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A New View of Mars Aqueous Alteration: First Results from The Mars Orbital Catalogue of Chemical Alteration Signatures (MOCCAS)

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1. Introduction

A decade of orbital and in-situ investigations of the hydrous clay mineralogy of Mars have revealed blanketing aqueous alteration involving a variety of formation and diagenetic mechanisms, and an evolution with time. A paradigm established 10 years ago has withstood intense scrutiny [1]. Mars experienced a clay-forming era early in its history (circa 4 Ga, probably since earlier times), which transitioned to evaporitic salty deposits, as the geologic and hydrologic activity of Mars waned. Open, fiercely-debated questions remain: e.g. did the bulk of alteration involve meteoric waters in open system environments, or was it restricted to the sub-surface under a mostly frozen-over surface, save for episodic climatic excursions [e.g. 2-4]. Also of critical importance for future exploration, the organic matter retention and preservation potential of Martian clay-bearing environments have yet to be fully assessed.

2. Global mapping: rationale

A methodological approach to the large and varied datasets of Mars aqueous alteration available should allow lifting some degeneracy as to the actual geochemical environments on ancient Mars. Here we report on the completion of the MOCCAS (*Mars Orbital Catalog of Chemical Alteration Signatures*) project. A decade of mapping hydrated minerals on Mars at the sub km resolution, using principally the OMEGA/Mars Express and CRISM/MRO imaging spectrometers, now provides a global view of aqueous alteration at Mars. The approach here is hybrid between the early mapping works [1,5], and subsequent cataloging projects [3,6,7]. This new vectorial database combines detailed spectral analysis providing the aqueous mineralogy, with high resolution spatial mapping for morphologic context and global scale distribution. The detailed methodology and goals of MOCCAS are further described in [8].

3. Early results

We present early results from this dataset which provide a new view of Mars alteration: 1. A statistically significant sample (100,000s deposits) globally at Mars which reveal the blanketing nature of Mars's Noachian alteration. Likely an order of magnitude more than established thus far. 2. New regions of extensive aqueous alteration with areas in par with those well studied thus far (e.g. Mawrth Vallis Plateaus, Nili Fossae, Sinus Meridiani). 3. Regional scale trends in Mars's alteration showing coupling between geologic/topographic context and composition.

Collectively, these early results show that Mars's alteration is still largely un-investigated, and there exist several regions of particular interest which would warrant further study and in-situ exploration. Several such example regions are shown here (figure) and will be presented.

4. Perspectives

A systematic, regional-scale investigation of Mars using the MOCCAS dataset is underway which aim is to provide insight on the diversity of alteration settings at Mars. The database itself is being refined to integrate, for each deposit, the geologic age from [9], while the largest deposits will have estimates of their thicknesses (when possible) and modal abundances [10]. These will help interpret the regional diversity, and be used to study *quantitatively* the global scale formation processes of clay minerals at Mars.

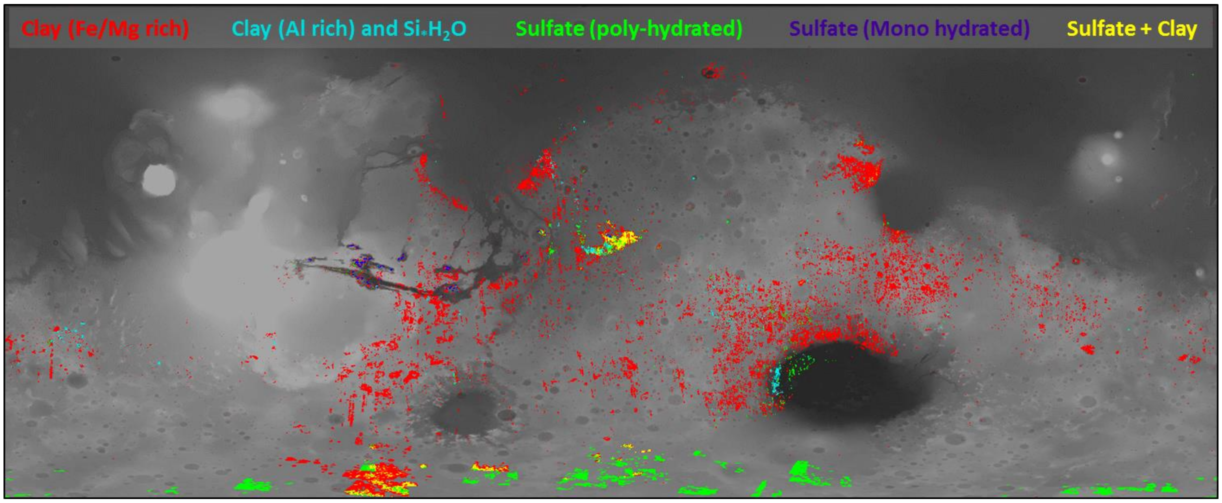

Figure 1. The global scale database. Several 100,000s exposures mapped and their mineralogy determined.

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Exploring the Atmosphere of Mars with Remote Observations: Activities in Japan for the Belgium-Japan partnership (AMAVERO)

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Recent successful explorations of Mars and Venus atmospheres by numerous spacecraft and ground-based telescopes have suggested their active photochemistry and dynamics. Characteristics of spatial and temporal variations of temperature, wind, and atmospheric constituents are essential to understand the photochemistry and dynamics. From April 2017 to March 2019, Japan-Belgium collaboration program, AMAVERO (Exploring the Atmosphere of MArs and VEnus with Remote Observations: A Belgium-Japan partnership) is running. In this project, we study the following aspects. (1) 3D distributions (i.e., spatial variation + vertical profiles) of temperature, wind, and trace gases on Mars, and (2) those at the middle atmosphere (from the cloud top to the upper atmosphere, 60-140 km) of Venus.

These objectives are achieved by collecting observational datasets from Belgium and Japan. Belgian side provides the data taken by European Mars orbiter Mars Express (MEx) and Trace Gas Orbiter (TGO), and Venus Orbiter Venus Express (VEx). From Japan, we provide the data taken by ground-based and spaceborne telescopes with Japanese Venus Orbiter Akatsuki. Moreover, we share tools to analyze the observational datasets, and develop the numerical models of the atmospheres to interpret the observational results.

In the spring in 2017, we sent scientists from Japan to Belgium and initiated the following researches based on the exchange of young research staffs, postdocs, and graduate school students:

(1) Collaboration of ground-based observation data, taken by ALMA sub-mm array, SOFIA IR airborne telescope, and MIRAHI IR heterodyne spectrometer. (for Mars + Venus). (2) Development of Limb retrieval code JACOSPAR for the utilization to ExoMars Trace Gas Orbiter and its test application for H_2O vertical profile derived from Mars Express data. (for Mars: to be appeared in this meeting as Toyooka et al.). (3) Distribution and dynamics of Venusian atmosphere observed by Akatsuki IR imagers. (Venus). (4) The inter-comparison of Venusian and Martian GCMs with cloud and water cycles in different approaches. (for Mars + Venus) (5) Variation of the homopause and atmospheric composition in the upper atmosphere with the comparison between VEX/SOIR + MAVEN + TGO.

This project was generated from the long-term collaborations between Japan and European groups for Mars and Venus sciences associated with Mars Express (2003-), Venus Express (2005-2015), CrossDrive project (Collaborative Virtual Environments for Mars Science Analysis and Rover Target Planning, 2014-2016), ExoMars TGO (2016-), with groundbased and numerical simulation works. In this meeting, we show the progress and the activities on-going in this project related to Mars Express and ExoMars with the link to MAVEN. Any proposals and collaborations are welcomed.

Table 1: Acronyms for the missions or instruments to be used in the project, with the corresponding PI

Satellite observations			
Acronym	Full name	Platform	Instrument/mission PI*
PFS / MEx	Planetary Fourier Spectrometer	Mars Express (MEx)	M. Giuranna
OMEGA / MEx	Visible and Infrared Mineralogical Mapping Spectrometer	Mars Express (MEx)	J. P. Bibring
SOIR / VEx	Solar Occultation in the InfraRed	Venus Express (VEx)	A.C. Vandaele
LIR / Akatsuki	Longwave Infrared Camera	Akatsuki	M. Tagushi
NOMAD / TGO	Nadir and Occultation for MArs Discovery sounder	ExoMars Trace Gas Orbiter (TGO)	A.C. Vandaele
Earth-based observations			
Acronym	Full name	Telescope	Instrument/mission PI*
EXES / SOFIA	Echelon-Cross-Echelle Spectrograph	Stratospheric Observatory for Infrared Astronomy telescope	S. Aoki for the measurements to be used here
COMICS / SUBARU	Cooled Mid Infrared Camera and Spectrometer	SUBARU telescope in Mauna Kea, Hawaii,	T. Sato for the measurements to be used here
MILAHI / T60	Mid-infrared laser heterodyne spectrometer	T60 60 cm telescope in Haleakala, Hawaii	H. Nakagawa, Tohoku University
ALMA	Atacama Large Millimeter Array		S. Aoki for the measurements to be used here
Models			
Acronym	Full name or short description		Responsible scientists*
ATMOSPHIT	Versatile line-by-line radiative transfer model with various retrieval schemes. Accommodates different geometries, line shapes etc Developed initially for Earth, it was successfully tested on PFS / MEx data		P. Coheur and ULB team
ASIMUT	Line-by-Line radiative transfer code allowing for different observational geometries and instruments. Allow simulation and retrieval. Developed for Earth, Mars and Venus.		A.C. Vandaele and BIRA-IASB team
GEM-Mars	3D GCM for the atmosphere of Mars from the surface up to 170 km. Builds on the GEM standard weather forecast model of Environment Canada		F. Daerden, BIRA-IASB
DRAMATIC-MGCM	Dynamics, RAdiation, MAterial Transport and their mutual InteraCtions; Mars General Circulation Model		T. Kuroda

* Underlined when part of the proposing consortium

Table 1: Missions and Instruments related to this project.

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Spectral inversion of OMEGA/MEx limb observations considering multiple scattering

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Abstract

This work presents the results of the OMEGA/Mars Express limb spectral inversion in the infrared, using a Bayesian inversion scheme. We used a multiple scattering radiative transfer code to simulate the light transmission and scattering in the Mars atmosphere. We will present the vertical profiles of the detected species and aerosols, i.e. CO_2, CO, H_2O, dust and ice.

1. Introduction

The OMEGA instrument on board Mars Express (MEx) is an infrared spectrometer taking observations of the Mars atmosphere since 2004 in the 0.35 to 5.1 µm wavelength region [1]. Amongst all the observations, OMEGA observed the Mars atmosphere in limb geometry, during which radiances were measured with a spectral sampling of 7 nm (0.35-1.0 µm), 13 nm (0.93-2.65 µm), and 20 nm (2.51-5.1 µm) and an instantaneous field of view of 1.2 mrad. These measurements show a good coverage of the planet in terms of latitude, longitude and solar longitude (Ls).

In this work, we present an algorithm used to invert the limb observations using a Bayesian approach [2]. In this scheme, the forward model, JACOSPAR, is a full radiative transfer code which accounts for multiple scattering of the Sun light by the atmospheric aerosols, in order to model the radiances with a high precision [3,4,5].

We intend to retrieve CO_2, H_2O and CO vertical profiles for the gas species, and water ice and dust vertical profiles for the aerosol species, which all show clear absorption and/or scattering structure in the considered wavenumber region.

2. The method

2.1 Forward model

JACOSPAR is a multiple scattering radiative transfer code that uses the backward-propagating Monte Carlo method, and the dependent sampling approach in order to reduce the computational time [6]. It calculates the scattering for a given number of wavenumber values and interpolates the radiance for the other wavenumbers [3,4,5]. JACOSPAR accounts for the instrumental field of view in its calculations.

JACOSPAR also computes precise analytical Jacobians relative to the radiances with respect to the absorption and scattering extinction profiles. They are used to derive the Jacobians to volume mixing ratios (VMR) of the different atmospheric gases and aerosols, as well as to the aerosols mean radius, which are used in the Bayesian algorithm.

We compute the aerosols single scattering albedo, phase function and extinction coefficients using the Mie theory [7], for altitude constant modified-gamma size distributions taken from [8], using refractive index of dust and water ice from [9] and [10], respectively.

2.2 Bayesian algorithm

We implemented the Bayesian algorithm approach developed by [2] using the Gauss-Newton method. Based on an a-priori atmosphere obtained from the GEM-MARS [11], we fit the logarithm of the different species VMR and the aerosols mean radius, assuming temperature and pressure conditions obtained from MCD for the latitude, longitude, time and Ls observation mean value.

2.3 Sensitivity study

We present a sensitivity study, conducted in different illumination geometries, to the different retrieved VMR profiles, which shows that the precision of the retrieved profiles is correlated with the distance of the MEx spacecraft to the impact point of the observations due to the field of view of OMEGA, as well as with the vertical sampling (vertical distance between two consecutive impact points). We show that the sensitivity to CO_2, H_2O and dust is reasonable, while is weaker for water ice and CO, due to their respective absorption strength and wavelength dependencies.

3. Results and discussion

We searched for the best covariance values to the a-priori atmosphere in order to best fit the OMEGA measured spectra, and we obtained good fits for the fraction of the observations that have already been inverted.

The vertical profiles derived from a few observations will be presented and discussed in different illumination geometries, geographical position and seasons, and compared to previous observations. We discuss variations of the different VMR vertical profiles as a function of time, latitude and Ls within the retrieved uncertainties, and compare with profiles from models, such as GEM-MARS. In particular, we focus on water and dust vertical profiles.

4. Future applications

The code is intended to be applied to the inversion of the NOMAD [12] on board ExoMars limb observations, that will be carried out from end of 2017. One of the channels of NOMAD, LNO, is a high resolution echelle grating spectrometer using the AOTF technology to select the wavenumber ranges to be measured, working in the infrared from 2.2 to 3.8 µm.

Acknowledgements

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Modification of the retrieval tool JACOSPAR for the Martian limb observation

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1. Introduction

Previous studies of the Martian atmosphere with limb/solar occultation observations generally use a radiative transfer code to retrieve atmospheric species. To reduce the potentially huge computational time, there are some approximations to the calculation system and to the scattering properties. For Limb observations, the pseudo-spherical approximation was found to be accurate within a few percent and was two orders of magnitude faster than the exact Monte Carlo calculation with the accuracy of a few percent [1]. There are potential requirements for the fast and accurate radiative transfer code that treats the multiple scattering of light by aerosols in a fully spherical system. JACOSPAR [2] [3] [4] is a fast radiative transfer model with multiple scattering. JACOSPAR has been already applied to the study of Earth's atmospheres to retrieve the slant column density of NO_2 and O_3[5]. We modified JACOSPAR in order to apply it to the limb observation of Martian atmosphere. Here we present test simulations to optimize the code for the Martian atmosphere.

2. Modification of JACOSPAR

2.1 Introduction of JACOSPAR

JACOSPAR considers refraction and multiple scattering of light by aerosols in the full spherical atmosphere. It can calculate radiance and Jacobians effectively with requested accuracy by applying "backward Monte Carlo method" that treats absorption and scattering of the radiation as a probability process of the model photons and track its trajectory from observed point to the space. It also adopts the "Dependent sampling method" [6] which simultaneously and multi-spectrally estimates the radiance and Jacobians, reducing the calculation amounts. The radiation sources can be solar beam or internal thermal emission, so that the model can be applied to both solar and infrared spectra in the same framework. Single scattering components are calculated analytically by integrating the source function. For multiple scattering components, JACOSPAR uses backward propagating Monte Carlo method. In order to run the radiative transfer codes for Martian atmosphere, gases absorption coefficients and mixing ratio profiles, aerosols scattering/absorption coefficients, phase functions and vertical profiles, temperature and pressure profiles, and the solar spectrum, are required as input information. The absorption coefficients of CO_2, H_2O, and CO were calculated with the line-by-line method. The single scattering optical properties of dust and water ice in the Martian atmosphere were calculated with the Mie-theory [7] and then integrated with the modified gamma distribution [10]. The refractive indices of dust and water ice are referred to from Wolff and Clancy (2003) and Warren (1984), respectively [11][12]. The mixing ratio of the gases in the Martian atmosphere were assumed to be 95.32% of CO_2 at 0-79km, 300ppm of H_2O at 0-79km, and 800ppm of CO at 0-79km. A Martian vertical temperature-pressure profile selected from the Mars Climate Database has been considered. [13]

2.2 Modified points

We modified two points of JACOSPAR in order to stably calculate the radiance in the thin atmosphere of Mars. (1) In the upper atmospheric layer of Mars where the multiple scattering rarely happens, the radiance can vary

20-30% depending on whether the observed light is the single scattered one or multiple one. This can cause unstable computation results. Thus, we modified the threshold to decide the occurrence of the scattering event. (2) When considering the finite size of field of view (FOV), the radiance is averaged by taking the number of line of sights(LOSs) within the FOV. The LOSs were selected randomly in JACOSPAR. However, a slight difference of LOSs can cause significance on the number of scatterings in the limb geometry. We modified to set the LOSs uniformly within the FOV.

