ATMOSPHERIC WINDOWS TO IMAGE THE SURFACE FROM BENEATH THE CLOUD DECK ON THE NIGHT SIDE OF VENUS.

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Introduction: The study of the Venusian surface is an arduous task. Surface probes are short-lived due to the harsh surface conditions (~735 K and 92 bars) [e.g., 1, 2] and sulfuric acid [3], requiring other means for long-term or comprehensive study of the surface. Generally, that involves the use of orbiting satellites or ground-based telescopes. With Venus, we have the option of using balloons which can float beneath the cloud deck where conditions are similar to Earth surface conditions [4]. It is well understood which parts of the surface emissivity spectrum can be viewed from space on the Venus night side through atmospheric windows. Here, we evaluate whether more of the spectrum can be observed by placing the sensor below the cloud deck and what effect this has on the scattering footprint. Moroz [4] examined possible windows at 0.65, 0.85, and 1.02 microns through which emission from the surface on the night side of Venus could reach a sensor. This work expanded on [4] by modeling the surface emission of bands from 0.7 to 250 microns using a total extinction coefficient data set from [5]. Hashimoto & Imamura [6] estimated the image blurring by the atmosphere to result in a footprint 50-100 km in diameter for an orbiting sensor. This is primarily the result of Mie scattering within the cloud deck [6]. The emission from the surface, its scattering and absorption, and the emission from the atmosphere were calculated from the surface to various heights beneath the cloud deck. We explored the effects of different sensor heights and surface emissivities, variation in surface elevation, and variations in the temperature profile on the possible atmospheric windows. We also explored combinations of these factors that represent the likely conditions for large portions of the surface of Venus (e.g., Ishtar Terra is 3-4 km above mean planetary radius with an emissivity that may be felsic or mafic). Then we estimated the altitude dependent scattering footprint at the various sensor heights using a method from Ashikmin et al. [7] that estimates spatial blurring by examining the most probable paths.

Methods: We defined a surface viewing atmospheric window as any wavelength at which 50% or more of the detected signal comes from the surface. We calculated the observed signal using the radiative transfer equation. We assumed thermodynamic equilibrium, which allowed use of the total extinction coefficients from [5] also as the emission coefficients of the atmosphere. Under Venus conditions, we generally expect mafic rocks (e.g., basalt) to have emissivities greater than 0.9, and more felsic rocks (e.g., granite) to be less than 0.9 [8, 9, 10]. We modeled emission at emissivities of 1.0, 0.95, 0.86, and 0.70. Sensor height was varied in 10 km intervals from 10 to 100 km, though we consider only the altitudes beneath the cloud deck due to approximations used to construct the total extinction coefficients we used. Surface elevations were 0 and 11 km, with surface temperatures of 735 and 650 K, respectively. The temperature profile of [1] was used with 20 K added, and then with 20 K subtracted from both the surface and temperature at all altitudes to simulate changes in the temperature profile that may occur at different latitudes [11].

We calculated the altitude-dependent scattering footprint using a path integral approach as shown in the equation below (1) [7]. This assumes that the

$$w^2 = \frac{1}{2}\left(\frac{2a}{3S} + \frac{16a}{bS^3}\right)^{-1} \quad (1)$$

spatial scattering, w, due to material in the scattering medium can be approximated by the most probable path. Spatial blurring is dependent on the absorption coefficients (α), scattering coefficients (b), path length (S), and the mean square scattering angle (α). We assumed that the Venusian atmosphere beneath the cloud deck causes only Rayleigh scattering of emitted light. The absorption and scattering coefficients come from Lebonnois et al. [5].

Discussion: The prospective windows are largely expanded versions of previously identified windows that have been exploited by satellites and ground-based observatories. Figure 1 illustrates the results for our nominal case, in which emissivity was unity, sensor altitude was 40 km, surface elevation was 0 km, surface temperature was 735 K, and the temperature profile was that from [1]. Under these conditions, surface viewing atmospheric windows occur at 0.758-0.867, 0.876-0.926, 0.940-0.942, 0.952, 0.958-1.033, 1.082-1.109, 1.136-1.142, and 1.171 microns. Sensor altitude and regional temperature variations had little effect on identified windows. If the assumed emissivity is reduced from 1.0 to 0.7, then the total bandwidth for which radiance from the surface exceeds the atmospheric radiance drops by 32.3%. Simulating a surface at 11 km elevation results in a 96.3% increase in total bandwidth and a new window centered at 1.27 microns as compared to the nominal conditions (Figure 2). Preliminary estimations of the scattering footprint are on the order of several hundred meters in diameter. This is approximately two orders of magnitude improvement in the scattering footprint compared to the 50-100 km footprint obtained from orbital observations. This improved spatial resolution would require improved topographic data to accurately and precisely extract the full surface information contained in the data, as temperature changes and therefore changes to the emitted signal become potentially significant compared to variations in emitted signal based on composition [10, 12]. On Venus, the surface temperature is tightly coupled to surface elevation and the estimated scattering footprint is approximately an order of magnitude smaller than the Magellan altimetry footprint (~10x20 km), which is currently our best (near) global topographic dataset, though there are some isolated topographic datasets of higher resolution derived from stereo-derived methods [e.g., 13].

