Planetary and Space Science 59 (2011) 284–291

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Assessment of a 2016 mission concept: The search for trace gases in the atmosphere of Mars

Richard W. Zurek [a],*, Augustin Chicarro [b], Mark A. Allen [a], Jean-Loup Bertaux [c], R.Todd Clancy [d], Frank Daerden [e], Vittorio Formisano [f], James B. Garvin [g], Gerhard Neukum [h], Michael D. Smith [g]

[a] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[b] European Space Agency, ESTEC, 2200 AG Noordwijk, The Netherlands
[c] CNRS Service d'Aeronomie du CNRS, Verrières-le-Buisson, France
[d] Space Science Institute, 4750 Walnut St., Suite 205, Boulder, CO 80301, USA
[e] Belgian Institute for Space Aeronomy, Ringlaan 3, B-1180 Brussels, Belgium
[f] IFSI Roma, Italy
[g] Goddard Space Flight Center, Greenbelt, MD 20771, USA
[h] Freie Universitaet Berlin, Malteserstr. 74-100, D-12249 Berlin, Germany

ARTICLE INFO

Article history:
Received 11 April 2010
Accepted 1 July 2010
Available online 24 July 2010

Keywords:
Mars
Atmosphere
Trace gases
Methane
Orbiter

ABSTRACT

The reported detection of methane in the atmosphere of Mars as well as its potentially large seasonal spatial variations challenge our understanding of both the sources and sinks of atmospheric trace gases. The presence of methane suggests ongoing exchange between the subsurface and the atmosphere of potentially biogenic trace gases, while the spatial and temporal variations cannot be accounted for with current knowledge of martian photochemistry. A Joint Instrument Definition Team (JIDT) was asked to assess concepts for a mission that might follow up on these discoveries within the framework of a series of joint missions being considered by ESA and NASA for possible future exploration of Mars. The following is based on the report of the JIDT to the space agencies (Zurek et al., 2009); a synopsis of the report was presented at the Workshop on Mars Methane held in Frascati, Italy, in November 2009. To summarize, the JIDT believed that a scientifically exciting and credible mission could be conducted within the evolving capabilities of the science/telecommunications orbiter being considered by ESA and NASA for possible launch in the 2016 opportunity for Mars.

1. Background

1.1. Science motivation

Observations from the planetary Fourier spectrometer (PFS) on *Mars Express* (Formisano et al., 2004) and from very high spectral resolution spectrometers using ground-based telescopes have detected variable amounts of methane in the atmosphere of Mars (Krasnopolsky et al., 2004; Mumma et al., 2009). Based on photochemical models and our current understanding of the composition of the Mars atmosphere (e.g., Atreya et al., 2007), methane should have a photochemical lifetime of ~300 years, which is very short on geological time scales. Thus, its presence in the Mars atmosphere suggests a subsurface source that has recently (geologically speaking) released methane into the atmosphere. There are both geochemical and biochemical processes that could produce methane within the martian subsurface, and its presence in the atmosphere does not by itself tell us the nature of the source. Whether geochemical or biochemical in nature, the observed methane indicates a chemically active subsurface exchanging with the martian atmosphere today.

The remote observations from Earth and from Mars orbit (Formisano et al., 2004) also indicate large, possibly seasonal, variability in the concentration of methane in the Mars atmosphere. Observed decreases are not consistent with a gas-phase photochemical lifetime of several hundred years, since an atmospheric trace gas with such a lifetime should be well mixed except

---

Abbreviations: AO, announcement of opportunity; CCD, charge-coupled device; CTX, *Mars reconnaissance orbiter* context imager; DMC, *ExoMars* descent module composite; EDL, entry descent and landing; ESA, European Space Agency; EXM, *ExoMars*; SFTIR, solar (occultation) Fourier transform infrared (spectrometer); SLNIR, solar (occultation/limb/nadir) infraRed (spectrometer); HRCSC, high resolution color stereo camera; HRSC, *Mars Express* high-resolution stereo camera; JEWG, Joint Engineering Working Group; JIDT, Joint Instrument Definition Team; JPL, Jet Propulsion Laboratory; MEP, Mars Exploration Program; MEPAG, Mars Exploration Program Analysis Group; MEX, Mars Express mission; MRO, Mars Reconnaissance Orbiter mission; MSO, Mars science orbiter; NASA, National Aeronautics and Space Administration; ODY, Mars Odyssey mission; PFS, planetary Fourier spectrometer; SAG, MEPAG Science Analysis Group; Sub-mm, sub-millimeter (spectrometer); TDI, time delayed integration; TIR, thermal infraRed (radiometer or spectrometer); WAC, wide-angle camera; s/c, spacecraft; LRO, Lunar Reconnaissance Orbiter mission; LOLA, LRO Lunar Orbiter Laser Altimeter

* Corresponding author. Tel.: +1 818 354 3725; fax: +1 818 393 3035.
E-mail address: Richard.W.Zurek@jpl.nasa.gov (R.W. Zurek).

0032-0633/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2010.07.007

as affected by the seasonal variation of the bulk of the atmosphere due to condensation and sublimation of carbon dioxide in the polar regions of the planet (Lefevre and Forget, 2009). Overall, there should be little decrease from one Mars year to the next. It has been proposed that heterogeneous chemical reactions on dust and ice suspended in the atmosphere (aerosols) or with surface materials could radically reduce the methane chemical lifetime, as apparently required by the present observations. Unfortunately, the present observations are incomplete in their time and spatial coverage and limited in their ability to detect other gases that should also be affected by such heterogeneous photochemistry.

