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Using engineering cameras on mars rovers and landers to retrieve atmospheric dust optical depth

C.A. Wolfe [a,*], M.T. Lemmon [b]

[a] Northern Arizona University, Flagstaff, AZ, 86011, USA
[b] Space Science Institute, Boulder, CO, 80301, USA

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ABSTRACT

Dust in the Martian atmosphere influences energy deposition, dynamics, and the viability of solar-powered exploration vehicles. The *Viking*, *Pathfinder*, *Spirit*, *Opportunity*, *Phoenix*, *Curiosity*, and *Perseverance* landers and rovers each included the ability to image the Sun with a science camera equipped with a neutral density filter. Direct images of the Sun not only provide the ability to measure extinction by dust and ice in the atmosphere, but also provide a variety of constraints on the Martian dust and water cycles. These observations have been used to characterize dust storms, provide ground truth sites for orbiter-based global measurements of dust loading, and help monitor solar panel performance. In the cost-constrained environment of Mars exploration, future missions may omit such cameras, as the solar-powered *InSight* mission did.

We seek to provide a robust capability of determining atmospheric optical depth from sky images taken with cameras that have not been designed for solar imaging, such as the engineering cameras onboard *Opportunity* or the *InSight* cameras. Our investigation focuses primarily on the accuracy of a method that determines optical depth values using a scattering model that implements the ratio of sky radiance measurements at different elevation angles, but the same scattering angle. MER engineering cameras are used to obtain non-solar sky images approximately 90° away from a low horizon Sun. A discrete ordinate radiative transfer algorithm and robust atmospheric scattering model are used in conjunction with the downlinked image files to produce both an image and model radiance profile. Optical depth is derived using a least-squares curving fitting routine within a scattering model that iteratively compares the two radiance profiles. Derived optical depth values are then compared against observed Pancam measurements to assess goodness of fit.

Operational use requires the ability to retrieve optical depth on a timescale useful to mission planning, and with an accuracy and precision sufficient to support both mission planning and validation of orbital measurements. We present a simulation-based assessment of an imaging strategy and its error budget, as well as a validation based on the comparison of direct extinction measurements from archival Navigation camera (Navcam) data. A preliminary validation using synthetic sky images was performed to test the robustness of the scattering model. Results from this preliminary validation are followed by observational results along with an in-depth error analysis. We conclude with a brief discussion regarding the implications of this study and what the future holds for ground-based optical depth retrieval.

1. Introduction

1.1. Overview

Robotic spacecraft have been sent to explore Mars since the early 1960's (James et al., 2017). These missions began as relatively simple science experiments with just a few instruments and gradually evolved into complex machines that would traverse and photograph the surface of the planet. Over the last 50 years, both orbital and ground spacecraft have sent back terabytes of data in the form of sensor measurements and images. As a result, our understanding of both the chemical and physical processes that occur on Mars has dramatically improved.

The Martian atmosphere is tenuous with a surface pressure that measures less than 1% of Earth's (Haberle et al., 2017). The atmosphere is nearly 95% carbon dioxide by weight, with other trace gases such as nitrogen and argon making up the remaining 5%. Even though the

* Corresponding author.
E-mail address: cw997@nau.edu (C.A. Wolfe).

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atmosphere measures only 600 Pa at the surface, it is still thick enough to support a variety of weather phenomenon, including clouds, fog, dust storms, and dust devils, all of which have been observed and studied using both orbital and ground spacecraft (Haberle et al., 2017). Near the polar ice caps, there is even observational evidence of carbon dioxide snow. This seasonal deposition and release of a large part of the Martian atmosphere at the poles can have a strong influence on global circulation patterns.

In addition to the molecular gasses that make up the atmosphere of Mars, there is also an abundance of dust consisting of small particles of iron oxide and other minerals (Kahre et al., 2017). Data from the MER rovers and previous studies indicate that suspended dust particles within the atmosphere have a radius of roughly 1.5 μm outside of global dust storms (Pollack et al., 1995; Markiewicz et al., 1999; Tomasko et al., 1999; Lemmon et al., 2019). Their presence is not only responsible for giving Mars its reddish hue, but also significantly affects the thermal structure of the atmosphere due to the dust particles absorbing sunlight, especially at 400–600 nm, as well as thermal radiation near 9 μm (Lemmon et al., 2004).

Dust is lifted into the atmosphere by mechanisms such as dust devils (Edgett and Malin, 2001; Greeley et al., 2006, 2010; Moores et al., 2015a, b) or dust storms (Toon et al., 1977; Wolff et al., 1997) and removed again by gravitational settling or turbulent dispersion. Dust storms are common on Mars, especially those that are regional or local in scale, and while they can occur at any time, they are most frequent during spring and summer in the southern hemisphere, when Mars is closest to the Sun and surface temperatures are at their highest.

Dust in the Martian atmosphere not only influences energy deposition and dynamics, but the viability of solar powered exploration vehicles as well. During a relatively clear day, the indirect or scattered component of sunlight remains relatively low. When there is lots of dust in the atmosphere, however, the majority of the total sunlight reaching the surface can be indirect. As a result, total irradiance is reduced, thereby reducing power generation. Over time, dust settles out of the atmosphere and onto solar panels (Haberle et al., 2017; Lorenz et al., 2021). This dust blocks and shifts the frequency of the incoming light, further degrading solar cell output. Dust deposition on the solar arrays was measured on the *Pathfinder* mission to degrade the performance at a rate of 0.28% per sol during the initial 30 sols of the mission (Landis and Jenkins, 2000), and dust on solar panels was involved in the loss of the *Spirit*, *Opportunity*, and *InSight* missions.

Currently, there are seven orbiting spacecraft that collect data and continue to monitor dust aerosols on Mars. A small fleet of landers and rovers including*Viking*, *Pathfinder*, *Spirit*, *Opportunity*, *Phoenix*, *Curiosity*, and *Perseverance* has also been deployed on Mars to not only explore the surface, but provide ground-based measurements of dust aerosols. Each of the aforementioned landers and rovers included the ability to measure irradiance from the Sun with a science camera that included a neutral density filter. Direct images of the Sun provide the ability to measure extinction by dust and ice in the atmosphere. These observations have been used to characterize dust storms, provide ground truth sites for orbiter-based global measurements of dust loading, and help monitor solar panel performance (Colburn et al., 1989; Smith and Lemmon, 1999; Lemmon et al., 2004, 2015).

The radiative impact of the dust on Mars varies with optical depth, a dimensionless parameter that describes the amount of radiation that is scattered and/or absorbed as a beam of incident sunlight travels through a planet's atmosphere. Optical depth can be derived from extinction of sunlight via the Beer-Lambert-Bouguer extinction law, $F = F_0 e^{-\tau\eta}$, where F is outgoing or observed flux near the surface, F_0 is the incident flux at the top of the atmosphere, τ is optical depth, and η is the airmass, which is defined as the optical depth along an arbitrary line of sight relative to that in the zenith direction (commonly approximated as sec(θ), where θ is the solar zenith angle). Values of τ less than one indicate low attenuation of sunlight. Values of τ greater than one, however, describe an atmosphere where particles absorb and/or scatter most of the incoming solar radiation, leaving very little sunlight that is able to penetrate directly to the surface.

Low and stable optical depths are typical of southern winter (and aphelion), while high and variable opacities correlate with southern summer (and perihelion) (Lemmon et al., 2015). Atmospheric dustiness may vary considerably through a Martian year, and although there is a general annual trend in dust loading there is also interannual variability, most significantly in the number and size of dust storms which occur (Newman et al., 2002). While relative variations of optical depth can be readily obtained from remote observations, absolute values are much trickier to obtain because they require accurate knowledge of important properties related to dust, such as the particle size distribution and the optical parameters (Montabone et al., 2015).

Optical depth measuring from landed payloads is a critically important component because of the higher accuracy and precision generally available from such measurements (Lemmon et al., 2015). Unlike Earth, which has a vast network of ground-based monitoring stations, Mars only has a small number of active landed missions at any time. And while orbital observations allow for a more complete characterization of dust loading over spatial and temporal scales compared to ground-based spacecraft, they generally embody more modeling or retrieval assumptions (e.g., Smith, 2004, 2008; Wolff et al., 2009). Obtaining ground-truth measurements from landed missions is important as they allow for the calibration of remote-sensing data and aid in the interpretation and analysis of what is actually being sensed.

While landed spacecraft on Mars have measured optical depth using direct solar imaging, this requires dedicated resources. In some cases, these measurements can divert resources away from other priorities. In addition to high-resolution science camera(s), rovers and landers typically have low-resolution cameras without filter wheels that are part of the engineering package (Maki et al., 2003). Deriving optical depth from non-solar sky images acquired by engineering cameras, therefore, places fewer requirements on the overall system. Such methods have been used to supplement solar-imaging methods, but have relied on cross-sky radiance measurements using camera articulation, which also places requirements on the system (e.g., Markiewicz et al., 1999).

Further, cameras on the surface of Mars are subjected to dust and dust deposition. This thin layer of dust that forms on the camera window modulates sky brightness and introduces extra extinction and scattering of light into the camera's field of view (FOV), therefore complicating solutions to the radiative transfer equation. In the case of MER/Pancam, one of the cameras on the MER rovers, interpretation of this extinction from the dust on the camera window was operationally significant as the error would interfere with the assessment of the performance of the solar arrays (Lemmon et al., 2015). Any method of optical depth retrieval must be robust against dust on optics.

The *InSight* mission (Banerdt et al., 2020), which operated over 2018–2022, was solar powered but did not include a camera for direct solar imaging to track dust optical depth. *InSight* had a MER/Navcam-like navigational camera on a robotic arm and a MER/Hazcam-like camera on the lander body (Maki et al., 2018). Their purpose was to capture images of the instruments deployed on the ground and acquire panoramic views of the terrain surrounding the landing site. Each camera had been upgraded from MER-heritage to acquire color images. In addition, *InSight* included an atmospheric-science investigation for which the tracking of dust optical depth would provide context (Spiga et al., 2018). The method described in this work was developed to allow a useful optical depth estimate to be made from sky images such as those *InSight* could acquire. The purpose of this paper is to describe a method for using *InSight*-like sky images and radiative-transfer modeling to determine optical depth and to present the results of a validation experiment that was performed with *Opportunity* rover data. Such a method was implemented for *InSight*, and this work provides background for measurements of atmospheric optical depth (e.g., Banfield et al., 2020; Viúdez-Moreiras et al., 2020).

