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Mars Express

MARSIS Phobos Commanding Architectures

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TABLE OF CONTENTS

ACRONYM & ABBREVIATION LIST

AIS	Active Ionosphere Sounding
LTP	Long Term Planning
MEX	Mars Express
MGS	Mars Global Surveyor
MOC	Mission Operation Centre
MOLA	Mars Orbiter Laser Altimeter
MSP	Master Science Plan
MTP	Medium Term Planning
OST	Operations Sequence Table
PI	Principal Investigator
PLA	Pulse Limited area
POR	Payload Operations Request
POS	Payload Operations Service
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PS	Project Scientist
PST	Project Scientist Team
PT	Parameter Table
Rx	Receiver
SAR	Synthetic Aperture Radar
S/C	Signal to Clutter ratio
S/N	Signal to Noise ratio
STP	Short Term Planning
SWT	Science Working Team
SZA	Solar zenith Angle
TBC	To Be Confirmed
TBD	To Be Defined
USGS	United States Geological Survey

DOCUMENT CHANGE LOG

Issue	Date	Pages/Paragraphs affected	Changes Description

The following documents shall be used as reference background and support information. These documents are herein referred as [RD-XX].

Id	*Document Number*	*Description*
[RD-01]	MRS-003/005/05	MARSIS Flash Memory Operations Requirements v11
[RD-02]	MRS-023/005/03	Planning Tool “Algorithms and Criteria to Select the Operative Modes”

1 INTRODUCTION

Science objectives for the MARSIS experiment was defined more than 15 years ago in the context of the objectives of the Mars Express mission and in the more general frame of the open issues in the study of Mars at that time. The primary objective for MARSIS, was to map the distribution of water, both liquid and solid, in the upper portions of the crust of Mars. Secondary objectives defined for the MARSIS experiment included subsurface geologic probing and surface characterization of Mars.

In order to achieve these ambitious scientific goals it was necessary to design an instrument with high computational capabilities, also to cope with some limitation imposed by the mission characteristics, such as the limited data-rate provided by the spacecraft and the limited available data volume.

For these reasons, the on-board software is characterized by an high grade of flexibility that allow the possibility to modify the signal processing in order to face unpredictable issues arising during the mission.

This capability was very useful when, after several years of Mars observation, Phobos became a scientific objective for MARSIS.

2 MARS OBSERVATION FUNDAMENTALS

A typical MARSIS observation of Mars consists of a sequence of Frames, being a Frame a set of Pulse Repetition Intervals (PRIs) as shown in Fig. 2.1.

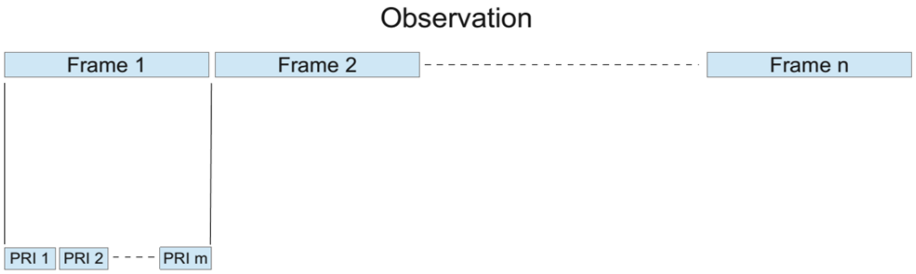

Fig. 2.1 Observation Structure

Each Mars observation Frame is made of the following sequence of operations performed on-board:

- Initial orbital parameters estimation, including Frame size estimation (NB, number of PRIs)
- Synthetic Aperture size estimation (NA, with NA < NB)
- Signal transmission (2 pulses) and echoes reception, repeated NA times
- NA Echoes coherent weighted accumulation (Synthetic Aperture)
- Doppler Processing
- Range Compression
- Surface Echo Tracking

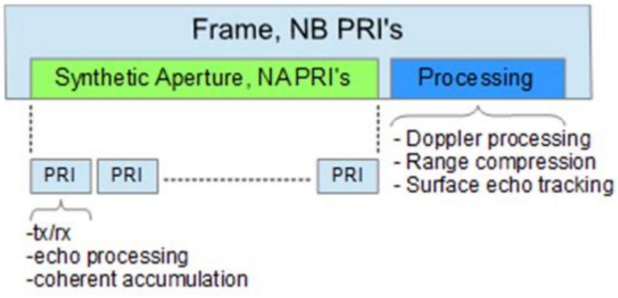

Fig. 2.2 Frame Structure

Frame size NB is computed adaptively during the flyby in order to separate contiguous synthetic apertures, so that their relative separation precisely matches with the distance covered by the Spacecraft in the time elapsed between the two apertures.

The space to be covered by the spacecraft during NB pulses is computed first as:

$$\Delta S = \sqrt{\frac{\lambda_1 \cdot H}{2}} + N_o \cdot \frac{V_{Tan}}{PRF} \quad (1)$$

where PRF is the Pulse Repetition Frequency (1/PRI = 127.267 Hz), N_o is a constant offset of 36 PRIs, λ_1 is the wavelength of the lowest Operative Frequency in use (available frequencies are 5Mhz, 4MHz, 3MHz and 1.8MHz), H and V_{Tan} are the Spacecraft Height and the tangential velocity for the Frame.

Frame size NB is then computed as :

$$NB = Int\left[\frac{\Delta S}{V_{Tan}} \cdot PRF\right] \quad (2)$$

Synthetic Aperture sizes NA_1 and NA_2 are also adaptively computed for each of the Operative Frequencies in use:

$$NA_1 = Int\left[\lambda_1 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_1 \cdot V_{Tan} \cdot \Delta S}\right] \quad (3) \qquad NA_2 = Int\left[\lambda_2 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_2 \cdot V_{Tan} \cdot \Delta S}\right] \quad (4)$$

where λ_1 and λ_2 are corrective frequency dependent values necessary to obtain the same azimuth resolution in different bandwidths.

