Diffraction-limited Titan Surface Imaging from Orbit Using Near-infrared Atmospheric Windows

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Abstract

The selection of Dragonfly enables regional Titan surface science, but global Titan geophysics, geology, hydrology, and meteorology require an orbiter. We consider the sources of signal and noise that would contribute to near-infrared surface imaging from such an orbiter both analytically and numerically. The fraction of light arriving at an orbiting camera directly from Titan’s surface, and therefore conveying full-resolution surface information, decreases at shorter wavelengths as additive atmospheric scatter and light blurred on the way out increase with higher haze optical depths. We apply the Monte Carlo radiative transfer model SRTC++ and show that up to 75% of observed flux in Titan’s 5 μm window comes directly from the surface, up to 47% comes directly at 2 μm, and up to just 7% comes directly in the 0.94 μm window. We find that diffraction-limited surface imaging with 10 m pixels is possible with a signal-to-noise ratio for surface features of 100 in the near-infrared at 5 and 2 μm using a 50 cm aperture. A Titan orbiter camera could image in color using 5 μm, 2 μm, and potentially other wavelengths using a pushbroom strategy with time-delay integration.

Unified Astronomy Thesaurus concepts: Saturnian satellites (1427); Radiative transfer simulations (1967); Infrared telescopes (794); Orbiters (1183); Planetary surfaces (2113)

1. Introduction

We will never be able to practically image Titan’s surface from orbit with pixels smaller than 1 m like the High Resolution Imaging Science Experiment (HiRISE) does regularly at Mars (McEwen et al. 2007). If the science requires meter-scale resolution, then we would need to use platforms within the atmosphere like balloons (Elliott et al. 2007), airplanes (Barnes et al. 2012), or quadcopters (Lorenz et al. 2018; Turtle et al. 2018). The imaging impediments are twofold: atmospheric extinction and haze scattering.

Because Titan’s low gravity leads to a large-scale height (~30–50 km; Harri et al. 2006), its atmosphere extends much further from its surface than Mars’ or Earth’s. Cassini’s lowest closest approach distance over 127 Titan flybys was 880 km (Waite et al. 2013), with that altitude carefully selected to intentionally dip into the atmosphere for sampling purposes (Ägren et al. 2012). To avoid atmospheric drag, the Titan Explorer flagship mission study (Leary et al. 2008; Lorenz et al. 2008) selected a circular orbit at 1700 km altitude for its mapping phase. The Oceanus New Frontiers Titan orbiter proposal suggested a similar 1500 km orbit altitude (Sotin et al. 2017a). Since future orbiters at Titan will have to operate at these safe, high altitudes, imaging must take into account long sight distances and a maximal path length through the atmosphere.

A fundamental limit on spatial resolution in an imaging system is the diffraction limit, which sets the best possible resolution of a telescope to be $1.22 \lambda/d$ (Schroeder 1987), where $\lambda$ is the wavelength at which the system observes and $d$ is the diameter of the primary mirror. The answer comes out dimensionless, which in this case corresponds to an angular resolution in radians. A 1.0 m diameter telescope in Titan orbit at 1500 km could then, in principle, achieve as fine as 1.0 m surface resolution (corresponding to $\sim$0.5 m pixel scale) if operating at 0.55 μm. But, even if the atmosphere would permit it, diffraction-limited 1 m imaging from 1500 km distance would necessitate a 6.2 m aperture in Titan’s most transparent window at 5 μm—think the James Webb Space Telescope in Titan’s orbit.

That’s where the second impediment, haze scattering, comes into play. Particulate aerosol haze fills Titan’s atmosphere such that the surface is all but invisible using 0.55 μm visible light (Smith et al. 1981; Richardson et al. 2004). Trying to see Titan’s surface from space with optical wavelengths is like trying to see downtown Los Angeles from the freeways next to NASA’s Jet Propulsion Laboratory in Pasadena on a smoggy day: you cannot.

