



<b>Publication Year</b>	2017
<b>Acceptance in OA</b>	2020-09-04T10:18:13Z
<b>Title</b>	CLUSIM: A Synthetic Aperture Radar Clutter Simulator for Planetary Exploration
<b>Authors</b>	Ilyushin, Ya. A., OROSEI, ROBERTO, WITASSE, O., SÁNCHEZ-CANO, B.
<b>Publisher's version (DOI)</b>	10.1002/2017RS006265
<b>Handle</b>	<a href="http://hdl.handle.net/20.500.12386/27135">http://hdl.handle.net/20.500.12386/27135</a>
<b>Journal</b>	RADIO SCIENCE
<b>Volume</b>	52

<sup>1</sup> **CLUSIM: A synthetic aperture radar clutter**  
<sup>2</sup> **simulator for planetary exploration.**

Ya. A. Ilyushin,<sup>1,2</sup> R. Orosei,<sup>3</sup> O. Witasse,<sup>4</sup> and B. Sanchez-Cano,<sup>5</sup>

---

<sup>1</sup> Atmospheric Physics Department,

Physical Faculty, Moscow State University,  
GSP-2, Lengory Moscow 119992, Russia,  
phone 007-495-939-3252

ilyushin@phys.msu.ru, rx3ahl@mail.ru

<sup>2</sup> Institute of Radio-engineering and  
Electronics, ulitza Mokhovaya, 11/7 Moscow  
125009 Russia phone 007 (495) 629-35-74

<sup>3</sup> Istituto di Radioastronomia, Istituto  
Nazionale di Astrofisica, Via Piero Gobetti  
101, 40129, Bologna, Italy  
roberto.rosei@inaf.it

<sup>4</sup>European Space Agency Keplerlaan 2200  
AG Noordwijk The Netherlands  
owitasse@cosmos.esa.int

<sup>5</sup>Radio and Space Plasma Physics Group,  
Department of Physics and Astronomy,  
University of Leicester, University Road,  
Leicester LE1 7RH, United Kingdom.  
bscmdr1@leicester.ac.uk

## Key Points.

- The clutter simulating program CLUSIM is developed and described in details
- Proposed clutter simulation approach is applicable to both vector and scalar wave fields
- Proposed approach is free of the Bragg diffractive artifacts caused by rectangular facet models
- **Ionospheric phase distortion correction procedure is robust with respect to the surface clutter.**

3 **Abstract.** In this paper we present the CLUtter SIMulator (CLUSIM),  
4 a special program simulating radar side echoes from rough planetary surfaces  
5 using realistic topography data sets. A numerical model of realistic topog-  
6 raphy of the Martian surface, based on Mars Orbiter Laser Altimeter data,  
7 is developed. A specially developed computer routine for evaluation of wide  
8 band radar echoes reflected from rough surfaces, capable of aperture synthe-  
9 sis simulation, is described. A synthetic radargram for a portion of Mars Ex-  
10 press (MEX) orbit 9466 is computed and validated against experimental data  
11 obtained by the MARSIS radar instrument. Finally, a previously developed  
12 ionospheric phase correction procedure is numerically tested with new sim-  
13 ulated echo signals. **Impact of the surface clutter on the ionospheric**  
14 **correction procedure is investigated with a direct numerical com-**  
15 **parison to a known benchmark result, which shows robustness of**  
16 **the correction algorithm with respect to the surface clutter.**

## 1. Introduction.

17 Ground Penetrating Radar (GPR) is a well-established geophysical technique employed  
18 for more than five decades to investigate the terrestrial subsurface. It is based on the  
19 transmission of radar pulses in the medium, in high and very high frequency (MF, HF and  
20 VHF, respectively) portions of the electromagnetic spectrum into the surface, to detect  
21 reflected signals from subsurface structures (see e.g. [*Bogorodsky et al.*, 1985]). Orbital  
22 GPR experiments (Figure 1) have been successfully employed in planetary exploration in  
23 Mars and in the Moon [*Phillips and et al.*, 1973; *Picardi*, 2004; *Seu et al.*, 2007; *Ono et al.*,  
24 2009], and are often called subsurface radar sounders. Recently, two GPR instruments,  
25 Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) [*Pettinelli*  
26 *et al.*, 2015] and Radar for Icy Moon Exploration (RIME) [*Bruzzone et al.*, 2013], have  
27 been selected for the interplanetary missions Europa Clipper [*Phillips and Pappalardo*,  
28 2014] and JUICE [*Grasset et al.*, 2013], respectively.

29 Another instrument, the bistatic radar sounder Comet Nucleus Sounding Experiment  
30 by Radiowave Transmission (CONSERT) onboard the ROSETTA space mission [*Kofman*  
31 *et al.*, 1998; *Herique et al.*, 1999] has revealed the difference of electrical properties of  
32 mantle and core of the cometary nucleus [*Ciarletti et al.*, 2015], which has been first  
33 theoretically investigated by *Ilyushin et al.* [2003]; *Ilyushin and Kunitsyn* [2008]. Re-  
34 cently, passive radar instruments [*Romero-Wolf et al.*, 2015; *Hartogh and Ilyushin*, 2016;  
35 *Schroeder et al.*, 2016] using radio noise emissions of Jupiter as a signal for radio probing  
36 Jovian icy moons were also discussed.

37 By detecting dielectric discontinuities associated with compositional and/or structural  
38 discontinuities, radar sounders are the only remote sensing instruments suitable for the  
39 study of the deep subsurface of a planet from orbit.

40 However, planetary landscapes are typically rough. The radar signal is therefore con-  
41 taminated by undesirable echoes, which mask useful subsurface reflections and should be  
42 filtered out from the radar data. Thus, this clutter should be taken into account during  
43 the radar data processing. In fact, the first successful GPR experiment on Apollo-17  
44 lunar-orbiting mission [*Peeples et al.*, 1978] revealed the need for context images of the  
45 sub-satellite landscape for visual identification of echo-producing surface features. In Mars  
46 Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) radar experiment on  
47 board Mars Express (MEX) spacecraft, dual antenna clutter cancelation scheme has been  
48 implemented [*Picardi, G., et al.*, 1999; *Jordan et al.*, 2009]. A monopole antenna, with  
49 zero gain in the nadir direction, receives side clutter only. This was then subtracted from  
50 the main dipole antenna signal. However, complete elimination of the clutter echoes is  
51 not yet possible.. More sophisticated radar techniques, such as focused aperture synthe-  
52 sis, synthetic aperture radar (SAR) interferometry etc., which require much higher data  
53 transfer and processing rates, might be a solution of this problem in future. Now, surface  
54 clutter can be simulated, compared to real experiment data and subtracted from it more  
55 or less accurately. Thus, numerical simulation of the clutter is a necessary stage of the  
56 radar data analysis and interpretation procedure [*Nunes et al.*, 2010, 2011].

57 Theoretical clutter estimates are also required at all the stages of the radar experiment,  
58 including instrument design and observational strategy planning. For these purposes, one  
59 needs a radar experiment model, allowing for these estimates. This model in turn should

60 consist of the physical model of the object structure (surface) and algorithm for the numer-  
61 ical solution of the electromagnetic equations, ruling an interaction of the electromagnetic  
62 wave with the object.

63 Development of SAR clutter simulation tool, capable of high resolution topographic data  
64 assimilation, and efficiently exploiting powerful resources of modern computing machinery  
65 available now, for the Martian applications is the motivation of this investigation.

66 The paper is organized as follows. The new clutter simulator CLUSIM, which is the  
67 main goal of this study, is described in the Section 2 (the Martian surface topography  
68 model and the algorithm for the electromagnetic scattering simulation in the Subsections  
69 2.1 and 2.2, respectively). Section 3 is entirely devoted to the ionospheric correction  
70 algorithm test, including the Martian ionospheric model and phase correction approach.  
71 Simulation results are validated against the experimentally measured data from the MAR-  
72 SIS instrument and briefly discussed in the Section 5, and in the Section 6 the conclusions  
73 are formulated and some final remarks are given.

## 2. Synthetic aperture radar clutter simulator.

74 Clutter simulators [*Spagnuolo et al.*, 2011; *Russo et al.*, 2008; *Nouvel et al.*, 2004] consist  
75 of two basic structure units: a topography interpolator and a radar echo simulator itself.

76 Both the rough surface model and the approach to the electromagnetic equations it-  
77 self can be deterministic or statistical. To validate the detection of subsurface interfaces,  
78 numerical electromagnetic models of surface scattering should be used to produce simu-  
79 lations of surface echoes, which are then compared to real echoes detected by the radar.  
80 A realistic model of the surface should be based on real observations.

81 Accounting for these considerations, a special package of computer codes named  
82 CLUSIM (CLUtter SIMulator) has been developed and tested by us for the Mars case.  
83 The package consists of the topography analyzer and numerical integration routine. To-  
84 pography analyser block in turn includes routines for Mars Orbiter Laser Altimeter  
85 (MOLA) data assimilation, their preprocessing and preselection, removal of suspicious  
86 (non-reliable) data, topography interpolation and visual control.

87 The main purpose of the package is the simulation of radargrams at any given part of  
88 the spacecraft orbit.

## 2.1. Topography interpolation

89 Historically, topographic datasets suitable for the simulation of surface electromagnetic  
90 scattering in planetary exploration have been obtained through remote sensing techniques,  
91 such as laser altimetry [*Smith et al.*, 2001, 2010], microwave radar altimetry (e.g. [*Ford*  
92 *and Pettengill*, 1992]), photogrammetry (e.g. [*Jaumann et al.*, 2007; *Kirk et al.*, 2008;  
93 *Preusker et al.*, 2011]) and photoclinometry (e.g. [*Kirk et al.*, 2003]).

94 For Mars, the MOLA database is probably the most used and best developed source  
95 of surface topography data. These data are available in the form of structured list of  
96 latitudes, longitudes and heights of the MOLA spots grouped in orbital tracks. The  
97 spatial resolution of these data is about 300 m along a track, and up to several kilometers  
98 across it from track to track [*Smith et al.*, 2001]. To build a Digital Elevation Model  
99 (DEM), which is an important part of the clutter simulating algorithm, these data must  
100 be interpolated on the planetary surface, giving the surface height as a function of latitude  
101 and longitude.

