National Aeronautics and Space Administration

# Novel radio occultation experiments to study Venus's sulfur cycle chemistry and potential volcanism

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**Program: FY21 R&TD Innovative Spontaneous Concepts**

## Background

**A key to studying Venus's atmospheric chemistry is to understand its sulfur cycle**, particularly below and within clouds (~35-70 km). Magellan's S/X-band radio occultation (RO) experiments [Steffes et al., 1994] provided H2SO4 abundances in the 32-90 km altitude range with 400–700 m vertical resolution, and with poor sensitivity to SO2. Venus Express (VEX) IR and UV solar and stellar occultations provided SO2 abundances above the cloud top (>65 km) [Belyaev et al., 2008], whereas VEX's IR and UV nadir-viewing radiometers provided only vertically-averaged SO2 abundances every 10-20 km, missing the vertical stratification of SO2. Akatsuki's X-band RO experiments retrieved H2SO4 mixing ratios between 38 and 56 km with <50% retrieval error [Imamura et al., 2017].

**Observational and instrumental limitations exist** that have prevented us from understanding Venus's sulfur cycle: 1) limited accuracy and spatial/temporal coverage of SO2 observations; and 2) unavailability of simultaneous retrievals of SO2 and H2SO4 with altitude.

Demonstrating the ability of RO to retrieve multiple atmospheric species could lead to instrument development/modifications that benefit future JPL missions, including the search for life. Our study could increase the science of JPL's VERITAS mission, whose pioneering X/Ka-band combination could provide better sensitivity to both H2SO4 and SO2 retrievals.

## Objectives

**OBJECTIVE:** Demonstrate, *for the first time*, how dual-frequency X/Ka-band RO measurements could be used to simultaneously determine the concentration and vertical distribution of sulfuric acid ($H_2SO_4$) and sulfur dioxide ($SO_2$) above 35 km with high vertical resolution (~ 200 m) and to quantify their accuracies.

1. **Develop** Radio Occultation (RO) retrieval software to infer vertical profiles of chemical species absorptivity (cf., Figure 1) from phase and amplitude X/S/Ka-band measurements.
2. **Develop** novel inversion techniques to infer chemical absorber abundances from RO-derived absorptivity profiles.

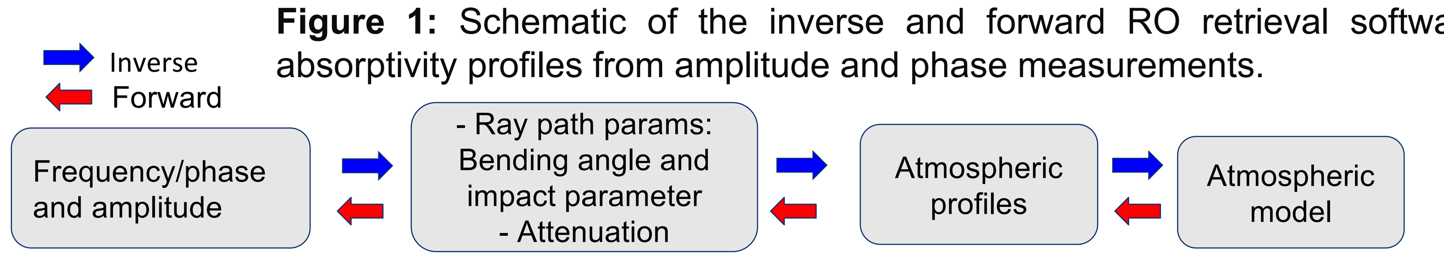


**Figure 1:** Schematic of the inverse and forward RO retrieval software to infer absorptivity profiles from amplitude and phase measurements.

## Approach

**STEP 1:** From Venus International Reference Atmosphere (VIRA) get Venus's background pressure and temperature profiles as a function of altitude.

**STEP 2:** Use Venus Express (VEX) satellite retrievals of $H_2SO_4$ mixing ratios at X-band to simulate the $H_2SO_4$ absorption within 38–56 km at S/X/Ka-band at 1 km vertical resolution [Akins and Steffes, 2020].

**STEP 3:** Initialize our in-house propagation model (available in 386G) with the VIRA background atmosphere and the simulated $H_2SO_4$ absorptivity profiles at S/X/KA-band.

**STEP 4:** Randomly initialize the free parameters: **a)** $H_2SO_4$ vapor mixing ratio, **b)** the $H_2SO_4$ liquid cloud density, and **c)** the $SO_2$ mixing ratio at every point within 38–56 km.

