MARSIS EXPERIMENT: DESIGN AND OPERATIONS OVERVIEW

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ABSTRACT

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) is a radio frequency subsurface radar sounder designed to operate on the international Mars Express mission, an ESA program for the orbital and in-situ study of the subsurface, surface, ionosphere and atmosphere of the planet Mars. The Mars Express Orbiter spacecraft is developed operated and fully funded by ESA with the exception of the seven payload scientific instruments which will be used for remote observation of the red planet. According to the current ASI/NASA agreement the MARSIS instrument has an Italian PI, an U.S. Co-PI, and Co-I's from the Italy, the U.S. and other countries. There is also an U.S. Experiment Manager and an Italian Deputy Experiment Manager.

Keywords: Mars, Marsis, Mars Express, Radar Sounding, Planetary missions

INTRODUCTION

The set of scientific objectives for the MARSIS investigation was defined [Picardi et. al,1998)] in the context of the objectives of the Mars Express Mission and in the more general frame of the current open issues in the study of Mars. The MARSIS primary objective is to map the distribution of water, both liquid and solid, in the upper portions of the crust of Mars.

Detection of such reservoirs of water will address key issues in the hydrologic, geologic, climatic and possible biologic evolution of Mars, including the current and past global inventory of water, mechanisms of transport and storage of water, the role of liquid water and ice in shaping the landscape of Mars, the stability of liquid water and ice at the surface as an indication of climatic conditions and the implications of the hydrologic history for the evolution of possible Martian ecosystems [Carr, (1996)].

Three secondary objectives are defined for the MARSIS experiment: subsurface geologic probing, surface characterization, and ionosphere sounding.

The first is to probe the subsurface of Mars, to characterize and map geologic units and structures in the third dimension. The additional secondary objective is to acquire information about the surface of Mars.

The specific goals of this part of the experiment are to characterize the roughness of the surface at scales of tens of meters to kilometers, to measure the radar reflection coefficient of the upper surface layer, and to generate a topographic map of the surface at approximately ten kilometers lateral resolution

A final secondary objective is to use the MARSIS as an ionosphere sounder to characterize the interactions of the solar wind with the ionosphere and upper atmosphere of Mars. Radar studies of the ionosphere will allow global measurements of the ionosphere electron density and investigation of the influence of the Sun and the solar wind on the electron density.

Due to the mission characteristics and the available data rate most of the data processing will be done on-board. In particular the digital processing is in charge of the following major task: range compression, Surface echo Acquisition/Tracking, Coherent echo processing (Synthetic Aperture) and multi looking.

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Ground processing will extract from the downlinked profiles significant information on the surface topography and composition, as well as on the location and possibly the dielectric properties of subsurface discontinuities.

MARSIS OPERATION REQUIREMENTS

According to the current baseline design for Mars Express the orbit will have distance at periapsis of 250 km, distance at apoapsis of 10142 km, inclination of 86,35° and orbital period of 6,75 h.

During normal operations, MARSIS may operate in one of the following four operation modes:

- Calibration
- Subsurface Sounding
- Active Ionosphere Sounding
- Receive Only.

Subsurface Sounding Mode is intended to obtain sounder data about the subsurface of Mars and the *Ionospheric Sounding Mode* is intended to obtain information about the ionosphere of Mars. *Subsurface Sounding Mode* is further subdivided into five separate sub-modes (SS1÷SS5). *Calibration Mode* is intended to obtain calibration information about the system. *Receive Only Mode* is intended mainly to measure and characterize, from the EM point of view, the environment in which MARSIS will work.

MARSIS has been designed to perform *Subsurface Sounding* at each orbit when the altitude is lower than about 800 Km. A highly eccentric orbit such as the baseline orbit places the spacecraft within 800 km from the surface for a period of about 26 minutes. This would allow mapping of about 100 degrees of arc on the surface of Mars each orbit, allowing extensive coverage at all latitudes within the nominal mission duration. To achieve this global coverage MARSIS has been designed to support both dayside and nightside operations, although performances are maximized during night time (solar zenith angle >80°), when the ionosphere plasma frequency drops off significantly and the lower frequency bands, which have greater penetration capability, can be used.

Active Ionospheric Sounding will be also carried out by MARSIS at certain passes when the orbiter is at an altitude up to 1200 Km both during day and night time.

MARSIS will be in *Calibration Mode* periodically during the operation phase of the mission. The purpose of this mode is to acquire a limited amount of data in an unprocessed format. This data can be acquired separately in the calibration mode or include even more limited quantities of data along with the processed data set for transmission to the ground. This operation is basically an adaptive matched filter computation which will then be used by the processor to compress the dispersed echo from the surface and subsurface.

