AN ORBITING MARS ATMOSPHERE, GRAVITY, NAVIGATION AND TELECOMMUNICATIONS SYSTEM.
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Introduction: We envision a constellation of several small satellites orbiting Mars that would provide (1) a global weather, climate and trace gas observing system including the precise wind and density information needed for entry, descent and landing (EDL), (2) radio navigation for EDL and rendezvous with orbiting sample return canisters, (3) high resolution gravity mapping on Mars like GRACE and GRAIL to understand the Martian interior and (4) telecommunications relay.

The common element tying this diverse set of science and infrastructure elements together is a smart, precise, multi-frequency radio system.

Weather, Climate and Trace Gas Inventory: As described in the planetary decadal survey and MEPAG documents, establishing a trace gas inventory and its variability together with identification of sources and sinks are critical to the search for past and present life and a successful sample return program. Understanding Martian climate, in particular the CO_2, water and dust cycles and initiation of dust storms remains a fundamental science focus at Mars. Precise knowledge of the wind and density structure in the lower atmosphere is critical for 100 m precision EDL needed for sample collection and return.

The core instrument capable of answering these needs would probe the atmosphere in the 320 to 360 GHz band. This mm-wave band contains absorption lines from a number of key Martian trace gas species such as water and CO and their isotopes, formaldehyde, hydrogen peroxide, ozone and sulfur dioxide. The instrument would operate in three modes: (1) satellite to satellite radio occultation (RO), (2) solar occultation (SO) and (3) thermal emission (TE) from the atmosphere. A prototype of the Earth analog of this instrument has been developed for climate and weather applications on Earth and is presently being used in field experiments [1].

A unique strength of RO for both science and EDL is its ability to probe right to the surface with very high vertical resolution (60 m) and precision, both day and night, independent of the dust loading or clouds. Comparable vertical resolution by other means would be difficult or costly. RO is well established in planetary science and GPS RO is now one of the most important data sets in numerical weather prediction (NWP) on Earth [2].

Two counter-orbiting satellites making RO measurements would yield approximately 40 daily, entry-probe-quality profiles of atmospheric density, temperature, pressure, winds, turbulence and concentrations of key trace constituents with 60 m vertical resolution in clear and dusty condition. Over the course of a Martian year, 30,000 entry probe quality profiles would be generated.

Solar Occultations. SO profiles would also be measured at the terminator providing approximately 20 profiles per day per orbiter. Adding a near-IR solar occultation spectrometer such as the SOIR or ACE instruments would add a number of key trace gas species such as methane and extend the trace gas measurements of ESA's planned Trace Gas Orbiter (TGO) (or provide the first such trace gas survey if TGO were not to fly).

A rapidly precessing, high inclination orbit would yield SO pole to pole coverage every 40 days. The same rapidly precessing, high inclination orbit would allow RO measurements to separate the behavioral dependence on the diurnal and seasonal cycles. The orbits of the two (or more) RO satellites would precess at the same rate to maintain the occultation geometry over time.

RO Sampling pattern. The orbits can be selected such that the RO profile sampling is distributed randomly across the globe or in a repeating pattern so that approximately 20 locations on the surface would be sampled every half sol, much like the weather balloon network on Earth except that the RO profiles would provide significantly more information per profile.

Winds for EDL. In order to precisely place a lander on the Martian surface with a $\leq$100m error, the atmospheric winds and density along the EDL flight path must be known quite accurately. Holding the landing error ellipse to 100 m given a 50 second parachute descent would require knowledge of winds to approximately 2 m/sec. This is challenging because winds in the lower atmosphere vary significantly with location, height, time of day and season and have yet to be measured directly except for a few entry probes.

The mm-wave instrument would profile line of sight (LoS) winds by profiling the absorption or emission by CO and its isotopes via RO, SO and TE. The winds are determined by simultaneously probing both sides of a given absorption line and using the asymmetry of the absorption or emission to infer the Doppler shift of the line center due to winds.