In summary, current photochemical models cannot explain the observed presence of methane in the atmosphere of Mars and its reported rapid variations in space and time. Its presence suggests ongoing activity in the subsurface, but the nature of the processes that could be producing methane and other trace gases is unknown, as is the location and the areal extent of the exchange with the atmosphere. Significant scientific progress on these issues would require: (1) detection or improved upper limits on the atmospheric concentration of a broad suite of atmospheric trace gases to elucidate the nature of the source (or sources); (2) mapping in space and time of key trace gas concentrations, together with measurements of temperature and aerosols, in order to understand the processes of removal and destruction; and (3) location and characterization of exchange with the surface to elucidate the nature and extent of ground sources.

Understanding these disequilibrium trace gases could have a profound impact on future missions to Mars, as we attempt to understand further the potential for habitability and the processes of climate change.

1.2. ESA–NASA mission concept studies

In late 2008 ESA and NASA began investigating the possibility of combining resources to implement joint missions in an integrated program of scientific Mars exploration. Mission concept studies were focused on the 2016, 2018, and 2020 Mars launch opportunities, with special emphasis given to the 2016 opportunity.

Thus far, two major mission concepts have been considered for a joint 2016 mission. In early 2009 ESA and NASA considered a joint mission concept that would combine the ongoing development of the ESA *ExoMars* rover mission with elements of a Mars science orbiter mission studied by a NASA Science Definition Team (Smith et al., 2007). The NASA study in turn had built on findings of the Science Analysis Group (SAG) formed by the Mars Exploration Program Analysis Group (MEPAG; Calvin et al., 2007). To coordinate the new study activities, ESA and NASA formed a Joint Engineering Working Group (JEWG).

Initially, options were explored in which NASA would provide a launch vehicle and carrier for the launch opportunity in 2016; these would deliver from Mars orbit the *ExoMars* Descent Module Composite (DMC; i.e., the Rover Module together with its entry, descent and landing [EDL] vehicle or descent module). The flight carrier for *ExoMars* was then sized such that it could accommodate an orbiter science payload and telecommunications package, in addition to deploying the *ExoMars* DMC from orbit. ESA and NASA agreed that the orbiter science payload should be a joint effort that would address the higher priority trace gas science objectives needed to follow up on the methane discoveries. ESA and NASA then formed a Joint Instrument Definition Team to review the viability of these objectives within the constraints of such a 2016 joint mission. The JIDT was to report their findings to the Joint Engineering Working Group, as well as to the convening ESA–NASA authorities.

The tasks assigned to the JIDT were grouped into three areas:

(1) Review the mission requirements (payload, orbit, and data return) needed to implement a 2016 science orbiter mission focused on:
  - Detection of a broad suite of atmospheric trace gases (with high sensitivity).
  - Characterization of their spatial and temporal variation.
  - Localization of sources of key trace gases (if local).

(2) Discuss the measurement requirements, including:
  - Payload: instrument types, mass, power, data rate, required fields of view, and observation cycles
  - Orbit: inclination, and altitude/period

(3) Endorse, refine, and/or augment the current requirements. Key questions to be addressed:
  - Should/can (within resources) a mapping capability be included?
  - What are the observation modes that must be accommodated?
  - What are the associated orbit requirements?

The members of the JIDT are the authors of this paper with the group being co-chaired by Agustin Chicarro (ESA) and Richard Zurek (JPL/Caltech for NASA). The JIDT met by telecon several times in April and May, with a face-to-face meeting on June 2, 2009. At the conclusion of the face-to-face meeting, an interim set of findings was reported to the ESA–NASA JEWG. These were folded into that group's presentation to the ESA–NASA Joint Executive Board, all in the first week of June 2009. A major finding of the JIDT was that it would be difficult to accommodate the payload needed to address the principal trace gas objectives within the then specified mission concept payload mass allocation of 70 kg.

Subsequent to that activity and following a bi-lateral meeting between the science directorates of ESA and NASA, it was decided to slip the launch and deployment of the *ExoMars* rover to the 2018 opportunity and to study combining its landing with that of a NASA rover concept already tentatively slotted for the 2018 launch opportunity.

For 2016, a modified mission concept emerged in which the orbiter would deploy a smaller entry, descent and landing module, the EDL demonstration vehicle. This would preserve a key technology development element of the ESA *ExoMars* program. The orbiter bus would carry a somewhat augmented science payload, again focused on trace gas science objectives, and a telecommunications package that would relay data from the technology demonstration vehicle and from the surface assets to be launched to Mars by NASA and ESA in 2018 and beyond. Provisionally, ESA would provide the technology demonstration lander and would take the lead in providing the orbiter bus; NASA would provide the launch vehicle and the relay telecommunications package. As before, ESA and NASA would jointly select an international science payload for the orbiter bus from responses to an open, competitive Announcement of Opportunity (AO).

ESA and NASA asked the JIDT to reconvene and to assess the viability of the trace gas science objectives within the capabilities of this new mission concept. To that end, the JIDT met three times in September via telecons and exchanged email on the updated mission concept. A report was then made to the JEWG on October 6, 2009 and a final report (Zurek et al., 2009) was submitted to ESA and NASA on November 10, 2009. Following that delivery, the JIDT was disbanded in anticipation of a competitive selection process for instruments on a 2016 orbiter mission.

