THE CASE AND APPROACH FOR CONTINUOUS, SIMULTANEOUS, GLOBAL MARS WEATHER MONITORING FROM ORBIT

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Introduction:

Past and present orbiters (such as Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, and the ExoMars Trace Gas Orbiter) have been able to provide a great picture of Mars' climate, and good insights into its meteorology. Other missions such as the Mars Atmosphere and Volatile Evolution (MAVEN) mission, Mars Orbiter Mission "Mangalyaan", and Tianwen-1have also provided sporadic observations of meteorological phenomena. The Emirates Mars Mission "Hope" has a specific low-inclination, high-altitude, elliptical orbit that allows it to observe large portions of the Martian disk at several local times, hence improving the monitoring of the evolution of meteorological phenomena.

However, weather observations by any single spacecraft are more or less discontinuous and asynchronous. Furthermore, a replacement of the ageing fleet of current spacecraft must be envisioned within the current decade, if one wants to continue the multi-annual record of meteorological events without interruptions.

Now is the right time to shift paradigm in atmospheric science at Mars and focus on weather monitoring, as a precursor to forecasting.

The Case for Weather Monitoring:

The dynamics of meteorological phenomena such as dust storms and water/CO_2 ice clouds are characterized by rapid temporal variability (sub-hourly), and multi-scale spatial extension (local, regional, planetary). As a result, only continuous, simultaneous, global observations would ideally allow comprehensive monitoring and understanding of Martian weather phenomena. In practical terms, this means carrying out observations at a sub-hourly cadence for the largest possible portion of the planet at once. Atmospheric and surface temperatures, three-dimensional aerosol and water vapour distributions, atmospheric wind, and surface pressure can be included in a list of recommended variables to be retrieved from orbit.

Weather monitoring from orbit can provide answers to key, long-standing, scientific questions such as "How do dust storms evolve into extreme, planet-encircling events?" and "How do dust dynamics and cloud formation vary throughout the diurnal cycle?" Deep scientific understanding of the onset and evolution of dust storms as well as of the multiscale weather dynamics is then likely to enable forecasting, which is a strategic requirement for future human exploration missions (see e.g. Goal IV, Sub-Objective B3, page 64 in the MEPAG "Mars Science Goals, Objectives, Investigations, and Priorities, 2020 Version" document).

Mars weather monitoring is a science objective that supplements those of current mission. It is also an "exploration science/reconnaissance" objective, precursor of future operational weather forecasting missions in support of human exploration. It is particularly well suited for a satellite constellation to be launched in the current decade, in parallel with the Martian Moons eXploration (MMX) and International-Mars Ice Mapper (I-MIM) missions as well as the Mars Sample Return (MSR) program (it should be noted that the future of I-MIM is uncertain at the time of writing, after the recent NASA's announcement that financial support to the development of this mission is terminated).

Areostationary Satellite Constellation:

As it happened for the study of meteorology on Earth in the 1970s, when geostationary satellites started to be launched in addition to platforms in low Earth orbit, the study of Martian meteorology could thrive at the turn of this decade by putting a constellation of satellites with weather-focused payloads in novel areosynchronous or areostationary orbits, in addition to platforms in low Mars polar or nearly-polar orbits. An areostationary orbit is circular, equatorial, Mars-synchronous, at 17,031.5 km altitude. Platforms located in such orbits would be able to provide an unequalled view of the evolution of meteorological phenomena in the horizontal dimensions, although limited in the vertical dimension. The periareion (equivalent to periapsis for Mars) of the "Hope" spacecraft is very close to the areostationary altitude, and its inclination is only 25°. This platform, when it orbits near its periapsis, provides the current best example of the type of weather observations that can be obtained by a single areostationary satellite.

The Approach for Weather Monitoring:

The MSR program will require a large part of NASA's and ESA's resources devoted to Mars science and exploration in the current decade. The other studied or planned Mars missions (including JAXA's Martian Moons eXploration –MMX- and the currently uncertain I-MIM and ExoMars rover) could take further resources. A low-cost approach to weather monitoring is, therefore, appropriate, if not necessary, in order to launch a satellite constellation in parallel with these missions.

Bottom-up approach. It is convenient to think about the minimum configuration and payload for a weather-monitoring satellite constellation, and build it up considering constraints (budgetary, programmatic, etc.) and available opportunities. Fig. 1 shows a possible minimum configuration.

