Simulations of the Atmospheric Microwave and Millimeter Wave Emission from Venus using a Radiative Transfer Model based on Laboratory Measurements.

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Introduction: The Georgia Tech Venus Radiative Transfer Model (VRTM) can be used to model the effects of the abundances of microwave and millimeter wave absorbing constituents on the emission from the Venus troposphere and mesosphere. The primary components of the Venus atmosphere are CO₂ and N₂, but variation in concentration of gaseous H₂SO₄ and SO₂, result in continuum brightness temperature variations from the troposphere at microwave and millimeter wavelengths.

Sulfur compound opacity formalisms have been empirically verified through laboratory experiments that use cavity and open resonators to differentially measure the complex permittivity of gas mixtures at temperatures and pressures representative of Venus conditions [1]. Such experiments can be used to validate pressure-broadened lineshape models. In cases where such line-based models do not match measured data, continuum best fit models are developed. These opacity formalisms are combined with temperature/pressure profiles from previous Venus missions to form the radiative transfer model.

Estimates of microwave and millimeter wave emission derived from this model have many applications in Venus radio astronomy, such as the interpretation of observations from the Combined Array for Research in Millimeter-wave Astronomy (CARMA) [2] and the Atacama Large Millimeter Array (ALMA) [3]. This radiative transfer model will be of specific use to remote study of atmospheric abundances of sulfur dioxide and sulfuric acid in accordance with VEXAG Goals I.C and III.B [4].

Model Components: The VRTM consists of a set of inputs built around a ray tracing algorithm. Atmospheric emission at radio frequencies is modeled by calculating the path of an energized ray through discrete atmospheric layers. This ray path is modeled as energy traveling towards the planet as opposed to being emitted, as the integrated forward and return paths are isomorphic. In each layer, the ray signal is attenuated and refracted according the homogeneous atmospheric composition of the layer in local thermodynamic equilibrium. The ray path of the signal may reach the surface with minimal refraction if the receiving source is closer to nadir pointing, but the signal can follow a much longer path in the case of limb sounding and even trace a path around the planet. Ray tracing can be used to model passive emission from the surface, radio occultation experiments, or communications between a lander and an orbiter.

In addition to calculating emission along a single pencil-beam associated with the ray tracing model, the VRTM can also calculate the cumulative disk-averaged emission from the Venus disk. Additionally, specific antenna gain patterns can be introduced which allow computation of the emission measured by a specific beamshape.

The inputs to the ray tracing model include empirical data about the composition and structure of the Venus atmosphere derived from prior missions and observations, as well as estimations of the emissivity for a surface with a bulk dielectric permittivity between 4 and 4.5 [5]. The effects of the opacity for each atmospheric layer form an integrated weighting function. At frequencies close to 5 GHz, absorption occurs primarily near the surface, but as the frequency increases, absorption from higher points in the atmosphere dominate the weighting function, as shown in Figure 1. Evaluations of the VRTM with previously recorded Venus disk-averaged emissions show agreement from 1-86 GHz [6].

![Figure 1: Frequency-Dependent Atmospheric Weighting Functions](image)

Sources of Model Uncertainty: The VRTM uses temperature-pressure profiles derived from the Pioneer-Venus Sounder and North probes measured at the equator and at a latitude of 60° [7]. Recent temperature-pressure profiles for the mesosphere have been obtained through Venus Express observations [8]. Radio occultations from the VeRa instrument suggest a diurnal variation of 30-40K between 65 and 55 km
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near the equator [9]. Additionally, nightside variations in temperature at higher altitudes have been measured through submillimeter variations in CO [10]. The effects of temperature discrepancies in the model could result in variations in the derived atmospheric weighting function, particularly at submillimeter wavelengths.

The CO₂ and N₂ abundance in the the atmosphere is assumed to be constant at 96.5% and 3.5%, treating sulfur-bearing components as trace gases. Due to the low mixing ratio of sulfur molecules, the modeled refractivity is attributed to the primary gases [1]. Equatorial H₂SO₄ abundance profiles are included from Mariner 10 radio occultations at the equator and Magellan radio occultations at 67° North and 88° South [11]. Variations in the abundance from these probes highlight the problem of H₂SO₄ spatial variation in any modeling attempts.

SO₂ abundance is modeled as a continuous distribution from the surface to 48 km. Above this altitude, the gas abundance model decays with a scale height of 3.3 km due to photolysis [6]. At the equator, the uniform mixing ratio is chosen to be between 75 ppm and 150 ppm. However, latitudinal and temporal variations in the abundance of SO₂ can be inferred from the variability of measurements made at the cloud tops [12]. Recent results from the Venus Express SOIR instrument suggest an abundance of 3 ppm of SO₂ at 70 km for lower latitudes, continuing a trend of wide measurement variability [13, 14].

These abundance profiles are combined with the opacity characteristics of CO₂, N₂, and pressure-broadened absorption of SO₂ and H₂SO₄ to estimate optical depth. Millimeter wave CO₂ and N₂ absorption is collision induced and dependent on the square of the frequency [15]. The opacity of SO₂ follows the Van Vleck-Weisskopf formalism using the JPL spectral line catalog [16]. The opacity of gaseous H₂SO₄ is given as a series of best fit expressions based on laboratory measurements at centimeter wavelengths [1]. Since these measurements occurred at lower frequencies, there is a degree of uncertainty in attempting to extrapolate these best fit curves to radio observations in the millimeter and submillimeter regions. A comparison between the best fit extrapolated opacity for H₂SO₄ and that of a Van Vleck-Weisskopf or Gross lineshape is a factor of 10 as shown in Figure 2. This uncertainty has motivated a new series of laboratory measurements of gaseous H₂SO₄ opacity in the 2-4 mm and 7-9 mm bands.

Model Discussion: Direct examples of the discrepancies between the sulfuric acid opacity models and the resulting effects of the uncertainty on the atmospheric weighting function will be discussed. Initial measurements of the millimeter wave absorption will be presented to motivate discussion. Discussion will also cover latitudinal variations in the abundance profiles for SO₂ and H₂SO₄ and subsequent effects on the weighting functions. In addition to gaseous SO₂ and H₂SO₄, other atmospheric components such as H₂S, OCS, CO, H₂O, HD, H₂SO₄ condensates are present in the upper troposphere and mesosphere. The absorption effects of these trace elements at millimeter wave-lengths will be reassessed. Discrepancies between the temperature pressure profiles obtained with the SOIR/VEra instruments and the Pioneer Venus probes in the upper troposphere region will be assessed. Suggestions will also be made for necessary model improvements.

Figure 2: Variations in H₂SO₄ opacity