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1 **Observations of Phobos by the Mars Express radar MARSIS: Description of the**
2 **detection techniques and preliminary results**

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19 **Keywords:** Phobos; Mars; Radar; Mars Express ESA mission; MARSIS; Ground penetrating radar.

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26 **ABSTRACT**

27

28 The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et
29 al., 2005) is a synthetic aperture low frequency radar altimeter, onboard the ESA Mars Express
30 orbiter, launched in June 2003. It is the first and so far the only spaceborne radar that has observed
31 the Martian moon Phobos. Radar echoes were collected on different flyby trajectories. The primary
32 aim of sounding Phobos is to prove the feasibility of deep sounding, into its subsurface.

33 MARSIS is optimized for deep penetration investigations and is capable of transmitting at four
34 different bands between 1.3 MHz and 5.5 MHz with a 1 MHz bandwidth. Unfortunately the
35 instrument was originally designed to operate exclusively on Mars, assuming that Phobos would not
36 be observed. Following this assumption, a protection mechanism was implemented in the hardware
37 (HW) to maintain a minimum time separation between transmission and reception phases of the
38 radar. This limitation does not have any impact on Mars observation but it prevented the
39 observation of Phobos.

40 In order to successfully operate the instrument at Phobos, a particular configuration of the MARSIS
41 onboard software (SW) parameters, called "Range Ambiguity," was implemented to override the
42 HW protection zone, ensuring at the same time a high level of safety of the instrument.

43 This paper describes the principles of MARSIS onboard processing, and the procedure through
44 which the parameters of the processing software were tuned to observe targets below the minimum
45 distance allowed by hardware.

46 **Some preliminary results of data analysis will be shown, with the support of radar echo**
47 **simulations. A qualitative comparison between the simulated results and the actual data, does**
48 **not support the detection of subsurface reflectors.**

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51

52 **1. Introduction**

53

54 Mars Express, the first European interplanetary mission, was designed to provide global
55 coverage of Mars' surface, subsurface, atmosphere and to study the Martian moons, Phobos and
56 Deimos (Chicarro et al., 2004). The Mars Advanced Radar for Subsurface and Ionosphere Sounding
57 (MARSIS) is one of the seven scientific instruments onboard of Mars Express orbiter. Its primary
58 goal is to search for water, both solid and liquid, in the subsurface of Mars. MARSIS, in order to
59 penetrate the surface and detect dielectric discontinuities, due to subsurface layers, transmits radio
60 signals characterized by low frequencies and wide band (Picardi et al., 2004).

61

62 With the aim to achieve these ambitious scientific goals and in order to cope with some limitation
63 imposed by the mission characteristics, such as the limited data-rate provided by the spacecraft and
64 the limited available downlink data volume, it was necessary to design an instrument with high
65 computational capabilities.

66

67 For these reasons, the onboard software is characterized by a high grade of flexibility that allows
68 the possibility to modify the signal processing in order to face unpredictable issues arising during
69 the mission. This capability was very useful when, after several years of Mars observation, Phobos
70 became a scientific objective for MARSIS too (Cicchetti et al., 2011).

71

72 **Phobos is a non-spherical body with a mean radius of 11 km, and its quasi circular orbit is**
73 **located on the equatorial plane of Mars. The distance from Phobos to the center of Mars is**
74 **about 9378 km while the orbital period is 7,65 hours.**

75

76 **The origin of Phobos, in spite of 45 years of spacecraft observations, is still debated (Duxbury**
77 **et al., 2014). The two main hypotheses on the origin of this moon are in situ formation and**

78 **asteroidal capture. Considering size, shape and past estimations of composition (Burns, 1978;**
79 **Forget et al., 2008; Murchie et al., 1991), the the theory of the asteroidal capture origin was**
80 **avored by the majority of researchers. However, more recent studies (Andert et al., 2010;**
81 **Giuranna et al., 2011; Pätzold et al., 2014; Rosenblatt et al., 2010; Witasse et al., 2014)**
82 **support the conclusion that the composition and bulk density are more consistent with the in**
83 **situ formation scenario. Thus, the moon is likely to have formed from a disk of impact ejecta**
84 **produced by a giant collision early in Mars history.**

85

86 The Martian moon could be observed during several close flybys, thanks to the high eccentricity of
87 the Mars Express orbit (Witasse et al., 2014). The first observation executed with the MARSIS
88 radar, was taken on November 4th 2005 (orbit 2323) . The shortest distance between the radar
89 antenna and the Phobos surface was only 215 km, that allowed to obtain a good signal to noise ratio
90 (SNR) of ~25 dB after the on ground data processing. Subsequent flybys allowed observations even
91 within 100 km of the surface (Safaenili et al., 2009).

92 In many Phobos flybys observed by the radar so far, we have been able to identify several
93 interesting secondary echoes, that could be generated either by surface lateral clutter or by sub-
94 subsurface reflectors.

95 **In order to discriminate between the two possible origins of detected echoes, an incoherent**
96 **surface backscattering simulator (Russo et al., 2008) was used.**

97 **The simulations, which try to reproduce the radar signal backscattering, use the digital**
98 **elevation model made available by the High Resolution Stereo Camera (HRSC) science team**
99 **(Willner et al., 2013), and were computed for one of the closest flybys.**

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104 2. Mars observation fundamentals

105

106 A typical MARSIS observation of Mars consists of a sequence of synthetic apertures
107 (frames), a Frame being a set of Pulse Repetition Intervals (PRIs) as shown in Fig. 1 and Fig. 2.

108

109 Each MARSIS observation Frame is made of the following sequence of operations performed
110 onboard:

111

- 112 - Initial orbital parameter estimation, including Frame size estimation (NB, number of PRIs).
- 113 - Synthetic aperture size estimation (NA₁ PRIs for the first band, NA₂ PRIs for the second band).
- 114 - Signal transmission (2 pulses) and echo reception, repeated NA₁ times and NA₂ times.
- 115 - Signal Processing for both the bands.

116

117 The frame size NB is computed adaptively during the flyby in order to obtain contiguous synthetic
118 apertures, so that their relative separation precisely matches with the distance covered by the
119 spacecraft, in the time elapsed between the two apertures. This guarantees the continuous coverage
120 along the orbit track.

121

122 The space to be covered by the spacecraft during NB pulses, related to a single frame, is computed
123 first as:

124

$$125 \Delta S = \sqrt{\frac{\lambda_1 \cdot H}{2}} + N_o \cdot \frac{V_{Tan}}{PRF} \quad (1)$$

126

127 where **PRF** is the Pulse Repetition Frequency (1/PRI = 127.267 Hz), **N_o** is a constant offset of 36
128 PRIs, **λ₁** is the wavelength of the lowest Operative Frequency in use (available center frequencies

129 are 5Mhz, 4MHz, 3MHz and 1.8MHz), \mathbf{H} and \mathbf{V}_{Tan} are the spacecraft altitude and the tangential
130 velocity respectively.

131

132 Frame size NB is then computed as :

133

$$134 \quad NB = Int \left[\frac{\Delta S}{V_{Tan}} \cdot PRF \right] \quad (2)$$

135

136 Synthetic aperture sizes \mathbf{NA}_1 and \mathbf{NA}_2 are also adaptively computed for each of the operative
137 frequencies in use:

138

$$139 \quad NA_1 = Int \left[\lambda_1 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_1 \cdot V_{Tan} \cdot \Delta S} \right] \quad (3)$$

140

$$141 \quad NA_2 = Int \left[\lambda_2 \cdot \frac{H \cdot PRF}{2 \cdot \gamma_2 \cdot V_{Tan} \cdot \Delta S} \right] \quad (4)$$

142

143 Where γ_1 and γ_2 are corrective frequency dependent values, necessary to obtain the same azimuth
144 resolution in different bandwidths.

145

146 A single PRI operation, repeated NA times ($NA = \max(NA_1, NA_2)$), will then include signal
147 transmission and echo reception, according to the scheme shown in Fig. 3.

148

149 MARSIS transmits two rectangular pulses, each one 250 μ s long, modulated in frequency (chirp)
150 with a 1 MHz bandwidth centered on the selected operative frequency. **In this way the radar free-**
151 **space range resolution is approximately 150m (Cook and Bernfeld, 1967, eq. 1-19), which**

152 **corresponds to 50-100 m in the subsurface, depending on the real dielectric constant of the**
153 **subsurface.** The time delay between the two transmitted pulses is fixed at 450 μs , while the *Trigger*
154 values for receive (RX) gate positioning are adaptively computed for each frame taking into account
155 the spacecraft height and the ionosphere effect (Safaenili et al., 2003), which introduces a delay
156 that can be from 50 up to 150 μs . The first frame (*Frame 1*) *Trigger* values are computed with the
157 following equation:

$$159 \quad \text{Trigger} = \frac{2 \cdot H}{c} [\mu\text{s}] + \Delta t \quad (5)$$

160
161 where c is the speed of light in the free space, H is the spacecraft altitude and Δt is a preset offset
162 added to compensate for the ionosphere delay. For the subsequent frames (*Frame n*, $n > 1$) *trigger*
163 values are estimated using the results of the surface echo tracking processing executed on the
164 preceding frame (*Frame n-1*).