Using longer wavelengths of light, however, out into the near-infrared, allowed Cassini to see through the haze (Porco et al. 2005; Sotin et al. 2005; Barnes et al. 2009; Turtle et al. 2009), with the opacity clearing progressively toward longer wavelengths (Barnes et al. 2007; Vixie et al. 2012). Huygens found that typical haze particles have radii of the order of...
The ability to achieve diffraction-limited imaging of the surface of Titan depends on a camera’s ability to detect and image across a fine-scale resolution image—therefore, they act as an additive offset to the resulting image, a sort of positive bias across the field. Because they are relatively uniform, additive photons can be straightforwardly subtracted from an image. But shot noise on this additive component contributes directly to the total noise in each pixel of an acquired image of Titan’s surface.

iii. Blurred photons have encountered the surface at least once and subsequently experience a scatter within the atmosphere on their way out toward an orbiting detector. So blurred photons do have some surface signature but that signature no longer contains complete surface resolution information owing to its directional change during scatter off of one or more haze particles. Blurred light dominates Cassini ISS views of Titan (see Figure 2), although the blurred component contains a surprising amount of surface resolution information owing to the highly forward-scattering nature of the haze particles (Doose et al. 2016; Karkoschka et al. 2019).

2.2. Signal-to-noise Ratio

Figure 1. In this diagram, we show the three different bins into which we sort each Titan photon. Direct photons have no scatters between the surface and an external observer and thus retain full-resolution information about surface features. Additive photons come entirely from the atmosphere, with no surface component. Blurred photons come from the surface but suffer from scattering within the atmosphere on their way out.
identify photons that arrive at the instrument without having experienced a scattering event: the direct component. We characterize this ability by calculating the S/N for that direct light within Titan’s atmospheric spectral windows. In this case, the signal in each pixel corresponds to the number of detected direct photons that arrive at the camera unscattered from the surface, \( n_{\text{direct}} \).

The complete noise corresponds to a combination of sources, including detector read noise and dark current, but a well-designed instrument is dominated by photon shot noise from both the direct component and photons that are scattered by the atmosphere, \( n_{\text{additive}} \) and \( n_{\text{blurred}} \). Using just this primary noise source, then

\[
S/N = \frac{n_{\text{direct}}}{\sqrt{n_{\text{direct}} + n_{\text{additive}} + n_{\text{blurred}}}}. \tag{1}
\]

In principle, then, full resolution can be achieved at any wavelength, so long as the image’s S/N is high enough to discern the direct component independently of the additive and blurred components. Cassini ISS coadds many long-exposure frames to more accurately determine surface signal for this reason (Turtle et al. 2011; Karkoschka et al. 2019; see also Figure 2). In practice, the optical depth of haze becomes so high at visible wavelengths (\( \tau \sim 10 \)) that only the blurred component contains surface albedo information for any practical optical system. Richardson et al. (2004), for example, detected only the blurred surface component from Voyager 1 imaging.

To evaluate the relative merit of each spectral window for surface imaging, we will assume a desired input S/N as might be required for a given scientific observation and calculate how many total photons from Titan’s surface would need to be collected to achieve that S/N. We define the fraction of direct light that corresponds to unscattered surface photons as

\[
f_{\text{direct}} = \frac{n_{\text{direct}}}{n_{\text{direct}} + n_{\text{additive}} + n_{\text{blurred}}}. \tag{2}
\]

Therefore, the total number of photons \( n = n_{\text{direct}} + n_{\text{additive}} + n_{\text{blurred}} \) that the detector must accumulate per pixel to achieve S/N is

\[
n = \left( \frac{S/N}{f_{\text{direct}}} \right)^2, \tag{3}
\]

of which the number of photons arriving unscattered from the surface is

\[
n_{\text{direct}} = nf_{\text{direct}} = \frac{(S/N)^2}{f_{\text{direct}}}. \tag{4}
\]