102 To do this, the following approach is applied. All the available MOLA spots are pro-  
103 jected on the tangent plane to the subsatellite point of the planetary surface, keeping their  
104 ordered track structure. After that, the height profile along each track is approximated  
105 by a cubic spline. Then, a regular grid of parallel lines is built on the tangent surface  
106 plane. This grid also considers the grid lines of the height profile, which are defined by  
107 the MOLA tracks in the crossing points. Again, this is approximated by a cubic spline.  
108 Finally, an uniform spaced rectangular grid is built on these grid lines, which gives an  
109 approximation of the rough surface terrain. Accuracy of this approximation in a given  
110 point of the surface should be on the order of height difference between adjacent MOLA  
111 spots nearest to this given point. On the MOLA spots, this approximation exactly cor-  
112 responds to the MOLA surface elevation data. Thus the surface topography is defined as  
113 a function of Cartesian coordinates on the tangent plane. The curvature of the spherical  
114 surface (deviations of the spherical surface from the tangent plane) can be now just added  
115 to the topography approximation, if necessary. In practice, the impact of the planetary  
116 surface curvature is small, so the tangent plane approximations yields the satisfactory  
117 results.

118 With that approximate topography defined on the tangent plane with Cartesian co-  
119 ordinates, one can evaluate the numerical solution of the electromagnetic problem of  
120 interaction of the sounding wave with the object of known shape.

## 2.2. Algorithms for solving electromagnetic field equations.

121 An approach to the numerical solving of the electromagnetic waves equations can also  
122 be deterministic [*Fa and Jin, 2010; Liu et al., 2014*] or statistical [*Ilyushin, 2014*]. In the  
123 deterministic case of an object of a given structure, there are no principal difficulties to

124 numerically solve electro-dynamical equations. A number of algorithms, such as Finite Dif-  
125 ference in Time Domain (FDTD) [*Yee, 1966*], Finite Element Method (FEM) [*Zienkiewicz*  
126 *et al., 2013*], Discrete Dipole Approximation (DDA) [*Purcell and Pennypacker, 1973*], T-  
127 matrix [*Waterman, 1965*] etc., are well developed now.

128 However, planetary radar echo simulations are characterized by a large object size  
129 (compared to the wavelength) and by a wide frequency spectrum of the signal. Strict  
130 approaches of the computational electrodynamics mentioned above (FEM,FDTD,DDA  
131 etc.), are in fact inapplicable to this particular case of the SAR sounding of the planetary  
132 surface because of the large size of the object. The known reported FDTD-simulations are  
133 one- or two-dimensional [*Xu et al., 2006*] or restricted to a little domain of the medium  
134 [*Boisson et al., 2009*]. Application of the aperture synthesis and other averaging signal  
135 processing techniques, such as migration [*Herique and Kofman, 1997*], requires their ad-  
136 equate representation in the numerical model, which in turn results in many repeated  
137 calculations of the same type with different input parameters, and the computation load  
138 is vastly increased. Estimates of mean signal parameters, averaged over many realizations,  
139 result in additional increase of computational complexity. Probably for this reason, most  
140 known clutter simulations are more or less simplified, e.g. lack the aperture synthesis  
141 [*Smirnov et al., 2014; Fa and Jin, 2010*]. In other simulation algorithms, the aperture  
142 synthesis is performed at the post-processing stages [*Berquin et al., 2015*].

143 Thus, for such problems of scattering from the large rough surfaces, approximate tech-  
144 niques are more appropriate. Since the height profile is not small compared to the  
145 wavelength, the small perturbation technique is also not appropriate. The only feasi-  
146 ble approach is Kirchhoff approximation [*Beckmann and Spizzichino, 1963; Ogilvy, 1991*],

147 which is typically used to solve these kind of problems. Making use of the vectorial  
148 Huygens-Fresnel principle, which is a counterpart for the conventional scalar Kirchoff  
149 approximation, allows one to consider polarization of the radar echoes and depolarizing  
150 effects. However, depolarization is known to be absent within the gently undulating sur-  
151 face approximation [*Beckmann and Spizzichino, 1963; Ogilvy, 1991*], which is a reasonable  
152 assumption for many planetary terrains. On the other hand, much depolarization of the  
153 reflected waves comes from the discrete objects and small scale structures, which available  
154 DEM of planetary surfaces do not account for.

155 It is worth mentioning here that given the wavelength of the MARSIS carrier signals, the  
156 presence of rocks, even if they were several decimeters in length, is unlikely to significantly  
157 effect the echo signal. *Neumann et al. [2003]* estimated the roughness of the Martian  
158 surface within the MOLA footprint (75 m across) from the widening of the pulse echo.  
159 They found that, over the vast majority of the Martian surface, the root mean square  
160 (rms) height of the surface is at most a few meters. Notable exceptions are the Olympus  
161 Mons areole and the Olympia Undae dune field. However, for much of the Martian surface,  
162 the small-scale roughness height is a very small fraction of the MARSIS wavelength, which  
163 ranges between 60 and 170 m.

In addition, a single reflection from a rough surface-to-vacuum interface, typical for the  
terrestrial planets, does not produce high reflection amplitude nor significant change of  
the wave polarization state in the experimental planetary radar studies [*Hagfors, 1967;*  
*Black et al., 2001a*]. Both anomalously high radar albedo and strong depolarization of  
radar pulses are typical for galilean satellites of Jupiter [*Ostro and Shoemaker, 1990*].  
These remarkable properties of the Jovian icy moons have been attributed to the vol-

ume scattering [*Hagfors et al.*, 1997], multiple subsurface reflections [*Eshleman*, 1986; *Ostro and Pettengill*, 1978] and coherent backscattering enhancement effect [*Black et al.*, 2001b; *Hapke*, 1990; *Hapke and Blewett*, 1991]. Since both volume scattering and coherent backscattering enhancement are not expected in the Martian crust at MARSIS wavelengths, we do not include these effects in our model model. These effects are discussed in [*Ilyushin*, 2012]. In our present study, we neglect the polarization of the waves and restrict our consideration to the conventional scalar Kirchhoff approximation. As it has been shown by *Ilyushin* [2014], the calculation of the reflected radar signal spectrum (complex surface reflection coefficient  $R(\omega)$ ) within this approximation reduces to the numerical evaluation of the Kirchhoff integral over the whole reflecting surface

$$R(\omega) = \int G(\mathbf{r}_0, \mathbf{r}) G(\mathbf{r}, \mathbf{r}_0) \exp(-2ikh(x, y)) dx dy, \quad (1)$$

164 where  $\mathbf{r}_0(\mathbf{t})$  and  $\mathbf{r}$  are the source (spacecraft) location point and surface point of integra-  
 165 tion, respectively, and  $h(x, y)$  is the local surface height.

The Green function of the Helmholtz equation in the paraxial approximation equals to

$$G(\mathbf{r}, \mathbf{r}') = \frac{k}{2\pi i |z - z'|} \exp \left( ik|z - z'| + ik \frac{(x - x')^2}{2|z - z'|} + ik \frac{(y - y')^2}{2|z - z'|} \right), \quad (2)$$

166 where  $k = \omega/c$  [*Goodman*, 1996].

For a dielectric surface with finite permittivity, this expression should be multiplied by the Fresnel reflection coefficient  $R_F$ . Due to the near-nadir sounding geometry of the orbital GPR instruments and moderate slopes typical for much of the Martian surface, the Fresnel reflection for normal incidence is a reasonable approximation

$$R_F = \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}, \quad (3)$$

167 where  $\varepsilon$  is a permittivity of the surface. Here we assume that the surface is homogeneous  
 168 and its permittivity is uniform everywhere.

169 In the Kirchhoff approximation, the complex amplitude of the radar echo depends on  
 170 the dielectric permittivity only through this coefficient (3). Since the primary objective of  
 171 our simulations is the ratio of the main nadir echo to the side clutter echoes rather than  
 172 signal-to-noise-ratio (SNR), we do not pursue the absolute signal level calibration here  
 173 and simply assume  $R_F = 1$  everywhere, which corresponds to an ideal reflective surface.

174 If the aperture synthesis is applied, an extra integration over the spacecraft coordinate  
 175 is needed (see Fig. 1). **Aperture synthesis is essentially averaging over a portion**  
 176 **of a satellite trajectory of length  $2L$  (synthetic aperture) with a weighting**  
 177 **function  $\exp\left(\frac{2\pi i s \nu}{2L}\right)$ , where  $s$  is the coordinate along the trajectory,  $\nu$  is the**  
 178 **Doppler filter number (positive or negative integer). In this paper we consider**  
 179 **only the most important case  $\nu = 0$ .**

Averaging the Eq. (1) over the synthetic aperture, we obtain

$$\frac{1}{2L} \int_{-L}^L R(\omega) dx_0 = \frac{k^{3/2} \sqrt[4]{-1}}{8L\pi^{3/2} z^2} \int e^{ik\frac{y^2}{2z} + 2ikz - 2ikh(x,y)} \left( \operatorname{erf} \left( \frac{1}{2}(-1)^{3/4} \sqrt{k}(L-x) \right) + \operatorname{erf} \left( \frac{1}{2}(-1)^{3/4} \sqrt{k}(L+x) \right) \right) d^2 \mathbf{r}, \quad (4)$$

180 assuming that satellite trajectory  $\mathbf{r}_0(\mathbf{t}) = \{x_0(t), 0, z\}$  is parallel to the  $x$  axis and the  
 181 horizontal. Small deviations from a horizontal trajectory can be easily accounted for in the  
 182 phase exponent in (4). Integrals of the quadratic exponent involved here, resulting in the  
 183 error function of complex argument in the Eq. (4), can be effectively expressed through  
 184 the so-called Faddeeva function [Abramowitz and Stegun, 1972]. Recently, a computer  
 185 code package in C++ and Fortran languages has been released by Johnson [2012]. With

186 it, all the computations can be implemented on modern high-performance computing  
 187 machines.

For the piecewise-planar approximation of the surface elevation with triangular or rectangular facets, the complex reflectance of an individual facet  $R_f(\omega)$  can be derived from (4) as follows (see the Figure 2)

$$R_f(\omega) = \int dy \int_{x_1(y)}^{x_2(y)} dx \frac{1}{2L} \int_{-L}^L R(\omega) dx_0, \quad (5)$$

188 where  $x_1(y)$  and  $x_2(y)$  are the left and right boundaries of the given facet. The inner  
 189 integration (over the  $x$  variable) can be performed analytically over the triangular or  
 190 rectangular facet (see [Ilyushin, 2004]). Total echo signal from the whole rough surface is  
 191 therefore a sum of contributions of all the facets  $R_f(\omega)$ , all of which is an one-fold integral  
 192 in spatial domain.