The Announcement of Opportunity for ExoMars Trace Gas Orbiter Instruments (Program Element Appendix [PEA] H6 of the

NASA Stand Alone Missions of Opportunity Notice [SALMON] 〈http://salmon.larc.nasa.gov/SALMONreflib.html#ExoMars〉) was jointly released by NASA and ESA in January 2010. This competitive process is ongoing at the time of this writing. The purpose of this report is to document the findings of the JIDT with respect to the overall mission science objectives and to the capabilities that the JIDT thought were required of this latest 2016 orbiter mission concept.

2. Findings of the JIDT

2.1. Findings (in italics): science objectives

The observed presence of methane in the Mars atmosphere and its reported rapid variation on seasonal time scales raises many questions regarding the minor gas composition of the Mars atmosphere. It was apparent at the *Workshop on Mars Methane* that the methane observations, particularly the reports of spatial and temporal variability, remain somewhat controversial due to the limits of our current observational techniques (Atreya et al., in this issue). Earth-based observations (e.g., Mumma et al., 2009) have very high spatial resolution but must look through the Earth's atmosphere with its own plethora of trace gases, including abundant methane and a forest of weak lines from still more abundant species such as water vapor and carbon dioxide. This is not a limitation to the observations from orbit (Formisano et al., 2004), but to date the instruments flown to Mars have been constrained by the payload resources available for atmospheric observations to have relatively low spectral resolution, so that precise spectral identification of many trace gases is difficult. Furthermore, many thousands of spectra may have to be averaged to get statistically significant results, which degrades spatial and/or temporal coverage.

Thus, confirmation of the methane distribution and detection of other species remain a high priority goal. Our current difficulties show that the needed measurement approaches would benefit from observing above the confounding atmosphere of Earth and observing with high spectral resolution with good signal to noise for a given time and place. The need to observe more than methane is motivated by the goal of characterizing the source and of understanding the interaction of atmospheric gases. Thus, the detection list contains species from all the key photochemical families and their isotopologues to the extent possible. Ultimately, it would be knowledge of this suite of trace gases that might reveal the nature of their sinks and sources (e.g., Allen et al., 2006).

Returning to the JIDT report, the JIDT reaffirmed that three observation activities would be required:

(1) *Detection* of a broad suite of atmospheric trace gases and of key isotopologues;
(2) *Characterization* of the spatial and temporal variability of key species, including methane *and* ideally representing each family of photochemically important trace gases (HO_x, NO_x, hydrocarbons, etc.) and their source molecules (e.g., H_2O);
(3) *Localization*, including deriving the time histories of key species (again including, but not limited to, methane) and their possible interactions, including interactions with atmospheric aerosols and as affected by atmospheric state (temperature and distribution of major source gases; e.g., water).

These trace gas science objectives are described in more detail in the following sections:

2.1.1. Detection

- Measure with very high sensitivity the following molecules and their isotopologues: H_2O, HO_2, H_2O_2, NO_2, N_2O, CH_4, C_2H_2, C_2H_4, C_2H_6, H_2CO, HCN, H_2S, OCS, SO_2, HCl, CO, O_3:
  - ○ Improve detection capabilities and upper limits by an order of magnitude for a broad range of trace gases, including, but not limited to, the above list.
  - ○ For many species this requires detection sensitivities in the parts per trillion range.
- Because current photochemical models cannot explain the present observations of methane, measurements of additional gases might be advocated (scientifically) in response to an AO.

2.1.2. Characterization

- Spatial and temporal variability of photochemical processes requires:
  - ○ Measurements to capture effects occurring on different time scales: (a) daily due to diurnal (i.e., local time) variations of insolation; (b) day-to-day and weeks due to atmospheric weather systems and associated transport; (c) seasonal due to changes in sunlight, atmospheric aerosol and water vapor distributions and exchange with surface gas reservoirs.
  - ○ Separating seasonal and local time effects with observations covering the diurnal cycle multiple times in a Mars year.
  - ○ Representative measurements of different environments, from the high latitudes to the equator, are also needed.
- A powerful approach for characterizing the relative roles of different photochemical processes is to correlate measurements of trace gas concentrations with observed environmental variations of temperature, dust and ice aerosols, and of source gases.

2.1.3. Localization of sources

- Inverse modeling may be able to link observed concentration patterns to regional transformations (e.g., in dusty air) or to localized sources; this requires simulations using circulation models constrained by dust and temperature observations with good vertical resolution. Direct measurements of wind would provide one powerful new means of validating the model simulations.
- Mapping and comparing concentrations of multiple tracers (including, but not limited to, aerosols, water vapor, CO, CH_4), including species with different photochemical lifetimes, would help constrain model simulations and identify source/sink regions.
- Identifying localized sources might require tracing some species (e.g., methane) at the ~1 part per billion concentration level at least at the regional scale; identifying very localized sources to be visited by future landers could require mapping at scales of many tens of meters within areas comparable to a future landing error ellipse (e.g., ~100 km^2).

