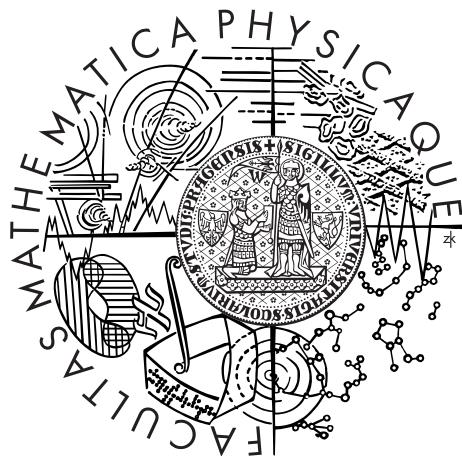


Charles University in Prague
Faculty of Mathematics and Physics

MASTER THESIS



Martin Pecka

Detection of 2D features in MARSIS ionogram pictures

Department of Software Engineering

Supervisor of the master thesis: RNDr. Jana Štanclová, Ph.D.

Study programme: Informatics

Specialization: Theoretical Informatics

Prague 2013

Dedication.

I declare that I carried out this master thesis independently, and only with the cited sources, literature and other professional sources.

I understand that my work relates to the rights and obligations under the Act No. 121/2000 Coll., the Copyright Act, as amended, in particular the fact that the Charles University in Prague has the right to conclude a license agreement on the use of this work as a school work pursuant to Section 60 paragraph 1 of the Copyright Act.

In Prague date

Název práce: Hledání 2D jevů v ionografických snímcích přístroje MARSIS

Autor: Bc. Martin Pecka

Katedra: Katedra softwarového inženýrství

Vedoucí diplomové práce: RNDr. Jana Šanclová, Ph.D., Katedra softwarového inženýrství

Abstrakt: Práce se zabývá technikami hledání význačných prvků v ionogramech zachycených přístrojem MARSIS umístěným na kosmické sondě Mars Express. Ionogramy jsou reprezentovány jako dvourozměrné obrázky s hodnotou kódovanou pomocí barvy. Využité techniky se snaží detektovat v takových snímcích různé zajímavé křivky (definované sadou parametrů), případně měřit další parametry nalezených objektů (perioda opakování přímek).

Klíčová slova: rozpoznávání vzorů, detekce, parametrické křivky, Mars Express, vektorizace

Title: Detection of 2D features in MARSIS ionogram pictures

Author: Bc. Martin Pecka

Department: Department of Software Engineering

Supervisor: RNDr. Jana Šanclová, Ph.D., Department of Software Engineering

Abstract: The work focuses on techniques for finding significant features in ionograms captured by the MARSIS instrument onboard the Mars Express spacecraft. Ionograms are 2D images with values represented in color. The developed techniques try to detect interesting curves (parametrically defined) in such images and measure some more parameters of the found objects (like the repetition period of lines).

Keywords: pattern recognition, detection, parametric curves, Mars Express, vectorization

Contents

Introduction	2
1 Mars Express, MARSIS and ionograms	3
1.1 Mars Express	3
1.1.1 HRSC (<i>High-Resolution Stereo Camera</i>)	5
1.1.2 OMEGA (<i>Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité</i>)	6
1.1.3 MARSIS (<i>Mars Advanced Radar for Subsurface and Ionosphere Sounding</i>)	6
1.1.4 PFS (<i>Planetary Fourier Spectrometer</i>)	7
1.1.5 SPICAM (<i>SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars</i>)	7
1.1.6 ASPERA-3 (<i>Analyser of Space Plasmas and Energetic Atoms</i>)	8
1.1.7 MaRS (<i>Mars Express Orbiter Radio Science</i>)	9
1.1.8 Beagle 2	9
1.2 The MARSIS experiment	10
1.2.1 Subsurface sounding	11
1.2.2 Surface sounding	11
1.2.3 Ionospheric sounding	11
1.3 Ionograms	11
1.3.1 Electron cyclotron echoes	11
1.3.2 Oblique ionospheric echoes	11
2 Title of the second chapter	12
2.1 Title of the first subchapter of the second chapter	12
2.2 Title of the second subchapter of the second chapter	12
Conclusion	13
Bibliography	14
List of Tables	18
List of Abbreviations	19
Attachments	20

Introduction

1. Mars Express, MARSIS and ionograms

1.1 Mars Express

First of all, let us briefly introduce the spacecraft carrying all the equipment needed to acquire ionograms. Its name is *Mars Express* (MEX) and it was launched by the *European Space Agency* (ESA) on 2 June 2003.

