ASSESSING THE SUB-PIXEL SENSITIVITY OF ATMOSPHERIC RETRIEVALS FROM THE EMIRATES MARS INFRARED SPECTROMETER

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Introduction: In planetary science, remote sensing instruments generally do not make direct observations of desired geophysical and/or atmospheric parameters. Instead, retrieval algorithms that rely on quantifiable light-matter interactions are employed to derive the sought-after parameters. Retrieval algorithms typically consist of a forward model that makes use of a radiative transfer code. The forward model calculates radiance at different wavelengths as a function of some parameter (i.e. atmospheric temperature). Inversion of this forward model using the observed spectra then provides a retrieval of that parameter.

In the case of the Emirates Mars Mission (EMM), dust and water-ice optical depth, surface and lower atmospheric temperatures, and water vapor abundance are all retrieved from thermal-IR spectra observed by the Emirates Mars Infrared Spectrometer (EMIRS) instrument. While observations made by EMIRS typically provide excellent global coverage, specific measurements are not always possible. In many cases a single field of view (FOV), or pixel, may contain numerous geologic units with varying surface temperature, thermal inertia, and surface roughness, complicating the retrieval process. Furthermore, pixels that are far from the sub-spacecraft point often span a wide range of emission angles and local times, leading to additional uncertainty.

In order for the EMIRS forward model to produce accurate retrievals related to the dynamics of the lower atmosphere, it is vital that we not only understand how retrieved parameters vary at the sub-pixel level, but how the sub-pixel resolution, or number of sub-pixels needed within a pixel, changes as a function of known forward model parameters. By quantifying sub-pixel variability and associated parameter uncertainties, as well as quantifying the minimum number of required sub-pixels, the acquisition of reliable results regardless of viewing geometry, latitude/longitude, season, local time, etc. can be achieved.

Methodology: Sub-pixel variability was modeled and determined by computing the standard deviation of a variety of forward model input parameters, including surface/atmospheric temperature, dust column optical depth, and water vapor abundance for each pixel in a synthetic disk observation **[1][2]**. By quantifying sub-pixel variability, pixels that exceed the modeled retrieval uncertainty associated with a particular parameter can be flagged. Pixels that exhibit high variability and have been flagged can then be assigned less weight or otherwise ignored, ensuring the accuracy of the forward model results and thus retrieved parameters.

The uncertainty associated with a retrieved parameter is calculated by dividing the average noise equivalent spectral radiance (NESR) of EMIRS, $\sim 2.8 \times 10^{-8}$ W cm-2 sr-1 cm-1 **[5]**, by the sensitivity associated with that parameter. Sensitivity, in this case, was determined by perturbing a known forward model input parameter by a small fraction of its average value (1%) and dividing the maximum residual spectral radiance (i.e. the difference between the average or standard spectral radiance and the perturbed spectral radiance) by the amount of perturbation (in units of the retrieved parameter) applied.

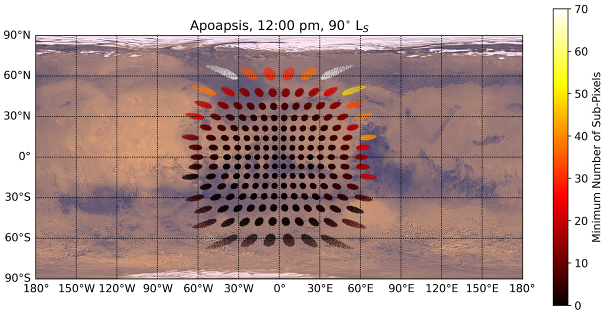

Figure 1: The minimum number of sub-pixels, or sub-pixel spatial resolution, required for the accurate retrieval of atmospheric parameters from EMIRS at apoapsis for northern hemisphere summer and a local time of noon.

In addition to sub-pixel variability and retrieval uncertainty, the number of required sub-pixels as a function of a known forward model input parameter was also investigated. Constraining the minimum number of sub-pixels needed to accurately retrieve parameters using the EMIRS forward model was accomplished through an iterative approach that compares the average spectral radiance difference of adjacent sub-pixels against the NESR of EMIRS **[3]**. If the difference between sub-pixels exceeds the NESR, the first sub-pixel in the pair of sub-pixels is counted, or in other words, deemed necessary for an accurate retrieval. The comparison then begins again, starting with the sub-pixel that was previously counted and comparing the spectral radiance with the next adjacent sub-pixel, continuing until all sub-pixels in a pixel are accounted for. Figure 1 provides an example of the number of sub-pixels necessary for each pixel in a synthetic EMIRS disk observation during northern hemisphere summer and a local time of noon.

