MARSIS radar:
the signal processing pipeline

OLD CATALOGUE:
INAF/IAPS-2014-09 / ISSUE 1 / REVISION 0

Issue 1, Rev 0

PREPARED by : Marco Cartacci[1], Andrea Cicchetti[1], Raffaella Noschese[1]

CHECKED by : Roberto Orosei[2]

APPROVED by : Roberto Orosei[2]

[1]INAF-IAPS Via Fosso del Cavaliere 100, 00133, Rome, Italy
[2]INAF-IRA Via Piero Gobetti, 101, 40129 Bologna, Italy

1. Introduction

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) is a nadir-looking pulse limited radar sounder, which uses synthetic aperture (SAR) techniques and is carried by ESA's Mars Express spacecraft. MARSIS has the main task of evidencing the presence of water, both liquid and solid, on Mars, with the secondary objective of characterizing the structure of the Martian ionosphere. Therefore, the MARSIS design has foreseen two operation modes: the SS (Sub-Surface) Mode and the AIS (Active Ionosphere Sounding) Mode.

In its SS mode, MARSIS transmits radar pulses that penetrate through the planetary surface and are reflected by any dielectric discontinuity in the subsurface. MARSIS pulses consist of "chirps" (linear FM), i.e. wave packets of duration T = 250 μsec, which are linearly modulated in frequency over a bandwidth B = 1MHz about a central frequency. The latter can be chosen between 4 different values (1.8, 3, 4 and 5 MHz), according to the predicted Sun Elevation Angle (SEA), so that the chirp frequency is always higher than the local plasma frequency.

Moreover, during the same SAR, MARSIS usually alternates two frequencies at PRF (Pulse Repetition Frequency) steps from a 40-m dipole antenna with a Pulse Repetition Frequency (PRF) of 127 Hz, to increase the probability that at least one of them propagates above the plasma frequency.

The radar vertical resolution after the range compression and after Hanning windowing, that is applied to reduce the amplitude of the pulse side-lobes, is approximately 210 m in the free-space. In the subsurface, the resolution is improved by a factor equal to the square root of the soil permittivity, assuming values of 50-100 m.

The SAR processing is designed to obtain synthetic apertures (called frames) adjacent to each other, with a ground resolution of 5.5-10 km along the track and of 17-30 km across the track, where lower and higher resolutions pertain to higher and lower S/C altitudes, respectively. The receiving window duration is 350 μs and the sampling frequency is f_s = 1.4MHz, so that each frame contains 490 samples that increase to 512 after zero padding and FFT processing.

Each synthetic aperture consists of about 200 radar pulses (this value depends on different parameters as signal frequency, altitude, tangential velocity etc.), transmitted in a segment of orbit approximately 5,5 km long (minimum value for a single synthetic aperture). Through unfocused SAR processing (azimuth and range compression), the measurements (the echo received for each pulse) are reduced to a single radar trace (frame) which represents the power backscattered from the surface and subsurface discontinuities versus the two-way travel time. A continuous sequence of frames produces the so called “radargram” where the X-axis represents the satellite orbital direction and the Y-axis the two-way travel time, while the power of the signal is coded by the grey scale color map.In order to reduce the data volume, MARSIS transmits to the ground the signals already compressed in range, so the main task of the processing pipeline is represented by the software dedicated to perform the range compression of the radar collected echoes during the subsurface modes.Since these data have been distorted by the Mars ionosphere, we cannot use an ideal reference function (the ideal chirp) for range compression. Therefore we shall use a dedicated algorithm, the Contrast Method (CM), to calculate a phase correction term to modify the Ideal Reference Function in order to compensate the ionospheric distortion and optimize the compressed signal.In details, the MARSIS ground processing pipeline is characterized by two steps:

Science Data extractions from scientific telemetries and production of an intermediate product level (L1B) in Planetary Data System format (PDS), deliverable to science community.

Range compression, through the CM, of the radar signals with production of the last deliverable product in PDS format, the L2.

2. Level 2 Elements

The Level 2 processing can be resumed in seven steps (see Fig. 1):

- Data Decompression: the 8 bit data format of the Level 1B is converted in a 32 bit (floating point) data format
- Ionospheric Dispersion Correction (Contrast Method)
- Range Compression
- Gain normalization
- Tracking effect removal

