User Guide for the msl_ice-dust-methane PDS Bundle

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Introduction

Several atmospheric observations were conducted using the cameras on the Mars Science Laboratory (MSL) rover to address some of the following science objectives to contribute towards characterization of the local environment in Gale Crater:

- Characterization of inter-annual variability of different populations of water-ice clouds
- Characterization of airborne dust and flux throughout Gale Crater

To address the first objective, the MSL Navigation camera (Navcam) was used to produce Zenith Movies, Phase Function Sky Surveys, Suprahorizon Movies, and Cloud Altitude Observations. The Zenith Movies are used to obtain cloud size, direction, and relative movement when pointed near zenith. The current iteration of the Suprahorizon Movies provides similar information when pointed just above the horizon, with the potential for obtaining more information on cloud morphology. Phase Function Sky Surveys are used to determine phase functions of these clouds, including their particle shape. Navcam is also used for Cloud Altitude Observations by comparing shadows of clouds cast against Aeolis Mons in conjunction with Zenith Movies with Cloud Shadow Movies.

The second objective is support by observations from Navcam and Mastcam. Images of the Gale Crater rim with the Navcam Line of Sight observation can be used to estimate the opacity between MSL and the crater rim. These observations can be compared against the Mastcam opacity observations (tau values) to evaluate the flux in and out of the crater at various times of day and year. These observations provide additional regional context for the Rover Environmental Monitoring Station (REMS) data that is taken at the present MSL location. Most of these observations follow a regular cadence of every few sols, with heightened regularity for the cloud observations during Aphelion Cloud Belt (ACB) season once they are introduced.

The observations included in this bundle currently include:

- Line of Sight (LOS)
- Zenith Movies (ZM), some that are taken as part of Cloud Altitude Observations (CAO)
- Suprahorizon Movies (SHM)
- Phase Function Sky Surveys (PFSS)
- Cloud Shadow Movies (CSM), taken as part of Cloud Altitude Observations

An overview of the MSL mission and overall science objectives can be found in (Grotzinger et al., 2012).

Bundle Structure

Data in the msl_ice-dust-methane are provided in two forms, the data_derived bundle that contains values for the reported data and interpretations of the observations, and the documents bundle that contains images in the form of movie gifs for observations that have been post-processed and are ready for use and interpretation. Each file in data_derived and documents has a corresponding xml file that can be downloaded for meta data.

Data in this bundle currently include observations taken starting in April 2022 to December 2023 (sols 3431 to 3902) for the ZM, SHM, PFSS, and CSM observations. The LOS derived data extends to the beginning of the MSL mission.

Line of Sight

The Line of Sight observation is used to examine dust loading in Gale Crater by calculating the dust extinction between the rover and the norther crater rim (Moore et al., 2016; Moores et al., 2015a; Smith et al., 2020). The LOS observation consists of a single-framed Navcam image, with a field-of-view of 45 x 23° (width x height). Every LOS image is processed onboard such that each pixel (512 x 256) is in units of spectral radiance. The images are taken with a site frame azimuth of 0°, pointing directly north, and a site frame elevation of 5° above the horizon, such that a portion of the sky, crater rim, and ground are each in the image.

Processing the images to calculate the dust extinction requires splitting the image in 3 distinct sections: 3.5 to 5.5° ('sky'), 0 to 2° ('crater rim'), and -3 to -10° ('ground'). The ground and sky sections are averaged vertically to become 1D arrays of radiances varying in azimuth. The crater rim section is a 2D array of radiances. The arrays are used in Equation 1 (See Moores et al., (2015a) for a full derivation) to find a dust opacity between the rover and the crater rim:

$$\tau = -\ln \frac{\left(1-\frac{I_S}{I_C}\right)}{\left(\frac{I_G}{I_C}-\frac{I_S}{I_C}\right)} \qquad (1)$$

where τ is the dust opacity, I_s is the array of sky radiances, I_c is the array of crater rim radiances, and I_G is the array of ground radiances. To allow comparison of the dust loading over time as the rover drives further from the crater rim, a digital terrain model is used to find the distance between the rover and crater rim for each image. The dust opacity, τ, is divided by the distance to the crater rim, giving an extinction in units of km^{-1}. The extinction uncertainty is calculated by finding the 95% confidence interval between extinctions calculated using 8-pixel wide subsections across each image. See Table 1 for more details.

Table 1. Table of LOS outputs and metadata descriptions.

Column Description	**Unit**
Sol	Sol
L_s – Solar Longitude	Degrees
MY – Mars year	MY
LTST – Local True Solar Time	Hour
Extinction value	km^-1
Extinction error	km^-1

While these data can be used as a complement to the Mast Camera solar disc images of the whole column (Lemmon et al., 2024), it is important to note that these data represent the dust extinction in only the bottom ~2km of the atmosphere (the approximate height of the crater rim).