1 Polar Orbiter	3 Areostationary Orbiters
Visible camera	Visible camera
Thermal IR Radiometer (limb)	Thermal IR Imager (nadir)
Vertical profiles, global, discontinuous, asynchronous	Horizontal distributions, equatorial and mid-latitudes, continuous, simultaneous
3D, global, continuous, simultaneous observations, but no new variables	

Figure 1: Minimum configuration for a weather-monitoring satellite constellation.

Three satellites in areostationary (or at least areosynchronous) orbits, with nadir-viewing payloads including at least a visible multi-colour camera (spatial resolution < 5 km) and a thermal infrared multi-wavelength imager (spatial resolution < 60 km), are required as a threshold to monitor the Martian weather quasi-globally, continuously, and simultaneously, although with limitations in the vertical dimension. This is a common outcome of a few mission concepts involving areostationary satellites that have been studied in the past five years in the USA and Europe [1, 2, 3, 4, and 5]. However, several options for enhancing the scientific return and/or the applications exist. In terms of payload, the addition of an ultraviolet camera and a near-infrared imager would allow extending the wavelength range to respectively refine the retrievals of dust and clouds and enable the retrieval of surface pressure. In terms of number of platforms, the addition of a fourth satellite in areostationary orbit would allow introduction of stereo view capabilities, improving the spatial coverage, and providing redundancy (see Figs. 2, 3). Further, in terms of science objectives and applications, areostationary satellites are also ideal platforms for space weather monitoring as well as communication/navigation applications, which are currently under study by various space agencies (see [3, 6] for detailed analyses of all benefits and applications of the areostationary orbit).

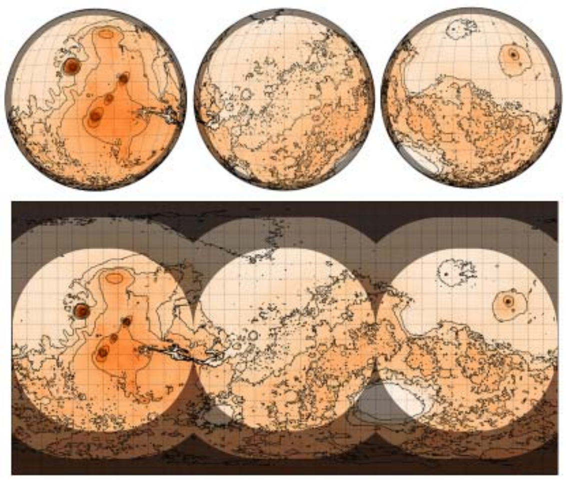

Figure 2: Mars views from a three-platform areostationary constellation. Dark grey areas are never observed, light grey areas are observed at the edge of the field-of-view (they correspond to emission an-

gles larger than ~70°). The longitude-latitude grid is 10° x 10°. Views are centred at 120°W, 0°, 120°E for convenience. Colour scale and contours represent topography.

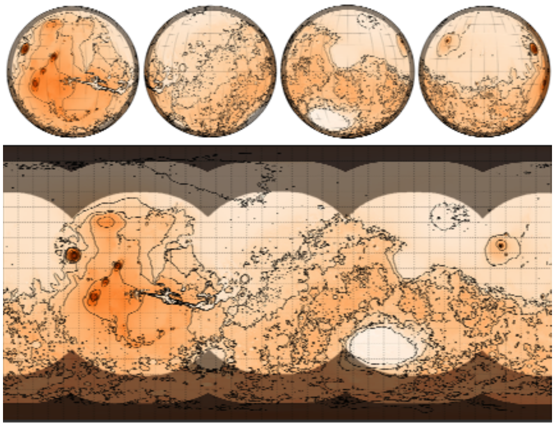

Figure 3: Mars views from a four-platform areostationary constellation. Views are centred at 180°W, 90°W, 0°, 90°E for convenience (stable and unstable longitudes are shifted by ~12°-18° westward, e.g., 17.92°W is a stable longitude).

In terms of synergy with other types of satellite orbits/payloads, the concurrent presence of limb-scanning instruments aboard satellites in low polar orbit would allow aerosol and water vapour profiling, extension of the vertical range of temperature information into the middle atmosphere, and coverage of the polar regions, thus achieving global three-dimensional, continuous and simultaneous weather monitoring. If more than one polar orbiter is deployed, for instance at two or three additional longitudinal nodes, vertical profiles at several local times at once could be obtained [2, 7]. Finally, if a payload including a sub-mm sounder and/or a Doppler near-infrared LIDAR is added aboard one of the polar orbiters, access to wind measurements (either line-of-sight winds or wind components) in the respective ranges of 0-40 km and ~10-100 km altitude becomes possible [8, 9].