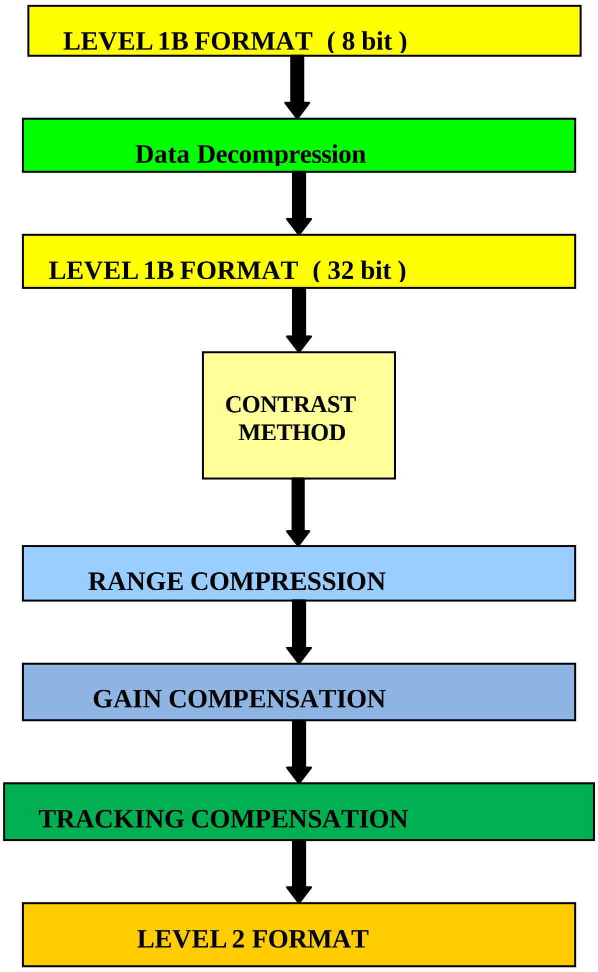

Fig. 1

2.1 Ionospheric Dispersion Correction

As it is well know if a radio-frequency pulse, of frequency f, propagates through a section a ionized medium with plasma frequency f_p, it will be subjected to an extra-phase shift with respect to the free-space propagation, causing a distortion of the range compressed signal. In order to maximize the penetration depth, MARSIS will use low transmission frequencies, as close as possible to the plasma frequency. As a consequence the chirp code transmitted by MARSIS will suffer a phase distortion that, if not compensated, will result in an unacceptable loss of performance on the compressed waveform. As a secondary effect, a percentage of the phase distortion produce an additive delay to the signal propagation.

In order to reduce the losses, the processing pipeline includes a dedicated algorithm, the Contrast Method.

Briefly , the CM consists in iterating the range compression of the radar echoes: at each step of the iteration, the following phase compensation is applied to the echoes

$$\Delta\varphi(f) = \hat{a}_2 (f - f_0)^2 + \hat{a}_3 (f - f_0)^3 + \hat{a}_4 (f - f_0)^4 \qquad (6)$$

where the $\hat{a}_2$ term is

$$\hat{a}_2 = \hat{a}_{2\,start} + \left(k - \frac{n}{2}\right) \Delta a_2 \qquad 1 \le k \le n \qquad (7)$$

Where n is the number of iterations, $\hat{a}_{2start}$ is the starting value and Δa_2 the iteration step. $\hat{a}_{2start}$ is set to zero for the first frame of a given orbit, while for all the following frames it is set equal to the best value of $\hat{a}_2$ estimated in the preceding frame.

The upper value of the iteration step is estimated as follow

$$\Delta a_2 \le \frac{2\pi}{B^2} = 6.28 \cdot 10^{-12} \qquad rad/Hz^2 \qquad (8)$$

In practice, in the Eq. (7) iteration, it is desirable to use a step smaller than Δa_2 in order to improve the estimation accuracy. Usually, $\Delta a_2 = 0.628 \cdot 10^{-12}$.

In order to determine the $\hat{a}_3$ and $\hat{a}_4$ terms to be used in the iteration defined in Eq. (6), we use a ionosphere model characterized by a constant plasma frequency $f_{p,max}$ and an equivalent slab thickness $L_{Eq.}$ Moreover, assuming that $(f_{pmax} / f_0)^2 << 1$ and having defined $\tau_0 = 2L_{eq}/c$, we obtain (eq. 17 [1]):

$$\hat{a}_3 \cong -\frac{\hat{a}_2}{f_o}\left(1-\frac{\hat{a}_2 f_o}{\pi\tau_o}\right) \tag{9}$$

$$\hat{a}_4 \cong \left(\frac{\hat{a}_2}{f_0^2}\right)\left(1-\frac{\hat{a}_2 f_0}{0.5\pi\tau_0}\right)$$

Actually, the algorithm selects the compensation term $\Delta\varphi$, and the related coefficients $\hat{a}_3$, $\hat{a}_3$ and $\hat{a}_4$ of the expansion defined by Eq. (4), that produces the range compressed signal with the best energy concentration in a defined time interval of the receiving window and uses it to perform the final range compression. The Contrast Method is applied to all synthetic apertures (frames) collected by MARSIS and for each frequency. Fig. 2 shows the improvements allowed by the CM in terms of quality of the range compressed data for a given frame: the black line shows the signal after range compression without correcting the phase through the CM, while the blue line shows it after the CM optimization procedure has been applied. It is evident that with the CM there is an improvement of the signal performances in terms of peak power, signal to noise ratio, a reduction of the main lobe width, and then a better range resolution; this allows to separate the surface and subsurface echoes that without correction would be merged together.