MEX arrived to Mars at its orbit with periapsis 250 km and apoapsis over 11,000 km on 25 December 2003 [27] with seven onboard scientific instruments and a landing module called Beagle 2. We're going to take a look at all of them in the following subsections; just Beagle 2 description is going to be rather short, because the landing sequence failed (for an unknown reason) and the lander didn't establish connection after it landed (if it landed at all)[27, p. 4].

The mission of MEX has several goals like “global studies of the surface, subsurface and atmosphere at unprecedented spatial and spectral resolutions” [27, p. viii]. One of the goals, however, stands out among all the others. It is the search for water (or its traces) on martian surface or subsurface.

Why water? There is lots of geological evidence of former water occurrence. But before the MEX mission nobody had proved or refuted presence of water on Mars in the present. Knowing more about water on Mars and its history, the scientists could postulate better hypotheses about the possibility of (former) life on the planet [27, p. ix].

The original mission lifetime of MEX was projected up to the end of 2005 (which would be 1 Martian year = 687 Earth days) [9]. However, overcoming some small problems (as the Solid State Mass Memory anomalies described in [13] or the MARSIS antennas deployment problems in 2004 [10, 11]), MEX has worked on its science goals up to this day and its science mission was extended until 2014 [15] (after 3 preceding similar extensions). Fred Jansen, MEX mission manager, said MEX had enough fuel for another 14 years of operation (at the beginning of 2012) [7]. So there is a hopeful prospect of further and even deeper Mars exploration (eg. [17] discovered an unexpected way of using the MARSIS instrument so that they “added magnetometer functionality” to MARSIS).

In the next subsections you can find out more about particular MEX instruments. The descriptions are based on [27] which you can see for more detailed information.

