Comparison between MARSIS & SHARAD Results

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***Abstract*—MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) is a low frequency nadir looking sounding radar selected by ESA as a payload of the Mars Express mission, whose primary Scientific Objective is to map the distribution of water both solid and liquid, at global scale on the Martin crust. MARSIS is the first instrument to be able to detect what lies beneath the surface of Mars (up to about 5Km). MARSIS operates with a very high fractional bandwidth: 1MHz bandwidth allows a vertical resolution of 150m in vacuum which corresponds to 50-100m in the subsurface, depending on the electromagnetic wave propagation speed in the crust. The center frequency of the pulses transmitted by MARSIS can be set to 1.8MHz, 3MHz, 4 MHz and 5MHz. On day side operations, it operates only in 4MHz and 5MHz due to the ionosphere plasma frequencies of Mars cutting of all frequencies lower than 3MHz. All the four carrier frequencies are available for subsurface sounding on night side. The Mars Shallow Radar Sounder (SHARAD), a facility instrument provided by the Italian Space Agency (ASI), is embarked on board the NASA Mars Reconnaissance Orbiter spacecraft. SHARAD began science operations on October 3rd 2006 : it has been collected data from surface and subsurface. This instrument penetrates to roughly half a kilometer below Mars' to search for information about underground layers of ice, rock and, perhaps, melted water. SHARAD operates with a center frequency of 20MHz and 10MHz bandwidth. These parameters allow vertical resolution on the order of 10-20m. The carrier frequency of 20MHz guarantees the capability of SHARAD to operate in day side as well as in night side. Both MARSIS and SHARAD use the principle of a Synthetic Aperture Radar (SAR) to achieve a fine along-track resolution. In particular, MARSIS is an un-focused SAR with best along-track resolution of 2Km; data coming from SHARAD can be processed with focusing algorithm (Chirp Scaling Algorithm), rising a best horizontal resolution of 300m. This paper provides a comparison between MARSIS and SHARAD images in different zones of the Mars' surface. From the preliminary analysis it has been evident that MARSIS detects signals from subsurface interfaces at 3Km of depth, while the signals received by SHARAD in the same zone and at the same depth are much weaker compared with the background noise. However, SHARAD radar-grams show subsurface interfaces at 100-200m of depth: these interesting targets can not be discriminated by MARSIS because of its coarse vertical resolution. At the same time, SHARAD data add to MARSIS data scientific information about the upper portions of the crust of Mars.**

Index Terms— MARSIS, penetrating radar, SHARAD, subsurface sounding.

I. MISSION OBJECTIVES AND CONSTRAINTS

Identification of water deposits, in either liquid or solid form, on or below the surface of Mars, is one of the current highest priorities in the exploration of the Red Planet. In particular, subsurface water deposits are suspected to exist as a relic of the ancient mars ocean.

Low-frequency radars, with their capability of penetrating deep into the planet surface, are natural candidates to the task of finding such deposits.

The MARSIS radar, operational onboard the ESA's Mars Express probe, is currently engaged in this mission.

While capable of great penetration (up to 5 km) the limited bandwidth of the system, imposed by the operational frequency, limits the range resolution and, consequently, its ability to discriminate radar returns close to the surface.

To complement the MARSIS investigation with an instrument capable of better resolution and ability to discriminate objects closer to the surface (at the expense of the penetration depth) the SHARAD (Mars Shallow Radar Sounder) instrument has been developed.

II. INSTRUMENT CONCEPTS AND DESIGN DRIVERS

The SHARAD instrument operates on a carrier frequency of 20 MHz, and uses chirped pulses with a bandwidth of 10 MHz to achieve a nominal range resolution (in free space and without weighting) of 15 m. In order to allow delectability of weak subsurface echoes in presence of a strong surface return, very low range compression sidelobes are required.

Synthetic aperture is used on-ground to achieve an along-track resolution down to 300 m in order to limit the unwanted echoes from off-nadir scatterers.