If we take \( S/N = 100 \), as might be appropriate for Titan surface imaging science, then the required total and unscattered photons are plotted in Figure 3 as a function of \( f_{\text{direct}} \). As evidenced by Figure 3, then, progressively more photons are needed to achieve the same S/N as \( f_{\text{direct}} \) decreases. At \( f_{\text{direct}} = 1.00 \), when all of the light is direct, only \( 10^4 \) photons would be needed in each pixel to achieve \( S/N = 100 \). To achieve the same S/N if \( f_{\text{direct}} \) decreases to 0.001 requires \( 10^{10} \) photons per pixel (!), which would take a million times longer integration time than it would at \( f_{\text{direct}} = 1.00 \). Clearly, a higher \( f_{\text{direct}} \) makes achieving a particular S/N easier.
2.3. Fraction of Direct Photons

We next proceed to analytically estimate \( f_{\text{direct}} \) for Titan’s atmospheric spectral windows. Calculating the light that both arrives at the surface unscattered and emerges unscattered (double-direct, the blue vector in Figure 1) would be pretty simple: just \( A e^{-\tau} \), where \( A \) is the surface albedo. That simple calculation severely underestimates the true direct component, however, because much of the light scattered within the atmosphere does eventually find its way down to the surface, illuminating it diffusely, as indicated by the purple vector in Figure 1.

Haberle et al. (1993) derive an equation to account for both direct and diffuse surface illumination, as garnered from the Mars literature, where it finds use estimating solar panel power in dust storms. For nonabsorptive, isotropic scattering (i.e., \( \omega_0 \), the single-scattering albedo of the atmosphere, is 1.000), the transmissivity \( T \) is given by

\[
T = \left( 1 + \frac{\tau}{2 + \mu} \right)^{-1},
\]

where \( \mu = \cos \theta \) and \( \theta \) is the angle of scattering measured from the zenith.

We consider the case where \( \mu = 1 \), as for a spacecraft viewing the surface at incidence and emission angles of zero (when the photons are transmitted directly forward or reflected backward). In that case, the additive (just-atmosphere) component corresponds to

\[
I_{\text{additive}} = R = 1 - T.
\]

In this simple model, the total observed intensity becomes

\[
I = 1 - T(1 - A).
\]

The nonadditive portion \((TA)\) interacts with the surface in some way, and the intensity of the direct component is

\[
I_{\text{direct}} = TAe^{-\tau},
\]

where \( A \) is the surface albedo (which we assume to be 0.2, typical for Titan bright terrain; Solomonidou et al. 2018). The remaining photons constitute the blurred component,

\[
I_{\text{blurred}} = TA(1 - e^{-\tau}).
\]

Parallel to Equation (2), we then calculate \( f \) as

\[
f_{\text{direct}} = \frac{I_{\text{direct}}}{I_{\text{direct}} + I_{\text{additive}} + I_{\text{blurred}}}.
\]

Equivalent calculations can then be done for \( f_{\text{additive}} \) and \( f_{\text{blurred}} \).

2.4. Application to Titan

In Figure 4, we show the relative mix of direct, additive, and blurred photons as a function of optical depth. The Figure 4 calculation assumes isotropic scattering (from Equation (5)), a single-scattering albedo of \( \omega_0 = 1.00 \) atmosphere, a surface albedo of \( A = 0.2 \), and zero phase angle. Hence, the result represents only an approximation of the actual Titan but a useful one.

When observing at a wavelength within Titan’s clearest window, at 5.0 \( \mu m \), the overwhelming majority of photons come directly from the surface to an orbiting camera. Although some processing would be required to subtract off the additive and blurred components, observing at 5.0 \( \mu m \) could yield full diffraction-limited images, suitable for geological interpretation even in their raw form.

If using 2.0 \( \mu m \), the situation becomes significantly more challenging. There only \( \sim23\% \) of the light consists of the direct component, less than both the blurred \( (27\%) \) and additive \( (50\%) \) components. At 2.0 \( \mu m \), diffraction-limited imaging is possible, but more photons would be required to achieve an adequate S/N, and significant data reduction would be necessary to make the images suitable for geological interpretation.

At the shorter 0.94 \( \mu m \) wavelength where Cassini ISS operates, 80\% of the light is additive component, and 20\% is blurred. Direct photons are a rounding error (around 1\%). Karkoschka et al. (2018) needed to coadd every Titan exposure acquired by Cassini over the course of its entire mission, therefore, to generate quality surface maps.