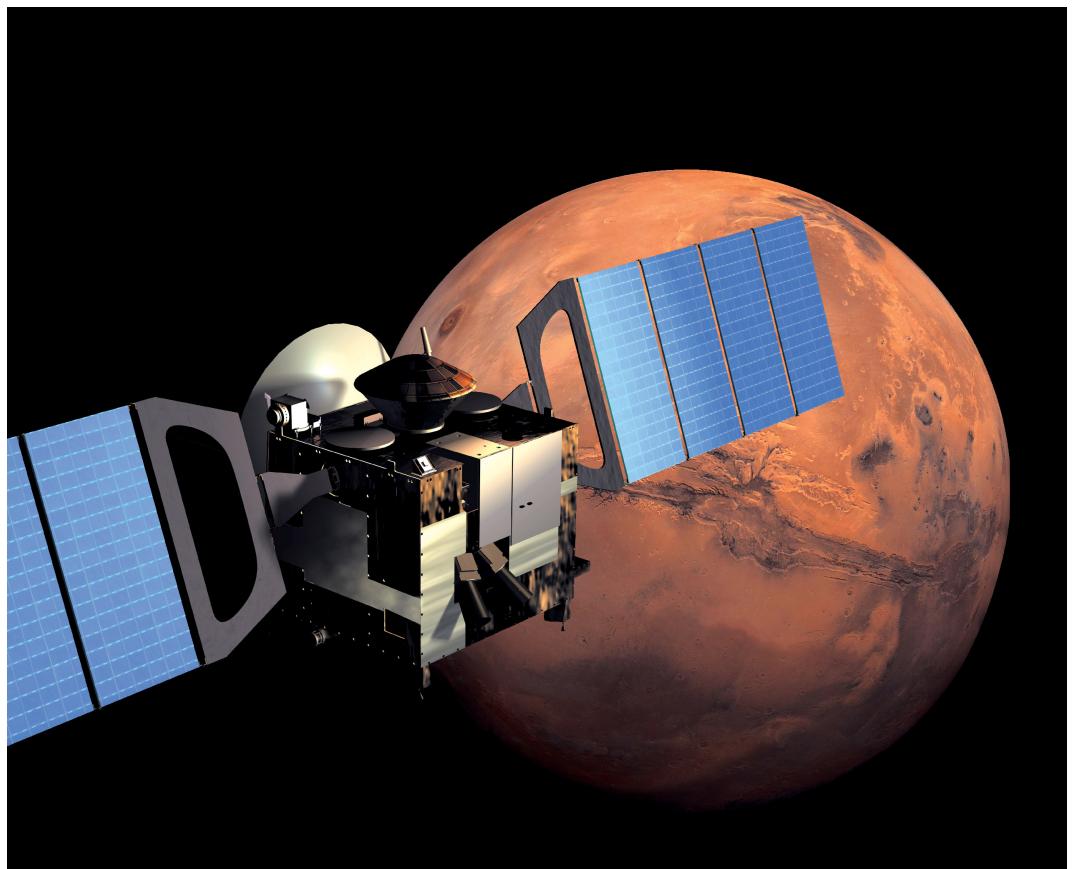


Figure 1.1: Mars Express spacecraft. Credit: ESA [12]

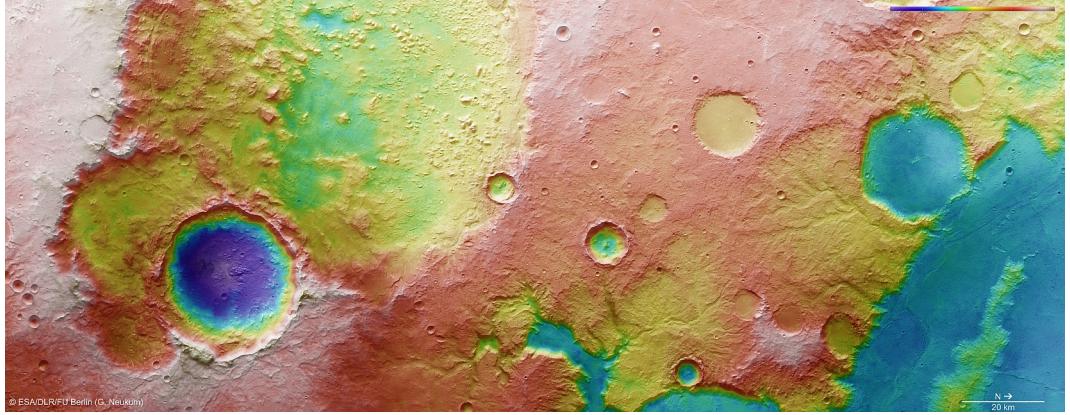


Figure 1.2: Example image taken by HRSC. Credit: ESA/DLR/FU Berlin (G. Neukum) [24]

1.1.1 HRSC (*High-Resolution Stereo Camera*)

HRSC is a high-resolution pushbroom¹ camera for surface imaging. Its goals are to characterize surface structure and morphology at resolution 10 m.px^{-1} (regions of interest at 2 m.px^{-1}), surface topology at high vertical resolution, atmospheric phenomena, physical properties of the surface and to classify terrain and to refine the martian cartographic base. It is also intended to observe martian moons Phobos and Deimos during their approaches.

HRSC is able to capture the surface at resolution up to 10 m.px^{-1} with field of view 11.9° , covering a 52.2 km wide strip of surface at height 250 km (which is the periapsis of MEX). The camera consists of 9 CCD sensors allowing it to acquire triple stereo images in 4 colors and 5 phase angles. What is a very useful property of these images, is that they are taken nearly simultaneously and thus having the same illumination and other observational conditions (which further helps in photogrammetric processing of the images).