The MARSIS instrument is a low-frequency nadir-looking pulse limited radar sounder and altimeter with ground penetration capabilities, which uses synthetic aperture techniques and a secondary-receiving antenna to isolate subsurface reflections. In standard operative mode the instrument will be able to operate in any of the following bands: 1.3 -2.3 MHz (centered at 1.8 MHz), 2.5-3.5 MHz (centered at 3.0 MHz), 3.5-4.5 MHz (centered at 4.0 MHz) and 4.5 -5.5 MHz (centered at 5.0 MHz). The MARSIS instrument is designed to operate as both a subsurface sounder and an ionospheric sounder. During subsurface sounding, MARSIS will operate in one of five sounding modes, which depend on the selection of different processing options, and selection of antennas. MARSIS is a one of few space radar that perform a complex on board scientific processing, in fact the radar perform Azimuth and Range compression (using also a particular algorithm to remove the ionospheric effect, the Contrast Method and the Front surface reflection), tracking, acquisition.

III. INSTRUMENT PERFORMANCE

Very low range side-lobes are mandatory to allow detection of weak sub-surface echoes in presence of the strong surface return. The approach of limiting to the minimum the amount of processing performed on-board was selected in order to allow the pulse compression process (critical from the point of view of range side-lobes) to be performed on ground, using the computed instrument Point-Target-Response (PTR) as correlation reference waveform. This is derived from:

- the electronics PTR, measured during instrument test;
- the antenna response, computed from the response of a flat surface during the calibration phase.

A. Side Lobe Control in SHARAD and MARSIS Imagery

Due to the above approach, the critical parameter is the stability of the Tx/Rx distortions instead of their absolute value. During thermal-vacuum tests, the reference function acquired in ambient conditions has been used to correlate simulated echoes collected over the whole temperature range: the achieved (weighted) Point Target Response, were well within the required limits (-55 dB for far lobes).

The basic block diagram of the range compression algorithm is shown in Fig.1. In the following text, the basic operations (multiplications and signal transformations) will be formulated according to the signal flow in the processing chain:

a) Loading raw data;
b) Time average of N pris (depending by the Synthetic Aperture Length);
c) Base-band conversion;
d) Fast Fourier Transform of the averaged signal ($S(f)$);
e) Generation of a based-band ideal chirp (SHARAD Replica);
f) Fast Fourier Transform of the ideal chirp ($R(f)$);
g) Inverse Filter Generation starting from $R(f)$: $R_I(f) = 1/R(f)$;
h) Application of an Hanning weighting function: $R_W(f) = H_W(f) \cdot R_I(f)$;
i) Multiplication in the frequency domain between $S(f)$ and the conjugate of $R_W(f)$: $S_C(f) = S(f) \cdot conj(R_W(f))$;
j) Modulus extraction of the Inverse Fast Fourier Transform.

The reference chirp can be modified to take into account for the distortions of the overall path of the electromagnetic signal. These distortions are present because the end-to-end chain of the signal is not ideal.

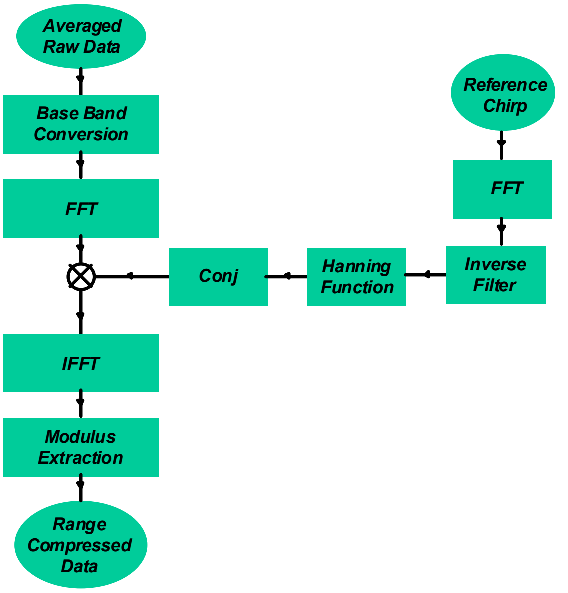

Figure 1 Block diagram of the range compression algorithm used for monitoring side-lobes.

