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The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS): concept and performance

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Abstract – The paper deals with the description of the key features and expected performance of a new radar sounder instrument currently under development by a team of Italian and US researchers and industrial partners, selected to fly with the ESA Mars Express orbiter scheduled for launch to Mars late in 2003. Very low transmitted frequency (1-5 MHz), large instantaneous bandwidth and coherent on-board processing techniques will make it possible to acquire a large amount of science-relevant data about the Mars interior, surface and atmosphere ensuring global coverage at all latitudes while respecting the Mars Express mission constraints.

I – INTRODUCTION

The subsurface exploration of the upper portion of the Martian crust has been clearly indicated as a high priority objective towards the comprehension of many key issues in Mars science including the Mars water/ice inventory [1], which is directly related to the possibility that life could have been present in some form on Mars during past ages.

Reliable detection of subsurface interfaces can be obtained using the properties of low frequency electromagnetic waves to penetrate into a dielectric medium, while subsurface layer thickness mapping can be effectively achieved using a pulsed radar system; hence, a low frequency radar system carried on a spacecraft orbiting around Mars represents the most effective way to address the above mentioned objectives, ensuring at the same time the widest possible coverage [2].

The ESA Mars Express orbiter, scheduled for launch in 2003, will be inserted into a high elliptic orbit around Mars with distance at periapsis of about 250 Km, distance at apoapsis of about 10.142 Km and inclination of 86,35°, allowing substantial coverage at all latitudes within the nominal mission duration. On-board the Mars Express orbiter will be carried a long wavelength nadir-looking radar instrument with ground penetration capabilities, able to perform subsurface sounding of the Martian crust down to presumably ice/water/permafrost containing layers, as well as standard large scale surface altimetry and Ionosphere soundings [3] [4]. Such instrument has been called Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), and is now under development by a team of international partners led by Italy and USA, with funding provided in equal parts by the Italian Space Agency (ASI) and the National Aeronautics and Space Administration (NASA).

II – MARSIS INSTRUMENT DESCRIPTION

Since in general low frequencies lead to better penetration capabilities but also to higher hardware complexity (long dipole antennas, high fractional bandwidth), the selection of the sounding frequencies must be carefully performed taking into account the available resources in terms of instrument mass and power consumption and reasonable electromagnetic models of the planet crust from which the absorption and scattering at the different frequencies can be evaluated. In addition, sounding at Mars will be further complicated by the presence of the Ionosphere, which will prevent from propagation the lowest frequencies, specially during dayside operations, and will induce strong dispersion effects on the spectrum of the propagating signals.

Specific studies concerning the modeling of the martian crust, surface structure and Ionosphere [3], recommended that the best selection of frequencies for a radar sounder at Mars be in the range 1-5 MHz, the lowest frequencies corresponding to the highest penetration depths. Following

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these recommendations, the MARSIS has been designed to operate in multi-band modality covering the entire frequency range between 1.3-5.3 MHz.

In the subsurface sounding mode the transmitter will allow up to three 1-MHz chirps to be interleaved on a single channel with a repetition rate of about 100-500 Hz and a duty cycle of about 30%, while in Ionosphere sounding mode the transmitter will step through the 0.8-5.3MHz range transmitting 20 KHz chirps with a repetition rate of 125 Hz. The transmitted signals under different sun illumination conditions are summarized in Tab.1.

Transmitted pulses will be radiated through the MARSIS main antenna, 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 1.3-5.3MHz range. A secondary receiving antenna, namely a short monopole mounted vertically aligned with the nadir axis, is also included, featuring a null in the nadir direction, in order to receive off-nadir surface echoes alone and help the separation of concurrent surface/subsurface echoes [5].

Received echoes on both channels are converted to a small offset frequency and digitized for on-board processing and later downlink. The on-board processor features adaptive range compression to obtain the required range resolution and remove hardware and ionosphere induced distortions and coherent (unfocused) Doppler processing to reduce along track surface clutter and to improve along track resolution and noise rejection. Cross track surface clutter reduction by dipole/monopole echoes combination can be performed either during on-board processing or during ground processing, provided that complex data are downlinked to Earth. In the former case non coherent integration of multiple Doppler filters (looks) can be also performed before downlink, to reduce statistical fluctuations of the final profiles.