HRSC also contains a super-high-resolution camera called SRC (*Super-Resolution Channel*) aimed at targeted observations of particular surface details. With image resolution 2.3 m.px^{-1} and field of view 0.54° it provides a detailed view of a 2.3x2.35 km large surface. Its main purpose is to take details of places of interest, eg. future landing sites for other landing modules.

Up to November 2011 HRSC had covered about 88 % of the martian surface [14, pp. 72–73] and still continues to gather new data. The scientific results of HRSC are for example better exploration of fluviaatile valleys [21], dicoveries of numerous glacial landforms, investigating lava flows, dicoveries of “dust devils” (fast moving dust storms) or providing data to derive a detailed topographic model of more than 20 % of Phobos [18, pp. 945–949].

¹A camera that scans the image by rows perpendicular to the flight direction. See http://earthobservatory.nasa.gov/Features/E01/e01_2.php for more details.

1.1.2 OMEGA (*Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité*)

OMEGA is a medium- and high-resolution spectrometer operating in visible and near-IR spectra (0.38–5.1 μm wavelength). Its medium-resolution operating mode (from heights of 1,500 to 4,000 km) can measure with the resolution 2–5 km targeting at global surface coverage, while the high-resolution mode (from the close vicinity of periapsis) brings resolution 350 m or better, but will cover only a small fraction of the surface.

As stated in [27, pp. 38–39], the main goals are to study the evolution of Mars, to detect minerals hidden to lower resolutions, to map mineralogical boundaries between geological units, to reveal gradients in hydration minerals related to fossil water flows and to monitor features associated with wind transportation. In particular, it is intended to find carbonates (not found on martian surface until the launch of MEX) and water ice. It is also able to measure atmospheric pressure, CO and H_2O column densities and surface temperature.

Recent contributions of the OMEGA payload are e.g. confirmation of liquid water on the surface when the planet was young [19], discovery of infrared and ultraviolet glows in the atmosphere [3], proving that Mars had a hot and wet period [6] (implying there were lots of greenhouse gases and a strong magnetic field, too [16, p. 90]), analyzing the south polar cap and finding out it is formed mainly of water ice [8], observation of CO_2 ice clouds [23] or finding ferric oxides near the equator [22].

1.1.3 MARSIS (*Mars Advanced Radar for Subsurface and Ionosphere Sounding*)

MARSIS is a long-wavelength radar using coherent wide-band pulses for sounding of the surface, subsurface and ionosphere of Mars. For these purposes it uses a 40 m dipole antenna (for both transmitting and receiving) and a shorter 7 m monopole antenna (only for receiving). Due to the used sounding frequencies ranging from 100 kHz to 5.5 MHz it is able to reach the depth about 5–8 km under the surface.

The primary goal of MARSIS is to detect liquid and solid water in the upper crust of Mars. There are also other objectives: subsurface geologic probing (to make a 3D characterization of the subsurface structures), surface characterization (to measure surface roughness, reflectance to radar signals and to estimate topography) and ionosphere sounding (to measure interaction between solar wind and the ionosphere) [27, p. 51].

To name some results of the MARSIS instrument, we can mention revealing the layered subsurface structure of both polar caps (strongly suggesting there were

oceans in distant history at these places) [16, pp. 98–102] along with estimating the volume of subsurface water ice in the polar cap [26], discovery of *Medusae Fossae Formations* (the youngest surface deposits) [16, pp. 102–105] or mapping the ionosphere and verifying the ionospheric density models [16, pp. 105–110].

One surprising and unexpected utilization of the MARSIS instrument is given by the electron cyclotron echoes found in ionograms (see section 1.3.1). It was found that they often correspond to the strength of the magnetic field, effectively allowing to measure that field and compare it to its model. Another type of echoes, the oblique ionospheric echoes (see section 1.3.2) were identified to correspond to the crustal magnetic field. Both these contributions were made by [17].

1.1.4 PFS (*Planetary Fourier Spectrometer*)

PFS is IR-spectrometer (based on double-pendulum interferometer) operating in the range 1.2–42 μm divided into two channels – the *Short Wavelength* (SW) channel (1.2–5 μm) and the *Long Wavelength* (LW) channel (5–42 μm). Its spatial resolution is 10 km for SW and 20 km for LW (from altitude 300 km). PFS uses an onboard *Fast Fourier Transform* circuit to select only the data scientists are interested in.

