SHARAD, A SHALLOW RADAR SOUNDER TO INVESTIGATE THE RED PLANET

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ABSTRACT

SHARAD is a sounder provided by ASI, which is participating as a facility instrument to 2005 NASA's Mars Reconnaissance Orbiter mission. SHARAD is, together with MARSIS, the only sounding instrument that orbits around Mars. It has a higher vertical resolution than MARSIS, however the latter has a greater penetration capability. Goal of this nadir-looking Altimeter with synthetic aperture capabilities is to investigate surface and subsurface of Mars and subsequently provide radar data that supply unique information concerning dielectric interfaces. The sounder's low-frequency and wideband features, meaning respectively a carrier band of 20 MHz and a bandwidth of 10 MHz, give the opportunity to achieve a theoretical vertical resolution of 15 meters in free space, maintaining an acceptable penetration capability of approximately 1500 meters. The instrument is composed of two main subsystems: the antenna (a 10 meter foldable dipole) and the SHARAD Electronic Box. In order to maximize the signal's received power and increase the quality of the data acquired, a certain number of calibration measurements on-ground and in-flight have been executed. The calibration outcome is part and parcel of the on ground processing of the radar. The processing method through which Planetary Data System compliant products are generated at the SHARAD operational center (SHOC) includes both range compression for the vertical resolution and synthetic aperture processing to achieve along-track resolution. To discern surface and subsurface echoes from clutter and thus support the scientific analysis of the data, the SHOC team developed an incoherent simulator for surface echoes [1].

1. INTRODUCTION

SHARAD (SHAllow RADar) is a sounding instrument provided by the Italian Space Agency, which is participating as a facility instrument to 2005 NASA's Mars Reconnaissance Orbiter mission. SHARAD is together with MARSIS the only Ground Penetrating Radar that orbits around the red planet, having however a higher vertical resolution, rather than MARSIS' great penetration ability. The orbit characteristics of MRO for the Primary Science Orbit, which started November the 8^{th} 2006, and thus of the SHARAD antenna are the following:

- Spacecraft altitude varies approximately between 250 km at the periapsis, placed over the south pole and 320 km at the apoapsis
- Inclination 92,6°
- Orbit period 112,1 minutes
- Eclipse duration between 30 and 39 minutes

Goal of this nadir-looking Synthetic Aperture Radar (SAR) and Altimeter is to investigate surface and subsurface of Mars and subsequently provide radar data, including high resolution views of the stratigraphy within the layered deposits, which supply unique information concerning dielectric interfaces. The latter can thus be analyzed and interpreted in terms of occurrence and distribution of expected materials, including water, ice, rock and regolith.

In order to maximize the signal's received power and increase the quality of the radar data acquired, a certain number of calibration measurements have been executed on-

ground by means of a scaled RF mock-up and in-flight after having planned a dedicated calibration campaign. The analysis of both on-ground and in-flight measurements has taken into account the most opportune spacecraft attitude and configurations, which are respectively the roll angles as well as the solar array and high gain antenna position.
The calibration outcome is part and parcel of the on ground processing of the radar data acquired since the beginning of the mission. The processing method through which Planetary Data System compliant products, so called Level 1B data, are generated at the SHARAD operational center (SHOC) includes both range compression for the vertical resolution and synthetic aperture processing to achieve horizontal resolution. Nevertheless, after having obtained and subsequently visualized the processed data, the scientific interpretation needs to be supported by means of tools that can help discern subsurface echo reflections from artefacts that appear as a consequence of off-nadir surface reflections. This can be achieved using for example a surface simulation software. For this purpose the SHOC developed an incoherent simulator.

2. RADAR CHARACTERISTICS

SHARAD can be considered as an exception among Synthetic Aperture Radars, because unlike the latter it performs nadir-looking acquisitions. This particular choice finds its reason in the attainment of the required sounding capabilities. The sounder's low-frequency and wideband features, meaning respectively a carrier band of 20 MHz and a bandwidth of 10 MHz, give the opportunity to achieve a theoretical vertical resolution of 15 meters in free space, maintaining an acceptable penetration capability of approximately 1500 meters. The radar sounder transmits its signal, observes in pulse limited geometry and considering the synthetic aperture technique, the resulting cross-track resolution varies from 3000 to 6000 meters, while the along-track resolution is around 300-1000 meters [2] [3].