A single PRI operation, repeated NA times (NA = max(NA_1, NA_2)), will then include signal transmission and echoes reception, according to the scheme shown in the following Fig. 2.3:

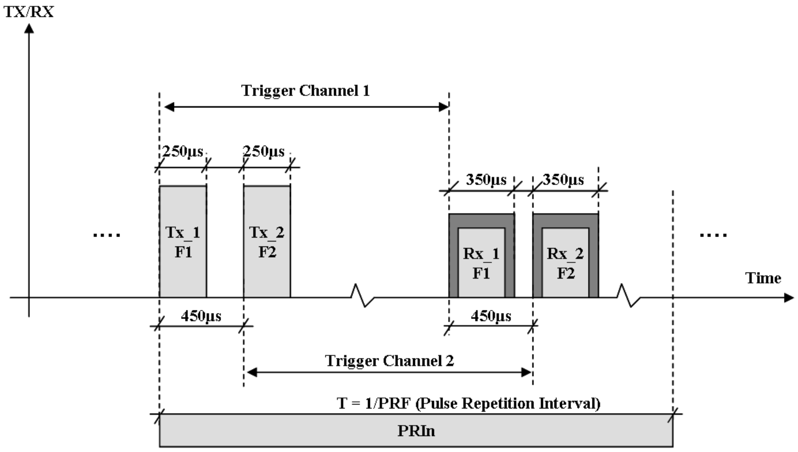

Fig. 2.3 PRI Timings

MARSIS transmits two square pulses each of width 250µs modulated in frequency with a 1 MHz bandwidth centered on the selected Operative Frequency. The time delay between the two transmitted pulses is fixed at 450µs, while the *Trigger* values for RX gates positioning are adaptively computed for each Frame taking into account the Spacecraft Height and the ionosphere effect, which introduces a delay that can be in the order of 50 up to 150 µs. More in detail, for the first Frame (*Frame 0*) *Trigger* values are computed with the following equation:

$$Trigger = \frac{2H}{c} + \Delta t \quad (5)$$

where ***c*** is the speed of the light in the vacuum and Δ**t** is a preset offset added to compensate the ionosphere effect. For the subsequent Frames (*Frame n*, *n* ≥ 1) *Trigger* values are estimated using the results of the Surface Echo Tracking processing executed on the previous Frame (*Frame n-1*).

During each Synthetic Aperture PRI received echoes are processed by MARSIS and a coherent weighted accumulation is also performed (see Fig. 2.4), synthesizing 3 Doppler Filters. At the end of the accumulation process final Doppler Processing is executed to finalize the Doppler Filter Synthesis. The geometry configuration of the Doppler filters is obtained using a different phase factor (see yellow panel of Fig. 2.4), in this way the three filters observe different areas on the surface. In particular the Doppler Filter 0 is nadir pointing, while the Doppler Filter -1 is watching ahead and the Doppler Filter +1 behind.

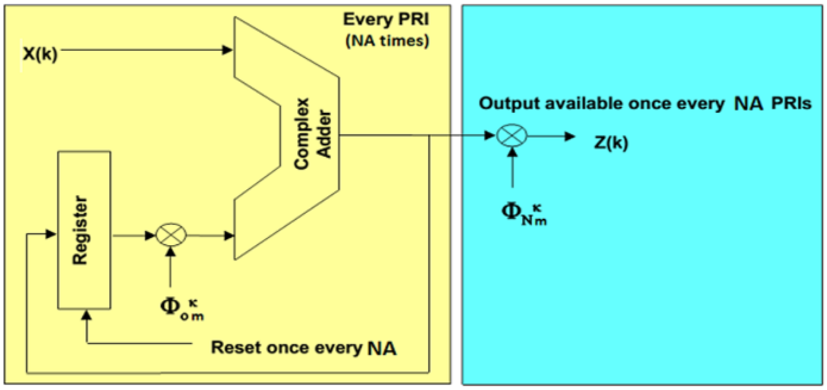

Fig. 2.4 Doppler Filter Structure

Doppler Processing results ,for all the 3 filters (see Fig. 2.5), are inserted into telemetry packets sent to the spacecraft for subsequent downlink to ground. They provide a good compromise between data volume and information content, allowing the scientists to perform further processing and analysis on-ground.

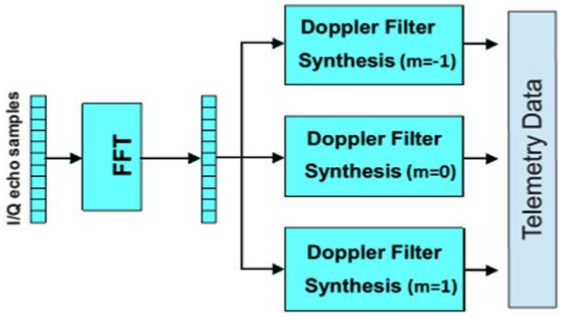

Fig. 2.5 Doppler Processing Telemetry Data

Range Compression processing is then executed by MARSIS on the central Doppler Filter data, followed by Surface Echo Tracking. As previously stated, Surface Echo Tracking results are used to fine-tune echoes reception in the next Frame, taking into account the surface echo delay measured into current frame.

This common way of operating the instrument, called "Subsurface Sounding", allows us to observe Mars continuously for up to ~30 minutes (a ground track ~1200 Km wide), without overloading the Spacecraft resources in terms of data rate and data volume capabilities.

Subsurface Sounding is usually performed when the Spacecraft altitude relative to Mars is lower than about 900 Km and higher than about 240 Km. In particular, the lower limit of 240 Km altitude, which is lower than the common Spacecraft Martian orbit pericenter altitude, is also a physical limitation implemented in MARSIS instrument as the lower *Trigger* value programmable for the RX gates positioning, as shown in Fig. 2.6:

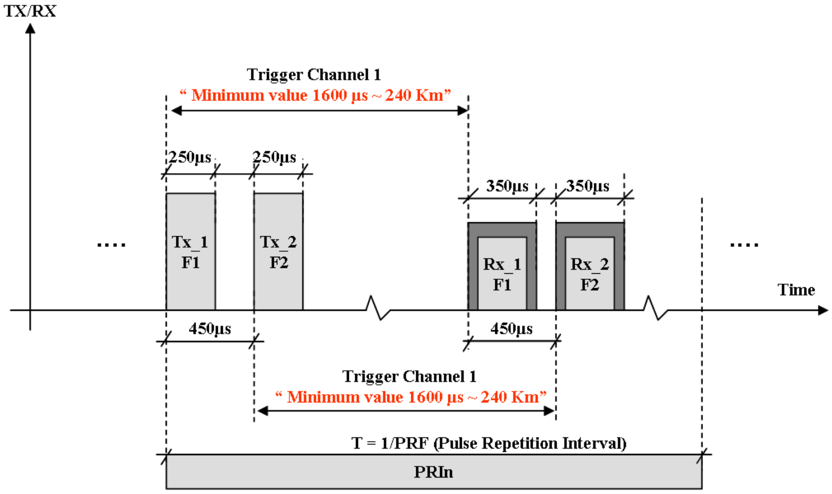

Fig. 2.2 RX Trigger Constraints

The Subsurface Sounding operative mode we initially designed was therefore optimized for Mars observation, but it was not suitable for Phobos probing, as the most favorable observation condition for Phobos is typically when Spacecraft altitude relative to Phobos is lower than 240Km, due to the small dimension of the target in comparison of the MARSIS swath width.