The objectives of this device are atmospheric studies like atmospheric composition (as it can detect eg. H_2O , CO and CO_2 spectra), solid-phase surface components detection and atmospheric dust measurements. PFS also captures the vertical temperature–pressure profiles and dust and ice opacity [27, pp. 115–116].

The contributions made using PFS so far are for example measuring the atmospheric temperature (finding out that there is a rather complicated situation around the peak of Olympus Mons), measuring the surface temperature, counting the atmospheric dust content, observing temperature inversion effects, detecting methane in the atmosphere (which could imply either organic life or volcanic activity, which are both unexpected phenomena), proving that the south polar cap is made mainly from CO_2 ice, or capturing the solar spectrum from the surroundings of Mars (which cannot be done from Earth) [27, pp. 122–135].

1.1.5 SPICAM (*SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars*)

The SPICAM instrument is made of two spectrometers, one operating in the UV spectrum (118–320 nm) and the other in the near-IR (1.0–1.7 μm).

Many tasks have been assigned to SPICAM, the major of them being investigating ozone, H_2O and aerosols vertical profiles in the atmosphere. These

should help constructing meteorological and dynamical atmospheric models, understanding the water vapour atmospheric cycles, characterize processes of water escape from the atmosphere, investigating the interactions between surface and atmosphere and revealing impact of aerosols on martian climate [27, pp. 97–100].

One of the latest surprises brought by SPICAM is martian atmosphere is supersaturated with water vapour which further prepares conditions for water escape from the atmosphere [20]. Another unexpected result are nocturnal aurorae observed in the upper atmosphere, along with the (expected) NO recombination nightglow [4]. Other results involve retrieving global spatial and temporal climatology of ozone [25], south polar cap observations [16, pp. 158–159], studies of UV dayglow [16, pp. 160–162], constructing the aerosol vertical profiles [16, pp. 175–180] or observation of CO₂ clouds on the nightside [16, p. 178].

1.1.6 ASPERA–3 (*Analyser of Space Plasmas and Energetic Atoms*)

ASPERA–3 is an instrument designed to study the interaction between solar wind and martian atmosphere. It comprises of four separate detectors. The first one is *Neutral Particle Imager* (NPI) measuring the *energetic neutral atom* (ENA) flux with high angular resolution. Another one neutral atoms sensor, the *Neutral Particle Detector* (NPD), measures the neutral atom flux resolving energy and mass of the atoms. The other two instruments are aimed at electrically charged particles. The *Electron Spectrometer* (ELS) is a top-hat electrostatic analyzer, while the *Ion Mass Analyzer* (IMA) is an ion mass composition analyzer working with H⁺, He²⁺, He⁺ and O⁺ ions [27, p. 122].

ASPERA–3 should focus on measuring ENAs in order to investigate the interaction between solar wind and martian atmosphere, to characterize the impact of plasma processes on atmospheric evolution and to obtain plasma and neutral gas distribution near Mars. It should also measure electrons and ions to complement ENA measurements, to study the dynamics and structure of plasma and to provide solar wind parameters [27, p. 122].

To present some results of ASPERA–3 we can mention discovering that the solar wind penetrates much deeper in martian atmosphere than was believed, being one of the atmospheric ions escape mechanisms [1], detection of ENA jets caused by solar wind [16, pp. 208–209], observing the ENA flux during Mars eclipse which laid foundation of a new method to measure planetary exosphere [16, p. 209] or proving there is a yet unidentified source of interplanetary ENAs [16, pp. 209–212].