Calibration Mode will be done after ground processing of the raw data collected during the calibration mode and the computed matched filter parameters uploaded to MARSIS. The basic characteristics of each Operation Mode are reported in Table 1.

Mode	Operating Frequencies	Pre-Summing	Monopole Channel	Doppler Filters per Channel	Data Rate kbps	Comments
SS1	2	N	Y	1	40	Complex Data on Ground
SS2	2	N	N	5	26	Power Detected Data
SS3	1	N	Y	1	16	Multilooking on board
SS4	1	N	Y	5	80	Complex Data on Ground
SS5	1	Y	Y	1	26	Four Short Pulses pre-summed
AIS	160	N/A	N	N/A	30	Power Detected Data
CAL	1 or 2	N/A	Y	N/A	30	Raw Data from two channels
RECEIV:	1 or 2	N/A	Y	N/A	30	Raw Data from two channels

Table 1: Operation Modes Description

EXPERIMENT DESCRIPTION

Subsurface Sounding

The basic principle of operation of the radar sounder is explained in Figure 1. The electromagnetic wave transmitted by the antenna impinges on the top of the Mars surface producing a first reflection echo which propagates backward to the radar, generating a strong return signal received at time $t_0=2H/c$, being H the spacecraft height and c the speed of light in vacuum. However, thanks to the long wavelengths employed, a significant fraction of the EM. energy impinging on the surface is transmitted into the crust and propagates downward with a decreased velocity $v=c/n$ (being n the crust refraction index related to the real dielectric constant ε_r by $n=\sqrt{\varepsilon_r}$) and an attenuation proportional to the penetration depth (z), to the wavelength (λ) and to the material loss tangent (*tan* δ, defined as the ratio of the imaginary part to the real part of the complex dielectric constant $\tan\ \delta=\varepsilon_i/\varepsilon_r$). Should subsurface dielectric discontinuities be present at depth z_0 below the surface, additional reflections would occur and the relevant echoes would propagate backward through the first layer medium and then to the radar generating further echo signals, much weaker than the front surface signal, with time delay $t_0+2\ z_0/v$. As consequence time domain analysis of the strong surface return, eventually after multi-look non-coherent integration, will allow estimation of surface roughness, reflectivity and mean distance, just like in classical pulse limited surface radar altimeters. Moreover the presence of weaker signals after the first strong surface return will enable the detection of subsurface interfaces, while the estimation of their time delay from the first surface signal will allow the measurement of the depth of the detected interfaces [Porcello et. al, (1974); Picardi, Seu and Sorge, (1998)].

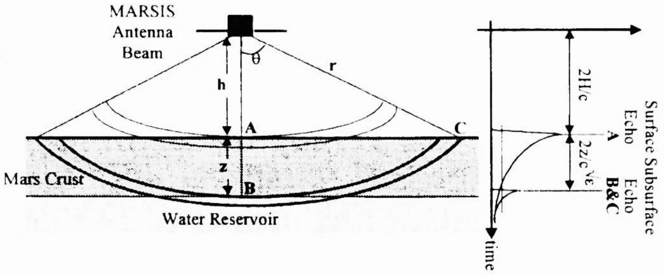

Figure 1: MARSIS Principle of Operation

The detection performance will be limited by two main factors, namely the surface clutter echoes and the noise floor entering the receiver [Picardi, Seu and Sorge, (1998)]. The surface clutter echoes are originated by reflections from those surface areas (marked C in Figure 1) which have two-way propagation path delay identical to the one of useful subsurface signal (point marked B in Figure 1). While this is not a problem for perfectly flat surfaces - since the angular backscattering law would impose a very high attenuation on such lateral reflections - most natural surfaces are not at all flat and surface clutter echoes can be very strong in practical situations; as a direct consequence, when the competing subsurface echoes are highly attenuated by the propagation into the crust, the surface clutter echoes may happen to mask the useful signal and limit the detection performance [Picardi et. al.,(1999)]. Furthermore, even when the surface clutter power is lower than the competing subsurface echo, the detection performance can be limited by the noise floor of the receiver. Such noise can be very high at the low frequencies commonly used for radar sounding due to the contribution of the cosmic noise temperature entering the receiver which is many order of magnitudes higher than receiver internal noise, for typical noise figures of 3-4 dB, and frequencies in the range 1-10 MHz [Picardi et. al, (1999)].

