National Aeronautics and Space Administration

High-resolution near-IR imaging of Venus' surface from below its clouds: A proof-of-concept

Principal Investigator: Anthony B. Davis (329);
Co-Investigators: Kevin H. Baines (322), Brian M. Sutin (382), James A. Cutts (404), and Leonard I. Dorsky (383)

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Objectives

In FY20, this team investigated the feasibility of nighttime imaging of the Venus' surface at high spatial resolution (~10 m pixels) in selected near-IR (NIR) wavelengths from a platform just beneath the opaque cloud layers. Posters describing our progress were presented by PI Davis and Co-I Baines respectively at the October 2020 DPS [A] and March 2021 LPSC [B] conferences. These posters were well-received, but some attendees raised questions about the validity of our analysis and whether we had included all sources of contrast loss. This motivated us to formulate a response in order to bring the study to publication-level maturity.

An expansion of our numerical model for the atmospheric point-spread function (APSF) was in order to demonstrate irrefutably the feasibility of realistic sub-cloud imaging of the Venus surface using a relatively simple sensor on a sufficiently stabilized platform. Specifically, we needed to better account for the possible occurrence of sub-cloud haze, and to compute the atmospheric modulation transfer function (AMTF) from the APSF. We are now poised to finalize and submit a paper to a journal widely read by the planetary exploration and science community [C]. After [D], two more conference presentations are planned to promote this study [E,F].

Background

Nighttime images of Venus' surface through NIR spectral windows have been captured from an orbital platform [e.g., 1,2] but, due to the multiple scattering by the optically thick clouds, their effective spatial resolution is ~100 km. Venus scientists therefore have great interest in imaging the planet's surface from a platform just beneath the opaque cloud layers. The Venus panel of the Planetary Science and Astrobiology Decadal Survey (PSADS) 2023-2032 invited JPL to brief them on our concepts for accomplishing this. JPL is currently considering concepts such as a stabilized tow-body tethered to a balloon, and this was incorporated in a PSADS-sponsored study. Possible collection of high-resolution surface imagery is tantalizing from the standpoint of detailed mineralogy [3] and proof of recent volcanic activity [4].

Figure 1 is a schematic for a push-broom camera achieving ~10 m pixel scales from 47 km altitude. Top panel shows five NIR windows between CO_2 absorption bands, where different contributions to the predicted radiance are color-coded. Direct light is what enables the sharp imaging, and there is not enough of it left at sub-micron wavelengths in comparison with scattered light. Lower panel shows how the focal plane array can be partitioned for both multispectral and stereo imaging.

Significance/Benefits to JPL and NASA

Our goal of elevating our project to publication-level maturity has been achieved, and a paper [C] is now being drafted. Most significantly, our methodology is an improvement in fidelity and accuracy over the two previous studies on the feasibility of surface imaging from below Venus cloud layers by Ekonomov [6] and Moroz [7] in 2015 and 2002, respectively. Notwithstanding, our conclusions are essentially the same as from those authors, even after addressing possible complications from sub-cloud haze that was either ignored [6,7] or assumed over an order-of-magnitude more opaque than observed by Pioneer [5,7]. Moreover, we started from a well-defined multi-spectral camera concept adapted to the task at hand.

The most important finding is that sub-cloud haze, at the levels detected by the Pioneer Venus—and up to 10 times more—does not represent a significant source of degradation in sub-cloud nighttime imaging. This reinforces the credibility of concepts for implementing sub-cloud imaging from Venus aerial platforms including the use of tow-bodies and sub-cloud sondes as currently being contemplated for the Decadal Survey Venus ADVENTS mission and JPL's New Frontiers Venus Cloud Explorer concept.

