Mars Atmospheric Profiling from an Orbital Constellation – Improving Data Coverage for Mars Data Assimilation

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Introduction:

Over the last decade considerable progress has been made in understanding the structure of the martian atmosphere and surface-atmosphere interactions. Current work focuses on identifying dynamical processes and radiative effects that are responsible for shaping the atmosphere of Mars.
One of the tools that promise further progress in our understanding of martian atmospheric processes is the assimilation of atmospheric data into Mars General Circulation Models. This could provide re-analyses of meteorological data similar to meteorological re-analyses on Earth, which are used for a multitude of applications and provide an accurate picture of the atmospheric state and dynamics. Assimilating near real-time data could pave the way towards forecasting martian weather in support of landing, aerocapture and surface operations of future robotic and manned missions.

Atmospheric data sets that have been available for assimilation consist of data on atmospheric state, dust and water ice opacity from orbital measurements. Assimilation efforts have been conducted using measurements by the Thermal Emission Spectrometer (TES) as well as the Mars Climate Sounder (MCS) [e.g. 1-5]. These measurements were obtained from platforms in sun-synchronous orbits such that they are typically available at only two local times per day.

Mars data assimilation has proven challenging. Due to the low atmospheric density, atmospheric variability is dominated by the diurnal variation of insolation, which leads to significant thermal tides of significant magnitude [6]. Heating due to dust plays an important role as a driver of the atmospheric circulation. Dust is locally variable, but influences the atmosphere on global scales. In addition, water ice clouds, which exert a significant radiative influence [7], are largely controlled by global temperature features rather than local transport. As a result, the Mars atmosphere exhibits more globally connected features than Earth, making data assimilation more difficult [5]. Furthermore, rapidly evolving processes (e.g. local dust storm growth) are often poorly sampled by existing observations, limiting the ability to validate model behavior. Many of these difficulties could be alleviated by simultaneous global measurements at multiple local times.