165
166 During each synthetic aperture NA₁/NA₂ PRI's received echoes are processed by MARSIS in order
167 to synthesize three Doppler filters. The geometric configuration of the doppler filters is obtained
168 using a different phase factor in order to observe different areas on the surface. In particular the
169 Doppler Filter 0 (in the along track direction) is nadir pointing, while the Doppler Filter -1 is
170 looking ahead and the Doppler Filter +1 is looking behind.

171
172 Range compression processing is then executed by MARSIS on the central Doppler filter data,
173 followed by surface echo tracking. As previously stated, surface echo tracking results are used to
174 fine tune echo reception in the subsequent frame, taking into account the surface echo delay
175 measured in the current frame.

176

177 This common way of operating the instrument, called “subsurface sounding,” allows us to observe
178 Mars continuously for up to ~30 minutes (a ground track ~1200 km long), without overloading the
179 spacecraft resources in terms of data rate and data volume capabilities.

180 **An example of the resulting radargram is shown for Band 2 (3MHz) and Band 3 (4MHz) in**
181 **Fig. 4, representing a typical MARSIS observation over Olympus Mons acquired in orbit**
182 **6051. The surface trace follows the profile expected from MOLA topography.**

183

184 Subsurface sounding is usually performed when the spacecraft altitude relative to Mars is between
185 900 km and 240 km. In particular, the lower limit of 240 km altitude, which is lower than the
186 typical Mars Express orbit pericenter altitude, is also a physical limitation implemented in MARSIS
187 instrument as the lowest *trigger* value programmable for the RX gate positioning, as shown in
188 Fig. 3.

189 The subsurface sounding operative mode we initially designed was therefore optimized for Mars
190 observation, but it was not suitable for Phobos, as the most favorable observation condition for
191 Phobos is typically when spacecraft range to Phobos is less than 240 km, due to the small
192 dimension of the target.

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203 3. System Constraints and Science Requirements

204

205 Due to Phobos' small dimensions, it is not possible to take advantage of the onboard
206 processing capabilities of the instrument. That is the nominal subsurface sounding onboard
207 processing, applied to Phobos would provide unreliable results, both for science (results of the
208 Doppler processing) and echo signal tracking (capability of optimizing the surface echo reception).
209 Moreover, as explained before, a physical design limitation precludes MARSIS operation, when the
210 target range is less than 240 km.

211

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

214

215 – Disable the automatic tracking capability of the onboard software, relying only on the
216 predicted observation geometry parameters.

217

218 – Use the same frequency for the two transmitted pulses and manipulate the observation by
219 injecting a range offset of $450\mu\text{s}$, in order to reduce the observation altitude limitation from
220 240 km down to ~ 180 km.

221

222 – Make use of a dedicated storage called Flash Memory (FM) that allows us to store a limited
223 but still significant amount of continuous raw unprocessed data, that once transmitted to the
224 ground can be processed with dedicated algorithms.

225

226 The removal of the tracking phase is not an issue for Phobos observations. Indeed, the main task of
227 the tracking is to remove the extra time delay introduced by the Martian ionosphere from the radar
228 signal. The absence of this constraint for Phobos allows the evaluation of the trigger value for the

229 reception of surface echoes, considering only the predicted spacecraft range and the speed of light
230 in free space.

231 The various processing phases also need to be modified, since they are designed to achieve the best
232 performance in the case of Mars observation. In particular, we decided to collect a single synthetic
233 aperture (“super frame”), instead of a number of short frames separated by gaps that would be less
234 useful for science analysis (see Fig. 5).

235

236 For this aim, we condition the onboard frame size estimation, enlarging the N_o parameter value in
237 Eq. (1), so that a pair of super frames will be executed during the observation. These settings,
238 together with the capability to send to the ground the raw radar signals using the FM feature, allow
239 us to process the data in an optimal way.

240

241 Due to the small dimensions and the irregular shape of Phobos, the possibility of reducing the
242 minimum altitude of the observations is important in order to improve the SNR of the received
243 signals. **Considering the well-known equation of the Signal To Noise Ratio (SNR) (Skolnik,**
244 **1990, eq. 1.1-1.4):**

245

$$246 \quad SNR = \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 H^4 k T_s B} \quad (6)$$

247

248 **Where P_t is the transmitted power, G_t the antenna gain, λ the wavelength, σ the radar cross**
249 **section, H the spacecraft altitude, k the Boltzmann's constant, T_s the system noise**
250 **temperature and B the receiver bandwidth. The theoretical improvement of the SNR, due to a**
251 **reduction of the operative altitude, is given by the following relation:**

252

$$253 \quad \Delta_{SNR}|_{dB} = 40 \cdot \log_{10} \left(\frac{H_1}{H_2} \right) \quad (7)$$

254

255 **Where H_1 is the minimum S/C altitude allowed by the instrument protection mechanism and**
256 **H_2 is the reduced altitude achieved injecting a range offset of $450\mu\text{s}$. Considering $H_1=240$ km**
257 **and $H_2= 180$ km, the improvement of the SNR is $\sim 5\text{dB}$.** This achievement is obtained through the
258 so called “range ambiguity” technique (see Fig. 6), that consists in the evaluation of the trigger
259 offset as follows:

260

$$261 \quad \text{Trigger} = \frac{2 \cdot H_{amb}}{c} [\mu\text{s}] - \Delta t \quad (8)$$

262

263 where H_{amb} represents the spacecraft height with an offset of $450\mu\text{s}$ ($H_{amb} = H + 450\mu\text{s}$) and the
264 value of Δt is a margin that takes into account the potential inaccuracy of predicted spacecraft range
265 to Phobos.

266 Adding this offset we force the instrument to receive the echo of the second transmitted pulse
267 (“echo F2” in Fig. 6) into the first receiving window (Rx_1_F1). The echo of the first transmitted
268 pulse (“echo F1” in Fig. 6) is therefore lost and the second receiving window (Rx_2_F2) will
269 sample just cosmic noise. **For this reason it is necessary to set the same frequency for both**
270 **transmitted bands, so that the receiver of the first receiving window is correctly configured**
271 **for the signal detection.** Thanks to the range ambiguity technique we can reduce the observation
272 altitude limitation, from 240 km down to ~ 180 km, thus improving the SNR.

273 The planning of a single super frame requires careful evaluation of the preset value for the trigger,
274 as this will remain fixed for the overall duration of the flyby.

275

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281 4. Data Acquisition Strategy

282

283 MARSIS is equipped with **16.77MByte** of Flash Memory device dedicated to raw data
284 storage.

285 The use of this feature is affected by some design constraints:

286

- 287 – raw data received during a single frame are initially stored in a temporary buffer
- 288 – stored data need then to be entirely moved from the temporary buffer to non-volatile
289 memory before new data can be acquired.

290

291 Due to the intrinsic data write latency of FM device, raw data need to be first stored into temporary
292 RAM buffers (one for each received channel). Each RAM buffer can store up to 3.21 MByte of
293 data. The time required for data transfer and storage into FM is $\sim 7.0\mu\text{s}$ per byte. While data transfer
294 to FM is in progress no raw data acquisition to RAM buffers may be executed. Given these
295 constraints the following considerations apply when we design a Phobos observation:

296

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

300

$$301 N_{\text{Echoes}} = \frac{\text{Buffer}_{\text{Dimension}} - \text{Header}_{\text{Dimension}} [\text{Byte}]}{\text{Echo}_{\text{Dimension}} [\text{Byte}]} \approx 3270 \quad (9)$$

302

303 Where the Header is a packet of ancillary data, automatically inserted by the onboard SW in
304 order to identify the echoes stored into the FM.

305

306 • Keeping a margin of 70 PRI, the maximum synthetic aperture size (NA) of a super frame is
307 equal to 3200 PRI per radar channel.

308

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

311

$$312 \quad readout_{Time} = 6400[PRI] \cdot 980[samples] \cdot 1[byte] \cdot 7 \cdot 10^{-6} \approx 44sec \quad (10)$$

313

314 • Considering the Pulse Repetition Frequency (PRF) of 127.267[Hz] the duration of each
315 "super frame" is given by the following equation:

316

$$317 \quad Superframe_{Duration} = \frac{1}{PRF} \cdot 3200[PRI] \approx 25.14sec \quad (11)$$

318

319 • Given the total capacity of FM device, the maximum number of Super Frames we can
320 acquire in a single Phobos observation is given by the following equation:

321

$$322 \quad N_{SuperFrames} = \frac{Flash_{MemoryDimension} [Byte]}{3200[PRI] \cdot 2[channels] \cdot 980[samples] \cdot 1[byte]} \approx 2.6 \quad (12)$$

323

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

326

327 – the spacecraft altitude at closest approach

328 – the spacecraft radial velocity near closest approach

329

330 we apply one of the three following strategies:

331

332 1) One super frames, centered on closest approach. This is typically used when the closest approach
333 altitude is higher than 180 km, as shown in Fig. 7

334

335 2) Two super frames, symmetric with respect to pericenter. This is typically used when the closest
336 approach altitude is lower than 180 km and the spacecraft is at an altitude lower than 180 km for
337 more than 25 seconds, as shown in Fig. 8

338

339 3) Three super frames, where the first and third super frame are symmetric to pericenter, while the
340 second super frame is centered on closest approach, as shown in Fig. 9. This is typically used when
341 the closest approach altitude is higher than 180 km and the space craft altitude, within the first and
342 third super frame is below 350 km, as that is the maximum space craft altitude to detect Phobos
343 with a reasonable SNR.