*Berquin et al.* [2015] make use of the vectorial Huygens-Fresnel principle and derive an expression for polarized radar echo from the planetary surface

$$\mathbf{E}_s(\mathbf{x}_0, \omega) = \int ik \bar{\bar{\mathbf{G}}}(\mathbf{x}_0, \mathbf{x}, \omega) \left( \eta [\hat{\mathbf{n}} \times \mathbf{H}](\mathbf{x}, \omega) + \hat{\mathbf{k}}_s \times [\hat{\mathbf{n}} \times \mathbf{E}](\mathbf{x}, \omega) \right) d\sigma(\mathbf{x}) \quad (6)$$

with the dyadic Green function

$$\bar{\bar{\mathbf{G}}}(\mathbf{x}_0, \mathbf{x}, \omega) = [\bar{\bar{\mathbf{I}}} - \hat{\mathbf{k}}_s \hat{\mathbf{k}}_s] \frac{e^{ik|\mathbf{x}-\mathbf{x}_0|}}{4\pi|\mathbf{x}-\mathbf{x}_0|}, \quad (7)$$

193 where  $\mathbf{E}$  and  $\mathbf{H}$  denote electric and magnetic fields, respectively,  $\hat{\mathbf{n}}$  is a unit normal to  
 194 the surface,  $\mathbf{x}$  is a point on the surface,  $\eta = \sqrt{\mu/\varepsilon}$  is the characteristic impedance of the  
 195 surface,  $\varepsilon$  and  $\mu$  are the permittivity and permeability,  $k$  is the wave number and  $\hat{\mathbf{k}}_s$  is  
 196 the unit vector pointing in the scattering direction. Assuming the length of the synthetic  
 197 aperture to be small compared to the spacecraft orbit height, we can regard  $\hat{\mathbf{k}}_s$  as a con-  
 198 stant and integrate over the synthetic aperture analytically, as is explained above for the

199 scalar case. However, if the gently undulating surface approximation is adopted, there are  
200 no depolarization of the radar echoes [*Beckmann and Spizzichino, 1963; Ogilvy, 1991*]. On  
201 scales well exceeding the sounding wavelengths, for which the Kirchhoff approximation  
202 and Huygens-Fresnel principle are valid, most Martian terrain can be regarded as smooth  
203 gently undulating surfaces [*Kreslavsky, M.A. and J.W. Head III, 2000*]. The radar echo  
204 can be more or less depolarized by the surface features (rocks, boulders etc.) compa-  
205 rable with the wavelength. However, because planetary GPR instruments have not yet  
206 had polarimetric capabilities, for purely energetic assessments we perform our numerical  
207 simulations within the conventional scalar Kirchhoff approximation.

208 *Berquin et al. [2015]* also derive an expression for the diffraction integral over the whole  
209 surface of the triangular facet as an approximate sum of an infinite series. These approx-  
210 imate expressions cannot be further integrated analytically, so the aperture synthesis can  
211 only be performed numerically on the post-processing stage. In addition to complicated  
212 procedure of adding up many terms of the sum, the approximation error results in spurious  
213 reflections coming from the edges of the facets, in turn causing the Bragg diffraction max-  
214 ima produced even by the perfectly flat surface approximated by such facets. To remove  
215 this, *Berquin et al. [2015]* proposed to use irregular grids for the facet approximation. Our  
216 approach with analytical aperture synthesis is free of these Bragg diffractive artifacts,  
217 and provides more flexibility in the choice of DEM, since it is not confined to the constant  
218 phase and linear phase approximations of the surface. The aperture synthesis approach  
219 which is proposed here, can also be applied to the case of vector field simulation. The  
220 exponent in the (7) is expanded in series in small variations of the spacecraft coordinate  
221  $\mathbf{x}_0$  and integrated over, yielding the expression containing the error function like (4) as

222 well as in the scalar case. After that, further integration over the rough surface can be  
 223 performed using different approaches, thus avoiding emulation of the aperture synthesis  
 224 at the post-processing stage.

When the radar echo spectrum is evaluated, the signal can be obtained with stan-  
 dard signal processing technique (matched filtration). An expression for the compressed  
 radar signal  $s(t)$  with partial correction of the ionospheric phase distortions [*Ilyushin and*  
*Kunitsyn, 2004*] writes

$$s(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H(\omega) F^*(\omega) F(\omega) R(\omega) \exp(-i\omega t + \phi(\omega) - \tilde{\phi}(\omega)) d\omega, \quad (8)$$

$$\phi(\omega) = 2k \int_0^z n(z) dz, \quad (9)$$

$$n(z) = \sqrt{1 - \frac{\omega_p^2(z)}{\omega^2}}, \quad (10)$$

$$\omega_p^2(z) = 4\pi r_e N(z) c^2 = \frac{N(z) e^2}{m_e \epsilon_0}, \quad (11)$$

225 where  $\omega = 2\pi f$  is the angular frequency,  $k = \frac{\omega}{c}$  is the wave number,  $H(\omega)$  is the spectral  
 226 window function,  $F(\omega)$  is initial radar pulse spectrum radiated by an instrument,  $R(\omega)$   
 227 is a complex reflection coefficient of rough surface,  $n(z)$  - height profile of the ionospheric  
 228 refractive index,  $\omega_p(z)$  is angular plasma frequency,  $N(z)$  is ionospheric plasma electron  
 229 concentration,  $r_e$  is classical electron radius, and  $c$  is light speed in vacuum. Natural  
 230 ionospheric phase shift  $\phi(\omega)$  is adaptively compensated by the phase curve  $\tilde{\phi}(\omega)$  [*Ilyushin*  
 231 *and Kunitsyn, 2004*]. As a compensating phase term, a phase curve  $\phi(\omega)$  of artificially

232 constructed model plasma layer with negative sign is often used. *Ilyushin and Kunitsyn*  
233 [2004] analyzed a wide set of radio occultation profiles of Martian ionosphere available at  
234 that time and found that the triangular vertical profile of plasma density distribution is  
235 optimal for compensating phase distortions occurring in real Martian ionosphere.

236 Further radar signal processing methods (migration etc.) can be then applied to the  
237 simulated signals if necessary. As it has been shown by *Ilyushin* [2010, 2009a], radar wave  
238 scattering due to the plasma frequency fluctuations is relatively weak, except of specific  
239 ionospheric situations (high plasma frequency and intense fluctuations during strong solar  
240 events). *Safaeinili et al.* [2003] studied not only ionospheric phase distortion, but also  
241 impact of the effect of Faraday rotation of wave polarization plane. They showed that  
242 in weak local magnetic fields, typical for Mars, this effect is not pronounced and may  
243 be neglected, even in measurements with polarization-sensitive antennas. Thus in most  
244 situations, the ionosphere can be regarded as a flat layered slab of an isotropic dispersive  
245 medium. Under assumed approximations the ionospheric phase delay  $\phi(\omega)$  and the phase  
246 correction term  $\tilde{\phi}(\omega)$  are represented by separate factors and can thus be considered  
247 independently in the simulations. We omit it everywhere, except in the section describing  
248 a test of ionospheric correction algorithm with newly simulated clutter data.

249 Practical success of this numerical approach therefore depends on the quality of the  
250 surface height approximation, discretization of the integral sum and approximation of  
251 the integrands by analytical expressions. [*Nouvel et al.*, 2004] adopted rectangular facet  
252 approximation of the rough surface. Such an approximation results in an analytical rep-  
253 resentation of the Kirchhoff integral over a single facet. Summing contributions of all the  
254 facets, one gets the complex amplitude of the monochromatic wave, reflected from the

255 whole surface. If the facet edges are properly oriented (parallel and perpendicular to the  
256 spacecraft trajectory), integration along this trajectory (aperture synthesis) can also be  
257 performed analytically, yielding a result expressed through the Fresnel integrals in closed  
258 form.

259 In some specific cases, practical realization of facet approach is rather effective and  
260 physically adequate. *Ilyushin* [2004] adopted a piecewise-planar approximation of Martian  
261 polar trough profile, and simulated MARSIS radar echoes coming from these troughs for  
262 different mutual orientation of the polar troughs and spacecraft trajectory. Essentially  
263 the one-dimensional character of the valley allowed for continuous piecewise linear profile,  
264 ensuring high simulation accuracy at reasonable computational expenses. It has been  
265 shown by [*Ilyushin, 2004*] that for proper (normal) mutual orientation of the orbit and  
266 the trough, surface clutter generated by the trough is well suppressed by aperture synthesis  
267 (practically, below the dynamic range of the radar sounder).

268 However, the rectangular plane tile (facet) approximation of arbitrary 3D rough surface  
269 is, generally speaking, discontinuous (Fig. 3). Such discontinuities of the model surface  
270 should generate artifacts, contaminating the result with unphysical reflections.

271 Continuous approximations are more complicated. The simplest one is the triangulation  
272 (planar approximation on the triangular grid, Fig. 4). Surface triangulation has been used  
273 for clutter simulation in some radar studies [*Fa and Jin, 2010; Liu et al., 2014*], however,  
274 aperture synthesis technique was not applied there. To do this, one has to average the  
275 complex reflection amplitude (1) over some portion of the satellite trajectory.

276 Diffraction integral in Eq. (1) over the triangular domain cannot be expressed in closed  
277 analytical form. However, integration over the spacecraft trajectory can be analytically

278 performed. Thus, evaluation of the signal spectrum reduces to the numerical estimate of  
279 the Kirchhoff diffraction integral (1) over the whole surface with the integration kernel (4).  
280 The compressed radar pulse in time domain can then be evaluated by common matched  
281 filtration technique. We used the same pulse compression procedure as in our previous  
282 studies, where this procedure is described in detail by [*Ilyushin*, 2004, 2008, 2009b]. Sys-  
283 tematic phase shift, introduced by the ionosphere, can be introduced separately as an  
284 independent exponential factor at the signal compression stage.

285 **The structure of the clutter simulation algorithm is shown in the flowchart**  
286 **(Fig. 5). Raw topographic data, obtained from the MOLA data archive (stage**  
287 **I), are interpolated along each track (stage II) and then across the tracks (stage**  
288 **III). For each point of the orbit, where the sounding with a sequence of chirp**  
289 **pulses (synthetic aperture) is performed, the interpolated topographic data**  
290 **are triangulated on the regular grid centered around the subsatellite point**  
291 **(stage IV). After that, the complex reflection coefficient of the rough surface**  
292 **(4) is evaluated (stage V) by the integration over the surface for each of the**  
293 **discrete frequencies, constituting the digital representation of the radar signal**  
294 **spectrum, in the cycle (stage VI). In the simulation 512 frequencies are used,**  
295 **as well as in the current MARSIS experiment.**

296 After that, the signal is evaluated from its spectrum with the Fast Fourier  
297 Transform (FFT) procedure (stage VII), using common matched filtration  
298 procedure with Hann spectral window [*Harris*, 1978], according to the MAR-  
299 SIS technical specifications [*Picardi, G., et al.*, 1999; *Picardi, G. et al.*, 2001].  
300 The signals are routinely calculated for a number of points along the MEX

301 spacecraft orbit (stage VIII, cycle) for which the measured signal records are  
302 available. All the signals are then assembled into the radargram (stage IX,  
303 final), characterizing radar clutter echoes coming from the surface terrain on  
304 the given portion of the planetary surface landscape. The radargram is then  
305 represented graphically in the standard way.