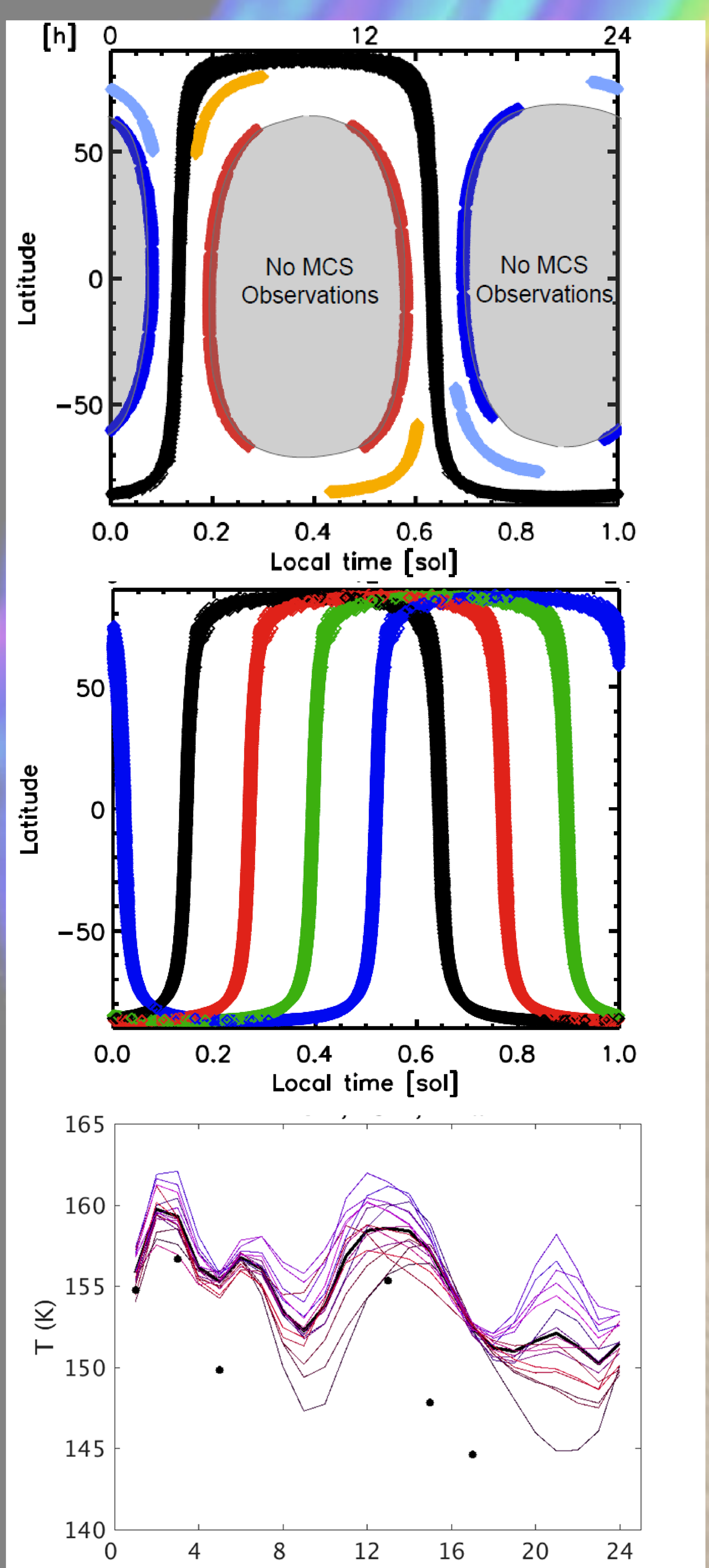


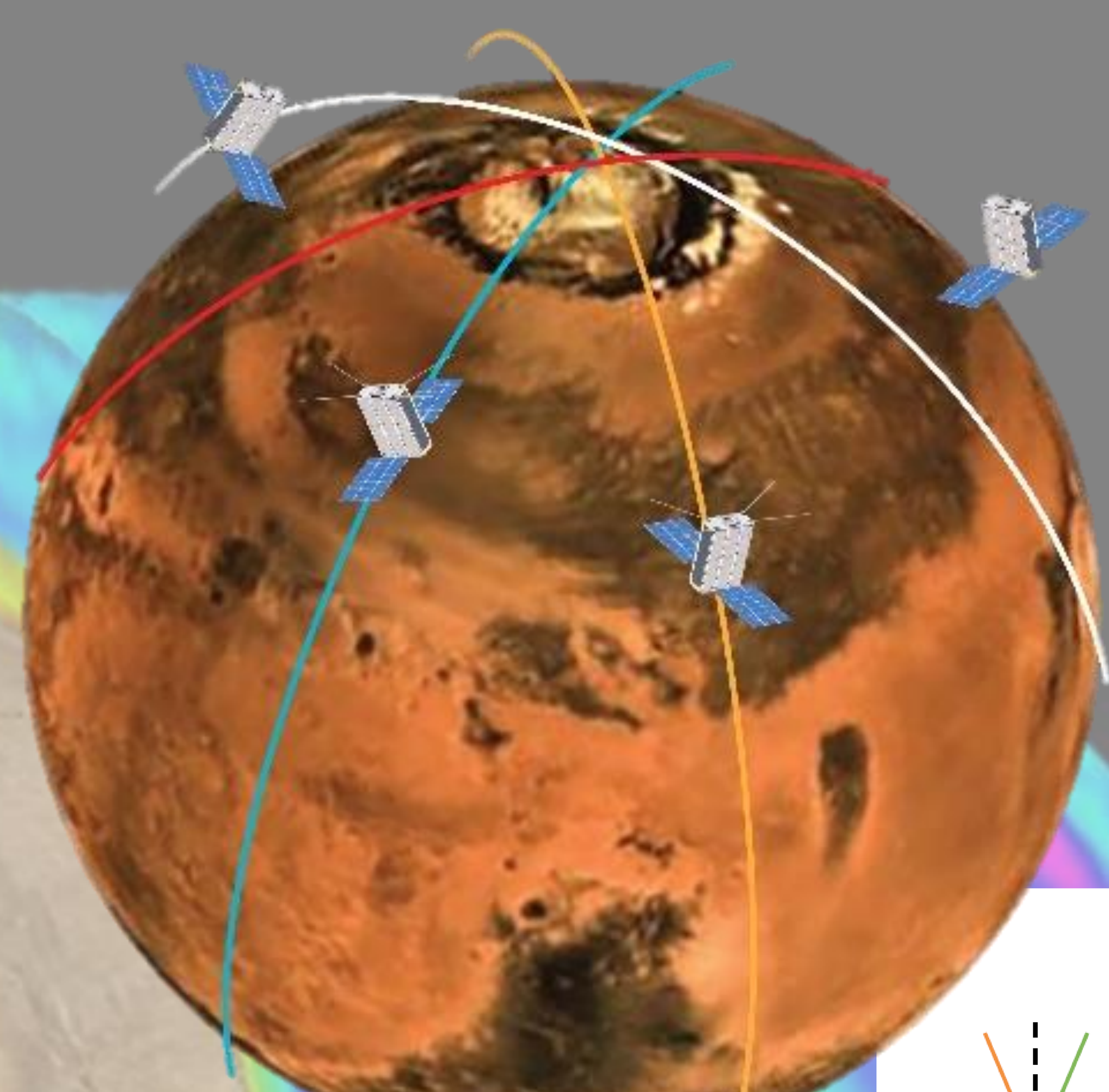
Figure 1: (Top) Positions of MCS atmospheric limb observations vs. latitude and local time. Black symbols indicate measurements along the orbit track, while red and dark blue symbols indicate measurements 90° perpendicular to the orbit track. Pale blue and orange symbols indicate off-track measurements at other angles. Gray shaded areas are inaccessible to MCS measurements. (Center) Simulated measurement coverage that would be achieved by along-track measurements from four sun-synchronous platforms with nodal spacings of 45°, corresponding to ~3 hours in local time. (Bottom) Ensemble members from an assimilation of MCS temperatures in EMARS [2] at 49° N latitude, a pressure level of 1 Pa, and L_s=270°. The thick black curve is the ensemble mean, the dots are the means of MCS observations. Ensemble members are colored according to their dust and ice radiative factors (black → red: more dust, black → blue: more ice).

