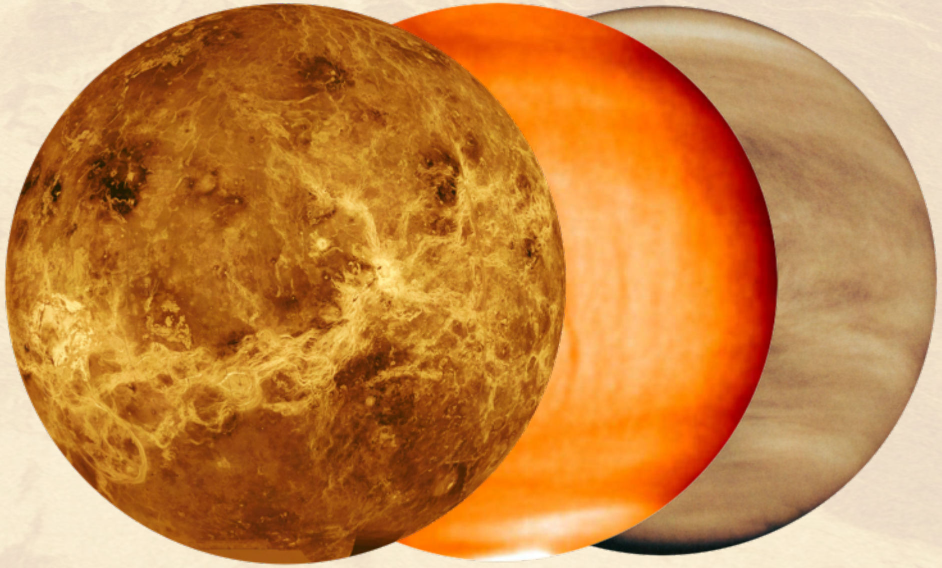
Ground and Space-Based Microwave Remote Sensing of the Venus Atmosphere in Support of the Decade of Venus



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Overview

- Microwave instruments can be used to remotely sense the lower atmosphere and surface of Venus
- EnVision and VERITAS will focus on surface remote sensing with HF radar, S Band radar/radiometry, and X Band InSAR
- We focus here on two lower atmosphere observation techniques and outstanding challenges
  - X/Ka Band radio occultations (RO)
  - Ground-based multi-wavelength passive microwave observations

X and Ka Band Radio Occultations

Venus radio occultations (RO)

- S Band (13 cm, 2.3 GHz) and X Band (3.6 cm, 8.3 GHz) ROs of Venus have been a topic of research for many years
  - Fjeldbo and Eshleman 1969 – first Venus RO with Mariner 5
  - Oschlisniok et al. 2021 – Analysis of ~800 Venus Express occultations
- High vertical resolution atmospheric measurements
  - Link frequency shift used to derive temperature
  - Link attenuation used to derive abundance of H_2SO_4 vapor

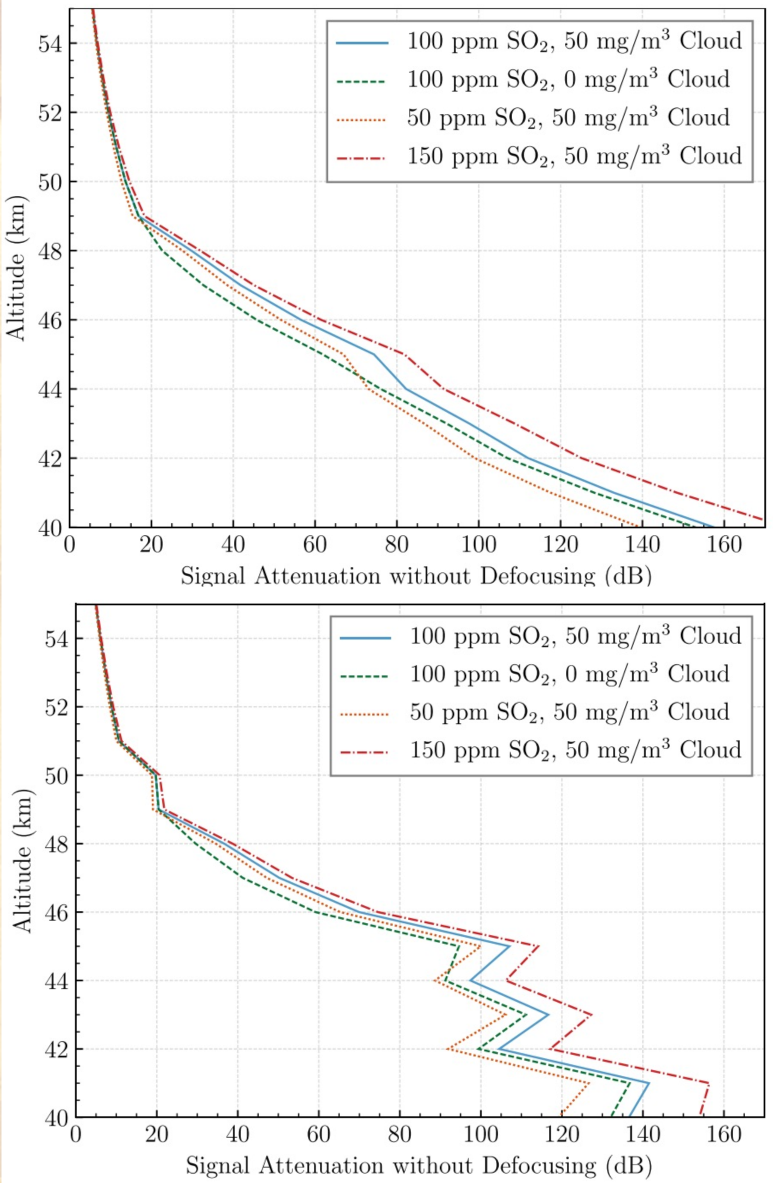
New Venus missions will conduct RO experiments

What's new this time around?