3. SHARAD'S HARDWARE DESIGN

The high level block diagram of SHARAD is shown in Figure 1. The chirp, which is a long pulse that is linearly modulated in frequency and represents SHARAD's transmitted waveform, is synthesised directly at the transmission frequency (15 to 25 MHz), amplified at the required power level and sent to the matching network and the antenna. In the receiver the signal is directly sampled on the carrier frequency.

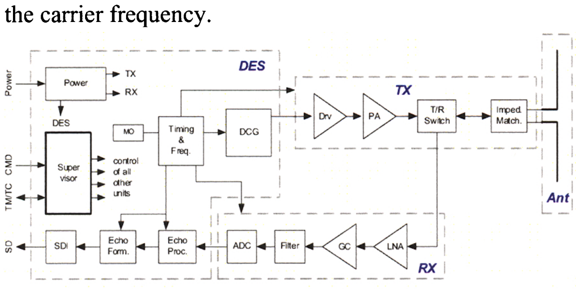

Figure 1: Block diagram of the SHARAD instrument

Physically, the instrument has two main subsystems: the antenna (a 10 meter foldable dipole) and the SEB (SHARAD Electronic Box) which, in turn hosts two main blocks:

- The RDS (Receiver and Digital Subsystem), which includes the controller, the DSP's, the chirp generator and the Rx module
- The TFE (Transmitter and Front-End) which encompasses power amplification, antenna matching and Tx/Rx duplexing.

After AD conversion, the only processing applied to the received signal is a coherent presumming with variable factors: 1 (no presumming), 2, 4, 8, 16, 28 and 32. This operation aims at reducing the output data rate. In nominal conditions, the instrument operates with a PRF of 700.28 Hz. This PRF value allows covering the whole orbit range foreseen for the Primary Science Phase as well as topographic margin [2].

4. RADAR CALIBRATION

The calibration data collected during the SHARAD on-ground tests have been analyzed to characterize the behaviour of the electronics (SEB) with respect to the temperature. This has been achieved by means of a dummy load, which has simulated the antenna impedance. Anyhow it is not sufficient to cover the real antenna gain and radiation pattern, which are in turn affected by the spacecraft configuration (orientation of the solar panels and of the high gain communication antenna). The influence of the spacecraft configuration on the antenna gain and radiation pattern has been studied first of all during the development phase using a scaled representative spacecraft model, leaving though the curiosity concerning the influence of the spacecraft attitudes once SHARAD would have started its data acquisitions over Mars.
For this reason an overall end-to-end calibration has been performed soon after the spacecraft Mars orbit insertion and the Sharad antenna deployment, in order to have an amplitude vs frequency calibration of the passive radiometric data (including a measurement of the galactic noise). Finally a second end-to-end calibration with the real antenna in different representative spacecraft configurations (Solar Array and High Gain Antenna position) and different Spacecraft attitude (either along or cross-track off-nadir pointing) has been executed.
The on-ground and in-flight calibrations are well in agreement to each other, confirming the validity of the approach followed during the design of the sounder.

5. SIGNAL PROCESSING

Main objective of the on ground signal processing, both in range and along the ground track, is to achieve the spatial resolution as it has been theoretically planned for SHARAD, which is respectively 15 m (free space) and 300 – 1000 meters. Range compression is the method through which the desired vertical resolution can be obtained, while the horizontal one can be enhanced by means of the azimuth – or synthetic aperture – processing. A processing tool

developed specifically for SHARAD radar data gives as an output Planetary Data System compliant products, which are defined as Level 1B data.
The Level 1B (L1B) Tool is the SHARAD Ground Data System software that is committed to perform range and azimuth processing and produce, after that, data which can be visualized as radargrams displaying the Martian surface and subsurface. The range processing counts three main steps. First of all the complex conjugate of the FFT of the discretely sampled transmitted signal, the so called filter or reference function, is computed. The latter is then multiplied by the FFT of the pulse echo. Finally an IFFT of the result is performed. Another issue concerns the ionospheric distortions that are unavoidable at SHARAD's 20 MHz frequency. The result of this phenomenon is a signal phase distortion all over the spectrum of the acquired radar pulses, which causes severe instrument performance degradation, especially in signal-to-noise ratio and pulse spreading. These undesired effects have been removed implementing in the range processing the Phase Gradient Autofocusing (PGA) algorithm [4]. Through this method the tool estimates range-independent phase error functions (PEFs) and corrects them.

