Determining Atmospheric Species Abundances Using Multi-Frequency Radio Signal Absorption

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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: Develop a novel multi-spectral radio science technique to simultaneously retrieve vertical distributions of H_2SO_4 and SO_2 in Venus atmosphere by measuring signal attenuation at X- and Ka-band frequencies. Our approach takes advantage of the differential radio absorption features of each absorber.

1. **Develop** Radio Occultation (RO) retrieval software to infer vertical profiles of chemical species absorptivity from phase and amplitude X/Ka-band measurements.
2. **Develop** novel data-driven atmospheric model to infer chemical absorber abundances from RO-derived absorptivity profiles with well-defined retrieval uncertainties exceeding the state-of-the-art.
3. **Explore** the science benefits of JPL's VERITAS KA-band measurements with the DSN and its applications to Venus's atmospheric studies.
4. **Improve** the current vertical resolution of temperature and trace gases retrievals using novel occultation softwares.

Approach

STEP 1: We used our end-to-end RO simulation software to generate phase and amplitude measurements for Venus atmospheric conditions at X- and Ka-band frequencies.

STEP 2: Use the simulated signal amplitudes to retrieve attenuation and absorptivity vertical profiles for H_2SO_4 and SO_2, which we used to initialize our atmospheric propagation model at different frequencies to simultaneously estimate the concentration and vertical stratification of sulfur species and cloud bulk density.

STEP 3: 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 30–70 km.

STEP 4: These free parameters are input to an objective function that computes the absorptivity at 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.

Our atmospheric propagation model used parameterized atmospheric chemistry equations, which are solved in an iterative approach based on least squares.

Results

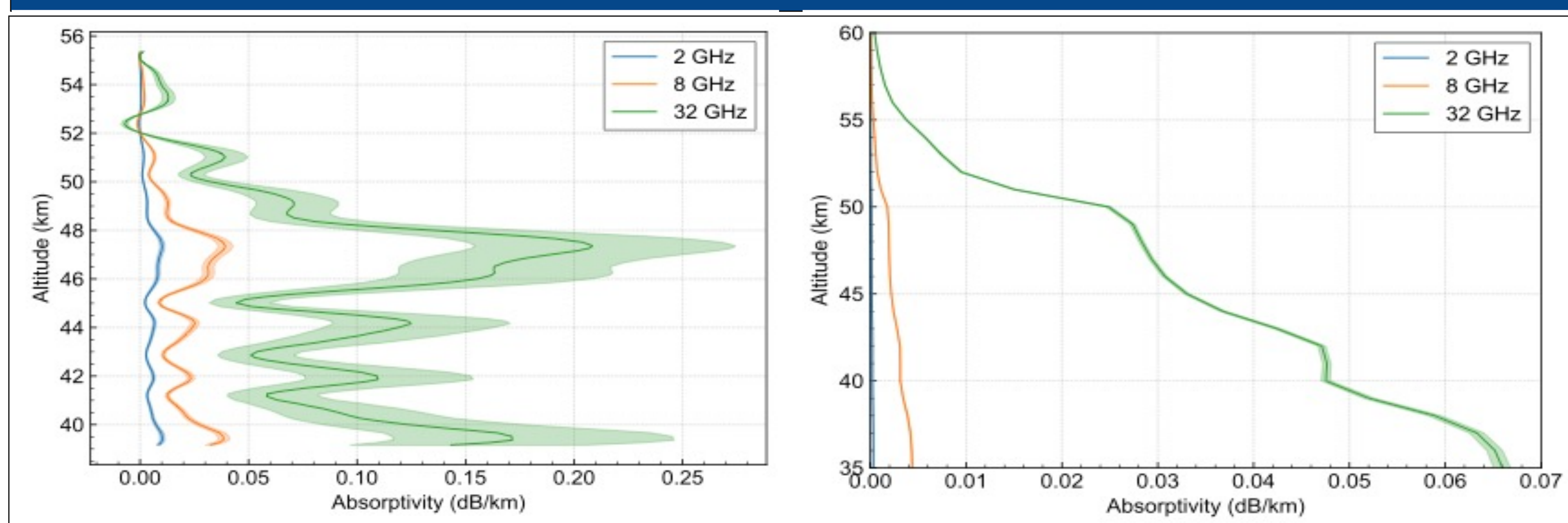

Figure 1. Atmospheric absorptivity vertical profiles H_2SO_4 (left) and SO_2 (right) for an equatorial model atmosphere. The bulk CO_2/N_2 atmosphere and sulfur species dictate the microwave opacity of the atmosphere, and the contribution of other trace gases is minimal. Shaded regions show 1-sigma uncertainties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

Set	H_2SO_4 vapor	H_2SO_4 aerosol	SO_2
1	VEX VeRa, 18°	Imamura and Hashimoto (1998), 0°	Krasnopolsky (2012)
2	VEX VeRa, 45°	Imamura and Hashimoto (1998), 30°	Bierson and Zhang (2020)
3	VEX VeRa, 80°	Oschlisniok et al. (2021), 60°	Rimmer et al. (2021)
4	VEX VeRa, 85°	Oschlisniok et al. (2021), 90°	Bertaux et al. (1996), ISAV-1
5	Oschlisniok et al. (2021), 0°	Oschlisniok et al. (2021), 0°	Krasnopolsky (2012)
6	Oschlisniok et al. (2021), 40°	Oschlisniok et al. (2021), 40°	Bierson and Zhang (2020)
7	Oschlisniok et al. (2021), 80°	Oschlisniok et al. (2021), 80°	Rimmer et al. (2021)
8	Oschlisniok et al. (2021), 40°	Oschlisniok et al. (2021), 40°	Bertaux et al. (1996), ISAV-1

Table 1. Latitude-dependent ground-truth atmospheric profiles for data-driven Simulated retrievals.