In standard sub-surface sounding operative mode MARSIS will be able to transmit and receive any of the following bands: 1.3-2.3 MHz (centered at 1.8 MHz), 2.5-3.5 MHz (centered at 3 MHz), 3.5-4.5 MHz (centered at 4 MHz), 4.5-5.5 MHz (centered at 5 MHz). The instantaneous bandwidth will be 1 MHz for all the frequency bands, and the transmitted waveform will be a pseudo-linear frequency modulated pulse (chirp). Since on the dayside of Mars the ionosphere will not allow the use of frequencies < ~3 MHz, only the two higher frequency bands (4 MHz and 5 MHz) will be used for surface/subsurface sounding during day time. However the best penetration capabilities will be obtained during night time observation, when also the longest wavelengths can be used.

Transmitted pulses will be radiated through a 40 m thin dipole mounted parallel to the surface and normal to the direction of motion, fed by a matching network which has the purpose of flattening the antenna frequency response over the full 1.3-5.5 MHz range. The reflected echoes will be received both from the primary dipole antenna and from a secondary receiving antenna, namely a short monopole mounted vertically aligned with the nadir axis which features a null in the nadir direction and thus records off-nadir surface echoes alone. Received echoes on both channels are converted to a small offset frequency and digitized for on-board processing and later downlink. Since the data rate of digitized samples would in the order of few Mbit/s strong data reduction has to be performed on-board to comply with the limits of data rate and volume of the Mars Express orbiter.

The on-board processor, which features adaptive range compression, azimuth compression and multi-look non-coherent integration, depending on the operative modes, performs data reduction. The obtained modes dependent Data Rate will be in the range 16÷80 kbps.

The *range compression* will allow a range resolution equivalent to *150 m* in vacuum and waveform sidelobes controlled to fulfil a system dynamic range in excess of 50 dB. *Azimuth compression* will be performed by coherent unfocused Doppler processing, to reduce along track surface clutter and noise power; the along track resolution after azimuth compression will be sharpened to values between *5-9 Km*, depending on the altitude. Cross track surface clutter reduction by dipole/monopole signals combination will be performed during ground processing, provided that complex data are downlinked to Earth. Non coherent average with multiple Doppler filters (looks) can be also performed before downlink, to reduce statistical fluctuations of the final profiles. Finally, echo profiles collected at different frequencies can be processed to enhance the discrimination of subsurface reflections, which are strongly dependent on the frequency, from the surface reflections, which are mostly frequency independent.

During ground data processing, downlinked data will be analysed for time delay to subsurface reflector(s), intensity of subsurface reflection(s), and a measure of "confidence" that a subsurface interface was detected. These parameters will be incorporated into a global map database, to allow interpretation of local and regional behaviour. Detailed analysis will be conducted for regions of interest. This will include modelling of the electrical properties of the layers and interfaces. The modelling will result in estimates of thickness of layers, depth to interfaces, dielectric properties of the materials, and an interpretation of the properties of the materials, including composition. It is anticipated that the abrupt dielectric contrasts that should exist at a Martian water table would allow an unambiguous identification of liquid water. If small (~10s of km in lateral extent) aquifers are present, the resolution and processing scheme of the MARSIS should allow their detection, unlike other systems that may require extensive, uniform layer and interface conditions. Boundaries involving the presence and absence of ground ice will be more difficult to distinguish, but regional trends (with latitude and elevation) should allow discrimination of ground ice boundaries.

Ionospheric Sounding

Ionospheric measurements will be also carried out with Marsis either with passive technique (to measure the plasma electron density close to the antenna in very accurate way) or with active technique (to obtain full electron density profiles of the topside ionospheric layer).

In the Active Ionosphere Sounding Mode MARSIS will transmit a stepped sequence of sinusoidal tones (91.43μs of pulse length) at frequency between 0.1 and 5.588 MHz and a step size (in frequency) of 10.937 kHz or its multipliers.

A total of 160 pulses will be transmitted for each sweep and the total duration of the sweep will be 1.23 seconds. The repetition interval of the sweep will be 7.38 seconds. As a consequence the plasma frequency distribution will be mapped with a vertical resolution of 15 Km, a spatial sampling step of about 30 km and a frequency granularity of 10.937 kHz.

At least two modes of operation are planned; continuous and interleaved. The continuous mode of operation would provide a contiguous series of ionospheric sounding sweeps, thereby providing the highest possible horizontal resolution. Since such a contiguous series of sweeps would not leave any time for subsurface soundings, this mode of operation would be used relatively infrequently, perhaps once ever ten orbits. The more frequently used mode of operation will be to interleave the subsurface soundings with the ionospheric soundings in some regular pattern. Interleaved subsurface/ionospheric soundings will be particularly useful if ionospheric electron density information is needed to interpret or optimize the subsurface soundings.