2. Procedure and preliminary validation

2.1. Radiative transfer equation and DISORT

Before optical depth can be derived, sky brightness, as seen from the ground, must be computed first. As a beam of sunlight propagates through a medium, such as the atmosphere of a planet, it is affected by absorption, emission, and scattering processes. The radiative transfer equation describes these interactions mathematically. Below is a compact form of the 1-D diffuse radiative transfer equation applicable to horizontally homogeneous, plane-parallel geometries. On the left-hand side is a differential describing the rate at which diffuse radiance (I), which is dependent on optical depth (τ), airmass (η), and azimuthal angle (φ), changes with path optical depth. On the right-hand side is the total diffuse radiance minus a source function (S), both of which are also dependent on optical depth, airmass, and azimuthal angle.

$$\eta\frac{dI(\tau,\eta,\varphi)}{d\tau}=I(\tau,\eta,\varphi)-S(\tau,\eta,\varphi) \tag{1}$$

The source term on the right of Equation (1) is the sum of direct single scattering and all higher orders of diffuse multiple scattering along the atmospheric slant optical path coinciding with the observer's viewing direction. Here unprimed and primed variables denote, respectively, variables evaluated before and after scattering. Variables with a *0* subscript indicate the top of atmosphere value. The source function can be written as follows, where ω is the single-scattering albedo or the ratio of scattering efficiency to total extinction efficiency and P is the phase function, described in more detail below:

$$S(\tau,\eta,\varphi)=\frac{\omega(\tau)I_0}{4}P(\tau,\eta,\varphi,\eta_0,\varphi_0)e^{-\tau/\eta_0}+\frac{\omega(\tau)}{4\pi}\int_0^{2\pi}\times\int_{-1}^{1}I(\tau,\eta',\varphi')P(\tau,\eta',\varphi',\eta,\varphi)d\eta'd\varphi' \tag{2}$$

The theoretical modeling of light scattering in planetary atmospheres is usually divided into two parts: single scattering by small volume elements in the atmosphere and multiple scattering by the entire atmosphere (Hansen and Travis, 1974). The first term in Equation (2) describes single scattering or the diffuse radiation arising from the scattering of the direct solar beam. The second term accounts for multiple scattering of diffuse radiation. Equation (1) is evaluated over the line-of-sight for a curved atmosphere, with the direct solar term calculated using spherical geometry. The diffuse radiance term is calculated for a plane parallel atmosphere via a discrete ordinates method (Stamnes et al., 1988). The latter approximation is valid as near-horizon light is only a small part of the actinic flux incident on the dust.

Within the source function is the phase function, a dimensionless quantity that characterizes the scattering process and describes the angular distribution of scattered light. On Mars, 3-μm diameter particles are large compared to the wavelength of incident radiation (Tomasko et al., 1999), producing size parameters (X), or ratio of the particle's circumference to wavelength, near 15. This size is traditionally within the Mie scattering regime, but since Mars dust is non-spherical, we use a phase function adapted from Tomasko et al. (1999) for the Navcam wavelength. This results in a strongly-forward peaked phase function, which makes it computationally intensive to obtain accurate solutions to the radiative transfer equation. Therefore, the multiple scattering term in the source function is evaluated using a numerical algorithm known as Discrete-Ordinate-Method Radiative Transfer (DISORT) (Stamnes et al., 1988). DISORT is a model of the transfer of monochromatic, unpolarized radiation from one location to another by scattering, emission, and absorption in a vertically homogeneous, plane-parallel atmosphere (Shaw et al., 2013). DISORT reduces the radiative transfer equation to a series of independent equations which allows us to solve for the azimuthally resolved intensity field.

DISORT uses the δ-M transformation (Wiscombe, 1977) to achieve optimum computational efficiency and accuracy for strongly forward-peaked phase functions. The essence of the δ-M method is to separate the phase function P into the sum of a delta-function in the forward direction and a truncated phase function P' which is expanded into a series of Legendre polynomials. As mentioned above, the phase function associated with the scattering of visible and near-infrared radiation by cloud and dust particles on Mars has a pronounced peak in the forward scattering direction primarily due to diffraction. This peak is several orders of magnitude larger than the values of the phase function at side- and back-scattering angles and as a result, requires a large number of expansion terms to accurately reproduce the original phase function. We use 256 expansion terms, or moments, to reconstruct the phase function. This was found to be more than enough to faithfully represent the dust particles. The equation for the truncated phase function is shown below, where M is the total number of Legendre polynomials and g is the asymmetry parameter, specifying the degree of scattering in the forward direction.

$$P(\tau,\cos(\Theta))=\sum_{l=0}^{2M-1}(2l+1)g_l(\tau)P_l(\cos(\Theta)) \tag{3}$$

In DISORT, the scattering phase function depends only on the scattering angle (Θ) between the incident and scattered beams. Therefore, the azimuthal(φ)-dependence in Equations (1) and (2) can be factored out if the phase function is expanded into Legendre polynomials (see Equation (3)) and the intensity is expanded in a Fourier cosine series (see Equation (4)). Once the phase function has been expanded using Legendre polynomials, the final step in factoring out the φ-dependence, is to expand the intensity in a Fourier cosine series. The azimuthal integration of this series drops all but the $m = 0$ term, therefore producing azimuthally-averaged intensities.

The equation for the expanded intensity is shown below, where once again, M is the total number of Legendre polynomials used.

$$I(\tau,\eta,\varphi)=\sum_{l=0}^{2M-1}I^M(\tau,\eta)\cos(m(\varphi_0-\varphi)) \tag{4}$$

Substitution of Equations (3) and (4) into the radiative transfer equation causes it to split into $2M$ independent integro-differential equations, one for each azimuthal intensity component so that we now have the following equation:

$$\eta\frac{dI^m(\tau,\eta)}{d\tau}=I^m(\tau,\eta)-S^m(\tau,\eta)\quad(m=0,1,\ldots,2M-1) \tag{5}$$

A discrete ordinate approximation of the equation above is given by approximating the integral within the source function by a quadrature sum and thus transforms the integro-differential equation (1) into the following system of differential equations where M is the total number of Legendre coefficients used and N is the total number of quadrature angles (streams):

$$\eta_i\frac{dI^m(\tau,\eta_i)}{d\tau}=I^m(\tau,\eta_i)-S^m(\tau,\eta_i)\quad(m=0,1,\ldots,2M-1)\quad(i=1,\ldots,\pm N) \tag{6}$$

For the upward-looking geometry, solutions were calculated using 64 streams, or discrete zenith directions (quadrature angles), and 256 Legendre polynomial moments to represent the angular distributions of atmospheric and surface scattering. The solution of this equation yields the intensity that an observer would detect if an instrument were located under a layer with optical depth τ for any given line of sight.

We also chose to ignore the effects of Rayleigh scattering as it only slightly modifies the phase function. Optical depth from Rayleigh scattering is trivial on Mars for wavelengths near 650 nm. Rayleigh scattering by the CO_2 atmosphere accounts for an optical depth that is roughly $(1.2 - 1.6) \times 10^{-3}$ when looking in the red portion of the visible spectrum and, therefore, is negligible when compared to the light scattered by dust particles. It is the resulting Mie scattering from atmospheric dust particles that is primarily responsible for the observed optical depth. Scattering by the fine dust grains suspended in the atmosphere results in an optical depth that can vary dramatically over the course of a Martian year (from 0.37 to 4.6), with a typical, or average, value being approximately 0.78.

For our specific case, we model the atmosphere as one layer with dust acting as the only aerosol and assume no vertical structure. The assumption that this single atmospheric dust layer is uniform is a reasonable approximation except near the horizon, in that the dust tends to be well mixed through the bottom scale height and moderately well mixed for a few scale heights. Using additional atmospheric dust layers in the modeling process, therefore, will not lead to more accurate results, as the rover on the surface is unable to discern between multiple layers of well-mixed dust particles.

Replacing the integral in equation (2) with the integral of the actinic flux, $\langle A \rangle$, making a simplifying assumption that $\langle A \rangle$ is approximately proportional to the solar flux at every altitude, integrating equation (1) over optical depth, and assuming the instrument response is proportional to radiance-on-sensor yields equation (7):

$$R^{*} \sim R_0 \left(\frac{\omega\ F\ P(\theta)}{4} + \omega \langle A \rangle \right) \int_0^{\tau_0} e^{-(\tau_0 - \tau)\eta_0}\ e^{-\tau\eta}\ \eta\ \mathrm{d}\tau \tag{7}$$

Where R^* is the signal measured and R_0 is the instrument response (signal/radiance). The first term in the parenthesis represents the single scattering of direct solar radiation, and the second term describes the diffuse radiation (approximated as proportional to the mean actinic flux). The integral is the path integral over the emission source and describes the amount of extinction. This particular form of the radiative transfer equation is useful to our study because the derived flux of each pixel in the processed images was derived from the observed signal (R^*) measured in data numbers per second (*DN/s*). For current engineering cameras, the proportionality constant, R_0, is poorly known and has not received the same subject of rigorous calibration that the science cameras have gotten.

2.2. Methodology

We seek to provide a robust capability of determining atmospheric optical depth from sky images taken with cameras that have not been designed for solar imaging, such as lander and rover engineering cameras. Typically optical depth is retrieved through direct solar imaging using a dedicated multispectral science camera with a neutral density filter (i.e. Pancam) and/or through retrievals using infrared spectra taken by the Mini-TES instrument (Smith et al., 2006). In this study, however, we will investigate the accuracy of a scattering model that derives optical depth using non-solar sky images acquired by the MER rover's engineering cameras.

Explained in this section is a method for deriving aerosol optical depth without directly imaging the Sun using the ratio of sky radiance measurements at two different elevation angles, but keeping the scattering angle fixed at approximately 90°. This particular approach to retrieving optical depth is useful not only because it has the ability to free up rover system resources, but it avoids reliance on absolute calibration of responsivity, R. Most importantly, however, it is another way to provide a ground truth measurement of optical depth.