Dual X and Ka Band RO

- VERITAS and EnVision will fly with X and Ka Band (0.9 cm, 32 GHz) comms
- Cloud-level atmosphere is significantly more opaque at Ka Band
- Can we quantify the abundance of absorbers besides H_2SO_4 vapor?
  - SO_2
  - H_2SO_4 aerosols

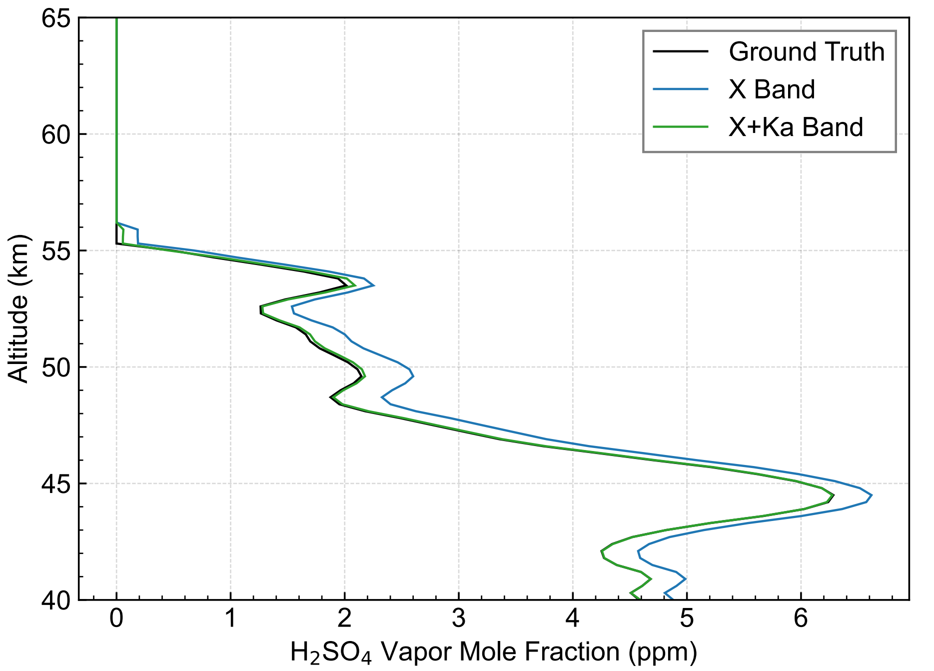
Estimates of Ka Band atmosphere opacity at high latitudes (top) and low latitudes (bottom) from Akins and Steffes (2020)



Effect on H_2SO_4 vapor retrieval from RO attenuation

- Previous bias removal methods
  - Average of simultaneous S/X Band-derived H_2SO_4 profiles (if both are available)
  - Saturation vapor pressure (SVP) correction
- Solving X/Ka Band RO retrievals assuming H_2SO_4 vapor + excess absorber reduces inversion-specific error to a negligible amount
- This approach removes the bias due to other absorbers, whereas S/X Band approach averages biased measurements
- SVP curve sets upper altitude cutoff

Comparison of retrieved H_2SO_4 vapor abundances from X Band RO and dual X/Ka Band RO.



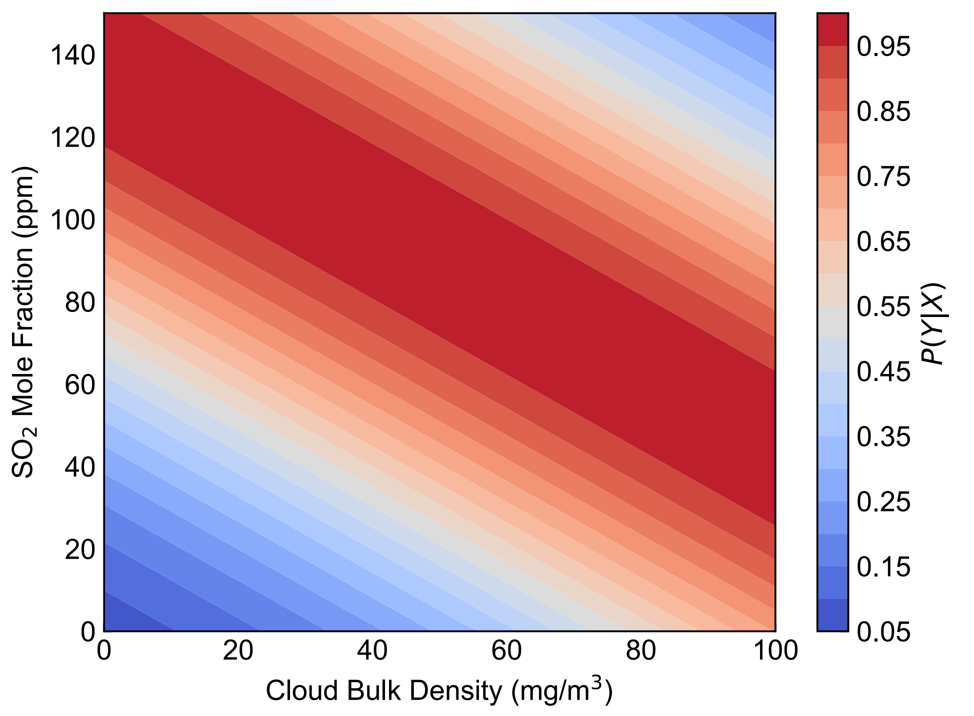
Solving for abundances at a single altitude

