SHARAD radar signal processing technique

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Abstract— **SHARAD (SHAllow RADar) is the sub-surface sounding radar provided by the Italian Space Agency (ASI) as a facility instrument to NASA's 2005 Mars Reconnaissance Orbiter (MRO). SHARAD has been launched on August '05 and has started its nominal observation phase since November '06. Primary objective of its investigation is to map, in selected regions, dielectric interfaces to depths of up to one kilometer in the Martian subsurface and to interpret these interfaces in terms of the occurrence and distribution of expected materials, including rock, regolith, water, and ice. SHARAD which is a wideband low-frequency nadir-looking pulse limited radar sounder is expected to map Mars surface with a theoretical range resolution of 15 m in free space propagation, an along-track horizontal resolution of 300-1000 m and an across-track horizontal resolution of 1500-8000 m, depending on spacecraft altitude and terrain roughness. These performances can be reached by means of a focused synthetic aperture processing. The processing chain has been specifically designed and developed by CORISTA within SHARAD Ground Data System development activities with the aim of generating Level 1B products.**

This paper will be focused on of Level 1B SHARAD data processing description. Some results will be presented using SHARAD first data.

Index Terms— **Mars, penetrating radar, processing, sub-surface mapping, synthetic aperture.**

I. INTRODUCTION

SHARAD is the sub-surface sounding radar provided by the Italian Space Agency (ASI) as a facility instrument to NASA's 2005 Mars Reconnaissance Orbiter (MRO) [1]. SHARAD is a wideband radar sounder transmitting at a centre frequency of 20 MHz. The bandwidth of the radar pulse is 10 MHz. The transmitted waveform is a chirp, which is a 85 μs pulse linearly modulated in frequency. The chirp allows a resolution that depends on the bandwidth of the pulse rather than on its duration.

The primary scientific objective of the SHARAD investigation is to map, in selected regions, dielectric interfaces to depths of up to one kilometer in the Martian subsurface. The different dielectric response of the subsurface material is generated by the occurrence and distribution of different rock types, regolith, water and ice. The presence of liquid water will be distinguished by other materials due to its high dielectric constant that will produce a strong radar signal. The SHARAD instrument is a nadir-looking pulse-limited radar sounder and altimeter [2], [3].

The SHARAD instrument is functionally composed by two building blocks:

The transceiver, composed by two units (named RDS and TFE) is located in the SHARAD Electronic Box (SEB)

The antenna is a 10 m foldable dipole parallel to the surface to the direction of motion.

The RDS implements both digital (including digital chirp generation) functions in the DES and the analogue, receiving functions in the RX [4].

Key elements for the radar design are represented by the identified centre frequency, 20 MHz, the bandwidth of the radar pulse equal to 10 MHz, and the requested spatial resolution which is expected to be better that 1000 m in the along-track direction and 7000 m in the cross-track direction. The selected frequency is able to penetrate Mars surface and can be used to estimate the dielectric properties. But, the need to penetrate Martian surface requires radar operation at a MHz frequency regime which make ionospheric distortions unavoidable. For this reason, SHARAD is expected to operate on the night side of the orbit. A possibility exists for SHARAD to be operated also on the dayside depending from mission constraints and requirements.

Orbit characteristics, for the Primary Science Orbit, are as follows:

- Altitude: 255x320 km
- Inclination: 92.66°
- Sun-synchronous orbit: AN @ -10.7°, LMST 15:00h +/- 15'
- Period: 112.2 minutes
- Eclipse duration: min 30 minutes, max 39 minutes.

SHARAD can be programmed upon need to perform radar measurements in different operating modes. Subsurface Sounding Mode is the main measurement mode for SHARAD. In this Mode the instrument shall perform scientific measurements by transmitting radar pulses and collecting, processing and formatting received echoes. Pulse repetition interval and duration are variable. According to the operating scenario, in facts, several levels of pre-summing can be selected, namely 2, 4, 8, 16, 28, 32. In this case, a coherent pre-summing of the received echoes is performed on-board.

