Dual Satellite Mars Climate and Chemistry Mission Concept
Planetary Science Decadal Survey White Paper
August 29, 2009

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Approximately two dozen key science questions about the Martian atmosphere involving the dust and hydrological cycles, atmospheric circulation, trace gas chemistry, upper atmosphere, and past climate are summarized in the Mars atmosphere group white paper (Mischna et al., 2009). So how do we answer the questions posed there? MAVEN, which launches in 2013, will address questions about the upper atmosphere. This white paper describes the rationale for and key elements of a dual satellite orbiting mission (DSM) concept that uses mm-wavelength satellite to satellite (sat-sat) occultations (Fig. 1) in combination with solar occultations (SO). The combination of sensitivity, accuracy and vertical resolution from the satellite to satellite occultation is simply not possible with radiometers and will provide ~30,000 globally distributed near-entry probe quality profiles each Martian year profiling the boundary layer and exchange between the atmosphere and surface, answering and strongly constraining most of the key lower and middle atmosphere Mars science questions previously thought unachievable from orbit.

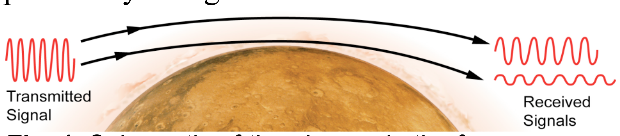

Fig. 1. *Schematic of the change in the frequency and amplitude of sat-sat occultation signals.*

It is extremely important that the Mars community specifically and planetary science community in general understand the science achievable from orbit via sat-sat occultations and, in the next decade, develop and utilize such observations in future mission architectures and answer the science questions highlighted in Mischna et al.

Rationale

Achieving the **global perspective** needed to answer the Mischna et al. questions very likely requires an **orbiting** mission. Clearly a landed network with the right instrumentation as discussed by Rafkin et al. (2009) would be very powerful and complementary to an orbiting mission, but the cost of a sufficient number of adequately equipped ground stations would likely be prohibitive, forcing such a network to be more limited in number and scope.

Answering the numerous questions about the vertical distribution of dust, water, trace gases and winds requires that the mission profile those variables at their key spatial and temporal scales. More challenging is answering the majority of the Mischna et al. questions related to the near surface environment. For instance, questions about (1) how dust storms are initiated, evolve and decay and (2) why some grow to a global scale while others remain local require globally distributed, near surface measurements of dust, winds, turbulence and their meteorological context over diurnal, seasonal and interannual time scales. Analogous requirements exist for answering questions about (3) the exchange of water with surface and subsurface reservoirs and (4) whether there is net transfer of water from one hemisphere to the other as well as questions about trace gas (5) sources and sinks, (6) interactions with the subsurface and (7) the role of heterogeneous chemistry.

Answering these questions therefore requires: i) routinely profiling the atmosphere right to the surface, independent of dust (*something not possible at IR and shorter wavelengths*) and surface emission variations (*something not possible for thermal emission measurements at any wavelength*), with a few hundred meter or better vertical resolution and high precision (≤10%) to resolve the boundary layer variations, ii) separating the seasonal and diurnal cycles which can be achieved with rapidly precessing, high inclination orbits, and iii) sufficient sampling density.

Temperature, pressure, dust, water vapor, trace gases, clouds, winds and turbulence should be profiled down to the surface ***simultaneously*** to constrain the interrelations such as dust and trace gases for heterogeneous chemistry and winds, turbulence and dust to determine how dust storms are initiated as well as to determine transport of dust and water. Measuring **isotopes** is critical to constraining present processes and sources as well as the past climates and evolution of Mars.

Current Limitations

The requirements noted above cannot be met with the Thermal Emission Spectrometer (**TES)** or the Mars Climate Sounder (**MCS**) both of which measure thermal emission (TE) in the infrared. Their vertical resolutions and high sensitivity to dust and surface emissivity are simply inadequate to address the many near-surface related questions. While **TES** and

MCS do provide indirect constraints on zonal wind shear via the thermal wind equation, the information is limited both by vertical resolution and the lack of constraints on near surface drag and pressure gradients that make winds in the near-surface environment so variable and challenging to model. Furthermore some of the most important transport questions involve meridional winds.