Given the constrained resources of the dual mission currently under study, the JIDT gave priority to a sensitive survey of atmospheric trace gas families and to characterizing the variations of selected species over much of the globe on diurnal, day-to-day, and seasonal time scales. Location of very localized sources could be beyond the present Mars orbiter's projected capabilities (see below), or require as-yet unavailable remote sensing capabilities.

2.2. *Findings (in italics): science payload*

2.2.1. *Trace gas science requirement flow down*

The purpose of Charter Task#2 was to demonstrate an existence proof that instrumentation needed to address the science objectives discussed in Section 2.1 could be flown within the capabilities of the 2016 orbiter bus mission concept and within the proposed schedule of the orbiter's development. The flow down from the trace gas science objectives [2.1] to proposed measurement objectives and proof-of-concept instrument capabilities is shown in Fig. 1.

For the purpose of scoping spacecraft conceptual capabilities, the JIDT choose representative instruments capable of making the measurements indicated above. All of these "straw man" instruments had considerable heritage in planetary and/or Earth orbiter missions. On the basis of that flight experience, the JIDT members provided estimates of mass, power, data volume, and key pointing attributes. These are summarized in Table 1 and discussed in more detail in the following sections;

2.2.2. *Representative measurement approaches*

Payload: The JIDT identified the following measurement capabilities (Table 1) as an existence proof that an orbiter mission concept could address the high priority trace gas scientific objectives.

Solar occultation measurements: this technique provides the best means of surveying atmospheric composition with high sensitivity as it measures absorption of a bright source (sunlight) passing through a large atmospheric path (along the tangent occultation path) with very high spectral resolution to reduce effects of line mixing, etc. A solar occultation Fourier transform IR spectrometer (SFTIR) can cover a wide spectral interval, enabling detection of a broad suite of trace gases. Other solar occultation instruments exploit narrower spectral intervals for specific trace gases, but can also look nadir at sunlight reflected from the surface and possibly at sunlight scattered into their views of the atmospheric limb (SLNIR). While these typically have less sensitivity (higher detection thresholds), they can link the solar occultation measurement locations (2 per orbit) to extended latitude coverage on each orbit.

Thermal emission measurements: sub-millimeter (sub-mm) and thermal infrared (TIR) spectrometers can be used to measure atmospheric thermal emission when viewing nadir or at the atmospheric limb. These characterize the atmospheric state by providing vertical profiles of temperature and profiles or column abundances of key source gases such as water vapor. Sub-millimeter measurements have the advantage that such measurements are largely unaffected by the presence of atmospheric dust; the thermal IR instruments have the advantage that they can map the distribution of atmospheric aerosols. Sub-millimeter and thermal IR spectrometers have different capabilities when measuring selected minor species; e.g., the TIR-spectrometer can measure methane, while the sub-mm cannot, but the latter is superb at measuring CO and water vapor. The sub-millimeter spectrometer in its limb-view mode could also measure atmospheric winds, which would provide a novel, powerful constraint on simulations of atmospheric transport. Thermal IR radiometers viewing nadir and the atmospheric limb can provide surface temperatures and vertical profiles of atmospheric temperature and of dust and ice concentration. The radiometers are less demanding than spectrometers in terms of data volume, but may have gas composition sensitivity to only water vapor and carbon dioxide.

Visual monitoring of atmospheric phenomena: wide-angle cameras (WACs) can provide daily monitoring of the global atmosphere and its regional atmospheric phenomena: clouds, storm systems, aerosol layers, dust storms, and boundary layer phenomena such as dust devils and wind streaks. Viewing from horizon to horizon provides important context for the single-track (per orbit) profiling and limited area mapping instruments. As with the TIR instruments, such devices

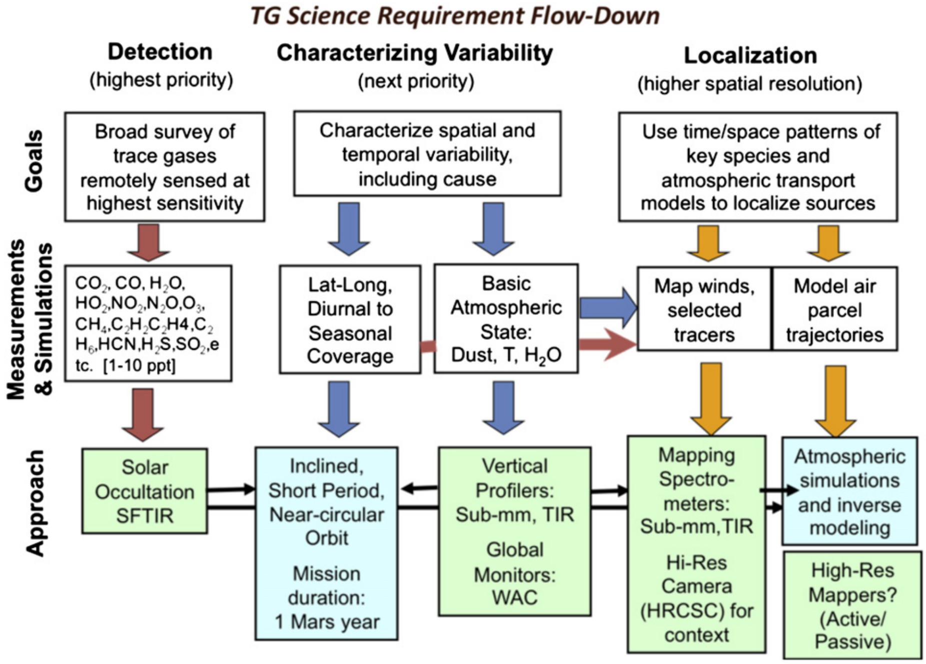

Fig. 1. Three major science goals of detection, characterization, and localization are linked to measurement and analysis goals and to possible instrumentation as part of the "existence proof" exercise conducted by the JIDT.