II. SHARAD DATA PROCESSING

In order to achieve the desired spatial resolution, both in depth and along the ground track, SHARAD received echoes have to be properly processed on ground. The method through which vertical resolution is achieved is called range processing, or range compression, while horizontal resolution is enhanced through what is called azimuth, Doppler, or synthetic aperture processing.

A. Range Processing

Pulse radars can discriminate between two targets at different ranges only if their echoes do not overlap, i.e. their distance divided by the velocity of light is greater than half of the pulse duration.

The waveform transmitted by SHARAD is a chirp, a long pulse that is linearly modulated in frequency. Chirps are used when the length of the pulse for the desired range resolution is so short that the pulse, to achieve good signal-to-noise ratio, would require a peak power exceeding the limits imposed by the mission design. The chirp allows the fine resolution associated with the wider bandwidth, which conceptually is achieved by passing the received echo through a filter whose time delay is a function of frequency. The filter should have a time delay such that the frequency transmitted first is delayed long enough so that it arrives at the output of the filter at the same time as the frequency transmitted last. All the frequencies in between also arrive at this time, so they are superimposed at a single instant of time in the filter output.

Of course, in a practical case, because of the finite bandwidth, a temporal delta-function output is not possible. With a bandwidth B the approximate width of the output pulse is 1/B, and if the transmitted amplitude is constant during the pulse, the output takes the form of a (sin x) / x pulse. In digital signal processing, passing the signal through a filter which superimposes simultaneously all the signal's frequencies is achieved through the correlation of the received echo with the transmitted signal.

B. Azimuth Processing

It is well known that the angular resolution of an optical instrument (i.e. its capability to separate two nearby objects in the observed field) is equal to λ / D, where λ is the wavelength and D is the diameter of the instrument aperture, apart from a factor of the order of unity which depends on the aperture geometry. Arrays of antennas, like those used in radio astronomy, achieve the angular resolution corresponding to the array size, rather than to the diameters of the array antennas, by coherently summing the signals coming from each antenna. This can be achieved, for example, by putting an equal length of cabling between the antennas and the processor performing the coherent (amplitude and phase) sum, thus ensuring that all signals reach the processor at the same time. In this way, the antennas behave as they were sampling points of a single aperture extending across the entire array. It is to be noted that, by its conformation, the array just described will constructively sum only the detected radiation coming from zenith: to focus other directions, it is necessary to adjust the length of the cables so as to allow the coherent sum of signals which have a non-zero delay from one antenna to the next.

Radars using aperture synthesis function according to this same principle, but sample the aperture in successive instants as they move. In digital signal processing, aperture synthesis consists of Fourier-transforming received echoes and then shifting the phase of their samples, which amounts to adding a delay in the time domain; then, the FFT's of pulse echoes are summed, resulting in the constructive sum of the signal components whose delay (phase shift) from one pulse to the next corresponds to the direction being focused.

III. L1B Processor Description

To accomplish SHARAD data processing, a specific software tool has been designed and implemented by Co.Ri.S.T.A. within the SHARAD Ground Data System (GDS) development activities funded by the Italian Space Agency.

The SHARAD Ground Data System (GDS) is the element of the Internet-distributed architecture defined for controlling and monitoring the instrument, and for receiving and processing the down linked Science Data.

The Level 1B (L1B) Tool is the GDS software devoted to basically accomplish Range and Doppler processing in order to produce radargrams of Mars sub-surface. It generates as output Level 1B data files formatted according to PDS (Planetary Data System) formatting specifications.

In Level 1B Tool, the range processing of each sampled pulse echo is performed by computing the complex conjugate of the FFT of the discretely-sampled transmitted signal (which is called filter or reference function), by multiplying it by the FFT of the pulse echo, and then by performing the IFFT of the result: because of the properties of Fourier transform pairs, this is equivalent to the computation of a correlation in the time domain.