References

[1] Markiewicz, W.J., et al. Venus monitoring camera for Venus Express. *Planetary and Space Science* **55**, 1701-1711 (2007).
[2] Basilevsky, A.T., et al. Geologic interpretation of the near-infrared images of the surface taken by the Venus Monitoring Camera, Venus Express. *Icarus* **217**, 434-450 (2012).
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National Aeronautics and Space Administration
www.nasa.gov
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PI/Task Mgr Contact:
Email: Anthony.B.Davis@jpl.nasa.gov

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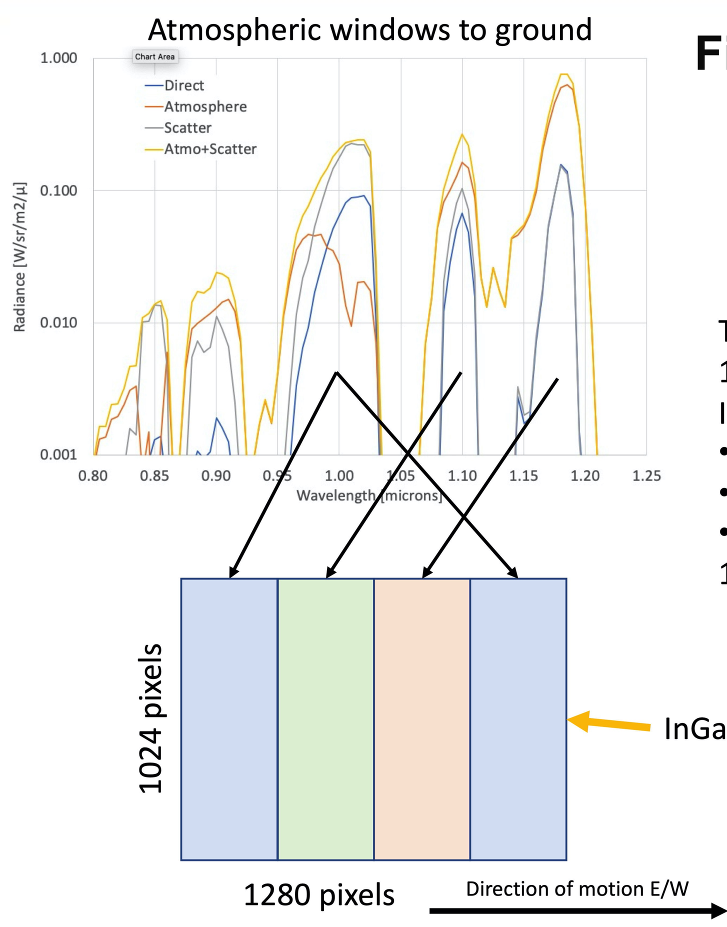


Figure 1

Notional InGaAs Camera
Takes an image every 50 seconds
10 m ground sample distance
Imaging in three bands:
- 1.01 microns @ SNR 140:1
- 1.09 microns @ SNR 70:1
- 1.18 microns @ SNR 100:1