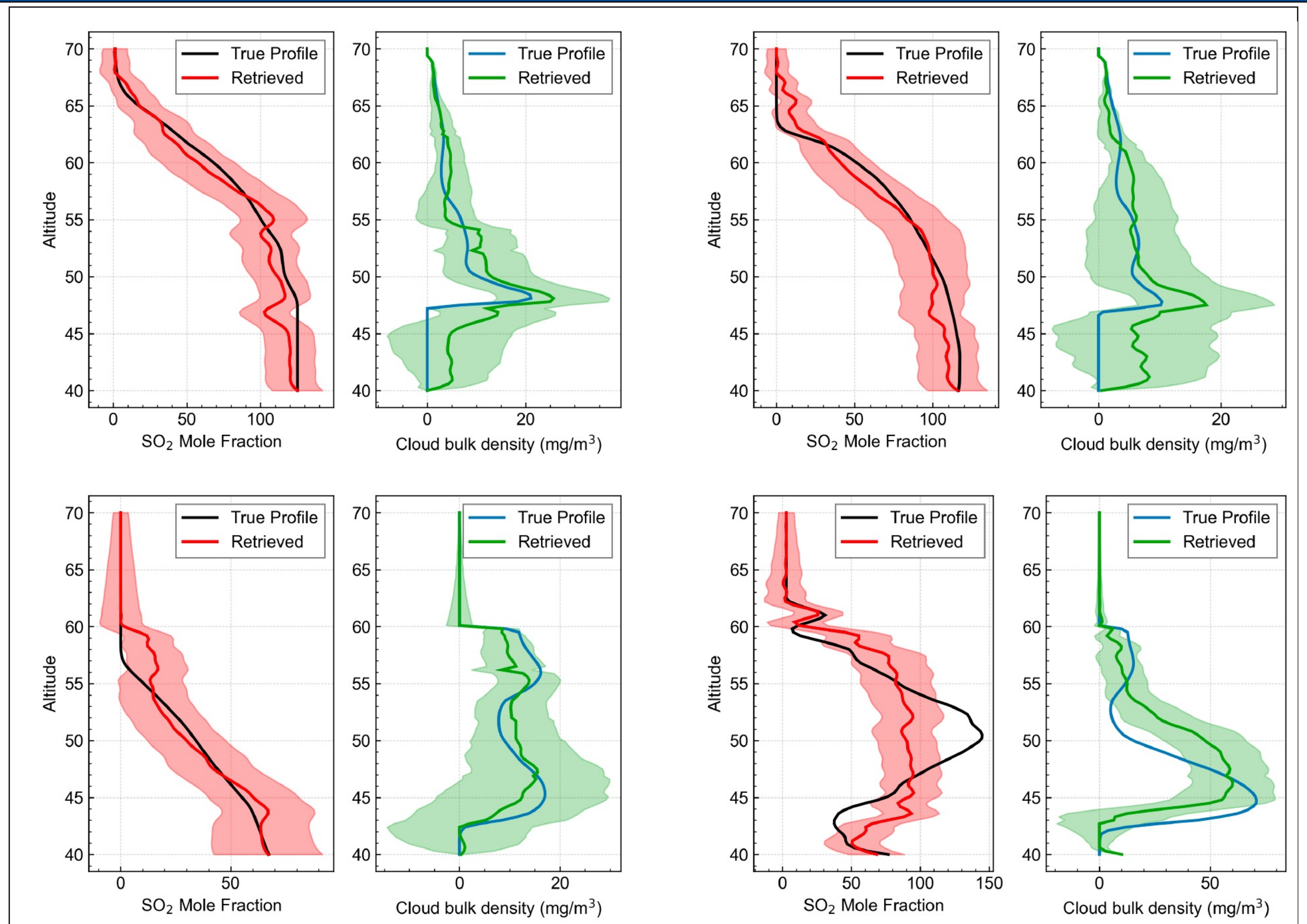

Figure 2. Retrievals of Set 1-4 model atmosphere shown in Table 1 (in order from top to bottom, left to right) abundances of SO_2 and H_2SO_4 aerosol using the data-driven estimate for determining a starting guess. The retrieved abundance of SO2 is regularized with a fifth-order finite difference matrix to encourage smoothness.