Thanks to its unique design, MARSIS will operate in a continuous mode at all available opportunities when the Mars Express spacecraft will be within 800 km of distance from Mars. During each orbital pass, a swath of echo profiles will be gathered with a footprint size at the surface of approximately 5 by 10 km, and a footprint spacing along-track of 5 km. After about 2000 non-repeating orbits, the swaths result in full global coverage, contiguous at the equator and with substantial overlap at higher latitudes. The Martian crust will be sensed down to several kilometers, and over a wide range of different surface dielectric and topographic conditions. Subsurface dielectric interfaces will be detected and located in three dimensions with high vertical resolution (50-100 m) and few kilometers horizontal resolution. The multi frequency observation will be used to estimate the crust attenuation and to simplify the interpretation of the dielectric composition of the detected interfaces. The scientific analysis of MARSIS data products will make available to the scientific community a large amount of new and extremely interesting data, including three-dimensional maps of subsurface dielectric interfaces which will allow us to map the presence of water bodies in the upper layers of the Martian crust. Surface height, reflectivity and roughness maps at wavelengths never experienced before will be also made available by MARSIS altimetric data products processing; finally the Ionosphere sounding mode will allow the extraction of accurate profiles of the electron density in the Martian Ionosphere, which is to date not well understood, especially on the night side. These ionospheric measurements are important not only for the study of the ionosphere, but also to aid in the interpretation of the subsurface and surface data.

III -EXPECTED PERFORMANCE

III-1 Maximum Dynamic Range

The MARSIS dynamic range after processing and on a single-look basis can be evaluated taking the ratio between the maximum expected power from the surface and the background cosmic noise level [4]:

$$\frac{S}{N}=\frac{P_p G^2 \lambda^3 \Gamma(0)}{128\pi^2 H K T_N L R_{AZ}} D.C. \qquad (1)$$

being P_p the peak transmitted power, G the antenna gain, Γ_0 the Fresnel reflectivity of the surface, H the altitude, K the Boltzmann constant, T_N the cosmic noise temperature, L the antennas and propagation losses, R_{AZ} the azimuth resolution, and D.C. the TX duty cycle. The backscattering cross section of a perfectly specular surface has been assumed, namely $\sigma=\Gamma(0)\pi H^2$. Equation (1) is reported in Tab.2 at the two frequencies of 1.8 and 4.8 MHz, which correspond to the lowest and highest bands used for subsurface sounding. As clearly seen in the table a dynamic range in excess of 50 dB is available in the full frequency range for subsurface sounding.

III-2 Crust Absorption and Reflection coefficients

In order to give a quantitative estimation of the Martian crust absorption, simple two-layers crust model have been considered [3] [4]. According to these models the Martian Crust is formed by a porous rocky regolith; andesite and basalt have been assumed as end-member representatives of the dielectric properties of the materials present in such regolith (see Tab.3). The pores in the regolith are the reservoir where H_2O can be stored either as ice or liquid water depending on the crust thermal properties, the geothermal flux and the average surface temperature. The porosity of the rock layer is maximum at the surface (ranging from 20-50%) and its decay with the depth can be assumed $\phi(z)=\phi(0)*Exp(-z/K)$ $(K=2.82\ Km)$. Any abrupt change in pore-filling material will create a subsurface dielectric discontinuity which will reflect the propagating radar pulse. Two kinds of interfaces appear to be most meaningful to consider for Mars crust modeling Ice/Water interfaces and

Dry/Ice interfaces. Given these simplified models the reflection coefficients at the surface and at the interface (including the absorption) can be determined:

$$\Gamma_s = \left|\frac{1-\sqrt{\varepsilon_{r1}(0)}}{1+\sqrt{\varepsilon_{r1}(0)}}\right|^2 \qquad (1)$$

$$\Gamma_{ss,z} = \left|\frac{\sqrt{\varepsilon_{r1}(z)}-\sqrt{\varepsilon_{r2}(z)}}{\sqrt{\varepsilon_{r1}(z)}+\sqrt{\varepsilon_{r2}(z)}}\right|^2 (1-\Gamma_s)^2 10^{-0.1\int_0^z \alpha(\varsigma)d\varsigma} \qquad (2)$$

being $\varepsilon_{r1}(z)$ and $\varepsilon_{r2}(z)$ the real dielectric constant of the first and second layer evaluated at depth z and $\alpha(\zeta)$ the two-way absorption per unit depth, given by [4]:

$$\alpha_{dB}(\varsigma) = 1.8\cdot 10^{-7} f_0\sqrt{\varepsilon}\tan\delta \quad \text{(dB/m)} \qquad (3)$$

The dielectric constants of the first and second layer are modeled starting from the dielectric constants of the basic elements of Tab.3 and the exponential law for the porosity decay with depth, and using the Maxwell Garnett mixing formula for biphase mixtures [4].