Approach:

Figure 1 (top) shows the local time coverage by obtained MCS from its host platform, the Mars Reconnaissance Orbiter. Black symbols indicate standard measurements with the instrument viewing the limb in the direction of the orbit track. Through its ability to slew in azimuth, MCS has access to local times up to ±1.5 h at low latitudes, and covers a somewhat larger local time range at high latitudes. However, many local times are inaccessible from a sun-synchronous orbit.

Figure 1 (center) shows the local time coverage that would be achievable with along-track only measurements from four sun-synchronous space-craft in low Mars orbit. A node spacing of 45° would provide pole-to-pole global coverage every 3 hours in local time. Measurements at different local times would occur simultaneously, providing much tighter constraints on atmospheric models than, e.g., measurements from a single orbiter at moderate inclination, which would drift through local times on timescales of months.

The bottom panel of Figure 1 shows an example of temperature ensembles created from assimilating MCS temperatures into a GCM using the ensemble assimilation scheme EMARS. MCS cross-track data in this northern mid-latitude example covers local times between 1 and 5 h both in the morning and in the afternoon. A significant semi-diurnal tide, indicated by a wave 2 pattern in local time, is present in the atmosphere. However, ensemble members with a higher aerosol radiative forcing due to dust or ice seem to develop another temperature maximum between 20 and 24 h local time, shifting the overall pattern from wave 2 to wave 3. No constraints on this behavior are provided by the MCS data. Data from a CubeSat constellation as proposed here would provide dense and regular local time coverage at all latitudes (Figure 1, center) which would provide strong constraints on the temperature pattern in the assimilation.