3 SYSTEM CONSTRAINTS AND SCIENCE REQUIREMENTS

Due to the small Phobos's dimensions and its low surface reflectivity index at the MARSIS operative frequencies, it is not possible to take advantage of the on-board processing capabilities of the instrument. That is, the nominal Subsurface Sounding on-board processing applied on Phobos would provide unreliable results, both for science (results of the Doppler Processing) and echo signal tracking (capability to optimize the surface echoes reception). Moreover, as explained before, a physical design limitation prevents MARSIS to operate when the target range is lower than 240Km.

In order to successfully observe Phobos at a distance closer than 240Km we therefore decided to apply the following strategy:

- Disable the automatic tracking capability of the on-board software, relying only on the predicted observation geometry parameters.
- Use the same frequency for the two transmitted pulses and manipulate the observation geometry injecting a range offset of 450µs, in order to reduce the observation altitude limitation from 240Km to ~ 180Km.
- Make use of a dedicated storage called Flash Memory (FM) that allows to store a limited but still significant amount of continuous raw unprocessed data, that, once transmitted on ground, can be processed with dedicated algorithms.

The removal of the tracking phase is not an issue for Phobos observation. Indeed, the main task of the tracking is to remove, from the radar signal, the extra delay time introduced by the Martian ionosphere. The absence of such constraint for Phobos, allows the evaluation of the trigger value for the reception of surface echoes, considering only the predicted Spacecraft Height and the speed of the light in the vacuum. Moreover, also the various processing phases need to be modified, since they are designed to achieve the best performances in the case of Mars observation. In particular, was decided to collect a single synthetic aperture (Super-Frame), instead of a number of frames scarcely reliable for Phobos analysis (see Fig. 3.1).

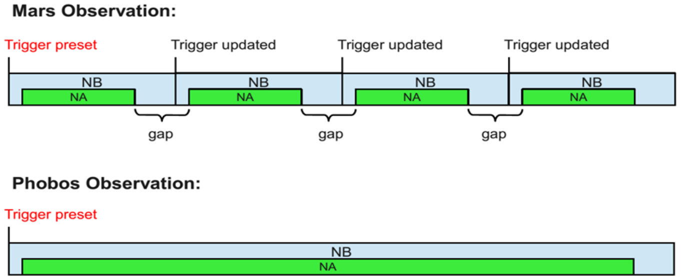

Fig. 3.1 Super Frame

For this aim, we condition the on-board Frame Size estimation, enlarging the N_o parameter value in Eq. (1), so that a single “Super-Frame” will be executed during the observation, instead of a sequence of subsequent short Frames. This settings, together with the possibility to send on ground the raw radar signal using the FM feature, allow to process the data in optimal way.

Considering the small dimensions and the irregular shape of Phobos, the possibility to reduce the minimum altitude at which perform the observations is very important in order to improve the SNR of the received signals. This achievement is obtained through the so called “Range Ambiguity” technique (see Fig. 3.2), that consists in the evaluation of the Trigger offset as follow:

$$Trigger = E\left[\frac{2H_{amb}}{c}\right] - \Delta t \quad (6)$$

where H_{amb} variable represents the Spacecraft Height with an offset of 450μs ($H_{amb} = H + 450\mu s$) and Δt value is a margin that takes into account the potential inaccuracy of predicted Spacecraft altitude relative to Phobos. Adding this offset we force the instrument to receive the echo of the second transmitted pulse (“echo F2” in Fig. 3.2) into the first receiving window. Echo of the first transmitted pulse (“echo F1” in Fig. 3.2) is therefore lost and the second receiving window will sample just cosmic noise, but thanks to the “Range Ambiguity” we can reduce the observation altitude limitation from 240Km to ~ 180Km greatly improving the performance of Phobos Observation. Anyway, the range ambiguity approach is possible only adopting the same frequency on both channels, otherwise the receiving phase doesn’t work.

It is worth noting that, having a single Super-Frame we need to be extremely careful in the evaluation of the preset value for the Trigger, as this preset value will remain fixed for the overall duration of the Super-Frame

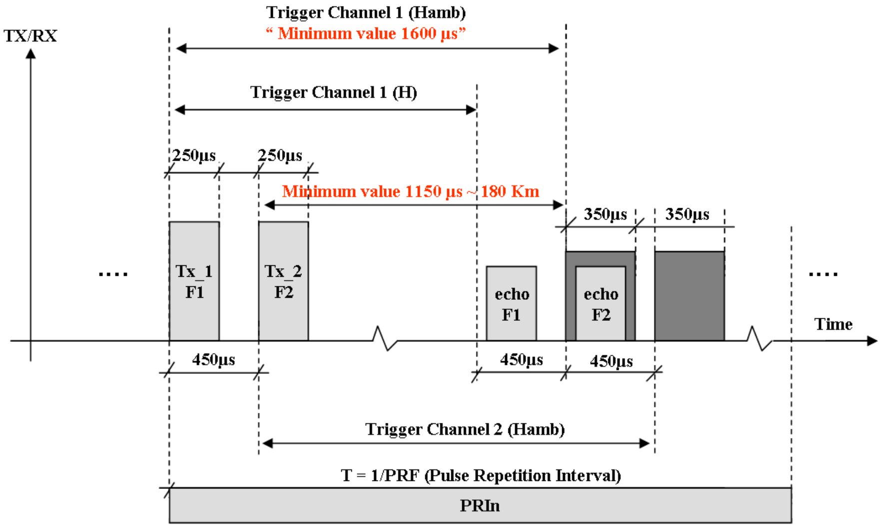

Fig. 3.2 RX Timings with Range Ambiguity

4 DATA ACQUISITION STRATEGY

MARSIS is equipped with **16.77MByte** of Flash Memory devices dedicated to raw data storage.
The use of this feature is conditioned by some design constraints:

- raw data received during a single Frame are initially stored into a temporary buffer
- stored data need then to be entirely moved from the temporary buffer to non volatile memory, before new data can be acquired.