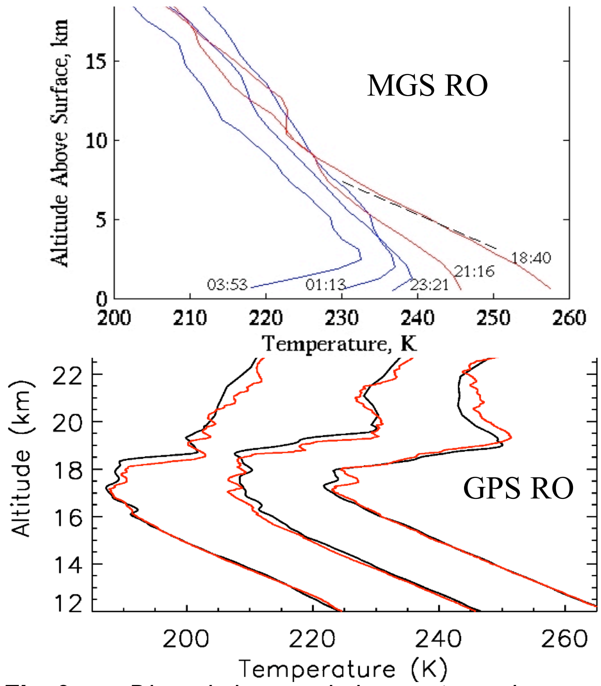

***Fig. 2. a.** Diurnal changes in lower atmosphere thermal structure in between 30°S and 60°S seen in MGS RO (radio occultation) measurements (Hinson et al. 1999). b. Comparison of close-coincidence GPS RO and balloon profiles in Earth's tropics near the transition between the troposphere and stratosphere demonstrating the vertical resolution of GPS occultations. Black: GPS, Red: balloon. The two profiles to the right are offset by 20 K each.*

Mm & **sub-mm** TE observations would be better because of their dust insensitivity. However, the 3-5 km vertical resolution achievable via such measurements and their sensitivity to surface emissivity would barely allow them to detect a hint of the large diurnal temperature swings observed via RO (Fig. 2a).

Solution

The only way to answer these near-surface questions from orbit ***is via satellite-to-satellite radio occultations*** (RO). RO is a simple, proven technique used since 1965 with Mariner 4 and more recently with MGS that provides precision, accuracy and vertical resolution typically one and sometimes two orders of magnitude beyond that of atmospheric emission observations. Fig. 2a shows the ability of MGS RO to profile the near-surface environment and capture the large diurnal temperature variations there. While RO profiles average horizontally over ~160 km so they don't capture as much small-horizontal-scale information as point profiles, they provide more representative results than point profiles and will profile turbulence via scintillations ("twinkling of a star") yielding entirely new constraints on atmospheric processes at Mars. Fig. 2b demonstrates the high vertical resolution achieved with terrestrial sat-sat RO measurements even at relatively low 1.6 GHz frequencies demonstrating in part why GPSRO was one of the missions recommended in the 2007 Earth Science Decadal Survey.

RO measurements in the 320-360 GHz range will precisely profile water, CO, and their isotopes to a few %, trace gases H_2O_2, O_3, H_2CO, SO_2, and OCS to ~5 ppb or better, winds to better than 2 m/s and turbulence independent of dust with 60 m Fresnel diffraction-limited vertical resolution to resolve the diurnal variations in the boundary layer. These *individual profile* errors will improve with averaging. Placing the two satellites in approximately counter-rotating, rapidly precessing, high inclination orbits will provide ~42 globally distributed RO measurements per day daily with full diurnal cycle sampling approximately every 44 days.

The sat-sat occultations are self-calibrating because the signal source is viewed before or after each occultation, eliminating long term drift for serious monitoring of climate. Furthermore, a properly designed RO receiver can also probe the atmosphere via SO and TE enabling ~200,000 TE profiles per Martian year. Spectroscopic errors will be reduced *while in orbit* via the RO & SO mm-wave obs.