B. SHARAD Image Generation

After A-to-D conversion, the only processing applied to the received signal is a coherent presumming, with variable presumming factors: 1 (no presumming), 2, 4, 8, 16, 28 and 32, to reduce the output data rate. Presumming is programmed (together with the number of bits to be transmitted) according to the operating scenario to achieve the minimum data rate compatible with the require data quality.

Focused SHARAD images are generated on-ground using the Chirp Scaling Algorithm (CSA), that is an attractive algorithm because it requires only Fast Fourier Transforms (FFTs) and complex multiplies [1], [2]. The Chirp Scaling Algorithm operates at zero Doppler Centroid , for this reason before applying the CSA, an accurate estimation of the Doppler Centroid is performed. The CSA is applied to SHARAD data after a preliminary processing. During this phase different operations are performed:

- Data decompression and quality check;
- Base Band Conversion;
- Remove Bias;
- Remove spurious signals;
- Compensate amplitude and phase distortion of the Rx/Tx chain;
- Range Compression;
- Compensate for ionosphere distortions (PGA technique);
- Compensate the Receive Window position;
- Compensate the Radial Velocity of the spacecraft;

In Fig. 2 a complete flow diagram of the SHARAD on-ground processing is depicted.

Tab. 1 lists the SAR parameters that the CSA uses.

The focused image resulting from the Chirp Scaling Processing can be compared with the MOLA map of Mars [3]. The Mars Orbiter Laser Altimeter, or MOLA for short, was one of the instruments on Mars Global Surveyor. MOLA sent back to Earth such information as Mars Topography, as well as information on the surface roughness. These information give a significant effort to the analysis of SHARAD images, in particular they can be used to correlate radar-grams with Mars topography.

TABLE I
SYSTEM PARAMETERS FOR CHIRP SCALING PROCESSING

Parameter	*Value*	*Comments*
Nominal science orbit altitude	155-320 Km	
Extended/contingency orbit altitude	230-407 Km	
Topographic margin	-20/+10 Km	
Centre frequency	20 MHz	
Chirp bandwidth	10 MHz	
Pulse width	85 usec	
PRF (nominal)	700.28 Hz	Can work with halved PRF
PRF (low orbit)	775.19 Hz	Can work with halved PRF
PRF (high orbit)	670.22 Hz	Can work with halved PRF
Radiated power	10 W	
Receive Window Length	135 us	
Sampling frequency	80/3 MHz	
Azimuth Resolution	300m÷500m	

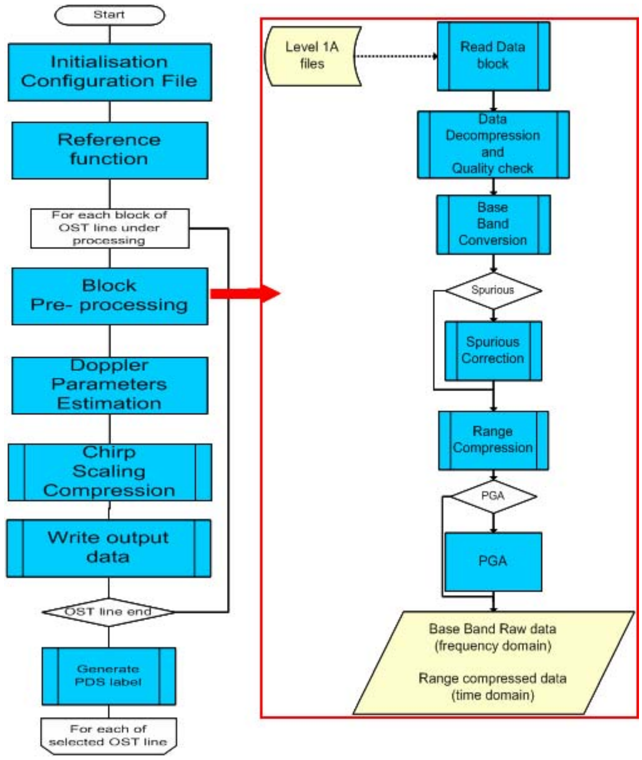

Figure 2. Flow Diagram of the ground processing applied on SHARAD data.