### 3. Ionospheric model and correction algorithm tests.

306 As planetary atmospheres are ionized by solar radiation, they become a dispersive  
307 medium for relatively long radar waves, used in subsurface sounding. The radar signals  
308 become distorted by the ionospheric phase dispersion [*Safaeinili et al.*, 2003; *Cartacci*  
309 *et al.*, 2013; *Sanchez-Cano et al.*, 2015]. The radar data processing routine must therefore  
310 include some special procedure for extra phase shift compensation [*Armand and Smirnov*,  
311 2003; *Ilyushin and Kunitsyn*, 2004; *Mouginot et al.*, 2008], adaptive or not. Impact of  
312 random wave scattering on the function of these algorithms have been previously studied  
313 [*Ilyushin*, 2008; *Ilyushin et al.*, 2012]. In this study, we perform a numerical test of  
314 the previously developed phase compensation algorithm [*Ilyushin and Kunitsyn*, 2004]  
315 together with a realistic surface clutter model. The reader is referred to [*Ilyushin and*  
316 *Kunitsyn*, 2004] for the detail description of the ionospheric correction approach tested  
317 here.

318 For these simulations, we use a new developed empirical model for the dayside electron  
319 density of the martian ionosphere (primary and secondary layer), called NeMars [*Sanchez-*  
320 *Cano et al.*, 2013]. The model is largely based on MARSIS Active Ionospheric Sounding  
321 (AIS) mode data [*Gurnett et al.*, 2005a; *Morgan et al.*, 2013; *Sánchez-Cano et al.*, 2012]  
322 and to a lesser extent on radio occultation data from the Mars Global Surveyor mission.

323 In addition, this model partially assumes the Chapman theory. This model reproduces  
 324 to a reasonable degree the main characteristics of the vertical electron density profiles  
 325 obtained with the two techniques by considering solar zenith angle, solar flux F10.7 as a  
 326 proxy of the solar activity, and heliocentric distance. Typical model profiles used for the  
 327 present simulation are shown in the Figure 6.

For testing purposed, a special MARSIS radargram with adaptive compensation of  
 model ionospheric distortions was simulated. As a source of initial ionospheric distortions,  
 the NeMars model has been used. For the adaptive compensation of the distortion, a phase  
 curve of a plasma slab layer with triangular height profile of the electron density [*Ilyushin  
 and Kunitsyn, 2004*]

$$\omega_p^2(z) = \omega_c^2(z)(1 - (z - z_0)/H), 0 < z - z_0 < H, \quad (12)$$

has been used. Partial phase distortion is mitigated by adjusting the phase curve of  
 the correcting plasma layer close to real ionospheric phase curve, which is unknown, and  
 subtracting it from the signal phase. In practice, the parameters of correcting plasma  
 layer (plasma critical frequency  $\omega_c^2$  and ionospheric layer thickness  $H$ ) have been adjusted  
 for optimal (maximal) intensity contrast [*Ilyushin and Kunitsyn, 2004*]

$$C_I^2 = \frac{\frac{1}{\tau} \int_{t_0}^{t_1} |s(t)|^4 dt - \left( \frac{1}{\tau} \int_{t_0}^{t_1} |s(t)|^2 dt \right)^2}{\left( \frac{1}{\tau} \int_{t_0}^{t_1} |s(t)|^2 dt \right)^2}. \quad (13)$$

328 In this work, the adaptive ionospheric phase correction is performed on the post pro-  
 329 cessing stage, after the matched filtration. However, within the paraxial approximation  
 330 adopted by us phase and clutter responses are multiplicative and can therefore be evalu-  
 331 ated independently.

#### 4. Results of numerical simulations.

332 We present here sample results obtained for the southmost portion of MEX 9466 or-  
333 bit. MOLA topography of the surface landscape surrounding the subsatellite track and  
334 its visual image provided by the High Resolution Stereo Camera (HRSC) [*Neukum and*  
335 *Jaumann, 2004*] are shown in the Figures 7 and 8, respectively.

336 **Figure 9 consists of five panels, each of them represents a measures or sim-**  
337 **ulated radargram. Each radargram shows the intensity of radar echo in gray**  
338 **shades against echo signal delay (vertical axis) and position of the spacecraft**  
339 **in the orbit (horizontal axis) in the standard way typically used for radar data**  
340 **representation. Simulated radargrams are shown in the Figure 9, panel *b-e*,**  
341 **together with the experimental MARSIS radargram ( the Figure 9, panel *a*).**

342 The radargrams presented in this paper represent about 118 s of observations  
343 at an altitude of 390 km and a speed of 4.2 km/s. MARSIS transmitted a  
344 linearly-modulated, 350 s-long pulse (a "chirp") that can be centered at 1.8,  
345 3, 4 or 5 MHz, with a 1 MHz bandwidth. In the observations considered in  
346 this paper, the central frequency of the chirp was 5 MHz. The pulse echo  
347 is down-converted to a central frequency of 0.7 MHz, and sampled by the  
348 analog-to-digital converter at 2.8 MHz sampling rate. In-phase and quadrature  
349 components (I/Q) synthesis then reduces the sampling rate at 1.4 MHz. The  
350 synthetic aperture length  $2L$  during observations ranged from 2016 to 2226 m.  
351 In the simulation, the value  $2L = 2500 m$  was used, which is close to optimal  
352 value for the unfocused aperture synthesis (half Fresnel zone size  $\sqrt{\lambda z}/2 =$   
353  $2100 m$ ).

354 For the assessment of the aperture synthesis efficiency, a single pulse radar sounder echo  
355 has been simulated (shown in the Figure 10 together with the synthetic aperture echo,  
356 for comparison). Namely, solid and dotted curves in the Figure 10 represent radar signals  
357 with the application of the aperture synthesis and without it.

358 Finally, to comparatively investigate complexity of ionospheric compensation with ide-  
359 ally flat and realistic rough surface, we show the plots of intensity contrast  $C_I^2$  (13) of  
360 simulated radar signals with partial compensation of the ionospheric phase distortion.  
361 The graphs of the contrast calculated for the reflection from ideally flat surface and re-  
362 alistic martian surface terrain are shown in the Figures 11 and 12, respectively. There  
363 is shown dependence of the contrast function  $C_I^2$  on the two leading terms of the Taylor  
364 series of phase mismatch  $\phi(\omega) - \tilde{\phi}(\omega)$  in (8), i.e.  $a_2(\omega - \omega_0)^2$  and  $a_3(\omega - \omega_0)^3$ , where  $\omega_0$   
365 is the central angular frequency of the radar chirp band.

## 5. Discussion of the numerical results.

366 Numerically simulated results are in good agreement both with measured data and  
367 theoretical predictions.

368 While the experimental radargram (panel *a* was computed from real radar pulses dis-  
369 torted by the ionospheric phase dispersion, and therefore was corrected for it, in the  
370 simulated radargram shown on the panel *b* ionospheric phase shifts were not taken in  
371 account. To demonstrate the ionospheric correction algorithm performance, the results  
372 of simulations with accounting for ionospheric frequency dispersion of the phase and its  
373 partial correction is presented in the Fig. 9 separately (panel *d*). It can be seen that the  
374 simulated results match the measurements with a reasonable degree of agreement.

375 Some inaccuracies may arise from intrinsic errors of the Kirchhoff approximation applied  
376 here for the electromagnetic wave scattering description. On the other hand, they may  
377 occur due to some object features (variable material properties etc.), completely missing  
378 in our simple model of perfectly reflecting surface of a given shape.

379 Ionospheric distortions, being properly compensated, also do not significantly impact  
380 the final result (the Fig. 9, panel *e*). To show how much distortion was in fact caused by  
381 the ionosphere in MEX orbit 9466, simulated radargram uncorrected for the ionospheric  
382 distortions is also shown in the Figure 9 (panel *c*).

383 The ionospheric parameters chosen for the simulations correspond to the true conditions  
384 of the Martian atmosphere, which took place during the MEX 9466 orbit measurements.  
385 This orbit crosses the solar terminator in its northern part, and in its southern part,  
386 which is analyzed here, the solar zenith angle changed within a range from 61 to 66  
387 degrees. According to radio occultation measurements [*Zhang et al.*, 1990] and MARSIS  
388 results [*Gurnett et al.*, 2005b], the maximal plasma frequency of the Martian ionosphere  
389 exceeds 3.5 MHz for the solar zenith angles (SZA) smaller than  $50^\circ$ , approaching 4 MHz at  
390  $SZA < 40^\circ$  and exceeding this value during solar events. The NeMars ionospheric model  
391 predicts the maximal plasma frequency values about  $f_p \approx 3.4 \text{ MHz}$  and  $f_p = 4.14 \text{ MHz}$   
392 for the  $SZA = 60^\circ$  and  $SZA = 0^\circ$ , respectively. Thus, to make a complete test of the  
393 ionospheric correction algorithm performance, we investigate a hypothetical worst case  
394 scenario with  $SZA = 0^\circ$  (the sun is all the time at the local zenith). Simulated radargram,  
395 corresponding to this scenario, is shown in the Fig. 9, panel *v*. One can see notable  
396 degradation of the radargram quality, however, it is still readable and interpretable.

397 Effectiveness of the aperture synthesis largely agrees with theoretical estimates. It can  
398 be seen in the Figure 10 that the aperture synthesis is able to suppress side clutter by  
399 15-25 dB. Strong echo at  $t = 100 \mu s$  delay probably comes from transversal direction,  
400 which is not suppressed by the aperture synthesis.