The RO instrument consists of a ~300 GHz transmitter using readily available tone generators and 20 cm antenna on one spacecraft and a 20 cm antenna and simple heterodyne RO 300 GHz receiver on the other spacecraft, both pointed to 1 mrad, a level easily achieved with star trackers. Unwanted non-atmospheric amplitude variations such as those due to antenna pointing variations are calibrated out using an extra occultation tone sufficiently far from the absorption line. The tone's *frequency* will be very stable to measure the change in frequency due to the atmosphere (Fig. 1) and profile temperature and pressure like the well-established X-band spacecraft occultations (e.g., Fig. 2a). ***The required components and assemblies of a 300 GHz RO system have been flown in space*** and simply need to be assembled into a new integrated observing system. ***No new technology development*** is required. A two aircraft system demonstration of the Earth version of this concept, called the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), is scheduled for 2010.

Answering the numerous dust and ice related science questions requires aerosol measurements coincident with the mm-wave measurements spanning the diurnal cycle with vertical resolution as close to the RO measurements as possible. This can be achieved via an ***uncooled, thermal IR limb emission ice and dust sounder*** (TIDS) derived from MCS ***with 2 km vertical resolution*** (limited by IR weighting functions) and channels optimized to sample near surface dust under a range of dust loading conditions.

A **Trace Gas Survey** necessitated by the recent discovery of methane is best achieved via a ***near-IR solar occultation*** (SO), ***nIRS,*** such as the French SOIR instrument or the Canadian fourier transform spectrometer (FTS) instrument on the Earth-orbiting Atmospheric Chemistry Experiment (ACE) (Bernath et al. 2005) that measure the spectra of a wide range of species to sub-ppb levels. A critical point here is the mission design requirements for RO and SO are highly compatible and synergistic because the same ***rapidly precessing orbits*** that provide diurnal coverage for the mm-wave and aerosol observations also provide pole to pole SO coverage over the same 44 day period.

With these combined elements, a DSM becomes a **global field campaign** that profiles the chemical, dynamic, thermodynamic and aerosol-opacity state of the atmosphere simultaneously down to the surface as well as the surface below with full diurnal cycle sampling. This combination, which is very difficult to achieve via landers because of prohibitive costs, in fact exceeds anything on Earth. These measurements will quantitatively determine the detailed behavior of the near surface environment and constrain (rather than merely address) the key processes at work providing knowledge critical to modeling and understanding both present and **past** climate.

The Water Cycle

The key observations needed to understand the water related processes and answer questions about the water cycle must be considered in the framework of the moisture balance equation (1):

$$dq/dt = -\vec{\nabla} \bullet \vec{u}q + source_{external} + source_{internal} \quad (1)$$

terms: 1 2 3 4

where q is the water vapor mixing ratio, t is time, u is velocity, *Term 1* is the time-varying 3D water distribution, *Term 2* is the water transport term, *Term 3* is the water source from the surface and *Term 4* is the change caused by water condensation or sublimation within the atmosphere. With the proper mission design, DSM can be **a global closure experiment** to measure each term in equation (1).

4D Water Climatology

Insight gained from the latitude vs. season and interannual climatology derived from TES added to recent evidence that the Martian orbital obliquity and precession variations likely cause large amounts of water to migrate around on Mars (e.g. Head et al. 2003) have driven several interesting and contradictory modeling studies. Determining what is actually happening and why requires that we understand how water varies in the present climate. Specifically, according to Eq. (1), we must begin by accurately measuring the water mixing ratio, q, at the important spatial and temporal scales at which it varies. Earth experience suggests that atmospheric water likely varies over vertical scales of ~10 km to ~10 m. Only mm-wave sat-sat occultations have the sub-km vertical resolution (extending down to the surface) necessary to observe these critical, process-revealing vertical scales.

As summarized in Table 1, by actively probing the 325 and 336 GHz water and HDO lines DSM's coincident measurements of water, temperature, pressure, HDO and ice, yield a 4D characterization of water in terms of five critical and complementary moisture variables: *(1) Vapor density* (water mass per volume), (2) *Mixing Ratio* (tracer for determining subtle flow pathways through the atmosphere), (3) *Relative Humidity* (related to condensation and sublimation), (4) *Vapor D/H Ratio* (to understand fractionation associated with condensation and photochemistry and identify subsurface reservoirs exchanging with the atmosphere and net transport from one hemisphere to the other), and (5) *Water ice* (transfer between vapor & ice phases).