INSTRUMENT DESCRIPTION

Functionally and also from the responsibility point of view of each organization involved in MARSIS, the instrument can be split into three subsystems:

Antenna (ANT) including both the primary Dipole antenna for transmission and reception of the sounder pulses and the secondary monopole antenna for surface clutter echoes reception only,

Radio Frequency Subsystem (RFS) including both the TX channel and the two RX channels for the dipole and monopole antenna respectively,

Digital Electronics Subsystem (DES) including the signal generator, timing and control unit and the processing unit

Anyway it is worth considering that from the *mechanical point of view* DES and RX Section of RFS subsystem are allocated in the same box inside the S/C (SISD)

Inside the S/C is also allocated the mechanical box for the TX electronics housing (SIST). The Dipole Antenna, element 1 and 2, and Monopole antenna are allocated outside the S/C.

The physical hierarchical configuration is shown in Figure 2

In nominal Subsurface Sounding operations MARSIS will transmit in rapid sequence up to four quasi-simultaneous pulses at maximum two different frequencies, selected among the four available frequency bands, and will receive the corresponding echoes both on the Dipole and on the

Monopole (depending from the selected sub-mode). The whole TX/RX cycle is repeated at a rate fixed by the system Pulse Repetition Frequency (PRF). The selection of the PRF is an important issue in the definition of the MARSIS timing scheme, because being the antenna pattern practically isotropic in the along track direction, spectral aliasing of surface clutter echoes could occur if the Doppler bandwidth is under sampled. In addition taking into account, that a folding localized into far range cells can be accepted at the highest frequency bands (due to unlikely penetration to the corresponding depths) a fixed *PRF of 130 Hz* has been selected as baseline for Subsurface Sounding. This selection is justified by the fact that the risk of folding in useful range cells seems to be very small while the implementation burden should be significantly reduced.

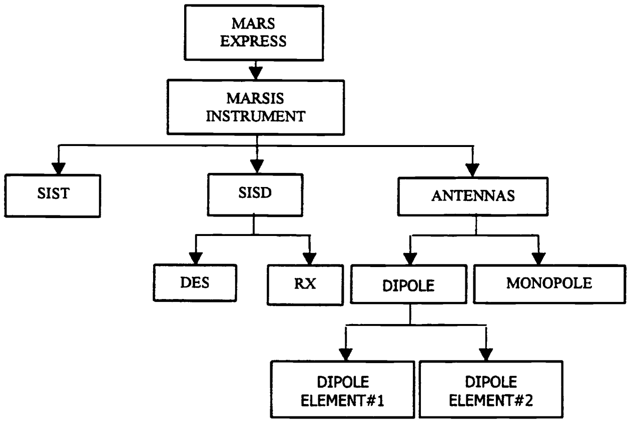

Figure 2: MARSIS hierarchical configuration

The typical MARSIS timing scheme (in SS1 and SS2 sub-modes), with such PRF selection, is depicted in Figure 3.

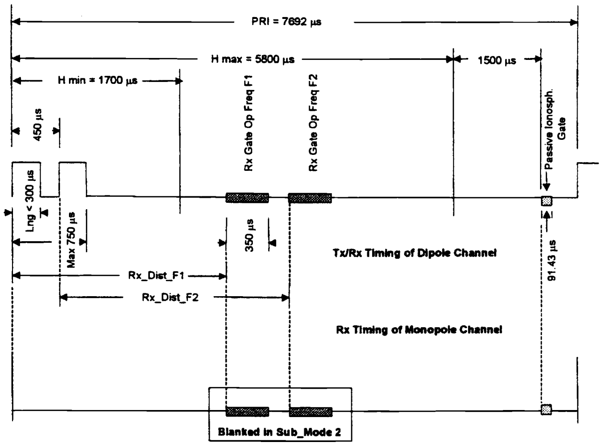

Figure 3: MARSIS Typical Timing Scheme

MARSIS transmitter will radiate through the main dipole antenna up to four chirps of nominal duration of *250 μs* waiting for approx. 200 μs between any two consecutive chirps. Two different center frequencies can be assigned to the TX pulses, selectable among the four operative frequency bands. After transmission is completed MARSIS turns into receive mode and the receiver records the signals received from both dipole and monopole channels for each transmitted pulse. The duration of the receiving window will be *350 μs*, allowing to accommodate an echo dispersion of about 100 μs, which corresponds to *about 5-8 Km of penetration*, depending on the propagation velocity in the crust. Upon reception, echoes will be down-converted and digitized to a format suitable for the on-board processor. Four processing channels are implemented, allowing to process two frequency bands received from dipole and monopole at each PRI. The digitized echo stream is processed by the on-board digital electronics subsystem (DES) in order to reduce the data rate and data volume and allow global mapping of the observed scene within the allocated amount of S/C mass memory.