In a single pixel, rocks, sand, and dust will have different temperatures as a function of the time of day due to the variations in thermal inertia **[6]**. The mixture of surfaces, and thus thermal inertias, complicates the process of retrieving atmospheric properties from spectral radiance. The current retrieval algorithm for EMIRS makes use of a single surface temperature. In many cases, this single surface temperature is unable to capture the variability within a single pixel.

To quantify the importance of rock abundance when retrieving atmospheric properties with EMIRS, we first compute an apparent and effective radiance associated with each pixel. Resulting Plank curves are then used to compute an apparent and effective brightness temperature at a specific wavenumber. Pixels are modeled based on a fractional mixture of a fine component thermal inertia, consisting of thermal inertias of 100, 200, and 300 J m^{-2} K^{-1} $s^{-1/2}$ as well a rock component with thermal inertia fixed at 1250 J m^{-2} K^{-1} $s^{-1/2}$. By modeling different mixtures of thermal inertia, we are able to understand the importance of rock abundance and whether it is capable of producing an appreciable ΔT across a pixel. ΔT values that exceed the maximum allowable change in surface temperature across a pixel, as dictated by the NESR of EMIRS, may result in the addition of noise or bias to a measurement.

In addition to rock abundance, surface roughness can also influence the signal received by a remote sensing instrument like EMIRS. Surface roughness often relates to changes in surface height over different horizontal length scales **[7]**. These small changes in topography, usually at scales much less than the spatial resolution of the instrument, can dramatically alter how light is scattered and emitted by the terrain, especially at mid-infrared wavelengths. The modification of spectral radiance by surface roughness thus influences how well a remote sensing instrument is able to retrieve atmospheric parameters.

The ground size of EMIRS pixels are quite large and can contain sub-pixel surface roughness effects across a range of spatial scales and phenomena. Surface roughness's role in atmospheric retrievals will be studied by constructing a multi-dimensional lookup table. This lookup table will consist of a variety of tunable parameters that will allow surface roughness to be derived for nearly any viewing geometry and surface/atmospheric condition. The following list provides many of the key parameters that will be used to build a lookup table to compute sub-pixel surface roughness: latitude, longitude, thermal inertia, slope, slope azimuth, albedo, elevation, surface roughness, rock abundance, emission angle, incidence angle, local time, season, dust optical depth.

Preliminary Results: The degree to which a retrieved parameter within a single pixel varies is largely dependent on its location and the area the pixel encompasses. In most cases, larger pixels result in higher variability. This is not always the case, however, as larger pixels can occasionally "smoothen" sub-pixel variability and show less variability than a smaller pixel. Though a complete range of scenarios has not been fully explored, there appears to be a seasonal and diurnal dependence on variability, with northern hemisphere summer and a local time of noon exhibiting the greatest variability.

Generally the further a pixel is from the sub-spacecraft point, or the higher its emission angle, the more sub-pixels are needed by the forward model to produce an accurate retrieval. Like sub-pixel variability, there appears to be a seasonal and diurnal dependence with the minimum number of required sub-pixels, largely determined by the average surface temperature of the pixel. The strong dependence on surface temperature is particularly apparent during northern and southern hemisphere summer. During these seasons, there is a significant increase in the number of pixels that require 30 or more sub-pixels.

Preliminary results suggest that rock abundance is an important parameter to consider, especially when performing atmospheric retrievals at night or morning. The brightness temperature difference for an individual pixel that is the result of rock abundance variability is greatest at night and in the early morning hours, especially at larger wavenumbers. Such differences may influence the accuracy of the forward model spectra and thus any retrieved parameters. Retrieved parameters that are likely to be impacted by this include water ice and dust optical depth. The importance of rock abundance also appears to be strongest near the equator and mid-latitudes, though this is likely dependent on the season.

Work involving sub-pixel surface roughness is ongoing, but it is also expected to play a crucial role in the retrieval of atmospheric parameters. The extent to which surface roughness influences surface temperatures, and thus spectral radiance, will be determined through the creation of a multi-dimensional lookup table. This lookup table will provide all the necessary parameters to create a modeled spectra that is more representative of the martian atmosphere for a given pixel and thus permit retrievals of greater accuracy.

References: [**1**] Kieffer, H. H., *JGR: Planets*, 2013, [**2**] Lewis, S. R. et al., *JGR: Planets*, 1999, [**3**] Forget, F. et al., *JGR: Planets*, 1999, [**4**] Meadows, V. S. and Crisp, D., *JGR: Planets*, 1996, [**5**] Edwards C. S., *Space Sci. Rev.*, 2021, [**6**] Piqueux, S., and Christensen, P. R., *JGR: Planets*, 2011, [**7**] Nowicki, S. A., and Christensen, P. R., *JGR: Planets*, 2007.