3. Results

In order to validate the codes, a test simulation has been performed under the framework of UPWARDS project, by comparing with the codes, MITRA [13] which has been used for the retrieval of water vapor with PFS/MEx [14]. Comparisons of the outputs by the two codes are in excellent agreement with the accuracy of less than 1 % on average. This demonstrated that these codes were ready to be applied to the data analysis of limb observations in the Martian atmosphere.

In addition to the validation, the output radiance and Jacobians have been investigated in order to confirm the JACOSPAR performance. By optimizing the number of the calculation points in the FOV, the calculation error of radiance and Jacobians related to the absorption less than 2% and those related to the scattering less than 10% were achieved. This work gives the baseline for the retrieval of vertical profiles of gases and aerosols from OMEGA/MEx limb observation, as reported by companion paper [15].

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Analysis of spectral orbital and laboratory data to further constrain Martian habitable environments

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Abstract

A large amount and a wide variety of information can be retrieved from the study of the thermal emission and reflectance spectra of a planetary object. An analysis of spectral orbital and laboratory data is used to create a map of the Martian surface showing the global distribution of potential habitable regions. This will be of highest interest to future Mars missions and it will be a key to further investigate the history and evolution of the planet. To achieve this goal, the surface mineralogy of the planet is retrieved implementing an advanced method for separating the spectral signatures of the Martian surface and atmosphere. The global distribution of potential habitable regions of the Martian surface will be mapped based on the analysis of the presence, type and abundance of aqueous alteration minerals observed in orbital spectral data.

1. Introduction

Understanding the history of water on Mars is of fundamental importance to disclose the evolution of its surface and atmosphere and its potential habitability. In particular, the mineralogical record provides significant clues on the geochemical environment and aqueous history of the planet. Evaporites, clays and other sedimentary rocks can prove the presence of liquid water environments during the Martian history on or near the surface. The mineralogical information, placed in its geological context, will allow to reconstruct the processes of formation of several structures observed on the Martian surface (i.e. fluvial structures such as valley networks, paleolakes and sedimentary deposits), which involve the chemical action of liquid water. Such kinds of processes have been sometimes responsible for the conditions of habitability on Earth, and this may be the same on Mars.

Much knowledge of Mars mineralogy relies on data collected remotely, using infrared spectroscopic tools [1,2,3]. Molecular lattice vibrations lead to distinctive minima, diagnostic of composition, in electromagnetic radiation thermally emitted from the surface [4]. Similarly, in the visible and near infrared wavelengths sunlight reflected from the surface of Mars has also characteristic features at certain wavelengths that are diagnostic of the surface composition [1]. Therefore, thermal and reflectance spectra contain a lot of information about the surface composition of a planet and its mineralogy, allowing building a picture of a planet's surface.

Nearly every mission to Mars has onboard an instrument devoted to spectroscopy. This includes instruments like Thermal Emission Spectrometer (TES) onboard Mars Global Surveyor [5], the imaging spectrometer Observatoire pour la Mineralogie, l'Eau, le Glace e l'Activite (OMEGA) [6] and the Planetary Fourier Spectrometer (PFS) [7] onboard Mars Express, and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard Mars Reconnaissance Orbiter [8] that provide remote measurements of mineralogy and thermophysical properties of the Martian surface.

But the interpretation of these data is often difficult and requires a big effort from the scientific community. This variety of information presents the complicated problem of isolating each of the atmospheric and surface components and determining their relative contribution to the measured radiance. The aim of this work is the use of a new surface-atmosphere algorithm to allow both surface and atmospheric contribution retrievals with the main goal to investigate the potential habitability in the history of Mars mainly through the identification of hydrated minerals (such as phyllosilicates, hydrated silica) and evaporites (such as carbonates, sulfates and chlorides).

Some works suggest, in fact, that aqueous alternation minerals, such as phyllosilicates, could have played a key role not only the origin of life on Earth [9] but also in the preservation of biosignatures [10]. For this reason, phyllosilicate regions on Mars may represent very interesting environments that can provide conditions favorable to preserving evidence of biomarkers [9, 10, 11].

However, the orbital spectra can only be interpreted by means of comparisons with those of planetary analogue samples, prepared and analyzed in laboratory. For this reason, an ongoing and detailed laboratory work on Martian analogues materials is planned for the best interpretation of spectral orbital data. Therefore, the main objectives of this work are:

- Mapping of the potential habitability of the Red Planet;
- Development of a good methodology for surface and atmospheric retrieval from orbital spectral data;
- Carrying out a unique laboratory work on planetary analogues materials.

2. Data and methods

To achieve the objectives discussed in the previous section, new detailed surface mineralogy is derived from the so far largely unexplored Mars Express PFS dataset. Surface mineralogy derived from TIR measurements is highly complementary to existing datasets from OMEGA and CRISM and due to the higher spectral resolution will significantly improve on early TES studies. For this purpose, we use newly calibrated PFS data and improved recalculated geometries for the observations.

In order to recalibrate the PFS data a new SAS (Surface-Atmosphere-Separation) algorithm will be implemented based on a combination of R-mode factor analysis and target transformation. By means of target transformation and factor analysis techniques PFS data can be modelled as a combination of atmospheric endmembers and a residual superficial component. A first application of multivariate techniques to PFS data confirmed that they can be fully represented by a linear model using only a limited set of end-member spectra identified by means of a target transformation technique [12]. R-mode factor analysis and target transformations were also applied to PFS measurements in the same region where OMEGA detected the phyllosilicates on Mars to retrieve and characterize the number and the spectral shape of the varying component present in the spectra [13]. Once all the atmospheric endmembers were identified and characterized, for each PFS measured spectrum, the residual of this fitting algorithm identify the surface spectral shape. This curve was again fitted by using a linear deconvolution of emissivity spectra for Martian analogue minerals measured at DLR-PSL (Deutsches Zentrum für Luft- und Raumfahrt - Planetary Spectroscopy Laboratory) [14]. The use of the PSL allows the access to a unique collection of samples and measurements that are used to build an improved spectral library, which is then applied to the PFS data. The application of this technique will be improved and extended to the entire PFS dataset.

Our study is a key for the geological and spectral characterization of the Martian surface and will be useful to determine whether the Red Planet ever had long-term environmental conditions able to support life.

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More and still unexploited atmospheric OMEGA/MEx observations

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Introduction: Since the beginning of the mission (January 2004) OMEGA, the VIS-NIR hyperspectral imager onboard Mars Express has acquired regular limbs observations in conjunction with others instruments (HRSC, PFS, SPICAM and VMC). Scattering by clouds and dust was detected at different Ls, altitude, locations and local time, as well as specific emission (O2, H2O, CO2, CO). Composition and grain sizes can be derived from these measurements. Atmospheric detections are also made in nadir mode. This constitutes an important database largely unexploited at this point. We will present examples of detections concerning clouds, dust and emissions, and identify themes of potential collaborations.

Examples of available observations:

Atmospheric observations acquired by OMEGA include :
- nadir spectral images of the morphology, grain size and composition of ice clouds (Figure 1)
- vertical sampling of the atmosphere above the limbe (Figure 2-6) at various spatial resolutions, from local studies above rovers (Figure 6) to global overview at a given time (Figure 3).
- recently Omega detected the double cyclonic vortex observed by from other instruments between 1995 and 2018 (fig 7)

All observations of the spatial distribution of clouds, either lateral of vertical, come with compositional spectral measurments covering the 0.4 to 5.1 microns range for most observations (Figures 1 ; 4-6).

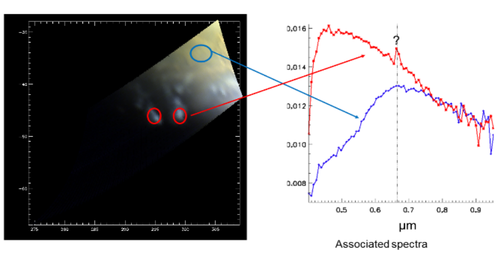

Fig 1: Clouds observed at sunset (SEA -2°) in visible

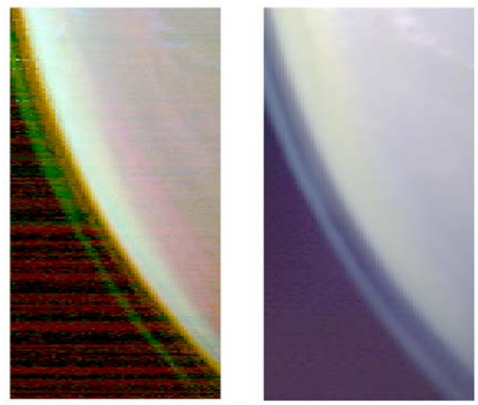

Fig 2 : deteched layer observed in IR and visible

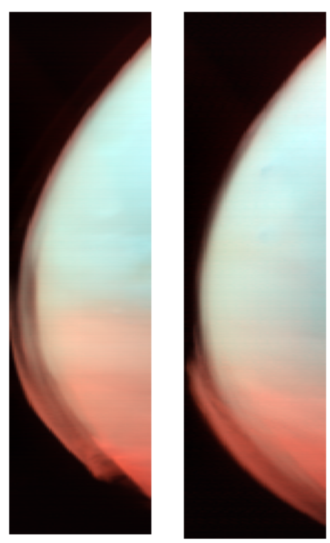

Fig 3 : Dust storm observed in december 2014

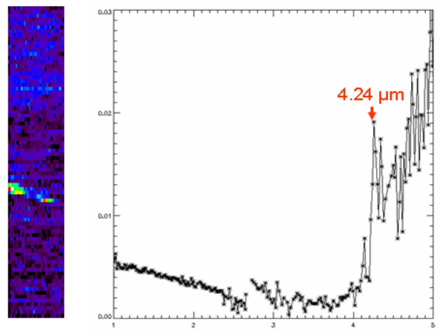

Fig 4 : CO2 clouds detected during limb observation. The grain size can be derived fom the shape of the visible part of the spectra.

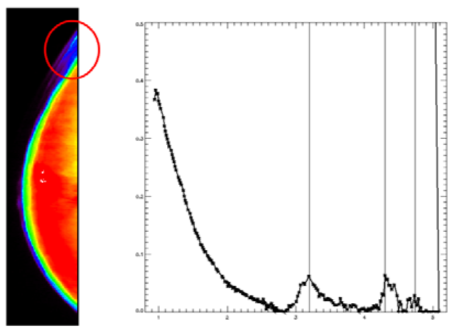

Fig 5: detached layer and associated spectrum (H2O and CO2 emissions)

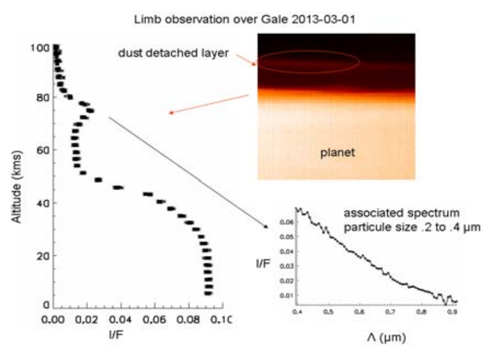

FIG 6 : Detached layer observation over Gale crater

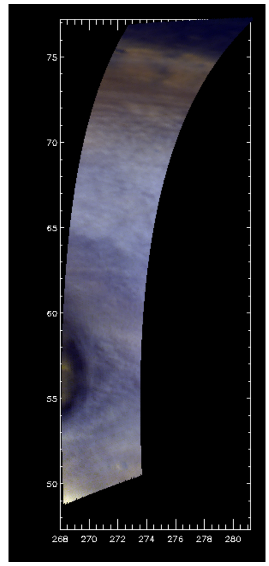

Fig 7: double Vortex observed by Omega/Mex in 2018

Discussion and Conclusion:
OMEGA measurements gathered over more than 12 years offer an opportunity to explore the yearly variability of the Martian atmosphere, with sufficient time sampling or spatial coverage to put constrains on several aspects of the atmospheric dynamic. OMEGA still provides unique aerosols compositional characterization capabilities that enable detailed analyses of CO2 clouds and other poorly known high altitude aerosols layers. Ongoing and upcoming collaborations with the Martian atmospheric community will further reveal the richness of this dataset for atmospheric studies.

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15 years of fascinating Mars press images and movies from the High Resolution Stereo Camera on Mars Express, prepared at Freie Universität Berlin

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Abstract

Almost 15 years have passed since the transmission of the first images of the High Resolution Stereo Camera (HRSC) to the experiment teams on Earth in January 2004. The HRSC is the most comprehensive German research instrument on a planetary mission, it has been orbiting Mars onboard ESA's Mars Express spacecraft since 2003. Decompression, calibration and projection of the raw image data are performed at the Institute of Planetary Research of the German Aerospace Center (DLR), before the level 2-4 data are transferred to the Planetary Sciences and Remote Sensing Team situated at Freie Universität Berlin (FU Berlin) for higher-level processing. Here, the camera data from the various channels (stereo, color, nadir) are combined to produce color images, anaglyphs, digital terrain models, 3D perspectives and movies of the Martian surface and Martian moons. In a joint effort, ESA, DLR and FU Berlin are publishing these HRSC products online on a regular basis since 2003. During the last 15 years more than 1000 images [1] and 24 movies were released, the latest on YouTube [2].

1. Achievements after five years

After five years in orbit HRSC has captured nearly half of the surface of Mars in high resolution <20 m/px, color and stereo. For the first time, a comprehensive set of digital terrain models was released through ESA's Planetary Science Archive [3] and NASA's Planetary Data System [4], platforms that are mostly used by scientists and planetary experts. To enable any interested user to work with the data, a public website hosted at FU Berlin was established [5]. A special release was prepared by FU Berlin to demonstrate the outstanding benefit of the camera to record data in three dimensions: a digital terrain model of Olympus Mons, the largest volcano on Mars (Fig. 1), composed of 16 orbit strips and with a terrain resolution of 150 m/px.

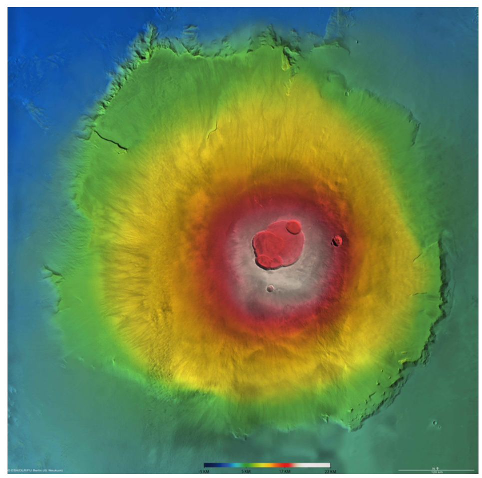

Figure 1: Color-coded digital terrain model of Olympus Mons, combined with ortho-image mosaic.

The combination of three-dimensional datasets with color information enabled unprecedented animations of the Martian landscape. In 2008 the first simulated flights were produced at FU Berlin featuring the Hebes Chasma canyon, the Mawrth Vallis outflow channel, and Nicholson impact crater. These movies were presented at the DLR 3D photo traveling exhibition 'Das neue Bild vom Nachbarn Mars' that was and is still presented in several national and international locations.

2. Achievements after ten years

After ten years in orbit, the HRSC has mapped about two-thirds of the surface of Mars with a resolution <20 m/px. In addition to numerous color and terrain model mosaics already released (e.g., Dao and Niger Valles region, Valles Marineris, Elysium), the up-to-date largest color mosaic consisting of 67 single image strips was produced and color-adjusted at FU Berlin (Fig. 2). It shows one of the largest outflow channel systems on Mars, the 3000 km Kasei Valles which was flooded several times and also shaped by tectonic and volcanic activity. The color mosaic and associated 100 m/px digital terrain model are the basis of an animation that was released in 2014 [6].