344

345 **In the following, results obtained applying the “Two Super Frames Technique” and the**
346 **“Three Super Frames Technique” will be presented, and data collected in two representative**
347 **Phobos flybys will be discussed.**

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356 **5. Application of Two Super Frames Technique (Phobos flyby 26 August 2015, orbit 14776)**

357

358 This flyby took Mars Express very close to Phobos with a minimum approach distance of
359 only 51 km from the surface of the Martian moon. The most appropriate observation strategy for
360 this scenario utilized two super frames, symmetric with respect to the closest approach.

361

362 Fig. 10 shows the simulation over about 4.5 minutes around closest approach. The red area
363 represents the instrument protection zone, where it is not possible to operate. The thin blue and red
364 curves represent the ideal receiving window boundaries for acquiring the two echoes reflected by
365 Phobos' surface from the two chirp waves transmitted by the radar. These ideal values vary
366 following the Phobos range profile. The marked blue and red lines represent the real boundaries we
367 programmed for receiving the two echoes. They are constant values, as it's not possible to make use
368 of the automatic echo tracking feature of MARSIS when we observe Phobos.

369

370 Once the receiving windows boundaries were determined, we had to calculate the exact timing of
371 the two super frames, before and after the closest approach. From T3 to T4 (approach super frame)
372 and from T7 to T8 (departure super frame) it is possible to collect up to 696 full echoes, however
373 considering that the optimal size for a single super frame is 3200 echoes we collected an additional
374 2503 reduced echoes per super frame. The best solution was therefore to enable the first super
375 frame at time T2 (2503/2 PRI before T3) and to enable the second super frame at time T6 (2503/2
376 before T7). Due to some inaccuracy of the predicted orbital parameters we obtained a slightly
377 different distribution of the data in the actual observation, as shown in Fig. 11 and in Fig. 12

378

379 The ground processing results of the collected data are presented in Fig. 13 and Fig. 14, for the
380 approach and departure super frame, respectively.

381

382 In the top panels of Fig. 13 and Fig. 14 the raw signals have been first compressed in range, with
383 the ideal chirp and then in azimuth in order to improve the SNR. The azimuth compression consists
384 of summing groups of echoes (10 range compressed echoes) after compensating the linear phase
385 term of the received signals. The dark red traces (a, b, c, d and e) of Fig. 13 and Fig.14 represent the
386 echoes reflected by the Phobos' surface. The slopes of the traces are due to the distance from
387 Phobos' surface to the radar, that gradually decreases over time for the approach super frame and
388 gradually increase for the departure super frame. The trace (a) of Fig. 13 is due to the tails of the
389 echoes generated by the first transmission phase and received in the first receiving window, as also
390 highlighted by the dotted rectangle "A" of Fig. 11. None of the signals of Fig. 13 and Fig. 14 have
391 been voluntarily realigned, without compensating the effect of Phobos to spacecraft range variation
392 over time, to provide a more realistic acquisition scenario to the reader.

393
394 The presence of separate tracks, "b" and "c" of Fig. 13 and "d" and "e" of Fig. 14 are a side effect
395 of the discrete Fourier transform, which focuses the signal's energy, initially spread over 250 μs ,
396 into a single μs at the beginning of the signal itself. Feeding the discrete Fourier transform with a
397 signal truncated of its initial part ($X \mu\text{s}$ truncation at the beginning of the signal), as happens after
398 time T_4 in Fig. 11 and before time T_7 of Fig. 12, produces a shift in time domain compressed signal
399 equal to $350-X \mu\text{s}$.

400
401 The bottom panels of Fig. 13 and Fig. 14 show the SNR behavior. The departure super frame (Fig.
402 14) presents a signal to noise ratio (SNR) with a maximum value of 25 dB, while the approach
403 super frame (Fig.13) presents a maximum value of just 15 dB; this difference of about 10 dB is
404 probably because of a more favorable radar environment in the departure super frame, like flatter
405 surfaces and surfaces more perpendicular to the radar propagation signals.

406

407 The data acquired continuously, during the spacecraft movement, are typically presented in the
408 form of radargrams, realigned with the target (Phobos) topography and shown in Fig. 15, in which
409 the horizontal dimension is the frame number, the vertical one is the round trip time of the echo, and
410 the brightness of the pixel is a function of the strength of the echo.

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433 **6. Application of Three Super Frames Technique (Phobos flyby 22 February-2013, orbit**
434 **11634)**

435 **This flyby took Mars Express to a minimum distance of 185 km from the surface of**
436 **Phobos; therefore the most appropriate timeline was deemed to be the three super frames**
437 **technique, as described in paragraph 4 and Fig.9.**

438 **The approach super frame started at 2013-02-22T11:51:09.483 and consisted of 2665 PRI; the**
439 **closest-approach super frame started at 2013-02-22T11:52:12.500 and consisted of 3200 PRI,**
440 **while the departure super frame started on 2013-02-22T11:53:22.518 and consisted of 2673**
441 **PRI. The technique adopted for determining the onboard configuration parameters is**
442 **identical to the one described in paragraph 5.**

443 **Data are analyzed for the closest-approach super frame only, as shown in Fig.16. In the other**
444 **two super frames, data quality was too poor, probably due to surface geometry, which was**
445 **unfavorable to radar detection.**

446 **The received signals from Phobos contain not only echoes from the sub-spacecraft portion of**
447 **the surface, but also secondary reflections; these latter could be produced by the presence of**
448 **dielectric discontinuities in the subsurface (i.e. subsurface layers). Surface contributions are**
449 **expected at the beginning of the echo, while additional signatures, like subsurface reflections,**
450 **should appear later in the echo. However, depending on surface morphology, surface**
451 **contributions could produce also secondary reflections. This may occur in case of surface**
452 **lateral clutter, that can be easily mistaken for subsurface features.**

453 **In order to clearly identify the source of all the signatures visible in the radargram, a radar**
454 **signal simulator of Phobos surface scattering based on the one produced for Mars by (Russo**
455 **et al., 2008) and using the Phobos Digital Elevation Model (Willner et al., 2013).**

456

457 **The very high quality of echoes collected in this flyby is clearly visible in the upper panel of**
458 **Fig.16, showing three strong signatures of radar interactions with Phobos.**

459 **The lower panel of Fig.16 shows the results of the incoherent simulations of radar returns.**
460 **Since the three signatures are present both in the real and in the simulated data, we conclude**
461 **that the presence of subsurface reflectors is unlikely.**
462 **Fig. 17 shows the signal behavior for one frame (frame 227, dotted lines in Fig.16). The**
463 **continuous line represents the actual echo, while the dotted line represents the simulated one.**
464 **The two profiles do not perfectly overlap, presumably because of approximations in the**
465 **Phobos shape model.**

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485 **7. Conclusion**

486 In this paper we have described the theoretical and technical efforts developed to allow a
487 radar sounder designed to probe Mars to also collect high quality data from a completely different
488 target such as Phobos. Thanks to the flexible design of the MARSIS onboard SW and architecture,
489 it has been possible to achieve this goal.

490 **The development of the “range ambiguity” technique allowed to overcome instrument**
491 **constraints and to collect valuable data, well below the original lowest operative altitude and**
492 **with an increased SNR.**

493
494 In spite of the complexity of the required radar settings and the challenging geometric conditions,
495 the experiment was a complete success; and for the first time a radar transmitting a signal of
496 decameter wavelengths observed Phobos, collecting data of high scientific interest.

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498 **A preliminary comparison (Fig.16) between simulated and actual signals provides no evidence**
499 **of subsurface reflectors, while secondary echoes seem to be due to surface clutter. However, a**
500 **more in-depth study of the signals collected in fifteen flybys is ongoing, because of their**
501 **potential relevance for future space missions carrying radar sounders and for the**
502 **understanding of Phobos’ formation processes.**

503 **Future activities in the analysis of MARSIS data acquired at Phobos will include:**

504 **1) performing an advanced comparison with simulated data obtained through a more**
505 **accurate surface backscattering simulator, based on physical optics and the method of**
506 **moments (Plettmeier et al., 2009).**

507 **2) investigating the capability to obtain information about the composition and the internal**
508 **structure of Phobos starting from the signal shape and power and if detected, from subsurface**
509 **reflectors.**

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511 **Acknowledgement**

512

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514 States (NASA), for the development and science operations of MARSIS. Operations of the Mars
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517 was one of the great pioneers in the observation of Phobos and one of the most active scientists of
518 the MARSIS radar team.

519 With fond memories of Professor Giovanni Picardi, conceiver of the MARSIS instrument, our
520 leader and friend, who passed away last in August 2015.