C. MARSIS Image Generation

The range and Doppler Processing, heart of the Subsurface Sounding, is built according to the functional block diagram of Figure 3.

Range processing is accomplished through digital implementation of the matched filtering. Input echoes are fast Fourier transformed using a 512 points complex FFT. The Fourier spectrum is then multiplied by the conjugate of the spectrum of a reference chirp and the result is inverse Fourier transformed to the range domain. Doppler filtering is operated in the frequency domain by coherently presumming the echoes before applying the reference function. Only few Doppler filters are needed to be synthesized, up to 5 depending on the specific submode.

Azimuth processing, in essence foresees the coherent summation of the radar returns by adjusting their phase. The level of complexity in the phase correction depends on the extent of the aperture length and thus on the azimuth resolution to be achieved. In the objectives of MARSIS sounder, the 5 to 9 Km resolution requested, allows to avoid the correction of quadratic phase terms; only linear ones are compensated. This circumstance, and the fact that few filters are needed to be synthesized, allows to simplify the processor architecture and to have a real time implementation of the processor using quite limited computer resources.

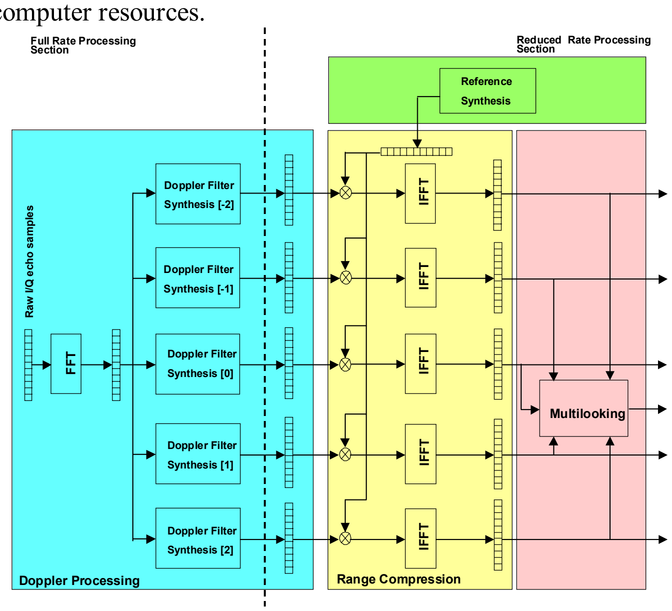

Figure 3. Range Compression and Azimuth Processing Flow Diagram

The coherent summation of the radar returns over the synthetic aperture is in fact achieved by a simple recursive scheme: each frequency bin of the currently transformed radar return is passed into the azimuth filter structure of Figure 4: 512 filters are run in parallel to process one return. The azimuth filter is a recursive structure in which a constant phase term Φ_o^k representing the elementary quantum of the linear phase correction to be applied over the aperture length, is progressively applied to the radar returns. The output of each structure is then further compensated by two additional phase terms, the first Φ_N^k needed to complete the linear phase correction over the aperture length, the second Φ_{mul}^k to correct the data from one aperture to the next in order to apply multilooking if desired. The linear phase correction is then implemented using for a single frequency bin just two phase terms, one recursively applied over the returns and one applied once at the end of the accumulation process. The phase terms are frequency dependent, in the sense that, because of the large signal bandwidth of the input signal respect to its carrier, the wavelength variation is so large that phase terms are to be customized for each frequency bin of the Fourier transformed input echo. To synthesize Doppler filter adjacent to the zero Doppler filter, the phase terms are to be further corrected with an additional linear phase term and thus a different set of 512 Φ_o^k , Φ_N^k phase terms are needed. However for the processing of one radar channel only 3072 phase terms shall be computed, leaving aside the optional multilooking phase correction term and taking advantage of the symmetry in the phase coefficients for filters –1 and 1, -2 and 2 respectively. Calculation of the coefficients is done off-line before starting the collection of the radar echoes required to the synthetic aperture synthesis.