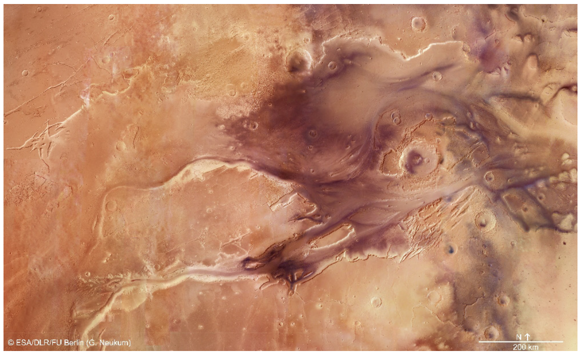

Figure 2: Kasei Valles color image mosaic of 67 orbits with accompanied digital terrain model.

A further highlight of color mosaic processing was the north polar ice cap of Mars produced from 32 orbit strips in 2017 [7]. This is the first image mosaic of this region in high resolution showing fine details of the dark troughs and trenches (Fig. 3).

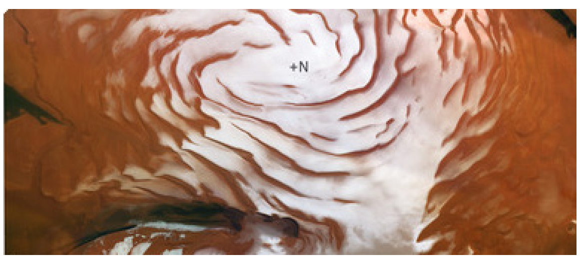

Figure 3: Section of the north polar ice cap mosaic.

3. Fifteen years and beyond

In order to calibrate the individual sensors of the HRSC and to guarantee the quality of the image data throughout the camera’s lifetime, the sensors can be directed over a wide extended area in a sweeping movement, a practice called ‘broom calibration’. One of these calibration orbits yielded a spectacular global view of Mars, displaying Tharsis, Valles Marineris and Noctis Labyrinthus, that will be released in June 2018 at the occasion of 15 years successful launch of HRSC on Mars Express (Fig. 4).

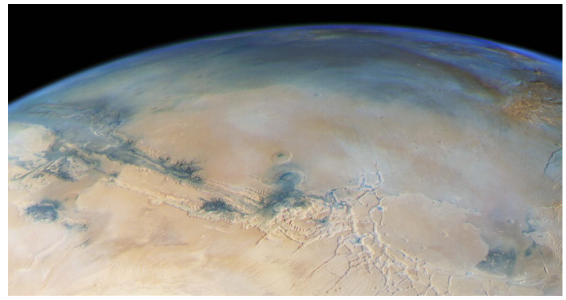

Figure 4: Section of the color composite of calibration orbit 17444.

In the future, the plan is to fill in successively the quadrangle scheme of 30 Mars charts (MC) with high resolution HRSC color mosaics and digital terrain models. The ambitious goal is a global dataset that can be used for Mars science research and also for public relations.

Acknowledgements

Image credit: ESA/DLR/FU Berlin (CC BY-SA 3.0 IGO). This work was supported by the German Space Agency (DLR Bonn), grants 50QM1301 and 50QM1702 (HRSC on Mars Express), on behalf of the German Federal Ministry for Economic Affairs and Energy. We want to thank our former team members that were involved in public relations. Our results build on the work of the former Principal Investigator of the HRSC, Gerhard Neukum, who also designed the camera technically.

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Clouds in the night side of Mars: an analysis using Mars Express VMC

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Abstract

We present a study of high altitude clouds detected in the night side of Mars close to its terminator using images taken by the Visual Monitoring Camera (VMC) onboard Mars Express. With the aid of a cloud-search algorithm, we have detected 200 events of high-clouds, which are analyzed in solar longitude, location and altitude.

1. Introduction

The camera VMC, a simple webcam initially designed to confirm the separation of the Beagle-2 probe, started taking routine images of Mars, initially intended for outreach, in 2007, and has been recently promoted to a scientific instrument [1,2]. When Mars Express is at apoapsis, it provides context images of Mars, with the whole planet visible and in which large and middle scale atmospheric features are often visible. At present, VMC image database covers over five Martian years, and therefore allows the study of the seasonal evolution of different atmospheric phenomena, which can be easily traced in VMC context images. In this work, we describe the appearance of illuminated clouds in the night side of the planet close to the terminator. An analysis of the database will provide information on possible correlations of the height and extension of clouds with location and season, and of the recurrence of the phenomena in different Martian years, thus giving clues on the state of the Martian atmosphere at different regions and seasons.

2. Navigation of images

VMC images are navigated automatically using python software based on SPICE kernels. Initial navigation is corrected via an automatic fitting of the limb of the planet, used to find the precise position of the center of the planet in the image (Figure 1). This corrects initial uncertainties in the navigation, probably related to errors in the bore-sight of the camera as given by SPICE. Together with the navigation of the image, the software calculates different geometrical parameters, such as subsolar and sub-spacecraft latitude and longitude.

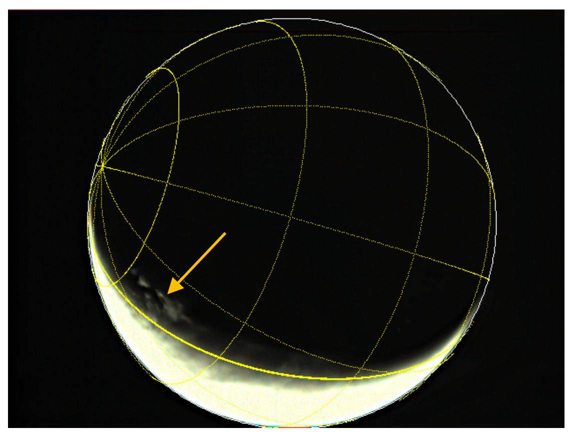

Figure 1: Illuminated clouds in the night side of Mars. Captured by VMC on February 20 2018 over Terra Sirenum.

3. Cloud-search algorithm

The ~20000 images of the database are distributed in series of images taken with different exposure times. We have analyzed 958 such series, of around 10 images each. Out of each series, we chose images with the longest exposure times.

We determine the altitude of the Sun as seen from all points in the visible surface of Mars, and the position of the terminator. Then, all pixels in the night side of the terminator are analyzed, looking for clusters of bright points that signal the presence of high clouds (Figure 1). The algorithm analyzes the context of any possible cloud and discards false candidates. Clouds connected to the terminator are also discarded, since these clouds are probably illuminated by light dispersed from the dayside, instead of by direct light from the sun.

4. Image analysis

Once a cloud detection is accepted by the software, the algorithm searches for the pixel that lies farthest from terminator, and uses it to estimate the minimum height of the cloud, that is, how high the clouds tops must be located to allow for direct illumination from the Sun (Figure 2).

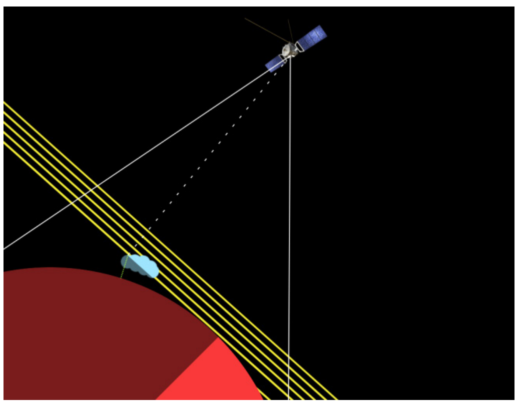

Figure 2: Geometry of the observation and scheme of the analysis for height determination. White lines determine the VMC-MEx field of view and yellow lines the sunlight illumination.

In order to perform a statistical analysis of the results, we determine the sample space of parameters: aerographic longitude and latitude, area coverage, cloud top height, orbital longitude L_s and Martian Year (MY). With this aim, every night pixel closer than 30º from the terminator has been registered and the minimum height that would allow direct sunlight to reach a cloud at that position, and consequently make the corresponding pixel brighter in the Martian night.

5. Results

The algorithm has retrieved so far about 200 clear cases of bright clouds in the night side of Mars. We present a statistical study of their distribution in terms of their aerographic location and Martian epoch of the year looking for their recurrence or singularity. We also classify the events in terms of their top altitude, looking for their possible origin (condensate water-ice and CO_2-ice clouds, and dust) when compared with a reference GCM model [3] and using complementary images from other instruments (e. g. MARCI onboard Mars Reconnaissance Orbiter) [4]. Finally, we will compare the result of this analysis with a previous work on high altitude features [1].

6. Conclusions

The VMC Mars Express camera has become a scientific instrument that can provide by itself new research of the Martian weather and at the same time complement studies performed with other instruments. In particular, it has proven very useful in the detection of high altitude structures in the atmosphere ([1] and this work). Ongoing investigations will profit from the new scientific status of the camera, which will allow planned observations of select targets and the radiometric calibration of the images.

Acknowledgements

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Topographic mapping of the Mars MC quadrangles using HRSC data

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Abstract

Panchromatic stereo and color images from single orbits of the High Resolution Stereo Camera (HRSC) have been used to produce digital terrain models (DTMs) and orthoimages of the Martian surface since 2004. Since 2014 new HRSC multi-orbit data products are generated. We report on the aim to use these products for a controlled topographic color orthoimage map series of Mars at a scale of 1:700,000.

1. Introduction

The High Resolution Stereo Camera (HRSC) of ESA's Mars Express mission [1, 2] is designed to map and investigate the topography of Mars and its satellites. As a push broom scanning instrument with nine CCD line detectors mounted in parallel, its unique feature is the ability to obtain along-track stereo images and four colors during a single orbital pass. The sub-pixel accuracy of derived 3D points allows producing DTMs with grid sizes of up to 50 m and height accuracy on the order of one pixel on the ground and better [3].

2. Data

Based on continuous coverage of an area of the Martian surface by adjacent HRSC stereo images, regional DTMs and orthomosaics can be produced by combining image data from multiple orbits using specifically adapted techniques for block-adjustment, DTM interpolation and image equalization [4]. The resulting DTMs and color orthomosaics are the baseline for our maps.

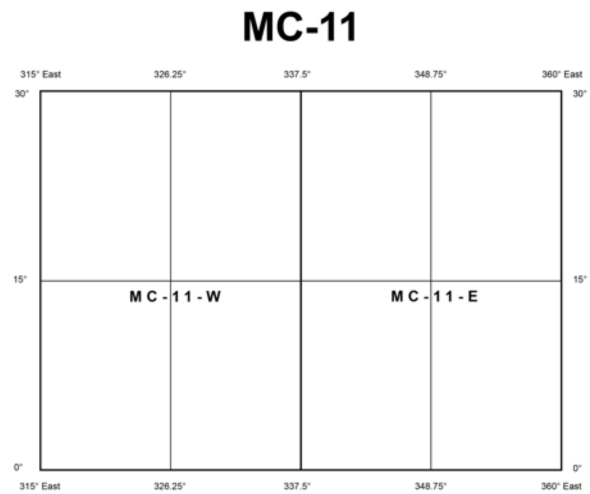

Figure 1: Tiling scheme of MC-11

3. Maps

We adopt the MC30 (Mars Chart) global mapping scheme of Greeley and Batson [5], which subdivides Mars into 30 quadrangles. To limit data volumes and map sizes, each quadrangle is further subdivided into 8 tiles (Fig. 1). Each tile has a map scale of 1:700,000, which is a compromise between the high DTM and orthomosaic resolution of 50 m/pxl and an acceptable hardcopy format of about 1 m in width to 2 m in height. This results in a printing scale of 14 pxl/mm (350 pxl/Inch). An example of the maps is shown in Figure 2. All maps will become available for the public at the Europlanet website (http://europlanet.dlr.de).

4. Summary and Outlook

After the completion of the first HRSC MC-30 half-tile DTM and color mosaic we developed a workflow to create the first four topographic maps [6]. We plan to finish the maps of the second half-tile within this year. We hope to generate a whole series of topographic maps from the upcoming MC quadrangles and with it to give the community a better overview and understanding of the mapped regions.

Acknowledgements

We thank the HRSC Experiment team at DLR, Institute of Planetary Research, Berlin, and at Freie Universität Berlin, the HRSC Science Team, as well as the Mars Express Project teams at ESTEC, ESOC, and ESAC for their successful planning and acquisition of data as well as for making processed data available to the HRSC team.

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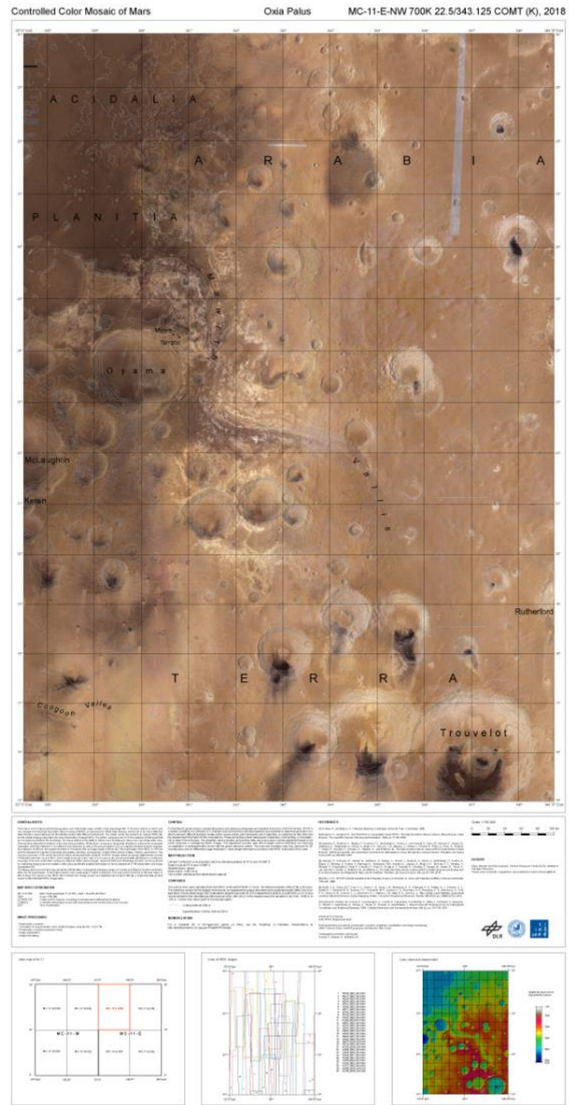

Figure 2: Topographic map of MC-11-E-NW

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Changing the paradigm of Mars history and evolution

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Abstract

Mars Express has triggered major discoveries, forcing an in-depth revisiting of critical paradigms of Mars history, with key outcomes for solar system evolution. Focused on findings from the OMEGA investigation, the discussion will outline key steps of Mars evolution, from geological and climatic to seasonal and diurnal timescale, with a special emphasis on the potential "habitability" of Mars in its ancient times.

Discussion

The ESA Mars Express "F-mission", although conceived as a small, fast and flexible one, has offered unprecedented results reappraising Mars formation and evolution processes. More specifically, OMEGA, the pioneer VIS/NIR hyperspectral imager, through the identification of the major surface and atmospheric constituents, put in their proper geomorphological and environmental context, has enabled a thorough deciphering of the major steps which paved Mars History.

On long timescales, distinct era were identified, primarily through the characterization of the changing environment responsible for specific alteration of the rock forming minerals. In particular, Mars seems to have hosted conditions favoring liquid water to be stable, in its ancient times, at a planetary scale. Specific phyllosilicates are the prime witnesses of this early aqueous alteration.

Mars then suffered a global climatic change, during which most gases, including the greenhouse species, escaped. Episodes of further aqueous events took place, responsible for an increased diversity of the alteration products; in a few places, they can be identified within a preserved stratigraphy, recording the time evolution of the relevant environment, thus characterized.

In happens that Mars, uniquely in the entire solar system, has preserved sites still witnessing these very early times, along its first billion years: they are of critical interest, since Mars might have then harbored a biochemical evolution. As a consequence, they constitute favor sites of astrobiological relevance, for the upcoming Mars *in situ* exploration (Mars 2020, ExoMars, HX-1).

Then started the long term era, lasting up to now, during which Mars became the arid planet we observe, with only its very shallow surface oxidized through atmospheric alteration, in ferric oxides. Transient processes, triggered by volcanic activity, impacts and obliquity changes, span over these 3.5 past billion years, with more local effects.

It is exemplary that Mars Express instruments addressed and are still addressing questions not even raised at the time they were conceived, selected and developed: their outcomes are profoundly modifying our vision of Mars history. As such, they have constituted and still constitute key drivers of the follow-on Mars exploration mission.

At a larger scale, Mars Express contributes to the true revolution of our present understanding of the processes responsible for the totally unexpected diversity of evolutionary pathways of planets within the solar system, and of stellar systems within the galaxy. The relative role of contingency, to genericity, in these processes, through the immense diversity of the specific form they can take, is key. Being able to comparing Mars to Earth, at all historical ages, is thus of utmost fruitfulness. Amongst the paradigms violently shaken, that Mars, as pioneering pointed by Mars Express, has the unique potential to renew: at what time and space scale is the Earth unique, and the life it harbors.