Table 1: *Variables determined by DSM*

Moisture Variable	Single Profile Accuracy	Alt. Range (km)	Horiz. & Vert. Resolution (km/m)
Concentration	1-3%	0-50	160 / 60
Mixing ratio	1-3%	0-50	160 / 60
Rel. humidity	4-6%	0-50	160 / 60
HDO/H_2O ratio	1-3%	0-20	160 / 60
Temperature	$\leq$ 0.5 K	0-50	160 / 60
Pressure	0.1%	0-50	160 / 60

Transport

Determining the **transport of water, trace gases and dust** requires wind measurements, preferably coincident with the concentration measurements. DSM will **directly** measure line-of-sight (LOS) winds via the Doppler shifts of $C^{17}O$, $C^{18}O$, ^{13}CO and CO lines in the ***329-347 GHz*** interval. RO, SO and TE measurements probing both sides of line center will determine the Doppler shift coincident with profiles of water, other trace gases and dust to accuracies shown in Fig. 3. Additional constraints will come from pressure gradients determined from the occultations that will enable indirect determination of the balanced portion of the winds. Vertical resolution is particularly critical near the surface to capture expected changes in wind direction and speed.

Meridional transport is central to the water cycling problem because of the latitudinal dependence of water sources (e.g. presence of ice caps only at the poles, strong latitudinal variation of near subsurface water determined by the Odyssey GRS) and the strong seasonal cycle of solar forcing. Meridional transport, equation (2), is the sum of two components: (1) the action of the steady, zonal mean meridional circulation on the steady, zonal mean water vapor distribution, and 2) the net effect of zonally and temporally varying meridional winds ("eddies") on the zonally asymmetric and time-varying vapor distribution.

$$\left[\overline{qv}\right] = \left[\bar{q}\right]\left[\bar{v}\right] + \left[\overline{q'v'}\right] \qquad (2)$$

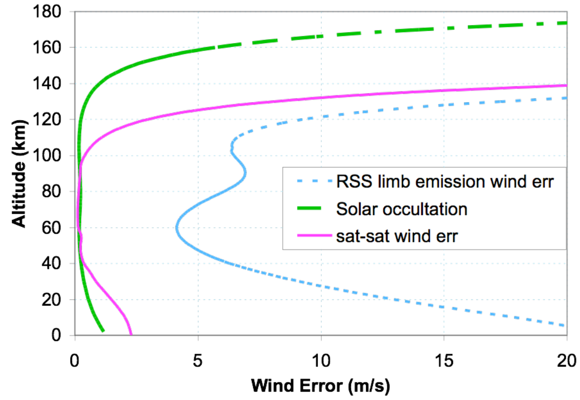

Fig. 3: *Accuracy of* ***individual*** *mm-wave Doppler wind measurements for sat-sat RO, SO and TE profiles. Accuracy improves further with averaging.*

Since the vapor and the meridional wind vary with height (the wind reversing in direction in many cases), these quantities must be vertically-resolved. As such, column-integrated vapor like that from TES cannot be used to make this calculation. MCS's dust dependent retrieval errors and several km vertical resolution will limit its utility to measure transport particularly near the surface (see Fig. 2a). In contrast, sat-sat mm-wave RO provides the critical measurements of high-precision temperature, pressure, water vapor, and line of sight winds with full diurnal and seasonal sampling and 60 m vertical resolution in both clear and dusty conditions that are needed to determine the water paths and fluxes, in fact to levels significantly exceeding any remote sensing capability orbiting Earth.

Exchange with Subsurface Reservoirs

Sat-sat mm-wave RO will reveal signatures of water exchange by measuring diurnal variations in profiles of near surface water vapor and temperature (Fig. 4) from which the exchange of water vapor and energy between the surface and atmosphere can be inferred over different regions of the globe. The orbital periods of the 2 satellites can be chosen to provide random coverage or a systematic, repeating pattern at 20 or more locations, for coverage like a balloon network on Earth.

Isotopic measurements will answer key questions related to transport. The observed HDO/H_2O ratio in water vapor varies from 2 to 10 over the annual cycle (Novak et al., 2005), decreasing as the precipitable water vapor increases over the annual cycle. This suggests that water vapor is exchanging with multiple reservoirs with different HDO/H_2O ratios, masses and recycling times (Fischer, 2007). Therefore, the variations in the near-surface HDO/H_2O ratio profiled globally over the diurnal and annual cycles via sat-sat occultations, can be used to determine the locations and D/H signatures of the different reservoirs exchanging with the atmosphere. Modeling can infer relative sizes and recycling times of the reservoirs thereby constraining their past history and the history of water on Mars. Furthermore, measuring the HDO/H_2O ratio of water emerging from a reservoir and then measuring HDO/H_2O ratio of water going into the reservoir later in the annual cycle will determine whether there is a net flux of water between reservoirs at present.