Table 1
Example payload for the 2016 orbiter concept. Upper panel: priority (#) and operations modes; lower panel: instrument attributes.

#	Acronyms	Descriptions	View modes	Observation modes
1	SFTIR	Solar Fourier transform IR spectrometer: **broad survey** of trace gases with high precision	Solar occultation only; passive radiative cooler	2 Solar occultations per orbit (∼24/day); processing interferorgrams throughout orbit
1	SLNIR	Solar–Nadir IR Mapper: detection and mapping of **specific** trace gases	Solar occultation; nadir and limb viewing; heat sink required (assumed to be provided by s/c)	2 solar occultations+dayside nadir/limb (60 min) on each orbit
2	Sub-mm	Sub-mm spectrometer profiler/ mapper: **atmospheric winds and temperature** plus **H_2O and specific** trace gases	Nadir and limb, including away from velocity vector (minimize effect of s/c motion on wind data)	Continuous operations switching between nadir, space, different limbs; observe both sides of ground track
2	TIR	Thermal IR profiler/mapper spectrometer or radiometer: atmospheric **temperature and dust**,+**H_2O and some** trace gases	Nadir and limb views, including away from velocity vector	Continuous operations switching between nadir, space, different limbs; observe both sides of ground track
2	WAC	Wide angle camera: imaging **atmospheric phenomena** for discriminating between surface, dust clouds, and ice clouds	Push-frame operation with ≥2 color bands; requires alignment with ground track motion	Cross-track (nearly orthogonal to velocity vector) horizon-to-horizon
3	HRCSC	High resolution color stereo camera: surface imaging	∼1 m/pixel ground sampling (at nadir) with TDI; fore/nadir/aft views	Designated targets of opportunity; requires alignment with ground track motion (mitigation needed)

	Mass (kg)	Accommodation issues	Power, avg. (w)	Power, Peak (w)	Data vol. (Mb/ day)	Comments
SFTIR	40	Anti-sun radiator a critical component	50	50	1900	On-board processing of interferograms
SLNIR	20	Includes 5 kg for radiator not previously included	20	30	900	Formerly labelled TGM/SOIR; radiator too large to place on instrument; assumed on s/c
Sub-mm	27	Power estimates reflect heritage technologies	80	99	800	Instrument includes ability to slew to view direction; some indications that power need could be cut in half
TIR	10	Data volume assumes mapping of selected trace gases	20	20	1000	Assumed 100 interferograms per orbit; T/dust/ice sounders typically return less data
WAC	3	Onboard processing (e.g., image compression) in instrument; gimbal to stay cross-track?	5	5	500	Typically framing cameras, some with spectral filters so orientation is important
HRCSC	25	5 kg added for low design maturity; 5 kg added for positioning platform; assumed 10 min/orbit peak power and 10 W standby	15	50	3000	1.6 Gb/image (compressed) requires velocity vector alignment during imaging; if s/c slews, other instrument radiators must be protected
Totals	125		190	254	8100	At max. range/aphelion power
Allocations	110	August-09	140		3000	150 kbps for single station pass

would also extend what is now a decade-long baseline of such atmospheric observations.

High-resolution surface imaging/mapping: very high spatial resolution imaging or mapping instruments (e.g., cameras and multi-beam active lidar altimeters) can provide geological context and location of small-area sources should they exist (e.g., a volcanic vent, rift, or crater). The resolution stated in Table 1 (∼1 m/pixel) envisioned that extended gas sources would be large enough to be found in the extensive coverage by MEX HRSC, ODY THEMIS, or MRO CTX. Thus, a new imager should have resolution significantly better than these (e.g., the 6 m/pixel for CTX), though not necessarily as high as the MRO HiRISE. (Note: resolutions better than 1 m/pixel are highly desired for landing site identification and safety assessment certification.) However, such high spatial resolution produces large data volumes for coverage of even very small regions.

The JIDT focused on a high-resolution color stereo camera (HRCSC) concept that would provide geologic characterization. To achieve adequate signal-to-noise at these high spatial resolutions most probably requires time-delayed-integration (TDI) which, as discussed below, requires precision pointing along the spacecraft ground track in order to sum columns of the CCD (TDI) detector. Active devices (e.g., laser differential spectrometers/altimeters) were briefly discussed, but were not pursued given time limitations on the JIDT deliberations. Such devices could appear in response to an AO (e.g., LRO LOLA class lidars.

2.2.3. *Measurement approach priorities*

Clearly, there are trades possible between the different mapping techniques. The JIDT anticipated that the competitive AO process could achieve an optimal selection of profiling and mapping instruments with different observing techniques, including those that the JIDT had little time to discuss.

Given the projected resources of the 2016 orbiter bus concept currently being studied by ESA–NASA, the JIDT established priorities (Table 1) *amongst these measurements with respect to the trace gas science objectives* (Section 2.1).