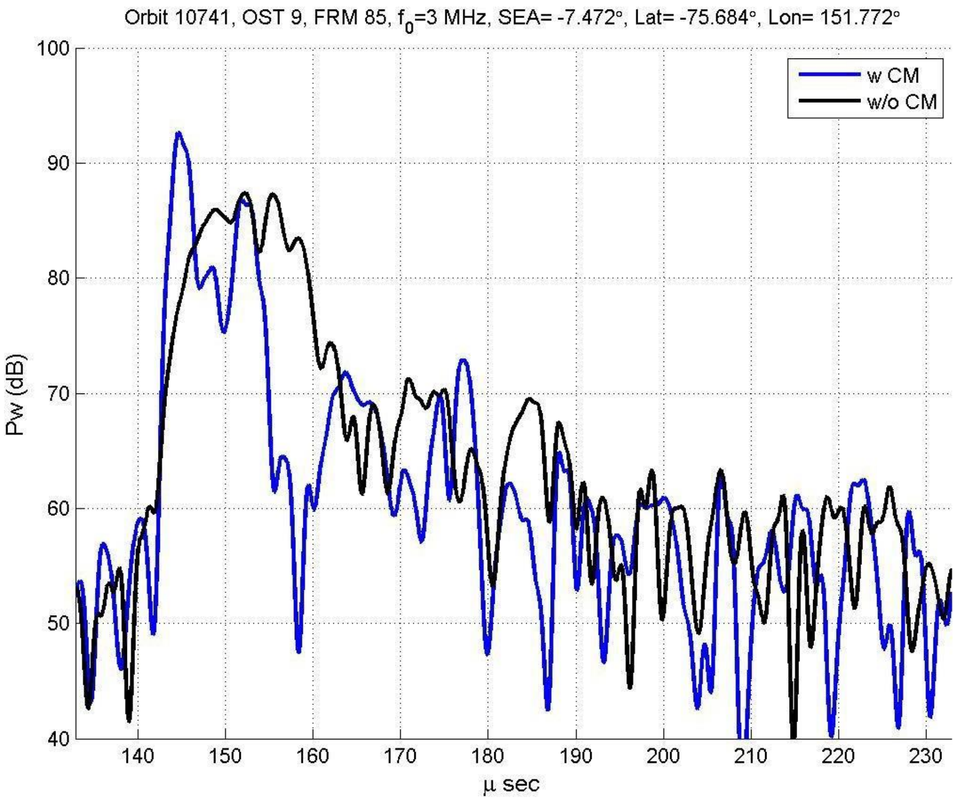

Fig. 2. Reflected power as a function of time during frame 84 of orbit 10741. The black line shows the uncorrected received signal; the blue line shows the reflected power after correction through the Contrast Method.

2.2 Range Compression

In this phase the ideal reference function modified by the correction term, obtained by the Ionospheric Correction phase, will be used for the range compression of all the Doppler Filters output.

In particular there are two ways to obtain the range compression:

- The classical matched filter
- The inverse filter

In both cases the signal will be weighed with the Hanning function to reduce the side lobe level:

- In time after compression for the matched filter
- In frequency before compression in the case of inverse filter

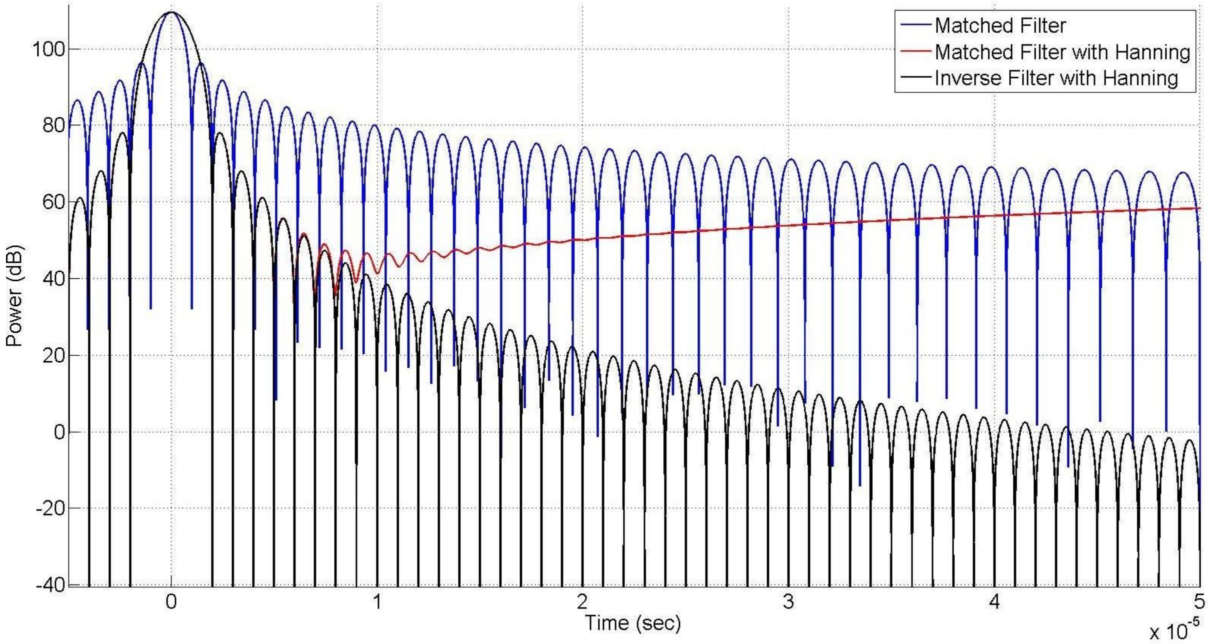

Fig. 3. Ideal chirp after range compression: the blue line shows the chirp compressed with the matched filter without any weighting function, the red line shows the chirp compressed with the matched filter and weighted with Hanning while the black line shows the chirp compressed with the inverse filter and weighted with Hanning.