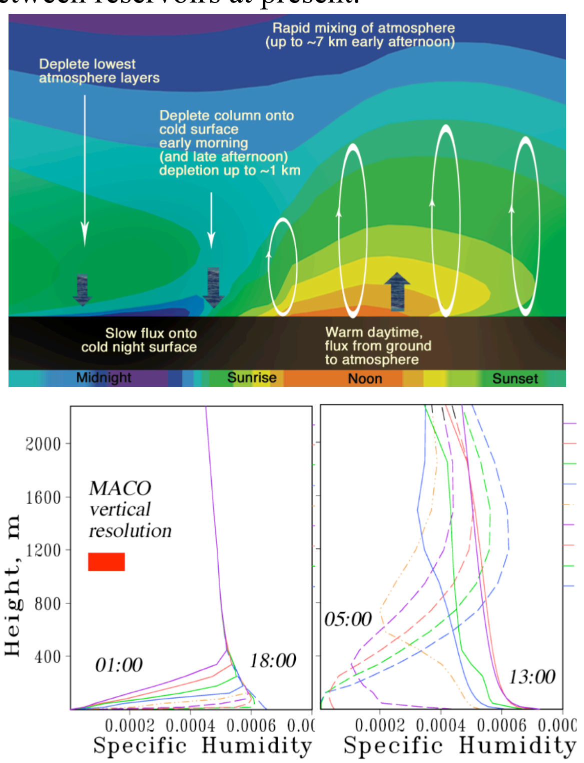

Fig. 4 (a) Illustration of diurnal evolution of surface-atmosphere water exchange for L_s = 110°, 22.5°N. Colors indicate temperature scale from 170 K (purple) to 240 K (orange). (b & c) Simulated profiles of water mixing ratio in the lowest 2200 m of the atmosphere. Horiz. scale: 0 to 800 ppm. (b) Hourly profiles from 18:00 to 01:00 showing the dramatic depletion of water in the lowermost atmosphere as it is transferred into the surface overnight. (c). Hourly evolution from sunrise to early afternoon.

Atmospheric Processes Revealed by D/H

Water isotopes also constrain important transport processes in the atmosphere. Globally and seasonally precise profiles of mixing ratios and temperatures, as well as HDO/H_2O ratios, that extend vertically through the depth of the tropical Hadley circulation will determine whether condensation is indeed limiting the mixing ratios in the upper branch of the Hadley circulation during the aphelion (northern summer) season and therefore impeding migration of water to the Southern Hemisphere as proposed by Clancy et al. 1996.

The average Martian D/H ratio in atmospheric water is enhanced by about 5.5 times over that of terrestrial oceans reflecting preferential loss to space of H relative to D, which can be used to constrain the initial H_2O reservoir on Mars (Owen et al. 1988, Kass and Yung 1999). In contrast, measurements of H Lyα and D Lyα emission (Krasnopolsky et al. 1998) showed that D/H in H_2 in the Martian upper atmosphere is about 11 times smaller than near the surface. Two mechanisms appear to be responsible: i) a reduced photo-dissociation cross section for HDO compared to H_2O (Cheng et al. 1999); and ii) fractionation during condensation and evaporation of H_2O (Bertaux and Montmessin, 2001). Simultaneous profiles of HDO, H_2O, and atmospheric temperature via solar and sat-sat occultations will allow photochemical and phase change fractionations to be resolved and constrain uncertainties in determining loss rates from the top of the atmosphere and the initial water reservoir. High vertical resolution close to the surface will be key to separating D/H effects due to different subsurface reservoir sources from D/H variations due to ongoing atmospheric processes.