1.1.7 MaRS (*Mars Express Orbiter Radio Science*)

Opposite to the already described devices, the MaRS experiment doesn't have a dedicated physical device like a sensor or transmitter. Instead, it utilizes the communication antennas to perform radio occultation experiments. It can use either the parabolic 1.6 m diameter *High Gain Antenna* or the smaller *Low Gain Antennas*. The second part of the occultation experiments (namely the receivers) cannot be carried on board MEX, because they need to be on the opposite side of Mars than MEX is. Thus, the receivers are placed on Earth (Kourou, French Guiana; Darmstadt, Germany; Perth, Australia; plus 3 NASA's *Deep Space Network* telescopes in Goldstone, USA; Madrid, Spain and Canberra, Australia). The experiment uses two frequency bands – the S-band at 2.1 GHz and the X-band at 7.1 GHz [27, pp. 153–154].

MaRS is intended to sound the neutral atmosphere to derive vertical density, pressure and temperature profiles, to sound the ionosphere as well (in order to get electron density profiles), to determine the dielectric properties of the surface, to detect gravity anomalies and to sound the solar corona at extra occasions [27, p. 141].

MaRS contributed towards improving existing atmospheric *global circulation models* [16, p. 227], towards the discovery of so called “meteor layer” of atmosphere containing ionized metallic atoms brought into the atmosphere by meteoric impacts [16, p. 230] and towards refining the crustal structure [16, p. 234].

1.1.8 Beagle 2

Beagle 2 is the lander module MEX was equipped with. It detached from the spacecraft on 19 December 2003 (6 days before MEX orbit entry) and its touch-down was planned to 25 December 2003. However, it hasn't transmitted any signal after the martian atmosphere entry. As of February 2004 it was declared lost. No particular reason came out on inquiry into its fault [5].

To accomplish its main goal (searching for existing or former life, or at least for conditions allowing development of life in the past) it was equipped with several scientific tools. To begin with, the *Gas Analysis Package* is a mass spectrometer used for examining the surrounding atmospheric gases as well as rock and soil samples (heated in ovens in order to vaporize). The *X-Ray Spectrometer* studies the composition of rock and soil samples using X-Ray fluorescence spectrometry being able to detect metals like Fe, Mg, Al, Ti and others. Another spectrometer, the *Mössbauer Spectrometer* is able to analyze materials containing iron. Its *Stereo Camera System* was intended to acquire stereoscopic images of the landing site in various spectral ranges. One of the largest contributions to Beagle's main goal should have been brought by the *Microscopic Imager* (by searching for



Figure 1.3: Visualization of the Beagle 2 lander on martian surface. Credit: Beagle 2 [2]

microscopic fossils). As a support for all the mentioned systems, the *Planetary Underground Tool* handles soil samples acquisition using a 1.5 m long drill. There is also a grinder available for removing unwanted material from the samples or the surrounding surface. There are also several sensors attached to Beagle 2 - the *oxidant sensor* monitoring the oxidizing effects of martian atmosphere, the *UV sensor* capturing the UVA and UVB spectral ranges (which are lethal for organisms), the *wind sensor* recording the speed and direction of wind, the *air pressure sensor* with resolution 0.003 hPa, the *air temperature sensor* with accuracy about 0.01 K and finally the *dust impact monitor* measuring the magnitude and impact rate of dust particles [27, pp. 165–191].

1.2 The MARSIS experiment

In this section we will discuss the individual parts of the MARSIS experiment. We are going to briefly describe the physical background of the experiments as well as the technical solution of the measurement mechanisms.

1.2.1 Subsurface sounding

The subsurface sounding attempts to detect the borders of the *cryosphere*, which is the crust layer in which the temperature remains constantly under the water-freezing point. Such borders can be identified owing to different dielectric properties of liquid water and ice or ice and atmospheric gases. The deeper border can be a water–ice interface because the cryosphere ends where the internal planetary heat flow raises the temperature above the water-melting point (so if there is a liquid water reservoir under the cryosphere, it can be detected). This interface is expected to be at 0–5,000 m depth. On the other hand, the higher border can be formed by the desiccated megaregolith (martian soil) where the desiccation is caused by subsurface ice sublimation (estimated to be at depths between 0 and 1,000 m).