Starting from the desired along track sampling rate of the surface the basic azimuth repetition interval is identified and all the pulses received within such interval (frame) are processed to yield a single echo profile referring to one azimuth location. Range compression will be performed on each pulse by classical matched filtering approach, although adaptive techniques will have to be implemented to update the matched filter reference function at each frame in order to correct for the time variant phase distortions introduced by the ionosphere propagation. The information needed for this adaptive filtering will be estimated by a dedicated processing of the initial pulses of each frame, and will then be used for all the remaining pulses of the same frame, thus assuming the fluctuations rate of the distortion slower than the frame duration. Thanks to the correct sampling of the surface and subsurface Doppler spectra, coherent integration of the range compressed echoes within each frame will be possible, enhancing the spatial resolution in the along track direction and linearly reducing the cosmic noise level. In order to simplify the HW and SW implementation, the unfocused Doppler processing has been performed entailing an *azimuth resolution of 5000* m at altitudes lower than 300 Km, increasing to *9000 m* at higher altitudes. Coherent integration will be performed using a fixed number of phase correction functions, thus synthesizing a bank of parallel Doppler filters around the zero Doppler point (or the Doppler centroid). However, since the small amount of computational and memory resources available in the processor limits the number of Doppler filters that can be synthesized to about five filters, the position and usage of these Doppler filters shall be optimized taking into account the behaviour of the observed surface. Specifically, in case of a flat surface specular scattering will be dominant and the greatest portion of the

	Units	BAND I		BAND II		BAND III		BAND IV	
Central Frequency (f_0)	*MHz*	1.8		3		4		5	
Wavelength (λ)	*m*	166.7		100		75		60	
Bandwidth (B_w)	*MHz*	1 (shaped by Hanning weighting)							
Range Resolution	*m*	150 (x 1.5 after weighting → 225)							
Depth Resolution (average ε_r=4)	*m*	75 (112.5 after weighting)							
Transmitted Chirp Duration	*μs*	250							
Receiving Window	*μs*	350							
Range FFT complex points	-	512							
Useful (compressed) range bins	-	140							
Orbital Altitude	***Km***	**250**	**800**	**250**	**800**	**250**	**800**	**250**	**800**
Tangential velocity in orbit (V_0)	*m/s*	4200	3800	4200	3800	4200	3800	4200	3800
Unfocused Resolution ($R_{az,un}$)	*Km*	4.56	8.16	3.53	6.32	3.06	5.47	2.74	4.89
Selected Resolution (R_{AZ})	*Km*	5	9	5	9	5	9	5	9
Synthetic Aperture Length (L_s)	*Km*	4.16	7.4	2.5	4.44	1.85	3.33	1.5	2.67
Azimuth Repetition Interval (T_V)	*sec*	1.19	2.37	1.19	2.37	1.19	2.37	1.19	2.37
Integration Time (T_I)	*sec*	1	1.95	0.59	1.17	0.44	0.88	0.36	0.70
Idle Time (T_V-T_I)	*sec*	0.19	0.42	0.60	1.20	0.75	1.49	0.83	1.87
PRF	*Hz*	130							
Number of integrated Pulses (N_{AZ})	-	130	254	76	151	57	113	46	91
Number of used Doppler Filters	-	5							

Tab. 2: Main design parameters (for Subsurface Sounding mode)

echo power will fall into the single Doppler filter that contains the point of specular reflection (the central Doppler filter in case of a non-tilted surface), leaving mostly noise to the lateral Doppler filters. In such condition it is clear that the best choice would be to use that single Doppler filter, eventually located by a Doppler tracking algorithm and discard the others. On the contrary in the case of a rough layer non coherent scattering will be dominant and the signal power would be distributed over several Doppler filters, so that it is worth to average echoes from the same 7 zone processed by different Doppler filters to improve SNR and reduce statistical fluctuations (speckle).
The table 3 below summarises the MARSIS main baseline parameters, as results from the previous description.

CONCLUSIONS

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) will fly aboard the European Space Agency Mars Express orbiter, planned to be launched in 2003, to perform subsurface, surface and Ionosphere soundings on a global scale at Mars. In this paper we have described the main features of the radar sounder. Based upon models of the Martian crust composition and geometric structure [(Picardi et. al, (1999)], *the estimated instrument performance are expected to allow the investigation of Mars Subsurface up to 8 km of depth under the Martian crust.*

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