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Ions accelerated by sounder-plasma interaction as observed by Mars Express

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Abstract

Ion sensor of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment detects accelerated ions during pulses of radio emissions from the powerful topside sounder the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) experiment onboard Mars Express. Accelerated ions (O_2^+, O^+ and lighter ions) are observed in a range up to $800eV$ when MARSIS transmits at a frequency close to the plasma frequency. The observed ion beams are often accompanied by a small decrease in electron flux observed by the Electron Spectrometer (ELS) of ASPERA-3. Observations indicate that the voltage applied to the antenna causes charging of the spacecraft to several hundreds of volts by the electrons of the ambient plasma. Positively charged ions are accelerated when the spacecraft discharges.

1. Introduction

Operation of active wave devices, such as high-frequency transmitters, in plasma lead to a strong modification of a surrounding environment. An intense radio pulse might results in high potentials in spatial plasma that far exceed the potential equivalent of thermal or flow energies of all the ambient plasma particle species. Prominent example of the related phenomena is charged-particle acceleration by RF fields in the vicinity of an active antenna [1].

The local acceleration of near-satellite plasma ions during the pulses of radio emission of the powerful (up to 400W) topside sounder MARSIS transmitter was detected on board the Mars Express (MEX) spacecraft by the Ion Mass Analyzer (IMA) of ASPERA-3 experiment. The investigation of sounder-accelerated particles observed on MEX can provide a much improved picture of the plasma behaviour in the near field of an active antenna as well as inspire a new plasma diagnostic technique. The ability to detect accelerated ions will allow Mars Express to conduct future active experiments at Mars.

2. Observations

The top panel (a) in Figure 1 shows the IMA O^+ differential number fluxes during 30 minutes around pericenter on orbit 12495 (pericenter reached at 2013- 10-31 05:46:31 UTC). The MEX altitude is superimposed on the same panel and is shown with red line.

Intense periodic disturbances in the ion data are seen when MEX altitude is below 1000 km. In each of the individual events accelerated O^+ ions are observed in 2-4 consecutive energy channels of IMA, that indicates almost monoenergetic ion beams. The beams are observed with energies starting from several 10s eV (typically 40 eV) but never exceed 800 eV. Corresponding differential fluxes are found to be in the range $10^4 - 10^5 particles/eV/s/str/cm^2$.

Detailed timing analysis showed that the appearance of accelerated ions coincides with periods when the MARSIS sounder is transmitting. This can be seen at panel (b) of Figure 1. White boxes shown with dashed lines correspond to the 1.257 s intervals of MARSIS active sounding phase. Intense fluxes of accelerated ions are only detected during these periods. Horizontal solid white lines within white boxes in panel (b) indicate time intervals within the 1.257 s long periods of the MARSIS active sounding phase, when MARSIS transmits in the frequency range from f_{pe} to $2f_{pe}$, where f_{pe} is local plasma frequency (corresponding electron density is shown with a red line in panel (b)). The peak flux of accelerated ions in each of the individual events occurs during these intervals. Analysis of the data collected by ELS indicates the presence of a negative potential around the spacecraft. Panel (c) in Figure 1 shows the electron differential flux measured during the period when the most intense fluxes of accelerated ions were detected. The total flux of electrons with energies up to 110 eV is shown with a

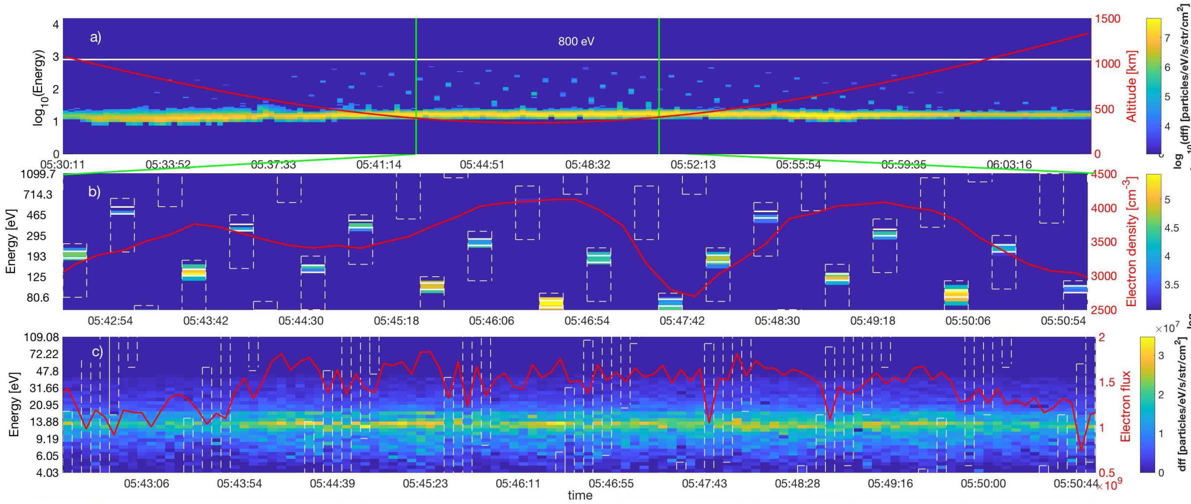

Figure 1: Data obtained by the ASPERA-3 ELS and IMA sensors on 2013-10-31 from 05:30 to 06:04 UTC. From top to bottom: (a) O^+ differential number flux (dff [$particles/eV/s/cm^2/str$]), MEX altitude is superimposed and shown with red colour; (b) zoomed-in time interval of O^+ from $05:42:26$ to $05:50:56$, the $1.257s$ intervals from the MARSIS active sounding phase are shown with white boxes and white lines within the boxes indicate time intervals when MARSIS was operating in the range of frequencies from f_{pe} to $2f_{pe}$, background plasma density measured by MARSIS is shown with red; (c) zoomed-in time interval for electrons overlaid with the total flux of electrons, for energies up to $110eV$ shown with a red line. White boxes show the $1.257s$ intervals of MARSIS active sounding phase.

red line. As before, the white boxes denote time intervals when MARSIS is turned on. One notices that the electron flux measured during these periods is considerably lower in comparison to measurements that were made when MARSIS was idle. The decrease in electron flux is believed to be caused by the negative potential that lasts several ms after the end of a pulse and prevents electrons from entering the ELS sensor.

3. Summary and Conclusions

Data collected by IMA onboard MEX enabled first ever study of the effect of charged particles acceleration in the vicinity of a powerful RF transmitter under plasma conditions other than that of the Earth's ionosphere. Preliminary study showed that the intense fluxes of accelerated ions (up to $10^6 particles/eV/s/str/cm^2$) are frequently observed during periods when MARSIS operates in the range of frequencies from f_{pe} to $2f_{pe}$. Accelerated ions have typical energy ranges up to $550-800eV$. Observation of the accelerated ions is often accompanied by a decrease in electron flux detected by ELS. A model for the RF-induced spacecraft potential [2] suggests that ions at the highest energies are collected when MARSIS is transmitting, while lower energy ions are collected during the few millisecond discharge period following the transmission.

The creation of substantial charged particle fluxes by RF transmitters has important implications for active experiments in space physics. Active diagnostic of the plasma composition can serve as one of the examples of such experiments. A combination of the time decreasing electric potential and time-of-flight effect results in acceleration of the lighter particles to higher energy, enabling identification of the ions species that are almost indistinguishable under normal conditions. This could be used to improve upon our knowledge of the ion composition of Martian ionosphere.

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Coordinated Science Opportunities around Mars: Mars Express and ExoMars 2016 Trace Gas Orbiter

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Abstract

In this contribution we focus on the science opportunity analysis between the Mars Express (MEX) and the ExoMars 2016 Trace Gas Orbiter (TGO) missions and the observations that can be combined to improve the scientific outcome of both missions. In particular we will describe the long term analysis of geometrical conditions that allow for coordinated science observations for solar occultation and nadir pointing. We will provide details on the calculations and results for simultaneous and quasi-simultaneous opportunities, taking into account the observation requirements of the instruments and the operational requirements for feasibility checks.

1. Introduction

1.1 Mars Express and ExoMars 2016 Trace Gas Orbiter

The Mars Express mission is still fully operational and has been providing great amounts of data since its arrival at Mars in Christmas 2003, covering a wide range of science objectives from the surface and sub-surface geology, atmosphere dynamics and composition, up to the interaction with the magnetosphere and the characterization of the Martian system including Phobos and Deimos.

The ExoMars 2016 Trace Gas Orbiter mission arrived successfully at Mars in October 2016 and after the first calibration observations in the initial capture orbit, started a long aerobraking phase of more than 12 months, aiming to reach the final nominal orbit and start its operational science phase in April 2018, where the first science operations are taking place following the scientific goals of the mission: atmospheric trace gases, climatology, surface geology and subsurface ice detection.

1.2 MEX and TGO Seasonal Evolution

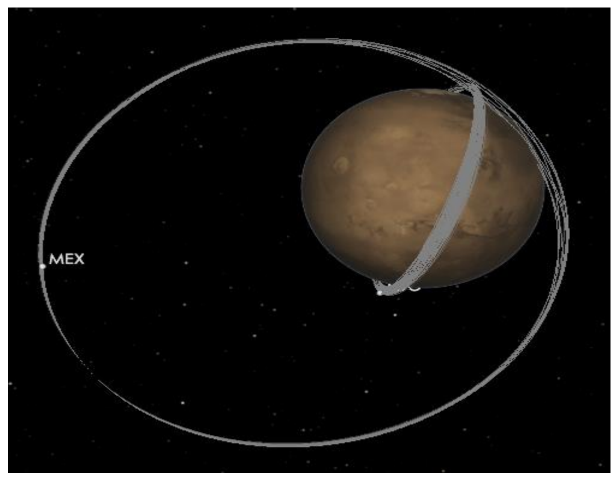

Figure 1: 3D Simulation of MEX-TGO crossing points at different distances.

Mars Express orbit has a high eccentricity that provides a very wide range of distances, allowing for the observation of the planet with very different resolutions and observing conditions. However the long term evolution of the orbit precession causes very stable and slow changing seasons, with very slow variations of the latitude and illumination at pericenter where we can identify long observation campaigns (3~6 months).

On the other hand, the ExoMars TGO evolution is very dynamic and has short observing seasons that vary regularly on a weekly basis, based on the orbital node regression. That allows for a full surface and local time coverage on a monthly basis, except for the polar regions that the spacecraft is not able to reach.

The main advantage of ExoMars TGO is the capability to perform continuous science observations, basically pointing Nadir by default and doing solar occultation measurements everywhere possible, although it does not have much flexibility. On the other hand Mars Express does not observe continuously, but has much more flexibility to perform observations as needed.

2. Combined Science Opportunities

2.1 Sun Occultations

We have performed an analysis of all the occultation opportunities MEX-Mars-Sun and TGO-Mars-Sun both for the in-gress and e-gress points (that is dusk and dawn). Though we may not always have observations of the exact same spot in time, we can identify many quasi-simultaneous occultations that can be observed in the same region of the planet within a few minutes difference.

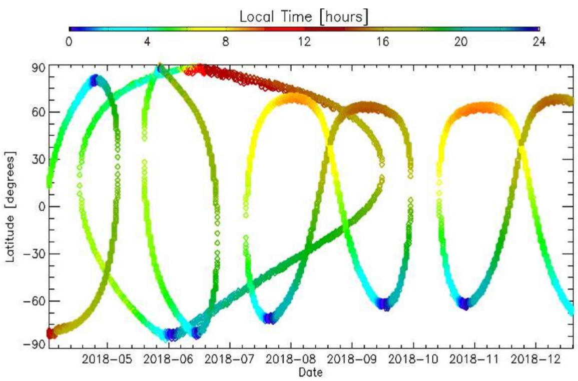

Figure 2: Latitude and local time of both TGO and MEX solar occultations in 2018.

2.1 Nadir observations

Both the Mars Express and Trace Gas Orbiter mission are also observing in Nadir geometry, for which we have performed another analysis of the crossing points where the orbits overlap, and we can easily see that there are always two points per orbit, although the distances may be very different due to the eccentricity of the MEX orbit.

The actual crossing points of both spacecrafts occur regularly and follow the general trend of the orbits, but the crossing points are more sparse whenever the MEX spacecraft is at pericenter. That is simply because the spacecraft is faster and therefore there are less chances of coinciding with TGO. On the other hand, when MEX is at the apocenter, it moves much slower and therefore there are many more crossing points.

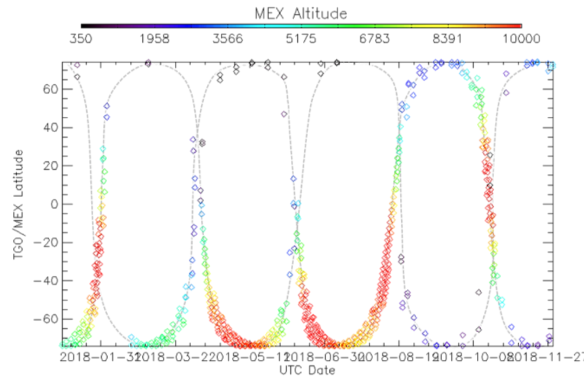

Figure 3: MEX-TGO nadir crossing points (angle <5deg). Note two crossing points per orbit, more often when MEX is at apocenter.

3. Conclusions

We have calculated the potential science opportunities for combined observations between Mars Express and Trace Gas Orbiter, both for sun occultations and nadir observations, and we have identified that interesting opportunities occur regularly on a weekly basis.

These opportunities are used as high priority input for both Mars Express and ExoMars TGO science planning cycles.

Acknowledgements

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Couplings between the lower and upper atmosphere of Mars

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1. Introduction

Over the last decade a wealth of observations has produced an unprecedented characterization of the atmospheric composition and activity from the near-surface to above the exosphere. In this overview, a synthesis of some of these observations collected will be presented. With the data at hand, it is now possible to assemble a single, coherent picture of the Martian atmosphere from the near-surface layers up until the layers interacting with the solar wind. Addressing the coupling between the lower and the upper atmosphere of Mars is central to our understanding of the key elements controlling the fate of volatiles on Mars. A focus will be made on the water vapor subliming from the seasonal and perennial ices that convert later into H atoms at higher altitude.

2. Observations

The study presented here focuses on several datasets that provide a fine characterization of the vertical distribution of some species of interest.
Water vapor profiles. The study presented in [1] reports the first monitoring of the seasonal evolution of water vapor profiles during a complete martian year. 120 profiles, obtained by Mars Express / SPICAM infrared channel, were retrieved. Northern spring-summer season and the southern spring of Mars Year (MY) 29 were covered. The seasonal evolution of water vapor mixing ratio vertical distribution reveals a strong dynamism, especially during southern spring, that is not predicted by models. The measured profiles exhibit often abrupt temporal variations and a great variety of shapes, with the frequent presence of detached layers. The water vapor vertical distribution is more reactive than expected to regional perturbations, which can propagate rapidly through the atmosphere, create abrupt water vapor and aerosol uptakes and influence the large-scale vertical evolution of these two constituents. This phenomenon has been This phenomenon has been observed several times during MY29.

2.1 Water vapor profiles.

The study presented in [1] reports the first monitoring of the seasonal evolution of water vapor profiles during a complete martian year. 120 profiles, obtained by Mars Express / SPICAM infrared channel, were retrieved. Northern spring-summer season and the southern spring of Mars Year (MY) 29 were covered. The seasonal evolution of water vapor mixing ratio vertical distribution reveals a strong dynamism, especially during southern spring, that is not predicted by models. The measured profiles exhibit often abrupt temporal variations and a great variety of shapes, with the frequent presence of detached layers. The water vapor vertical distribution is more reactive than expected to regional perturbations, which can propagate rapidly through the atmosphere, create abrupt water vapor and aerosol uptakes and influence the large-scale vertical evolution of these two constituents. This phenomenon has been This phenomenon has been observed several times during MY29.

2.1 The polar mesospheric ozone layer

At low-to-mid latitudes, martian ozone is distributed vertically in two main layers, a near-surface layer and a layer at an altitude between 30 and 60 km [2]. In [3] evidence is reported for the existence of a previously disregarded ozone layer that emerges in the southern polar night at 40–60 km in altitude, with no counterpart observed at the north pole. Comparisons with global climate simulations for Mars indicate that this layer forms as a result of the large-scale transport of oxygen-rich air from sunlit latitudes to the poles, where the oxygen atoms recombine to form ozone during the polar night. However, transport-driven ozone formation is counteracted by the destruction of ozone by reactions with hydrogen radicals, whose concentrations vary seasonally on Mars, reflecting seasonal variations of water vapour. The observed dichotomy between the ozone layers of the two poles, with a significantly richer layer in the southern hemisphere, can be explained by the interplay of these mechanisms.