As far as Doppler processing is concerned, we have to notice that SHARAD is quite different from a classic SAR (Synthetic Aperture Radar), because Doppler bandwidth and centroid are strictly dependent on surface scattering. In particular Doppler bandwidth is a direct consequence of surface roughness, while surface slope affects tightly Doppler centroid. This has lead to design the tool in order to perform an accurate Doppler parameters estimation (centroid and bandwidth) before starting processing chain. Moreover, realignment of each range line before Doppler parameters estimation and range Doppler processing has been faced to remove very high variability of receiving window position.

The Chirp Scaling Algorithm has been adopted to perform data processing. Depending on Doppler bandwidth of the received signal, this algorithm can provide a maximum full resolution of 300 meters by compensating range migration effects. Since a 55dB in signal dynamic is requested, each source of distortion (Mars ionosphere, on board noise) is compensated by the tool.

Moreover, it is worth notice that the need to penetrate Martian surface requires radar operation at a MHz frequency regime which make ionospheric distortions unavoidable. This will result in a signal phase distortion across the spectrum of the received radar pulses which may cause severe degradation of the instrument performances in term of SNR and pulse spreading and therefore in sub-surface interface resolving capabilities. These undesired effects on the radar signals have been removed making use of Phase Gradient Autofocusing (PGA) algorithm. PGA method enabled the tool to estimate range-independent phase error functions (PEFs) due to the unknown components and correct for them.

The SHARAD Level 1B Tool main block diagram is reported in Fig. 1.

In Fig. 2 the Chirp Scaling Compression algorithm is presented.

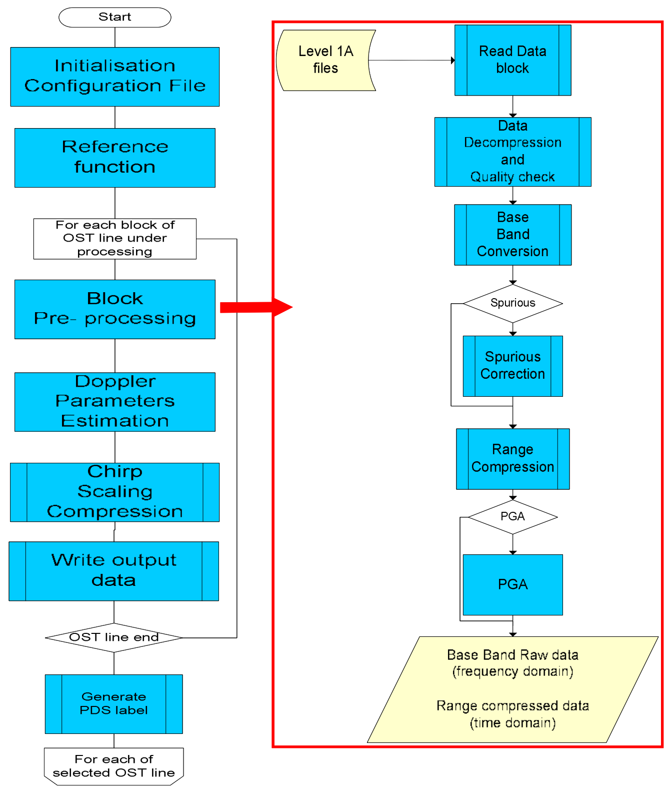

Fig. 1: SHARAD Level 1B Tool main block diagram

IV. SOME RESULTS

SHARAD has been launched on August '05 and has started its nominal observation phase since November '06, following commissioning activities during which antenna system has been successfully deployed. The instrument is now fully operative and is properly collecting data from Mars surface.

Since then, Level 1B Tool has been intensively used, showing a correct functioning.