401 The problem of correction of systematic phase distortion and random scat-  
402 tering of the radar signal acting simultaneously, has once been investigated  
403 for the diffraction on the ionospheric irregularities by [*Ilyushin, 2008*]. From  
404 the algorithmic point of view, the problem effectively reduces to the finding of  
405 the correction phase  $\tilde{\phi}(\omega)$ , corresponding to the maximal value of the function  
406 being optimized (i.e. intensity contrast). Under plausible assumptions about  
407 the ionospheric irregularities structure, it has been shown that when random  
408 scattering is present, the peak of the contrast function  $C_I^2$  is slightly flattened  
409 and widened, but still remains unique and unambiguous. So, as a conclusion,  
410 random scattering does not significantly complicate the elimination of system-  
411 atic regular phase distortion in the radar signal. However, no realistic model  
412 of kilometer scale irregularities in the Martian ionosphere is know. Due to  
413 that, simplified assumptions have been made in that study.

414 The results of the present investigation largely agree with that previous  
415 study. As one can see from these two figures 11 and 12, both graphs demon-  
416 strate a clear unique maximum of the contrast function. In the case of realistic  
417 surface roughness model, the maximum is somewhat lower and wider than for  
418 ideally flat surface, however it can still be easily found algorithmically with  
419 standard optimization routines. Thus, the phase correction algorithm based

420 on the contrast optimization principle proves to be stable and robust with  
421 respect to the surface clutter, as well as to the ionospheric random scattering.

## 6. Conclusions and remarks.

422 In the paper presented here, a clutter simulating program CLUSIM, capable of emulat-  
423 ing realistic radar echoes coming from rough planetary surface, is developed and described  
424 in detail. A model of surface landscape topography, based on interpolation of Mars Or-  
425 biter Laser Altimeter data set, has been elaborated. Surface echo simulator, exploiting  
426 Kirchhoff approximation and capable of simulation of aperture synthesis, developed as  
427 a C++ programming language procedure suitable for parallel computing systems using  
428 OpenMP parallel programming standard. A sample synthetic radargram is computed  
429 and compared to realistic radar instrument data obtained by the MARSIS experiment on  
430 board Mars Express interplanetary space mission. Previously elaborated routine for iono-  
431 spheric distortion correction is also tested with simulated radar echo together with vertical  
432 plasma density profiles provided by NeMars ionospheric model, build with data recorded  
433 with the other mode of the MARSIS radar. **Comparative numerical tests confirmed**  
434 **the robustness of the ionospheric phase distortion correction algorithm with**  
435 **respect to the surface clutter.**

## 436 Acknowledgments.

437 This work was supported by ESA-ESTEC Faculty and the Italian Space Agency (ASI)  
438 through contract no. I/032/12/1. Support from Russian Fundamental Research Fund  
439 with the grant 15-02-05476 and Russian National Fund with the grant 17-77-20087 is also  
440 kindly acknowledged.

441 B.S.-C. acknowledges support through STFC grants ST/K001000/1 and ST/N000749/1.

442 Y.I. is grateful to the administration of the Scientific Research Computing Center of  
443 the Moscow State University for granting the access to the computational resources of the  
444 parallel computing systems SKIF-GRID "Tchshebyshev" and "Lomonosov".

445 Authors thank all the reviewers of this paper for constructive reviews and valuable com-  
446 ments. The authors also thank Henrik Melin and Padraig Donnelly for their useful com-  
447 ments. MARSIS subsurface sounding data can be accessed through the Planetary Science  
448 Archive of ESA (<https://www.cosmos.esa.int/web/psa/mars-express>) or the PDS  
449 Geosciences Node of NASA (<http://pds-geosciences.wustl.edu/missions/mars-express/marsis.htm>).  
450 Laser altimetry data from MOLA instrument are available from the archive  
451 <http://pds-geosciences.wustl.edu/missions/mgs/mola.html>. Requests for any other  
452 data should be sent directly to the corresponding author (Ya.I) ilyushin@phys.msu.ru

## References

- 453 Abramowitz, M., and I. A. Stegun (1972), *Handbook of Mathematical Functions with*  
454 *Formulas, Graphs, and Mathematical Tables*, Dover Publications, New York.
- 455 Armand, N., and V. Smirnov (2003), Distortion of radar pulses by the martian ionosphere,  
456 *Radio Science*, 38(5), 11/1–11/12.
- 457 Beckmann, P., and A. Spizzichino (1963), *The Scattering of Electromagnetic Waves from*  
458 *Rough Surfaces*, Macmillan and Company, New York.
- 459 Berquin, Y., A. Herique, W. Kofman, and E. Heggy (2015), Computing low-frequency  
460 radar surface echoes for planetary radar using Huygens-Fresnel's principle, *Radio Sci-*  
461 *ence*, 50(10), 1097–1109, doi:10.1002/2015RS005714.

462 Black, G., D. Campbell, and S. Ostro (2001a), Icy galilean satellites: 70 cm radar results  
463 from Arecibo, *Icarus*, *151*(2), 160 – 166, doi:10.1006/icar.2001.6615.

464 Black, G., D. Campbell, and P. Nicholson (2001b), Icy galilean satellites: Modeling  
465 radar reflectivities as a coherent backscatter effect, *Icarus*, *151*(2), 167 – 180, doi:  
466 10.1006/icar.2001.6616.

467 Bogorodsky, V., C. Bentley, and P. Gudmandsen (1985), *Radioglaciology*, Reidel, Dor-  
468 drecht.

469 Boisson, J., E. Heggy, S. M. Clifford, A. Frigeri, J. J. Plaut, W. M. Farrell, N. E. Putzig,  
470 G. Picardi, R. Orosei, P. Lognonne, and D. A. Gurnett (2009), Sounding the subsurface  
471 of Athabasca Valles using MARSIS radar data: Exploring the volcanic and fluvial  
472 hypotheses for the origin of the rafted plate terrain, *Journal of Geophysical Research:*  
473 *Planets*, *114*(E8), doi:10.1029/2008JE003299, e08003.

474 Bruzzone, L., J. Plaut, G. Alberti, D. Blankenship, F. Bovolo, B. Campbell, A. Ferro,  
475 Y. Gim, W. Kofman, G. Komatsu, W. McKinnon, G. Mitri, R. Orosei, G. Patterson,  
476 D. Plettemeier, and R. Seu (2013), RIME: Radar for icy moon exploration, *European*  
477 *Planetary Science Congress Abstracts*, *8*, EPSC2013–744–1.

478 Cartacci, M., E. Amata, A. Cicchetti, R. Noschese, S. Giuppi, B. Langlais, A. Frigeri,  
479 R. Orosei, and G. Picardi (2013), Mars ionosphere total electron content analysis from  
480 MARSIS subsurface data, *Icarus*, *223*(1), 423 – 437, doi:10.1016/j.icarus.2012.12.011.

481 Ciarletti, V., A. Levasseur-Regourd, J. Lasue, C. Statz, D. Plettemeier, A. Herique,  
482 Y. Rogez, and W. Kofman (2015), Consert suggests a change in local properties of  
483 67p/Churyumov-Gerasimenko’s nucleus at depth, *Astronomy and Astrophysics*, *583*,  
484 doi:10.1051/0004-6361/201526337.

485 Eshleman, V. R. (1986), Radar glory from buried craters on icy moons, *Science*,  
486 *234*(4776), 587–590, doi:10.1126/science.234.4776.587.

487 Fa, W., and Y. Jin (2010), Simulation of radar sounder echo from lunar surface and sub-  
488 surface structure, *Science China Earth Sciences*, *53*(7), 1043–1055, doi:10.1007/s11430-  
489 010-3070-8.

490 Ford, P. G., and G. H. Pettengill (1992), Venus topography and kilometer-scale  
491 slopes, *Journal of Geophysical Research: Planets*, *97*(E8), 13,103–13,114, doi:  
492 10.1029/92JE01085.

493 Goodman, J. (1996), *Introduction to Fourier Optics*, 2nd ed., McGraw-Hill.

494 Grasset, O., M. Dougherty, A. Coustenis, E. Bunce, C. Erd, D. Titov, M. Blanc,  
495 A. Coates, P. Drossart, L. Fletcher, H. Hussmann, R. Jaumann, N. Krupp, J.-P. Lebre-  
496 ton, O. Prieto-Ballesteros, P. Tortora, F. Tosi, and T. V. Hoolst (2013), JUPiter ICy  
497 moons explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the  
498 Jupiter system, *Planetary and Space Science*, *78*, 1 – 21, doi:10.1016/j.pss.2012.12.002.

499 Gurnett, D. A., D. L. Kirchner, R. L. Huff, D. D. Morgan, A. M. Persoon, T. F. Averkamp,  
500 F. Duru, E. Nielsen, A. Safaeinili, J. J. Plaut, and G. Picardi (2005a), Radar soundings  
501 of the ionosphere of Mars, *Science*, *310*(5756), 1929–1933, doi:10.1126/science.1121868.

502 Gurnett, D. A., D. L. Kirchner, R. L. Huff, D. D. Morgan, A. M. Persoon, T. F. Averkamp,  
503 F. Duru, E. Nielsen, A. Safaeinili, J. J. Plaut, , and G. Picardi (2005b), Radar soundings  
504 of the ionosphere of Mars, *Science*, *310*, 1929, doi:DOI: 10.1126/science.1121868.

505 Hagfors, T. (1967), A study of the depolarization of lunar radar echoes, *Radio Science*,  
506 *2*(5), 445–465, doi:10.1002/rds196725445.

507 Hagfors, T., I. Dahlstrom, T. Gold, S.-E. Hamran, and R. Hansen (1997), Refraction  
508 scattering in the anomalous reflections from icy surfaces, *Icarus*, *130*(2), 313 – 322,  
509 doi:10.1006/icar.1997.5844.

510 Hapke, B. (1990), Coherent backscatter and the radar characteristics of outer planet  
511 satellites, *Icarus*, *88*(2), 407–417, doi:10.1016/0019-1035(90)90091-M.

512 Hapke, B., and D. Blewett (1991), Coherent backscatter model for the unusual radar  
513 reflectivity of icy satellites, *Nature*, *352*(6330), 46–47.

514 Harris, F. J. (1978), On the use of windows for harmonic analysis with the Discrete Fourier  
515 Transform, *Proceedings of the IEEE*, *66*(1), 51–83.

516 Hartogh, P., and Y. Ilyushin (2016), A passive low frequency instrument for radio wave  
517 sounding the subsurface oceans of the Jovian icy moons: An instrument concept, *Plane-*  
518 *tary and Space Science*, *130*, 30 – 39, doi:10.1016/j.pss.2016.05.008, atmospheres, Mag-  
519 netospheres and Surfaces of the outer planets, their satellites and ring systems: Part  
520 XI .

521 Herique, A., and W. Kofman (1997), Reconstruction by migration of undersampled 2D  
522 signals, *IEEE Transactions on Signal Processing*, *45*(9), 2406.