3. Numerical Treatment

3.1. Radiative Transfer Model

While informative in a general sense, the unrealistic assumptions employed in the calculations from Section 2 limit their accuracy. To infer the visibility of surface features through a real Titan atmosphere, without the isotropic-scattering and plane-parallel assumptions inherent in our analytical treatment, we turn to a numerical radiative transfer model. Barnes et al. (2018b) developed SRTC++ as a fully three-dimensional, spherical Monte Carlo radiative transfer model to complement existing plane-parallel approaches (e.g.,
McKay et al. 1989; Young et al. 2002; Rannou et al. 2003; Rodriguez et al. 2006; Griffith et al. 2012a; Hirtzig et al. 2013; Maltagliati et al. 2015). We designed SRTC++ to address spatial problems, rather than spectral ones, which, in prior work, we used to calculate the evening and morning sunset illumination at Titan’s surface beyond its terminator (Barnes et al. 2018a).

For the Titan imaging case that we consider here, we develop a new type of SRTC++ algorithmic detector in the code that separately images the direct, additive, and blurred components. Each photon bundle that arrives at the detector with Titan’s surface as its last scatter point gets binned as direct. Those that have not ever experienced any surface scattering get sent to additive. And those that encounter the surface at least once in their history, but not as the last scatter, get put into blurred.

We assume a Titan atmosphere as per Tomasko et al. (2008) with modified single-scattering albedos longward of 0.9 μm following Hirtzig et al. (2013). The Tomasko et al. (2008) model uses different haze scattering phase curves as a function of wavelength and altitude. We neglect Rayleigh scattering for now, as it is not an important factor in the near-infrared.

In an attempt to model the real Titan, we assign surface albedos of μ = 0.07 at 5 μm and μ = 0.2 at 2 μm and 0.94 μm. These values correspond to typical inferred albedos of bright terrains (Solomonidou et al. 2014). Tuti Regio (Barnes et al. 2006) and Hotei Regio (Soderblom et al. 2009) as 5 μm bright regions (Barnes et al. 2005) are brighter, but these unusually lakebed deposits (Moore & Howard 2010; Barnes et al. 2011) comprise only a small fraction of Titan’s surface area (MacKenzie et al. 2014). Therefore, we consider the albedos of typical Equatorial Bright terrain (Barnes et al. 2007) to be the most relevant value.

3.2. Numerical Output

We first run global SRTC++ tests to calculate fdirect, fadditive, and fblurred as a function of the incidence angle, emission angle, and phase angle. In these global calculations, we instantiate a 640 × 640 pixel detector with 10 km pixels. We fire 961 photon bundles into each 10 × 10 km location at the top of Titan’s atmosphere, leading to 446,096,641 total photons at each wavelength that, together, illuminate the whole globe (we actually illuminate beyond the 640 × 640 detector so as to account for photons scattered in the outer atmosphere, hence more photons than 961 per pixel). We show the SRTC++ output for these global runs in Figure 5 as I/F.

As expected based on both the analytical results from Section 2 and from intuition based on Cassini data and atmospheric optical depths, very little direct I/F comes from Titan at 0.94 μm (top left panel in Figure 5). Even then, the 0.94 μm direct component exceeds the predicted value from Figure 4 because the haze’s very forward-scattering phase function illuminates Titan’s surface better than an isotropic scatterer would. Proceeding down the leftmost (Idirect/F, in blue) column of Figure 5, both 2 μm and 5 μm show strong Idirect/F, with 2 μm being slightly brighter due to Titan’s higher surface reflectivity at 2 μm relative to that at 5 μm.

The middle left column of Figure 5 (in red) shows the purely atmospheric Iadditive/F. Note the different image stretch here relative to that for I/F—the direct images would be six times dimmer (and nearly invisible) if stretched equivalently to these Iadditive/F images. Commensurate with the analytical curves from Figure 4, Iadditive/F at 0.94 μm overwhelms that at 2 μm and 5 μm. Iadditive/F increases near Titan’s limb in a limb brightening that results from higher slant optical depths through the atmosphere at those higher emission angles.