11.5 degree stereo @ 1.01 microns

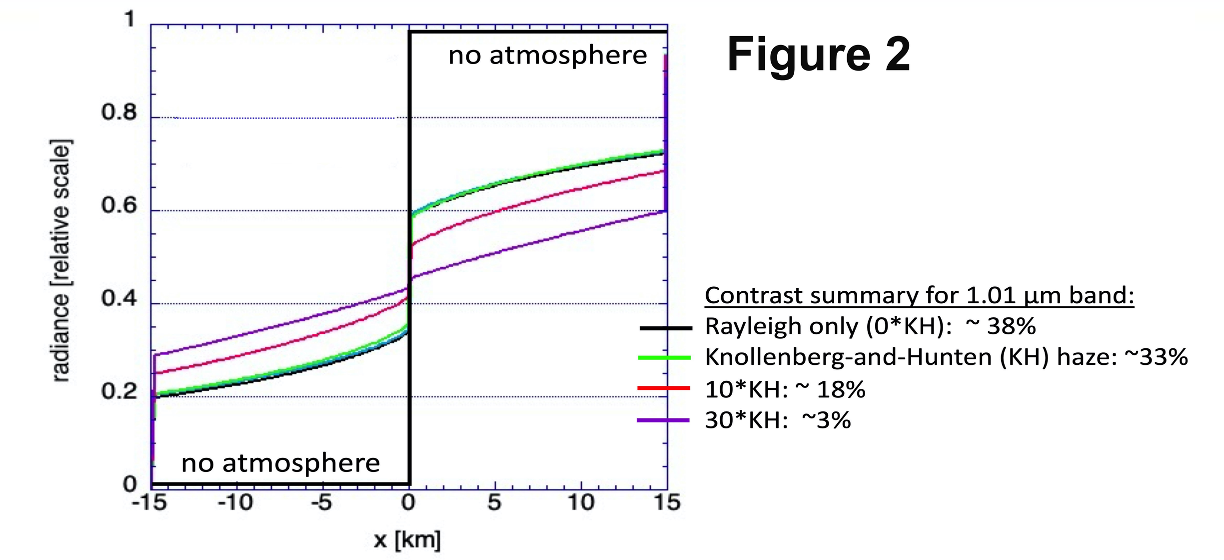
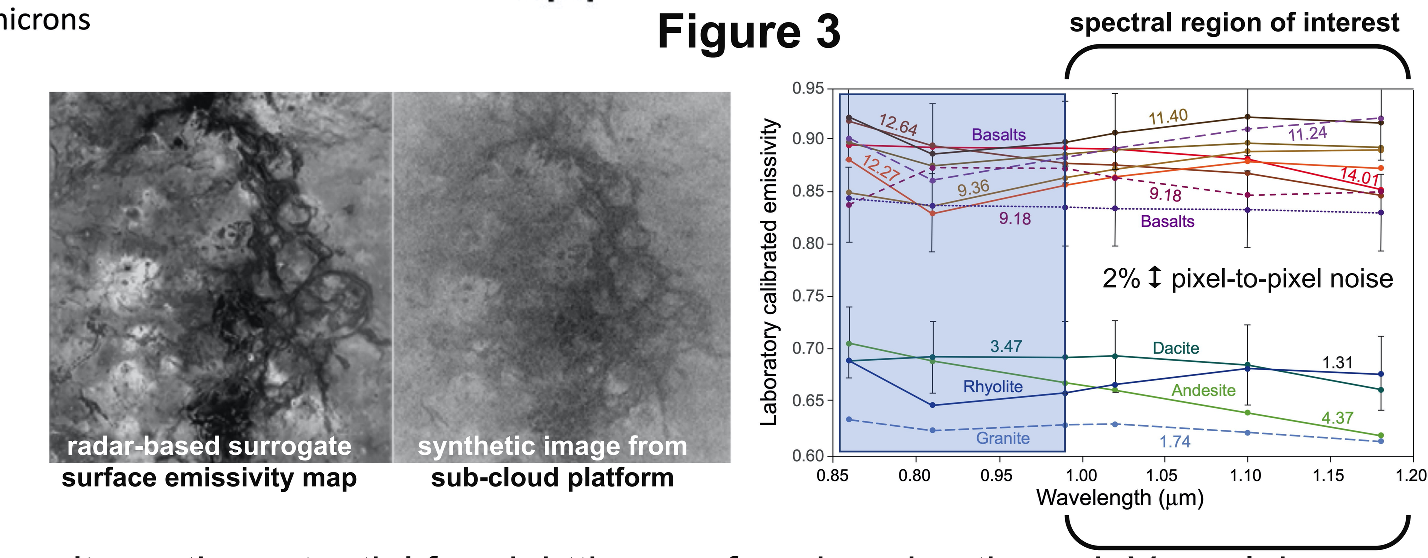


Figure 2

Figure 3



Approach and Results

This team had obtained preliminary but compelling positive results on the potential for nighttime surface imaging through Venus' dense CO_2 below-cloud atmosphere from an altitude of 47 km in the NIR (3 spectral windows, ~1.0 to 1.2 μm). Theoretically achievable resolution is indeed the pixel-scale of the camera (~10 m ground-sampling distance in Fig. 1), given sufficient platform stability, which had been established in an independent study [P. McGaray, private comm.]. Our previous and present work are based on computational 3D radiative transfer (RT) using Monte Carlo techniques to estimate APSFs that quantify the impact of volume scattering or emission and boundary reflections on image sharpness.