Zenith Movies and Suprahorizon Movies

Zenith Movies (ZMs) consist of eight full-frame Navcam images pointed at an elevation angle of 85°. To avoid saturating the camera, the azimuthal pointing is flipped between seasons to point away from the Sun, pointing due north (0°) between Ls = 0 - 190° and due south (180°) between Ls = 190 - 359°. Through sol 2450, the ZMs were subject to 2x2 binning prior to downlink to save on data volume, resulting in the products received on the ground having a resolution of either 511x511 px or 512x512 px depending on the season. Beginning on sol 2451, ZMs were downlinked at their original resolution of 1024x1024 px or 1022x1022 px.

Suprahorizon Movies (SHMs) are functionally identical to the ZMs, but point just over the horizon rather than overhead. Over the duration of the mission, they have been subject to changes in their pointing, downlinked size, number and temporal spacing of frames, and the image compression that is applied onboard prior to downlink. See Table 2 for a summary of these changes. Until lossless compression was implemented on sol 3724, the azimuthal pointing of the SHMs was occasionally adjusted from the listed values to minimize the amount of nearby terrain in the frames. This was done because the lossy ICER compression tends to allocate greater bitdepth to the high-contrast ground than the low-contrast sky, effectively compressing the clouds out of existence when the foreground terrain takes up a large fraction of the frame.

Table 2. A summary of the changes made to the SHM since the beginning of the mission.

Sol Range	Pointing Azimuth	Pointing Elevation	Width [px]	Height [px]	Number of Frames	Time Between Frames [sec]	Image compression
1–593	134°	38.5°	512	512	8	13	ICER
594–910	125.1°	10°	512	1024	4	13	ICER
911–1031	134.6°	43.5°	512	512	8	38	ICER
1032–2450	0° / 180°	26°	512	512	8	38	ICER
2451–3723	0° / 180°	26°	1024	1024	8	38	ICER
3724–4043	0° / 180°	26°	1024	1024	8	38	LOCO
4044–	0° / 180°	26°	1024	1024	16	19	LOCO

The goal of both observations is to determine the motions, morphologies, and opacities of the clouds above and around Gale (Moores et al., 2015b; Kloos et al., 2016, 2018; Campbell et al. 2020, 2021; Hayes et al. 2024). These clouds are optically thin and thus are almost never visible in the raw movies. To extract the clouds from the background sky, we employ a method known as mean-frame subtraction (MFS). First, an average frame is constructed by finding the average value of each pixel across all frames.

This average frame, representing everything in the movie that does not change with time, is then subtracted from each frame, leaving behind everything in the frame that is time-variable (i.e. the clouds). To further enhance the contrast, each frame is re-normalized to remove the highest and lowest 2% of values. Note that all the cloud opacity processing is done on the MFS data, *not* the re-normalized data.

For both observations, cloud opacities are derived using two models that make different assumptions about the nature of the clouds being observed. The first of these is the High Clouds (HC) model, which assumes that the clouds are at high altitudes (above the bulk scattering centers) and are composed of water ice crystals. The HC equation is as follows:

$$\Delta\tau_{HC} = \frac{4\pi\mu I_{\lambda,VAR}\Delta\lambda}{P(\Theta)F_0 e^{-\tau_{COL}/\mu}}$$

where, μ is the cosine of the solar zenith angle, $I_{\lambda,VAR}$ is the difference in spectral radiance between a high- and low-radiance point in a MFS frame (representing a cloudy and cloudless portion of the image, respectively), $\Delta\lambda$ is the spectral bandpass of the Navcams (250 nm; Maki et al. 2012), $P(\Theta)$ is the scattering phase function of the clouds, F_0 is the in-band solar flux at the top of the atmosphere, and τ_{COL} is the atmospheric column density as measured by Mastcam imaging of the solar disc (Lemmon et al. 2024).

It should be noted that the HC opacity values in this archive were determined using a flat scattering phase function that takes on a constant value of 1/15 at all scattering angles. This is generally not an appropriate assumption, so any analysis of these data should begin by dividing the HC opacities by 15 and replacing the $P(\Theta)$ term with one's preferred phase function.

The second model, known as the Whole Atmosphere (WA) model assumes that clouds are at lower altitudes and have similar properties as the bulk atmosphere (i.e. are dust-based rather than ice-based).

$$\Delta\tau_{WA} = -\ln\left(1 + a - \frac{a}{e^{-\tau_{COL}}}\right)$$

Here, *a* is $I_{\lambda,VAR}$ (as in the HC model) divided by the mean radiance of the frame.