III-3 Back-Scattering Evaluation

The Martian surface geometric structure has been modeled [3] [4] [6] with a two-scale model applied to a gaussian spectrum surface, one component (related to the large scale topography) being governed by the Kirchhoff mechanism and the other (related to the small scale height variations) governed by the Bragg mechanism (Small Perturbation Method). Based on data set presented in the literature the roughness parameters for the surface have been assumed as in Tab.4. Closed form expressions of both contributions have been derived and are described in [4]. From the performed analysis it results that the backscattering cross section of the surface or subsurface layer may be reduced of as much as ~15 dB with respect to the maximum (perfectly specular) surface cross section, in case of high RMS slopes. Furthermore off-nadir surface clutter fall off with a rate strongly dependent on the surface RMS slope [4] [6], as shown in Fig.1, where the surface scattering level is reported as function of the depth of the iso-range subsurface return.

III-4 Penetration Depth Evaluation

In Fig. 1 there are reported the envelope of the expected surface and subsurface returns at the various frequency bands used by MARSIS, according to the models described above. Subsurface returns attenuation curves are shown for ice/water interfaces as function of the RMS slope of the interface layer and in the two extreme conditions of (i) best case attenuation (andesite regolith with 50% surface porosity) and (ii) worst case attenuation (basalt regolith with 20% surface porosity).

The effect of the along track and cross track surface reduction techniques under typical operative conditions [5] is further reported in Fig.2. All the levels are shown normalized to the maximum expected surface return. According to the previous discussion subsurface echoes will be detectable at a certain depth if two conditions are simultaneously met:

(i) the total subsurface attenuation (given by the reflection coefficient, absorption and scattering loss) does not exceed the available dynamic range (see §III.1):

(ii) the subsurface level is higher than the competing surface clutter level

Based on these criteria the conclusions on the penetration depth reported in Tab.5 can be derived. As easily seen when sounding upon flat areas with low RMS slopes the penetration depth will be primarily limited by the noise level, whereas when sounding upon rough areas with high RMS slopes the limiting factor will be the surface clutter residual, after cancellation [6].

CONCLUSIONS

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) will fly aboard the European Space Agency Mars Express orbiter, launching in 2003, to perform subsurface, surface and Ionosphere soundings on a global scale at Mars. We have briefly described the main features of the radar sounder and have shown the expected penetration performance according to simplified models of the martian crust composition and geometric structure.

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Tab. 1: Transmitted Signal under different conditions

	DAYSIDE	NIGHTSIDE
SUBSURF. #1	3.3-4.3 MHz chirp	1.3-2.3 MHz chirp
SUBSURF. #2	4.3-5.3 MHz chirp	2.3-3.3 MHz chirp
SUBSURF. #3	N/A	3.3-4.3 MHz / 4.3-5.3 MHz chirps
IONOSPH.	0.8-5.3 MHz stepped chirp (20 KHz steps)	

Tab. 2: Maximum dynamic range evaluation (SNR equation)

MARSIS DYNAMIC RANGE EVALUATION				
	H=300 km	H=800 km	H=300 km	H=800 km
	λ=166.7 m (1.8 MHz)		λ=62.5 m (4.8 MHz)	
	dB	dB	dB	dB
P_D(12W)	11	11	11	11
G^2	0	0	0	0
λ^3	67	67	54	54
$\Gamma(0)$	-7	-7	-7	-7
$128\pi^2$	-31	-31	-31	-31
H	-55	-59	-55	-59
K	228	228	228	228
T_c=TFL	-78	-78	-66	-66
V_0	-35	-35	-35	-35
R_{AZ}	-37	-37	-37	-37
DC(0.3)	-5	-5	-5	-5
S/N	58	54	57	53