523 Herique, A., W. Kofman, T. Hagfors, G. Caudal, and J.-P. Ayanides (1999), A char-  
524 acterization of a comet nucleus interior: inversion of simulated radio frequency data,  
525 *Planetary and Space Science*, *47*(6-7), 885 – 904, doi:10.1016/S0032-0633(98)00144-5.

526 Ilyushin, Y. (2008), Distortions of the ultrawideband signals of deep-sensing radars in  
527 an irregular ionosphere, *Journal of Communications Technology and Electronics*, *53*(4),  
528 377–386, doi:10.1134/S1064226908040025.

529 Ilyushin, Y. (2010), Influence of anisotropic fluctuations of the ionosphere plasma density  
530 on deep radio sounding by a ultra wide band radar with synthesized aperture, *Cosmic*  
531 *Research*, 48(2), 157–164.

532 Ilyushin, Y., and V. Kunitsyn (2004), Methods for correcting ionosphere distortions of  
533 orbital ground-penetrating radar signals, *Journal of Communications Technology and*  
534 *Electronics*, 49(2), 154–165.

535 Ilyushin, Y. A. (2004), Martian northern polar cap: Layering and possible implica-  
536 tions for radar sounding, *Planetary and Space Science*, 52(13), 1195 – 1207, doi:  
537 10.1016/j.pss.2004.08.002.

538 Ilyushin, Y. A. (2009a), Impact of the plasma fluctuations in the martian ionosphere  
539 on the performance of the synthetic aperture ground-penetrating radar, *Planetary and*  
540 *Space Science*, 57(12), 1458 – 1466, doi:10.1016/j.pss.2009.07.005.

541 Ilyushin, Y. A. (2009b), Influence of the ionospheric plasma density fluctuations on the  
542 subsurface sounding of the martian soil by a synthetic aperture radar, *Radiophysics and*  
543 *Quantum Electronics*, 52(5-6), 332–340.

544 Ilyushin, Y. A. (2012), Coherent backscattering enhancement in highly anisotropically  
545 scattering media: Numerical solution, *Journal of Quantitative Spectroscopy and Radia-*  
546 *tive Transfer*, 113(5), 348 – 354, doi:10.1016/j.jqsrt.2011.12.003.

547 Ilyushin, Y. A. (2014), Subsurface radar location of the putative ocean on Ganymede:  
548 Numerical simulation of the surface terrain impact, *Planetary and Space Science*, 92,  
549 121–126.

550 Ilyushin, Y. A., and V. E. Kunitsyn (2008), Radio sensing of a cometary nucleus: Possi-  
551 bilities for investigating the surface layer, *Journal of Communications Technology and*

553 Ilyushin, Y. A., T. Hagfors, and V. E. Kunitsyn (2003), Cometary surface layer properties:  
554 Possible approaches to radio sounding retrieval during the consort experiment-numerical  
555 simulation and discussion, *Radio Science*, 38(1), 8/1–8/9, doi:10.1029/2001RS002487.

556 Ilyushin, Y. A., S. V.M., and Y. O.V. (2012), Deep subsurface radar sounding of rough  
557 extraterrestrial terrains: Numerical simulations, *2012 6th International Conference on*  
558 *Ultrawideband and Ultrashort Impulse Signals, UWBUSIS 2012 - Conference Proceed-*  
559 *ings*, pp. 112–114.

560 Jaumann, R., G. Neukum, T. Behnke, T. Duxbury, K. Eichertopf, J. Flohrer, S. Gasselt,  
561 B. Giese, K. Gwinner, E. Hauber, H. Hoffmann, A. Hoffmeister, U. Kohler, K.-D.  
562 Matz, T. McCord, V. Mertens, J. Oberst, R. Pischel, D. Reiss, E. Ress, T. Roatsch,  
563 P. Saiger, F. Scholten, G. Schwarz, K. Stephan, and M. Wahlisch (2007), The high-  
564 resolution stereo camera (HRSC) experiment on Mars Express: Instrument aspects and  
565 experiment conduct from interplanetary cruise through the nominal mission, *Planetary*  
566 *and Space Science*, 55(78), 928 – 952, doi:10.1016/j.pss.2006.12.003.

567 Johnson, S. G. (2012). [http : //ab – initio.mit.edu/wiki/index.php/Faddeeva\\_Package](http://ab-initio.mit.edu/wiki/index.php/Faddeeva_Package)

568 Jordan, R., G. Picardi, J. Plaut, K. Wheeler, D. Kirchner, A. Safaeinili, W. Johnson,  
569 R. Seu, D. Calabrese, E. Zampolini, A. Cicchetti, R. Huff, D. Gurnett, A. Ivanov,  
570 W. Kofman, R. Orosei, T. Thompson, P. Edenhofer, and O. Bombaci (2009), The Mars  
571 Express MARSIS sounder instrument, *Planetary and Space Science*, 57(14–15), 1975 –  
572 1986, doi:10.1016/j.pss.2009.09.016.

573 Kirk, R. L., E. Howington-Kraus, B. Redding, D. Galuszka, T. M. Hare, B. A. Archinal,  
574 L. A. Soderblom, and J. M. Barrett (2003), High-resolution topomapping of candidate

575 MER landing sites with Mars orbiter camera narrow-angle images, *Journal of Geophys-*  
576 *ical Research: Planets*, 108(E12), 8088, doi:10.1029/2003JE002131.

577 Kirk, R. L., E. Howington-Kraus, M. R. Rosiek, J. A. Anderson, B. A. Archinal, K. J.  
578 Becker, D. A. Cook, D. M. Galuszka, P. E. Geissler, T. M. Hare, I. M. Holmberg,  
579 L. P. Keszthelyi, B. L. Redding, W. A. Delamere, D. Gallagher, J. D. Chapel, E. M.  
580 Eliason, R. King, and A. S. McEwen (2008), Ultrahigh resolution topographic mapping  
581 of Mars with mro hirise stereo images: Meter-scale slopes of candidate phoenix landing  
582 sites, *Journal of Geophysical Research: Planets*, 113(E3), doi:10.1029/2007JE003000,  
583 e00A24.

584 Kofman, W., Y. Barbin, J. Klinger, A.-C. Levasseur-Regourd, J.-P. Barriot, A. Herique,  
585 T. Hagfors, E. Nielsen, E. Grn, P. Edenhofer, H. Kochan, G. Picardi, R. Seu, J. van Zyl,  
586 C. Elachi, J. Melosh, J. Veverka, P. Weissman, L. Svedhem, S. Hamran, and I. Williams  
587 (1998), Comet nucleus sounding experiment by radiowave transmission, *Advances in*  
588 *Space Research*, 21(11), 1589 – 1598, doi:10.1016/S0273-1177(97)00952-6.

589 Kreslavsky, M.A., and J.W. Head III (2000), Kilometer-scale roughness of Mars: results  
590 from MOLA data analysis, *J. Geophys. Res.*, 105(E11), 26,695–26,711.

591 Liu, C., H. Ye, and Y.-Q. Jin (2014), Simulation of radar echoes from Mars’ sur-  
592 face/subsurface and inversion of surface media parameters, *Radio Science*, 49(7), 473–  
593 484, doi:10.1002/2013RS005367.

594 Morgan, D., O. Witasse, E. Nielsen, D. Gurnett, F. Duru, and D. Kirchner (2013), The  
595 processing of electron density profiles from the Mars Express MARSIS topside sounder,  
596 *Radio Science*, 48(3), 197–207, doi:10.1002/rds.20023.

597 Mougnot, J., W. Kofman, A. Safaeinili, and A. Herique (2008), Correction of the iono-  
598 spheric distortion on the MARSIS surface sounding echoes, *Planetary and Space Science*,  
599 *56*(7), 917–926.

600 Neukum, G., and R. Jaumann (2004), *HRSC: the High Resolution Stereo Camera of Mars*  
601 *Express*, 17 - 35 pp., Noordwijk, Netherlands: ESA Publications Division.

602 Neumann, G. A., J. B. Abshire, O. Aharonson, J. B. Garvin, X. Sun, and M. T. Zu-  
603 ber (2003), Mars orbiter laser altimeter pulse width measurements and footprint-scale  
604 roughness, *Geophysical Research Letters*, *30*(11), doi:10.1029/2003GL017048, 1561.

605 Nouvel, J.-F., A. Herique, W. Kofman, and A. Safaeinili (2004), Radar signal sim-  
606 ulation: Surface modeling with the facet method, *Radio Science*, *39*(1), doi:  
607 10.1029/2003RS002903.

608 Nunes, D. C., S. E. Smrekar, A. Safaeinili, J. Holt, R. J. Phillips, R. Seu, and B. Camp-  
609 bell (2010), Examination of gully sites on Mars with the shallow radar, *Journal of*  
610 *Geophysical Research: Planets*, *115*(E10), doi:10.1029/2009JE003509, e10004.

611 Nunes, D. C., S. E. Smrekar, B. Fisher, J. J. Plaut, J. W. Holt, J. W. Head, S. J. Kadish,  
612 and R. J. Phillips (2011), Shallow radar (SHARAD), pedestal craters, and the lost  
613 martian layers: Initial assessments, *Journal of Geophysical Research: Planets*, *116*(E4),  
614 doi:10.1029/2010JE003690, e04006.

615 Ogilvy, J. (1991), *Theory of Wave Scattering from Random Rough Surfaces*, Adam Hilger,  
616 Bristol.

617 Ono, T., A. Kumamoto, H. Nakagawa, Y. Yamaguchi, S. Oshigami, A. Yamaji,  
618 T. Kobayashi, Y. Kasahara, and H. Oya (2009), Lunar radar sounder observations of  
619 subsurface layers under the nearside maria of the Moon, *Science*, *323*(5916), 909–912,

620 doi:10.1126/science.1165988.

621 Ostro, S. J., and G. H. Pettengill (1978), Icy craters on the galilean satellites?, *Icarus*,  
622 *34*(2), 268 – 279, doi:10.1016/0019-1035(78)90167-7.

623 Ostro, S. J., and E. M. Shoemaker (1990), The extraordinary radar echoes from Eu-  
624 ropa, Ganymede, and Callisto: A geological perspective, *Icarus*, *85*(2), 335 – 345,  
625 doi:10.1016/0019-1035(90)90121-O.

626 Peeples, W. J., W. R. Sill, T. W. May, S. H. Ward, R. J. Phillips, R. L. Jordan, E. A.  
627 Abbott, and T. J. Killpack (1978), Orbital radar evidence for lunar subsurface layering  
628 in maria Serenitatis and Crisium, *Journal of Geophysical Research: Solid Earth*, *83*(B7),  
629 3459–3468, doi:10.1029/JB083iB07p03459.