1.2.2 Surface sounding

1.2.3 Ionospheric sounding

1.3 Ionograms

1.3.1 Electron cyclotron echoes

1.3.2 Oblique ionospheric echoes

2. Title of the second chapter

- 2.1 Title of the first subchapter of the second chapter**
- 2.2 Title of the second subchapter of the second chapter**

Conclusion

Bibliography

- [1] BARABASH, S. et al. Martian atmospheric erosion rates. *Science (New York, N.Y.)*. January 2007, 315, 5811, pages 501–3. ISSN 1095-9203. doi: 10.1126/science.1134358. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/17255508>.
- [2] BEAGLE_2. *Beagle 2 lander*. In *Space In Images* [online], 2002. [Accessed 03/24/2013]. Available from: http://spaceinimages.esa.int/Images/2001/11/Beagle_2_lander.
- [3] BERTAUX, J. L. et al. First detection of O 2 1.27 μ m nightglow emission at Mars with OMEGA/MEX and comparison with general circulation model predictions. *Journal of Geophysical Research*. March 2012, 117, pages E00J04. ISSN 0148-0227. doi: 10.1029/2011JE003890. Available from: <http://www.agu.org/pubs/crossref/2012/2011JE003890.shtml>.
- [4] BERTAUX, J.-L. et al. Nightglow in the upper atmosphere of Mars and implications for atmospheric transport. *Science (New York, N.Y.)*. January 2005, 307, 5709, pages 566–9. ISSN 1095-9203. doi: 10.1126/science.1106957. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/15681381>.
- [5] BONACINA, F. *Lessons Learnt From Beagle 2 And Plans To Implement Recommendations From The Commision Of Inquiry*. In *Ireland / ESA in your country* [online], 2004. [Accessed 03/24/2013]. Available from: http://www.esa.int/ESA_in_your_country/Ireland/Lessons_learnt_from_Beagle_2_and_plans_to_implement_recommendations_from_the_Commission_of_Inquiry.
- [6] CHEVRIER, V., POULET, F., BIBRING, J.-P. Early geochemical environment of Mars as determined from thermodynamics of phyllosilicates. *Nature*. July 2007, 448, 7149, pages 60–3. ISSN 1476-4687. doi: 10.1038/nature05961. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/17611538>.
- [7] CLARK, S. *Mars Express back in business at the red planet*. In *Spaceflight Now* [online], 2012. [Accessed 03/20/2013]. Available from: <http://www.spaceflightnow.com/news/n1202/15marsexpress/>.
- [8] DOUTÉ, S. et al. South Pole of Mars: Nature and composition of the icy terrains from Mars Express OMEGA observations. *Planetary and Space Science*. January 2007, 55, 1-2, pages 113–133. ISSN 00320633. doi: 10.1016/j.pss.2006.05.035. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0032063306001243>.

- [9] ESA. MARS EXPRESS MASTER SCIENCE PLAN Part I - Introduction. Technical Report 1, 2004. Available from: <http://www.rssd.esa.int/SB/MARSEXPRESS/docs/MSPDOC/MSPOverviewDocumentation-PartI.pdf>.
- [10] ESA. *Mars Express Radar Deployment Postponed*. In *ESA Science & Technology* [online], 2004. [Accessed 03/20/2013]. Available from: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=35021>.
- [11] ESA. *Mars Express 2nd Boom Deployed*. In *ESA Science & Technology* [online], 2005. [Accessed 03/20/2013]. Available from: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=37608>.
- [12] ESA. *Mars Express and the mystery of Phobos*. In *ESA Kids Liftoff* [online], 2010. [Accessed 20. 3. 2013]. Available from: http://www.esa.int/esaKIDS/SEM8534KV5G_Liftoff_1.html.
- [13] ESA. *Mars Express steadily returns to routine operation*. In *ESA Our Activities* [online], 2011. [Accessed 03/20/2013]. Available from: http://www.esa.int/Our_Activities/Operations/Mars_Express_steadily_returns_to_routine_operation.
- [14] ESA. Programmes in Progress. *Bulletin Space for Europe issue 148*. 2011, pages 72–73. Available from: <http://esamultimedia.esa.int/multimedia/publications/ESA-Bulletin-148/pageflip.html>.
- [15] ESA. *Fact Sheet*. In *ESA Science & Technology* [online], 2013. [Accessed 03/20/2013]. Available from: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47364>.
- [16] FLETCHER, K., WITASSE, O. *MARS EXPRESS: The Scientific Investigations*. Noordwijk, Netherlands : ESA Communication Production Office ESTEC, PO Box 299, 2200 AG Noordwijk, Netherlands, 2009. Available from: <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47218>. ISBN 978-92-9221-975-8.
- [17] GURNETT, D. a. et al. Radar soundings of the ionosphere of Mars. *Science (New York, N.Y.)*. December 2005, 310, 5756, pages 1929–33. ISSN 1095-9203. doi: 10.1126/science.1121868. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/16319123>.
- [18] JAUMANN, R. et al. The high-resolution stereo camera (HRSC) experiment on Mars Express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. *Planetary and Space Science*. May 2007, 55, 7-8, pages 928–952. ISSN 00320633. doi:

- 10.1016/j.pss.2006.12.003. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0032063306003448>.
- [19] LOIZEAU, D. et al. Characterization of hydrated silicate-bearing outcrops in Tyrrhena Terra, Mars: Implications to the alteration history of Mars. *Icarus*. May 2012, 219, 1, pages 476–497. ISSN 00191035. doi: 10.1016/j.icarus.2012.03.017. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0019103512001108>.
 - [20] MALTAGLIATI, L. et al. Evidence of water vapor in excess of saturation in the atmosphere of Mars. *Science (New York, N.Y.)*. September 2011, 333, 6051, pages 1868–71. ISSN 1095-9203. doi: 10.1126/science.1207957. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/21960630>.
 - [21] MANGOLD, N. et al. Geomorphic study of fluvial landforms on the northern Valles Marineris plateau, Mars. *Journal of Geophysical Research*. August 2008, 113, E8, pages E08009. ISSN 0148-0227. doi: 10.1029/2007JE002985. Available from: <http://www.agu.org/pubs/crossref/2008/2007JE002985.shtml>.
 - [22] MASSÉ, M. et al. Mineralogical composition, structure, morphology, and geological history of Aram Chaos crater fill on Mars derived from OMEGA Mars Express data. *Journal of Geophysical Research*. December 2008, 113, E12, pages E12006. ISSN 0148-0227. doi: 10.1029/2008JE003131. Available from: <http://www.agu.org/pubs/crossref/2008/2008JE003131.shtml>.
 - [23] MONTMESSIN, F. et al. Hyperspectral imaging of convective CO₂ ice clouds in the equatorial mesosphere of Mars. *Journal of Geophysical Research*. November 2007, 112, E11, pages E11S90. ISSN 0148-0227. doi: 10.1029/2007JE002944. Available from: <http://www.agu.org/pubs/crossref/2007/2007JE002944.shtml>.
 - [24] NEUKUM, G. *Amenthes Planum topography*. In *Space In Images* [online], 2013. [Accessed 03/21/2013]. Available from: http://spaceinimages.esa.int/Images/2013/02/Amenthes_Planum_topography.
 - [25] PERRIER, S. et al. Global distribution of total ozone on Mars from SPICAM/MEX UV measurements. *Journal of Geophysical Research*. 2006, 111, E9, pages E09S06. ISSN 0148-0227. doi: 10.1029/2006JE002681. Available from: <http://www.agu.org/pubs/crossref/2006/2006JE002681.shtml>.
 - [26] PHILLIPS, R. J. et al. Mars north polar deposits: stratigraphy, age, and geodynamical response. *Science (New York, N.Y.)*. May 2008, 320, 5880,

- pages 1182–5. ISSN 1095-9203. doi: 10.1126/science.1157546. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/18483402>.
- [27] WILSON, A. (Ed.). *Mars Express: the scientific payload*. Noordwijk, Netherlands : ESA Publications Division, 2004. Available from: www.esa.int/esapub/sp/sp1240/sp1240web.pdf. ISBN 92-9092-556-6.

List of Tables

List of Abbreviations

Attachments