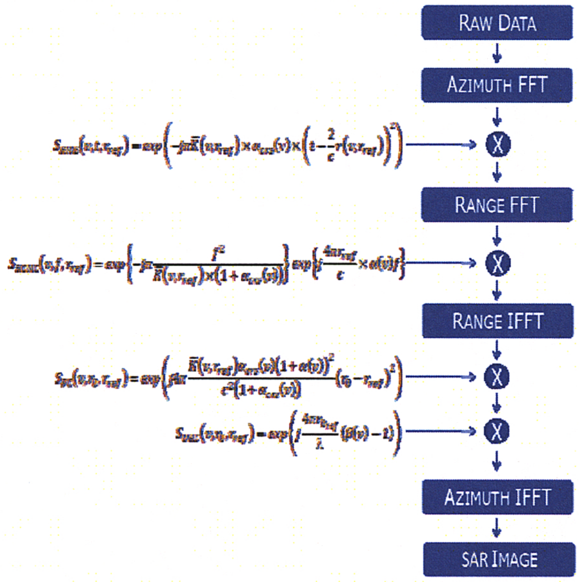

Figure 2: Sharad Chirp Scaling Compression algorithm flow diagram

Concerning the synthetic aperture processing, there's a clarification to be made. Due to the strict dependence of both the Doppler bandwidth and centroid from the surface scattering, SHARAD has to be considered as a particular SAR. Doppler bandwidth is directly affected by the surface roughness, while the slope influences the centroid. This phenomenon leads to the fact that the L1B tool needs to perform accurate Doppler parameter estimation. Besides, SHARAD is characterized by a high variability of the receiving window position, fact that has to be taken into account by realigning each range line before both the Doppler parameter estimation and processing.
What has been described above finds its application in the Chirp Scaling Algorithm (see figure 2) [5], which has been implemented to perform the data processing. The maximum resolution reached by means of the Chirp Scaling is 300 meters, although the Doppler bandwidth of the received signal affects this value. Moreover, the achieved resolution value is a consequence of the compensation of the range migration effects as well, obtained through the algorithm's application.
A further need, solved by means of the Chirp Scaling, is to compensate any known source of distortion, for example caused by on board noise. This permits to reach the requested 55 dB signal dynamic and thus provide high quality data ready for scientific analysis [6].

6. RADAR PERFORMANCE

The quality of the scientific inferences derived from the sounder data depends on the strength of the returned echoes from the surface and subsurface layers as well as the instrument detection characteristics. In particular the detection of a specific subsurface feature depends on the strength of that particular subsurface return echo clearly rising above either the overall noise level of the system, the sidelobes and the level of the off-nadir surface clutter.
Signal to noise ratio is therefore a fundamental element in the evaluation of the overall radar performance.
One of the first SHARAD signals acquired in September 2006 after the antenna deployment is shown in figure 3.

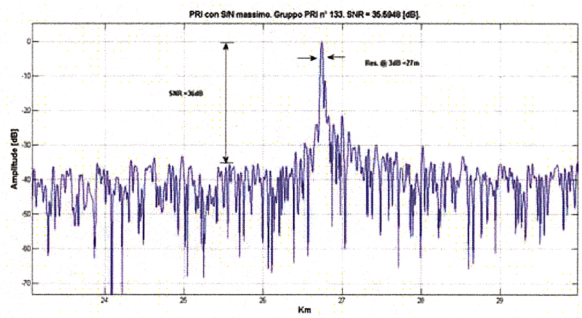

Figure 3: SHARAD echo acquired after the antenna deployment

The analysis of these first echoes demonstrated that, in line with the science requirements, the signal to noise ratio of the detected echo can be of the order of 36 dB after ground processing and the 3 dB resolution can be of the order of 27 meters (in free space) after the application of Hanning weighting.
Performance of the instrument can however be highly dependent on the operating environment and in particular on the reflectivity of the surface and the subsurface, on the effect of the ionosphere and on the level of clutter echoes, which in turn depend on the surface topography.
Though ionosphere distortions have been compensated using an adaptive algorithm in the data processing, there is