We will contrast the intensity derived from sky images at two elevations and the same scattering angle in order to constrain the optical depth. Near the Sun, the phase function strongly varies with the scattering angle and is primarily driven by the particle size distribution, depending little on particle shape. When roughly 90° away from a low Sun, however, the phase function is smooth and the scattering angle is nearly orthogonal to the elevation angle. In this case, the scattering angle controls the phase function and the elevation angle controls the airmass (η). Using this relationship and applying it to sky images that obey the appropriate geometrical criteria, we can derive optical depth using a relatively simple method. For the low optical depth limit, radiance (I) is simply proportional to optical depth (τ) × airmass (η), but for the high airmass and/or optical depth limit, multiple scattering becomes important. Therefore, in order to reduce errors from absolute calibration in the high airmass and/or optical depth case, we take the ratio of two sky radiance measurements at the same scattering angle, but different elevation angles. Thus, not only is the absolute radiance calibration removed, but the angular variation of the scattering is removed to first order.

The equation below demonstrates the mathematical approach of the ratio method where R^* is the observed signal measured in *DN/s* and the subscripts a and b represent two different elevation angles.

$$\frac{R_a^*}{R_b^*} \approx \frac{\int_0^{\tau_0} e^{-(\tau_0-\tau)\eta_0}\ e^{-\tau\eta_a}\ \eta_a\ \mathrm{d}\tau}{\int_0^{\tau_0} e^{-(\tau_0-\tau)\eta_0}\ e^{-\tau\eta_b}\ \eta_b\ \mathrm{d}\tau} \tag{8}$$

Since R^* is proportional to radiance (I), the left-hand side of Equation (8) may be rewritten such that the ratio of light intensity at two different elevation angles corresponds to a specific optical depth value. We assume that optical depth remains the same regardless of elevation angle and that it is the airmass, η, that varies with the viewing angle. Variations within the line of site tend to be $< 5\%$ (Lemmon et al., 2015) This information may then be used to produce a brightness profile such as the one in Fig. 1. Constructing a brightness profile allows for the prediction of optical depth if intensity ratio is known, or vice versa. More importantly, however, it informs us of the correlation strength between the two parameters.

2.3. Model description

In addition to the ratio method described in the previous section and the radiative transfer algorithm DISORT, a parameterized dust light-scattering model from (Tomasko et al., 1999) is used and supplemented by parameters from (Johnson et al., 2003) to describe the optical properties of the dust particles in the Martian atmosphere. This treatment of light scattering by randomly oriented, irregularly shaped particles uses a combination of Mie theory, physical optics, geometrical optics, and parameterization (Pollack and Cuzzi, 1980). For the particular geometrical setup outlined in this work, the observed sky brightness originates from sunlight scattered by dust particles into the line-of-sight of each

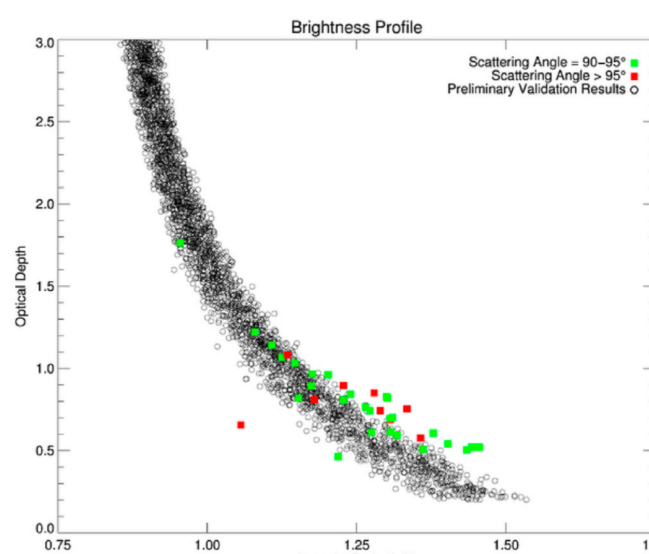


Fig. 1. Brightness profile resulting from the preliminary validation. It shows the model radiance ratio vs. the optical depth that got that ratio. Each individual data point corresponds to a single synthetic sky image that was constructed from user defined, randomly varied scattering parameters.

pixel, and thus depends primarily on a variety of scattering parameters which are summarized in Table 1.

While the modeled single-scattering properties of a distribution of particles has been shown to be insensitive to the specific function used to describe the size distribution of the particles, a modified-gamma distribution function described by Hansen and Travis (1974) is used in this work. We begin with a size distribution of spheres with radii that have been chosen to have volumes equal to that of the irregular particles for two regimes (small particles and large particles). We also adopt a convention similar to the one used by Pollack and Cuzzi (1980), in which a size parameter less than some upper bound results in Mie theory being used to calculate both the scattering cross section and phase function. For larger particles ($X > 5$), appropriately scaled Mie theory results are used to define the scattering cross section and the phase function is constructed from the sum of three components: diffraction, external reflection, and internal transmission (Pollack and Cuzzi, 1980).

For the particles within the large size regime, the diffraction component is assumed to be that of an opaque circular disk having an area equal to the irregular particle's projected area (Pollack and Cuzzi, 1980). The external reflection component for large particles results from a randomly oriented ensemble of convex, irregularly shaped particles reflecting light incident on their surfaces in precisely the same manner as an ensemble of equal area spheres with the same index of refraction (van de Hulst, 1981; Hansen and Travis, 1974; Hodkinson and Greenleaves, 1963). The internal transmission component is primarily responsible for the deviation in the scattering behavior of irregular particles from that of their spherical counterparts (Pollack and Cuzzi, 1980). These three components for large particles, along with the results from Mie theory for smaller particles, are used to obtain a composite phase function.

The shape of the phase function at small scattering angles is determined primarily by diffraction and external reflection and is therefore not significantly affected by particle irregularity. The main deviation in the scattering behavior of large, irregular particles from spheres arises in that component which is internally transmitted and refracted (Pollack and Cuzzi, 1980).

The single scattering parameters shown in Table 1 and used in the scattering model are derived, in part, from their size distribution. These parameters include the mean radius (effective particle size) and variance of radius, imaginary index of refraction (measure of how much light a particle absorbs/attenuates), Tomasko G and $\theta_{\min}$ (2 parameters describing the shape of the phase function), optical depth, ground reflectivity (fraction of incident radiation reflected by the ground), and scale height, which represents the vertical distance above the surface at which the density or pressure of the atmosphere decreases by exactly $1/e$. For larger particles, the Tomasko G parameter, which is related to the slope of the natural log of the phase function for internally transmitted light, and the Tomasko $\theta_{\min}$ parameter, or the scattering angle at which the log of the phase function reaches a minimum value, are used to collectively describe the shape of the phase function.

It is also important to note that within the scattering model, there is a section of code dedicated to truncating out information stored in elevation angles less than 15°. This is necessary as it reduces the chance of the Martian terrain obscuring sky images and the importance of the vertical distribution of dust. This truncation of elevation angle also allows us to ignore the effects of spherical geometry, which can be quite complex to model. Additionally, we make a first-order correction for Mars' vertically extended atmosphere (H/R, the scale height to radius ratio, is 0.003, causing the plane-parallel assumption to fail near the horizon). The atmospheric scattering model is relatively insensitive to the specific form or details of the surface scattering function. Therefore, for elevation angles less than 15°, we assume the ground essentially acts as a Lambertian surface.

Once the appropriate input values for the single scattering parameters described above are provided, the scattering model then calculates the volumetric or bulk optical properties of the particle size distribution, including the scattering coefficient and average phase function. These outputs provided by the scattering model, along with several additional input parameters, are then used by the DISORT radiative transfer code to calculate diffuse sky radiance.

Table 1
Parameters used by the scattering model to derive bulk optical properties of the dust aerosols present in the Martian atmosphere. Included within the table are the range of values the parameters were varied over as well as truth values acquired from previous literature.

Scattering Parameter	Range Varied Over	Truth Value*
Mean Radius (μm)	0.50–2.94	1.6
Variance of Radius	0.200–0.899	0.2–0.5
Imaginary Index of Refraction	0.5013–1.999 $\times 10^{-3}$	0.00211
Tomasko 'G' Parameter	50.03–199.99	70
Tomasko '$\theta_{\min}$' Parameter	120.08–209.97	145
Optical Depth	0.200–2.998	0.528
Ground Reflectivity	0.20008–0.34999	0.25
Scale Height (km)	8.501–12.497	10.5

*From Tomasko et al. (1999) and Johnson et al. (2003).

2.4. Preliminary validation and results

A preliminary validation was done to test the robustness of the ratio method given uncertainty in scattering parameters. In order to recreate the Martian sky and simulate the rover imaging the sky, a database of synthetic sky images or set of truth models with randomly-varied scattering parameters was generated. These images would make up the "actual" sky conditions on Mars and have units of I/F. A database with a new set of randomly-varied parameters, or assumed conditions, was also generated in order to simulate the rover acquiring images of the observed sky.

Once the steps above were completed, sky radiance values obtained from DISORT were used to simulate looking at the near horizon sky 90° away from the Sun. The scattering model permits the user tune various geometrical properties, thereby allowing one to view and select sky radiance values from two different elevation angles, while still keeping the scattering angle fixed. This essentially allowed control of the "rover's camera" and the ability to point it in any direction in the computer generated sky images.

After the synthetic sky images were prepared and had the correct viewing geometry applied, the scattering model evaluated the images via the ratio method. In this model vs. model analysis, the "assumed" conditions represent the model output from which optical depth was derived from. The ratio method used herein is a simplification: one can gain accuracy using an elevation (ε) profile of $d\ln(I)/d\varepsilon$ from a sky image, taken at constant scattering angle. This method is analogous to acquiring multiple Sun images at different elevation angles in order to calibrate solar optical depth.