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615 **Figure Captions**

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617 **Fig. 1** Sequence of Frames in a typical observation of Mars, a frame being a set of Pulse Repetition
618 Intervals (PRIs)

619 **Fig. 2** Internal structure of a generic MARSIS frame

620 **Fig. 3** Single PRI operation, repeated NA times. It includes signal transmission and echo reception.

621 **Fig. 4** MARSIS typical acquisition data from orbit 6051, showing a typical observation over
622 Olympus Mons.

623 **Fig. 5** Top panel shows frames separated by gaps to achieve the best performance on Mars. Bottom
624 panel shows a single synthetic aperture ("Super Frame") more appropriate for the
625 observation and science analysis of Phobos.

626 **Fig. 6** Scheme of acquisition with the "Range Ambiguity Technique". The instrument is forced to
627 receive the echo of the second transmitted pulse ("echo F2") into the first receiving window
628 (Rx_1_F1). The echo of the first transmitted pulse ("echo F1") is therefore lost and the
629 second receiving window (Rx_2_F2) will sample just cosmic noise.

630 **Fig. 7** Acquisition architecture of single super frame, centered on closest approach. This is typically
631 used when the closest approach altitude is higher than 180 km.

632 **Fig. 8** Acquisition architecture of two super frames symmetric with respect to pericenter. This is
633 typically used when the closest approach altitude is lower than 180 km and the spacecraft is
634 at an altitude lower than 180 km for more than 25 seconds.

635 **Fig. 9** Acquisition architecture of three super frames, centered on closest approach. This is typically
636 used when the closest approach altitude is higher than 180 km and the space craft altitude,
637 within the first and third super frame is below 350 km.

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641 **Fig. 10** Simulation over about 4.5 minutes around closest approach. The red area represents the
642 instrument protection zone. The thin blue and red curves represent the ideal receiving
643 windows boundaries for acquiring the two echoes reflected by Phobos' surface from the two
644 chirp waves transmitted by the radar. These ideal values vary following the Phobos range
645 profile. The marked blue and red lines represent the real boundaries programmed for
646 receiving the two echoes.

647 **Fig. 11** Approach Super Frame, actual signal distribution. Due to some inaccuracy of the predicted
648 orbital parameters, we obtained a slightly different distribution of the data.

649 **Fig. 12** Departure Super Frame, actual signal distribution. Due to some inaccuracy of the predicted
650 orbital parameters we obtained a slightly different distribution of the data.

651 **Fig. 13** Phobos science results of the approach super frame. The top panel shows the range and
652 azimuth compression processing. The bottom panel shows the signal to noise ratio(SNR)
653 behavior. The traces "a", "b" and "c" represent the echoes reflected by the Phobos surface.

654 **Fig. 14** Phobos science results of the departure super frame. The top panel shows the range and
655 azimuth compression processing. The bottom panel shows the signal to noise ratio(SNR)
656 behavior. The traces "d" and "e" represent the echoes reflected by the Phobos surface.

657 **Fig. 15** Phobos radargram of orbit 1476 re aligned with the surface topography. The top panel
658 shows the approach super frame, while the bottom panel shows the departure super frame.

659 **Fig. 16** Phobos radargram of the closest Super Frame. The top panel shows the range and azimuth
660 compression processing of the real data, while the lower panel shows the incoherent
661 simulation of the radar surface returns.

662 **Fig. 17** Frame 227 behavior. The continuous line represents the actual processed data while the
663 dotted line represents the simulated data.

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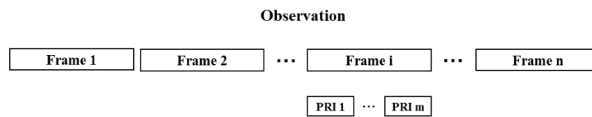


Fig. 1 Sequence of Frames in a typical observation of Mars, a frame being a set of Pulse Repetition Intervals (PRIs)

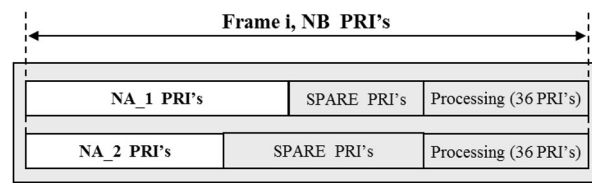


Fig. 2 Internal structure of a generic MARSIS frame

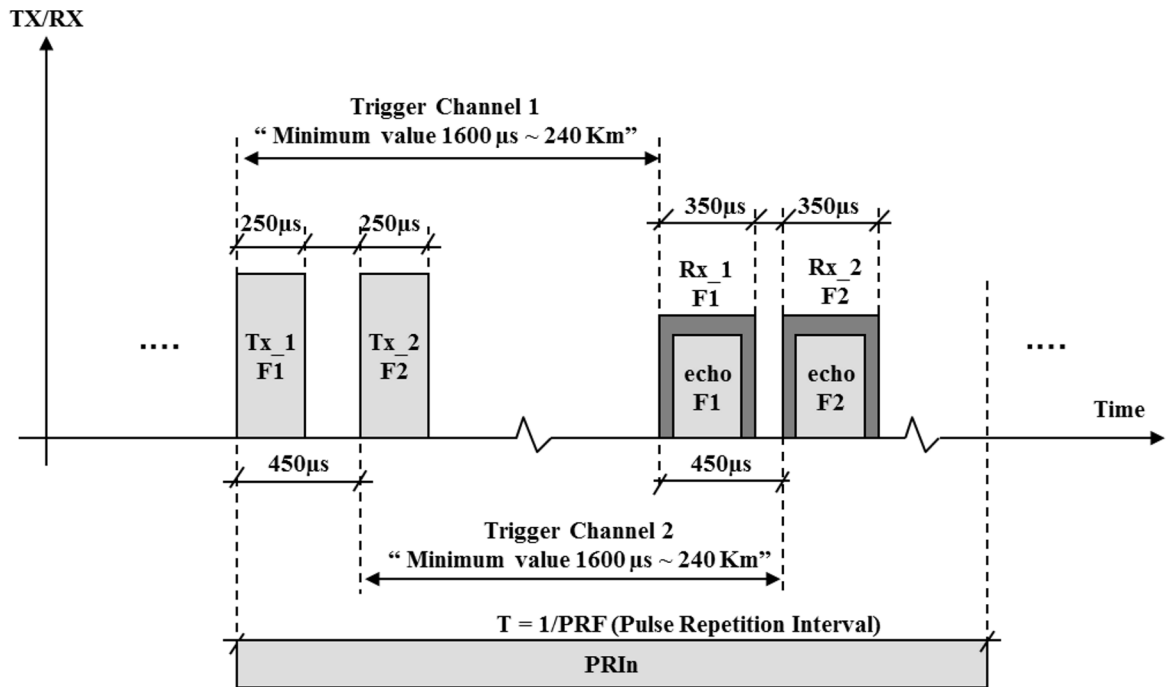


Fig. 3 Single PRI operation, repeated NA times. It includes signal transmission and echo reception.

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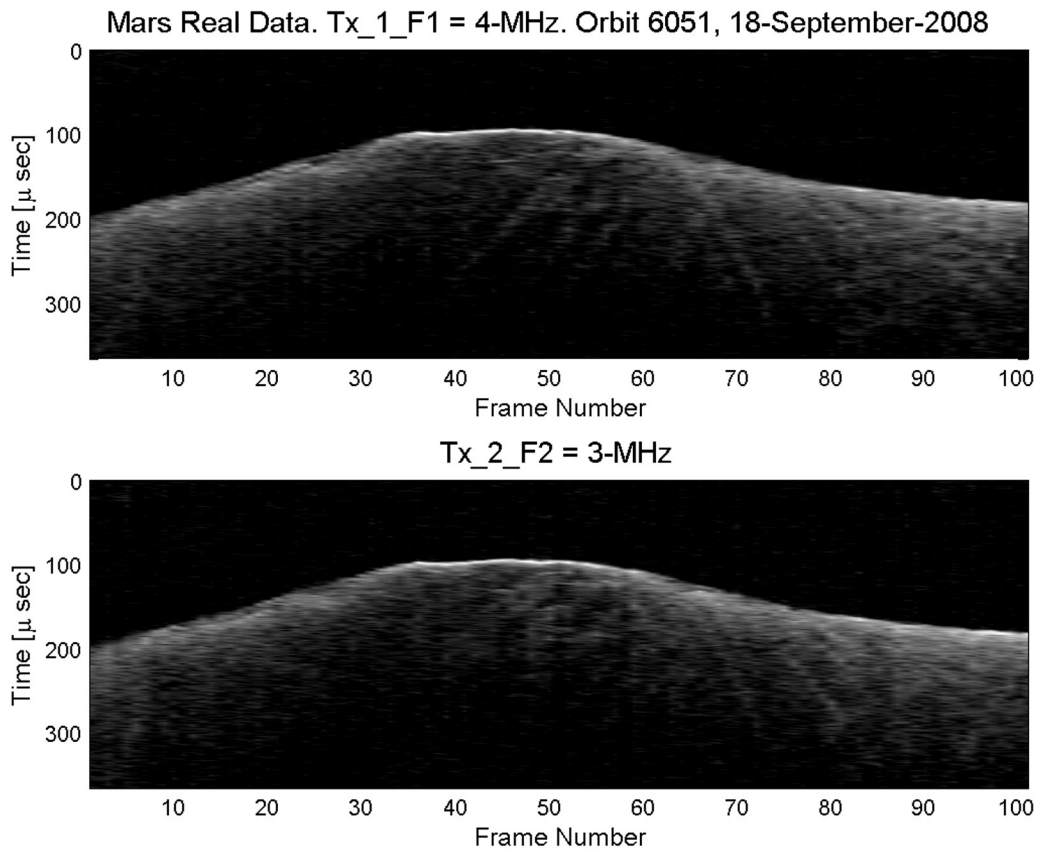


Fig. 4 MARSIS typical acquisition data from orbit 6051, showing a typical observation over Olympus Mons.