The highest scientific priority was assigned to detection of a broad suite of trace gases with high sensitivity to establish the atmospheric inventory, but also to provide insights into the nature of the trace gas source through detection of suites of gases or through ratios of gases and isotopologues (e.g., volcanic in nature or biogenic?). The ability to map certain key species (e.g., methane) outside the limits of solar occultation geometries was also given high priority, because of the limited spatial coverage possible even with an orbit designed to facilitate solar occultation measurements (see below). Vertical column measurements would be useful; vertically resolved profiles would be better, although trade-offs between horizontal and vertical resolution would need to be assessed.

The second priority was assigned to measurements and low resolution imaging of atmospheric state (aerosols, temperature, and winds) and to mapping of key trace gas species other than methane. Besides source gases such as water vapor, candidates included CO, H_2O_2, SO_2, and higher order hydrocarbons. Given that present photochemical models do not reproduce the reported variations of methane, it was difficult to come to consensus on which trace gas species should be mapped, and the JIDT recognized that responses to an AO might successfully argue for species not listed here. Finally, some redundancy in measuring key trace gases is useful. While there can be some trade-off between the different instrument approaches, the JIDT believed that more than one instrument technique would likely be required.

Thus, the JIDT ranked mapping/profiling of atmospheric temperature, aerosols, and water vapor [atmospheric state], and of some key trace gas species just below the atmospheric inventory [detection]. Monitoring of atmospheric phenomena was given a similar priority, including direct measurements of atmospheric winds.

The third priority was assigned to high-resolution surface mapping, as its utility for trace gas science is identifying localized sources, which may or may not exist, and providing their geological context, if they do. While there are important objectives for surface change science (detection of new impacts, new or changing aeolian features, monitoring of polar ice deposits), extended imaging/mapping is difficult to accommodate within the capabilities of the current 2016 orbiter bus concept (Table 1; Section 2.2.4). However, the JIDT concluded that there might be a niche for an imaging system that achieves 1–2 m/pixel ground sampling distances (field of view). This resolution was chosen in order to improve significantly on the extensive imaging by the *Mars Express* HRSC and the *Mars Reconnaissance Orbiter* CTX (e.g., the latter has covered ~ 60% of the planet at ~6 m/pixel ground sampling distance). Color and stereo capabilities would significantly increase the value of surface observations by allowing some limited mineralogical distinction and topographic context, though their inclusion would greatly expand the data volume that must be returned.

Other possibilities for identifying local sources of trace gases were briefly discussed, but not pursued in any detail by the JIDT. Locating small-area sources would be very challenging, even given guidance provided by regional mapping. Active systems (e.g., differential lidar/laser spectrometers or gas correlation radiometers) can resolve trace gas variations at the scales of small-scale geologic features ($<100\,\text{km}^2$ areas). However, the mass and power requirements of such instruments are potentially significant and—when added to the resources required by the trace gas instruments discussed above—might be outside the capability of the current mission concept. However, innovative instruments might emerge in response to the AO that employ such techniques.

These priorities are indicated in the first column of Table 1.

2.2.4. *Other payload and mission considerations*

2.2.4.1. Mass and power. Important features of the mass and power estimates are that they were intended to include mechanisms needed to point the instrument away from the spacecraft provided reference attitude (in the current concept, the spacecraft would be sun-pointed) and that they include the maturity margin; i.e., larger estimates were included, which might be reduced should new concepts or new technologies be successfully proposed. In this way the JIDT tended to be conservative in estimating the resources required, while recognizing that some optimization might occur in a selection process. As can be seen, the mass and power estimates to carry out the measurement program needed to achieve the proposed mission science objectives exceeded the initially revised allocations (last row in Table 1) envisioned in the mission concept as of August 2009.

*The JIDT recommends mass and power allocations of ~125 kg and ~190 W (*orbital average*). As noted above, these numbers were scoped to include maturity margins and pointing mechanisms. This disconnect was reported to the JEWG, and it appears that some mitigation is possible within the system design.

2.2.4.2. Data return. Another vital resource for this payload is the volume of data that could be returned. The table reflects conditions at greatest Earth–Mars range and thus at the lowest expected data rate; it also takes into account spacecraft housekeeping data return, Earth occultation, and downlink to a single station back on Earth. The high spectral resolution of several instruments results in large data volumes to be returned. These would be even larger (by an order of magnitude) without the onboard compression and data reduction that is assumed here (and included in the mass and power numbers). For example, it is assumed that the SFTIR observes the Sun in occultation mode twice per orbit and then spends the rest of the orbit reducing and transferring data for transmission to Earth. The numbers for the TIR instruments assume spectrometers rather than multichannel radiometers, as the former typically produce more data volume.

Each image of any suitable high-resolution imager (HRCSC) can produce more than a gigabit of data. The calculation here envisioned 3 stereo views each in 3 colors, all with significant compression for each "target" to be observed.

As seen from Table 1, even the data return needed from the spacecraft without high-resolution imaging exceeds the postulated capability of 3 Gbits/day to a single station at maximum range. The JIDT reported these numbers to the JEWG in October; augmenting the proposed baseline to use two stations per day would yield ~5 Gbits/day for science near greatest Earth–Mars range. This, together with other aspects of the mission concept, is still being worked.