- Assume known temperature, pressure, H_2SO_4 vapor ; 5% measurement error
- Linear relationship assumed between opacity and mole fraction
- e.g at 32 GHz:

$$\partial F/\partial x = \begin{bmatrix} 2586.66(p/1.01325)^{1.092}(553/T)^3 \\ 0.014\epsilon''(T)/|\epsilon(T)+2|^2 \\ 300.13(p/1.01325)^{1.12}(300/T)^{2.72} \end{bmatrix} \begin{matrix} H_2SO_4\ (g) \\ H_2SO_4\ (l) \\ SO_2 \end{matrix}$$

- Problem: Retrieval of other absorbers is not unique

$$-2\ln P(\mathbf{y}|\mathbf{x}) = (\mathbf{y}-\mathbf{K}\mathbf{x})^T \mathbf{S}_\epsilon^{-1}(\mathbf{y}-\mathbf{K}\mathbf{x})$$

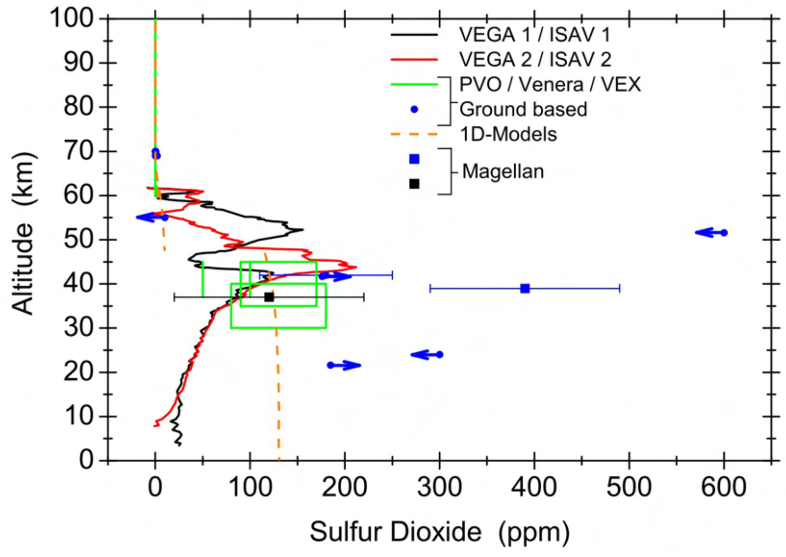


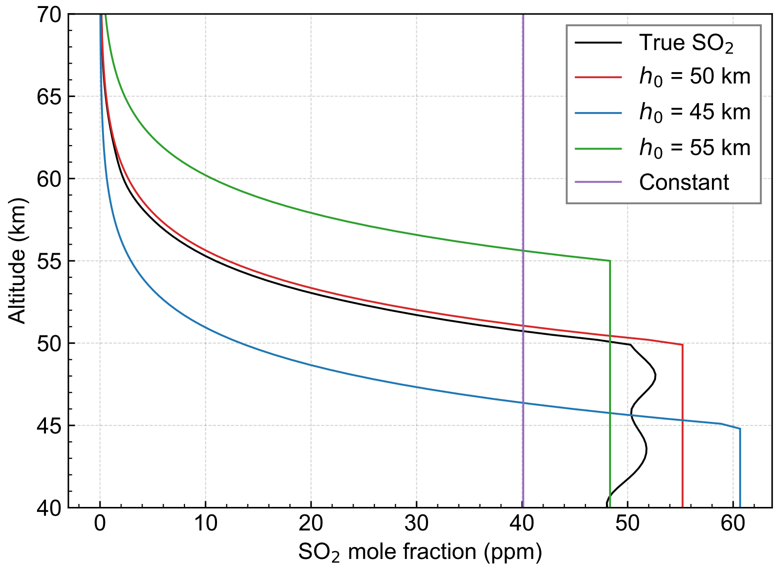
Conditional probability of SO_2 abundance for a given H_2SO_4 aerosol abundance for single-altitude retrieval

Parameterizing SO_2 abundance for RO retrievals

- SO_2 abundance profile decreases within the vertical extent of the clouds
  - Depletion via unknown chemistry?
  - Vertical transport inhibited?
- Using three fit parameters to describe SO_2
  - x_0: Sub-cloud abundance (uniform)
  - h_0: Depletion altitude
  - s_0: Depletion scale height

Prior measurements of sub-cloud SO_2 abundance (figure from Ph.D. thesis of J. Oschlisniok)