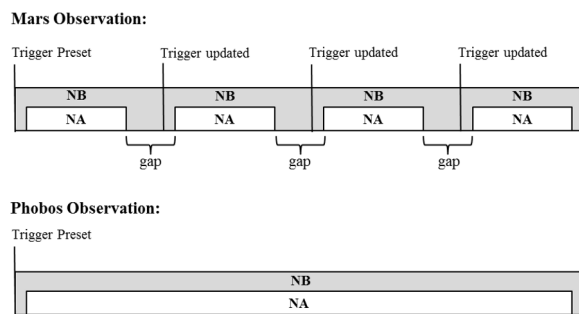
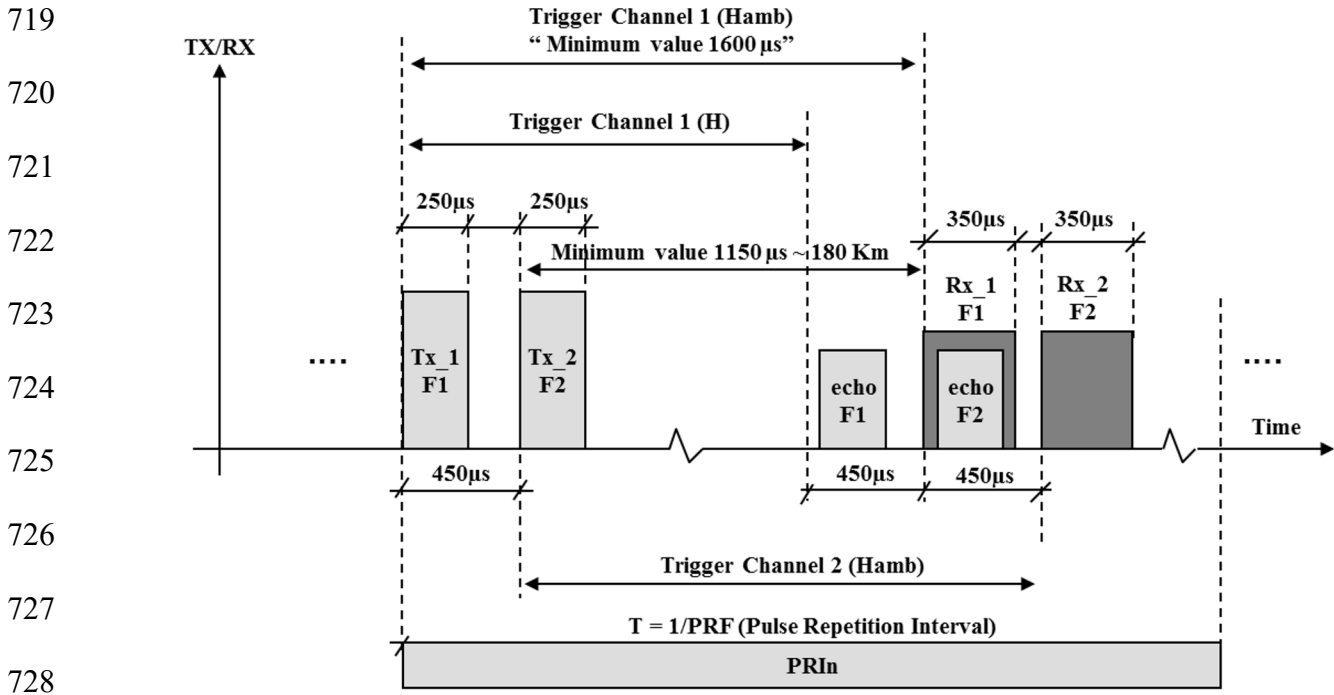
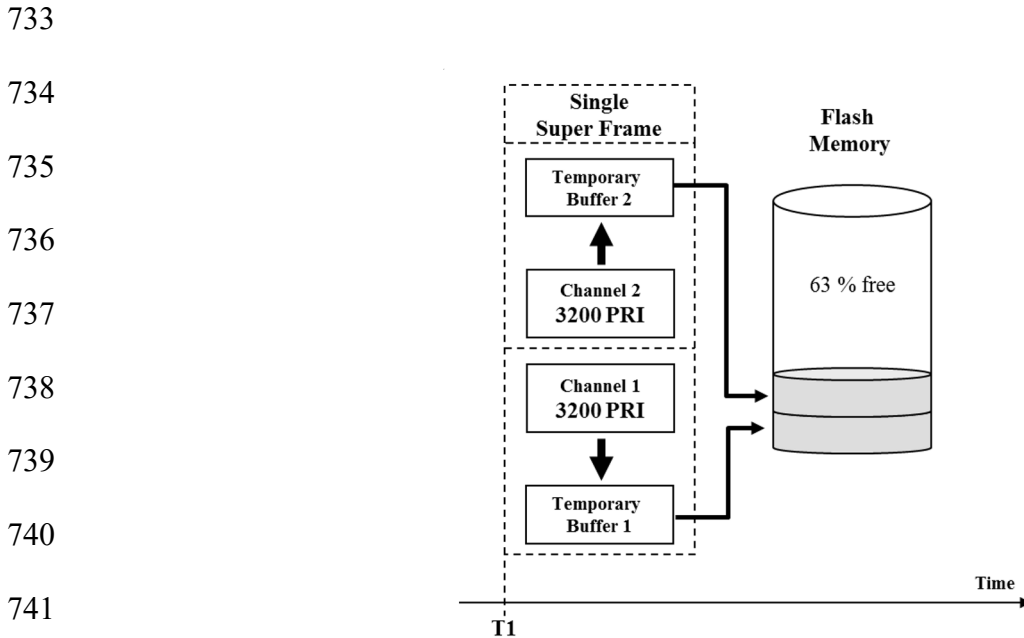