The APSF is key to our approach. It is a familiar concept in Earth observation, with applications ranging from horizontal visibility studies to sophisticated techniques for atmospheric compensation of satellite imagery, i.e., removal of confounding effects by a (multiplicative) factor for attenuation, an (additive) "airlight" term, and any cross-pixel smearing. However, it is not yet a well-known tool in planetary observation. By definition, the APSF is the image of a unitary source at a single point in the scene. Because RT is linear in its source terms, the image of an arbitrary scene is a convolution product of the APSF and the actual distribution of light sources.

Figure 2 is a simple but informative example of synthetic imagery at 1.01 μm where we look straight down at the interface between two half-planes with different brightness in case of no atmosphere, in the presence of Rayleigh scattering only, and various Rayleigh-plus-haze mixtures. Rayleigh scattering alone reduces the contrast ratio between direct light (the jump at x = 0 km) and the ambient diffuse light. Additional haze reduces this ratio, partly by reducing the direct transmission, partly by boosting the diffuse transmission. The nominal haze level results in only a very small change in contrast. It is defined as what was observed in the Pioneer Venus probe data by Knollenberg and Hunten [5]. We determined numerically that 30-fold increase of the haze above that level is a threshold where the contrast was degraded to the point that it was commensurate the sensor noise level.

Figure 3 summarizes our findings. The left panel (from [6]) is a simulation of the effect of the atmosphere on an image according to our "AC/DC" model: a uniform background radiance is added (DC component), and all Fourier modes are uniformly reduced in amplitude (AC component). The right panel (form [8]) is visual proof that a 3-band camera can discriminate between various minerals expected to be on the surface of Venus.

Publications and Presentations

[A] A.B. Davis, K.H. Baines, J.A. Cutts, L.I. Dorsky, L.H. Matthies, and B.M. Sutin. "Near-IR Imaging of Venus' Surface Features from Below its Clouds: A Radiative Transfer Study," at 52nd *Annual Meeting of the AAS Division for Planetary Sciences (DPS 2020)*, Virtually Anywhere, October 26-30, 2020.
[B] K.H. Baines, J.A. Cutts, P. McGarey, B.M. Sutin, and A.B. Davis, "High Spatial Resolution Imaging of the Surface of Venus via a Balloon-Borne Tow-Body Camera System," at 52nd *Lunar and Planetary Science Conference (LPSC)*, Virtually, March 15-19, 2021.
[C] A.B. Davis, K.H. Baines, B.M. Sutin, L.I. Dorsky, and J.A. Cutts, "Feasibility of Nighttime Near-IR Imaging of Venus' Surface Features from a Sub-Cloud Platform: A Radiative Transfer Investigation," *Planetary & Space Science* or *Icarus* (in preparation).
[D] K.H. Baines, J.A. Cutts, A.B. Davis, B.M. Sutin, and P. McGarey, "High Spatial Resolution Imaging of the Surface of Venus via a Sub-Cloud Balloon-Borne Camera System," at *International Planetary Probe Workshop 2021*, Virtually, August 3, 2021.
[E] K.H. Baines, A.B. Davis, B.M. Sutin, J.A. Cutts, and L.I. Dorsky, "The Effect of Underlying Hazes on Sub-Cloud Nighttime Near-IR Imaging of Venus' Surface Features," at 53rd Annual Meeting of the AAS Division for Planetary Sciences (DPS 2021), Virtually, 3-8 October 2021. (accepted)
[F] A.B. Davis, K.H. Baines, B.M. Sutin, J.A. Cutts, and L.I. Dorsky, "Feasibility of Nighttime Near-IR Imaging of Venus' Surface Features from a Sub-Cloud Platform: A Radiative Transfer Investigation," at HYBRID AGU Fall Meeting 2021, New Orleans (La), December 13-17, 2021. (submitted)