Upon completion of the azimuth processing, the output of the Doppler filters is multiplied by the reference chirp function and finally inverse Fourier Transformed to complete the range compression. The reference chirp function accounts for the ideal chirp signal characteristics and the hardware distortions estimated from the calibration data, modified to account for the ionosphere distortions, estimated on board by proper analysis of the output of the central Doppler filter.

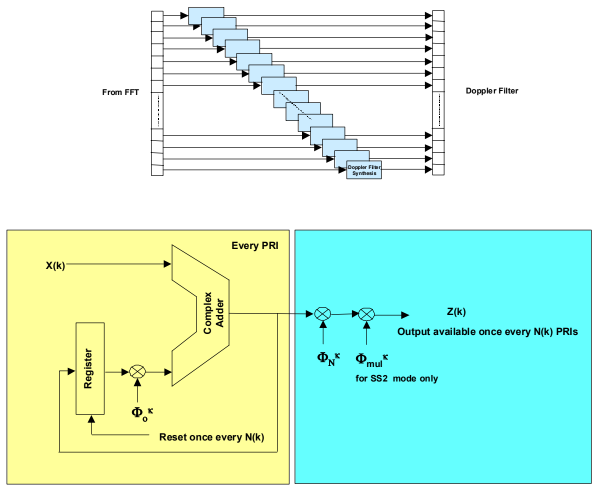

Figure 4 Azimuth Filter Structure

D. *SHARAD & MARSIS: Images Comparison*

Figure 5 (2) shows one of the SHARAD focused image generated during the North-Polar Campaign, orbit 2026, day side. Figure 5 (1) shows a view of the corresponding Mars map extracted by MOLA data: the ground-track of the spacecraft is the line at zero kilometers.

The scene size is approximately 5Km (free-space) × 1000Km range by azimuth, with near range in the upper side of the image. The image has uniform weighting in azimuth and Hanning weighting in range. The resulting resolution is about 24m in range and 300m in azimuth. According to the well known principle of operation of a subsurface radar, a pulse of electromagnetic energy, transmitted by the antenna, cutting into the top of the Mars surface produces a first reflection echo, which propagates backward to the radar. Thanks to the long wavelengths employed, a significant fraction of the e.m. energy is transmitted into the crust and propagates downward. Additional reflections, generated by possible subsurface discontinuities would occur and the relevant echoes would propagate backward to the radar generating further echo signals, much weaker than the front surface signal.

Radar-gram on orbit 2026, traversing ~79°-83°N from right to left, contains interesting subsurface layers in the upper portion of the Mars crust: they are perfectly identified by SHARAD thanks to its high range resolution. In Figure 5 (2) the vertical axis is "time," and an approximate depth scale is obtained by assuming a relative dielectric constant of 3, which yields a thickness of ~1000 m for the finely-structured unit.

The image quality analysis on the main point target responses is summarized in the following:

- Measured azimuth and range resolution: 315 X 23.9 m (theoretical values: 300 X 23.8 m);
- Peak side-lobe ratio < -30dB;
- SNR after focusing< 42dB;

The deviation of the azimuth resolution from the theoretical value are due to the non ideal motion compensation.