As it is clearly visible in fig. 3, the use of the Hanning function, combined with a classical matched filter, allows to reduce the side lobes level (SLL) from a starting value of 13 dB to 32 dB, even if this implies a loss in term of range resolution (the main lobe is wider using Hanning). Anyway, for a radar sounder the possibility to reduce the SLL is very important, because this means that is increased the ability to reveal subsurface layers near the surface. On the other side, using the inverse filter allows to maintain this capability for increasing depth, while with the matched filter the SLL sharply rise again. For these reasons the default settings of the Level 2 processor are represented by the inverse filter together with the Hanning function.

2.3 Gain Compensation

As anticipated in the introduction, a single frame is the result of an integration of, at least, 200 echoes. During this process, the amplitude of each echoes is normalized by an Automatic Gain Control (AGC). The attenuation introduced by the AGC is constant within a single frame, but can vary between adjacent frames. Moreover the AGC is quantized with step of 4 dB. The result of this processing is that a radargram is characterized by the presence of “stripes”.

Fig.4 shows a radargram where the AGC effect is not compensated, while in fig. 5, has been performed the gain normalization.

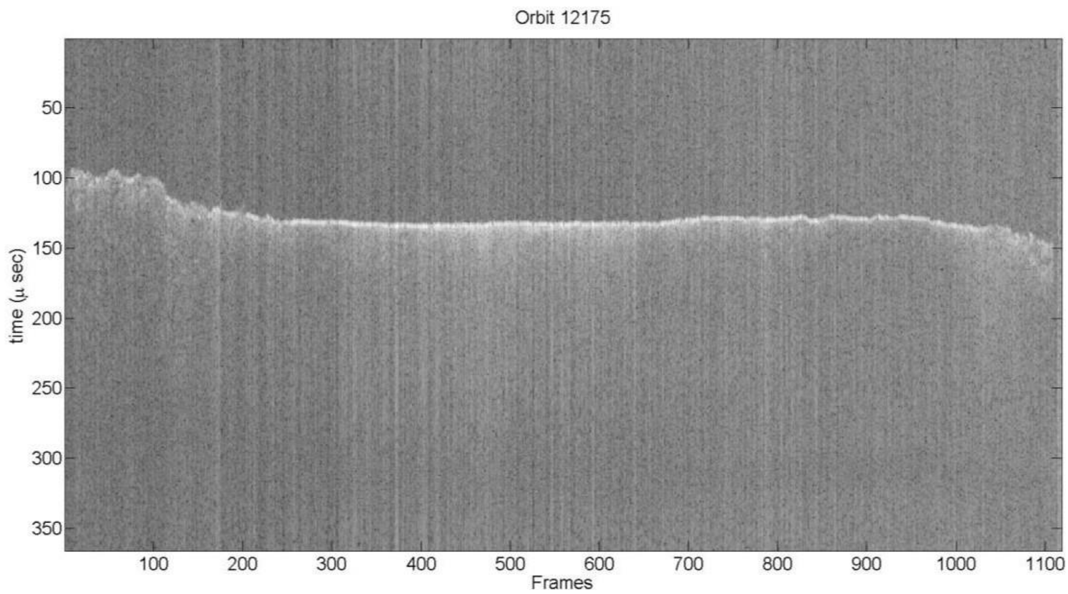

Fig. 4. A radargram with the effect of the AGC (“stripes”).