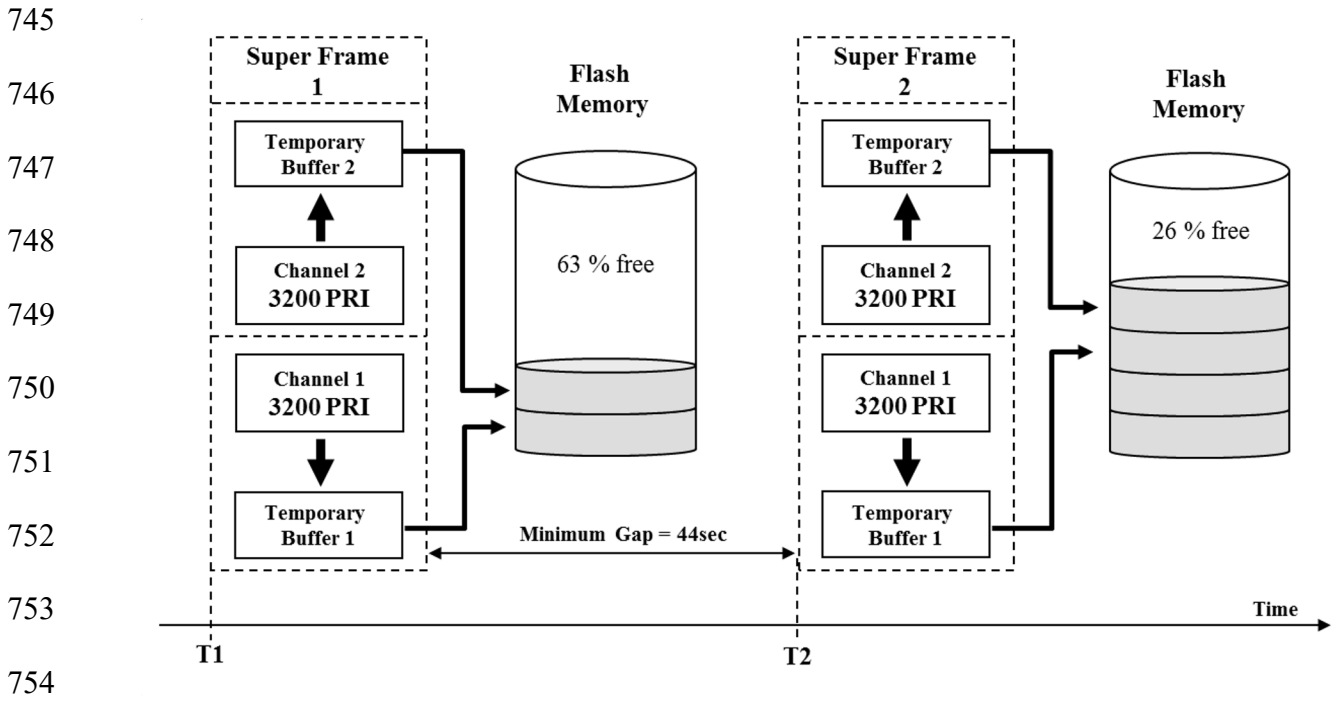
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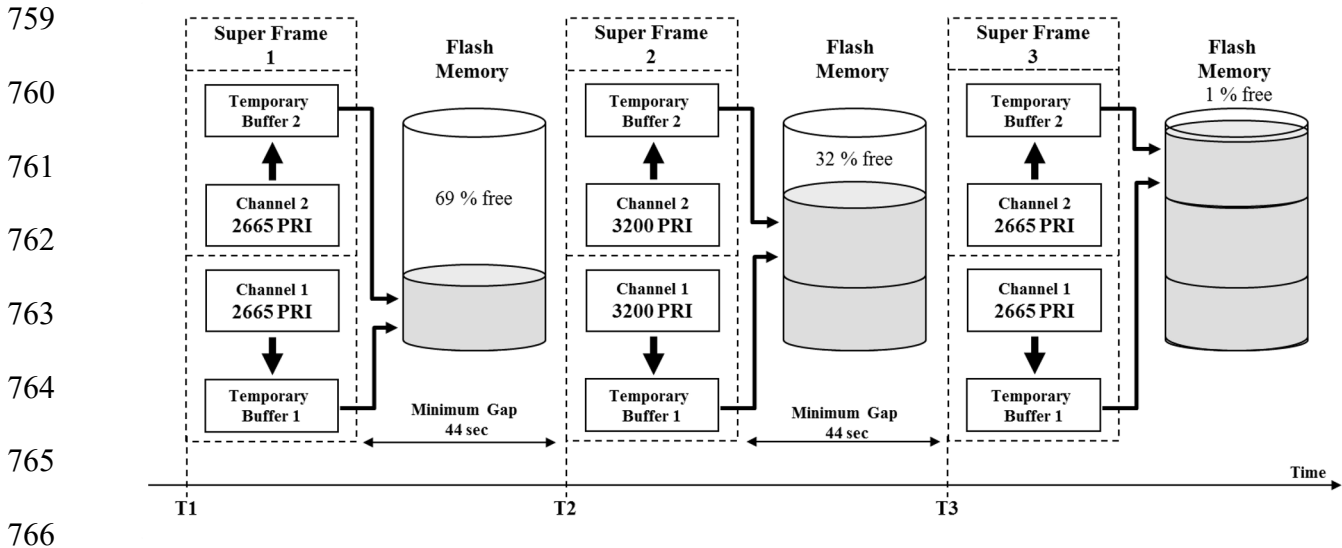
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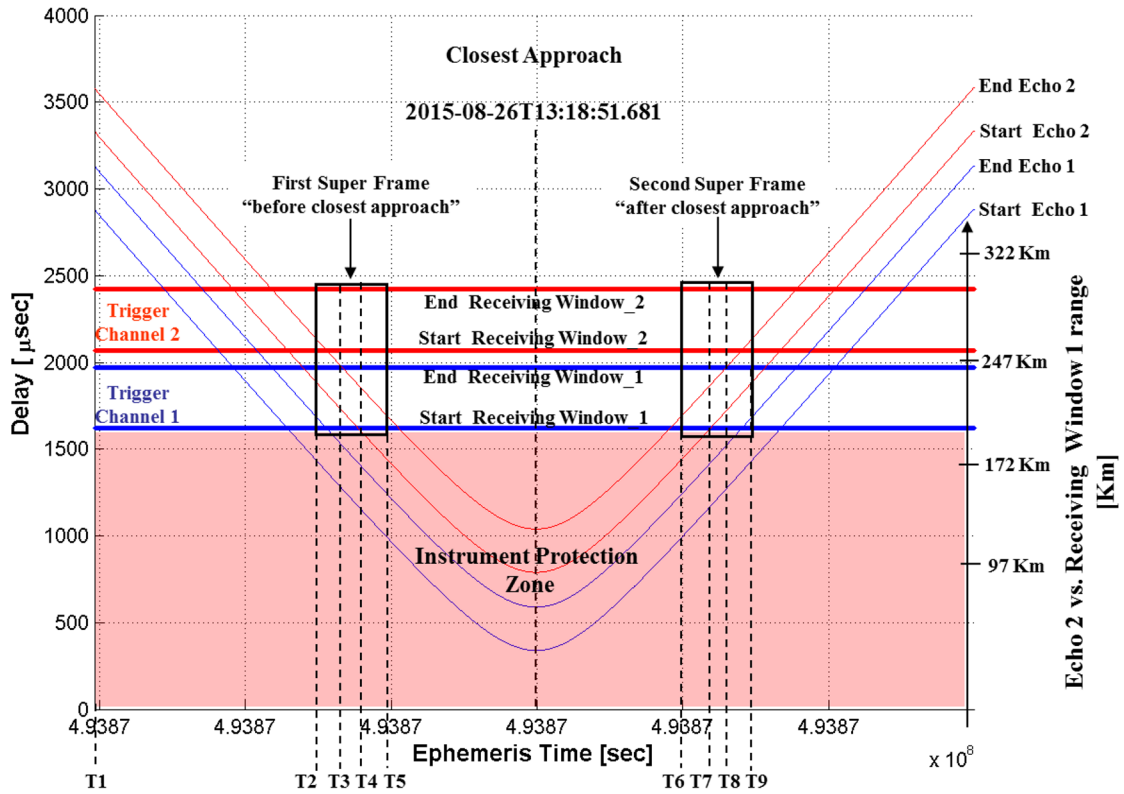


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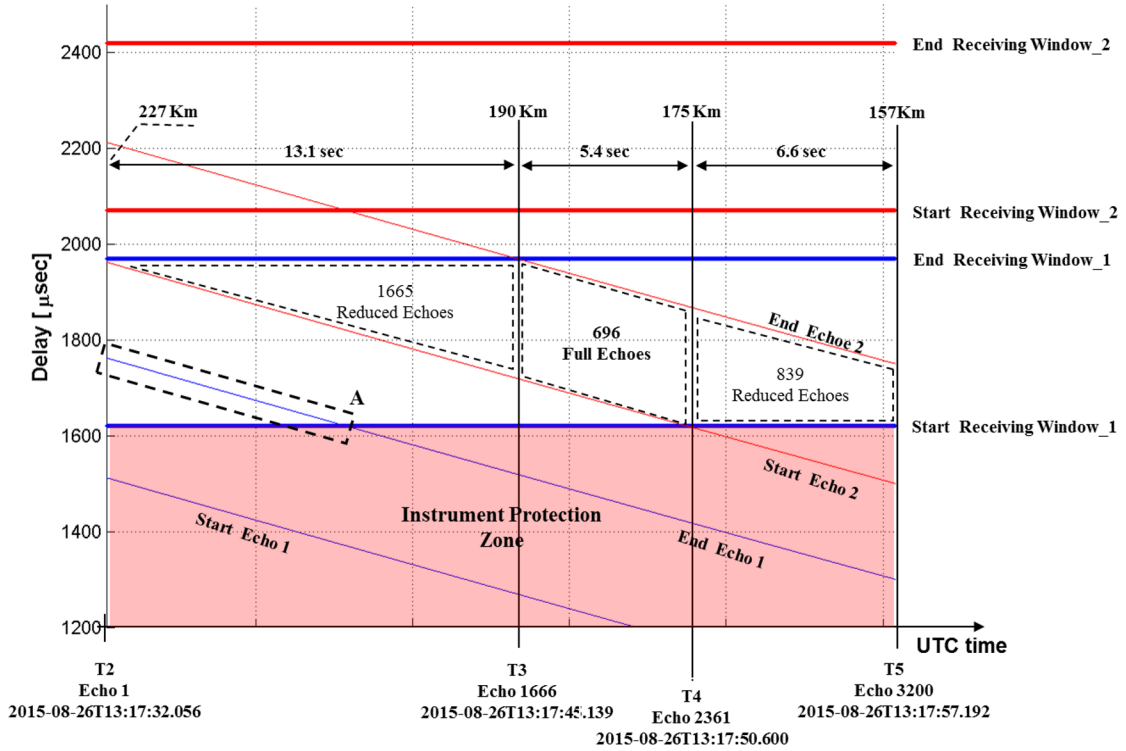
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808 **Fig. 11** Approach Super Frame, actual signal distribution. Due to some inaccuracy of the predicted
 809 orbital parameters, we obtained a slightly different distribution of the data.