These observations imply that oxygen and hydrogen radicals can be carried from pole-to-pole thanks to planetary scale flows. In particular, models indicate that hydrogen can populate the upper branches of the solsticial Hadley cell, reaching altitudes >100 km [2]; to then access the deep polar night. The enhanced population of H and O atoms at such altitude is a consequence the large-scale transport an of the presence of exposed water vapor molecules in the sunlit regions of mars.

2.2 Hydrogen corona variability

An order-of-magnitude change in the Martian hydrogen escape rate in 2007, inconsistent with established models for the source of escaping hydrogen was reported in [4], supported by joint observations of the Hubble Space Telescope. This result was obtained from the analysis of 121.6 nm (hydrogen Lyman-α) airglow observations by SPICAM over the second half of 2007. The enhanced escape rates that were observed may be due to lower atmospheric heating and overturn during the 2007 (Mars Year 28) global dust storm, suggesting that hydrogen escape from Mars during dust storms may dominate loss of the planet's water inventory.

3. Discussion

The joint monitoring of H2O and O3 total abundances has confirmed the suspected role of OH and H as oxidants;

The characterization of H2O vertical distribution revealed unexpected amounts of water above 30 km where it can be photodissociated into H and OH;

The detection of ozone as discrete layers lying above the pole provides a nearly-direct evidence of the deep (up to 100 km) transport of H atoms;

The seasonal evolution of H above the exobase, as retrieved from limb staring modes, has revealed a behavior of H contradicting the canonical view of a upper reservoir of H seasonally disconnected from its precursor, water vapor in the lower atmosphere: the H corona shows similar seasonal variability as H_2O in the lower layers, suggesting a tighter connection between the two.

Based on the ensemble of these evidences, the following scenario unfolds: the communication between the well-mixed lower atmosphere and the outer layers where atoms (H in particular) can freely escape is more direct and much faster than anticipated. Escape processes for water need to be re-evaluated in light of this consideration. The Martian atmosphere appears as one single coherent system which is able to react on short timescales.

Acknowledgements

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Mars Express characterization of the Martian ionosphere

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Abstract

15 years after its launch, Mars Express has collected a large dataset of ionospheric observations. These include electron density profiles and the total electron content of the ionosphere. Mars Express measurements cover more than one solar cycle and have allowed for an unprecedented characterization of the Martian ionosphere, its temporal and spatial variability, and its couplings with the lower atmosphere and with the space environment.

1. Introduction

Sounding the ionosphere of Mars to characterize the interaction of the atmosphere with the space environment of the planet was one of the primary objectives of Mars Express when the mission was launched. 15 years later, it is a good time to look back and check to what extent this objective was achieved.

2. Mars Express ionospheric measurements

Most of the ionospheric observations performed by Mars Express comes from two instruments, MaRS and MARSIS.

Mars Express Radio Science experiment (MaRS) uses radio occultation observations at two frequencies to obtain vertical profiles of electron densities from the base to the top of the ionosphere [8], being the only current instrument able to measure the whole ionospheric altitude range. To date it has collected about 900 profiles. The distribution of the observations can be seen in Fig. 1

The Mars advanced radar for subsurface and ionospheric sounding (MARSIS) is a synthetic-aperture radar [2]. It can operate in two different modes, both of them providing information about the ionosphere. The Active Ionospheric Sounding (AIS) mode allows obtaining electron density profiles above the main ionospheric peak. More than 40000 of these electron density profiles have been obtained during the Mars Express mission, and their distribution is shown in Fig. 2. The Subsurface Sounding mode provides as a by product the total electron content of the ionosphere [10].

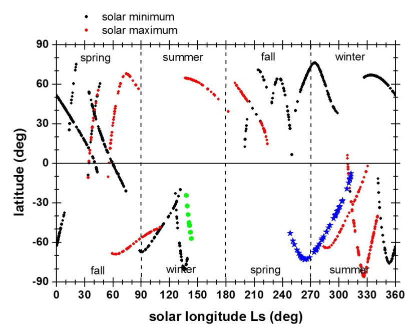

Figure 1: Latitudinal and seasonal distribution of the MaRS electron density profiles

Other Mars Express instruments provide complementary information about the ionosphere. SPICAM measured the CO_2^+ UV doublet, a UV dayglow emission produced by ionization of CO_2 [3]. ASPERA provides information about the interaction of the ionosphere with the solar wind [4].

In addition, Mars Express observations have fostered the development of computational models of the ionosphere, including semiempirical models [6, 11], 1D models [9] and GCMs [1].

All these datasets result in an unprecedented amount of information about the ionosphere of Mars that allow for a much more complete characterization of the region, its variability and its couplings with other regions. The long duration of the mission allows to study

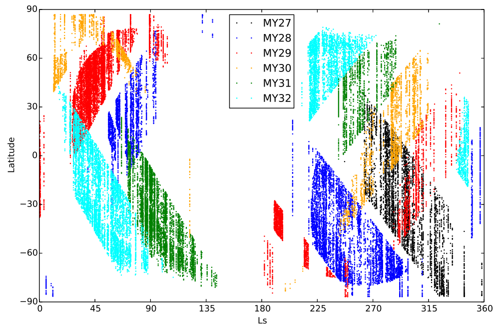

Figure 2: Latitudinal and seasonal distribution of the MARSIS AIS dataset, with different colors representing data obtained at different Mars Years

the solar cycle and interannual variability of the Martian ionosphere. The quality of the obtained data has allowed for some breakthroughs, such as the discovery of an electron density peak in the lower ionosphere never seen before [7] or an unprecedented characterization of the nightside ionosphere [5].

In the talk we will show how Mars Express has advanced our knowledge of the ionosphere describing its most relevant ionospheric discoveries. Complementarity with other missions will also be discussed.

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EPSC Abstracts
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15 years in the induced magnetosphere of Mars: ion escape and all around

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Abstract

This review talk presents the contribution of the Mars Express mission to the big picture of the solar wind interaction with the non-magnetized atmospheric planet Mars

1. The ion escape

Mars Express carries an ion, electron, and energetic neutral atom (ENA) instrument ASPERA-3 (Analyzer of Space Plasmas and Energetic Neutral Atom) carrying out measurements in the energy range few eV to few 10s keV relevant to study the solar wind - Mars interaction. The focus of the experiment was to establish the rate of the atmospheric erosion caused by the interaction with the solar wind. For 15 years of operation at Mars ASPERA-3 not only fully fulfilled the main objective but also provided us with a new picture of the induced magnetosphere, a "bubble" in the solar wind created by magnetic fields of currents induced in the Martian ionosphere.

The energy transfer from the solar wind to the planetary ions results in the ion escape. Mars Express established the average rate of the ion escape:

$$Q=(2.7\pm0.4)\cdot10^{24}\ s^{-1}.$$

15 years of observations for more than one solar cycle allowed to determine the dependences of the escape rate on the solar wind and solar conditions by constraining of all other parameters. Using these dependences one could extrapolate the escape rate back in time and establish the total amount of the atmospheric loss for the last 4 Ga year Δp

$$\Delta p < 10 \text{ mbar. Very little!}$$

The majority of the escaping ions are O^+ and O_2^+, CO_2^+ is only 20% of these ion fluxes.

2. ..And all around

Mars Express revealed that the bubble of the induced magnetosphere is not empty from the solar wind electrons, protons, and He^{++}. Channeling along open field lines of the crustal magnetic anomalies or penetrating the thin magnetic barrier due to large gyroradius these particles deposit energy and matter to the atmosphere. Solar wind α-particles contribute to the Martian helium balance. The magnetosheath electrons cause aurora-like phenomena.

The induced magnetosphere as seen by Mars Express is a dynamical object responding to the solar wind disturbance such as interplanetary shocks, co-rotation interaction regions, coronal mass injections. The disturbances result in increase of the escaping ion fluxes but also reducing the size of the induced magnetosphere shape. As a result the total escape rate does not change significantly. The magnetosphere dynamics is also manifested in oscillations of the magnetospheath plasma parameters with the characteristic period 50 s and 300 s as revealed by ENAs, electron and ion observations.

Mars Express also introduced a few new techniques to study induced magnetospheres. Measurements of the characteristic 10s eV photoelectrons allow tracing the open filed lines of the crustal anomalies up to the Mars Express apocenter. Mars Express for the first time characterized ENAs generated in the Martian environment paving the way for the future global imaging missions to Mars.

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High resolution spectra of CO2 ice based on SPICAM/MEX observations

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1. Introduction

CO2 cycle on Mars defines fundamental processes both on surface and in atmosphere. On poles condensation of a large part of the atmosphere (up to 30%) results seasonal growth and retreat of polar caps [1], changing reflectance and emissivity of surface, that has dramatic consequences for energy budget [2] and changes local and global climate on the planet [3]. IR spectroscopy is one of the ways to measure abundance of carbon dioxide ice on Mars. CO2 ice has narrow features in NIR that allows to distinguish it from gaseous absorption in atmosphere. These features allowed to map distribution and seasonal evolution of condensation and sublimation of CO2 ice on polar caps [4]. Meanwhile, spectrum of carbon dioxide ice in NIR still hasn't been studied in details yet, because low resolution spectrometers cannot resolve weak sharp lines.

2. Observations

Since 2004 SPICAM IR spectrometer on Mars-Express has been carrying out measurements of the Martian atmosphere and surface in near-infrared range from 1 to 1.7 μm with the spectral power about 2000. The observations collected information about ices distribution on the surface for Martian years from MY27 to MY34. The analysis of SPICAM dataset related to surface features had not been made before. To process surface spectra of SPICAM and clean them from atmospheric signatures algorithm was developed based on the latest spectroscopic databases HITRAN2016 and Martian general circulation model v5.3. Here we present accurate high resolution spectra of Martian poles (figure 1) and seasonal maps for multi-annual distribution of carbon dioxide ice on surface of Mars.

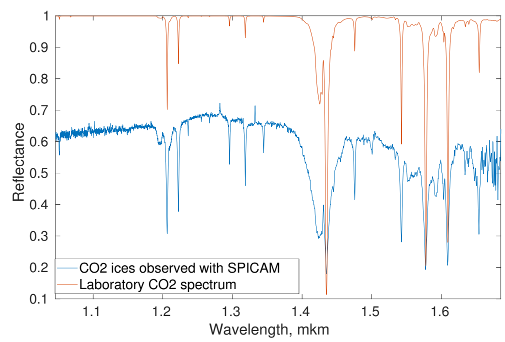

Figure 1: Comparison of SPICAM data and laboratory measurements by Hansen et al. (2005)

Acknowledgements

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Global distribution of mafic minerals abundances and associated chemical composition at Mars: a legacy of OMEGA

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Abstract

One of the major goals of the OMEGA/Mars Express instrument was to constrain the igneous terrains of Mars. The entire NIR OMEGA dataset, acquired over 3.6 Martian years, was used and formatted for such an analysis. To derive the modal composition and grain sizes at a planetary scale, a radiative transfer model was used to reproduce these millions of spectra representative of igneous terrains of Mars. The lithology can be summarized in five mineral maps at km-scale (Figure 1): plagioclase, pyroxenes, olivine and Martian dust analogue. The corresponding oxide composition translates into a Martian crust of basaltic composition. These data products are a part of the OMEGA/MarsExpress legacy and will be distributed throughout the PSUP portal and PSA archive.

1. Introduction

The knowledge of the igneous composition of Mars surface allows a better understanding of the volcanic and magmatic history of the planet. Previous past global orbital analyses focusing on the igneous mineralogy on Mars have shown that its crust consists in tholeiitic basalt [1], and that the dark albedo regions are dominated by plagioclase, pyroxene, and at a more local scale olivine ([2],[3],[4]). The mineral abundances of regolith-like surfaces can be derived from the spectral modelling of NIR reflectance spectra with a radiative transfer model ([5], [6]). We present here the analysis of all NIR hyperspectral data to derive abundances of the mafic minerals on Mars at the global scale with a spatial sampling of ~1.85 km/px at the equator.

2. Dataset

We used the complete near-infrared dataset of OMEGA from 1 to 2.5 µm. All raw OMEGA image-cubes were processed and compiled into a global hyperspectral cube of the Martian surface from 60°S to 60°N that covers more than 85% of the surface. The methodology to obtain the global cube, its validation and first applications are detailed in [7]. The work presented here aims at characterizing the surface mineralogy in terms of igneous assemblages, as a result only terrains exhibiting strong pyroxene signature were selected for the modelling. The high latitudes were also excluded for modelling purpose [9] reducing the sample to be modelled to 10.3 million of spectra from 30°N to 60°N.

3. Modal mineralogy

We applied Shkuratov radiative transfer model [6] to all selected OMEGA spectra. We simulated a mixture of 5 different minerals referred to as end-members: plagioclase, two poles of pyroxenes (both low- and high- calcium), olivine and palagonite as a Martian dust analogue for the low albedo terrains selected here. The corresponding abundance maps are represented on Figure 1.

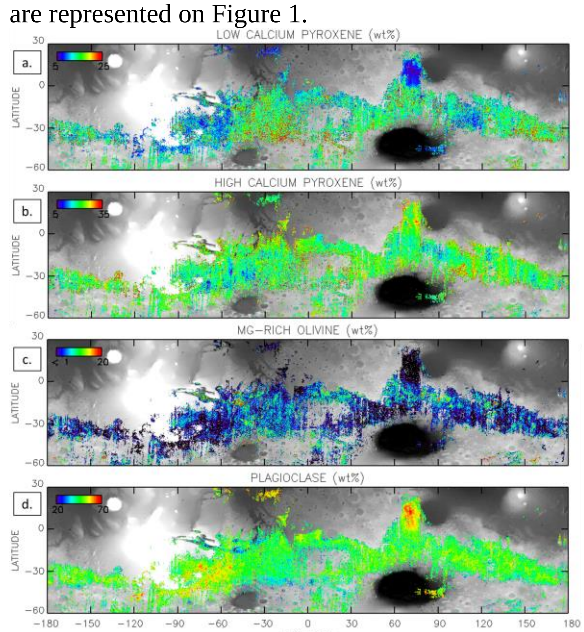

Figure 1: Abundance maps (wt%) of (a) LCP, (b) HCP, (c) Olivine, (d) Plagioclase.

We found that those terrains are dominated by plagioclase (~50 wt% on average) and pyroxenes (~40 wt%). An evolution of the LCP/(HCP+LCP) ratio is observed with time at the global scale. This suggests a decrease of the degree of partial melting of the magma with throughout the geological eras.

4. Oxide composition

The abundances maps of mafic minerals were used to predict the chemical composition according to the minerals found on the surface. We used individual oxide composition and density of each end-member. The OMEGA-based global chemistries corresponds to the basaltic rock class (tholeiitic basalt) with a few pixels associated to more mafic rocks (picritic type mainly enriched in olivine)This distribution is in good agreement with previous orbital and *in situ* analysis of chemical composition [1]. Spatial variations are observed and well correlated with some geological units [9]. Conversely, the mineralogical/chemical diversity observed from *in situ* invesigations (e.g. [10],[11]) is not highlighted.
Additionnally, we found that the OMEGA-derived iron content (Figure 2) predicts a surface depleted in iron compared to other orbital based data from GRS and *in situ* measurements [12]. The discrepancies between GRS and OMEGA may be explained by the fact that both instruments sample different depth of the surface (few cm compared to few µm) and are thus no sensitive to surface alteration in the same way.

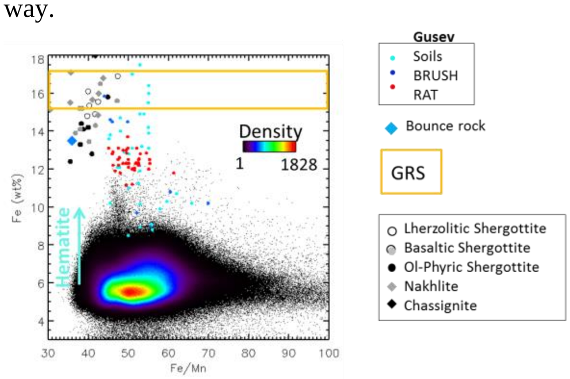

Figure 2: Fe with respect to Fe/Mn ratio. OMEGA data are represented in density. The vertical blue line indicates the trend when hematite is used instead of palagonite as the dust analogue.