The JIDT notes that data return to two Earth ground stations at greatest Earth–Mars range would be required to service just the trace gas and atmospheric state instruments but would still be inadequate for high-resolution surface imaging for several months around superior conjunction.

Several images per day may be possible as data rates increase with decreased Earth–Mars range. Major discoveries motivating imaging could be accommodated by interrupting the occultation, profiling, and mapping observations, but this is not recommended here as a nominal mode for a trace gas mission (during its primary science phase of one martian year).

2.2.4.3. Observation modes. The science objectives and the measurement approaches considered here have 3 distinct observing modes: (1) solar occultation viewing [SFTIR, SLNIR]; (2) repeated vertical profiling and/or column measurement, typically including space views [TIR, sub-mm, SLNIR]; (3) imaging along [HRCSC] or orthogonal to [WAC] the spacecraft ground track.

Visual imaging instruments, of course, would observe on the dayside, and the solar occultation instruments would observe at two occultation points (sunrise/sunset) per orbit, except for those periods when the occultation line of sight remains just above the atmosphere (Fig. 2).

Limb viewing geometries for the profiling instruments would provide the needed vertical resolution for aerosol and temperature distributions; approaching a half-scale height (<7 km) resolution, this would be needed for driving and validating atmospheric model simulations of transport and thus for inverse modeling to identify surface sources. Furthermore, limb viewing would provide increased sensitivity to trace gases

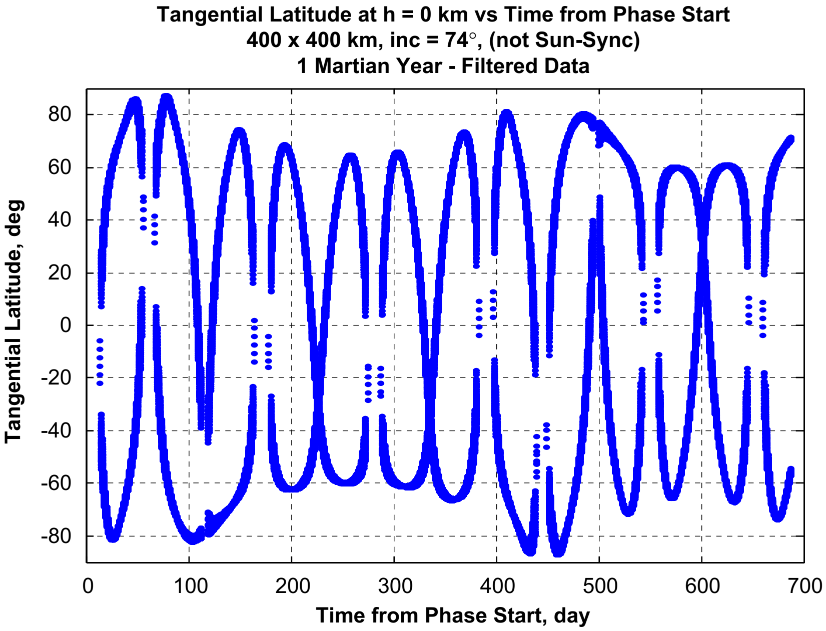

Fig. 2. Solar occultation tangential latitudes versus time over a Mars year in a 400 km orbit with a 74° inclination. This shows one combination of altitude and inclination that would provide essential latitudinal coverage each Mars season for this observational mode.

due to the longer path viewed through the atmosphere and, for the sub-millimeter or similar devices, could provide direct measurements of horizontal winds by measuring the Doppler shift of spectral lines. The limb and nadir viewing instruments measuring thermal emission from the atmosphere would typically be observing throughout each orbit on both the day and night sides.

2.2.4.4. Orbit requirements. To achieve adequate vertical and longitudinal resolution for the limb/nadir viewing instruments and to achieve high-spatial resolution surface imaging would require an orbit ~400 km or lower in average altitude. Small changes in altitude (~ tens of kilometers) would also affect the ground track walk, which determines how quickly ground tracks repeat and thus the longitudinal sampling of the observations on various time scales. A ground track that is essentially fixed in that it repeats each day is not favored, as areas between the ground tracks would always be viewed obliquely. A fixed ground track is part of the current mission concept for the relay phase (to optimize over-flights of a landed asset each day), but the JIDT favors a rapid repeat cycle of 3–5 days in which the longitudinal span between two adjacent orbits on one day is divided in roughly equal portions of 3–5 parts over that period.

The JIDT does not favor fixed ground tracks for the science phase of the mission. The JIDT recommends an orbit altitude ~400 km or somewhat lower as needed to achieve an appropriate ground track repeat cycle.

To capture photochemical variations on the key cycles of daily, day-to-day and seasonal time scales and to get representative coverage for the solar occultation and thermal emission profiling instruments requires an inclined orbit for which the solar occultations move in latitude as the equator crossing time of the orbit precesses through all times of day in 1–2 cycles per season. The change of occultation points in latitude is shown in Fig. 2 for one choice of parameters. Typically, the trade-off here is that lower inclinations move the solar occultation points and the mapping instruments through a full diurnal cycle more quickly, while higher inclinations produce an extended latitude range with coverage of potential polar reservoirs.

The JIDT considered an orbit inclination of 74° (± 10°) acceptable.

This would provide adequate temporal coverage and separation of the key cycles while still enabling viewing of the high-latitude atmosphere, although generally not of the central polar caps and their temporal reservoirs of volatile material. The exact inclination and altitude could be optimized once the payload and science teams are selected.