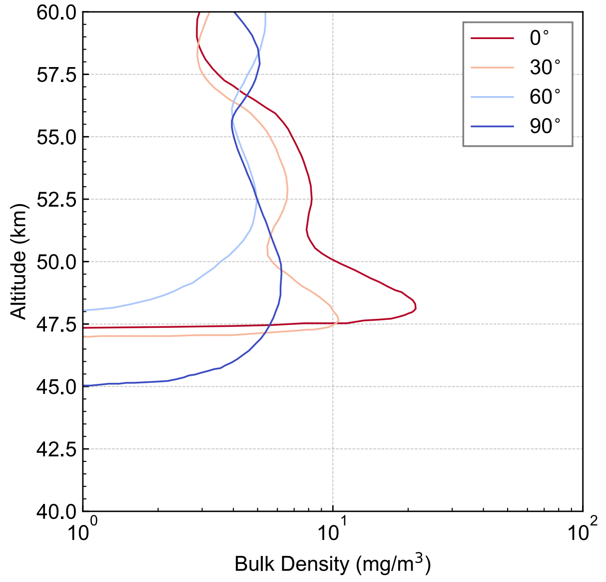


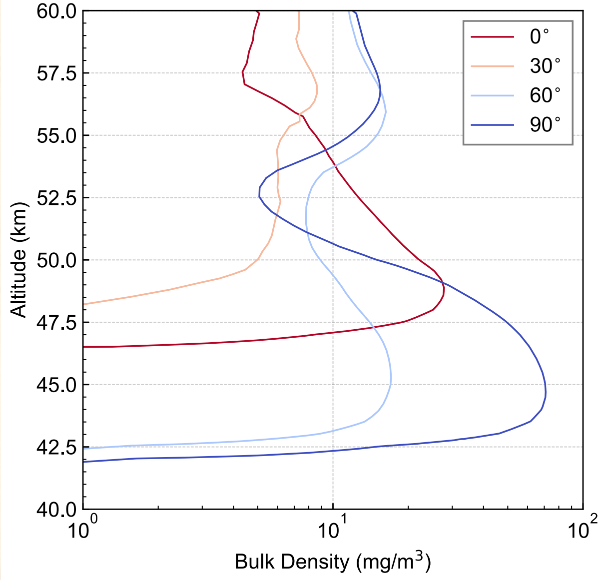
Fits of SO_2 prior profiles (s_0=3.3) to H_2SO_4-subtracted RO absorption and compared with simulation ground-truth

Parameterizing cloud bulk density for RO retrievals

- Results of 2D dynamics codes with simplified chemistry
  - e.g. Imamura and Hashimoto 1998, Oschlisniok et al. 2021
- Only used to infer cloud structure since SO_2 transport/depletion is poorly understood
- Problem: Different meridional circulation patterns significantly affect the predicted cloud bulk density as a function of latitude

Results of Imamura and Hashimoto



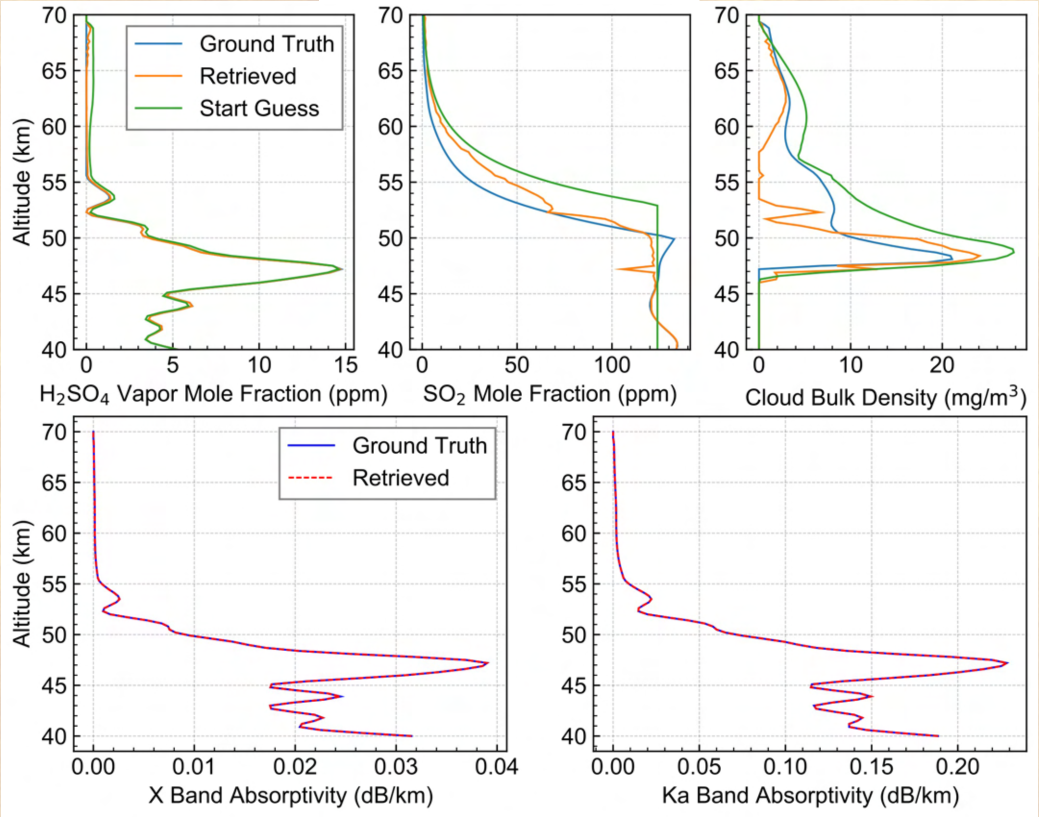


Results of Oschlisniok et al.