This may also be confirmed with *in situ* measurements suggesting that olivine is primarily affected by the weathering on Mars ([13],[14]). The olivine alteration translates into alteration rinds that can mask olivine detection which may partly explains the decrease in iron content observed, if this phenomenon occurs at the global scale.

5. Conclusion

At the global scale we observe on average a rather homogeneous surface in terms of chemistry and mineralogy, however the mineral abundance maps reveal strong localized variations. Such variations have to be put in a geological context to better understand their origin. The next step will be to use a more local approach based on the global maps presented here (Figure 1). These additional analyses at a smaller scale should be very promising to provide constraints on the compositional heterogeneity of any mafic region/volcanic edifice and on mantle compositional models.

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Mars Express: 15 years of hard work and discoveries

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After almost 15 years in orbit Mars Express remains one of ESA's most scientifically productive Solar System missions whose publication record now exceeds 1120 papers. Geological maps of Tharsis volcanoes have just been released. Characterization of the geological processes on a local-to-regional scale by HRSC, OMEGA and partner experiments on NASA spacecraft has allowed constraining land-forming processes in space and time. Recent results suggest episodic geological activity as well as the presence of large bodies of liquid water in several provinces (e.g. Eridania Planum, Terra Chimeria) in the early and middle Amazonian epoch and formation of vast sedimentary plains north of the Hellas basin. New analysis of the subsurface dielectric properties by MARSIS radar sounder revealed that the deposits in Meridiani Planum, previously interpreted as ice-rich, may contain little or no ice at all. Mars Express observations and experimental teams provided essential contribution to the selection of the Mars-2020 landing sites.

More than a decade-long record of the atmospheric parameters such as temperature, dust loading, water vapor and ozone abundance, water ice and CO2 clouds distribution, collected by SPICAM, PFS and OMEGA spectrometers as well as subsequent modeling have provided key contributions to our understanding of the martian climate. Recent spectroscopic monitoring of the dust storms revealed dust properties and their spatial and temporal variations during the dust storm events.

More than 10,000 crossings of the bow shock by Mars Express allowed ASPERA-3 to characterize complex behavior of the magnetic boundary topology as function of the solar EUV flux. ASPERA-3 observations of the ion escape during complete solar cycle revealed important dependencies of the atmospheric erosion rate on parameters of the solar wind and EUV flux and established global energy balance between the solar wind and escaping ion flow. This led to important conclusion that the ion escape at Mars is production rather than energy limited. Comparison to the similar observation record by Venus Express would allow quantification of the role of planet gravity in the escape processes.

The structure of the ionosphere sounded by the MARSIS radar and the MaRS radio science experiment was found to be significantly affected by the solar activity, the crustal magnetic field, as well as by the influx of meteorite and cometary dust. MARSIS and ASPERA-3 observations suggest that the sunlit ionosphere over the regions with strong crustal fields is denser and extends to higher altitudes as compared to the regions with no crustal anomalies. Reconnection of solar magnetic field lines carried by the solar wind with field lines of crustal origin opens channels through which the ionospheric plasma escapes to space, producing strong and narrow cavities in the density. The situation is very different on the night side where the ionosphere has patchy structure. Such patchy ionizations are observed in the regions where field lines have a dominant vertical component. Through these patches the ionospheric plasma from the dayside penetrates and supplies the nightside ionosphere. Several models of the upper atmosphere and plasma environment are being developed based on and in support of the collected experimental data. The models aim at creating user-friendly data base of plasma parameters similar to the Mars Climate Database that would be of great service to the planetary community.

A significant recent achievement was the flawless transition to the "gyroless" attitude control and operations mode on the spacecraft, that would allow mitigating the onboard gyros aging and extending the mission lifetime. The mission extension till the end of 2020 is approved pending technical evaluation in 2018. The extension plan includes both augmenting the coverage and extending long-time series, as well as new elements and potentially new opportunities for discoveries. It will be boosted by collaboration and synergies with NASA's MAVEN, ESA-Roscosmos Trace Gas Orbiter (TGO) and other missions. In 2018 the major challenge would be to pass the bi-annual extension review and elaborate a convincing science case for new extension till the end of 2022. The talk will give the Mars Express status, review the recent science highlights, and outline future plans focusing on synergistic science with TGO.

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Release of 12+ years of MEX-MARSIS Subsurface data in the ESA's Planetary Science Archive

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Abstract

The European Space Agency's (ESA) Mars Express (MEX) mission to Mars has been returning valuable scientific data for ~15 years. This data is available to the public for free via the Planetary Science Archive (PSA), which houses the raw, calibrated, and higher-level data returned by the ESA's planetary missions, including data provided by the various MEX instrument teams. Previously the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) [1] instrument's subsurface data had a gap of several years, but in 2018 this issue was fixed and now 12+ years of subsurface radar sounding data, both in raw and calibrated form, are available for further scientific analysis by the public. This poster will also cover the ways in which to search for the data via the various PSA interfaces.

1. Introduction

MEX was inserted into Mars orbit in December 2003, though several instrument test observations also exist from the cruise phase of the mission, prior to arrival at Mars. Thus, this long-lived Mars mission covers 15+ years of data with its 7 instruments. Note that MARSIS uses 3 antenna booms, which were not extended, in stages, until mid-2005 [2, 3]. The MEX instruments can have various sub-channels and/or operating modes. In the case of MARSIS, the two primary types of data collection modes are active ionospheric sounding (AIS) and subsurface sounding. The AIS data has been published regularly through the PSA over the mission's lifetime. For the subsurface data, initial data has been available, but then some problems with the data pipeline caused a gap of several years in delivery of this type of data. Thanks to the effort of the MARSIS Principal Investigator (PI) Roberto Orosini and his team, with assistance from the PSA, an updated pipeline was created. Thus, the entirety of the MARSIS subsurface data, covering 12+ years of observations (~300 GB of data, 34,000+ observations) are now available in the PSA, in both raw and calibrated format.

2. The PSA user interfaces

The ESA's PSA uses the Planetary Data System (PDS) format developed by NASA to store the data from its various planetary missions. In the case of MEX, the data is stored in the PDS3 format, which primarily uses ASCII files to store and describe the data. Newer missions, from ExoMars onward use the PDS4 data standard, which uses XML files. There are two primary ways in which to find the data. One is the FTP area, which houses all the public data in the PSA. Here, there are no advanced search capabilities, but it does provide access to all the supporting files and documentation for the various datasets. When first searching for new data, users would benefit from using the newly developed Table View search interface [4]. Here the user can search using various parameters, such as mission name, target (e.g. Mars), instrument name, processing level, observation times, etc. The development of the PSA's search capabilities continues, thus more search parameters will be added over time. Also available in the Table View interface is a section for "Free Search", allowing one to use Contextual Query Language (CQL) to search over additional parameters. These various search methods rely on the metadata provided by the instrument teams in the labels associated with each of the data products.

3. Summary and Conclusions

Thanks to the efforts of the MARSIS PI team, over 12 years worth of subsurface radar sounding data are now available to the public. This data can be freely accessed at the ESA's PSA, at https://archives.esac.esa.int/psa/. There are multiple ways of browsing the MARSIS and other instrument teams' data, including from other planetary missions, which will be explained in this poster. The development of the PSA's user interface is an ongoing project, and we welcome feedback from the community for suggestions on new ways to search this wealth of data. Feedback and suggestions can be sent to psahelp@cosmos.esa.int.

Acknowledgements

The MEX Archive Scientist and the entire PSA team would like to extend their thanks to Roberto Orosei and the entire MARSIS team for their effort in creating a new data pipeline and delivering both raw and calibrated subsurface sounding data from Mars to the public via ESA's PSA. Our thanks go also to the European taxpayers, whose contributions to the European Space Agency enable the gathering and dissemination of this scientific knowledge, and preserving it for future generations of scientists to work on.

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The Roles that HRSC Digital Terrain Models Have in Supporting Martian Polar Science

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Abstract

Thirty-three (33) single-strip High Resolution Stereo Camera (HRSC) Digital Terrain Models (DTMs) over the Martian South Pole have been processed and used to produce ORIs (orthorectified images). This paper describes the DTM production and some applications in Martian Polar Science.

1. Introduction

The Martian polar regions have generated a lot of research interest because of numerous changes appearing around their ice layers. There is a lack of coverage of high-resolution DTMs in this region and corresponding ORIs, hindering possibilities of further scientific analysis. We describe the DTM production method and some applications.

2. Method

The full resolution DTMs are produced using a NASA-VICAR-based pipeline developed by the German Aerospace Centre, with modifications from Kim and Muller [1] through replacement of the image matching based on the (Gruen-Otto-Chau, aka Gotcha) algorithm [2], modified for the polar region. Other than products in MOLA sphere height reference (DT), we have also published products using an areoid height reference (DA) by differencing DTM products with the Mars geopotential surface data. Striping artefacts occur in these areoid products because of resolution limitations in the geopotential surface data in the polar region and integration of values to 16bit integer. A Gaussian filter is used to reduce these striping effects.

3. Results

We have produced 33 single-strip HRSC DTMs over the south pole [3] to fill the gaps between Mars Orbiter Laser Altimeter (MOLA) DTMs with higher resolution images such as CTX, MOC-NA, and HiRISE. The HRSC DTMs have an uniform grid-spacing of 50 m/pixel and have been assessed against the MOLA South Polar MEGDR and MOLA PEDR.

The resultant south polar HRSC DTMs have then been used to orthorectify the corresponding HRSC images. Figure 1 shows a Mosaic of the produced ORIs after de-shading using the method described in [3].

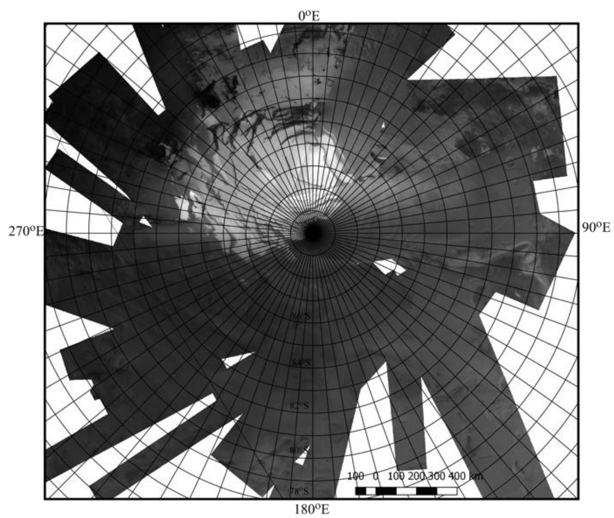

Figure 1: Mosaic of HRSC Orthorectified Images over the South Pole [3]

The HRSC products, both the DTMs and the ORIs have then been employed in several polar research areas. The ORIs have been used as base images for co-registering thousands of high-resolution Martian images [4] around South Polar Residual Cap (SPRC). Figure 2 shows a map of distribution of co-registered

CTX images around the south pole, with high concentration near the SPRC. Co-registered images are an important prerequisite for change detection research to ensure that the changes obtained are not related to misregistration errors [5].

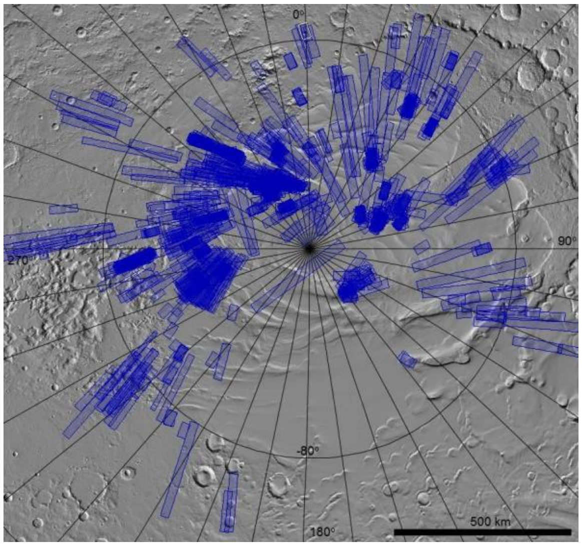

Figure 2: Co-registered CTX image maps around SPRC

The DTMs have also been used to help geological research over the Cavi Angusti region and have also utilized in subsurface layer reconstruction in the Promethei Lingula region [6].

The same HRSC DTM production method is also being applied to produce north polar DTMs, opening up wider possibilities for Martian Polar Research.

4. Conclusions

In this paper, we have presented some highlights of our production of HRSC orbital strip DTMs in MOLA and areoid reference and their corresponding ORIs for SPRC and the South Polar region of Mars (82^{o}S-90^{o}S). We also mention some of the roles of the produced HRSC DTMs and ORIs in related Martian Polar Science research which will be further elaborated at the conference.

Acknowledgements

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We also express gratitude to the HRSC team and the MOLA team for the usage of HRSC and MOLA data, Marita Wählisch for kind assistance with the areoid conversion and Alexander Dumke for the exterior orientation processing results used within this research.

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Inversion of vertical profiles of CO_2 in the Mars daylight thermosphere from its non-thermal emission at 4.3 μm

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Introduction

Several instruments on board Mars Express (MEx) have observed daytime atmospheric emissions in the IR, although the data at high altitudes and in a limb geometry have not been sufficiently exploited so far [1, 2, 3]. Exploiting atmospheric emissions in a limb geometry is a real challenge because this geometry favours optically thick conditions, difficult to handle. In addition, the emissions of CO_2 and CO at the low pressures at these altitudes are no longer in LTE (local thermodynamic equilibrium), i.e. they cannot be described by the local kinetic temperature. This is a limitation and a complication because the state populations, i.e., the emission observed is not analytically related to the temperature in a simple manner. These observations should allow for a first-time exploitation of the non-thermal CO_2 emission in a terrestrial planet other than Earth, in at least the strongest system of ro-vibrational bands of this molecules, that in the 4.3 μm spectral region.

Although spectroscopically well characterised and theoretically well understood and modelled [4, 5, 6], the scientific exploitation of these non-LTE emissions is difficult for several reasons. Some of these are common to previous similar investigations and IR remote sounding on the Earth upper atmosphere (sensitivity to rate coefficients not well determined in the lab, propagation of errors in the temperature retrievals, etc.) and some of them specific to a CO_2 atmosphere like the Martian case (large number of CO_2 bands contributing, lower spectral resolution of spectrometers on Mars orbit, larger optical thickness of a CO_2 atmosphere, stronger limitations from lab data available).

One of the goals of the UPWARDS project [7] was the exploitation of these limb emissions as captured by OMEGA and PFS on Mars Express and the delivery of the major results obtained (densities and temperatures at thermospheric altitudes) to open repositories for its scientific dissemination.

In this presentation we will describe the essential tools used (non-LTE models and retrieval suite), the datasets selected, the major difficulties found in the retrievals and a sample of the results obtained so far.

The Mars Express datasets

The two IR sounders on board Mars Express, OMEGA and PFS, performed limb observations in the IR region, detecting the strong 4.3 μm CO_2 emissions [1, 3]. The two instruments have different spectral resolutions, spatial and temporal mapping of the limb, and very different FoV and sampling rates. Although their joint analysis presents a very interesting challenge, their measurements are actually uncorrelated, and their inversion should rather proceed independently from each other.

For this study we selected the OMEGA *qubes* as our primary goal due to the much larger number of vertical profiles that can be built from the 2D limb-projected data. The PFS dataset, on the other hand, presents tangential tracks with large horizontal extensions, more suitable for atmospheric variability studies.

The non-LTE retrieval scheme

Our team at the Instituto de Astrofísica de Andalucía (IAA/CSIC) has experience in the simulation of CO_2 emissions in the upper atmospheres of the three terrestrial planets, under conditions of non-LTE [2, 6, 8]. In addition, our team has helped to develop, in partnership with the University of Karlsruhe, a line-by-line radiative transfer model (KOPRA) [9], used to simulate emission and absorption spectra primarily of the Earth's atmosphere. This was used to perform retrievals of CO_2 densities in the Earth's atmosphere in the infrared [10, 11]. And this is the scheme extended and applied to the Martian case. The results have been catalogued for dissemination and discussed at length in an manuscript in preparation [12], and this talk will focus on the presentation of these preliminary results.

Extensions and future applications

One of the major difficulties of the study has been the strong and non-linear dependence of the CO_2 non-thermal emission on the CO_2 density (target of the inversion). This dependence enters twice into the iterative process, making the inversion time consuming and very sensitive in the upper mesosphere. For operational reasons, we are deriving densities only at thermospheric altitudes at the moment. A first extension is therefore to cover the Martian mesosphere with our scheme, which will probably involve a revisit to the non-LTE model. A second application is the similar dataset of limb emissions by VIRTIS/Venus Express in the other CO_2 neighbour atmosphere, Venus. And another effort in parallel, regarding ExoMars, an obvious extension is the application of the retrieval scheme to solar occultation observations by NOMAD and ACS, on board the Exomars 2016 TGO, which are essential and systematic data of such mission. These instruments offer unique capabilities to study the Martian thermosphere with unprecedented vertical resolution. The adaptation of this retrieval scheme to the two instruments will be presented elsewhere [13].