Due to the intrinsic data write latency of FM devices, raw data need to be at first stored into temporary RAM buffers (one for each received channel). Each RAM buffer can store up to **3.21 MByte** of data. The time required for data transfer and storage into FM is ~**7.0µs** per byte (1.1429 bit/µs). While data transfer to FM is in progress no raw data acquisition to RAM buffers may be executed. Given these constraints the following considerations apply when we design a Phobos observation:

- For each PRI a single received echo, after A/D conversion, is made of 980 8-bit samples. The maximum number of consecutive echoes we can acquire is therefore given by the following equation:

$$N_{Echoes} = \frac{Buffer_{Dimension}}{Echo_{Dimension}} \approx \quad (7)$$

- Keeping a margin of 70 PRI, the maximum synthetic aperture size (NA) of a Super Frame is equal to 3200 PRI per radar channel.

- The time necessary to transfer 6400 PRI (3200 PRI per channels) from RAM buffers into FM devices is given by the following equation:

$$readout_{Time} = 6400[PRI] \cdot 980[samples] \cdot 1[byte] \cdot 7 \cdot 10^{-6} \approx 44\text{sec} \quad (8)$$

- Considering the PRF of 127.267[Hz] the duration of each super frame is given by the following equation:

$$Superframe_{Duration} = \frac{1}{PRF} \cdot 3200PRI \approx 25.14\text{sec} \quad (9)$$

- Given the total capacity of FM devices the maximum number of Super Frames we can acquire in a single Phobos observation is given by the following equation:

$$N_{SuperFrames} = \frac{Flash_{Memory_{Dimention}}[Byte]}{3200[PRI] \cdot 2[channels] \cdot 980[samples] \cdot 1[byte]} \approx 2.6 \quad (10)$$

In order to maximize the quality of the acquired data, taking into account all of the above consideration and depending on:

- the Spacecraft Altitude at pericenter
- the Spacecraft Radial Velocity near pericenter

we apply one the two following strategies:

1) two Super Frames, symmetric with respect to pericenter. This is typically used when the closest approach altitude is lower than 180Km and the Spacecraft stays at an altitude lower than 180Km for more than 25 seconds, as shown in Fig. 3.3

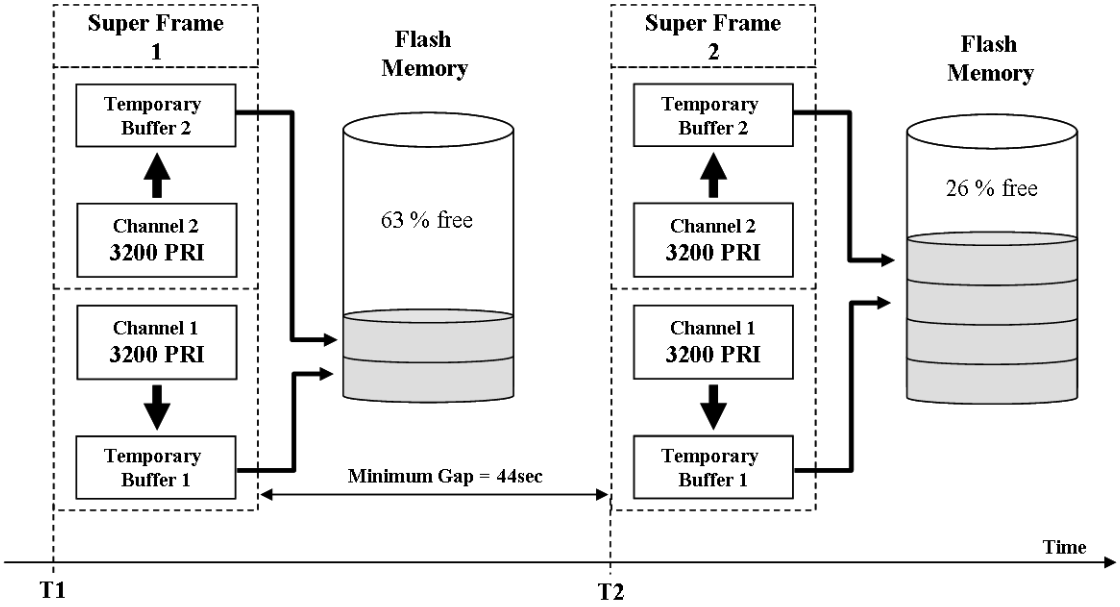

Fig. 3.3 Two Super Frames acquisition technique

2) a single Super Frames, centered on pericenter. This is typically used when the closest approach altitude is higher than 180Km, as shown in Fig. 3.4

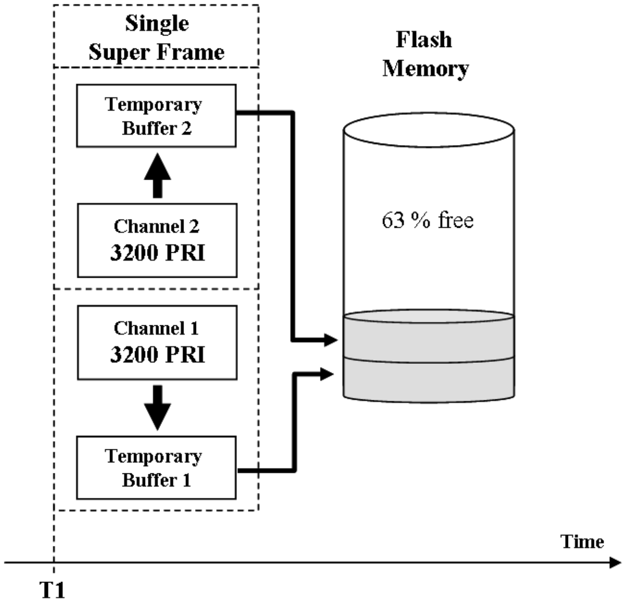

Fig. 3.4 One Super Frame acquisition technique

In the following paragraphs the results obtained applying these two observation strategies will be presented analyzing the data collected in two of the main representative Phobos flybys.

5 PHOBOS FLYBY 12-MARCH-2015

This flyby took Mars Express to fly very close to Phobos with a minimum approach distance of only 47.82 Km from the surface of the Martian moon. The most appropriate observation strategy for this scenario foresees two Super Frames, symmetric with respect to Phobos Pericenter. Fig. 5.1 shows the simulation over about 4.5 minutes cross Pericenter. The red area represents the instrument protection zone, where it is not possible to operate. The thin blue and red curves represent the ideal receiving windows boundaries for acquiring the two echoes reflected by the Phobos's surface in response to the two chirp waves transmitted by the radar. These ideal values vary following the Phobos range profile. The marked blue and red lines represent the real boundaries we programmed for receiving the two echoes. They are constant values, as it's not possible to make use of the automatic echoes tracking feature of MARSIS when we observe Phobos.