Fig. 3 depicts a detail of Mars north pole, 47° - 67° longitude, 81°- 86° latitude. The product ID number is 0202601 flown on 2007-001 (year-DOY). It is a 300m azimuth resolution focused radargram. Range compression has been performed using Hanning weighting function and ideal chirp. Because of solar azimuth angle values (80° up to 84°) it has been necessary to compensate ionosphere effects. Figures 4 and 5 shows peak to noise ratio and a range cut of fig. 3.Fig. 6 shows the same product processed without PGA. Comparing fig. 3 and 6, it is clear the improvement in range compression by using PGA method. In terms of peak to noise ratio, PGA gains up to 3dB in signal compression.

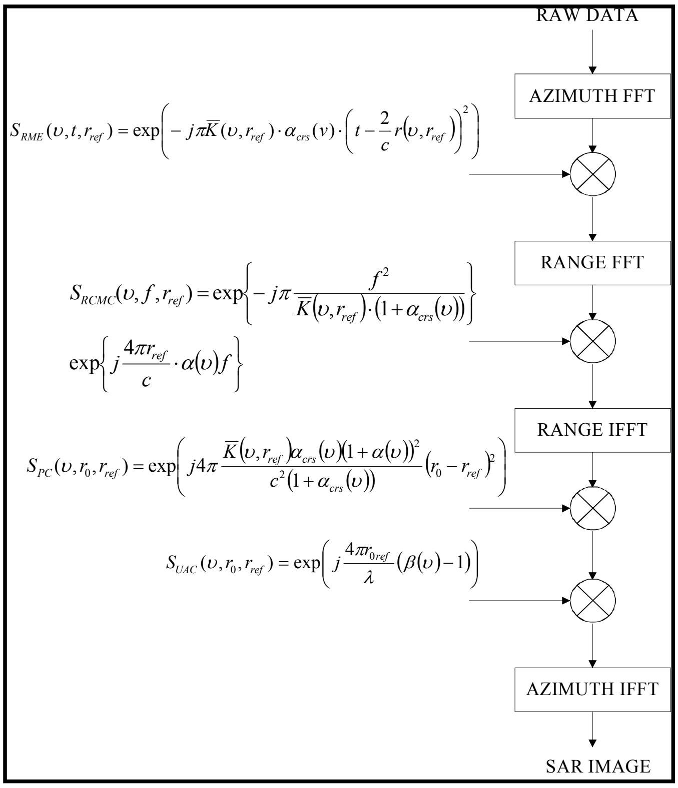

Fig. 2: Chirp Scaling Compression algorithm flow diagram

TABLE I
DESCRIPTION OF FIG. 2 USED SYMBOLS

r_{ref}	reference range
υ	Doppler frequency
f	range frequency
r	range
r_0	minimum range
C	speed of light
α_{crs}	scaling factor
t	fast Time
$\bar{K}$	scaled chirp rate
$\beta = \dfrac{1}{\alpha_{crs}+1}$	

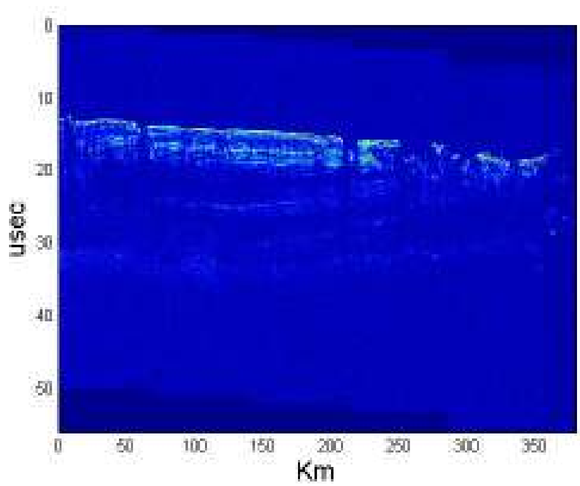

Fig. 3: 0202601 partial radargram.