We show the blurred component as the green column in Figure 5 in the middle right panel. We stretch these Iblurred/F images differently again, so that Idirect/F would appear three times dimmer at this stretch and Iadditive/F twice would appear as bright. Finally, on the right (in black), we show full I/F images that represent the sum of the direct, additive, and blurred components.

To convert I/F to fdirect, fadditive, and fblurred, we divide the image of each component by the totals to display in Figure 6. These images all use the same stretch for direct comparison. While the raw Idirect/F at 2 μm exceeds that at 5 μm, the fraction of direct photons fdirect maximizes at 5 μm. Once ratioed to the full flux, fdirect at 0.94 μm becomes nearly invisible.

The blurred component fblurred dominates fdirect at 0.94 μm. At 2 μm, however, fblurred and fdirect become comparable in magnitude. At 5 μm, fdirect always greatly exceeds fblurred, and fdirect exceeds fadditive except near Titan’s limb and terminator (areas of high emission angle ε and high incidence angle i, respectively).

Looking at the final Itotal/F results at the right of Figure 5, those full, identically stretched images mostly mirror the assumptions with which we modeled them. At 0.94 μm the atmospheric optical depth is high. Therefore, with the high single-scattering albedo of the haze at that wavelength the image is bright. At 2 μm, the atmosphere is thinner, and more light gets down to the surface where we have assumed the surface albedo to be A = 0.2 based on Cassini observations. At 5 μm, Titan’s surface is rather dark, and thus with optically
3.3. Comparison to Analytical Results

The closest parallel to Section 2’s analytical results would come when incidence angle $i = 0^\circ$ and emission angle $e = 0^\circ$. In Figure 7, we plot $f_{\text{direct}}$, $f_{\text{additive}}$, and $f_{\text{blurred}}$ as a function of incidence angle $i$ with emission angle $e$ fixed at $e = 0^\circ$. These values correspond to those that a Titan orbiter might see if using fixed nadir pointing.

Unsurprisingly, the fraction of direct photons always increases toward lower incidence angles. Therefore the best S/N would always occur near the subsolar point and for an orbiter in a noon-midnight orbit rather than one closer to Titan’s terminator. At higher incidence angles, $i$, corresponding to Titan’s polar regions where the Sun never rises high in the sky, $f_{\text{direct}}$ decreases markedly. Even at $5 \mu$m $f_{\text{additive}}$ exceeds $f_{\text{direct}}$ for incidence angles of $i > 75^\circ$. Because the poles display some of Titan’s most scientifically compelling terrain (Hayes 2016; Birch et al. 2017), imaging in these more challenging high-incidence conditions will drive camera design requirements.

The blurred component shows more complex behavior. Proceeding to higher incidence angles from $i = 0^\circ$, $f_{\text{blurred}}$ initially increases. In both the $2 \mu$m and $0.94 \mu$m cases, however, the blurred component eventually reaches a maximum value (near $i = 65^\circ$ for $2 \mu$m and near $i = 35^\circ$ for $0.94 \mu$m) beyond which $f_{\text{blurred}}$ drops. What’s happening is that for modest incidence, increasing $i$ leads to lower illumination of the atmospheric haze and a higher phase angle where the haze function is lower, hence decreasing $f_{\text{additive}}$, leading to a relative increase for $f_{\text{blurred}}$. But once $i$ gets sufficiently high so that the atmospheric slant optical depth grows beyond $\tau \sim 3$ or so, then less and less light even reaches the surface in the first place, and an increasing fraction of light scatters back before going down, leading to a higher $f_{\text{additive}}$ that overwhelms the blurred component. This effect is the same as that which causes the downturn near $\tau = 1.0$ for $f_{\text{blurred}}$ in Figure 4.

As mentioned in the previous section, $f_{\text{direct}}$ at $0.94 \mu$m, while very low at $7\%$, greatly exceeds that predicted by the analytical isotropic-scattering solution (although it remains dwarfed by more than five times more blurred and additive light). Titan’s highly forward-scattering haze particles scatter most of their light down to the surface and not back out as an additive component. Hence, while $f_{\text{direct}}$ attenuates severely into $f_{\text{blurred}}$ on the way out, more light interacts with the surface and does not become $f_{\text{additive}}$ than the isotropic-scattering case predicts.