Investigations by Helbert et al. [10] and Dyar et al. [12] indicate that as few as two of these windows enable basic rock segmentation (i.e., felsic vs. mafic composition), which can provide important information about the geodynamic history of the surface and interior. Provided a clear determination of hematite or magnetite, the redox state of the surface can be inferred from one of these bands based on the strength of the emitted surface signal [12]. This would provide constraints on the past surface water inventory of Venus. Any lander or balloon mission should make use of 1.0, 1.1, 1.18, and 1.27 micron windows as these provide a comprehensive ability to extract information about the surface from the night side. These windows have the potential to elucidate questions about the surface of Venus and its evolution through time.

References: [1] Seiff et al. (1985) *Adv. Space Res*. Vol 5. 3-58. [2] Crisp & Titov. (1997) *Venus II*. 353-384. [3] Bezard & de Bergh. (2007) *JGR*. Vol 112. 1-10. [4] Moroz. (2002) *Planet. Space Sci*. Vol 50. 287-297. [5] Lebonnois et al. (2015) *JGRP*. Vol 120. 1186-1200. [6] Hashimoto & Imamura. (2001) *Icarus*. Vol 154. 239-243. [7] Ashikhmin et al. (2004). Technical report CUCS-017-04. [8] Jensen. (2007) *Remote Sensing of the Environment*. [9] Lillesand et al. (2015) *Remote Sensing and Image Interpretation*. [10] Helbert et al. (2018) *LPSC XLIX* Abstract #1219. [11] Haus & Arnold. (2010) *Planet. Space Sci*. Vol 58. 1578-1598. [12] Dyar et al. (2017) *VEXAG XV* Abstract #8004. [13] Herrick et al. (2012) *Eos*. Vol 93. 125-126.

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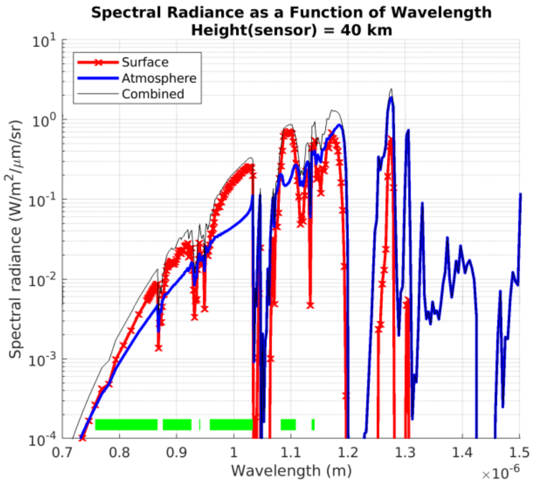

Figure 1. Surface vs Atmospheric emission for our nominal conditions. There is approximately 0.27 microns of total bandwidth. “Windows” where surface emission exceeds 50% of the total observed signal correspond to the green band across the bottom of the graph.

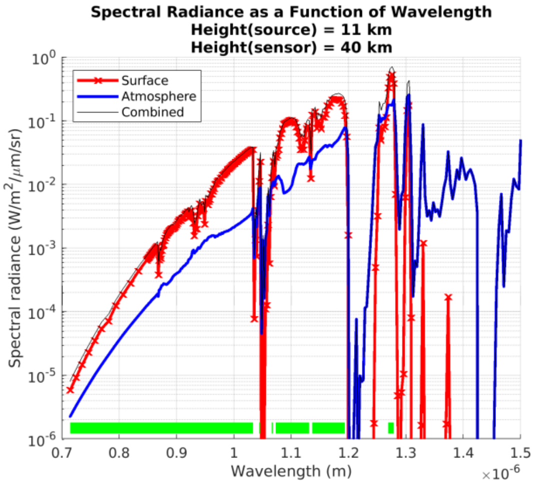

Figure 2. Surface vs Atmospheric emission for elevated surface elevation. Nearly all of the infrared from 0.7 to 1.2 microns becomes an atmospheric window and a new window appears at 1.27 microns, though the 1.10-1.18 micron windows are suspect due to an underprediction of CO2 opacity at these wavelengths [11]. This new window is normally blocked by O_2 airglow at ~95 km [11].