The preliminary results generated using the ratio method and database of synthetic sky images are shown in Fig. 1. For each of the 3000 computer generated images, a ratio of sky radiance was calculated and compared with the corresponding optical depth that yielded that ratio in order to construct a brightness profile. Even with random errors in single scattering that are large compared to uncertainties, the model still results in a strong correlation of radiance ratio with optical depth across the range of parameters. It is important to note that 95% of all visible optical depths on Mars are < 1.5 and that using a $d\ln(I)$ profile increases sensitivity.

The spread in the data indicates the effect of varied parameters with the general trend indicating the predictability of optical depth. Low optical depths are relatively well constrained while higher optical depths are less well constrained when using the specific elevation angles of 15° and 30°. Higher optical depths become better constrained when using other angles (eg. 25° vs. 40°), hence the process of fitting all angles, not just using a ratio when looking at observational data.

3. Observational validation plan

3.1. MER rover and navigational camera (Navcam)

The Mars Exploration Rovers *Spirit* (MER-A) and *Opportunity* (MER-B) arrived on the surface of Mars January 4 and 25 of 2004 respectively. *Spirit* landed in a region of Mars known as Gusev Crater and *Opportunity* at a site designated Meridiani Planum. Both sites are located close to the equator of Mars, where temperature and temperature variations are less extreme. Each rover is powered by a triple junction solar array and equipped with a science payload that includes a variety of instruments including sensors, detectors, spectrometers, and cameras. The main scientific objective of the rovers was to explore their respective landing sites for evidence of past surface water and to assess past environmental conditions at those sites and their suitability for life (Squyres et al., 2003). While *Spirit* is no longer operational, *Opportunity* continues to traverse the surface of Mars, providing new images and data on a regular basis.

Operating a surface rover is an image intensive process. Due to time delays between Earth and Mars, it is impossible to communicate with and control the rovers in real time. The free-roaming nature of the rovers, therefore, requires the daily acquisition and downlink of stereo image data in order to operate and safely drive the vehicle (Maki et al., 2003). Image data from the onboard cameras is quickly analyzed in order to select new targets based on scientific merit, assess the possible traverse options, and command the rover to drive to the designated target. After the rover has completed the traverse, additional image data is used to verify the post-traverse location of the vehicle relative to the commanded location (Maki et al., 2003). Each MER rover has a total of 10 cameras, 6 of which are designated as engineering cameras and support the operation of the vehicles on the Martian surface.

The Navigation cameras (Navcams, two per rover) are a mast-mounted stereo pair each with a 45° square field of view (FOV) and an angular resolution of 0.82 milliradians per pixel (mrad/pixel) (Maki et al., 2003). The cameras have a small aperture opening (*f*/12) with a focal length of 14.67 mm. The depth of field of the Navcam camera ranges from 0.5 m to infinity, with best focus occurring at 1.0 m. The Navcams use a combination of filters (Schott OG590, KG5, and an ND1.3) to create a red band-pass filter centered at 650 nm (Maki et al., 2003). They are primarily used to acquire images of the local terrain and Martian landscape, which are then evaluated upon downlink to help in the navigation of the rover. In addition to providing terrain context for traverse planning, images from Navcam are also used to aid in Pancam and Mini-TES pointing.

While the FOV of the Navcams allows the instrument to observe a larger portion of the sky at once compared to Pancam, it also means that Navcam pointing is more restricted so as to minimize high levels of stray light entering the optics (Moores et al., 2015a,b). Thus, for good results, more angular clearance needs to be kept between the selected sky location and bright targets, such as the sun. In order to help reduce internally relected or scattered stray light from entering the optics, the MER rovers are equipped with a sunshade baffle that surrounds the Navcam instrument. Over time, ground based spacecraft on Mars get dusty. While wind can occasionally provide a cleaning event, any system needs to be robust against dust contamination of the optics. Dust that settles on the optics may result in camera artifacts, which can be made worse by instrumentally reflected light or shadows cast by the window baffle. To reduce the chances of camera artifacts appearing, Navcam is only aimed $> 60^\circ$ away from the Sun in order to keep direct sunlight off the optics.

3.2. Data acquisition

All images used in this work are from the Planetary Data System (PDS), which archives and distributes scientific data from NASA planetary missions, astronomical observations, and laboratory measurements. PDS archives raw images, or images that have undergone no camera model linearization or radiometric correction, in a standard format called the Experiment Data Record (EDR) (Eliason et al., 2009). The files contained in the EDR archive volume have attached PDS labels identifying and describing the objects within the file. The labels also contain descriptive information needed to interpret or process the data objects in the file.

In addition to a PDS label, Navcam images have a descriptive product identifier (PRODUCT_ID) that includes a sequence identifier, a spacecraft clock time at the time of image acquisition, as well as site and location identifiers. An example of a PRODUCT_ID is 1N451342530EDNCCQOP1567L0M1, where “1N” indicates *Opportunity's* Navcam instrument, “451342530” is a 9-digit time stamp, “EDN” indicates a downsampled EDR, “CCQO” is a location identifier, “P1567” represents a sequence identifier, “L0” indicates left camera with 0 specifying no filter was used, “M” is the producer code, and “1” indicates the version number.

Non-solar Navcam sky images were captured with the appropriate geometry (i.e. 20° elevation angle and 90° scattering angle) beginning February 17, 2014 as part of a dedicated campaign to create an optical depth validation record in preparation for the *InSight* mission. Included in this campaign are a set of observations which were given the name “navcam_insight_tau_pm”. This particular observational sequence, illustrated by Fig. 2, commands the Navcam engineering camera to acquire series of 5 sky images. Starting at an azimuthal angle of 0°, an image with the Sun centered in the frame is acquired. The rover then rotates its mast assembly, acquiring a 2×2 mosaic, with one pair west of north and the other east of north. Each pair of images was separated from north by approximately 20°. Note that the Sun image contains saturation artifacts as well as sky and instrumental scattered light.

The purpose of having multiple images was to ensure the right data could be acquired even if changes to the procedure were made. Only one of the five images, however, is used in the derivation of an optical depth value. The “extra” images that are not used by the scattering model are an artifact of designing the sequence so that it was robust against seasonal changes given operational constraints.

Fig. 3 provides several examples of the type of images that were used in this work. All images shown were acquired by *Opportunity's* Navcam instrument: (a) is a typical or “normal” Navcam sky image, (b) is partially contaminated by patchy clouds, and (c) is contaminated by the way the sunlight hits the Navcam optics. The majority of images acquired by the rover resemble (a). A few images downlinked contained cloud formations like those observed in (b), which may result in abnormally high optical depth values. The scattering model assumes a uniform sky of equal brightness, and therefore, has difficulties interpreting discrete cloud formations. Several images were also contaminated by the window baffle that shadows the optics and look similar to (c). In this case the Sun casts a shadow onto the window, which becomes visible due to the dustiness. Since light scatters off the dust on the window regardless of the viewing angle, we are interested to see if this substantially affects the ratio if the Sun is not shining directly on the optics.

3.3. Radiometric calibration

Each MER rover payload instrument acquires unique data that is saved onboard as separate products. Upon transmission to Earth, the products are split into parts and packaged inside telemetry packets. Each packet is identified according to the type of data it carried, plus additional ancillary information required for data product reconstruction on the ground (Alexander et al., 2006). The Multimission Image Processing Laboratory (MIPL) analyzes the telemetry data product to create a first order, or “raw”, EDR image. Each MER EDR contains the instrument data reformatted into a useable product, plus a complete label that is fully compliant with PDS rules and guidelines, making the EDR archive-ready (Alexander et al., 2006).

A full-frame, uncompressed raw image file from a MER camera is $1024 \times 1024 \times 12$ bits, or 1.5 megabytes in size. Because the onboard flash memory available for data storage is only 256 megabytes, of which

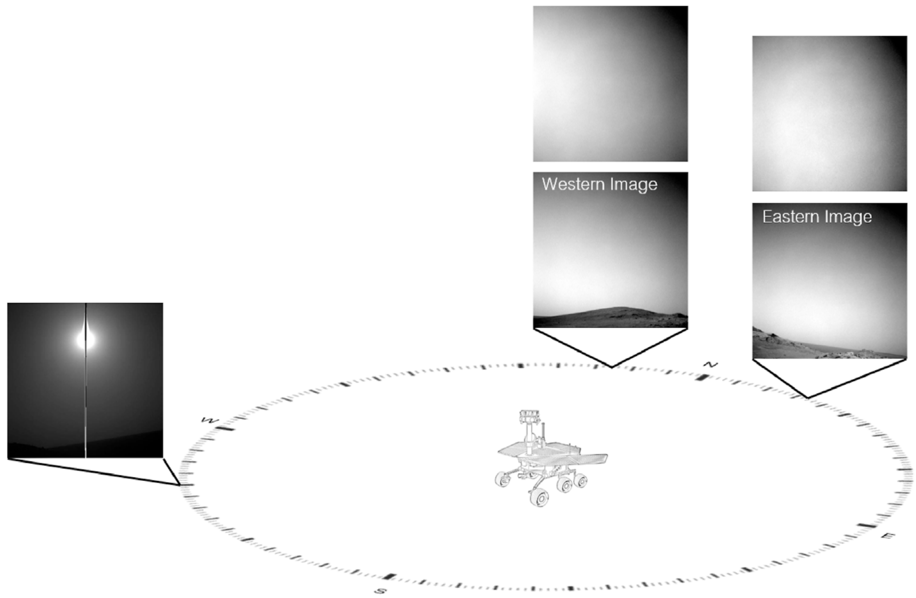


Fig. 2. Visual representation of the Navcam *InSight* tau" sequence executed by *Opportunity* showing the directionality of both western and eastern images. The sky images were captured with the camera facing approximately 90° away from north, acquiring one pair west of north and the other east of north. Images shown in figure were taken on sol 4034.

(a) (b) (c)

Fig. 3. Examples of *Opportunity* Navcam non-solar sky images acquired on sol (a) 3848, $L_S = 237.5°$, (b) 3640, 119.5° and (c) 3733, 167.4°.

200 megabytes is available for instrument data storage, the maximum number of full-frame, uncompressed images that can be stored in memory is approximately 130 (Soderblom, 2007). This is roughly equivalent to 2 weeks of downlinked image data at the nominal downlink rates of 100 Mbits/day (Maki et al., 2003). To work within these constraints, the MER imaging system provides the capability to produce additional, less volume-intensive image data products.