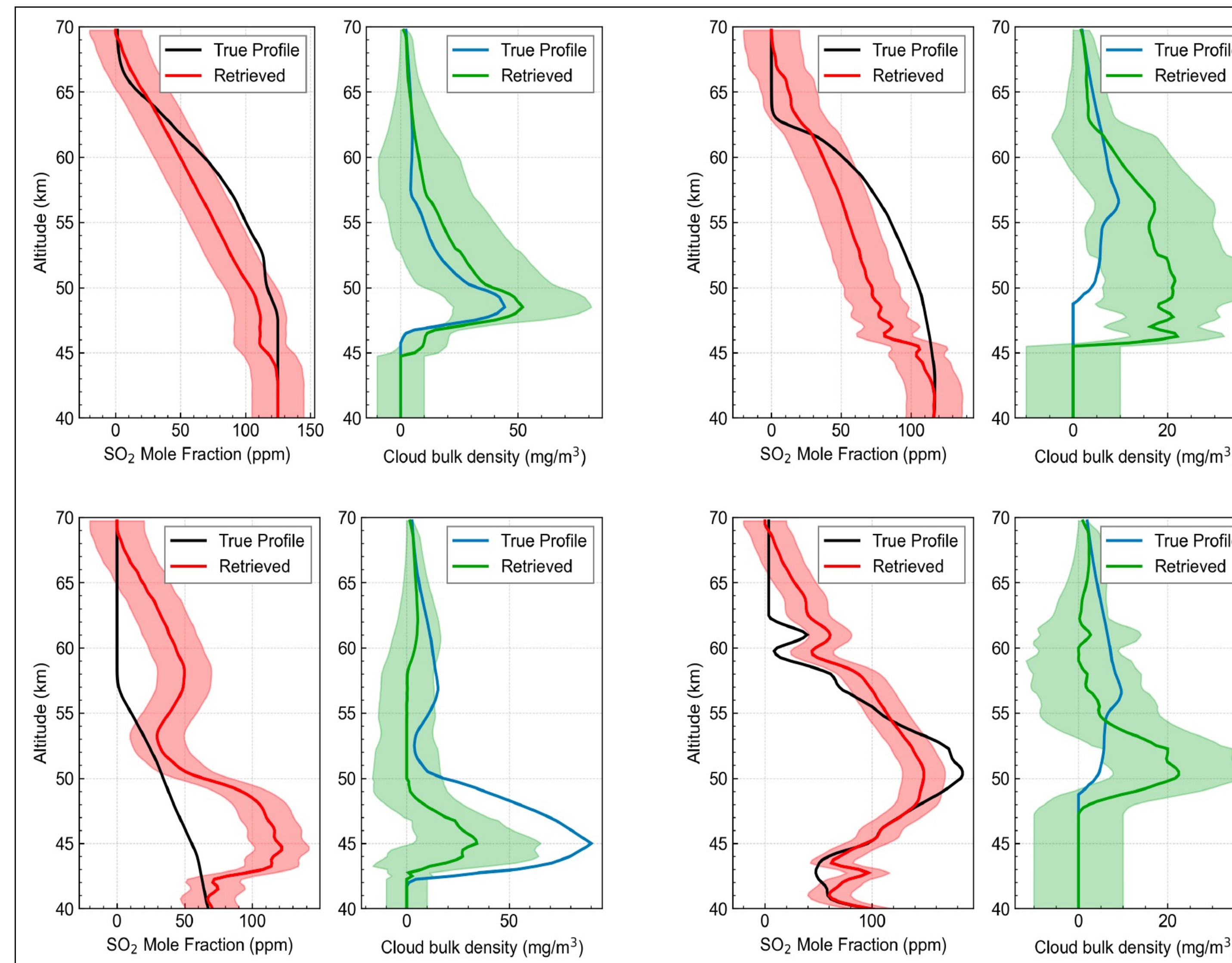

Figure 3. Retrievals of Set 5-8 model atmosphere shown in Table 1 (in order from top to bottom, left to right) abundances of SO_2 and H_2SO_4 aerosol using the model-driven estimate for determining a starting guess. The retrieved abundance of SO_2 is regularized with a fifth-order finite difference matrix to encourage smoothness.

Significance to NASA and JPL

- Allow **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.
- Help understand Venus's sulfur cycle and to the **assessment of Venus's volcanic activity** through SO_2 measurements.
- Could lead to **instrument development that would benefit future JPL missions**, including the search for life.
- Could enable increased global and temporal coverage of planetary atmospheres needed planetary evolution studies.

References

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Publications

Asmar et al., "Time Variable Venus Atmospheric Structure via Radio Crosslinks with Low-Cost VASCO Mission Concept", submitted to COSPAR 44th Scientific Aseembly, Athens, Greece, 16-24 July 2022.

Akins et al., "Profiling H2SO4 aerosol and SO2 abundances in Venus' atmosphere with dual X/Ka band radio occultations", submitted to COSPAR 44th Scientific Aseembly, Athens, Greece, 16-24 July 2022.

Akins et al., "Preparing for X/Ka band radio occultations of Venus with VERITAS and EnVision: Retrieving sulfur abundances," submitted to Venus Exploration Analysis Group Meeting, Virtual, 8-9 November 2021.

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