HIGH-SPATIAL-RESOLUTION NIGHTTIME NEAR-IR IMAGING OF THE SURFACE OF VENUS VIA A BALLOON-BORNE TOW-BODY CAMERA SYSTEM.

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Introduction: Since the first space-based near-infrared images and spectra of Venus' nighttime surface were obtained by the Near Infrared Mapping Spectrometer (NIMS) during the Galileo flyby in 1991 [1,2], thousands of near-infrared images and spectra have been obtained by other flyby and orbiting spacecraft, including Cassini [3], Venus Express [4–9] and Akatsuki [10]. In these observations, thermal radiation in the 0.85-1.18 μm wavelength range upwelling from the hot (~740 K) surface is scattered by the optically-thick yet conservatively scattering cloud deck, resulting in dramatic degradation of the spatial resolution of the imagery to about 100 km.

However, apart from atmospheric seeing, the spatial resolution of such thermal surface imagery obtained below the cloud deck near the 47-km (~ 100C) level, should be able to achieve any value desired, dependent only on the design of the instrument and its platform (e.g., aperture and pixel size, and camera platform stability [11,12]). For example, if seeing is on the order of 45 arcseconds (the apparent maximum size of Jupiter in Earth's skies), then the surface spatial resolution can be as good as 10 meters from an altitude of 47 km. Assuming the camera optics are designed to achieve this resolution, then the actual spatial resolution obtainable largely depends on camera stability (e.g., jitter; spatial and angular drift of camera pointing during the exposure).

Such high-resolution NIR imaging in several spectral bands provides a means to characterize rock composition in geological features such as tessera and coronae, and to identify and characterize volcanic phenomena such as hot magma flows and water vapor enhancements[13]. Further, such high-resolution imagery, including stereoscopic views, allows the exploration of the morphology of the surface at scales sufficient to establish the nature of layering within the planet's enigmatic tessera terrain [14] and support efforts to identify/map expected aeolian deposits [15].

We performed Monte-Carlo-based radiative transfer modeling [12] to show that sharp (~10m resolution) images of the surface can be achieved at night in spectral windows free of CO_2 absorption between 1.0 and 1.2 μm via a camera at 47 km altitude, just below the planet's optically thick clouds. This capability is in spite of the Rayleigh scattering by the dense but still semi- transparent lower atmosphere, and the potential for considerable underlying hazes beneath the clouds, up to about 30 times the sub-cloud haze content determined in-situ by the Pioneer Venus particle size spectrometer (LCPS) [16]

Quasi-isotropic Rayleigh scattering dominates in the 1.0 μm window. Combined with near-Lambertian reflections off the base of the cloud layer, the diffuse light field builds up a background radiance from surface emission that is averaged spatially out to several 10s of km, i.e., beyond the camera's field-of-view. At longer wavelengths (1.1 and 1.18 μm windows), the sub-cloud atmosphere itself partially absorbs (hence less direct light), and therefore weakly emits (hence more background light), but commensurately there is a rapid decrease in Rayleigh scattering and that then maintains the contrast. In all cases, we find that the directly-transmitted surface emission component encapsulated within the native sensor resolution element (say, ~10 m) is a substantial fraction of the total radiance and thus can be detected above the background light, irrespective of its original source.

Possible High-Resolution Imaging Platforms: Relatively stable observations are theoretically possible from a balloon platform. However, the relatively high temperatures near 47 km altitude are currently beyond spacecraft/aircraft design limits. This constraint thus precludes the use of a constant-altitude (super pressure) balloon, although such design issues may be overcome in the next decade [13]. Variable-altitude balloons can briefly dip to subcloud altitudes from cooler regions [13], but at increased risk to the balloon and with additional overall operations costs.