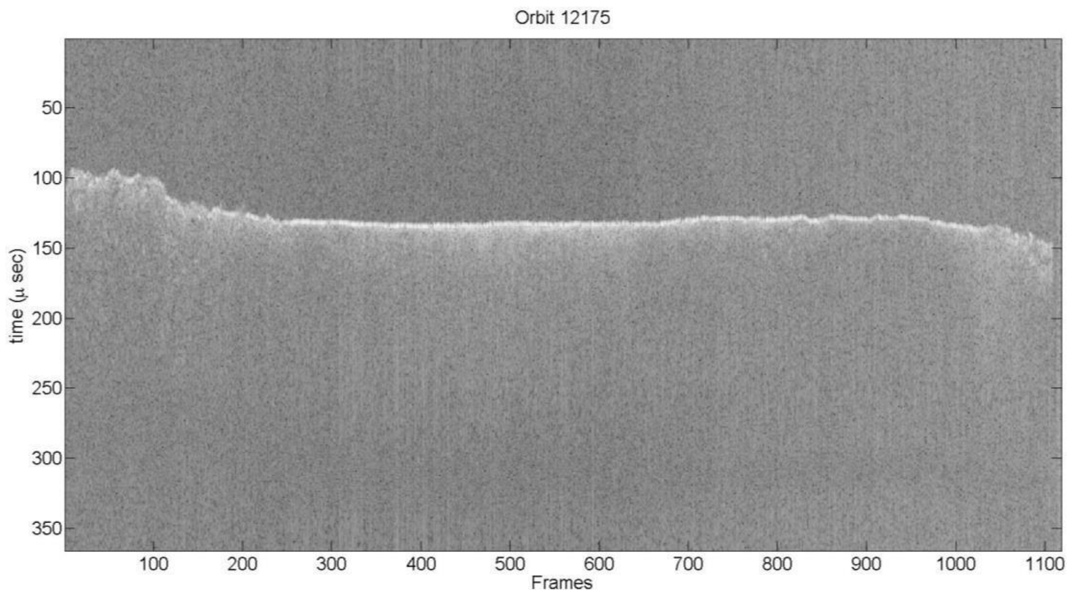

Fig. 5. The same orbit of fig. 4, after the gain normalization.

2.4 Tracking Compensation

One of the most important subsystem of MARSIS is represented by the tracking loop. Its task is to maintain the received signal within the receiving window, following (tracking) the surface regardless any effect introduced by the Martian topography and any delay produced by the Mars ionosphere. Unfortunately, a collateral effect of using the tracking loop is represented by the fact that the data have no more information about the observed scenario.

It is easy to see from fig. 6, that the effect of the tracking loop is to flatten a radargram so, apparently, the surface has no features. Obviously, this effect is undesirable, and is removed when the signal is processed by the Level 2.

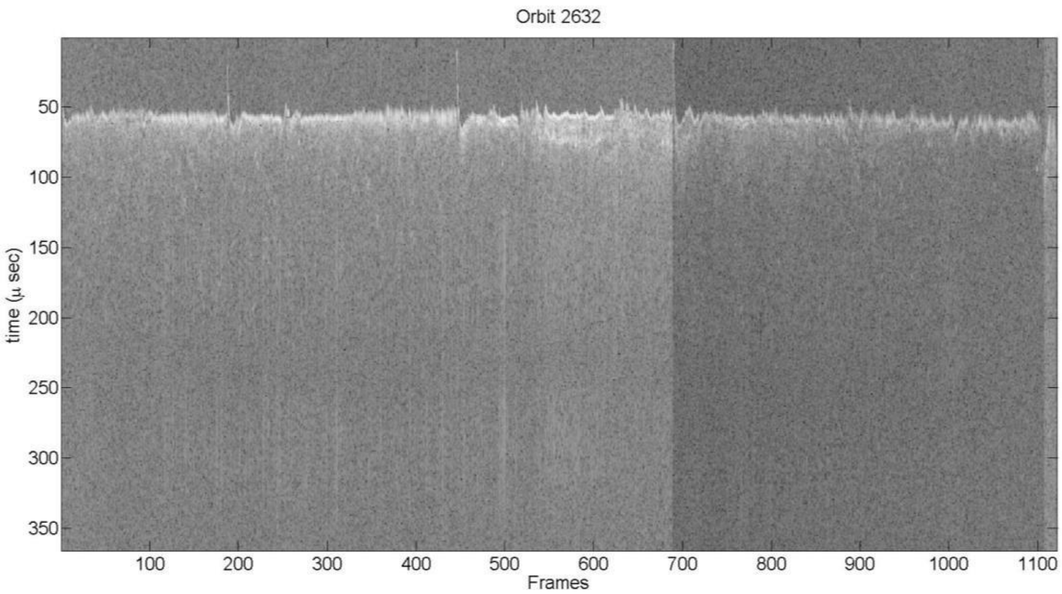

Fig. 6. A radargram where the secondary effect of the Tracking Loop is not removed.

3. Level 2 Input

The main source of inputs for the Level 2 is the Level 1B, that is in PDS format.

The Level 1B contain all the data produced by the Marsis instrument (Subsurface Data, Active Ionosphere Sounding Data, Passive Ionosphere Sounding Data, Auxiliary Data…), reconstructed from the scientific telemetry. Moreover there are many other spacecraft telemetry relevant for calibration and processing, as spacecraft position, radial and tangential velocity, altitude… (Geometry Data).

Not all these information are useful for Level 2.

Then in this section we will consider only the data necessary for Level 2 processor.

The Level 1B structure will be as illustrated in the fig. 4.

The Data directory will be organized in set of ten orbits, while the subdirectories named EDR_XXXX (Experiment Data Record) will contain the instrument data sorted by operative mode for each orbit.

Than for each Operative Mode there will be the collection, for different status (acquisition or tracking), of the relatives frames in a dedicated file.

The structure of these files is described in fig.5, for the frames collected during the subsurface modes.

Therefore, according to the operative modes used in the timeline, a different amount of data will be transmitted from Marsis and then the information of the orbit subdirectory will vary.

It is worth noting that, according with the Operative Mode SS1, SS3, SS4 and SS5, the scientific information will consist in a variable number of Doppler Filter that represent the signal after the on board azimuth compression. As it is show in fig. 5 the signal will be given in frequency and will be represented by 512 samples for the Real and the Imaginary part, in a 8 bit format (compressed).

Only exception is the Operative Mode SS2, where the signal is transmitted to the ground already compressed in time and also after a multilooking processing. In this case the 512 samples represent the power of the signals obtained with two different frequencies.