The Flight Software (FSW) has the ability to perform certain image processing tasks onboard the rovers in order to both maximize storage efficiency and maintain a level of image integrity. We use data that has been reduced from 1024 × 1024 to 512 × 512 by pixel averaging, had 12-bit raw data scaled to 8-bit data for communication relay via a look-up table (square-root compression), and compressed images with a moderate quality setting. On the ground, images were radiometrically corrected by removing the effects of exposure time and temperature, and applying a flat-field correction to remove known camera artifacts. The result is calibrated to physical units for MER of $W/m^2/nm/sr$.

3.4. Geometric reduction

Before the observed intensities of the Martian sky can be compared with model calculations, the viewing and illuminations geometries of the observation, or where the rover's camera was pointed relative to the Sun, must be known. The incidence (i), emission (e), and scattering (θ) angles must first be derived for each pixel in the Navcam images. Derivation of these observing geometries uses image-label information describing the rover's orientation relative to Mars, the solar incidence vector, and the pointing of the camera relative to the rover.

The MER Navcam geometric camera model described by Maki et al. (2003) employ the CAHVOR (Center, Axis, Horizontal, Vertical, Optical, and Radial) projection model developed by Yakimovsky and Cunningham (1978) and Gennery (2001). This model uses five three-dimensional vectors that describe the camera geometry and a set of 3 numbers that describe radial distortion in order to calculate the pointing vector of each pixel in an image. Using the CAHVOR camera model allows a point in XYZ space to be traced into the image plane. The model also includes corrections for geometric distortions in the camera optics, including any radial distortions (Maki et al., 2003). A quaternion describes the rover attitude, allowing conversion between the rover-aligned frame and the local site frame (a north-east-down coordinate system).

4. Model application and results

4.1. Model application

Once the radiometrically calibrated images have been geometrically reduced, the sky radiance is computed for a particular direction for each individual pixel in the image according to the observed viewing geometry. This geometric information is then also relayed to the radiative transfer model so that model sky images can be reconstructed using the appropriate geometry. For this work we are interested in modeling sky brightness from non-solar Navcam sky images that exhibit elevation angles greater than 15° and scattering angles roughly 90°. Discussed below is the application of the scattering model and minimization algorithm employed to obtain sky brightness.

In addition to the geometric parameters derived from the CAHVOR camera model components, sol, elevation angle, solar azimuthal angle, and radiance are extracted from the calibrated images and image headers. The geometric information, along with a variety of setup parameters, are then used as input to an atmospheric scattering model. The scattering model simulates a random size distribution of irregularly shaped dust particles to produce a bulk (average) phase function. This phase function is then imported into a radiative transfer code to model sky brightness in the form of radiance factor (*I/F*) according to the image geometry.

Following the steps above, the output from the radiative transfer model is then compared to the radiance (*I*) data from the image file. The comparison is done iteratively, varying optical depth using MPFIT, an optimizer designed for non-linear least-squares curve fitting using the Levenberg-Marquardt technique (Markwardt, 2009). By varying optical depth and leaving the remaining single scattering parameters fixed, one alters the resulting radiance profile generated by the radiative transfer program. The idea behind this process is to find the optical depth that results in a radiance profile that matches, or comes close to matching, the radiance profile from the image file.

The MPFIT code is based upon the well-known and tested MINPACK-1 FORTRAN minimization library (Moré and Sorensen, 1984). The features of MPFIT include the ability to bound parameter values, to control step sizes, and to calculate either one-sided or two-sided numerical derivatives for the Jacobian. The figure of merit for convergence is the traditional χ^2 statistic weighted by the observational errors. The retrieved parameter uncertainties are calculated directly from the diagonal of the covariance matrix (Moré and Sorensen, 1984).

The inputs for MPFIT include the function to be minimized and an array of starting values for each of the parameters of the model. In this case, "model" is the radiance profile generated from DISORT and "data" is the radiance profile extracted from the image file. Also included within Equation (9) are the variables *N*, or total number of observations, *h*, a scaling factor chosen to minimize χ^2 for each model parameter, which thus aids in fitting the modeled data to the shape of the curve, and *w*, a weighting factor related to observational errors. The input parameter tau (optical depth) is allowed to vary throughout the curve-fitting process, while the remaining parameters that determine the phase function are kept constant.

$$\chi^2 = \frac{1}{N}\frac{\sum_{j=1}^{N} h\left[model(I/F)_j - data(I)_j\right]^2 w_j}{\sum_{j=1}^{N} w_j} \tag{9}$$

MPFIT is used to fit the modeled data from DISORT to the observed radiances from the image file by adjusting optical depth. By looking at the average intensities of both outputs starting at the zeroth moment, MPFIT evaluates the error at each quadrature angle, minimizing slope errors by varying optical depth, until it reaches a global minimum. If a best fit is not found, the routine starts over choosing new starting parameters and repeats the curve-fitting process again. Once a best fit is found, the error is returned along with a corresponding optical depth value for the sky radiance profile.

Fig. 4 illustrates the comparison of model data with the observed data using the MPFIT routine. The apparent pattern is a 1° azimuth and elevation grid, sampled from the image and calculated in the model. The logarithmic sky intensity for each grid point in the image file (black) is compared against the logarithmic sky intensity computed using the model data (green) for the same set of grid points. The image on the left demonstrates the effect clouds have on the model derived sky brightness, whereas the image on the right is a "typical" or clear sky frame. In both cases, the model still manages to produce a radiance profile that is in close agreement with that observed from the image file.

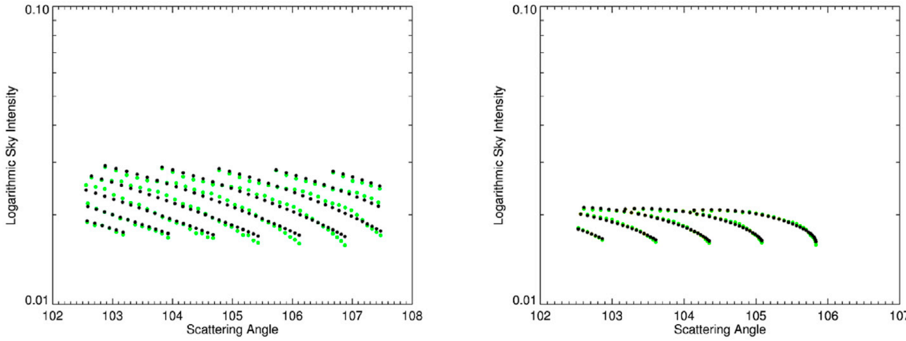
4.2. Results

The low-sky images taken by Navcam span an elevation range of roughly 30–45° with azimuthal angles that are nearly perpendicular to the Sun's location in the sky. This was done in order to reduce instrumentally reflected sunlight and replicate the geometry outlined in the model description. Optical depth was modeled from the images using the resulting brightness profile at constant scattering angle. The derived optical depth values were then compared to daily, solar-imaging optical depth measurements from Pancam (Lemmon et al., 2015) to evaluate goodness of fit. Using the same sol range as the Navcam observations, the average uncertainty of the Pancam optical depth data set was found to be 0.058. While this is considered fairly typical for error during this particular sol range, it is high for the data taken as companion to the Navcam "*InSight* tau" sequence. For example, the optical depth acquired by Pancam on sol 4034 is 0.853 ± 0.062 near noon, but 0.827 ± 0.028 70 s after the Navcam "*InSight* tau" is acquired. This is normal, however, and to be expected, as the uncertainty is controlled by airmass.

The scattering model performs an iterative comparison of 37 Navcam images spanning approximately one Martian year. In order to guarantee a near-90° scattering angle without adding to the operational complexity of the rover, a mosaic acquired 2 images for each desired image, where one, depending on the season, was either too far west or too far east (i.e. western images had the correct angle in the northern hemisphere spring/summer, the eastern images did so in the northern hemisphere fall/winter). The 37 additional images also had sky brightness modeled and were analyzed for completeness.

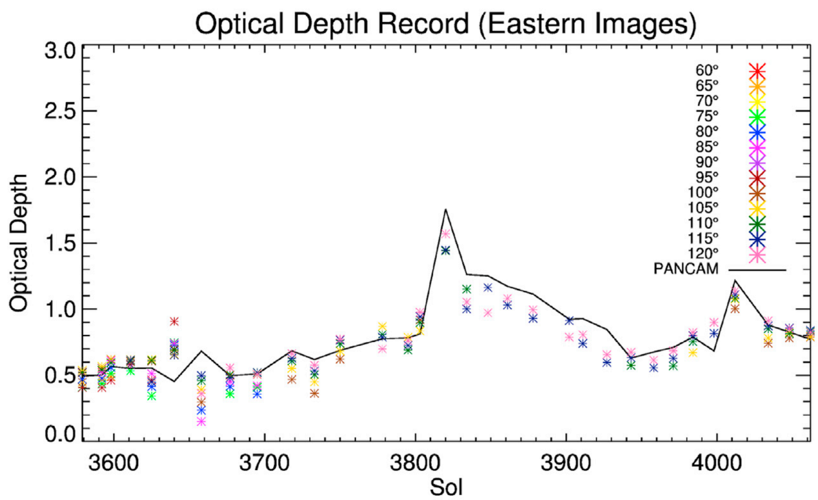
Using *I/F* values from DISORT and the MPFIT routine embedded within the scattering model, optical depth was derived for scattering angles ranging from 60 to 120°. This information is presented in Fig. 5 and shows the importance of maintaining an appropriate angular separation between the Sun and camera line of sight. The figure shows the results from eastern and western images; the western images were aimed more toward the Sun, as the data were taken before sunset. For all sols, but especially 3580–3680, the nearer-Sun image resulted in much more scatter; this is noise due to sunlight directly on the dusty optics. The eastern image produced more accurate results due to minimal contamination by stray light. We note that the highest optical depths were underestimated for retrievals using all scatter angles over 3800–3920, but not 3940–4060; this may be an indication the results are biased low for high optical depth (as expected given the radiance ratio should approach a constant value at arbitrarily high optical depths). To determine which scattering angle produced the best results, an in-depth statistical analysis was applied to the data set. For each scattering angle variance, standard deviation, RMS error, and a reduced χ^2 value were computed. From these statistical tests, it was found that a scattering angle of 105° resulted in a derived optical depth with the best fit when compared to the Pancam data set that was taken in conjunction with the Navcam data on the same sol.