3.4. Synthetic Images

As a final, full test of imaging quality within Titan’s atmospheric windows, we simulate $10$ m sampling of the surface as viewed from a spacecraft. Figure 8 shows resulting simulated images. To appropriately account for the blurred component from outside the field of view of the detector, we initially illuminated an area $10$ times wider than indicated and later uniformly filled in light scattered more broadly (outside the $10 \times 10$ area).

For the calculations, we assume a Lambertian surface with either a “black” or “white” surface albedo. For $0.94 \mu$m and
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2 $\mu$m, “black” corresponds to a surface albedo of $A = 0.05$ and “white” to $A = 0.20$. At 5 $\mu$m, “black” is $A = 0.02$ and “white” is $A = 0.07$, which is appropriate for Titan’s overall lower surface reflectivity in the 5 $\mu$m window. The simulation assumes a best-case, $i = e = 0^\circ$ observation geometry.

The high fraction of direct light at 5 $\mu$m in Figure 8 leads to readily discernible surface features that would be straightforward to interpret geomorphologically. The 2 $\mu$m contrast might be workable in good observation geometry scenarios but would require long integration times to achieve an adequate S/N. As expected, while a whiff of surface signal can be seen at 0.94 $\mu$m to the naked eye, the very low fraction of direct light would not allow for useful geomorphological interpretation.

Note that the speckle noise evident in Figure 8 results from numerical noise in SRTC++ and is not meant to convey photon shot noise. The forward-scattering lobe of Titan’s haze phase function has a particularly narrow peak, particularly at shorter wavelengths. That narrow peak leads to a high signal at a SRTC++ detector when a photon happens to scatter on a trajectory that was headed near the detector anyway, and that high scatter signal requires many, many input photons to be sufficiently averaged out.

While the full radiative simulations shown in Figure 8 assume best-case observation geometry of 0° incidence and emission, ideal observations for topography and geomorphology might prefer or require different values. To accentuate shading due to topography, which can improve interpretation of geomorphology, for instance, higher incidence angles between $i = 30^\circ$ and $i = 60^\circ$ work better. According to Figure 7, $f_{\text{direct}}$ always decreases as incidence increases; however, the effect is small for modest values of incidence less than $i \sim 30^\circ$ or so. A 2AM/2PM polar orbit, therefore, would alter integration times and S/Ns but would not fundamentally impede imaging at either 2 $\mu$m or 5 $\mu$m. Diffuse sky illumination from haze scattering, however, would favor 5 $\mu$m to maximize the effect of shading.

Similarly, off-nadir imaging by up to $e \sim 30^\circ$, as might be used for stereo imaging, degrades $f_{\text{direct}}$. The effect would not preclude such imaging for modest emission angles below $e \sim 30^\circ$. The degradation in stereo imaging quality would be similar for 2 $\mu$m and 5 $\mu$m and would not favor one window over the other as a choice for a spacecraft instrument.

4. Spacecraft Application

Titan’s 5 $\mu$m atmospheric window is the most transparent and therefore has the highest fraction of direct photons when viewing the surface from space. With all things being equal, then, 5 $\mu$m would be the best wavelength for a Titan orbiter camera. But all things are not equal radiometrically; the Sun is brighter at 2 $\mu$m, for instance. To quantitatively evaluate the relative utility of Titan’s near-infrared spectral windows for surface imaging, we apply a near-infrared imager performance model to typical orbiter parameters.

The performance model was written by one of us (R.H.B.) for instrument development in support of the JET Discovery proposal (Sotin et al. 2011) and refined for the Oceanus New Frontiers proposal (Sotin et al. 2017b). The model book keeps signal and noise as functions of varying parameters, incorporating shot noise, read noise (25 e−), and Poisson noise from the subtracted dark current. User-configurable parameters include detector temperature, fractional pixel blurring (defined by the
integration time; we set this to 0.5), target $I/F$, and the number of coadded pixels from time-delay integration (TDI). For the Titan case, all of the signal is reflected light (Titan is too cold to emit detectable blackbody radiation, even at 5 $\mu$m). We summarize the results from the performance model in Table 1.