One potential subcloud surface imaging technique would be to acquire images during descent from a probe or lander outfitted with phase-change-material to provide cooling. Alternatively, it may be viable to release an imaging probe from a balloon platform situated in the relatively benign environmental found at 55 km altitude. However, with present technology, this approach limits sub-cloud imaging to about an hour during descent, providing relatively little areal coverage. Moreover, probes may spin and nod as they descend, degrading the observed resolution and resulting in images obtained at uncertain azimuth and elevation angles that require considerable post-processing (à la the Huygens probe [17]).

The Tow-Body Concept: A more promising solution may be to use a tethered platform that is repeatedly raised and lowered from the balloon. The platform would incorporate phase-change material for repeated cooling. For sub-cloud excursions of ~1–2 hours, the platform would be lowered from the balloon to below the ~47-km cloud-deck altitude. Towed by the balloon, the platform would traverse the surface at the speed of the 55-km-altutude winds and thus scan the changing scenery at a rate of ~60 m/s, or ~220km/hr [18]. Thus, imaging exposure times would be < 0.16 sec to limit the lateral smear to 10 meters. The zonal wind typically differs by ~3 m/s over the 8km altitude difference between the tow-body and the balloon [19]. The tow-body would thus be dragged behind the balloon at this relative airspeed, potentially enabling the platform to use aerodynamic forces and control surfaces, such as a tail appendage, to maintain relatively stable pointing into the relative wind. Reasonable pitch stability could be achieved with a stabilator/elevator and/or a canard, a common design implementation for underwater tow vehicles on Earth.

Current estimates for tow-body mass, incorporating rechargeable battery power, the phase-change material, pressure/temperature sensors, airspeed sensor, accelerometer, the near-infrared imager and a top-mounted CCD camera for balloon and sky/cloud viewing on deployment and retraction is ~2–3 kg. The tether would need to extend ~ 9 km to account for its downwind drift in the prevailing relative wind and would be comprised of high-strength tensile fibers, a Gb-speed optical comm link, and a protective coating for the acidic atmosphere. The estimated tether mass is 3.6 kg. The deployment/retraction system on the balloon gondola – essentially a motorized reel for the "fishing line" tether –- has an estimated mass of ~ 5 kg.

Near-Infrared Imaging Tow-Body Camera: As currently conceived, the camera would image at three near-IR surface-emission wavelengths - 1.01, 1.10, and 1.18 μm. A fourth image (again at 1.01 μm) would provide stereo imagery at an angular separation of ∼12°. This arrangement provides a means to further correlate surface composition with small (<20 m) surface elevation variations and associated geological processes. These wavelengths have reasonably large fluxes that – given the mass and volume limitations of the camera system – can achieve a sensor SNR of better than 130, 65, and 90, respectively for 1.01, 1.10, and 1.18 μm, at a ~10-m/pix scale from 47 km in less than the 0.16 sec image-smear time noted earlier. Two other possible wavelengths - 0.85 and 0.90 μm observed by Cassini/VIMS [3] - have an order of magnitude lower surface thermal emission flux, which precludes their use for achieving 10-m resolution imagery from a fast-moving aerial platform. Yet, this decrease in light signal can be mitigated by degrading the spatial resolution to ∼100 m to achieve the desired SNR of ∼100 or better. These wavelengths could thus be included in a sub-cloud tow-body camera design.

In our nominal concept, four images would be acquired simultaneously on a single 1280 (E/W) × 1024 (N/S) pixel array – cooled to 35ºC by phase-change material – with each wavelength segment covering 3.15 km east-west and 10.24 km north-south. A four-segment image set would be acquired every 50s (i.e., every 3 km of travel), based on a 60 m/s groundspeed. Over a one-hour subcloud excursion, 72 images would be collected that cover each of the three wavelengths and the second 1.01 μm stereo image, spanning contiguously a region ∼216 km east-west and 10.2 km north-south at 10-m spatial sampling. Assuming 16-bit digitization, the per-hour data volume would be 94.4 Mbytes. With 2:1 data compression of the eight most significant bits, the average uplink rate would be about 100 kbps, if transmitted in real time.

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