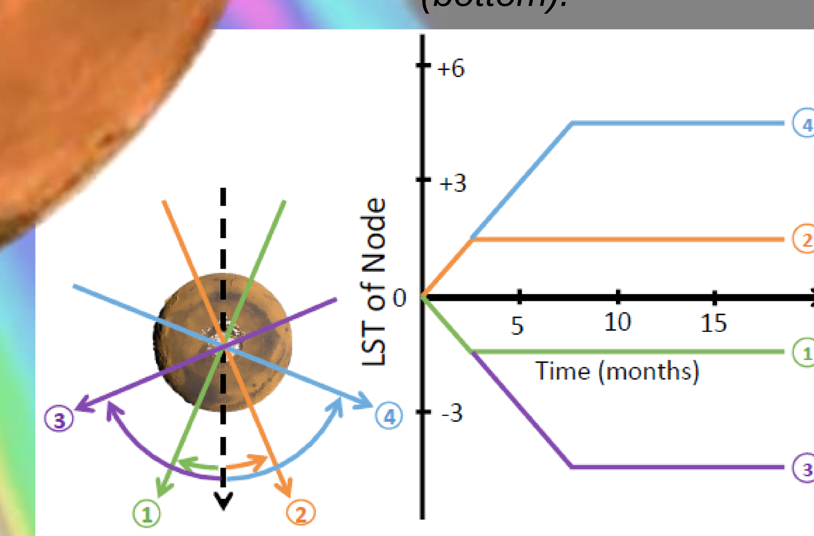


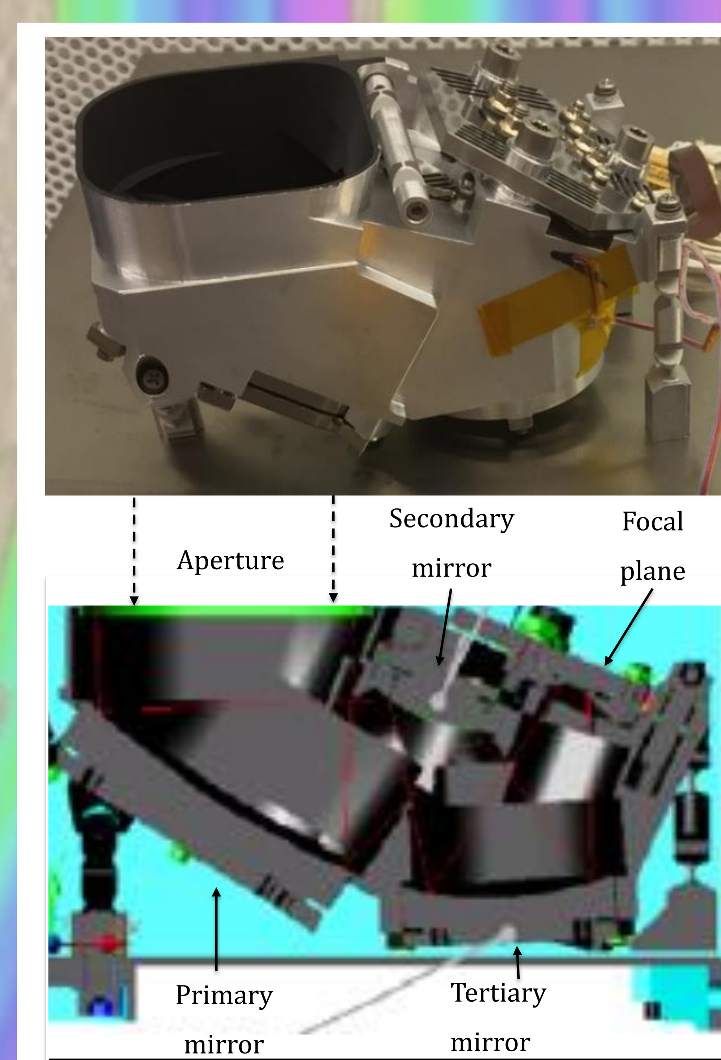
Figure 3: Artist's concept of a constellation of CubeSats at Mars (left). After deployment the CubeSats would drift to their desired nodes within a few months (bottom).

Mission Concept:

The proposed approach requires global profile measurements of atmospheric temperature, dust, water ice and water vapor, as well as surface temperature, at multiple local times. We suggest a constellation of SmallSats or CubeSats in Mars orbit [8] to perform these measurements (Figure 3). Limb- and nadir radiometry measurements would require a low-altitude orbit of moderate to high inclination around Mars. Four satellites with a constant node spacing of 45° between orbits would ensure that atmospheric and surface observations over the same areas would be performed in regular local time intervals of 3 hours. Satellites in a CubeSat form factor could reach their desired nodes under their own propulsion within a few month if deployed from Mars orbit (Figure 3, inset). If the satellites were to perform their own orbit insertion a larger form factor would likely be required. An ideal scenario would be the deployment of CubeSats from a large Mars orbiter in low Mars orbit. In this case the main orbiter could host an MCS-type instrument in its standard design [9,10] and also serve as a relay satellite for the CubeSats. This mission concept could be implemented during the decade of 2023-2032.

Instrumentation:

Measurements would be based on passive infrared radiometry in limb and nadir geometry as demonstrated by MCS [9] operating on MRO since 2006. Profiles of temperature, dust and water ice with 5 km vertical resolution have been retrieved from these measurements [11,12] together with atmospherically corrected surface temperature [13]. Eight spectral channels in the IR from 12-45 µm as well as a visible/near-IR channel would be used to fulfill the measurement objectives (Figure 2, bottom). Each channel would consist of a linear array of uncooled thermopile detectors, which instantaneously measures a radiance profile when vertically pointed at the limb. Most channels are heritage from MRO/MCS. MCS capabilities would be enhanced by adding a functional water vapor channel at far-infrared wavelengths. The MCS technology has high heritage. Deployment from a CubeSat would allow descoping the MCS actuators as the CubeSat itself could be used for pointing the instrument at the limb, nadir, and space. The design of the MCS telescope (Figure 2, top) is very compact for the wavelength range it works in, fitting in an envelope of only 0.8 U.



Telescope/ Channel #	Bandpass cm^{-1}	Band Center - µm	Measurement Function
A1	595 - 615	16.5	Temperature 0 - 30 km
A2	615 - 645	15.9	Temperature 30 - 50 km; Pressure
A3	635 - 665	15.4	Temperature 50 - 90 km, Pressure
A4	820 - 870	11.8	Water ice extinction 0 - 90 km
A5	400 - 500	22.2	Dust extinction 0 - 90 km
A6	3300– 33000	1.65	High altitude hazes and particle size discrimination
B1	290 - 340	31.7	Dust and CO_2 ice extinction 0 - 90 km
B2	220 - 260	41.7	Water vapor 0 - 40 km
B3	231 - 243	42.2	Dust and Water ice extinction 0 - 30 km

Figure 2: The MCS telescope design has high heritage and is very compact, fitting in only ~0.8U. The proposed measurement channels [10] are largely heritage from MRO/MCS [9].

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