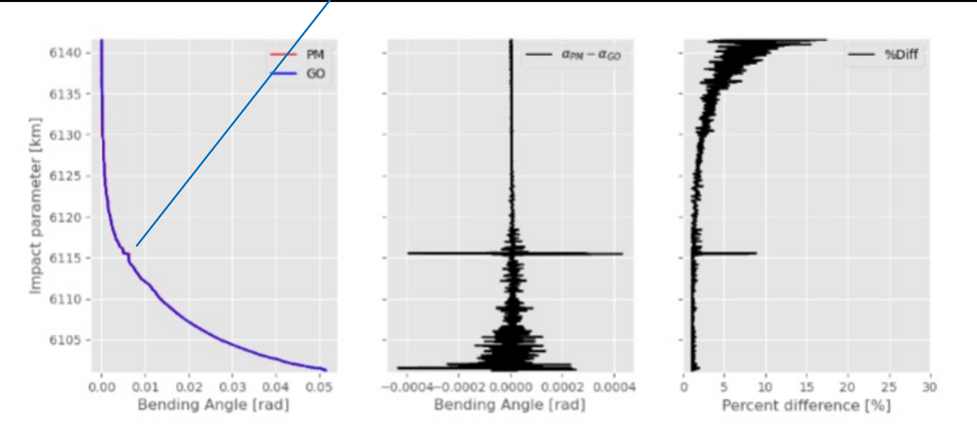
- Sub-Fresnel vertical resolution

$$\Delta h_{GO} = 750\text{ m}$$
$$\Delta h_{PM} = 120\text{ m}$$



- Detection of multi-path propagation

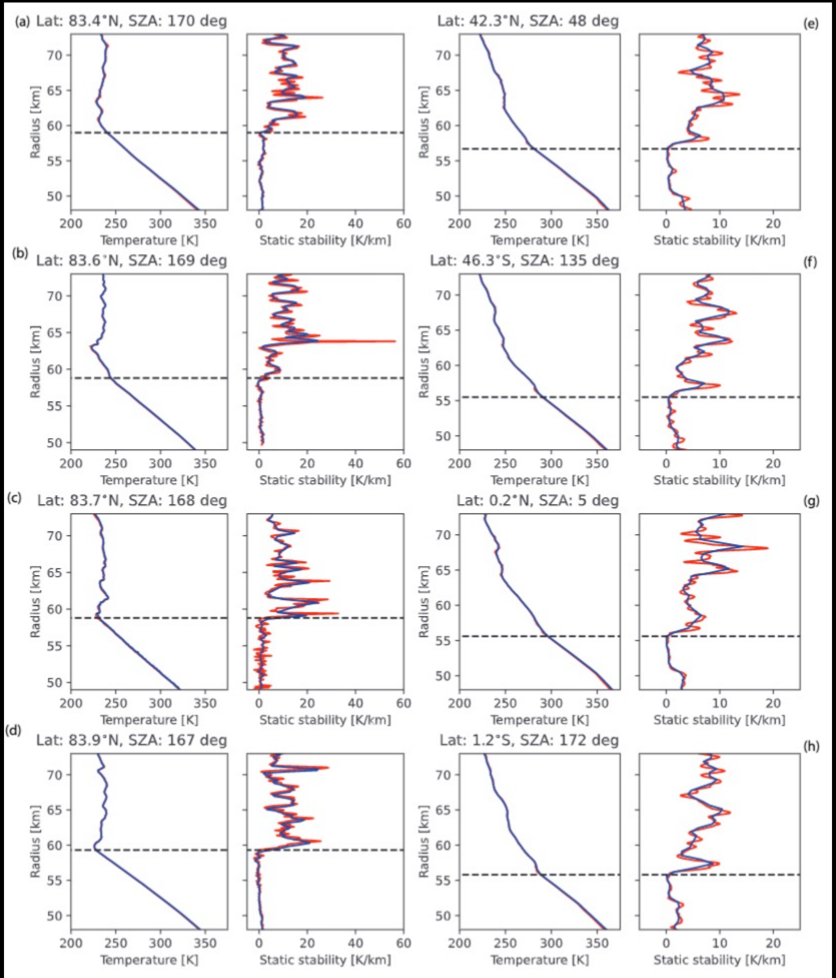




Phase Matching for Venus RO

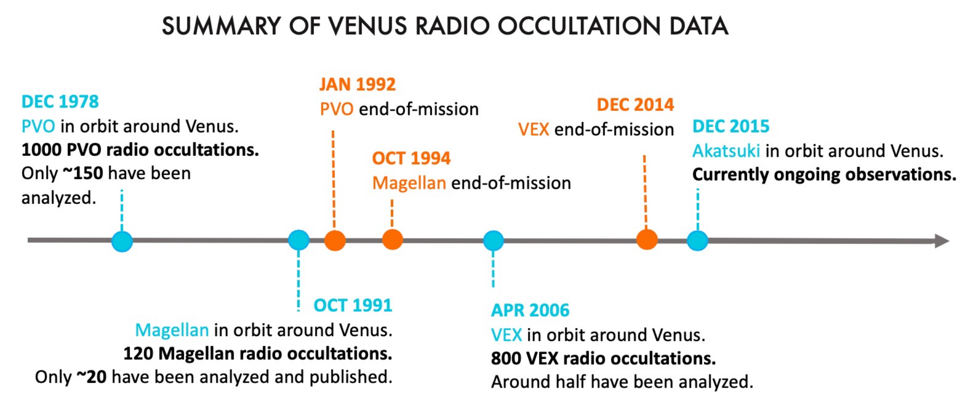
- Clear differences between derived temperature and static stability profiles with GO (in blue) and PM (in red), owing to higher vertical resolution and the ability to resolve multipath interference using PM.
- Largest differences in static stability occur above the tropapause.
    - Weak-stability layer observed at 62 km.
    - Thin instability layers induce convective mixing which is a characteristic of turbulence generation by gravity wave breaking.