RMS error as a function of scattering angle, with Pancam providing

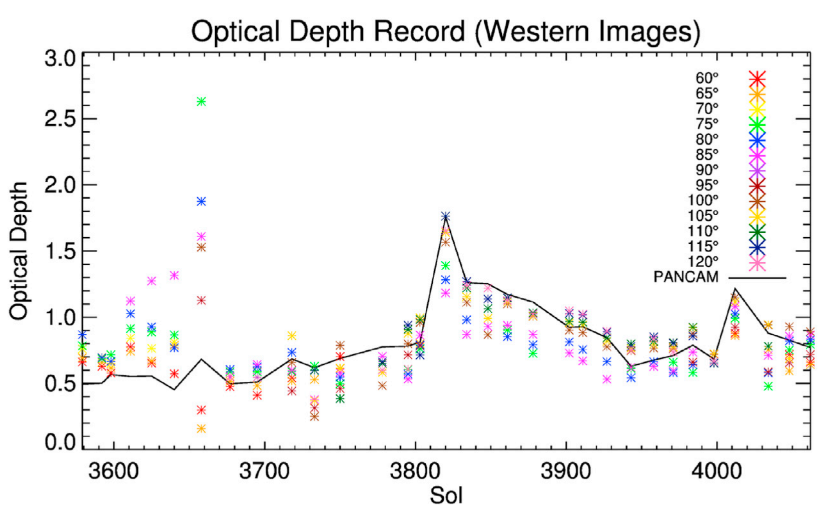


(a) Sol 3640 (b) Sol 4012

Fig. 4. Output from scattering model showing a 1° azimuth and elevation grid sampled from the image file and calculated within the model. Image sky is show in black with the model sky in green for both cloudy conditions (a) and clear skies (b).



(a) Derived optical depth values from eastern Navcam images for both northern hemisphere spring/summer (left) and fall/winter (right).



(b) Derived optical depth values from western Navcam images for both northern hemisphere spring/summer (left) and fall/winter (right).

Fig. 5. Derived optical depth values obtained from scattering model for sols 3579–4248. Sky optical depth was derived for a range of scattering angles ($60-120^\circ$) and compared against observed Pancam values (black line) for both dusty ($L_S = 180-0^\circ$) and dust-free ($L_S = 0-180^\circ$) seasons. The top left and bottom right plots are used in the construction of a complete optical depth record.

the observed measurement, is examined in Fig. 6. This was done in order to show which angles produced a derived optical depth value with the smallest error and justify our reason for choosing a scattering angle of 105° as our standard. There is no significance choosing 105° as opposed to any of the other scattering angles within a ±5° range, as long as the selection process carefully considers what season the image was acquired in, or where the rover's camera was pointed relative to the Sun's location in the sky.

Fig. 6 also demonstrates that throughout the Martian year, especially $L_S = 0 - 180°$, western images were often acquired too close to the Sun. This resulted in a higher overall RMS error that is observed in both sets of western images. Eastern Navcam sky images, on the other hand, appear to produce optical depth values that are in close agreement with Pancam results across a much wider range of scattering angles than western sky images. This is because these images tended to be focused on a region of sky that was further away from the Sun, and thus, more forgiving. Standard deviation and reduced χ^2 as a function of scattering angle were also looked at and used to further verify the conclusions made above.

We use a scattering angle of 105° as our reference and examine the data set further by performing a variety of statistical tests. An analysis including which low horizon sky images (western or eastern) to use in order to produce an accurate and consistent optical depth record was also done. Results from the observational campaign can be summarized in Table A1 found in Appendix A. The Elevation Angle and Derived Navcam Tau columns are a constructed by choosing the appropriate (i.e. seasonally correct) images. From sol 3579–3750, eastern sky images were used to construct the Elevation Angle and Derived Navcam Tau columns, sol 3778–4048 use western sky images, and sol 4062–4248 use eastern sky images. This selection criteria is based on having the image boresight close to 90° away from the Sun as the azimuth of sunset seasonally moves. The last column, Error, is simply the difference of the derived Navcam optical depth from the observed Pancam optical depth.

Sky optical depths ranging from 0.391 to 1.64 were tested using the scattering model. The value of optical depth did not seem to have any affect on the model's ability to derive an accurate measurement when compared to the corresponding Pancam value. The standard deviation of the derived Navcam optical depth data set was found to be 0.239. When compared with the Pancam data set, the standard deviation of the residual error was measured to be 0.07. Taking the absolute value of the last column in Table A1, the RMS error was also computed, with having a value of 0.124. The RMS error is a measure of the error around the regression line, in the same sense that the standard deviation is a measure of variability around the mean. Approximately 65% of the data was found to lie within one RMS error when a regression line was constructed.

Using the results in Table A1, a Navcam optical depth record was constructed as seen in Fig. 7. The Pancam derivation, as reported in Lemmon et al. (2015) and the PDS archive, includes a correction for 1/2 optical depth on the Pancam windows, while the Navcam data show no need for window-dust correction. To further demonstrate the robustness of the atmospheric scattering model, derived Navcam optical depth values were superimposed with the preliminary results generated from the database of synthetic sky images. The brightness profile in Fig. 8 shows that the majority of derived data points are in close agreement and capture the same general pattern as the preliminary results, which were used to model the Martian sky. Several Navcam sky images did not exhibit a scattering angle of 90° for the selected elevation angles of 15° and 30°, which resulted in the inaccurate derivation of optical depth, and thus produced outlying data points. Nonetheless, this brightness profile demonstrates the strong correlation of radiance ratio with optical optical depth for the observed data. Furthermore, the strong correlation between these two parameters allows for a quick approximation if one is interested in knowing what the intensity ratio is for a specific optical depth or vice versa.

With the exception of a few minor instances, we have demonstrated that retrieving optical depth from Navcam non-solar sky images using a robust scattering model works with a high degree of accuracy. Even with dusty optics, the ratio method employed by the scattering model is able to fit the model radiance profile to the image radiance profile with very little error.

The robustness of the scattering model originates from utilizing the optical and bulk scattering properties of the dust particles rather than the physical properties (shape, composition, etc.). Thus, no specific information about the dust itself is needed, other than aerosol optical depth, for the scattering model's ratio method to produce high fidelity results. Assuming no bias and that the RMS error of 0.124 can be attributed to a combination of the (unknown) error of the model fitting process and the intrinsic Pancam error of 0.058, we can estimate that the intrinsic Navcam error is 0.084.

4.3. Error investigation

After performing a statistical analysis on the data set, an investigation

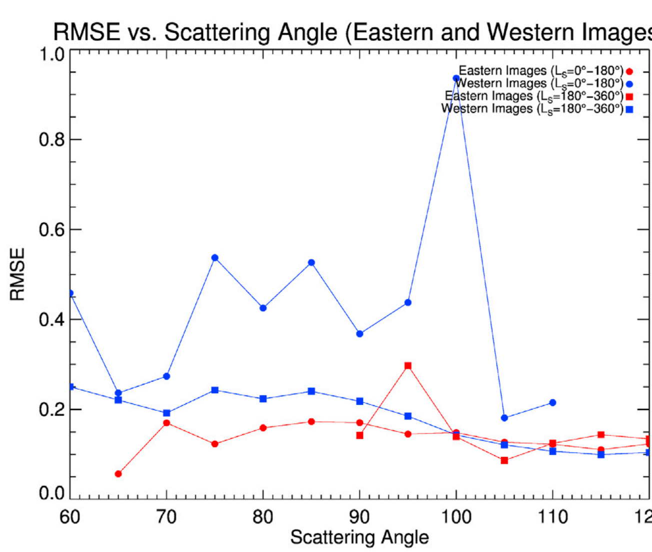


Fig. 6. Root Mean Square Error (RMSE) vs. Scattering Angle. The different colors represent the directional pointing of the image, east-facing (red) and west-facing (blue), and the different shapes represent the season the image was acquired in, $L_S = 0 - 180°$ (circle) and $L_S = 180 - 360°$ (square).

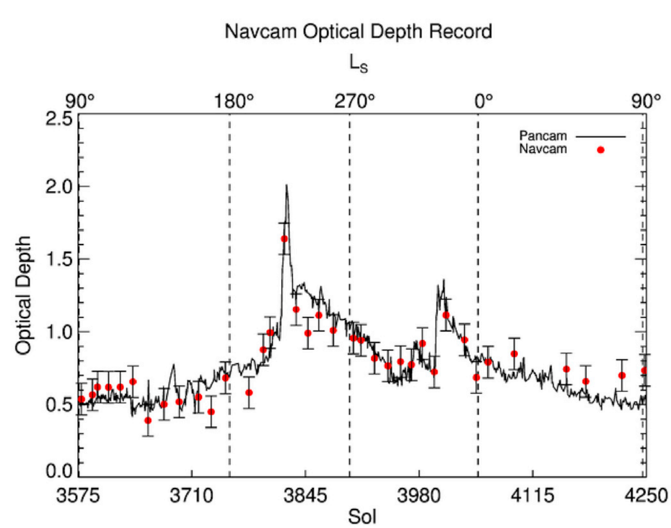


Fig. 7. Derived optical depths are shown (red), and compared to the daily solar-filter optical depth record from Pancam (Lemmon, 2014). Error bars are the overall RMS error.