The Dust Cycle

Atmospheric dust has a huge impact on the strength and interannual variability of the Martian circulation, due to its effect on radiative transfer within the thin Martian atmosphere (e.g. Kahn et al. 1992). Feedbacks between surface dust lifting and atmospheric circulation produce significant spatial and temporal variability (Murphy et al. 1995, Newman et al. 2002, Basu et al. 2004), particularly during the southern spring and summer 'storm season', making it hard both to predict the atmospheric state for a given storm season and to infer how the circulation may have differed in past orbital epochs. The direct (radiative) and indirect (dynamical) effect of dust on atmospheric temperatures also impact in a major way the present water cycle and its evolution over geologic time, as do dust particles acting as condensation nuclei for water ice (affecting radiative heating, scavenging of dust to form condensation nuclei and surface deposition rates of both dust and water). MGS TES observations of dust, ice and water vapor (Liu et al. 2003, Smith 2004) show differences between years with and without major dust storms (such as lower vapor abundances over the summer pole during a global storm). As yet the available data sets are inadequate for us to understand fully the processes producing this behavior. DSM measurements will address the following science questions related to dust and its impact on the water cycle:

What determines where and when dust storms originate? Despite recent progress in modeling Martian dust storms (Newman et al. 2002, Basu et al. 2004, Kahre et al. 2005), models remain unable to capture the full range of storm types and interannual variability. The best (perhaps only) way to improve our understanding is to measure the near-surface atmospheric state (particularly winds, wind shear, turbulence, and stability provided by mm-wave RO) at the *same time and location* as changes in dust abundances (which can then be linked to injection rates). For example, DSM should observe a distinctive afternoon peak in dustiness if dust devils are the dominant source.

Models seem unable to capture the relatively rapid decline of global dust storms observed on Mars, possibly because they do not typically account for enhanced scavenging by water ice during this period, a hypothesis that DSM measurements of dust and water ice would test.

The revolutionary sensitivity and resolution of the combined DSM temperature, wind, dust and water observations will enable us to study in detail how regional and global dust storms affect the circulation and water transport and help us understand whether large dust storms alter the distribution of water and its inter-hemispheric transport.

Locating sources of plumes

Determining whether the source of methane is geochemical or biogenic likely requires placing a lander near the source of a methane plume. Determining a source location potentially anywhere on the globe requires tracing an observed plume back to its source which requires a detailed knowledge of (1) winds and (2) mixing caused by turbulence.

Ultimately, the best estimates of plume source locations will come from plume dispersal reconstructions derived from atmospheric state estimates produced by a numerical weather prediction data assimilation system that combines an atmospheric model with observations to initialize and steer the model. The quality of such estimates depends critically on the model's realism which, to a large extent, will be as good as the observational constraints used to evaluate the model. Such constraints must include profiles of wind and turbulence at resolutions sufficient to determine important features relevant to advection and mixing. As on Earth, boundary layer winds are undoubtedly complex, exhibiting sharply defined vertical changes in speed and direction that depend on albedo, thermal inertia, topography, season, weather and diurnal cycle. As confirmed by the Phoenix LIDAR, these scales are far too sharp to be resolved by 5 km vertical resolution of a mm-wave radiometric spectrometer which together with 5 to 20 m/sec precision (Fig. 3) will limit the impact of such observations on plume source reconstructions. In contrast, the nearly 2 orders of magnitude better vertical resolution and 1 order of magnitude better precision of RO line-of-sight winds profiled together with mixing ratios, potential temperature and turbulence within and above the boundary layer will provide the quantitative constraints at scales and precisions needed to evaluate and improve models, enable a data assimilation system to steer numerical models correctly towards reality and determine how methane and other constituents are dispersed.

Heterogeneous chemistry

Apparent spatial and temporal variations in CH_4 abundance reported in Mumma et al. (2009) argue for a CH_4 lifetime << 6 months, far shorter than the photochemical lifetime of 300 years (Summers at al., 2002), implying a dramatically different chemistry for CH_4 than has generally been assumed. It has been proposed that the highly oxidized state of the surface and greatly elevated local CH_4 loss rates can arise from ion production associated with dust charging (Atreya et al. 2006; Delory et al. 2006). Highly elevated, local H_2O_2 abundances are predicted (Atreya et al., 2006). Because the standard photochemical models (e.g., Nair et al. 1994) reproduce (actually predicted) the column density of atmospheric H_2O_2 very well (Encrenaz et al. 2004), the dust storm dissociative electron attachment (DEA) chemistry can only operate locally. Mechanisms of dust charging during a dust storm argue that charge separation occurs primarily between saltating grains and small easily lofted grains. Discharge occurs over distances of ~10 cm due to the near optimal atmospheric pressure for discharges. This restricts dust charging effects and associated DEA chemistry to the atmospheric boundary layer (whose depth varies over the diurnal cycle: see Fig. 4) and perhaps much closer to the surface depending on the lifetime of the H_2O_2 because reaction rates depend strongly on the field strength which may be highest within a few cm of the surface. Because the efficiency of heterogeneous chemistry depends on the water vapor present and may therefore be quite variable, concurrent measurements of H_2O and H_2O_2 are critical.