In conclusion as described in fig. 7 the radar signals of a single frame will be stored in the files named Marsis Data FRM with the correspondent Ancillary and Geometry data.

- The Marsis Ancillary Data File shall contain characteristic parameters used and/or estimated on board during the operational activity of Marsis (Acquisition Phase, Tracking Phase, Individual Echoes, Active Ionosphere Sounding, Receive Only and Calibration).
- The Geometry Data File shall contain orbital parameters (tangential velocity, radial velocity, altitude…) coming from MEX.
- The PIS data files shall contain the information collected during the Passive Ionosphere Sounding mode.

Furthermore for each EDR_XXXX stored in the DATA directory there is an equivalent EDR_XXXX in the CALIB directory that shall contain a LOG file with a set of parameters estimated on board during, for instance, the Contrast Method or the FSR Method. These LOG file shall contain also the a set of Reference Functions calibrated during the Calibration Phase and the information necessary to the ADC Correction and the HW Calibration phases (see the table in the next page).

LEVEL 1B

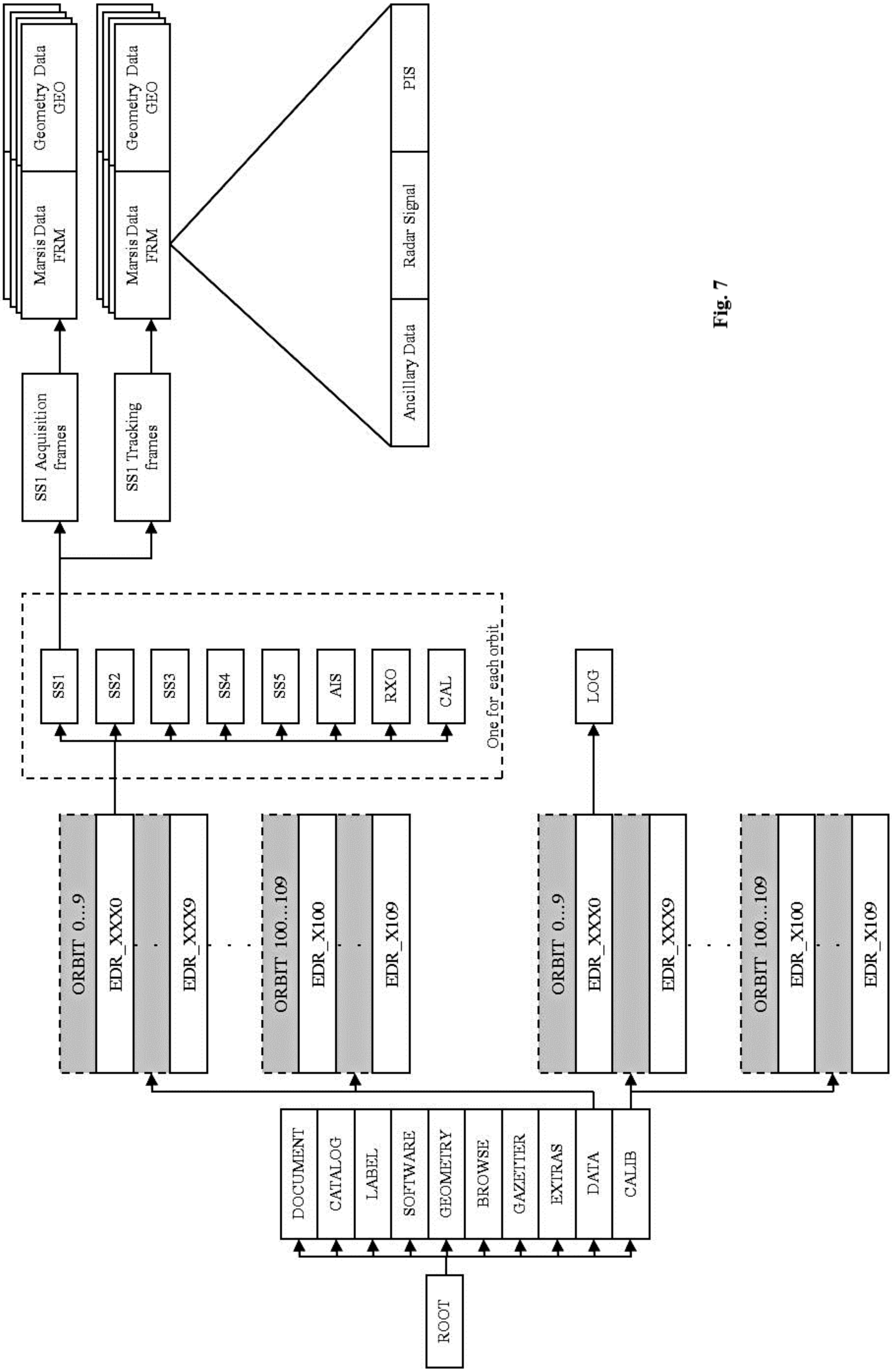

Fig. 7

RADAR SIGNAL (SS1, SS3, SS4, SS5)							
DIPOLE F1 Doppler Filters (-2, -1, 0, 1, 2)		DIPOLE F2 Doppler Filters (-2, -1, 0, 1, 2)		MONOPOLE F1 Doppler Filters (-2, -1, 0, 1, 2)		MONOPOLE F2 Doppler Filters (-2, -1, 0, 1, 2)	
512 samples (8 bit/sa RE)	512 samples (8 bit/sa IM)	512 samples (8 bit/sa RE)	512 samples (8 bit/sa IM)	512 samples (8 bit/sa RE)	512 samples (8 bit/sa IM)	512 samples (8 bit/sa RE)	512 samples (8 bit/sa IM)