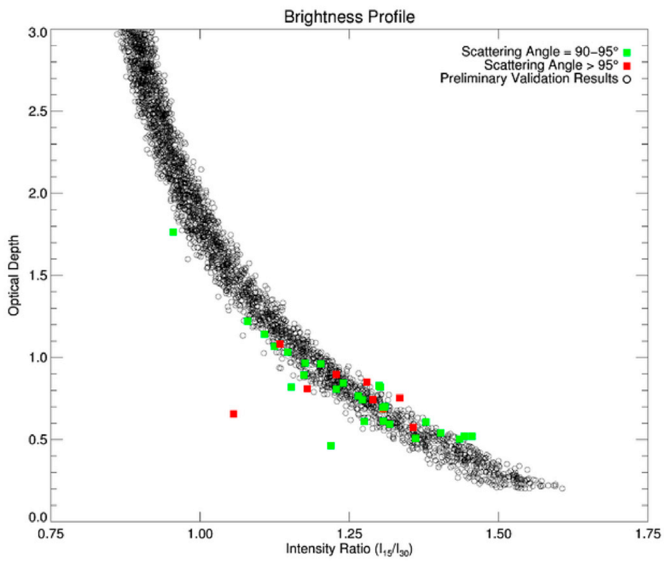
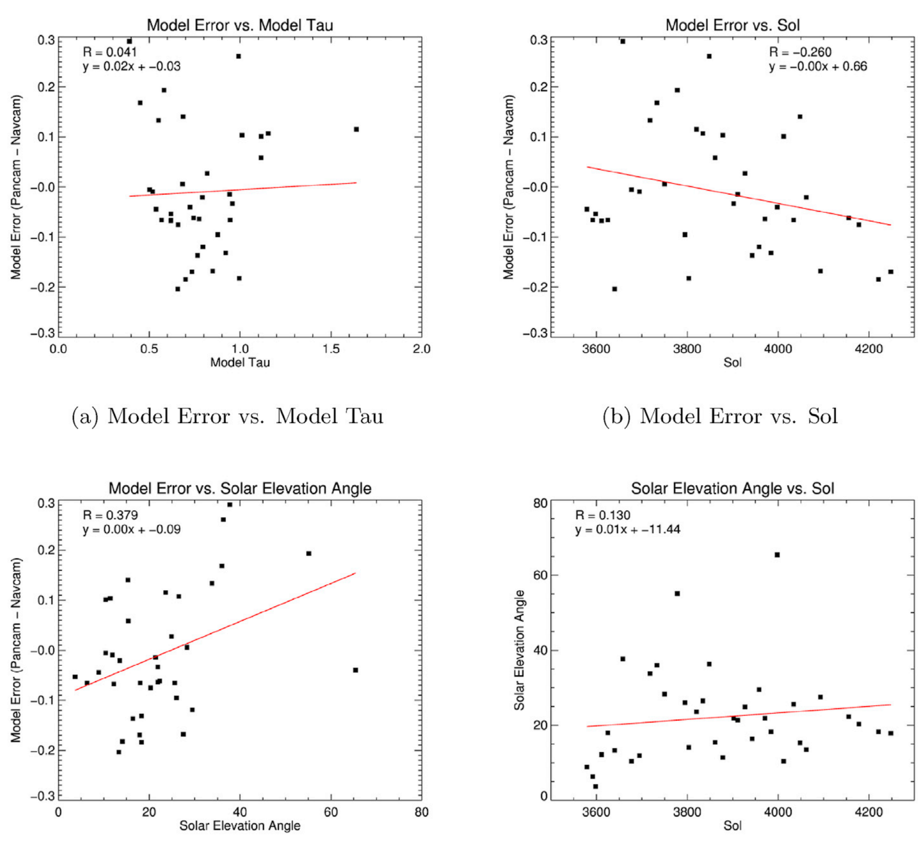


Fig. 8. Derived Navcam optical depths superimposed with the preliminary validation results. Despite a few outlying data points, the model is able to fit the retrieved data to within a high degree of accuracy and shows the same strong correlation of radiance ratio with optical depth as the preliminary data resulting from the synthetic sky images.

searching for possible sources of error was undertaken. Model error was compared to a variety of parameters including model optical depth, elevation angle, and sol. Elevation angle as a function of sol was also examined, searching for a potential relationship between the two variables. As seen in Fig. 9, however, no correlation was found between any of these parameters.

Once it was established that optical depth values for a scattering angle of 105° were the data set of record, a closer look was taken to understand how the error in derived model optical depth affected the logarithmic sky intensity generated by DISORT. A test, therefore, using perturbed model optical depth and radiance as a function of elevation angle was used to investigate error propagation. In addition to model sensitivity, this test was also used to determine whether the derived optical depth values obtained from a scattering angle of 105° were in fact the best values (i.e. had the smallest error difference) when looking at an elevation profile and comparing the results with daily solar imaging observations from Pancam.

Fig. 10 shows the acquired Navcam sky image and resulting elevation profile from the scattering model. The best fit series (black diamonds) is the difference in sky radiance resulting from the derived optical depth value which produced the smallest error and the sky radiance computed from the image file. This comparison of model radiance with image radiance is done several times by perturbing the best fit optical depth value (shades of blue and green diamonds) to demonstrate the accuracy and robustness of the scattering model. The perturbed fits were computed by offsetting the best fit value by a standard deviation of ±1 (0.239) and ±2 (0.478) respectively. A closer look at Fig. 10 reveals that the best fit series for each sol captures the observed Pancam measurements very well, while the perturbed series do much worse and begin deviating far away from what is actually observed. The cloudy day (sol 3640) doesn't do quite as well when matching the derived data set with the observed Pancam record due to the spatial variability of the clouds since the scattering model assumes a uniform, homogeneous sky.



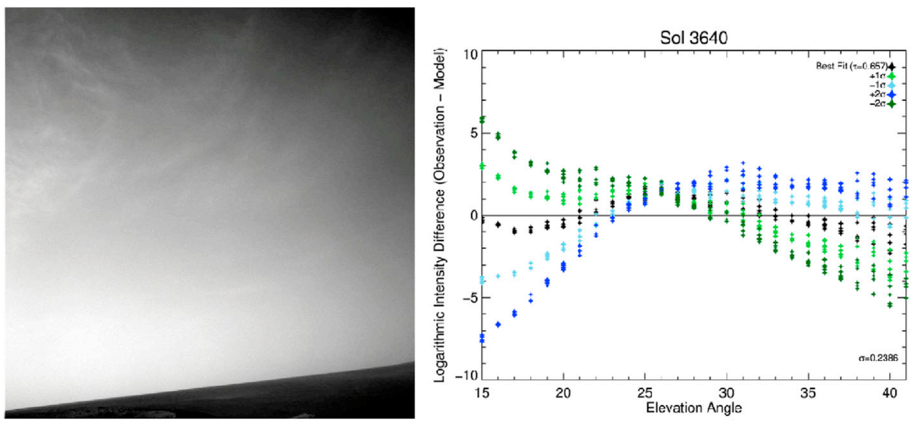
(a) Model Error vs. Model Tau

(b) Model Error vs. Sol

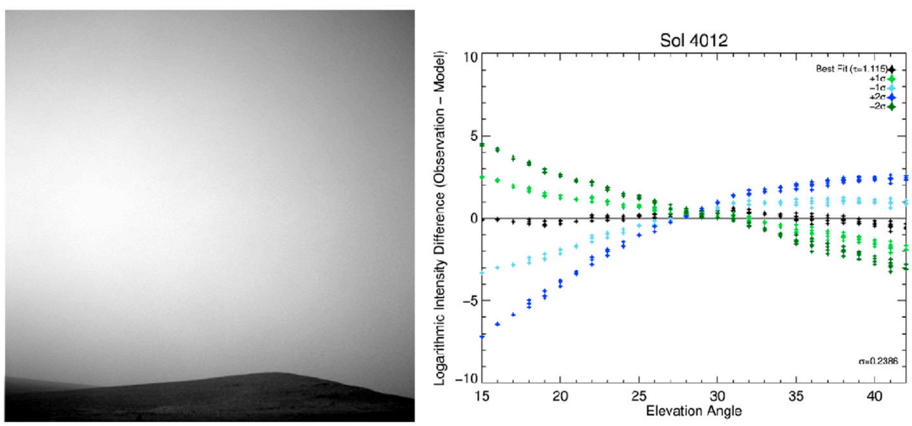
(c) Model Error vs. Elevation Angle

(d) Elevation Angle vs. Sol

Fig. 9. Model error compared to various parameters in an attempt to find possible correlations hidden within the data, and thus, potential sources of error and error propagation.



(a) Navcam sky image and model error with perturbed fits for sol 3640



(b) Navcam sky image and model error with perturbed fits for sol 4012

Fig. 10. Elevation profiles showing the logarithmic difference in sky intensity between the image sky and model sky. The best fit series (black diamonds) is the sky radiance resulting from the derived optical depth value which produced the smallest error and subtracted from the sky radiance computed from the image file. This comparison is done several times using perturbed fits (shades of blue and green diamonds) to show the accuracy of the scattering model.

5. Discussion

5.1. Seasonal variation of optical depth

The derived optical depth values obtained from Navcam were able to capture the seasonal variability of optical depth over the course of about one Mars year. The TES climatology (Smith, 2004) and previous observations over the last 5 Mars years (Lemmon et al., 2015) would suggest that optical depths would decline into aphelion season, rise slightly near $L_S = 135°$, and become dusty during perihelion season, with dust increases around $L_S = 180°$, $L_S = 220°$, and $L_S = 320°$. Other than a few slight variations, this typical seasonal pattern in optical depth was observed once again at the *Opportunity* site during this simulation-based imaging campaign. Fig. 11 presents a climatological optical depth record created from 5 Mars years worth of data. The derived optical depth record generated during this campaign is overlaid on a pseudo-composite optical depth record created from minimum/maximum sky optical depth values collected at the *Opportunity* site from the last 5 Mars years. Throughout most of the year, the derived optical depth record stays fairly close to the shaded band of optical depth values. Patchy clouds, which are discussed in the next section, and dusty camera optics are among the few things responsible for small deviations in the derived Navcam optical depth record seen in Fig. 9.