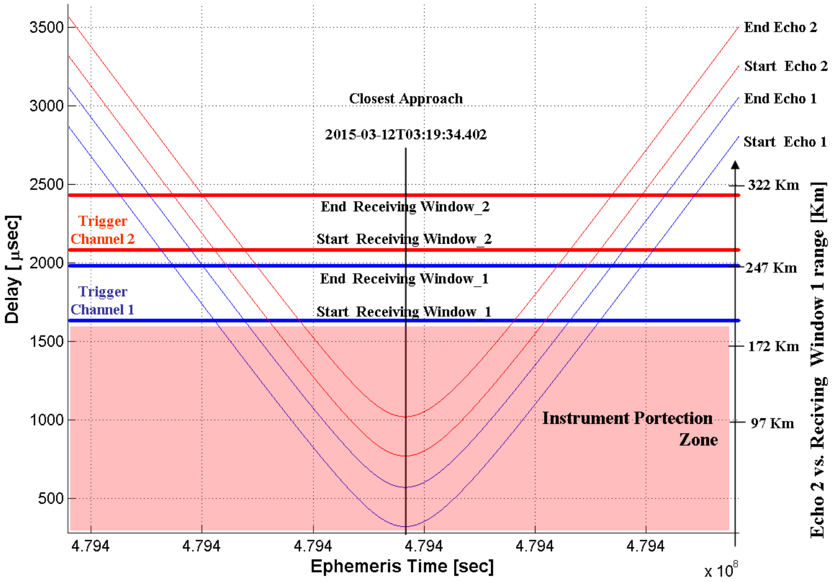

Fig. 5.1 Overall architecture of the Transmitting and Receiving phase

Once fixed the receiving windows boundaries, we had to calculate the exact timing of the two Super Frames, before and after the Phobos's Pericenter. Fig. 5.2 shows the areas of interest for the approach frame. From T2 to T3 it is possible to collect up to 697 full echoes, however considering that the optimal size for a single Super Frame is 3200 echoes it is worth to collect additional 2503 reduced echoes. The best solution was therefore to enable the Super Frame 2503/2 PRI before T2. This configuration was expected to produce 1252 reduced echoes before T2 and 1252 reduced echoes after T3. Due to some inaccuracy of the predicted orbital parameters we obtained a slightly different distribution of the data in the real observation, as reported in Fig. 5.3.

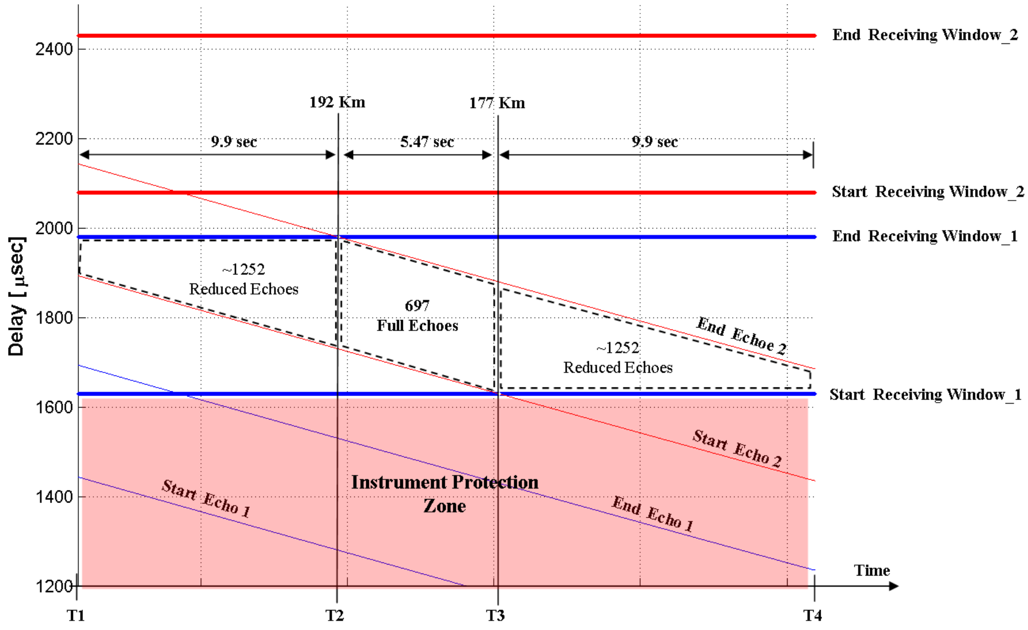

Fig. 5.2 Approach Super Frame, planned data collection

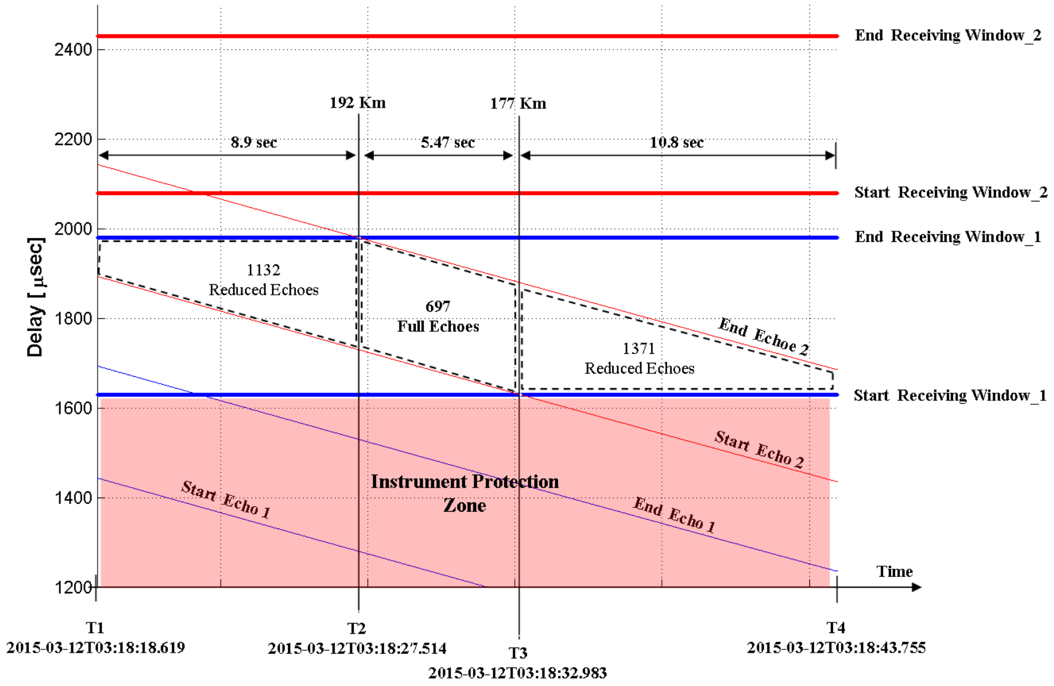

Fig. 5.3 Approach Super Frame, real observation data collection

Similar considerations apply to the departure Super Frame, illustrated in Fig. 5.4. In this case we obtained in the real observation 702 full echoes instead of the expected 697. This discrepancy is due to a little asymmetry of the flyby geometry itself.