630 Pettinelli, E., B. Cosciotti, F. Di Paolo, S. E. Lauro, E. Mattei, R. Orosei, and  
631 G. Vannaroni (2015), Dielectric properties of Jovian satellite ice analogs for sub-  
632 surface radar exploration: A review, *Reviews of Geophysics*, *53*(3), 593–641, doi:  
633 10.1002/2014RG000463.

634 Phillips, C. B., and R. T. Pappalardo (2014), Europa CLIPPER mission concept: Ex-  
635 ploring Jupiter’s ocean moon, *Eos, Transactions American Geophysical Union*, *95*(20),  
636 165–167, doi:10.1002/2014EO200002.

637 Phillips, R. J., and et al. (1973), Apollo lunar sounder experiment, *330*(22), 1–26.

638 Picardi, G. e. (2004), MARSIS: Mars advanced radar for subsurface and ionosphere sound-  
639 ing, *Mars Express: the scientific payload*, pp. 51–69.

640 Picardi, G., et al. (1999), Martian advanced radar for subsurface and ionospheric  
641 sounding (MARSIS): Models and system analysis, *Tech. Rep. MRS-001/005/99 V.2.0*  
642 *21/05/1999*, InfoCom Dpt.

643 Picardi, G. et al. (2001), MARSIS flight user manual, *Tech. Rep. ID-MAR-0008-INF*,  
644 InfoCom Dpt.

645 Preusker, F., J. Oberst, J. W. Head, T. R. Watters, M. S. Robinson, M. T. Zuber, and  
646 S. C. Solomon (2011), Stereo topographic models of Mercury after three MESSENGER  
647 flybys, *Planetary and Space Science*, 59(15), 1910 – 1917, doi:10.1016/j.pss.2011.07.005.

648 Purcell, E. M., and C. R. Pennypacker (1973), Scattering and Absorption of Light  
649 by Nonspherical Dielectric Grains, *The Astrophysical Journal*, 186, 705–714, doi:  
650 10.1086/152538.

651 Romero-Wolf, A., S. Vance, F. Maiwald, E. Heggy, P. Ries, and K. Liewer (2015), A  
652 passive probe for subsurface oceans and liquid water in Jupiter’s icy moons, *Icarus*,  
653 248, 463 – 477, doi:10.1016/j.icarus.2014.10.043.

654 Russo, F., M. Cutigni, R. Orosei, C. Taddei, R. Seu, D. Biccari, E. Giacomoni, O. Fuga,  
655 and E. Flamini (2008), An incoherent simulator for the SHARAD experiment, *Radar*  
656 *Conference*.

657 Safaeinili, A., W. Kofman, J.-F. Nouvel, A. Herique, and R. Jordan (2003), Impact of  
658 Mars ionosphere on orbital radar sounder operation and data processing, *Planetary and*  
659 *Space Science*, 51(7-8), 505–515, doi:10.1016/S0032-0633(03)00048-5.

660 Sánchez-Cano, B., O. Witasse, M. Herraiz, S. M. Radicella, J. Bauer, P.-L. Blelly, and  
661 G. Rodríguez-Caderot (2012), Retrieval of ionospheric profiles from the Mars Express  
662 MARSIS experiment data and comparison with radio occultation data, *Geoscientific*  
663 *Instrumentation, Methods and Data Systems*, 1(1), 77–84, doi:10.5194/gi-1-77-2012.

664 Sanchez-Cano, B., S. Radicella, M. Herraiz, O. Witasse, and G. Rodriguez-Caderot (2013),  
665 NeMars: An empirical model of the martian dayside ionosphere based on Mars Express

666 MARSIS data, *Icarus*, 225(1), 236 – 247, doi:10.1016/j.icarus.2013.03.021.

667 Sanchez-Cano, B. b., D. Morgan, O. Witasse, S. Radicella, M. f. Herraiz, R. Orosei,  
668 M. Cartacci, A. Cicchetti, R. Noschese, W. j. Kofman, C. Grima, J. Mouginot, D. Gur-  
669 nett, M. Lester, P.-L. Blelly, H. Opgenoorth, and G. Quinsac (2015), Total electron  
670 content in the martian atmosphere: A critical assessment of the Mars Express MAR-  
671 SIS data sets, *Journal of Geophysical Research A: Space Physics*, 120(3), 2166–2182,  
672 doi:10.1002/2014JA020630.

673 Schroeder, D. M., A. Romero-Wolf, L. Carrer, C. Grima, B. A. Campbell, W. Kofman,  
674 L. Bruzzone, and D. D. Blankenship (2016), Assessing the potential for passive radio  
675 sounding of Europa and Ganymede with RIME and REASON , *Planetary and Space*  
676 *Science*, 134, pp.52–60, doi:10.1016/j.pss.2016.10.007.

677 Seu, R., R. J. Phillips, D. Biccari, R. Orosei, A. Masdea, G. Picardi, A. Safaeinili, B. A.  
678 Campbell, J. J. Plaut, L. Marinangeli, S. E. Smrekar, and D. C. Nunes (2007), SHARAD  
679 sounding radar on the Mars Reconnaissance Orbiter, *Journal of Geophysical Research:*  
680 *Planets*, 112(E5), doi:10.1029/2006JE002745, e05S05.

681 Smirnov, V., O. Yushkova, I. Karachevtseva, and I. Nadezhdina (2014), The influence  
682 of relief on formation of reflected signals of subsurface sounding radar, *Solar System*  
683 *Research*, 48(3), 176–181, doi:10.1134/S003809461403006X.

684 Smith, D. E., M. T. Zuber, H. V. Frey, J. B. Garvin, J. W. Head, D. O. Muhleman, G. H.  
685 Pettengill, R. J. Phillips, S. C. Solomon, H. J. Zwally, W. B. Banerdt, T. C. Duxbury,  
686 M. P. Golombek, F. G. Lemoine, G. A. Neumann, D. D. Rowlands, O. Aharonson,  
687 P. G. Ford, A. B. Ivanov, C. L. Johnson, P. J. McGovern, J. B. Abshire, R. S. Afzal,  
688 and X. Sun (2001), Mars Orbiter Laser Altimeter: Experiment summary after the first

689 year of global mapping of Mars, *Journal of Geophysical Research: Planets*, 106(E10),  
690 23,689–23,722, doi:10.1029/2000JE001364.

691 Smith, D. E., M. T. Zuber, G. A. Neumann, F. G. Lemoine, E. Mazarico, M. H. Torrence,  
692 J. F. McGarry, D. D. Rowlands, J. W. Head, T. H. Duxbury, O. Aharonson, P. G. Lucey,  
693 M. S. Robinson, O. S. Barnouin, J. F. Cavanaugh, X. Sun, P. Liiva, D.-d. Mao, J. C.  
694 Smith, and A. E. Bartels (2010), Initial observations from the Lunar Orbiter Laser  
695 Altimeter (lola), *Geophysical Research Letters*, 37(18), doi:10.1029/2010GL043751,  
696 118204.

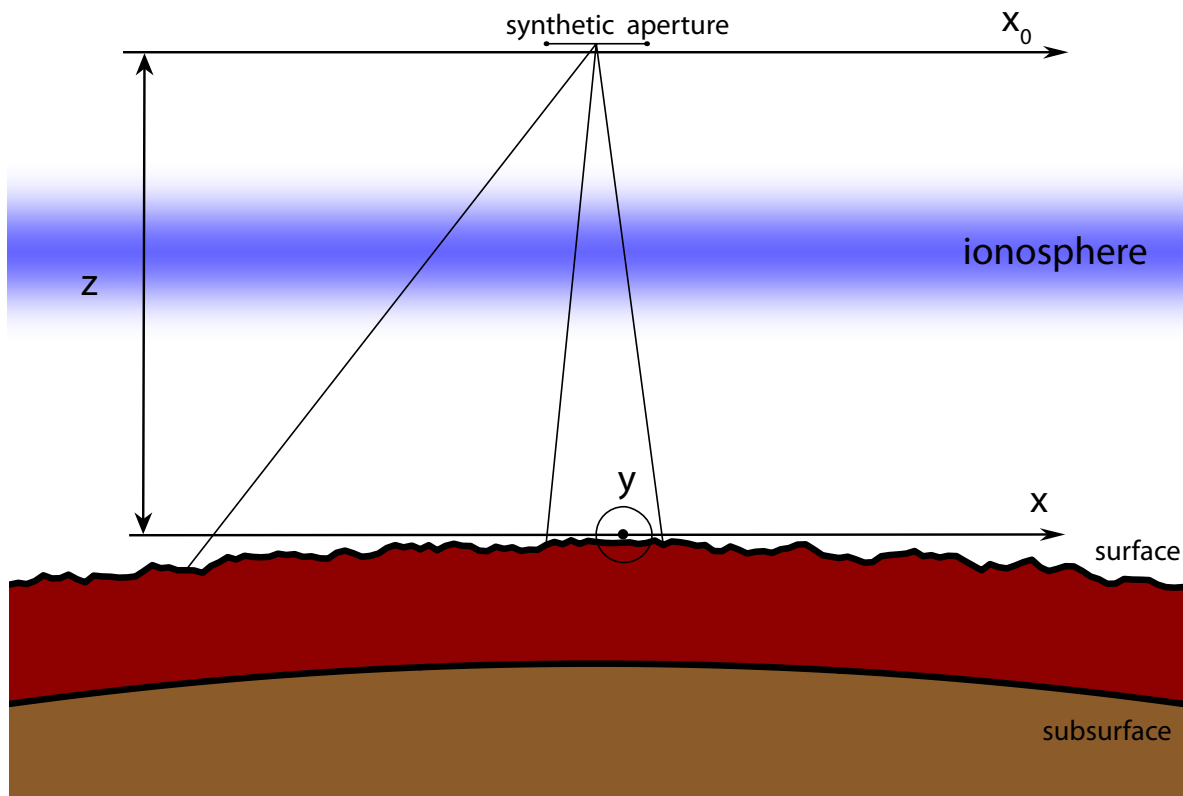
697 Spagnuolo, M., F. Grings, P. Perna, M. Franco, H. Karszenbaum, and V. Ramos (2011),  
698 Multilayer simulations for accurate geological interpretations of SHARAD radargrams,  
699 *Planetary and Space Science*, 59(11-12), 1222–1230, doi:10.1016/j.pss.2010.10.013.

700 Waterman, P. (1965), Matrix formulation of electromagnetic scattering, *Proceedings of*  
701 *the IEEE*, 53(8), 805–812, doi:10.1109/PROC.1965.4058.