MARSIS DATA FRAME (SS1 MODE)							
DF 0 Dipole f_{01}		DF 0 Dipole f_{02}		DF 0 Monopole f_{01}		DF 0 Monopole f_{02}	
RE	IM	RE	IM	RE	IM	RE	IM

MARSIS DATA FRAME (SS2 MODE)	
Dipole f_{01}	Dipole f_{02}
512 samples (8 bit/sa POWER)	512 samples (8 bit/sa POWER)

MARSIS DATA FRAME (SS3 MODE)											
DF -1 Dipole f_{01}		DF 0 Dipole f_{01}		DF +1 Dipole f_{01}		DF -1 Dipole f_{02}		DF 0 Dipole f_{02}		DF +1 Dipole f_{02}	
RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM

MARSIS DATA FRAME (SS4 MODE)																			
DF -2 Dipole f_0		DF -1 Dipole f_0		DF 0 Dipole f_0		DF +1 Dipole f_0		DF +2 Dipole f_0		DF -2 Monopole f_0		DF -1 Monopole f_0		DF 0 Monopole f_0		DF +1 Monopole f_0		DF +2 Monopole f_0	
RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM

MARSIS DATA FRAME (SS5 MODE)											
DF -1 Dipole f_0		DF 0 Dipole f_0		DF +1 Dipole f_0		DF -1 Monopole f_0		DF 0 Monopole f_0		DF +1 Monopole f_0	
RE	IM	RE	IM	RE	IM	RE	IM	RE	IM	RE	IM

Fig. 8

4. Level 2 Output

The Level 2 software output is in PDS format and maintain the organization of the Level 1B as illustrated in the following scheme:

As it is well know the primary task of Level 2 data processor is the Range Compression of the Marsis collected echoes during the subsurface modes (except for the SS2 Mode).

Since these data have been distorted by the Ionosphere the Level 2 processor shall use the Contrast Method to estimate the Ionospheric distortion and to calculate a complex correction to modify the Ideal Reference Function in order to optimize the signal compression.

This means that each file of raw data (the echoes compressed in azimuth) will be replaced with a file containing the same data compressed in range too. Obviously the subdirectories will change the names, in fact the EDR_XXXX will be replaced with RDR_XXXX.

The Level 2 will be in PDS format and will maintain the organization of the Level 1B as illustrated in the fig. 6, moreover the Level 2 processor shall convert the 8 bit data format of the Level 1B in a 32 bit (floating point) data format.

The only change in the Level 1B structure is the introduction of all the information about the Level 2 steps in the LOG file.

It is worth noting that, even if the Level 1B data shall be given in their complex (I and Q) components, the data product of the Level 2 shall be represent the signal in module and phase (see fig. 7).

Note that even if the raw data provided by Level 1B are in frequency, the output of Level 2 is in time.

The last thing to note is that, as anticipated in the previous section, the signals collected during the Operative Mode SS2 has been already compressed in range, than the only variation about these information is related to the passage from the original 8 bit format to the new 32 bit format.