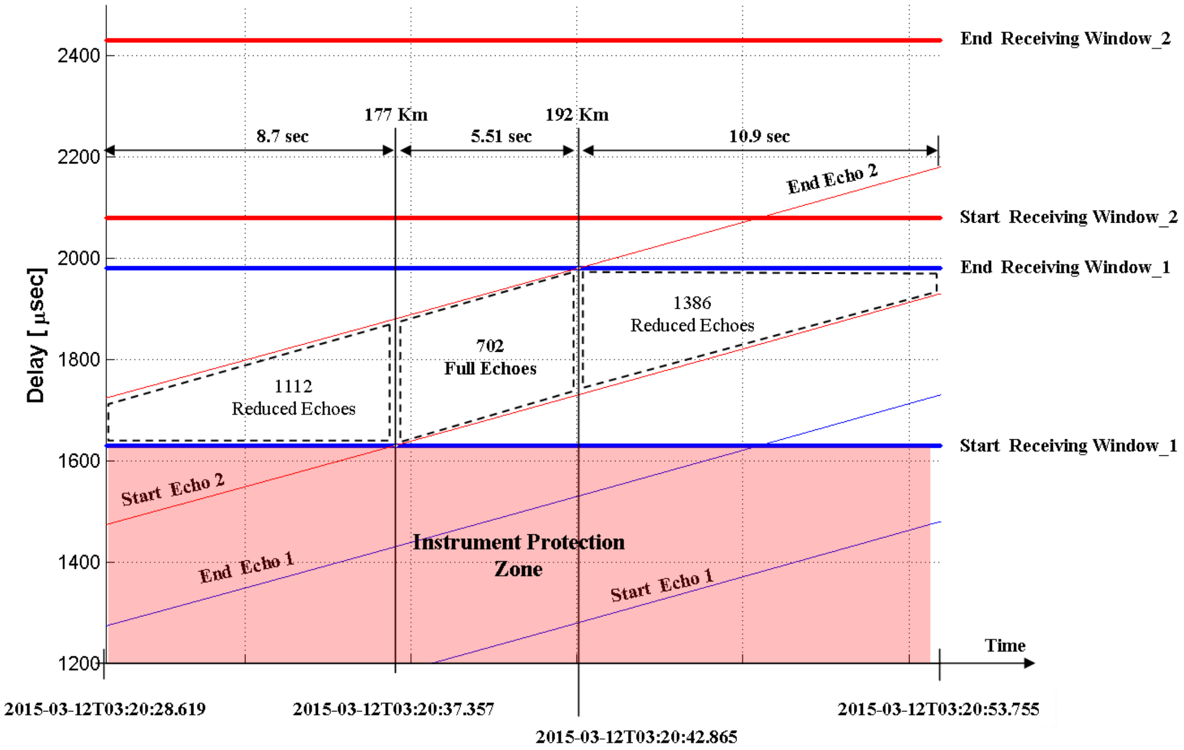

Fig. 5.4 Departure Super Frame, real observation data collection

The on-ground processing results of the collected data are visualized in Fig. 5.5 for the Approach Super Frame. In particular, in the top panel the raw signals have been just compressed in Range with the ideal Chirp, without any other manipulation like for example the range compensation. Two dark red lines, that represents the echoes reflected by the Phobos's surface, are just about visible; the maximum Signal To Noise Ratio (SNR) is only 8 dB. The slope of the two traces are due to the distance from the Phobos's surface to the Radar that gradually decrease over time.

The presence of two separated traces is a side effect of the Discrete Fourier Transform, which focuses the signal's energy, initially spread over 250 µs, in a single µs at the beginning of the signal itself. Feeding the Discrete Fourier Transform with a signal truncated of its initial part (X µs truncation at the beginning of the signal), as happens after time T3 in Fig. 5.3, produces a shift in time-domain compressed signal equal to 350 µs - X µs.

Middle panel of Fig. 5.5 shows the result obtained applying Azimuth Compression on the Range compressed signal, in order to improve the SNR. The two traces are much more evident, with a maxim SNR value of 16 dB. The Azimuth Compression consists of summing groups of echoes (30 Range Compressed echoes), after compensating the linear term of the signal's phase.
In bottom panel of Fig. 5.5 the Azimuth Compressed signals have been just realigned compensating the effect of Phobos to Spacecraft range variation over time.

A double signature, highlighted by the letters "a" and "b", is well evident in the middle and bottom panels of Fig. 5.5. The nature of the second signature is still under investigation: it might be a secondary echo arising from a subsurface interface or coming from surface topographic features causing a reflection at the same time delay (surface ‘‘clutter’’).