One of the MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) [4]-[6] observations (Orbit 3749) is very close to orbit 2026 and it can be compared with the SHARAD image (see Figure 5 and 6). It's important to note that MARSIS is an unfocused SAR and its maximum resolution is about 2Km in azimuth and 150m in range. The cross-check between SHARAD and MARSIS data will be used for achieving primary scientific objectives: map the distribution of water, both liquid and solid in the upper portions of the crust of Mars with increased azimuth and range resolution. . The SHARAD orbit 2026 doesn't match perfectly with the MARSIS one, however some Mars zones are covered by both the sounder. In these zones, we can compare perfectly the radar-grams of MARSIS and SHARAD.

By a preliminary analysis it is evident that MARSIS detects signals from subsurface interfaces at 3Km of depth, while the signals received by SHARAD in the same zone and at the same depth are very weak compared with the background noise. However, SHARAD radar-grams show subsurface interfaces at 100-200m of depth: these interesting targets can not be discriminated by MARSIS because of its coarse vertical resolution. These images confirm that MARSIS and SHARAD are complementary instruments. SHARAD radar-grams are more detailed than the MARSIS ones (pixel size in SHARAD image 10 times less than the pixel size in MARSIS image) in the first kilometers below the Mars's surface, but SHARAD has not visibility down to 2Km (weak penetration capability) according to the different value of the transmitted wavelength . This means that MARSIS images can be used to identify zones of Mars that can be interesting for SHARAD; in those zones SHARAD will be able to penetrate a few hundred of meters below the surface with a finer horizontal resolution and vertical resolution providing a unique insight into the Martian stratigraphy at scale comparable to those of optical images. At the same time, SHARAD data can be used to add scientific information, about the upper portions of the crust of Mars, to MARSIS data.

IV. Conclusions

This paper has compared the performance results of the two Radar Sounder working around the red planet: MARSIS and SHARAD. The two instruments have successfully demonstrated the capability to achieve the required performance. This paper gives evidence that the two Italian Sounders are complementary. In particular MARSIS images can be used to identify zones of Mars that can be interesting for SHARAD; in those zones SHARAD will be able to penetrate a few hundred of meters below the surface with a finer horizontal resolution and vertical resolution providing a unique insight into the Martian stratigraphy at scale comparable to those of optical images. At the same time, SHARAD data add to MARSIS data scientific information about the upper portions of the crust of Mars.

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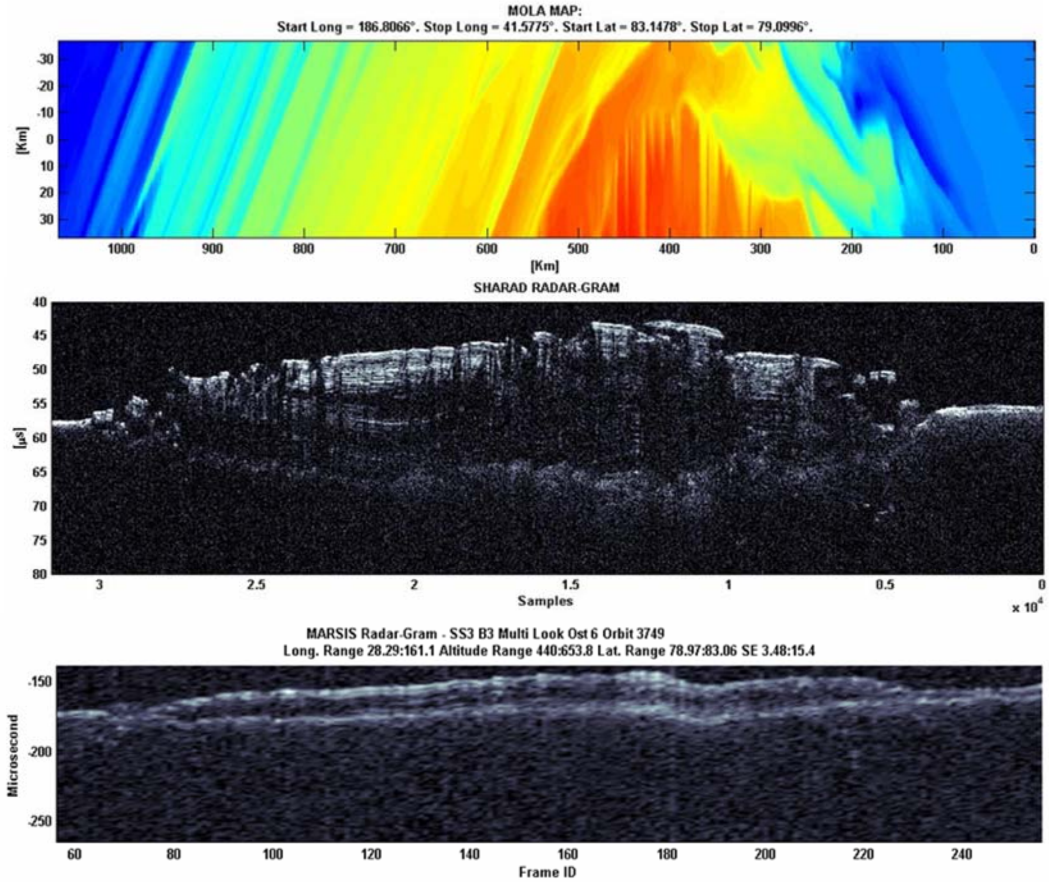