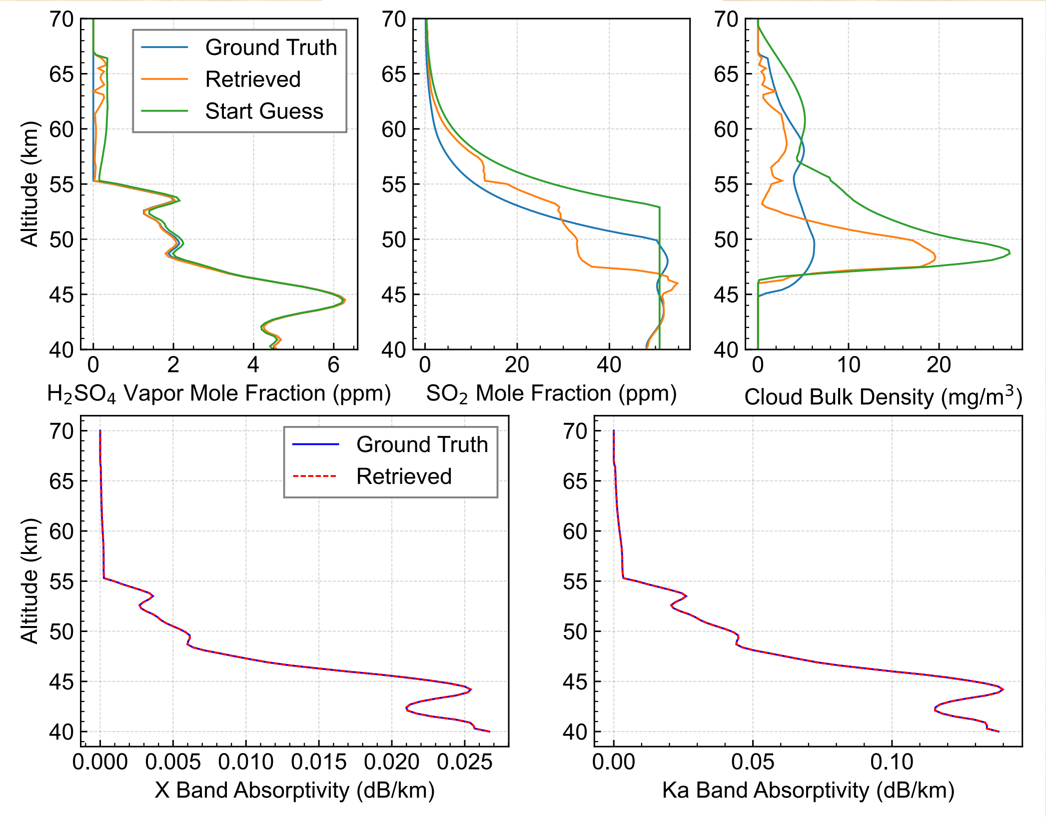
Least-squares retrieval with starting guesses

- Accuracy is still lacking without regularization or a priori statistics
- SO_2 can be retrieved with high accuracy below the cloud base
  - Cloud base is near Ka Band absorption limit (~45 km) in some cases