Several new observations have been implemented since landing to supplement the standard ZM and SHM cadences. First is the Cloud Altitude Observation (CAO), described elsewhere in this document. Half of this observation consists of a ZM identical to those taken independently, and so are archived here rather than in the CAO archive. ZMs taken as part of a CAO are marked with "CAO" in the "Types" column.

Occasionally, the rover produces significantly more power than it uses on a given sol, which may lead to its on-board batteries maintaining a high state of charge for an extended period. Because this practice would lead to faster degradation of the batteries' maximum capacity, excess power must be "shunted" to the environment, releasing it as waste heat. To minimize the amount of shunting, the "Shunt Prevention Environmental Science Navcam Drop-In" (SPENDI) observation was created, allowing the rover to use excess power to do science. The SPENDI observation consists of movies taken at six different pointings, two of which are similar to the standard SHMs and thus are archived here. The south-facing pointing is identical to the south-facing SHM executed between sols 2451 - 3723, while the north-facing pointing has had its elevation pointing adjusted to 15° to allow it to serve double-duty as a line-of-sight (LOS) observation (described elsewhere in this document). Each observation consists of two (SPENDI), four (SuperSPENDI), or six (UltraSPENDI) SHM-like movies. This is noted in the "Types" column.

Table 3. ZM and SHM table of outputs and metadata descriptions.

Column Description	**Unit**
Filename – corresponds to the gif file	N/A
MY – Mars Year in which the observation was taken	N/A
Sol – sol number on which the observation was taken	N/A
ACB – whether the observation was taken during Aphelion Cloud Belt Season	Y (yes) or N (no)
Type – what the observation was part of	–ZM, SHM for regular Zenith Movies and Suprahorizon Movies –CAO if the ZM was taken as part of a Cloud Altitude Observation –SPENDI, SuperSPENDI, or UltraSPENDI if the SHM was taken as part of shunt prevention
Ls – Solar Longitude	Degrees
LTST – Local True Solar Time	hh:mm:ss
Mcam Tau – Mastcam tau value	unitless
Width – Image width	Pixels
Azimuth – Navcam pointing azimuth	Degrees
Elevation – Navcam pointing elevation	Degrees
High SA – scattering angle of high radiance points	Degrees
Low SA – scattering angle of low radiance point	Degrees
High Mu – Cosine of high radiance point	unitless
Low Mu – Cosine of low radiance point	unitless
Quality – subjective movie quality	unitless
Frame – Frame number selected for analysis	unitless
highX – column number of high radiance point	unitless

highY – row number of high radiance point	unitless
lowX – column number of low radiance point	unitless
lowY – row number of low radiance point	unitless
a – radiance difference between high and low radiance points divided by the mean radiance of the frame	unitless
IVAR – radiance difference between high and low radiance points	$W\ m^{-2}\ sr^{-1}\ nm^{-1}$
high sd – standard deviation of high radiance point	$W\ m^{-2}\ sr^{-1}\ nm^{-1}$
low sd – standard deviation of low radiance point	$W\ m^{-2}\ sr^{-1}\ nm^{-1}$
Tau (WA) – whole atmosphere opacity	unitless
Noise (WA) – whole atmosphere noise	unitless
Tau (HC) – high cloud opacity	unitless
Noise (HC) – high cloud noise	unitless

Phase Function Sky Survey

The phase function sky survey (PFSS) consists of nine three-frame movies at different pointings forming a dome around the rover. Each movie is made of 512x512 pixel frames taken by the Navcams. Its purpose is to image clouds at a range of scattering angles in order to derive a single scattering phase function (Cooper et al, 2019; Innanen et al, 2024). The observation is performed only during the ACB season, and has both morning and afternoon versions. The movies all undergo mean frame subtraction to resolve cloud features.

Cloud Altitude Observations

The Cloud Altitude Observation (CAO) consists of two parts, a zenith movie and a cloud shadow movie (CSM) in order to capture aerosol movement and its corresponding shadows to calculate a direct altitude. This observation is taken on a weekly cadence during the Aphelion (ACB) season, where clouds are more regularly seen (Lemmon et al., 2015; Campbell et al., 2020). The zenith movie is an 8-frame movie with 1024x1024 pixel frames pointed vertically overhead and processed in the same manner as a typical ZM (see section above). The CSM is likewise an 8-frame movie of 1024x1024 pixels, processed in the same manner, but points towards East at Aeolis Mons (Mt. Sharp). When Aeolis Mons is not visible at the time, the CSM azimuthal pointing can be changed to view other features that could show shadow movement. Both movies undergo mean frame subtraction to resolve cloud and shadow features. See Campbell et al, (2023) for details on angular wind speed, absolute wind speed, and estimation of aerosol altitudes.

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Record of Revisions

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