Tab. 3: Dielectric constant and loss tangent of crust materials

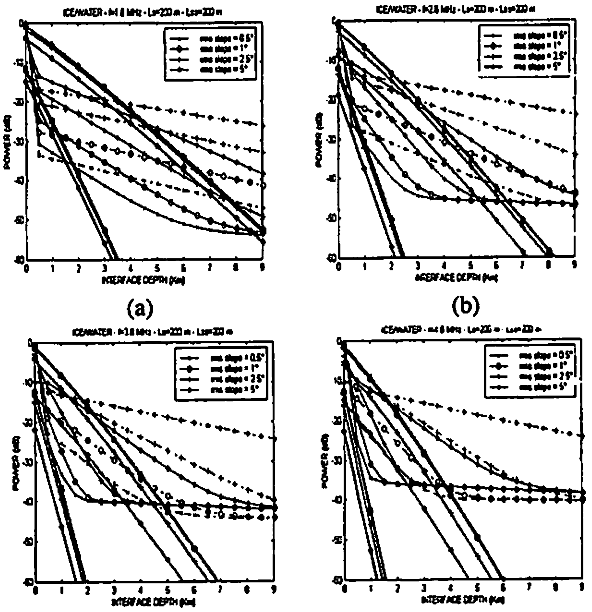
	HOST MATERIAL		PORE-FILLING MATERIAL	
	Andesite	Basalt	Ice	Water
ε_r	3.5	*7.1*	*3.15*	88
Tan δ	*0.005*	*0.014*	*0.00022*	*0.0001*

Tab. 4: Statistical parameters of the Mars surface

LARGE SCALE MODEL		SMALL SCALE MODEL	
RMS slope	Corr. Length	RMS Slope	RMS height
0.01-0.1rad. *(0.57°-5.7°)*	*200–30000m*	*0.1 – 0.6 rad.* *(5.7° - 34.3°)*	*0.1 – 1 m*

Tab. 5: Summary of Ice/Water interface sounding depth (Km)

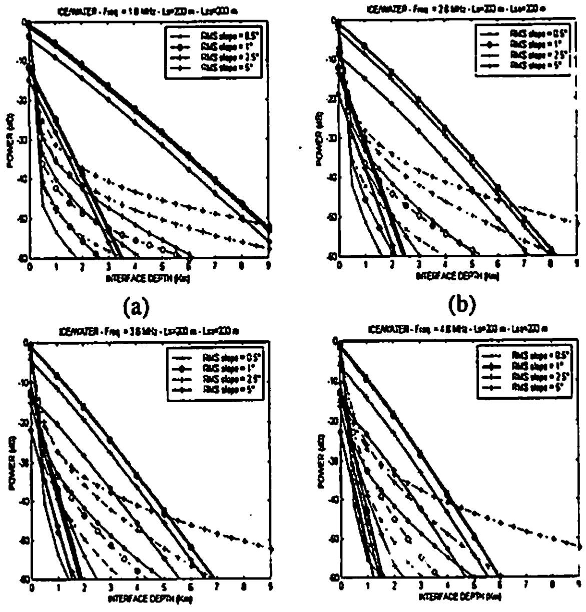
PENETRATION DEPTH SUMMARY (Km) - H=800 Km				
SURFACE	**rough (5° RMS slope)**		**smooth (1° RMS slope)**	
Absorption	**best case**	**worst case**	**best case**	**worst case**
BAND #1	*8*	*1.5*	*8*	*3*
BAND #2	*5*	*0.5*	*7*	*1*
BAND #3	*3.5*	*0*	*6*	*0.5*
BAND #4	*2.5*	*0*	*5*	*0*



(a) (b)

(c) (d)

Fig. 1: Surface (thin lines) and Ice/Water interface (thick lines) power levels normalized to $\Gamma_0\pi H^2$ at 300 Km (-) and 800 Km (-..) altitude. Surface and Interface correlation length is 200 m. Frequencies are (a) 1.8 MHz (b) 2.8 MHz (c) 3.8 MHz and (d) 4.8 MHz.



(a) (b)

(c) (d)

Fig. 2: The same curves of Fig.1 are shown after coherent clutter cancellation (Doppler Filtering + Dual Channel Cancellation).