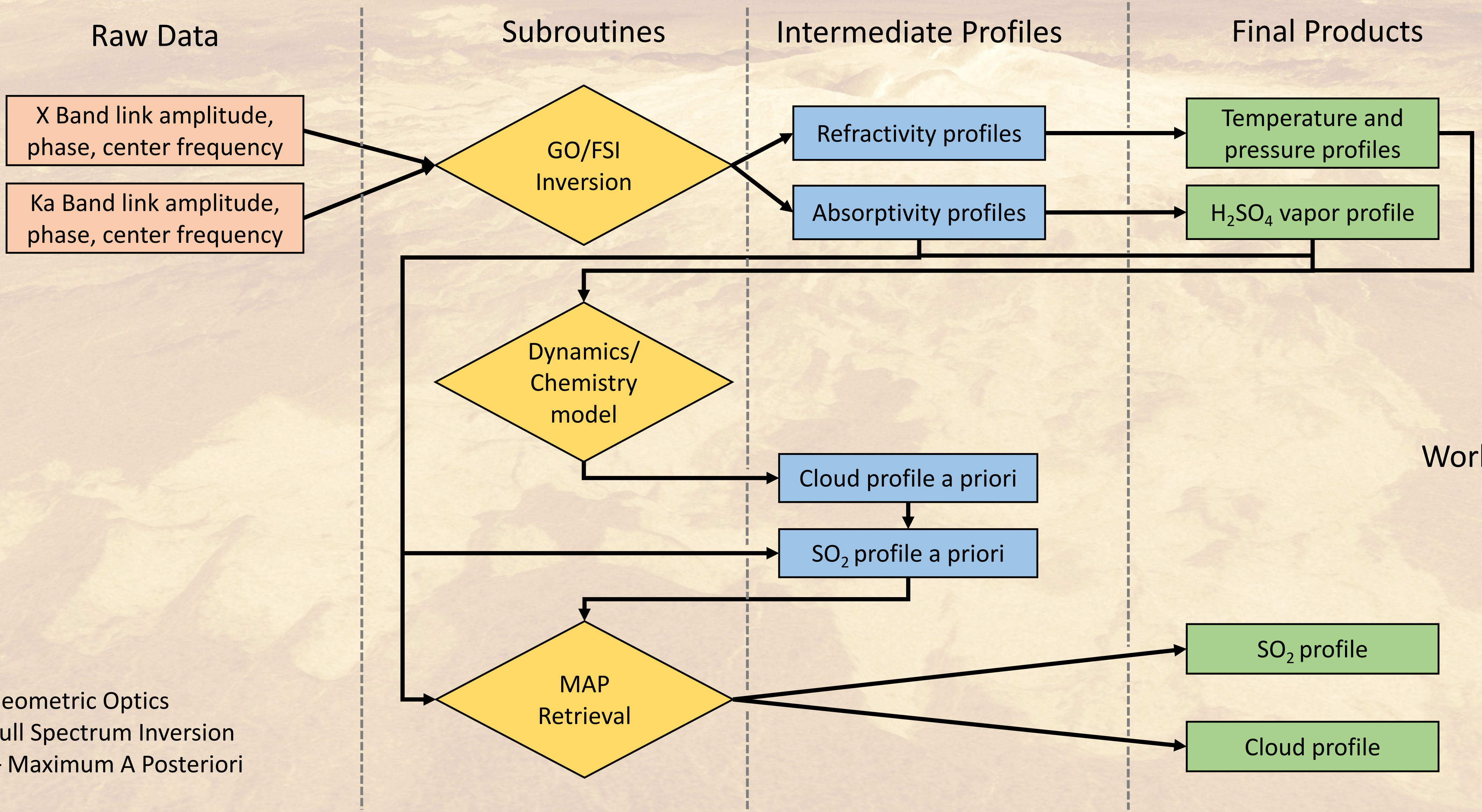
Low latitude case



High latitude case



Coupled algorithm to improve prior estimates

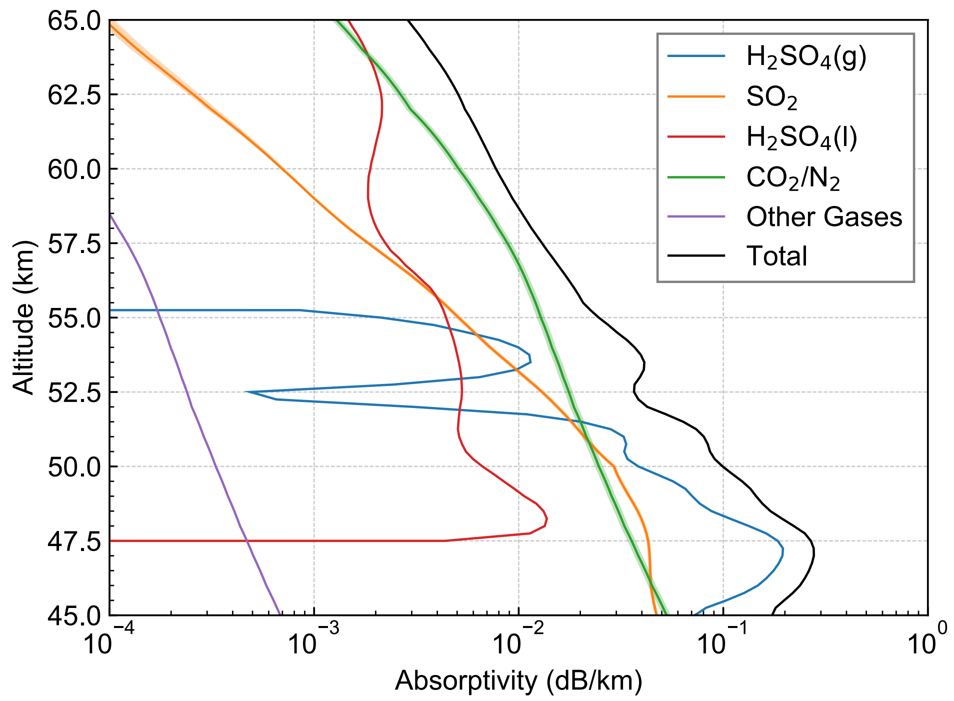


Work in progress!

GO - Geometric Optics
FSI - Full Spectrum Inversion
MAP – Maximum A Posteriori

Uncertainties in measured absorptivity

- Uncertainties in retrievals from absorptivity generally consider:
  - Antenna mispointing
  - Refractive defocusing
  - Propagated uncertainties in refractivity derivation
- We have derived uncertainties in models of Venus atmospheric opacity for consideration in future error assessments



Ka Band opacity of Venus atmospheric constituents bracketed by uncertainties in model parameterizations. Largest sources of uncertainties are the Ka Band H_2SO_4 vapor opacity model and lack of knowledge of cloud H_2SO_4 weight percent