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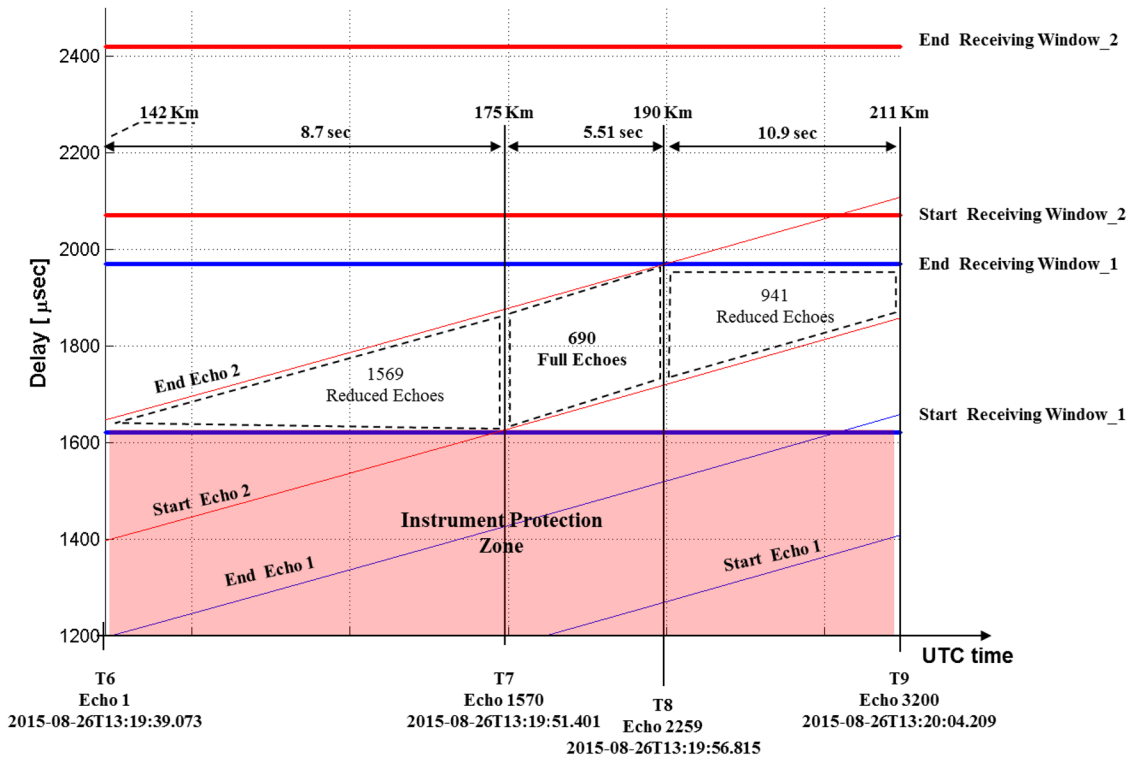
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821 **Fig. 12** Departure Super Frame, actual signal distribution. Due to some inaccuracy of the predicted
 822 orbital parameters we obtained a slightly different distribution of the data

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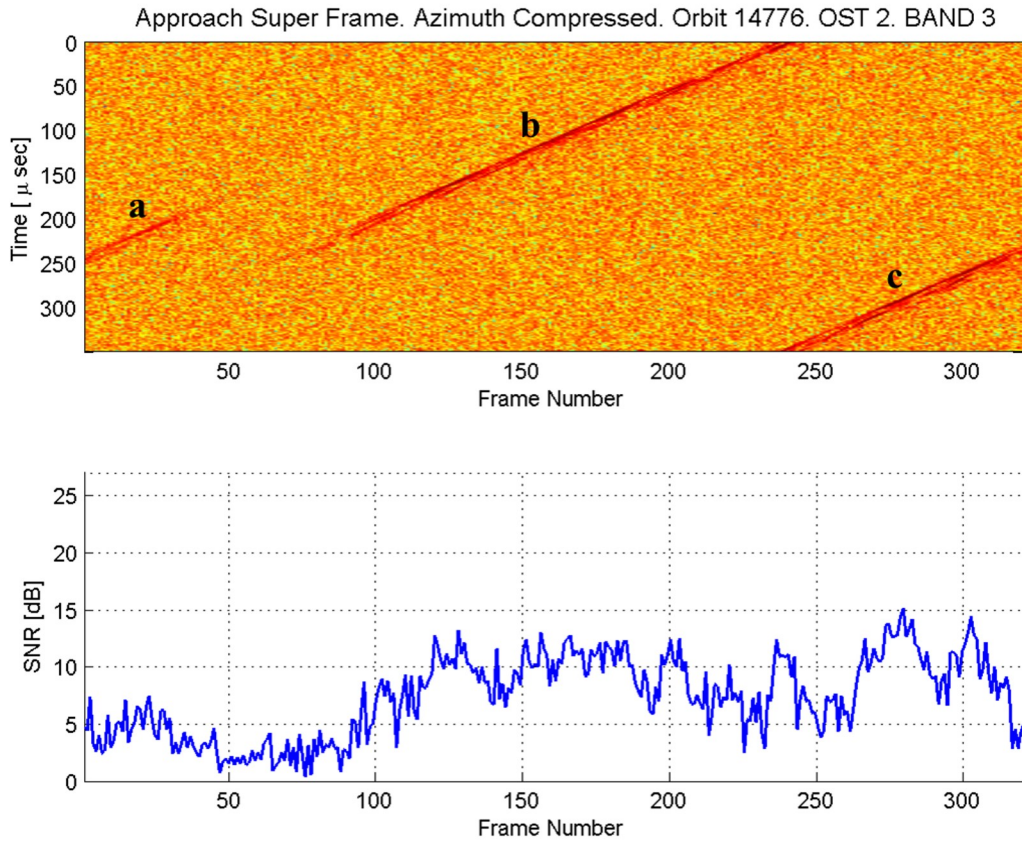


Fig. 13 Phobos science results of the approach super frame. The top panel shows the range and azimuth compression processing. The bottom panel shows the signal to noise ratio(SNR) behavior. The traces "a", "b" and "c" represent the echoes reflected by the Phobos surface.

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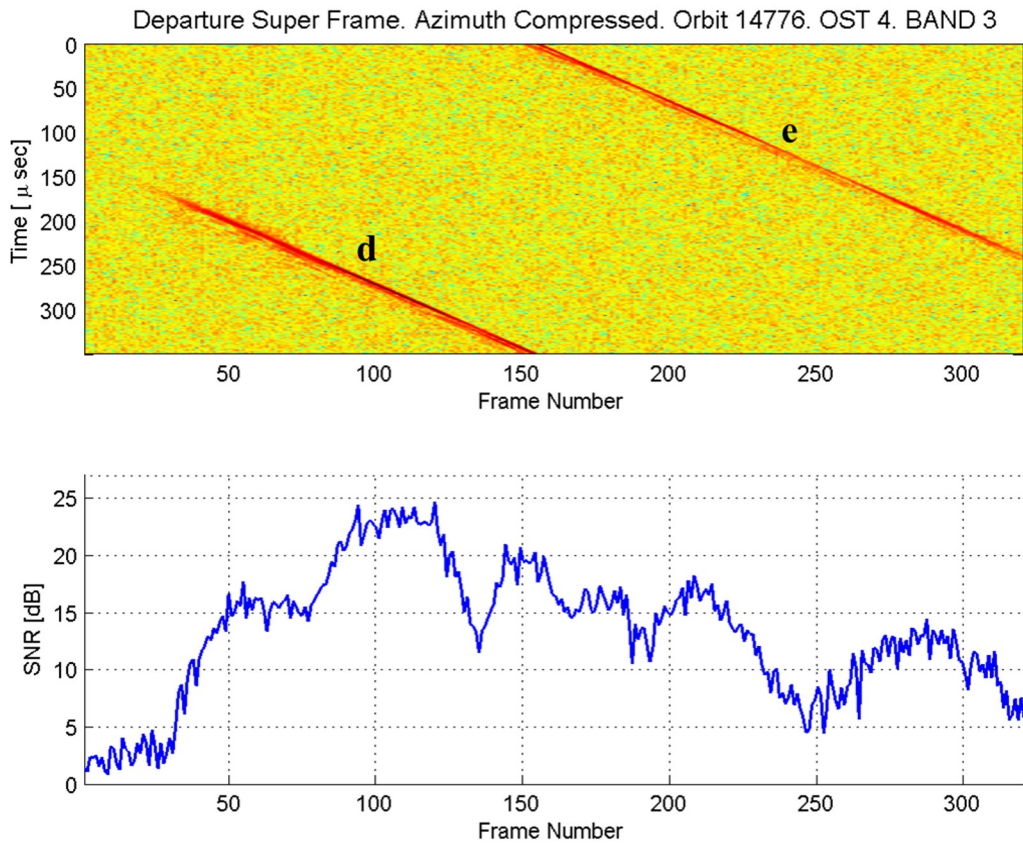


Fig. 14 Phobos science results of the departure super frame. The top panel shows the range and azimuth compression processing. The bottom panel shows the signal to noise ratio (SNR) behavior. The traces "d" and "e" represent the echoes reflected by the Phobos surface.