2.2.4.5. Mission duration. The JIDT recommends that the science phase, with occultation, profiling, mapping, monitoring, and imaging observations, last at least one Mars year.

This would enable coverage of all Mars seasons in a search for trace gas sources and sinks.

2.2.4.6. Spacecraft positioning. Perhaps the most controversial of the issues considered by the JIDT was a proposed mission scenario in which the spacecraft would stay sun-pointed throughout the orbit (virtual sun-point on the night side). From the spacecraft developers' point of view, this would have several advantages: (1) solar arrays would require only 1 axis of gimbal motion and receive maximum insolation [an important issue as seen in the discussion of payload power]; (2) the spacecraft could readily point the solar occultation instruments to their target without large slews; (3) body-mounted instrument coolers could have a fixed, anti-Sun view on a spacecraft whose orbit plane is moving in local time. The difficulty is—as noted in the earlier discussion of observation modes—that the visual imagers must view precisely along and/or orthogonal to the ground track to achieve their measurement objectives.

The JIDT did not fully resolve this issue. While a turntable (gimbal) might be adequate for the WAC with its relatively low resolution and small size, it is not desirable for a higher resolution, heavier instrument such as the conceptual TDI-based HRCSC that requires precise alignment with respect to the ground track. Furthermore, micro-phonics (vibrations) from gimbaling instruments could affect other instruments as well. The profiling/mapping instruments typically include within their instruments some means of alternating between space, limb, and nadir views, but a sun-pointed spacecraft in the recommended orbit might require additional (e.g., azimuth as well as elevation) scanning hardware. An alternate proposal of slewing the spacecraft attitude back and forth between the two geometries would have the disadvantages of repositioning slews using up the timeline and, more importantly, of now introducing radiator field of view and power problems as the orientation with respect to the sun and planet changes.

The JIDT concluded that the sun-pointed spacecraft would be an excellent choice for the solar occultation instruments, would require gimbals and/or articulation for the profiling instruments and WAC, but is not desirable for the very high-resolution imaging/local mapping devices.

3. Summary

The JIDT believes that a scientifically exciting and credible mission could be conducted within the evolving capabilities of the current mission concept for a 2016 science/telecom orbiter delivering an EDL demonstrator on direct entry to Mars. Some lingering issues need to be addressed, but these are viewed by the JIDT to be technically workable. The JIDT has no doubt that an appropriate science payload could be selected in response to an open, competitive Announcement of Opportunity and that—once those instrument teams are assembled and working with the spacecraft developers—the mission envisioned here could be further refined for the 2016 launch opportunity and flown successfully.

There will assuredly be surprises in what this mission would discover in the Mars atmosphere—after all, we already have a tantalizing atmospheric signature in the reported methane patterns. The promise of this mission is that it would reveal just how chemically active the Mars subsurface and atmosphere are today, with the goal that it might reveal the specific nature of that activity—geological, geochemical, or biological in origin?

Acknowledgements

The JIDT activity described in this report was supported by ESA and NASA Headquarters and the ESA ExoMars Project. The Mars Program Office at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, also supported the JIDT activity, including the preparation of the final report and this paper.

References

Allen, M., Sherwood Lollar, B., Runnegar, B., Oehler, D.Z., Lyons, J.R., Manning, C.E., Summers, M.E., 2006. Is Mars alive? EOS 87 443, 439.

Atreya, S.K. et al., in this issue.

Atreya, S.K., Mahaffy, P.R., Wong, A.-S., 2007. Methane and related trace species on Mars: origin, loss, implications for life, and habitability. Planet. Space Sci. 55, 358–369.

Calvin, W. et al., 2007. Report from the 2013 Mars Science Orbiter (MSO) Second Science Analysis Group, 72 pp., posted June 2007 by the Mars Exploration Program Analysis Group (MEPAG) at 〈http://mepag.jpl.nasa.gov/reports/index.html〉.

Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N., Giuranna, M., 2004. Detection of methane in the atmosphere of Mars. Science 306, 1758–1761.

Krasnopolsky, V.A., Maillard, J.P., Owen, T.C., 2004. Detection of methane in the martian atmosphere: evidence for life? Icarus 172 537–547.

Lefevre, F., Forget, F., 2009. Observed variations of methane on Mars unexplained by known atmospheric chemistry and physics. Nature 460 (7256), 720–723.

Mumma, M.J., Villanueva, G.L., Novak, R.E., Hewagama, T., Bonev, B.P., DiSanti, M.A., Mandell, A.M., Smith, M.D., 2009. Strong release of methane on Mars in Northern Summer 2003. Science 323, 1041–1045.

Smith, M.D. et al., 2007. Report of the NASA Science Definition Team for the Mars Science Orbiter (MSO), 39 pp., posted February 2008 at 〈http://mepag.jpl.nasa.gov/reports/index.html〉.

Zurek, R.W., Chicarro, A., Allen, M.A., Bertaux, J.L., Clancy, R.T., Daerden, F., Formisano, V., Garvin, J.B., Neukum, G., Smith, M.D., 2009. Final Report from the 2016 Mars Orbiter Bus Joint Instrument Definition Team (JIDT), November 2009, 17 pp., posted 2010 at 〈http://mepag.jpl.nasa.gov/reports/index.html〉.