We assume nadir imaging from a 1500 km circular orbit. To achieve a 20 m diffraction limit (10 m pixels) in the 5 $\mu$m window would require a 50 cm aperture, similar to that of HiRISE at Mars (McEwen et al. 2007). At 0° incidence (the subsolar point), $f_{\text{direct}}$ at 5 $\mu$m would be 0.75 according to Figure 7, so the necessary full S/N to achieve an S/N of 100 for the direct surface component would be 133. Assuming surface reflectivity of 0.07 as we did for our calculations, the performance model indicates that S/N = 133 would require 125 coadds in the downtrack direction with software TDI, assuming 0.5 pixels of smear controlling the integration time based on the spacecraft orbit velocity. On-chip hardware TDI could require fewer coadds as read noise would only be added once at the end of the summed integrations.

The equivalent TDI requirement at 2 $\mu$m would be 20 coadds (with a brighter surface having albedo of 0.20 and more photons from the Sun). So under ideal conditions, both 5 $\mu$m and 2 $\mu$m can easily be achieved on a 1024 $\times$ 1024 pushbroom detector in TDI mode, with 2 $\mu$m being a bit better.

To do the same at 0.94 $\mu$m might barely be possible. Using typical $I/F$ = 0.27, as seen from VIMS at 0.94 $\mu$m, with $f_{\text{direct}} = 0.07$ drives the required S/N for the full measured flux to S/N = 1430. We calculate that coadding 970 pixels would achieve S/N = 1430; this may be barely possible with a 2048 $\times$ 2048 detector, although spacecraft stability and drift will present challenges for such a long TDI period.

Once observation geometry deviates from ideal, however, more TDI coadds are required to achieve surface of S/N = 100 owing to dimmer oblique illumination and lower $f_{\text{direct}}$. At $i = 60^\circ$ incidence, for instance, which corresponds to the best possible case for imaging the north polar lake district, the required coadds for 5 $\mu$m and 2 $\mu$m rise to 600 and 180 TDI coadds, respectively. Beyond $i = 60^\circ$, 5 $\mu$m imaging becomes easier than 2 $\mu$m imaging. The required coadds for 0.94 $\mu$m at $i = 60^\circ$ would be 50000: not practically achievable.

These calculations assume adequate subtraction for the additive and blurred components. While relative pixel-to-pixel variations would be sufficient for geomorphology, the accuracy of absolute albedo derivations for intercomparison of distal regions depends on knowledge of the magnitude of the blurred component. Because the blurred component responds to surface albedo on scales of kilometers to tens of kilometers, comprehensive radiative transfer modeling would be required for accurate comparison of areas tens of kilometers apart. Therefore, longer wavelengths (e.g., 5 $\mu$m more than 2 $\mu$m) allow for better absolute surface albedo determination owing to their relatively less significant blurred and additive components.

Based on our analysis, ~20 m resolution imaging Titan’s surface at either 5 $\mu$m or 2 $\mu$m should be possible. Given the trade-offs, and the potential benefits of multispectral imaging (e.g., Rodriguez et al. 2006; Barnes et al. 2007; Soderblom et al. 2007, 2010; Griffith et al. 2012b; le Mouëllic et al. 2012; Dhingra et al. 2019), the best option would be to use both, perhaps complemented by additional channels within other Titan atmospheric windows at 1.3 $\mu$m (at coarser resolution) and/or 2.7 $\mu$m.

### 5. Conclusion

An orbiter with global geophysical, geological, hydrological, and atmospheric science objectives would make for a rational next step in Titan exploration to complement the Dragonfly relocatable rocurtord lander. Fine-resolution surface imaging from the orbiter would address geology. Sampling of 10 meter diffraction-limited surface from the orbiter using a near-infrared camera with bandpasses centered at 5 $\mu$m or 2 $\mu$m would be capable of meeting the required surface resolution and S/N with existing technology.

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