Figure 5. (1) MOLA map of the zone covered by the radar during the observation on orbit 2026. The line at zero kilometers is the ground-track of the radar;(2) Focused SHARAD image; (3) MARSIS Image on orbit 3749

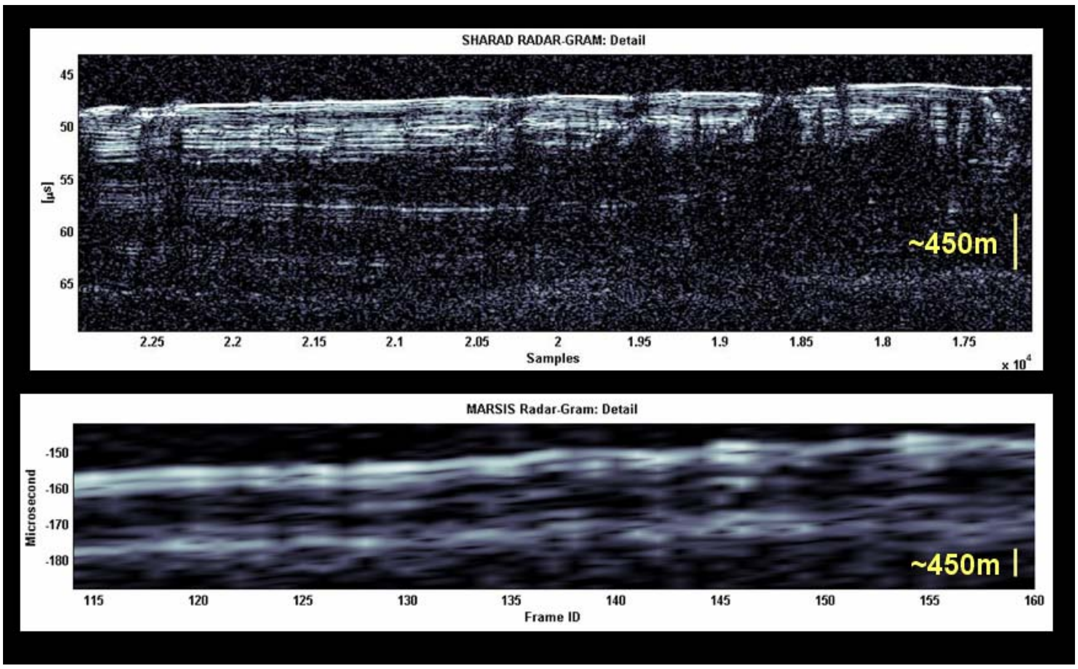

Figure 6. Comparison between SHARAD and MARSIS radar-grams on the same Mars area