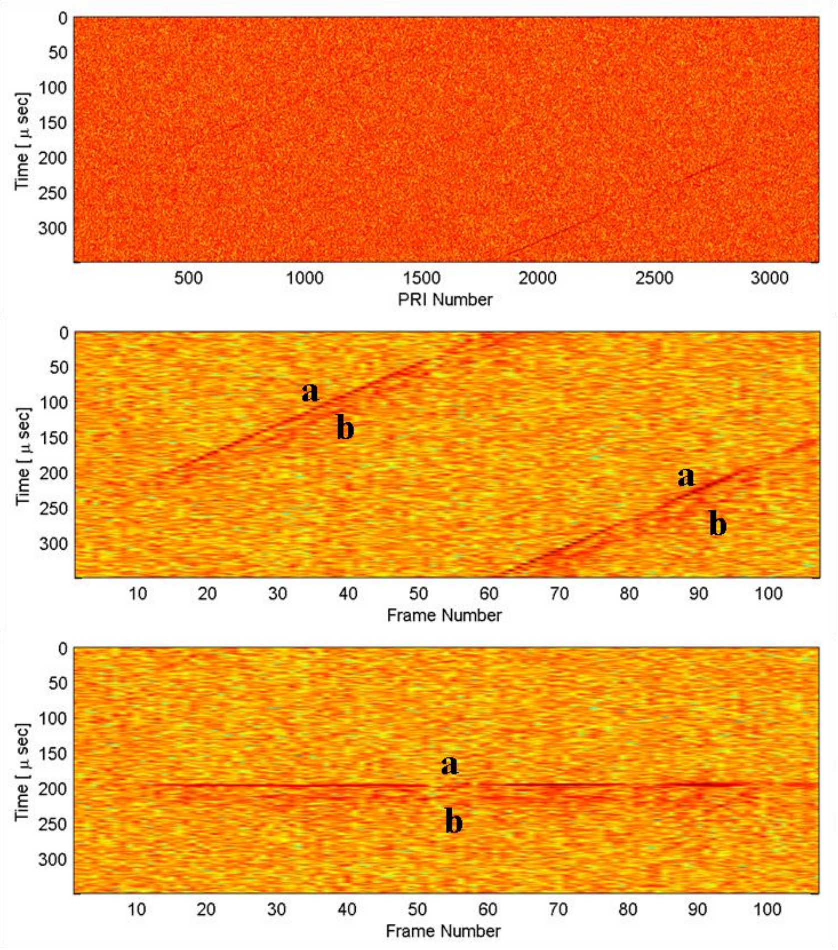

Fig. 5.5 Approach Super Frame processing results

We applied the same processing and analysis to the data acquired in the departure Super Frame. Fig. 5.6 presents the results we obtained. In this case no double signature is visible, meaning that no sources of secondary echo (either subsurface interface or surface topographic features) were present in the portion of Phobos probed in the departure segment of the flyby.

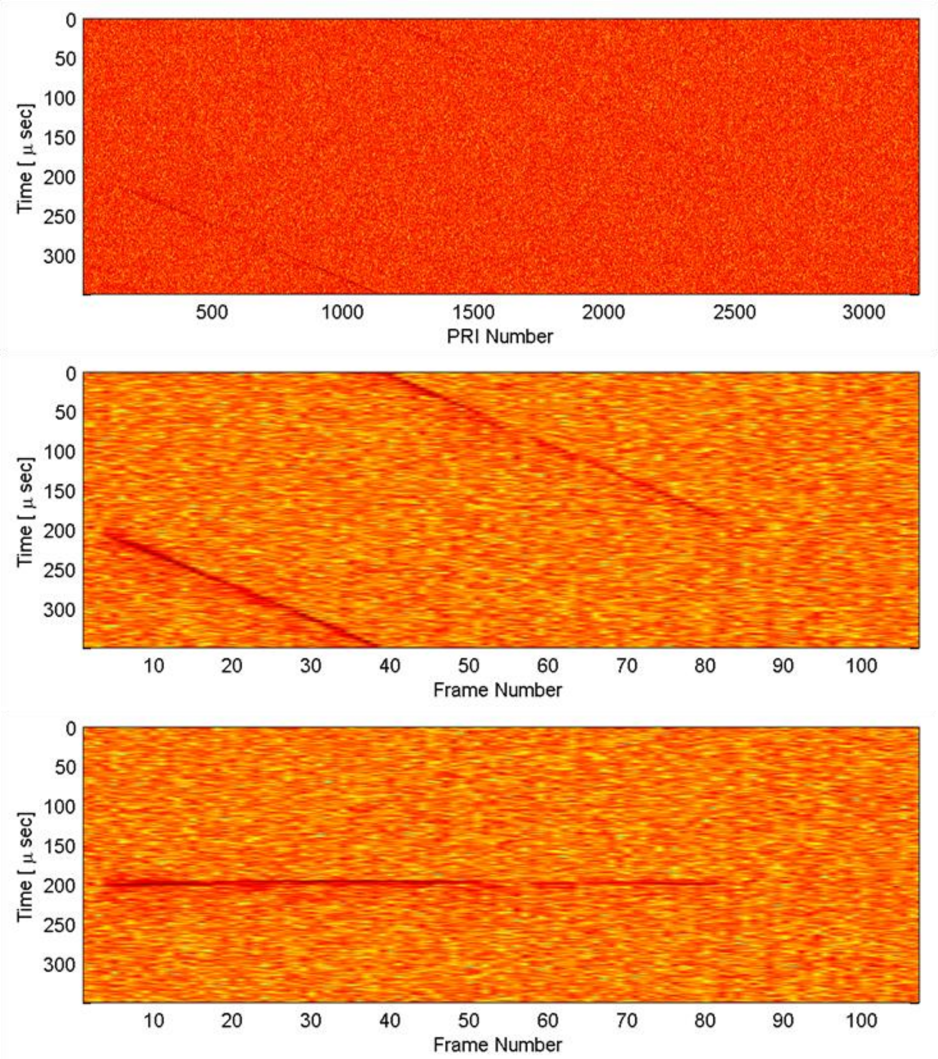

Fig. 5.6 Departure Super Frame processing results

6 PHOBOS FLYBY 14-MAY-2015

In this second flyby the closest approach distance from Phobos surface was estimated to be about 208 Km, as shown in Fig 6.1. In this case the observation strategy we adopted was the single Super Frame centered on Pericenter. Due to the particular flyby geometry we could collect up to 3200 full echoes in the single Super Frame (see Fig. 6.2).