**STEP 5:** These free parameters are input to an objective function that computes the absorptivity at S/X/Ka-band frequencies for the corresponding free parameters abundance profiles using opacity models developed by Paul Steffes and students, and the square of the differences between these newly calculated absorptivity profiles and the assumed true starting absorptivity profiles.

## Results

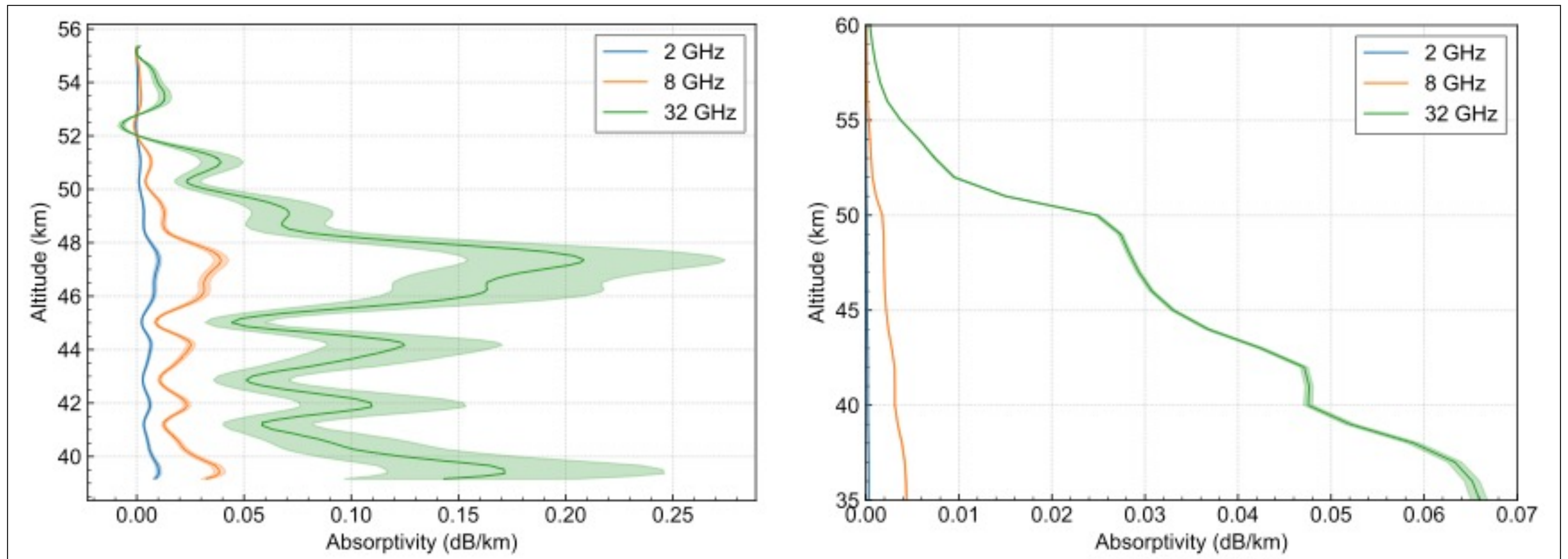


**Figure 2.** Atmospheric absorptivity vertical profiles $H_2SO_4$ (left) and $SO_2$ (right) for an equatorial model atmosphere. The bulk $CO_2/N_2$ atmosphere and sulfur species dictate the microwave opacity of the atmosphere, and the contribution of other trace gases is minimal. Shaded regions show 1-sigma uncertainties associated with absorptivity models.