LEVEL 2

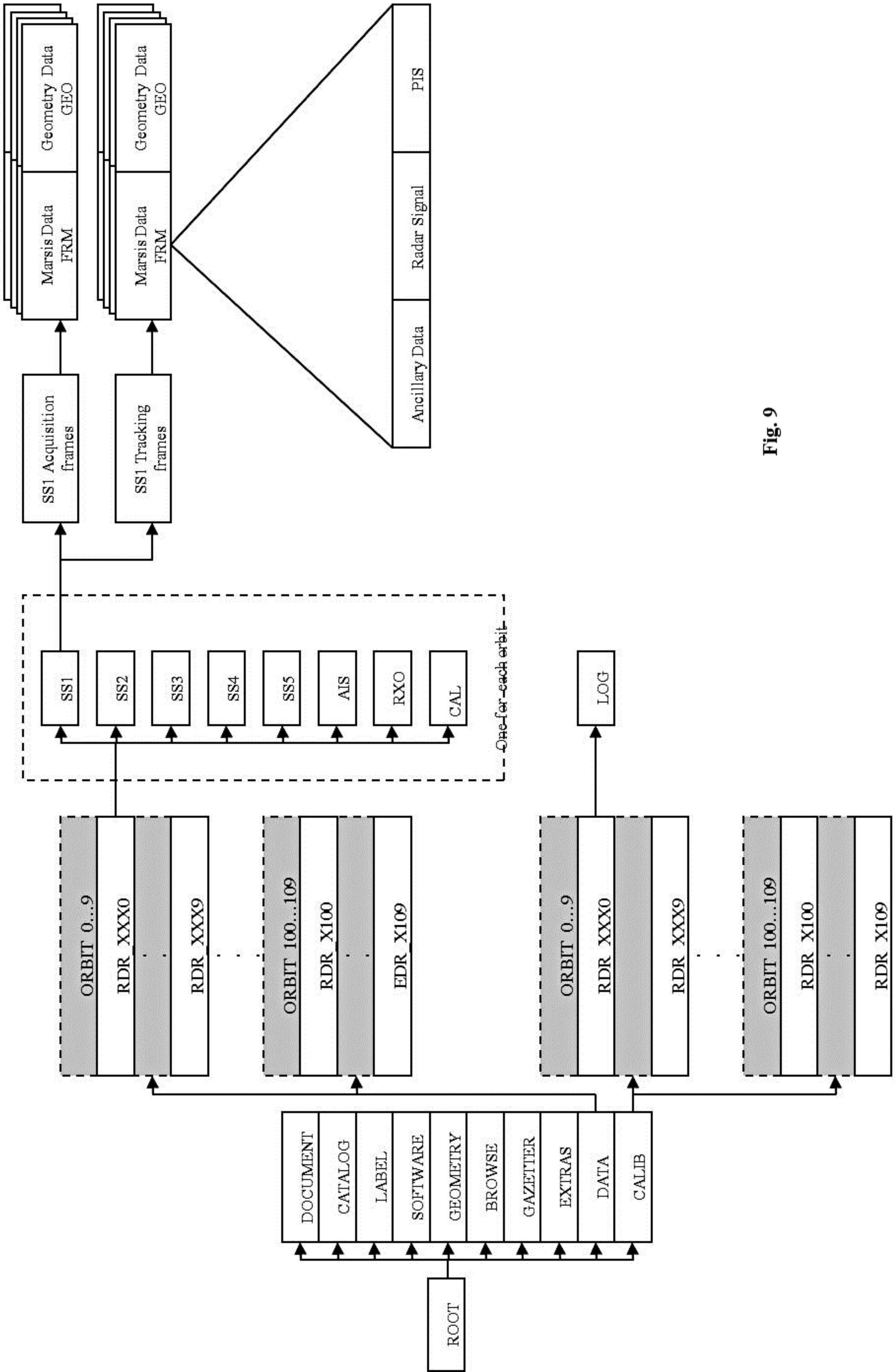
ROOT
DOCUMENT
CATALOG
LABEL
SOFTWARE
GEOMETRY
BROWSE
GAZETTER
EXTRAS
DATA
CALIB
ORBIT 0...9
RDR_XXX0
RDR_XXX9
ORBIT 100...109
RDR_X100
EDR_X109
RDR_X109
SS1
SS2
SS3
SS4
SS5
AIS
RXO
CAL
One for each orbit
LOG
SS1 Acquisition frames
SS1 Tracking frames
Marsis Data FRM
Geometry Data GEO
Ancillary Data
Radar Signal
PIS

Fig. 9

RADAR SIGNAL (SS1, SS3, SS4, SS5)							
DIPOLE F1 Doppler Filters (-2, -1, 0, 1, 2)		DIPOLE F2 Doppler Filters (-2, -1, 0, 1, 2)		MONOPOLE F1 Doppler Filters (-2, -1, 0, 1, 2)		MONOPOLE F2 Doppler Filters (-2, -1, 0, 1, 2)	
512 samples (32 bit/sa Module)	512 samples (32 bit/sa Phase)	512 samples (32 bit/sa Module)	512 samples (32 bit/sa Phase)	512 samples (32 bit/sa Module)	512 samples (32 bit/sa Phase)	512 samples (32 bit/sa Module)	512 samples (32 bit/sa Phase)

MARSIS DATA FRAME (SS1 MODE)							
DF 0 Dipole f_{01}		DF 0 Dipole f_{02}		DF 0 Monopole f_{01}		DF 0 Monopole f_{02}	
Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph

MARSIS DATA FRAME (SS2 MODE)	
Dipole f_{01}	Dipole f_{02}
512 samples (8 bit/sa POWER)	512 samples (8 bit/sa POWER)

MARSIS DATA FRAME (SS3 MODE)											
DF -1 Dipole f_{01}		DF 0 Dipole f_{01}		DF +1 Dipole f_{01}		DF -1 Dipole f_{02}		DF 0 Dipole f_{02}		DF +1 Dipole f_{02}	
Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph

MARSIS DATA FRAME (SS4 MODE)																			
DF -2 Dipole f_0		DF -1 Dipole f_0		DF 0 Dipole f_0		DF +1 Dipole f_0		DF +2 Dipole f_0		DF -2 Monopole f_0		DF -1 Monopole f_0		DF 0 Monopole f_0		DF +1 Monopole f_0		DF +2 Monopole f_0	
Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph

MARSIS DATA FRAME (SS5 MODE)											
DF -1 Dipole f_0		DF 0 Dipole f_0		DF +1 Dipole f_0		DF -1 Monopole f_0		DF 0 Monopole f_0		DF +1 Monopole f_0	
Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph	Mo	Ph

Fig. 10