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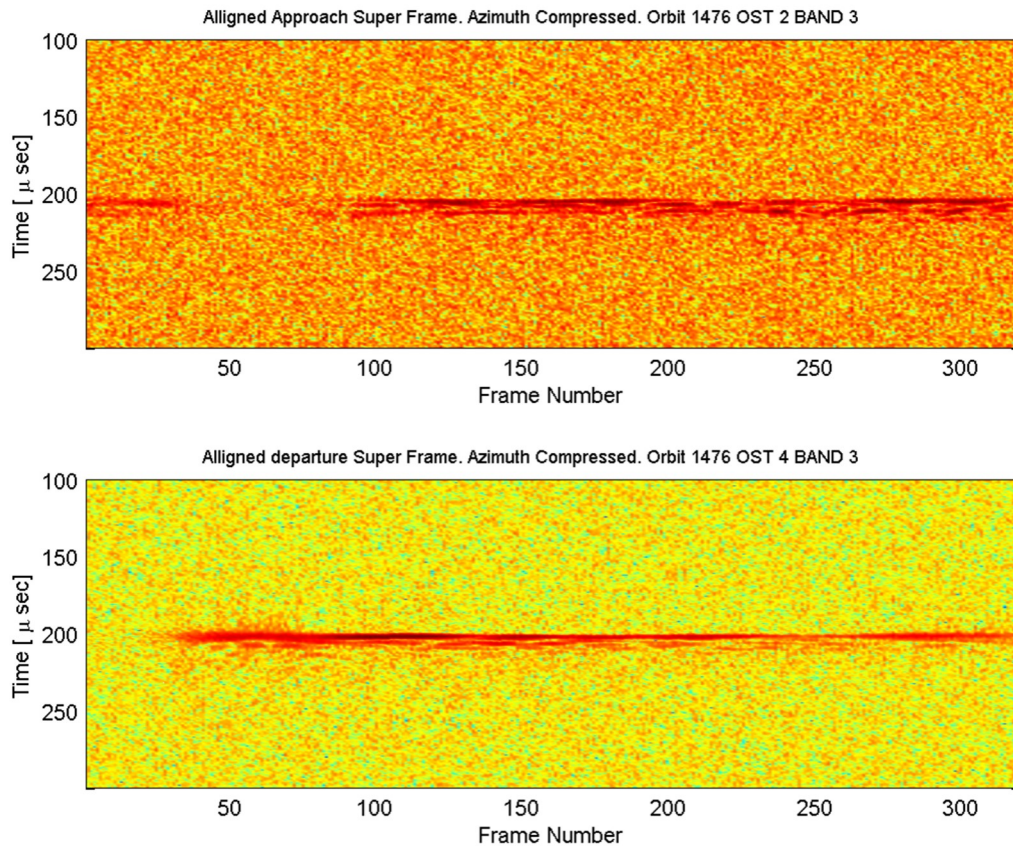


Fig. 15 Phobos radargram of orbit 1476 re aligned with the surface topography. The top panel shows the approach super frame, while the bottom panel shows the departure super frame.

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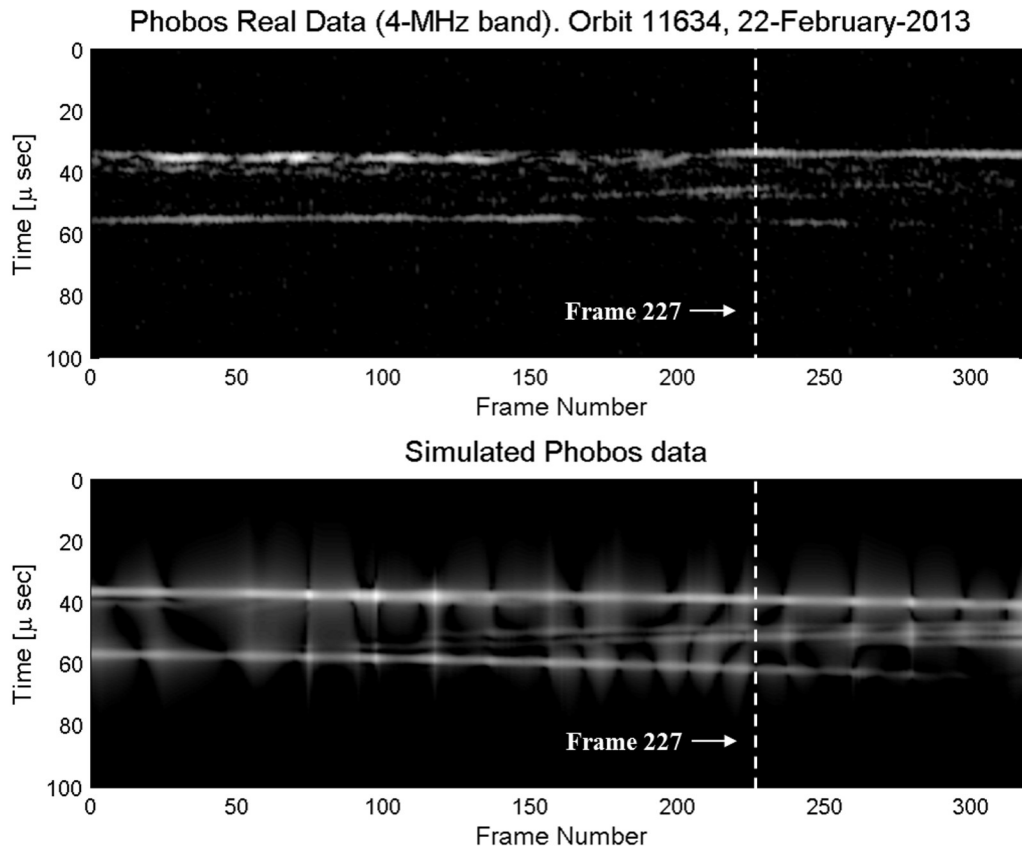
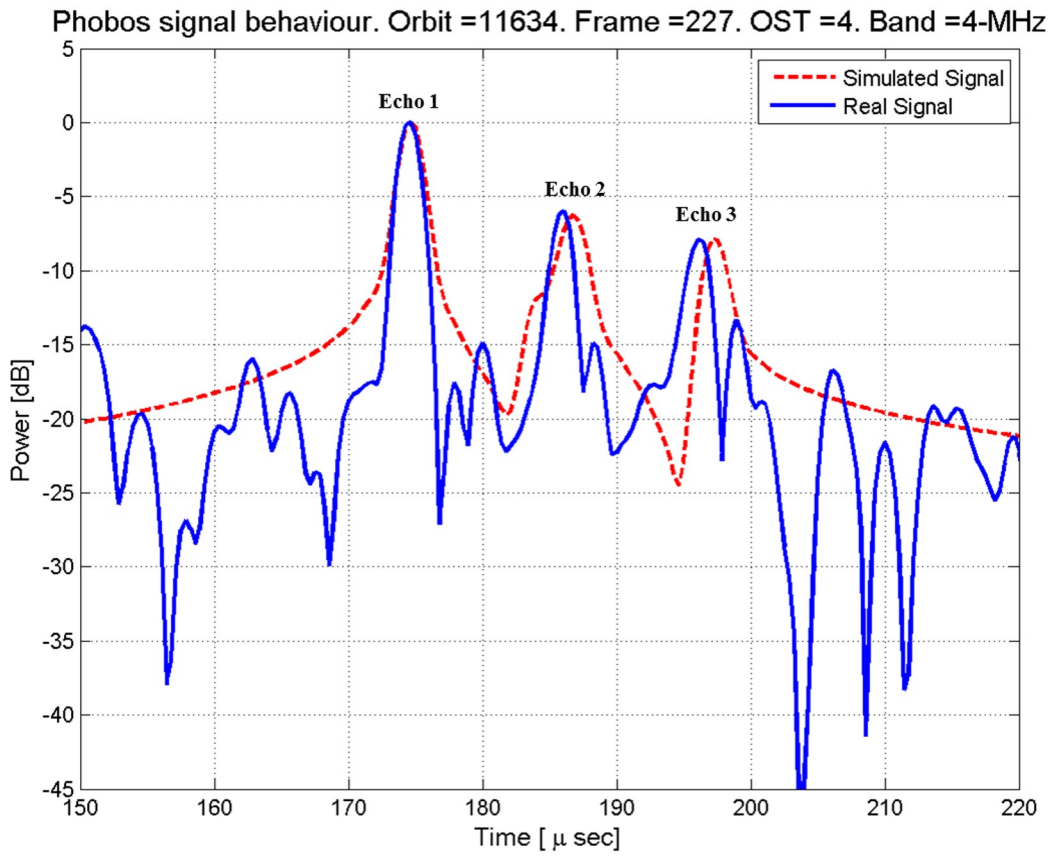


Fig. 16 Phobos radargram of the closest Super Frame. The top panel shows the range and azimuth compression processing of the real data, while the lower panel shows the incoherent simulation of the radar surface returns

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939 **Fig. 17** Frame 227 behavior. The continuous line represents the actual processed data while the
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