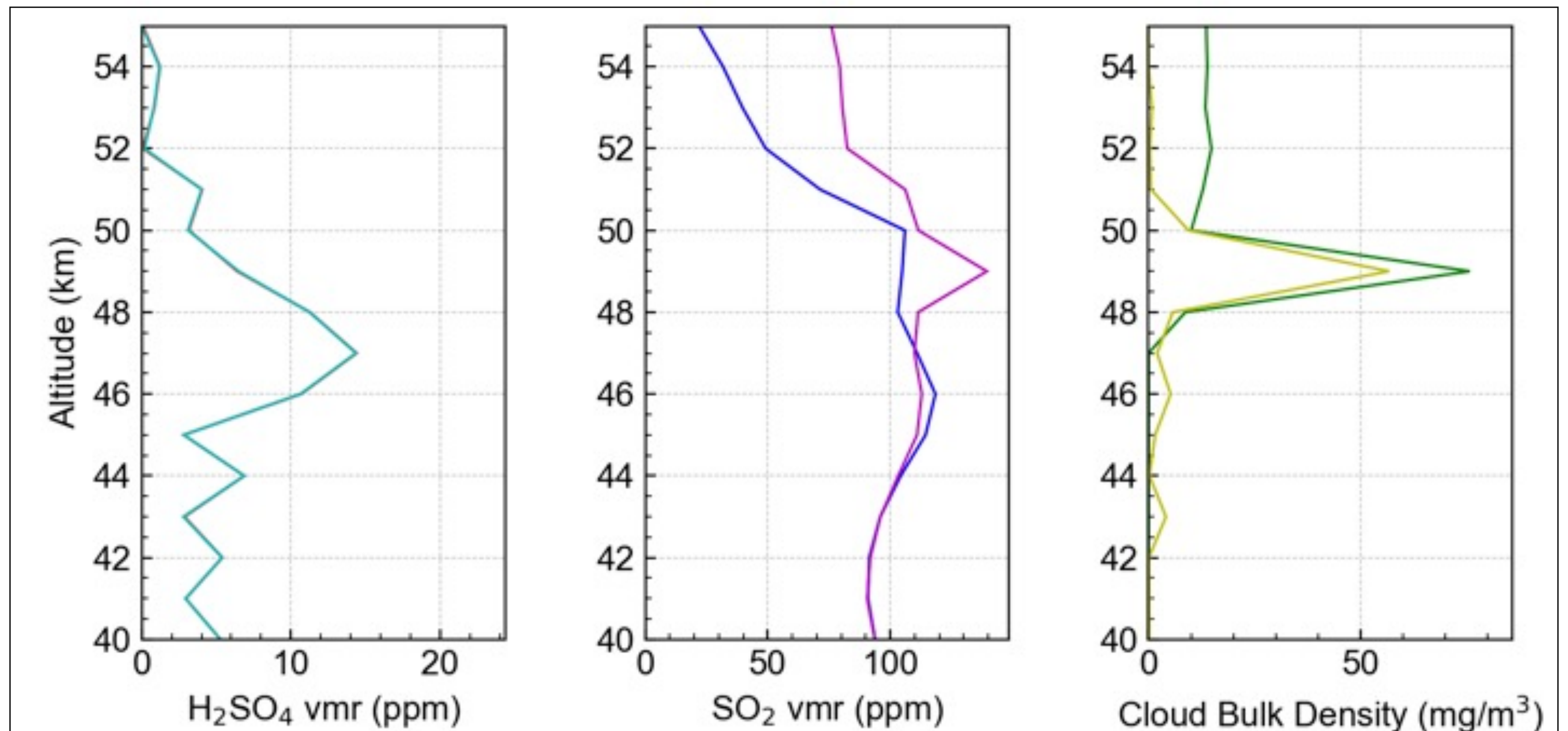


**Figure 3.** Vertical profiles $H_2SO_4$ mixing ratio (left), $SO_2$ mixing ratio (middle), and cloud bulk density (right) at equator. In each graph, the red, blue, and green colors show the original abundances and the cyan, magenta, and yellow colors present the retrieval fits from our atmospheric propagation model.

## Milestones Achieved

Key milestones achieved during this proposal concept:

A) **Demonstrated** $H_2SO_4$ retrievals from simulated dual-frequency X/Ka-band RO data paralleling VEX satellite observations.

B) **Demonstrated** improved $H_2SO_4$ retrieval accuracy than that provided by previous or existing missions.

C) **Developed** novel software capable to simultaneously retrieve $H_2SO_4$ and $SO_2$ mixing ratios.

**We exceeded expectations** by also achieving the following additional milestones:

D) **Demonstrated** retrieval of additional physical variables not included in the original proposal such as, the vertical cloud density, and

E) **Developed** simulation experiments to relate observing errors to chemical species abundance.

Currently, we refine our methods for improved products.

## Significance to NASA and JPL

Our study provides a novel technique to simultaneously retrieve chemical sulfur species in the atmosphere of Venus with the addition of a Ka-band frequency.

- Allow for the first time an **effective separation of the absorption spectra of $H_2SO_4$ from $SO_2$** and observationally retrieve their abundances.
- **Potentially increase the science return of JPL's VERITAS mission** through X/Ka-band RO observations, with no changes to the mission design.
- Contribute to the understanding of Venus's sulfur cycle and to the **assessment of Venus's volcanic activity** through precise $SO_2$ measurements.
- Could lead to **instrument development/modifications that would benefit future JPL missions**, including the search for life.
- Could enable increased global and temporal coverage of planetary atmospheres, improving our understanding of planetary evolution.

## References

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