Direct confirmation of the products of DEA chemistry, H_2O_2 in particular, requires observations of the chemical products in a dusty environment with a vertical resolution no worse than the extent of the boundary layer and preferably much smaller. A nIRS has limited ability to probe through dust. Near-surface sub-mm-wave limb TE observations are limited by 3-5 km vertical resolution and sensitivity to surface emissivity. Sat-sat mm-wave occultations will profile H_2O_2, H_2CO and H_2O, as well as winds, turbulence and temperature, with ~60 m vertical resolution down to the surface over the diurnal cycle while TIDS simultaneously determines the amount of dust and ice present to determine how near surface H_2O_2 concentrations and other chemical constituents vary with dust and H_2O as well as winds, turbulence, boundary layer depth, temperature and stability. Together these observations will determine whether hypotheses involving dust and DEA chemistry are indeed the missing CH_4 loss mechanism and its dependence on conditions.

Contributions to Mars Infrastructure

A DSM would provide redundant telecommunication relays. The meteorological observations provide density for aerobraking at high altitudes and low level pressure, winds and turbulence for EDL.

Implementation Options and Costs

In 2006, the one year Mars Astrobiology and Climate Observatory (MACO) DSM Scout mission was proposed for $465M. Increasing development costs by 25% to compensate for optimistic Scout cost estimates, adding 5 years of 3% inflation, $50M for higher launch costs and $30M for longer mission operations raises the cost to $700-750M.

ESA & NASA recently announced a 2016 trace gas mission with an ESA spacecraft bus and 200 kg lander and a NASA launch vehicle. If this mission were to fly the RO, SO & TE capable mm-wave receiver noted here, the sat-sat RO could be implemented by flying the RO transmitter on another spacecraft of an international partner such as Japan. The RO transmitter would use ~100 W when transmitting and <10 W when not transmitting for a ~25W orbital average.

References

Atreya, S., et al., *Astrobiology*, **6**, 439-450, 2006.
Basu, S., et al., *JGR,* **109** (E11), 11006, 2004.
Bernath, P., et al., *GRL*, **32**, L15S01, 2005.
Bertaux, J.& F. Montmessin *JGR,***106**, 32879, 2001.
Cheng, B., et al, *GRL*. **26**, 3657, 1999.
Clancy, R.T., et al. *Icarus* **122**, 36, 1996.
Delory, G. T., et al., *Astrobiology*, **6**, 451, 2006.
Encrenaz, Th., et al. *Icarus* **170**, 424, 2004.
Fisher, D., *Icarus* **187**, 430, 2007.
Head, J. W., et al., *Nature* **426**, 797, 2003.
Hinson, D*., et al., JGR*, **104**, 26997, 1999.
Kahn, R., et al., The Martian dust cycle, in *Mars* (H.H. Kieffer et al., Eds.), 1017, 1992.
Kahre, M., et al., *GRL*, **32**, L20204, 2005.
Kass, D. & Y.Yung, *GRL*, **26**, 3653, 1999.
Krasnopolsky, V., et al., *Science* **280**, 1576, 1998.
Liu, J., et al., *JGR,* **108**, 5089, 2003.
Mischna, M., et al., mepag.jpl.nasa.gov/decadal, 2009.
Mumma, M., et al., 2009, *Science*, **323**, 1041, 2009.
Murphy, J., et al., *JGR*, **100**, 26357, 1995.
Nair, H., et al., *Icarus,* **111**, 124, 1994.
Newman, C., et al., *JGR*, **107** (E12), 5124, 2002.
Novak, R., et al., *BAMS*, **35**, 660, 2005.
Owen, T., et al., *Science,* **240**, 1767, 1988.
Rafkin, S., et al., mepag.jpl.nasa.gov/decadal, 2009.
Smith, M., I*carus* **167**, 148, 2004.
Summers, M., et al., *GRL*, **29**, 2171, 2002.