Precision of wind profiles will be 2 m/sec or less for both the SO and RO observations. The big advantage of RO lies in its ability to profile the LoS winds with 60 m vertical resolution down to the surface as required to accurately profile winds in the boundary layer over the diurnal cycle. While the TE wind measurements are significantly less accurate, they are still useful because they can measure both horizontal components of the wind and be made continuously between RO and SO events.

To obtain very accurate wind estimates needed for EDL, we also envision use of a Martian numerical weather prediction (NWP) model and data assimilation system that would assimilate the wind profiles from the mm-wave instrument. Over time, systematic discrepancies between the observations and NWP model would become apparent. Based on these discrepancies, the model developers would refine the model's physical parameterizations to make the NWP results better match the observations, thereby improving the prediction accuracy.

Of particular note here is the importance of RO's ability to profile the planetary boundary layer (PBL) height and strength of turbulence. These are directly related to surface heating, energy transfer and the depth of convection which affect the vertical structure of the winds in the lower atmosphere and its variations over the diurnal cycle. This is new information that will be critical to properly representing the winds in the lower atmosphere in the NWP model.

We also note that (1) with the orbits selected such that the RO profiles sample repeatedly over the same ~20 surface location, and (2) adjusted such that one of those 20 sites is the desired landing site, a RO wind profile would be measured over the landing site twice per sol, such that the latest profile would be measured no more than 12 hours before the EDL event. Thus this system would provide the wind information when and where it was most needed, without the technological challenges and expense of implementing and maintaining a landed network.

Dust measurements. The addition of a small thermal IR instrument derived from the MCS instrument would measure aerosols coincident with the mm-wave measurements. This information combined with the dynamics information from the mm-wave instrument would greatly increase our understanding of the dust cycle and dust storm genesis on Mars.

MACO. A two satellite version of this atmospheric remote sensing concept called the Mars Atmospheric Climate Observatory (MACO) was proposed to the Mars Scout program in 2006. MACO in many ways would have outperformed the global satellite observing system on Earth. It received an unusual level of interest from the science review panel but 2 satellites in a Scout budget was viewed too risky for selection.

Gravity Recovery Option: Two satellites followng one another in orbit, carrying the same mm-wave instrument used for RO would provide a GRACE/GRAIL-equivalent high resolution determination of the gravity field. The use of mm rather than the cm wavelengths used by GRACE & GRAIL could improve sensitivity by an order of magnitude.

Navigation: On Earth, GPS has revolutionalized precise orbit determination (POD) and positioning. High precision orbiting GPS receivers now used for RO and POD cost only $1M apiece. Since these science instruments already have very stable clocks and high precision transmitters, they can readily be used to generate navigation signals, much the same as the GPS does on Earth. With more of these satellites orbiting Mars, they would provide precise navigation for assets on and around Mars as well as a higher density of RO sampling of the atmosphere for better weather, climate and trace gas characterization and prediction. With such a navigation system, vehicles could determine their precise position in real time during EDL and make corrective adjustments as necessary during descent to hold itself on target.

The orbits of these satellites would be determined via a combination of tracking one another and from other satellites tracking the signals from the navigation satellites. DSN tracking would further tie down the orbits. To tie the navigation satellite orbits tightly to the Mars frame of reference, we envision one or more navigation instruments would be placed on the Martian surface. To support navigation, the instruments would include a small rubidium or cesium atomic clock which is readily available.

Telecom Relay: With several orbiting satellites, the number of overflights over surface assets would increase relative to the present, allowing more frequent and higher bandwidth communications to Earth.

Presentation at the Meeting: The presentation will supply more information on instrument and spacecraft accomodations in terms of size, mass, power and performance parameters for the mission

References: [1] Kursinski E.R. et al. *Atmos. Meas. Tech.*, 5, 439–456, 2012. [2] Cardenalli, C. *ECMWF Technical Memorandum* 599, 2009.