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ScienceDirect

Advances in Space Research 60 (2017) 2289–2302

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Observations of Phobos by the Mars Express radar MARSIS: Description of the detection techniques and preliminary results

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Received 9 June 2017; received in revised form 7 August 2017; accepted 10 August 2017
Available online 24 August 2017

Abstract

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al., 2005) is a synthetic aperture low frequency radar altimeter, onboard the ESA Mars Express orbiter, launched in June 2003. It is the first and so far the only spaceborne radar that has observed the Martian moon Phobos. Radar echoes were collected on different flyby trajectories. The primary aim of sounding Phobos is to prove the feasibility of deep sounding, into its subsurface.

MARSIS is optimized for deep penetration investigations and is capable of transmitting at four different bands between 1.3 MHz and 5.5 MHz with a 1 MHz bandwidth. Unfortunately the instrument was originally designed to operate exclusively on Mars, assuming that Phobos would not be observed. Following this assumption, a protection mechanism was implemented in the hardware (HW) to maintain a minimum time separation between transmission and reception phases of the radar. This limitation does not have any impact on Mars observation but it prevented the observation of Phobos.

In order to successfully operate the instrument at Phobos, a particular configuration of the MARSIS onboard software (SW) parameters, called “Range Ambiguity,” was implemented to override the HW protection zone, ensuring at the same time a high level of safety of the instrument.

This paper describes the principles of MARSIS onboard processing, and the procedure through which the parameters of the processing software were tuned to observe targets below the minimum distance allowed by hardware.

Some preliminary results of data analysis will be shown, with the support of radar echo simulations. A qualitative comparison between the simulated results and the actual data, does not support the detection of subsurface reflectors.

Keywords: Phobos; Mars; Radar; Mars Express ESA mission; MARSIS; Ground penetrating radar

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1. Introduction

Mars Express, the first European interplanetary mission, was designed to provide global coverage of Mars’ surface, subsurface, atmosphere and to study the Martian moons,

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http://dx.doi.org/10.1016/j.asr.2017.08.013
0273-1177/

Phobos and Deimos (Chicarro et al., 2004). The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al., 2005) is one of the seven scientific instruments onboard of Mars Express orbiter. Its primary goal is to search for water, both solid and liquid, in the subsurface of Mars. MARSIS, in order to penetrate the surface and detect dielectric discontinuities, due to subsurface layers, transmits radio signals characterized by low frequencies and wide band (Picardi et al., 2004).

With the aim to achieve these ambitious scientific goals and in order to cope with some limitation imposed by the mission characteristics, such as the limited data-rate provided by the spacecraft and the limited available downlink data volume, it was necessary to design an instrument with high computational capabilities.

For these reasons, the onboard software is characterized by a high grade of flexibility that allows the possibility to modify the signal processing in order to face unpredictable issues arising during the mission. This capability was very useful when, after several years of Mars observation, Phobos became a scientific objective for MARSIS too (Cicchetti et al., 2011).

Phobos is a non-spherical body with a mean radius of 11 km, and its quasi circular orbit is located on the equatorial plane of Mars. The distance from Phobos to the center of Mars is about 9378 km while the orbital period is 7.65 h.

The origin of Phobos, in spite of 45 years of spacecraft observations, is still debated (Duxbury et al., 2014). The two main hypotheses on the origin of this moon are in situ formation and asteroidal capture. Considering size, shape and past estimations of composition (Burns, 1978; Forget et al., 2008; Murchie et al., 1991), the theory of the asteroidal capture origin was favored by the majority of researchers. However, more recent studies (Andert et al., 2010; Giuranna et al., 2011; Pätzold et al., 2014; Rosenblatt et al., 2010; Witasse et al., 2014) support the conclusion that the composition and bulk density are more consistent with the in situ formation scenario. Thus, the moon is likely to have formed from a disk of impact ejecta produced by a giant collision early in Mars history.

The Martian moon could be observed during several close flybys, thanks to the high eccentricity of the Mars Express orbit (Witasse et al., 2014). The first observation executed with the MARSIS radar, was taken on November 4th 2005 (orbit 2323). The shortest distance between the radar antenna and the Phobos surface was only 215 km, that allowed to obtain a good signal to noise ratio (SNR) of ~25 dB after the on ground data processing. Subsequent flybys allowed observations even within 100 km of the surface (Safaeinili et al., 2009).

In many Phobos flybys observed by the radar so far, we have been able to identify several interesting secondary echoes, that could be generated either by surface lateral clutter or by sub- subsurface reflectors.

In order to discriminate between the two possible origins of detected echoes, an incoherent surface backscattering simulator (Russo et al., 2008) was used.

The simulations, which try to reproduce the radar signal backscattering, use the digital elevation model made available by the High Resolution Stereo Camera (HRSC) science team (Willner et al., 2013), and were computed for one of the closest flybys.

2. Mars observation fundamentals

A typical MARSIS observation of Mars consists of a sequence of synthetic apertures (frames), a Frame being a set of Pulse Repetition Intervals (PRIs) as shown in Figs. 1 and 2.

Each MARSIS observation Frame is made of the following sequence of operations performed onboard:

- Initial orbital parameter estimation, including Frame size estimation (NB, number of PRIs).
- Synthetic aperture size estimation (NA_1 PRIs for the first band, NA_2 PRIs for the second band).
- Signal transmission (2 pulses) and echo reception, repeated NA_1 times and NA_2 times.
- Signal Processing for both the bands.

The frame size NB is computed adaptively during the flyby in order to obtain contiguous synthetic apertures, so that their relative separation precisely matches with the distance covered by the spacecraft, in the time elapsed between the two apertures. This guarantees the continuous coverage along the orbit track.

The space to be covered by the spacecraft during NB pulses, related to a single frame, is computed first as:

$$\Delta S = \sqrt{\frac{\lambda_1 \cdot H}{2}} + N_o \cdot \frac{V_{Tan}}{PRF} \tag{1}$$

where PRF is the Pulse Repetition Frequency (1/PRI = 127.267 Hz), N_o is a constant offset of 36 PRIs, λ_1 is the wavelength of the lowest Operative Frequency in use (available center frequencies are 5 MHz, 4 MHz, 3 MHz and 1.8 MHz), H and V_{Tan} are the spacecraft altitude and the tangential velocity respectively.

Frame size NB is then computed as:

$$NB = Int\left[\frac{\Delta S}{V_{Tan}} \cdot PRF\right] \tag{2}$$

Synthetic aperture sizes NA_1 and NA_2 are also adaptively computed for each of the operative frequencies in use:

$$NA_1 = Int\left[\lambda_1 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_1 \cdot V_{Tan} \cdot \Delta S}\right] \tag{3}$$

$$NA_2 = Int\left[\lambda_2 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_2 \cdot V_{Tan} \cdot \Delta S}\right] \tag{4}$$

where γ_1 and γ_2 are corrective frequency dependent values, necessary to obtain the same azimuth resolution in different bandwidths.