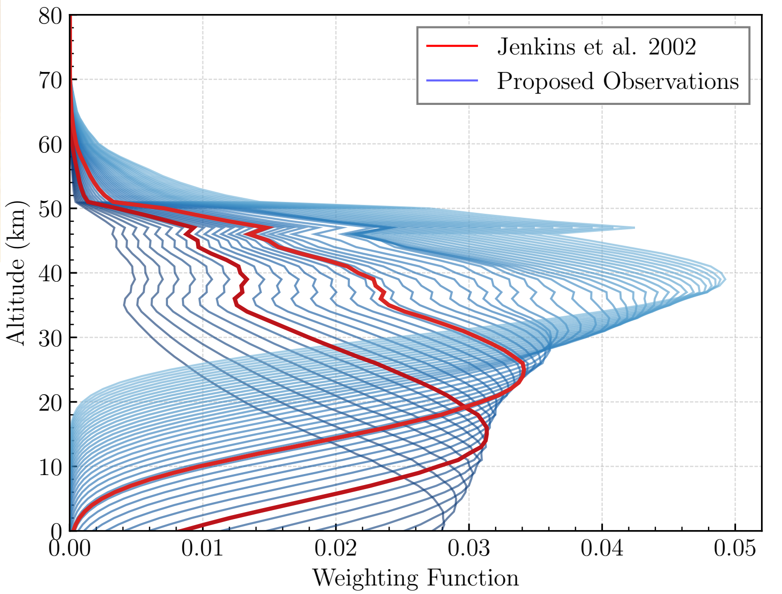
Passive Microwave Observations

Complementary to mission capabilities

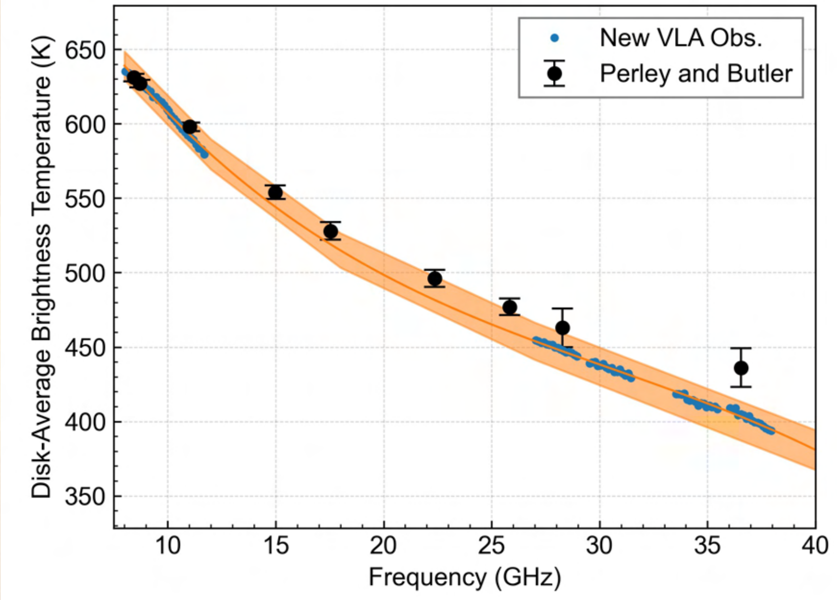
- DAVINCI will measure atmospheric structure and composition as it descends through the atmosphere
  - Pro: **Excellent vertical resolution**
  - Con: **Sampling at a single location/point in time**
- Ground-based multispectral passive microwave observations of Venus can be used to retrieve atmospheric temperature structure and abundance of H_2SO_4 vapor/SO_2
  - Pro: **Measures a range of latitudes and longitudes simultaneously**
  - Con: **Coarse vertical resolution** (e.g. 20 km, Jenkins et al. 2002)

Recent VLA observations

- Venus observed from Aug. – Sep. 2021at 8-40 GHz
- First observations of Venus with the EVLA
  - Bandwidth upgrade: 100 MHz → 8 GHz
  - High spectral resolution: λ/Δλ ~ 4500 at 9 GHz



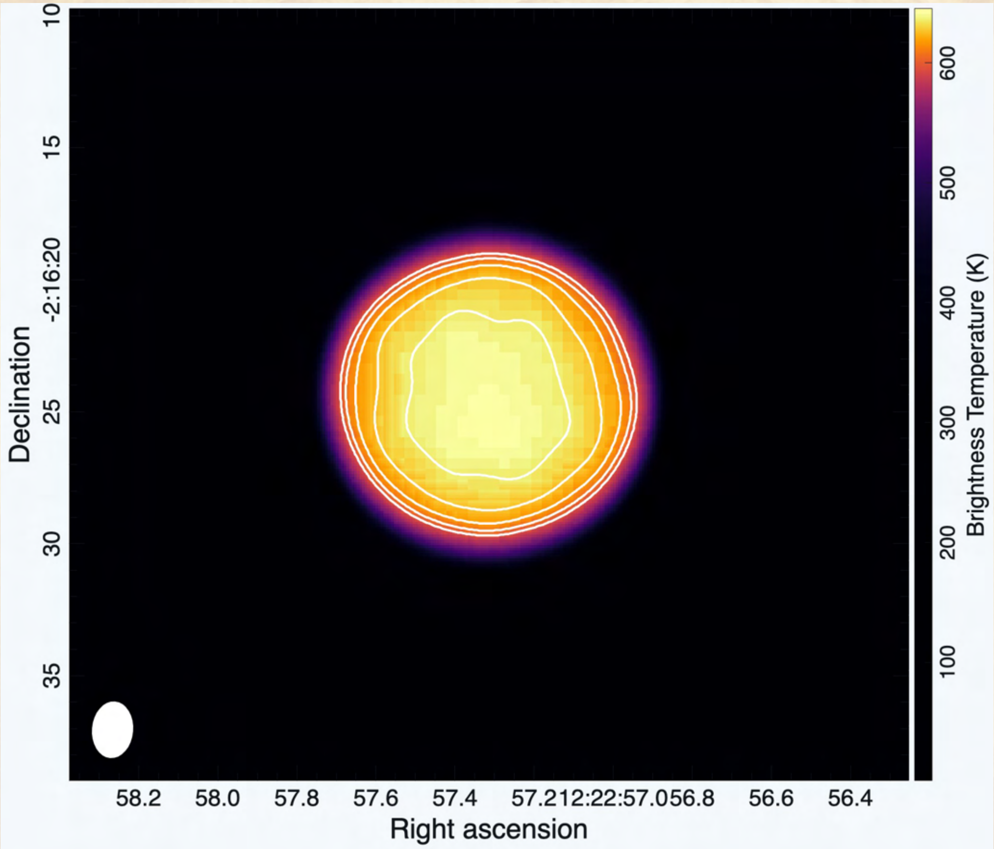
Atmospheric weighting functions in 1 GHz intervals for recent observations as compared to those of Jenkins et al. 2002