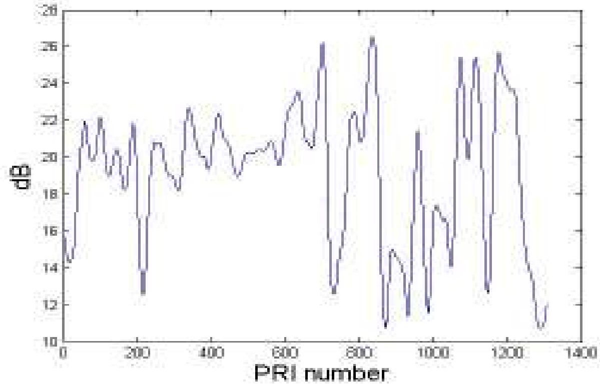

Fig. 4: Peak to noise ratio

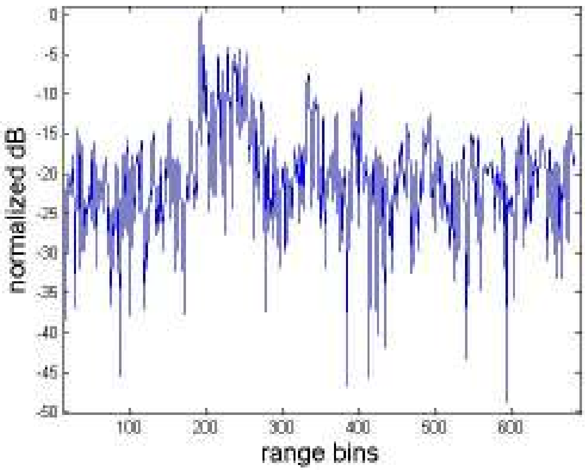

Fig. 5: A range-cut plot example of the 0202601 partial radargram

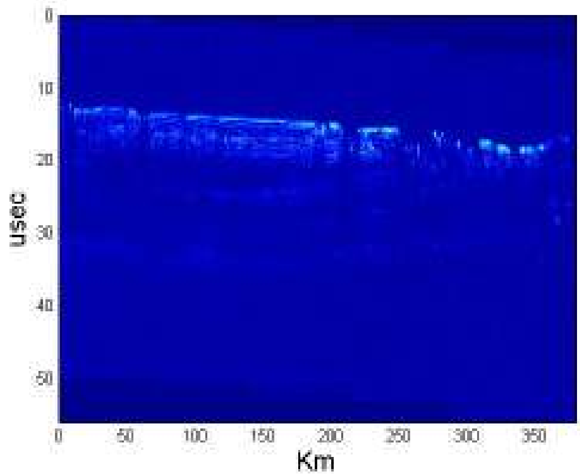

Fig. 6: 0202601 partial radargram without Ionosphere compensation

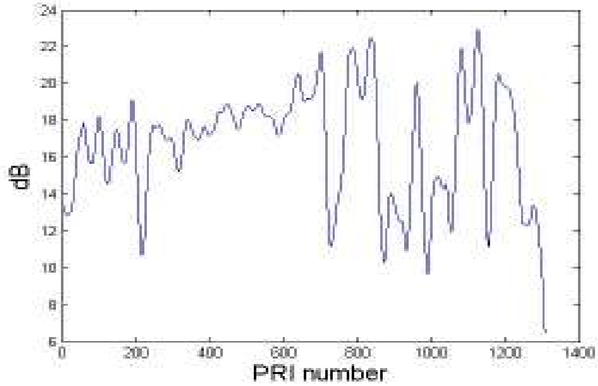

Fig. 7: Peak to Noise ratio for the No-Ionosphere-Compensation case

V. Conclusion

This paper has presented the SHARAD Level 1B Tool, which has been developed by CO.RI.S.T.A. within the SHARAD Ground Data System activities.

SHARAD, the sub-surface sounding radar provided by the Italian Space Agency (ASI) as a facility instrument to NASA's 2005 Mars Reconnaissance Orbiter (MRO), has started its observation phase since November '06 and is successfully collecting data from Mars surface.

The Level 1B Tool has been intensively used since then. Results and radargrams have been showed, confirming its proper functioning.

VI. Acknowledgment

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