Navcam sky images were acquired starting on $L_S = 91.1°$, during the relatively dust-free aphelion season. Beginning around $L_S = 149.5°$, a gradual increase in optical depth was observed, hinting at the possibility of an inbound dust storm. By $L_S = 220.0°$, a regional dust storm had

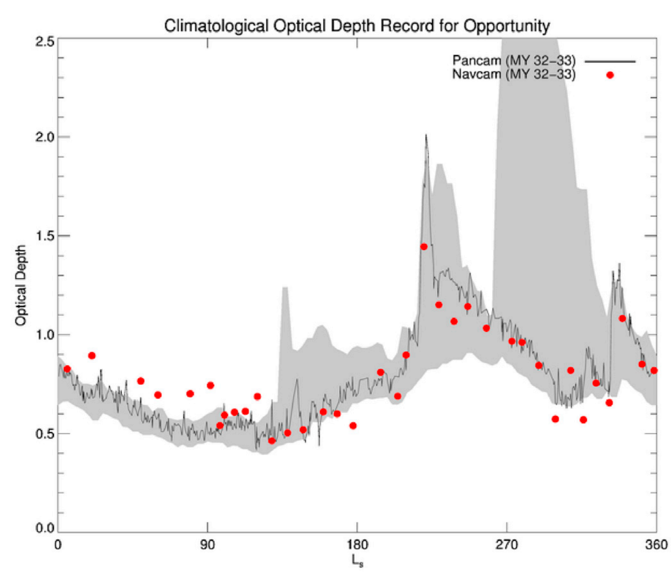


Fig. 11. Climatological optical depth record at *Opportunity* site. The shaded region represents 97.5% of all tau values that were collected over 5 Mars years. The black line is the Pancam optical depth record for MY 32–33 and the red dots are the derived optical depth record from Navcam.

formed over Cape Tribulation on the western rim of Endeavor crater with optical depth abruptly rising to a value of 1.640. This was followed by a steady, but relatively steep decline in optical depth to a local minimum of 0.766 occurring on sol 3943. Such a decrease translates to a change of 0.71% per sol, which is consistent with initial reports of 0.6–0.7% per sol by (Lemmon et al., 2004). Regional-scale dust storms like this one occur every Martian year during the dusty season, particularly near $L_S = 225°$ and 315°, when cross-equatorial flushing dust storms occur (Smith, 2008).

After this fairly substantial decrease in optical depth, a short-lived fluctuation of $\Delta\tau = 0.2$ occurs around $L_S = 320.0°$ before jumping to $\tau = 1.115$ around $L_S = 340.0°$. Once again this sharp rise in optical depth is followed by a steady decline that persists until the end of MY 32 and continues through MY 33 until $L_S = 90.0°$ when non-solar Navcam sky observations ceased and one Mars year worth of data had been collected. During this relatively inactive time period spanning from $L_S = 0°–180°$, there are no very large dust storms and the atmosphere is characterized by a much lower background level of dust optical depth. Local dust storm activity is confined largely to the region near the edge of the seasonal polar ice caps, especially along the retreating north cap during northern spring, and along the southern cap at the end of southern winter (Smith, 2008).

Throughout most of the imaging campaign, the sky optical depth derived from non-solar Navcam sky images captured the same seasonal changes in dust loading and followed the same general pattern as measured by Pancam. The derived optical depth measurements resulting from the scattering model's ratio method have been shown to be precise enough to detect small changes in sky optical depth, allowing a detailed and accurate optical depth record to be constructed. Creating climatological optical depth records like the one in Fig. 11, therefore, are not only important for understanding seasonal changes in dust loading, but may also provide engineers with the necessary information to ensure the safety of solar-powered rovers and landers during a mission.

5.2. Clouds

In addition to dust, aerosols in the form of condensate clouds occur frequently on Mars. During the aphelion season, condensate clouds made up of water ice and CO_2 ice are intermittently observed by both ground and orbiting spacecraft. Such clouds contributed to the observed optical depth at the *Opportunity* site during $L_S = 105–119°$, with peak activity occurring near $L_S = 119°$. Wispy cloud formations were also observed around $L_S = 20°$.

The Navcam images acquired by *Opportunity* are not indicative as to the cloud composition. Water ice is likely, however, given the aphelion cloud belt was at its maximum extent over the *Opportunity* site during this time period. Water ice hazes may have been present as well. Nonetheless, it is during this seasonal phenomenon that several data points are seen to lie above the general trend characterized by Pancam measurements, as shown in Fig. 11. It is possible that, as the ice-to-dust ratio increased, this introduced an upward bias to the measurement; however, there is insufficient data to robustly conclude this.

This low-latitude belt of clouds described above appears to repeat every year with very similar amplitude and spatial distribution. The cloud belt begins to form around $L_S = 0°$, building to maximum intensity and spatial coverage by about $L_S = 80°$. The cloud belt has significant optical depth between 10°S and 30°N latitude, with higher optical depth over topographic highs. Repeated imaging of the sky shows that clouds are common at the *Opportunity* site between $L_S = 20°–140°$, and often have a morphology similar to terrestrial cirrus clouds (Smith, 2008). The optical depth of water ice clouds is often anticorrelated with that of dust. Whereas large dust storms form preferentially during the dusty, perihelion season ($L_S = 180°–360°$), the greatest extent of water ice clouds are observed during the cooler aphelion season ($L_S = 0°–180°$) and in the polar regions in the winter hemisphere (Tamppari et al., 2000; Pearl et al., 2001; Liu et al., 2003; Smith, 2004).

Despite their relatively small spatial coverage, ice clouds on Mars have a significant effect on the global water cycle. The radiative effects of water ice clouds on the temperature profile of Mars can also be quite substantial. Infrared properties inherent of water ice, combined with the low-mass of the Martian atmosphere, can lead to strong thermal cooling by water ice clouds during the night (Smith, 2008). Indirectly these clouds may also play a critical role in dynamics of the planet.

In addition to affecting the Martian climate, clouds also affect sky brightness. This is particularly problematic when clouds, especially those that have a wispy-like structure, are present in Navcam's FOV. This is because the scattering model assumes horizontally homogeneous scatterers, creating a layer of uniform sky brightness. Depending upon spatial coverage, discrete cloud formations can result in derived optical depth values deviating as much as 1-sigma from what was observed with Pancam. Such occurrences are rare however, as clouds were only noticeably visible in 2 of the 37 observations that were made with the Navcam instrument. Despite the scattering model having some difficulty interpreting cloudy images, it still remains fairly robust and is able to derive optical depth values that fit closely to Pancam observations taken on the same sol.

6. Conclusions and future work

We have shown that radiative-transfer modeling of sky images can reproduce a direct-solar imaging optical depth record with only a modest decrease in accuracy. An optical depth record for the *Opportunity* rover was generated using non-solar sky images from the onboard engineering cameras and a robust scattering model. The data set spans approximately one Mars year, including periods of local and regional dust storms as well as the intermittent appearance of discrete cloud formations. Even with dusty optics, this simulation-based imaging strategy retrieved solar-extinction optical depth with good accuracy, with an intrinsic Navcam error of 0.084 and RMS error of 0.124.

The scattering model has known modes of failure or low-accuracy, as was observed when the camera was pointed too close to the Sun or clouds were in the camera's FOV. Missions that rely on sky images for optical depth should have a plan to avoid near-Sun images, which are prone to stray-light intrinsic to the hardware as well as that caused by dusty optics. Further, images should be inspected for clouds prior to validating the derived optical depths. Our tests used only data from $> 10°$ elevation angle, following the Tomasko et al. (1999) finding that plane-parallel models were typically adequate above that elevation but were increasingly poor at lower angles. The tests were done over an optical depth range of 0.5-1.5; the method is unlikely to work with optical depths $>> 1$ due to homogenization of the sky.

With planetary science budgets getting ever tighter, it is not always possible to equip landers and rovers with science cameras that include dedicated solar filters. The encouraging results obtained from the scattering model's robust ratio method are not only important for *InSight*, but other future missions equipped with similar cameras as well. Besides providing significant contributions in terms of spacecraft cost and development, these results will also benefit mission operations and planning. Furthermore, innovative imaging techniques, such as the one described in this work, also provide rovers and landers with greater functionality. Despite their basic purpose, engineering cameras have the ability to provide a good estimate of the amount of dust in the Martian atmosphere when coupled with a robust scattering model.

Author statement

Chris Wolfe: Writing- Original draft preparation, Investigation, Methodology, Visualization, Validation.

Mark Lemmon: Data curation, Conceptualization, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Navcam *In Sight* Tau Results

Table A1
Derived Navcam *InSight* tau results with observed Pancam measurements acquired on the same sol for comparison.

Sol	Elevation Angle (°)	Derived Navcam Tau	Pancam Tau	Error
3579	8.9	0.537	0.493	−0.044
3592	6.3	0.567	0.501	−0.066
3598	3.7	0.620	0.567	−0.053
3611	12.2	0.619	0.552	−0.067
3625	18.0	0.620	0.554	−0.066
3640	13.3	0.657	0.453	−0.204
3658	37.7	0.391	0.682	0.291
3677	10.4	0.502	0.497	−0.005
3695	11.9	0.519	0.510	−0.009
3718	33.8	0.551	0.685	0.134
3733	36.0	0.450	0.619	0.169
3750	28.3	0.683	0.689	0.006
3778	55.1	0.582	0.775	0.193
3795	26.0	0.877	0.782	−0.095
3803	14.1	0.995	0.813	−0.182
3820	23.6	1.640	1.756	0.116
3834	26.5	1.154	1.261	0.107
3848	36.3	0.991	1.252	0.261
3861	15.4	1.114	1.173	0.059
3878	11.4	1.010	1.114	0.104
3902	21.9	0.957	0.924	−0.033
3911	21.4	0.942	0.928	−0.014
3927	24.9	0.818	0.845	0.027
3943	16.4	0.766	0.629	−0.137
3958	29.5	0.795	0.676	−0.119
3971	21.9	0.774	0.710	−0.064
3984	18.3	0.920	0.789	−0.131
3998	65.4	0.724	0.684	−0.040
4012	10.4	1.115	1.216	0.101
4034	25.6	0.945	0.879	−0.066
4048	15.3	0.686	0.826	0.140
4062	13.5	0.792	0.771	−0.021
4093	27.5	0.849	0.681	−0.168
4155	22.3	0.744	0.682	−0.062
4178	20.3	0.659	0.584	−0.075
4221	18.3	0.700	0.516	−0.184
4248	17.9	0.735	0.566	−0.169

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