X and Ka Band disk-averaged spectra for recent observations. Error bracket results from amplitude calibration uncertainties

Preliminary results at X Band

- Contrast-enhanced, 10 K contours, shown with resolution beam
- First attempts at data reduction/imaging yield ~1K sensitivity, <0.5 K should be achievable with more thorough error assessment

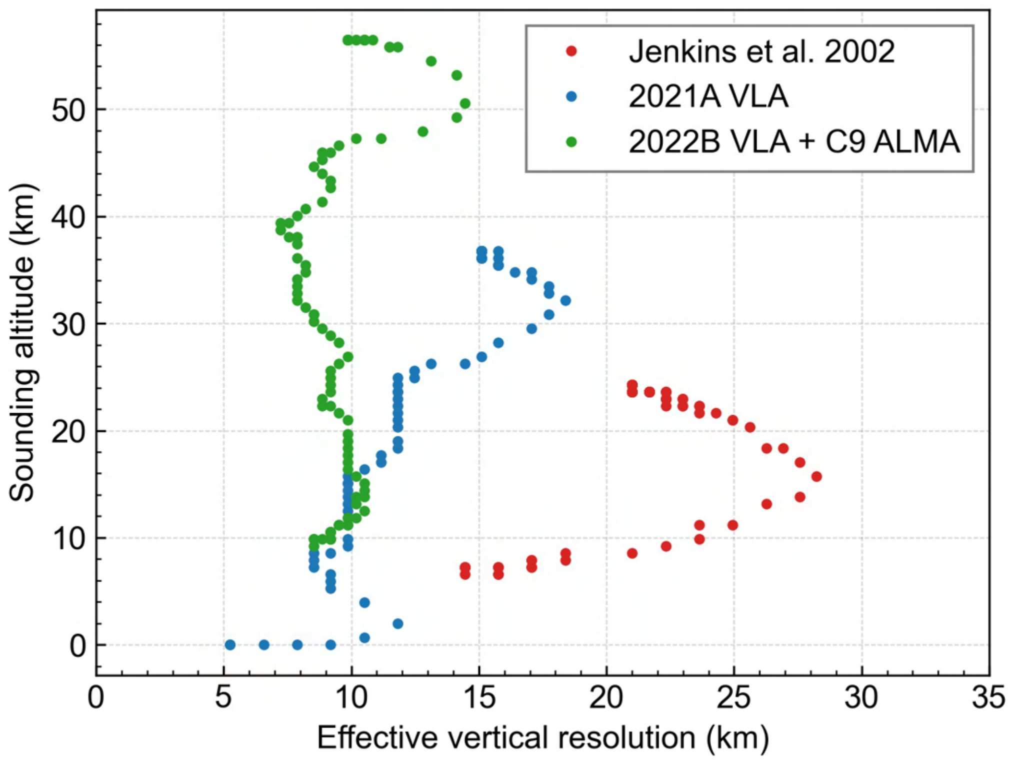


Improvements in vertical resolution

- Vertical resolution of retrieved thermal structure can be estimated from the half-width of the averaging kernel corresponding to observation weighting functions

$$\mathcal{A} = (\mathbf{K}^T S_e{}^{-1}\mathbf{K} + S_a{}^{-1})\mathbf{K}^T S_e{}^{-1}\mathbf{K}$$

- High spectral resolution permits 2x improvement in vertical resolution of retrieved temperature profile
- Future VLA + ALMA observations could achieve ≤10 km vertical resolution over the troposphere
- Sufficient to resolve sub-cloud variations in lapse rate



Averaging kernel half-width as a function of altitude for VLA observations of Jenkins et al. 2002, recent VLA observations, and hypothetical VLA + ALMA observations

Conclusions

- Dual X/Ka Band RO can be used to study SO_2 depletion in the clouds of Venus
  - Coupling retrievals with dynamics models is necessary to reduce uncertainty
- Model-dependent uncertainties RO retrievals have been derived for Venus' atmosphere
- New VLA observations of Venus have been obtained
  - Vertical resolution of retrieved atmosphere structure is ~10 km