Keywords: Mars Express, OMEGA, inverse methods, remote sounding, CO_2, non-LTE, ExoMars TGO, clustering techniques, Mars, NOMAD, PFS, ACS.

Acknowledgements

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Construction and use of a 4D cloud database derived from MEx/OMEGA data – Cloud life cycle over polar regions

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Abstract

We have derived a product characterizing water ice clouds from a long series of OMEGA images covering 7 Martian years, the ice cloud index (ICI). Individual ICI pixel values are binned onto a 4D regular grid (longitude, latitude, solar longitude Ls and local time LT). The resulting gridded ICI enables the (partial) climatological reconstruction of the diurnal cloud life cycle by aggregating values from large regions, covering several degrees of longitude and latitude during specific seasons. Clouds are more frequent around summer solstice (Ls=45-135°) early in the morning and in middle and late afternoon than around noon (12 h LT) in the tropics and northern low to mid-latitude regions (lat < 40°N). In the north polar region (lat > 75°N), clouds are present during a large part of the long daytime period during northern spring before disappearing abruptly around Ls=55°. In the south polar region (lat < 75°S), clouds present mainly in the afternoon disappear more progressively and mainly during southern spring around Ls 230-250°, before reappearing more abruptly at the end of southern summer, around Ls=340°.

We also plan to compare the ICI from OMEGA to water ice optical depth derived from MARCI/MRO reflectances and expect to find a qualitative agreement between both datasets on cloudy areas.

1. Introduction

Due to their heliosynchronous orbits, most recent and current Martian satellites have observed the planet only at a specific local time (LT) during the day (typically at 2-3 p.m. and 2-3 a.m. LT) over most regions except around the poles, and therefore cannot provide information about the diurnal cloud life cycle. Recently launched satellites MAVEN, MOM/Mangalaayan and Exomars/TGO) move along non-heliosynchronous orbits, but have only provided images at best over a short period (~2 years). The OMEGA spectrometer onboard the Mars Express (non-heliosynchronous) satellite has been providing spectral images at various times of the day over ~7 Martian years (MY 26-33, i.e. 2003-2016). For each valid pixel from this abundant spectral image data, we derived parameters representative of the presence and abundance of clouds and used them to construct a daily and annual climatology on a regular spatial grid.

2. Methodology

The detection of clouds is based on the measure of the depth of a water ice absorption band, initially applied at 1.5 µm [1]. In practice, we now use the slope of an absorption band around 3.4 µm to define the original ice cloud index (ICIo) and the reversed ice cloud index (ICI = 1 – ICIo) [2]. After comparison with a threshold value, this ICI indicates if the pixel is cloudy or not.

In a second step a cloud climatology is constructed. The ICI values of pixels are binned into a 4D array according to their longitude, latitude, Ls and LT, and then averaged. The bins have sizes of 1° in latitude and longitude, 5° in Ls and 1 (Martian) hour in LT. Due to the small number of 4D gridpoints containing valid ICI data (~2% of daytime gridpoints), we integrate and average several gridpoints covering larger spatial areas and longer time periods in order to form 2D subsets showing the evolution of clouds.

3. Seasonal cloud life cycle

We show the annual cloud life cycle over different periods of the day : morning (6-10 h LT), noon (10-14 h LT) and afternoon (14-18 h LT), on Ls–lat diagrams (fig. 1). During all 3 periods, cloudiness (i.e. high values of ICI) are present and dominant in the same areas wherever data is available, namely at the edge of the polar hoods (or belt) and in the tropics during northern summer (Ls=30-150°, aphelion belt). The main difference is the relative attenuation of cloudiness around noon in the aphelion belt, explained by the presence of a thermal tide.

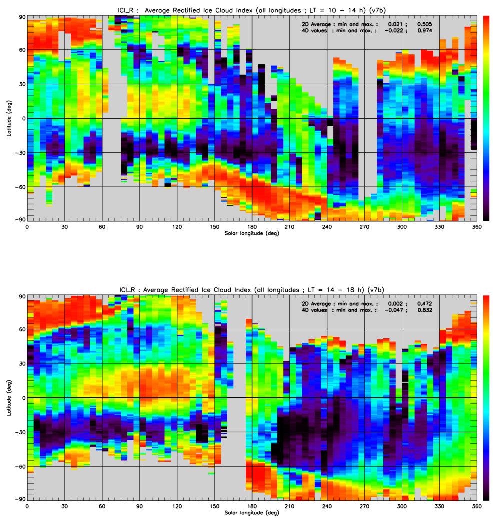

Figure 1 : Ice Cloud Index (ICI) as a function of Ls (solar longitude) and latitude, all longitudes, around noon (10-14 h LT ; top) and in the afternoon (14-18 h LT ; bottom). Color scale : black: no cloud ; from purple (low ICI, thin clouds) to red (high ICI, thick clouds) ; gray: no data.

4. Cloud life cycle at the poles

We have averaged the 4D ICI values around each pole (at latitude > 75°). Figure 2 shows that during the long period of solar illumination in northern spring, clouds are abundant at all times during the day (6-18 h LT) after Ls=30°, but also in the evening (18-24 h LT) after Ls=35°. Clouds are less abundant in the early morning (0-6 h LT). They disappear completely at Ls=70°. Clouds around the south pole evolve with a more progressive pattern : clouds are present and abundant durning early spring (Ls=180-200°), are then present during the late evening and early morning (LT=19-5h LT). The cloud cover decreases progressively until summer solstice. An abrupt increase of cloudiness can be observed at the end of summer, at Ls=330°, at different instants of the day and the night.

4.1. Comparison of MARCI-derived optical depth and ICI

In order to validate the OMEGA-derived ICI, we will compare ICI values with water ice optical depth values derived from MARCI data, and resampled onto the same 4D grid. Whereas the comparison is only possible over a limited temporal range (around 15 -16 h LT) in the tropics and midlatitudes, it will be possible over a larger range of local times accessible high latitudes due to MRO's orbit. This should improve and validate the determination of the diurnal cloud life cycle around the summer solstices in the polar regions.

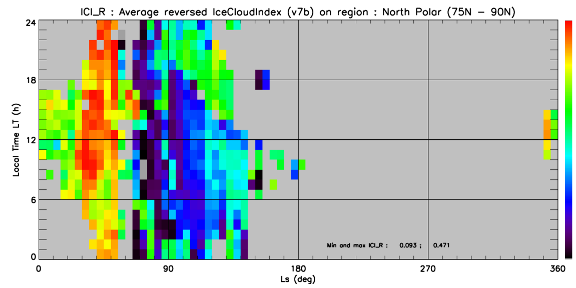

Figure 2: Ice Cloud Index (ICI) , function of Ls and LT, over the North Polar region (75-90°N ; all longitudes). Color scale : black: no cloud ; from purple (low ICI, thin clouds) to red (high ICI, thick clouds) ; gray: no data.

5. Conclusion

The ICI derived from OMEGA is a valuable indicators for detecting and characterizing Martian water ice clouds. By using statistical results, Olsen et al. [3] have already shown that the ICI is strongly related to the water ice column (which in turn depends on the radius of ice particles and on the water ice optical thickness). Comparisons of the ICI with optical thickness derived from SPICAM – measurements from 2 instruments on the same platform – are planned. Comparisons with data from other instroments on heliosynchronous satellites (CRISM, THEMIS...) could also help to determine the diurnal cycle of clouds over polar regions.

Acknowledgements

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Mars Express Science Ground segment evolution along 15 years of mission, new challenges and future perspectives.

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Abstract

We present the synthesis of 15 years of mission operations from the perspective of the Science Ground Segment (SGS), showing the evolution of the planning mission system and summarizing the new challenges for the remaining years of the mission. We will analyze some observation statistics and we show the proposed system improvements.

Nomenclature

ESA European Space Agency

ESTEC European Space Research and Technology Centre

LTP Long Term Plan

MEX Mars Express

MOC Mission Operations Centre

MRBs Mission Review Boards

MTP Medium Term Plan

PS Project Scientist

PSA Planetary Science Archive

RAB Resource Allocation Board

SGS Science Ground Segment

TGO Trace Gas Orbiter

1. Introduction

Mars Express remains one of ESA's most scientifically productive missions and has fully accomplished its mission objectives . The mission provides a unique platform for Mars climate evolution research to help understand the complex atmospheric processes.

The Mars Express (MEX) Science Ground Segment team is composed of 6 scientist-engineers, responsible for the definition and maintenance the overall scientific plan in cooperation with the Project Scientist (PS). The overview of the SGS system is shown in figure 1 .Some of the team duties are:

- coordinating the candidate observation selection process between the Instrument Teams and the relevant Mission Operation Centre (MOC) teams, supporting the planning activities of the MEX Principal Investigators (PI) in the preparation of science operations for their instruments and shielding MOC from the details of this iterative process,

- producing a set of consolidated instrument payload operations requests and pointing timeline requests based on the Long Term Plan (LTP) and the output of the medium term planning (MTP) exercise, and transferring these to MOC,

- iterating the instrument payload operation requests with the MOC and the PIs to resolve inconsistencies,

- Coordinating software patching for instruments,

- Participating in the Resource Allocation Board (RAB) which convenes during the MTP and STP phases,

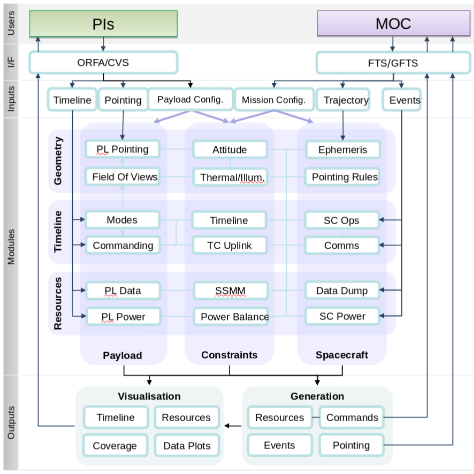

Figure 1: SGS system based on the mission planning tool structure.

- Participating in Mission Review Boards (MRBs) for instrument anomalies.

2. Recent changes in science operations

After operating for 15 years, through changing Martian seasons and changes in the spacecraft condition, planning the science operations of the mission continue to be a challenge. We will present the improvements over the last few years of to our operating methodologies, instrument operation changes, software improvements and scientific observation modifications.

3. Some planning statistics

Versatility in SGS is the key to success, as there are continue changes in the Martian seasons, data volume, illumination conditions, eclipses and many other factors.

We will provide some mission downlink observation statistics for the overall MEX mission science as well as useful statistics for comparison with other ESA planetary missions.

Note the figure 2 only represents volume of data, which is not necessarily correlated with either the quantity or quality of the final science data. It must be considered as a tool for trend analysis among different

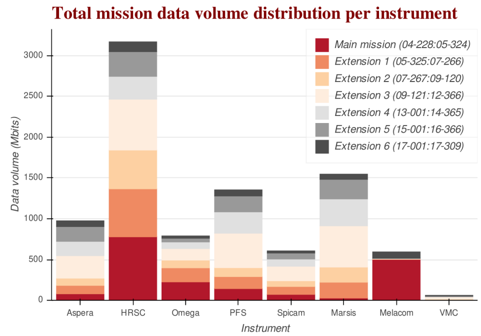

Figure 2: Downlink mission statistics per instrument along mission phases.

mission phases. For many years, the MEX archive has supported the archiving of high level science products as a service to the science community. Detailed information can be found at the official website of the Planetary Science Archive (PSA).

4. Future of the mission and system improvements

Finally we will summarize the future objectives for the long term planning period up to 2020 and the general status of the spacecraft, instruments and staffing. All these are aligned with the changing Martian seasons as represented in figure 3. Among these activities are:

- Continue the observations of all instruments to fulfill the scientific objectives of the mission extension and new scientific challenges.
- Prepare joint science observations with Trace Gas Orbiter (TGO), providing scientific context to the new observations.
- Updates of the ground segment to ensure the extended lifetime of the mission with new operational constraints.
- Support the communications with surface assets and characterize landing sites for future robotic missions.

5. Summary and Conclusions

Flexibility is key for science missions and it requires a qualified science operations team with both engineer-

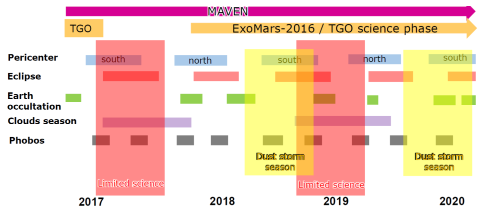

Figure 3: Mission scheme in function of the Martian climate and joint science with other space missions.

ings and scientific experience to achieve the goals of the mission. In order to improve SGS planning systems for planetary missions it is vital to take advantage of long term missions as MEX in order to transfer the planning knowledge and experience to complex planetary missions of the future.

Acknowledgements

The members of the Science Ground Segment team are particularly grateful for the assistance provided by the Flight Control Team at the MOC and the collaboration of all the instrument teams. Without their excellent and constant collaboration in the science planning process, the Mars Express mission would not have obtained such prolific scientific results.

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MARSIS Observations of Phobos: Preliminary Results of the Search for Underground Reflectors

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Abstract

In this paper, we present recent MARSIS observations of the Martian moon Phobos, considering the continued search for underground reflectors.

1. Introduction

The MARSIS radar instrument aboard MARS EXPRESS[1, 2] is a low frequency radar capable of operating at multiple bands with center frequencies of 1.8 MHz to 5 MHz. As described in [3], the instrument was re-programmed to be able to observe the Martian moon Phobos (see also [4] for a summary). Phobos is planned to be the target of several missions, including sample return missions.

In [5], we presented a simulation tool to compute an accurate backscattered radar echo from the surface of a body of arbitrary shape.

Recently, new geo-models of Phobos have been presented[6], derived from HRSC observations, represented as a spherical harmonics coefficient set. Using these new models, we re-computed the surface reflections in order to compare these with MARSIS measurements.

2 Results and discussion

Fig. 1 shows the simulation of the backscattered echo of orbit 4814 at 4 MHz center frequency. When comparing these with the on-board Doppler and SAR processed measurements performed by the MARSIS instrument shown in Fig. 2, it can be seen that echoes in the measurements are also present in the simulated radargram.

Fig. 3 shows echo nº 4 of Figs. 1 and 2 in an overlay. The positions were aligned so that the echo peaks of measurements and simulation match. Signal powers were normalized separately: the simulation is normalized to the strongest echo, while the measured data were normalized to the strongest echo in *all* Doppler filter banks.

3 Conclusions

As of yet, in those MARSIS measurements we analyzed, the radar echoes could be attributed to surface backscattering. There are some hypotheses wich might cause these phenomena. Firstly, with an assumed resolution of ≈60 m when assuming a permittivity of $\varepsilon_\mathrm{r} = 6.25$, surface regolith layers within that range are not separable. Secondly, primary layering might hinder deeper penetration if the material is very lossy. Lastly, multi-path propagation phenomena need to be investigated. Further investigation of the MARSIS data will give a better insight. Mapping the simulated and measured echoes to their respective surface locations will resolve ambiguities in the Doppler and SAR processed echoes.

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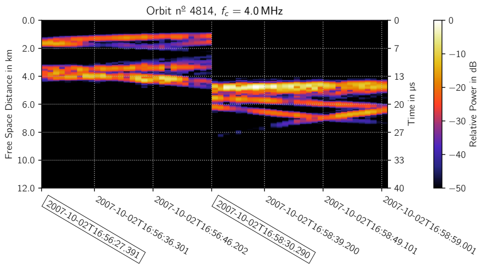
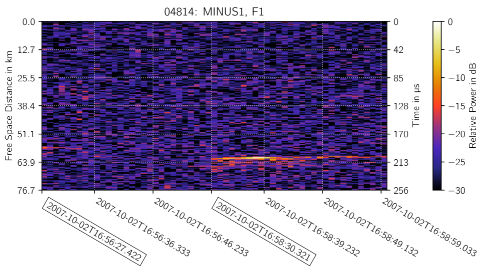
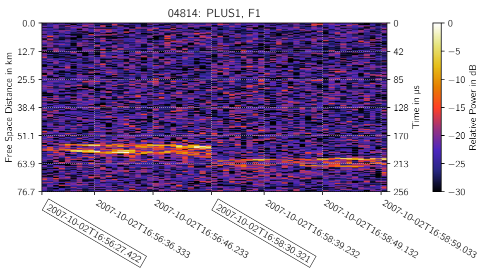


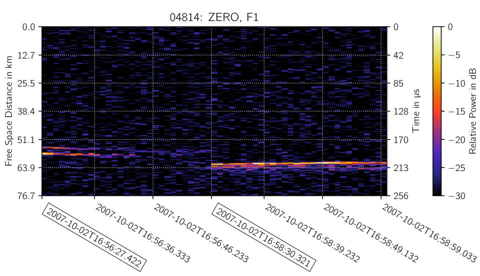
Figure 1: Simulated Radargram at 4 MHz center frequency.