Modular approach. The ultimate weather-monitoring constellation does not necessarily need to be launched all at once. The platforms listed above can be added and/or replaced over time. Provided the minimum configuration is in place, for instance, a fourth areostationary satellite or further polar orbiters could be launched separately. More capable platforms could replace initial ones.

SmallSat approach. Another way to reduce the cost of a constellation is to "think light, small, and simple". In other words, use low-mass/small-volume payloads with as much heritage as possible, simplify the concept of operations, use on-board autonomy for operations and science, and accept lower reliability of single platforms, possibly compensated by redundancy in their number. Note that there are long-term cost savings in autonomous systems, but there is an up-front cost to their development. Therefore, the use of such systems is compatible with a low-cost mission only if the mission has not to bear the cost of the autonomy development, or if there is a long-term plan.

International collaboration. Given the international nature of MSR (as well as MMX, I-MIM and ExoMars), it is conceivable and desirable that a weather-monitoring constellation develop as an international, coordinated endeavour. Even if single platforms might be low-cost, the cost of the full constellation is likely going to be too high for a single entity in the current decade. International collaboration allows sharing of the costs and risks, while increasing benefits for all partners (access to Mars, development of national space exploration programs, technological and scientific breakthroughs, commercial involvement, public engagement, etc.). The ExoMars mission and the I-MIM concept clearly show that international collaboration has its own risks, but a bottom-up, modular, low-cost SmallSat approach can efficiently reduce them. Multiple, focused SmallSats are more easily entirely contributed by small entities, such as ESA member-state space agencies, other small space agencies, university consortia, commercial entities, etc. This increases the resilience to possible collaboration break up with respect to the case of a larger spacecraft requiring multiple contributions.

Use of available opportunities. Using platforms and instruments that require only minor or moderate modifications, and finding rideshare or piggyback launch opportunities are other ways to reduce the cost of building up a weather-monitoring constellation at Mars. Last but not least, joining forces with missions with compatible objectives could open opportunities to put weather-focused payloads in orbit around Mars. This might be the case for I-MIM, which is currently planned to be in a low, near-polar orbit (assuming this mission concept is still actual), or for a communication/navigation constellation concept in areosynchronous orbit, currently being studied by ESA (MARs COmmunication and Navigation Infrastructure –MARCONI- see [3] for the general concept).

Simulation of new observations. In a low-cost context, it becomes important to optimize the configuration and payload of a weather-monitoring satellite constellation, and quantify the expected impact of the new observations. The Observing System Simulation Experiment (OSSE) framework has been used for more than 30 years as a tool to evaluate the benefits of future instruments for the Earth, so it is timing to use it also to simulate the impact of atmospheric observations that do not yet exist for Mars [10]. As Fig. 4 shows, OSSEs can provide a quantitative assessment of the improvement in weather characterization due to the introduction of specific new observations, using a Global Climate Model (GCM) and a data assimilation scheme.

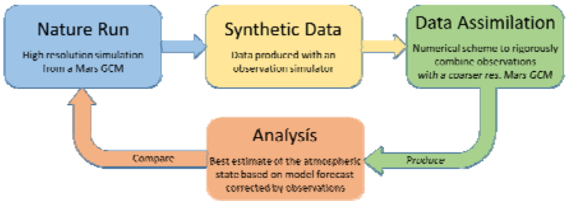

Figure 4: Components of an OSSE.

About a surface weather station network:

This abstract is focused on Mars weather monitoring from orbit. We recognize the importance of having a scattered network of weather monitoring stations on the surface of Mars for carrying out measurements near the ground and in the boundary layer. An orbital constellation and a surface network are complementary and both essential to ultimately monitor and forecast the weather evolution, as the example of the Earth clearly points out.

However, on Earth, the surface network was introduced before the orbital component because we were already living on the planet, while landing on Mars is still a big (and costly) challenge compared to putting a satellite into orbit. Building up an orbital constellation at Mars can be currently done faster and at lower cost than a surface network. Therefore, while looking for ways to reduce the cost of multiple landing, we should focus on the orbital component within the current decade.

However, all landers and rovers that are already planned to be sent to Mars in the forthcoming future should carry meteorological instruments to contribute to the currently available surface network.

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