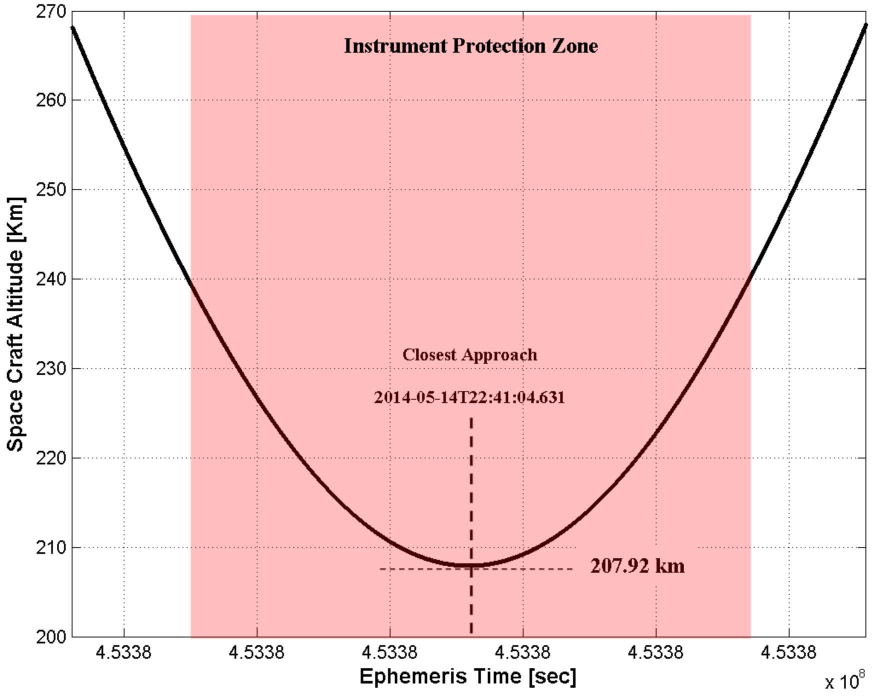

Fig. 6.1 Spacecraft altitude versus instrument protection zone

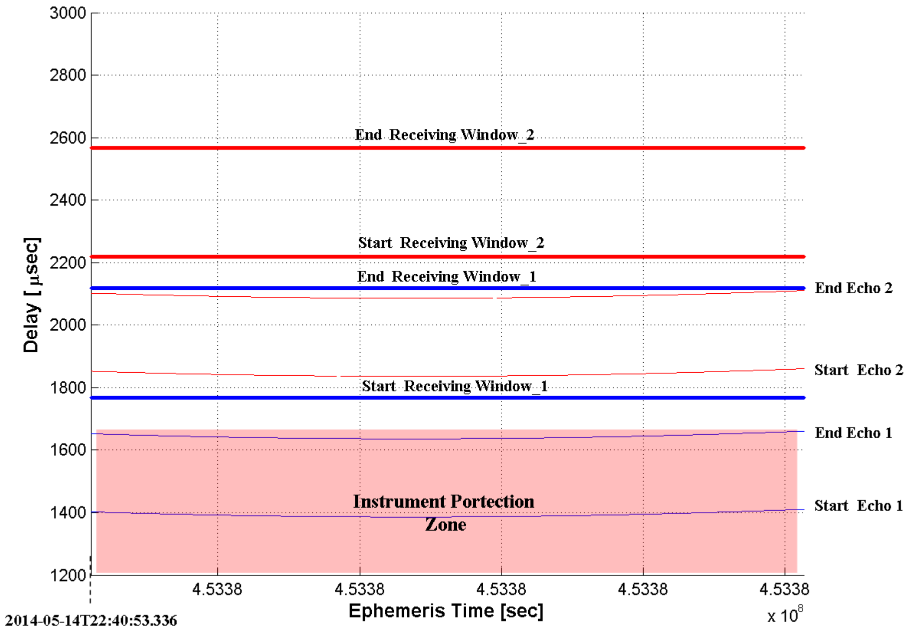

Fig. 6.2 Single Super Frame, real observation data collection

Data processing results are shown in Fig. 6.3. No time shifts are present in the range compressed data presented in the top panel, as all the collected echoes are full signals, with a maximum SNR of 11.6 dB. In the middle panel is again well evident the substantial improvement of the SNR, with a maximum value of 21.5 dB applying the Azimuth Compression on the Range-Compressed data. The realigned range-compensated data in bottom panel make a little bit more evident the presence of a faint secondary signature barely visible in the middle panel, highlighted by the letters "a" in Fig. 6.3, also in this case the nature of this signature is still under investigation.

It is interesting to note that in this second flyby the data quality is much better than the previous one, even though it was further away. The potential explanation of this inconsistency on the science results, is mainly due to the following factors: surface topography, surface roughness, surface reflectivity and Space Craft pointing.

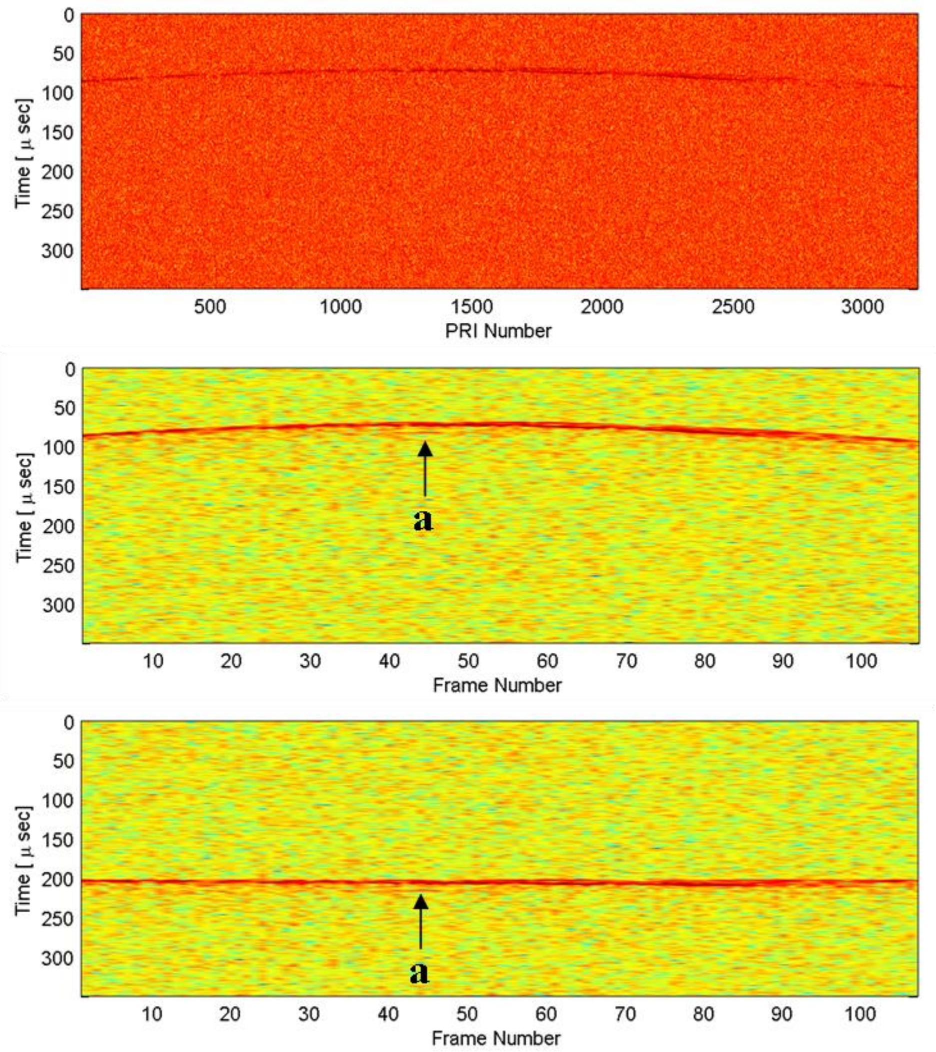

Fig. 6.3 Radargram: Phobos flyby 14-May-2015