To study short-scale atmospheric processes in the upper cloud region radio-holographic methods should be applied

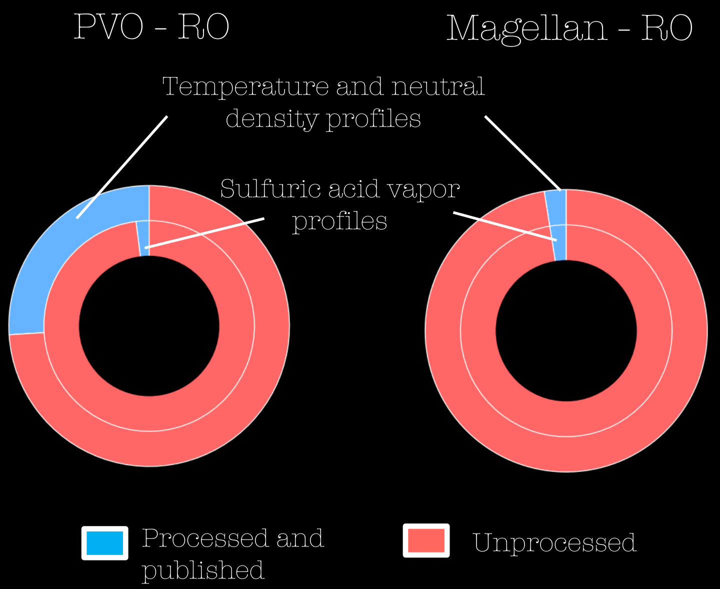


Reprocessing Venus RO with radio holographic methods

- Investigate the thermal structure of the atmosphere and the formation, extent, variability and composition of the clouds.



Spacecraft	PVO	Magellan	VEX
Time span	1978-1992	1991-1994	2006-2014
Occultation events	~1000	120	~800
Vertical range (km)	38-100	33-90	40-100
Local time coverage	Day & night side	Day & night side	Day & night side
Latitudinal coverage	Both hemispheres	45° N – 88° N, 60° S – 88° S	Both hemispheres
Percentage of events published in peer-reviewed papers	26% (thermal and density profiles) 2% (sulfuric acid profiles)	2.5% (thermal and density profiles) 2.5% (sulfuric acid profiles)	50% (thermal and density profiles) 8% (sulfuric acid profiles)
Percentage of events included in VIRA	12.3%	0%	0%
Total archived level 1 events	~ 1000 (PDS)	120 (PDS)	4 (PDS), ~800 (PSA)
Total archived level 2 derived data products	0 (PDS)	3 (PDS)	0 (PDS), 0(PSA)
Total archived level 3 derived data products	0 (PDS)	3 (PDS)	0 (PDS), 0(PSA)
Total archived level 4 derived data products	0 (PDS)	3 (PDS)	0 (PDS), 0(PSA)

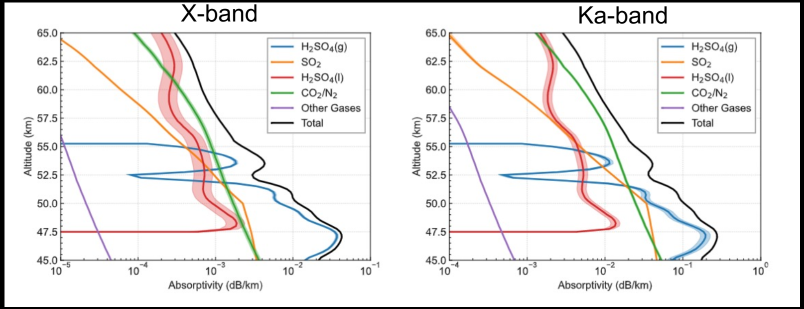


Future Venus RO experiments

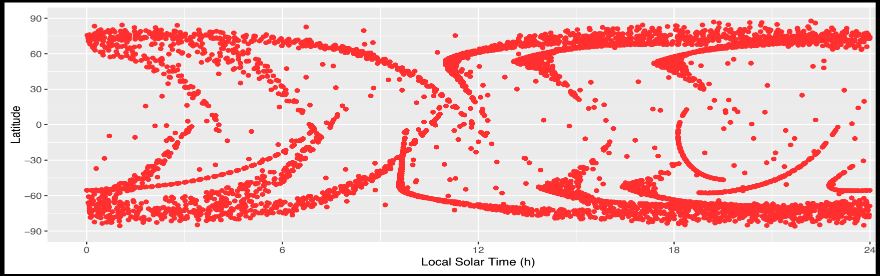
- NASA's VERITAS and ESA's EnVision mission will conduct radio occultation experiments in X/Ka-band

Science objectives:

- Determine the concentration and vertical distribution of SO_2 and H_2SO_4
- Determine whether volcanic activity is responsible for the temporal and spatial variability of SO_2



VERITAS and EnVision near-circular orbits (science phase) will provide better coverage



Simulations suggest that X/Ka radio occultation observations can simultaneously determine SO_2 and H_2SO_4 abundance profiles, which has not been possible with previous missions.

Outlook for planetary radio occultation

- Explore synergies between GNSS-RO and planetary RO processing
  - Methodologies, data calibration, RO receivers, planetary cross-link RO using cubesats
- Plans for upcoming planetary RO experiments:
  - ESA's JUICE (Jupiter ICy moons Explorer)
    - Jupiter's rings characterization
    - Ionosphere of Ganymede
  - NASA's VERITAS
  - ESA's EnVision
  - Future NASA Uranus flagship mission

Jet Propulsion Laboratory
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