no possibility yet to automatically remove or reduce the clutter.

The clutter mitigation technique consists in associating to the analysis of possible subsurface interfaces from a radargram the surface scattering simulation results obtained using a MOLA DEM (see paragraph 7) and making a visual inspection of topography plots or images of the area over flown by MRO during the SHARAD data takes.

As a possible example, figure 4 shows a radargram from the data acquired on orbit 6760 and the relative MOLA topography. Comparing the over flown area on the lower part of the figure with the radargram, the matching between MOLA topography and radargram features is clearly recognizable, although the apparent subsurface echoes are indeed echoes coming from off-nadir and are due to reflections from the craters.

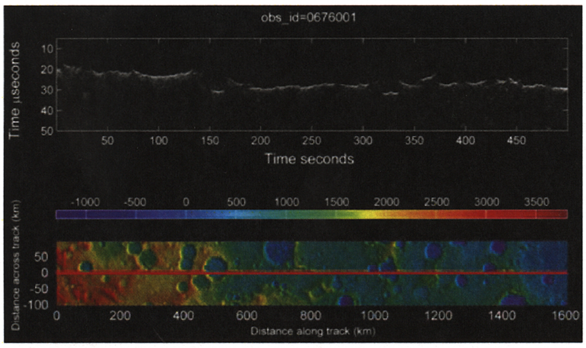

Figure 4: Sharad radargram and corresponding MOLA topographic map

7. SURFACE SIMULATION

Given that the received signal is the result of the combination of surface and subsurface echoes and off-nadir surface reflections (clutter), reaching the radar after nadir surface echoes, thus appearing as subsurface reflections (artefacts), which can affect negatively the scientific interpretation of the radargram.

In order to discern surface and subsurface echoes from clutter, the SHOC team developed an incoherent simulator for surface echoes. The simulator operates in time domain and uses MOLA DEM (MOLA is a laser altimeter operated on board the NASA Mars Global Surveyor mission), SHARAD ancillary data as well as surface scattering models (Optical geometry, Hagfors) as input data. MOLA DEM has a constant angular sampling of 1/128° in latitude and longitude while SHARAD ADC has a sampling frequency of 80/3 MHz. The Mars area to be simulated has been modelled with plane square facets whose dimensions are those of the MOLA data set sampling. Each facet is characterized by its center and normal vector. As SHARAD wavelength is 15 meters, incoherent backscattering models for rough surfaces have been superimposed to each facet. SHARAD operates in pulse limited geometry, therefore every position of the spacecraft corresponds to an illuminated area. The incoherent sum of the echoes from different point scatterers located in the observed area generates the surface echo totally received by the sensor in the orbital position considered. The subsequent visualization of the simulated SHARAD observation gives the opportunity to distinguish artefacts from subsurface reflectors [1].

8. CONCLUSIONS

SHARAD radar sounder has shown through its acquired radar data performances as they have been expected. Perfect tracking of the surface and high signal-to-noise ratio are the foremost evidence. In addition to that, a successful in-flight calibration campaign has been performed, that has supplied results comparable to those obtained after the on-ground calibration, confirming the validity of the approach followed during the design of the sounder. Moreover, the Chirp Scaling Algorithm processing applied to the collected SHARAD data solved a great number of difficulties related for example to the planet's characteristics (i.e. ionospheric distortions), reaching the expected spatial resolution and thus providing high quality scientific data.

Finally, the development of an incoherent simulator for surface echoes has been giving good results, when comparing a radargram with a simulated one and offers a great support for studying and analysing SHARAD data.

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