(a) Doppler Filter −1.



(b) Doppler Filter 0.



(c) Doppler Filter +1.

Figure 2: MARSIS Doppler processed measurements of Orbit 04814.

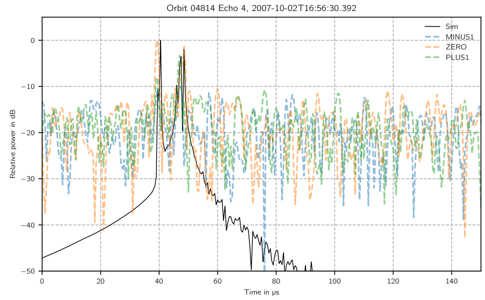


Figure 3: Time-shifted and power-normalized overlay of the measured Doppler filters and the simulation for Echo nº 4 of orbit 04814.

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Mars Express going Gyroless - Impact on science operations systems

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Abstract

Mars Express was originally designed to explore Mars for a period of 1 Martian year. The mission has been very successful and has been extended in several occasions and today it has been flying for more than 15 years. Due to its long lifetime in space the gyros had started to degrade, and a decision was made to extend the spacecraft lifetime by developing a new AOCS software to allow for switching off the gyros during an extended part of the operations, thereby reducing the duty cycle of the IMUs. As such change impacts the way the spacecraft is operated and the science operations are run, we describe the main science operations changes, those related to the science planning activities and tools, for uplink and downlink.

1. Introduction

The Mars Express (MEX) mission, the first ESA mission to have visited another planet of our Solar System, has substantially evolved in the course of its 15 years in space and around Mars. The spacecraft (S/C) arrived at Mars in December 2003 for what was planned to be a two-year mission. It has gone on to spend nearly 15 years gathering a wealth of data from the red planet, taking high-resolution images covering most of the surface, detecting minerals that form only in the presence of water, observing hints of methane in the atmosphere and conducting close flybys of one of its moons, Phobos.

During the last few weeks, MEX has been getting a new AOCS software, delivered across over 150 million km of empty space. This so-called "Mars Express v2.0"[1] is designed to respond to increasing degradations of its gyroscopes, thereby extending the mission lifetime. MEX was never designed to fly without its gyros continuously available, therefore an AOCS upgrade was necessary to avoid an end of mission forecast in early 2019. This software update not only affects the spacecraft operations but also the science operations, including procedures and planning processes.

The Science Ground Segment (SGS) team, located at the European Space Astronomy Centre (ESAC) near Madrid (Spain), is responsible for the generation, coordination and maintenance of the overall scientific plan in cooperation with the Project Scientist (PS) and the Principal Investigator (PI) teams. The duties of the SGS include coordination of the observations plan with the PI teams and the Mission Operations Centre (MOC); located at the European Space and Operations Centre (ESOC) team in Darmstadt, Germany, which support the planning activities in preparation of instrument science operations. The SGS produces a set of consolidated instrument payload operations requests and pointing timeline requests based on a Long Term Plan (LTP) and the output of the Medium Term planning (MTP) cycles, and iterates further the instrument payload requests with the MOC and the PI teams to resolve inconsistencies, as necessary.

Here, we present the impact that operating a spacecraft in gyroless mode has had on SGS activities. A significant redesign of the operational concept, together with intensive coordination between teams, has been required in order to continue providing smooth science operations. One of the most significant changes was to adapt planning tools to the new requirements.

MAPPS, the Mission Analysis and Payload Planning System, is a planning and simulation tool that as-

[1] https://www.esa.int/Our_Activities/Operations/Mars_Express_v2.0

sists the SGS team with the complex process of instrument operations scheduling, simulation and validation [2] . The tool receives as inputs the observations requests from the instrument teams, which are merged into a plan that the science operations engineers can run. The instruments are simulated and modeled extensively, allowing to find any possible conflict or constraint violation in the plan. The result of a validated plan is the generation of a multi-instrument operational timeline that is sent to the MOC for uplink to the spacecraft.

The MAPPS tool was developed originally only to visualise the coverage of MEX experiments onto the Martian surface. Progressively, the tool has been extended to provide planning capabilities and to support other missions. For several years the tool has proven to be very stable and very few changes were needed for MEX. The gyroless mode development has created the need to adapt the tool and implement new features. We describe the changes implemented and how these are helping MEX to extend its science return in the coming years.

The scientific data acquired by the MEX instruments are processed by the respective instrument teams. Hence the SGS system only includes limited downlink functionalities. Spacecraft housekeeping data are retrieved from the MOC and processed by an automatic pipeline ref13. The generated products include auxiliary parameters describing the orientation of the solar panels, spacecraft attitude quaternions estimated by the on-board system, as well as indicators of the pointing stability. Information about the correlation between the spacecraft clock and the ground reference time is also obtained by the system.

SPICE is an information system which provides scientists the observation geometry needed to both plan scientific observations and analyse the data returned from those observations. SPICE is comprised of a suite of data files, usually called kernels, and software - mostly subroutines **??**. SPICE is implemented for MEX by the ESA SPICE Service **??** and has been in place since the start of the mission. SPICE is extensively used for science planning and data processing and analysis by the SGS and the PIs. The quality and the different flavours of SPICE data for MEX has evolved in the last 15 years, including a recent implementation of on-board measured attitude, additional kernels and a complete review of the S/C and Payload models (which is currently on-going). Enhancements of the SPICE Kernel distribution, validation and reporting along with the availability of a public 3D Visualization Tool (Cosmographia) and a Web-based SPICE tool (WebGeocalc) **??** are also an asset that has been recently incorporated, almost in parallell with the implementation of the gyroless mode that has presented some challenges to the SPICE implementation.

[2] `http://www.esa.int/Our_Activities/Space_Engineering_Technology/Talking_technology/Software_at_the_service_of_space_science`

2. Recent changes to science operations

Flying without gyros has a significant impact on most of the science pointing modes. This is highly dependent on the Sun-Mars-S/C geometry, which vary along Mars seasons, and on the types of observations. Some instruments may be more affected than others in terms of science return. Therefore it was necessary to elaborate a science planning scheme considering that some pointings may not be able to be performed during specific time periods.

A new, temporary procedure for waiving top-priority observations has been used in collaboration with the MOC. For the period of time from May-June 2018 for instance, joint Sun occultation observations with the ExoMars2016 Trace Gas Orbiter (TGO) became essential, as the TGO started its science phase. It remains in fact possible to observe in gyrostellar mode (with gyros turned on) along short, designated periods of time.

In the long run, new agreements and procedures will have to be developed to continue optimising the science return at Mars and to fine tune the gyroless operations so as to preserve the health of the gyros.

3. Gyroless implementation impact on MAPPS

MAPPS, the tool used to harmonise and schedule the science operations, had to be enhanced in order to cope with the new gyroless mode of operating the spacecraft.

One of the first changes was to adapt the interfaces. Mainly, the interface between the instruments teams and the SGS team at ESAC and the interface between the SGSteam and the MOC team.

The interface between the instruments teams and the SGS is run via MREQ pointing requests files. The SGS team is responsible for collecting the different MREQ files from the instruments teams and importing them into MAPPS, which will then generate a conflict-free plan following harmonisation. The MREQ file format was extended to indicate whether the pointing requests should use or not the gyros.

MAPPS uses the information from the different MREQ files to create the pointing blocks and slews that are needed to create the pointing request file (PTR). The PTR file is an essential interface between the SGS team and the MOC. The interface extends to the Flight Dynamics team which confirms whether a requested pointing should use or not the gyros.

Interface changes were not the only changes required. A new configurable constraint had to be added to MAPPS to ensure that Mars Express never exceeds a maximum duration in gyrostellar mode during an MTP (Medium-Term Plan). If the constraint is violated, the plan is flagged as invalid and cannot be delivered to the MOC until the constraint violation is resolved.

Another important change to the MAPPS software was to add the power of the two Inertial Navigation Units (IMU) to the power module during the gyroless mode implementation and inflight testing, as the gyros were kept on for safety reasons until robustness of the new mode was confirmed. The power module in MAPPS is used among other things to model the Depth of Discharge (DoD) of the batteries. Hence, the importance of adding the additional power. This will be required during any of the short periods in gyrostellar mode.

Finally, the telecommands budget that is used to populate the short MTL (Mission Time Line) had to be adapted. Besides the number of telecommands needed to operate the instruments on-board, an additional 10 timetagged telecommands are added for each science-pointing block included in the plan. The new gyroless mode, needs to add an extra 40 commands for each maintenance block.

4. Gyroless implementation impact on SPICE

The new gyroless software was uplinked on 8 April 2018. This was followed by an intentional Hardware Safe Mode triggering on 16 April to activate the new AOCS software. After successful reconfiguration of the S/C, it was noted that the S/C onboard time had suffered a considerable jump of around 20 seconds which is under investigation.

One of the main components of SPICE are the so-called Spacecraft Clock Kernels (SCLK). The spacecraft clock is the onboard time-keeping mechanism that triggers most spacecraft events, such as shuttering of a camera. Since telemetry data are downlinked with this clock's time attached to it, SCLK time is the fundamental time measurement for referencing many spacecraft activities. It is natural, then, that SCLK have an important role in the SPICE system. In fact, all SPICE pointing data are referenced to SCLK.

Most of the complexity of dealing with SCLK time values arises from the fact that the rate at which any spacecraft clock runs varies over time. As a consequence, the relationship between SCLK and ET or UTC is not accurately described by a linear function; usually, a piecewise linear function is used to model this relationship. The mapping that models the relationship between SCLK and other time systems is updated as a mission progresses. While the change in the relationship between SCLK and other systems will usually be small, you should be aware that it exists; it may be a cause of discrepancies between results produced by different sets of software.

The Safe Mode caused an impact on the generation of the SCLK that affected the generation of SPICE attitude data for several weeks and required re-generation of data and modifications of the auxiliary data conversion pipelines that generate SPICE kernels for MEX. The updates that had to be done and its effect will be outlined in this contribution.

5. Summary and Conclusions

From the science perspective, flying without gyros supposed new methodologies in the way the harmonisation among instruments is done. After a 2-week gap in science operations to allow for gyroless software activation and inflight testing, science data taking was resumed on 27 April with the initial commanding periods run with gyros still on. Specific observations such as joint Sun occultations with TGO were considered as high priority while the system was still being monitored for operational robustness.

In order to continue providing smooth science during the AOCS transition period and over the coming years, the SGS team has had to find solutions to many challenges. Among them, being able to adapt the planning tools in a very short period of time, align the systems interfaces with the MOC systems to provide the proper outputs and being able to communicate the implications of the changes to the PI teams. As of 16 May, Mars Express is running routine science operations with its gyros turned off.

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HRSC at Mars: 15 years of research (and counting)

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Abstract

Since Mars Express entered orbit around Mars in December 2003, the High Resolution Stereo Camera (HRSC) experiment has taken a total of >40,000 images of Mars and its moons, Phobos and Deimos. Almost the entire surface has been imaged in color and stereo at a scale of 10-20 m/pixel, and large parts have been observed more than once, enabling multitemporal studies. More than 600 peer-reviewed papers have been published since 2004, and numerous public releases and exhibitions helped to disseminate HRSC results. The camera is still in excellent technical shape and continues to deliver high-quality data.

1. Introduction

The High Resolution Stereo Camera (HRSC) of ESA's Mars Express Mission is designed to simultaneously map the morphology, topography, structure and geologic context of the surface of Mars as well as atmospheric phenomena [1]. The HRSC directly addresses two of the main scientific goals of the Mars Express mission: (1) High-resolution three-dimensional photogeologic surface exploration and (2) the investigation of surface-atmosphere interactions over time; and significantly supports: (3) the study of atmospheric phenomena by multi-angle coverage and limb sounding as well as (4) multispectral mapping by providing high-resolution three-dimensional color context information. The unique multi-angle imaging technique of the HRSC supports its stereo capability by providing 3 to 5 stereo observations from each mapping orbit, making the photogrammetric processing very robust [2]. The stereoscopic imagery and derived products (Digital Elevation Models, slope maps) are especially useful to characterize landing sites and their geologic context [e.g., 3]. HRSC data products bridge the gap in scale between highest ground resolution images (HiRISE) and global-scale observations (e.g., MOLA, THEMIS-IR).

2. Observations

2.1 Surface studies

Mars has been shaped by endogenic and exogenic processes over its entire history, hence it displays a variety of surface features that is second only to Earth. The large areal coverage of HRSC (an individual image sequence is typically 10^4 km^2) at typical scales between ~15 m (panchromatic), 30-50 m (color), and 50-100 m (DEM) is ideal for studying landform assemblages and landscapes (e.g., Fig. 1) while still enabling the investigation of individual landforms such as a fault or a river valley. The simultaneous acquisition of color/textural *and topographic information* is particularly important in this context, as the study of the land surface in 3D analysis is essential in the verification or calibration of physical models, linking process and form (geomorphometry; e.g., [4]).

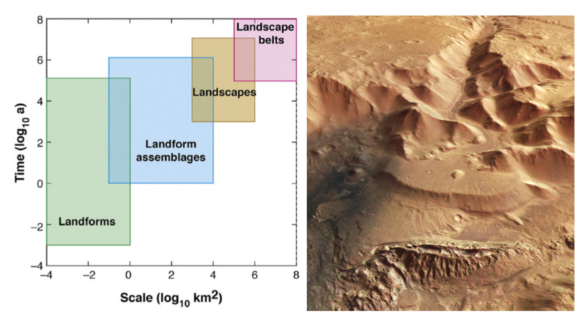

Figure 1: Surface characterization with HRSC. *(left)* Spatiotemporal hierarchy of landforms and landscapes (after [5]). The spatial resolution of HRSC makes it especially useful to analyze landform assemblages and landscapes, but also enables investigating the full range from large landforms to landscape belts. *(right)* Example of perspective view derived from HRSC color and stereo data, showing a landform assemblage in the Nephentes region (from background to foreground: valley, delta, possible fissure volcano).

An example for such studies is the investigation of Martian river channels and deltas, the dimensions of which could be quantified with HRSC DEM to model the formation timescales of deltaic deposits [6]. Another example is the 3D investigation of tectonic faults to constrain the strain, e.g., at rifts on Mars [7].

2.2 Phobos

Mars Express is currently the only spacecraft exploring Mars from an elliptical orbit. This allows regular, close flybys (<150 km) of Phobos. A prerequisite for such spectacular images (Fig. 2) is a very accurate knowledge of the orbital position of Phobos. Since 2003, measurements of the positions of the Martian moons in relation to the stars have repeatedly been obtained by examining images acquired by the Super Resolution Channel (SRC; [8]), which is part of the HRSC. Such astrometric measurements are used to continuously determine the positions of the Martian satellites and improve the ephemerides [9]. Stereo-photogrammetric methods were applied to derive a global digital terrain model (DTM) with 100 m/pixel resolution, enabling to re-determine to volume and improving the knowledge of the bulk density [10].

Figure 2: Phobos as seen by HRSC from a distance of approximately 115 kilometres.

2.3 Atmospheric investigations

HRSC regularly monitors clouds in the Martian atmosphere. The different viewing geometry between the individual channels enables determining the altitude and across-track velocity of clouds [11]. Numerous limb observations were obtained and provide a great potential to investigate the vertical layering of the atmosphere. Moreover, a close cooperation between HRSC and the MEX Interdisciplinary Scientists has recently been started to monitor the atmosphere from greater distances.

2.4 Combination with other data sets

HRSC DEM can be combined with other data to determine their three-dimensional extent. This is a perfect approach to study the stratigraphy of, e.g., alteration minerals. Such studies are part of HRSC's ongoing efforts to better characterize the Martian (paleo)environment [12].

3. Summary and Conclusions

HRSC is healthy and fully operational. Future observations will focus on improved 3D coverage of the Martian surface, Phobos imaging, and monitoring of atmospheric phenomena to initiate new science investigations.

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