702 Xu, Y., S. A. Cummer, and W. M. Farrell (2006), Application of an orbital radar sounder  
703 model to detecting martian polar subsurface features, *Journal of Geophysical Research:*  
704 *Planets*, 111(E6), doi:10.1029/2005JE002547, e06S17.

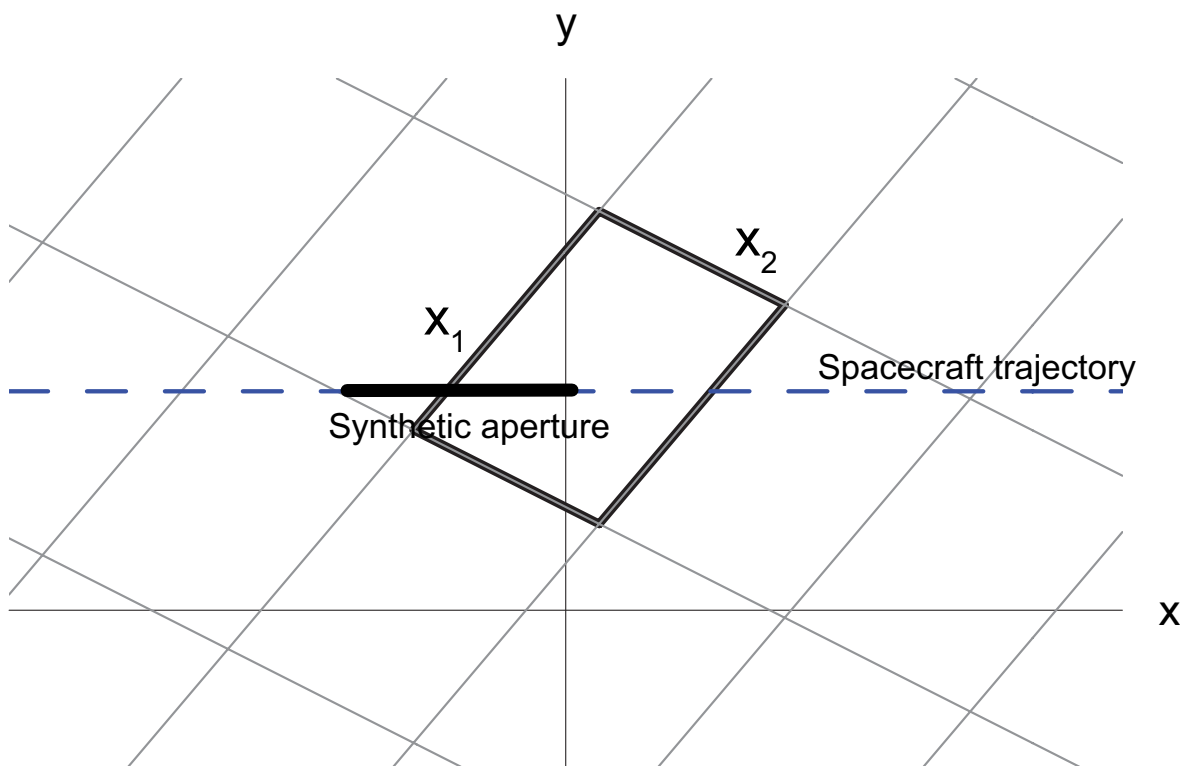
705 Yee, K. (1966), Numerical solution of initial boundary value problems involving Maxwell’s  
706 equations in isotropic media, *Antennas and Propagation, IEEE Transactions on*, 14(3),  
707 302–307.

708 Zhang, M. H. G., J. G. Luhmann, and A. J. Kliore (1990), An observational study of the  
709 nightside ionospheres of Mars and Venus with radio occultation methods, *J. Geophys.*  
710 *Res.*, 95, 17,095–17,102, doi:10.1029/JA095iA10p17095.

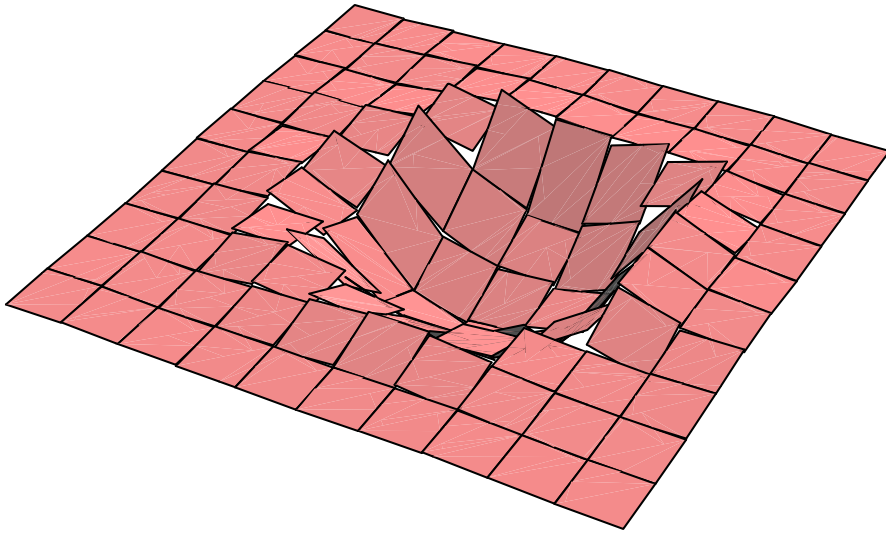


**Figure 1.** Schematic description of the subsurface radar sounding experiment.

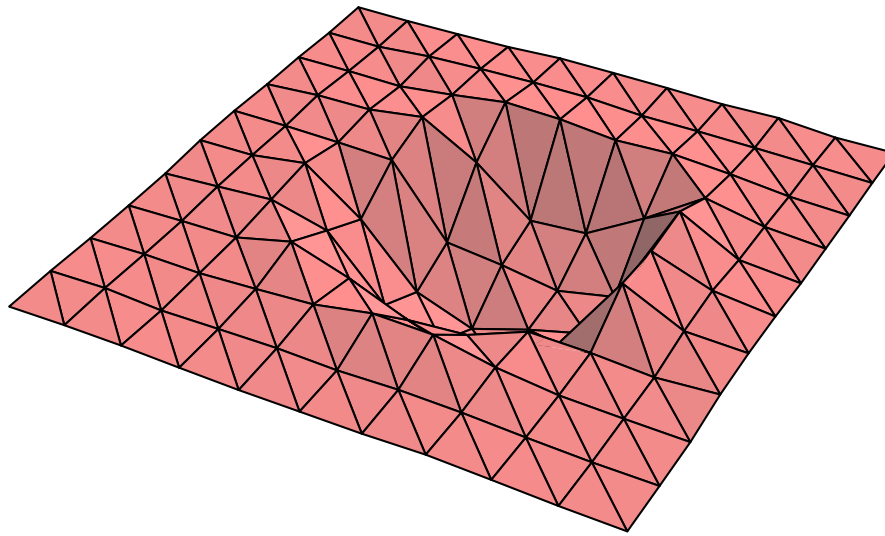
711 Zienkiewicz, O., R. Taylor, and J. Zhu (Eds.) (2013), *The Finite Element Method: its*  
 712 *Basis and Fundamentals (Seventh Edition)*, seventh edition ed., i - pp., Butterworth-  
 713 Heinemann, Oxford, doi:10.1016/B978-1-85617-633-0.00019-8.



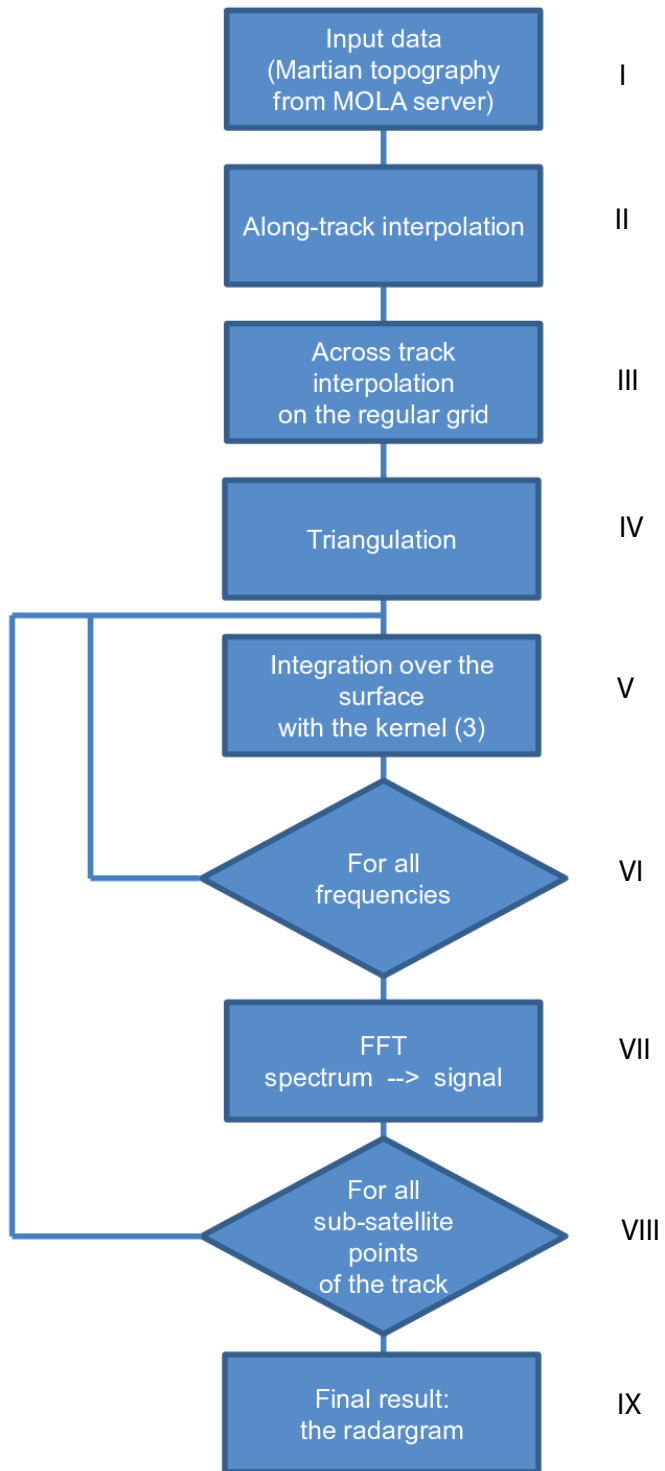
**Figure 2.** Schematic facet geometry.



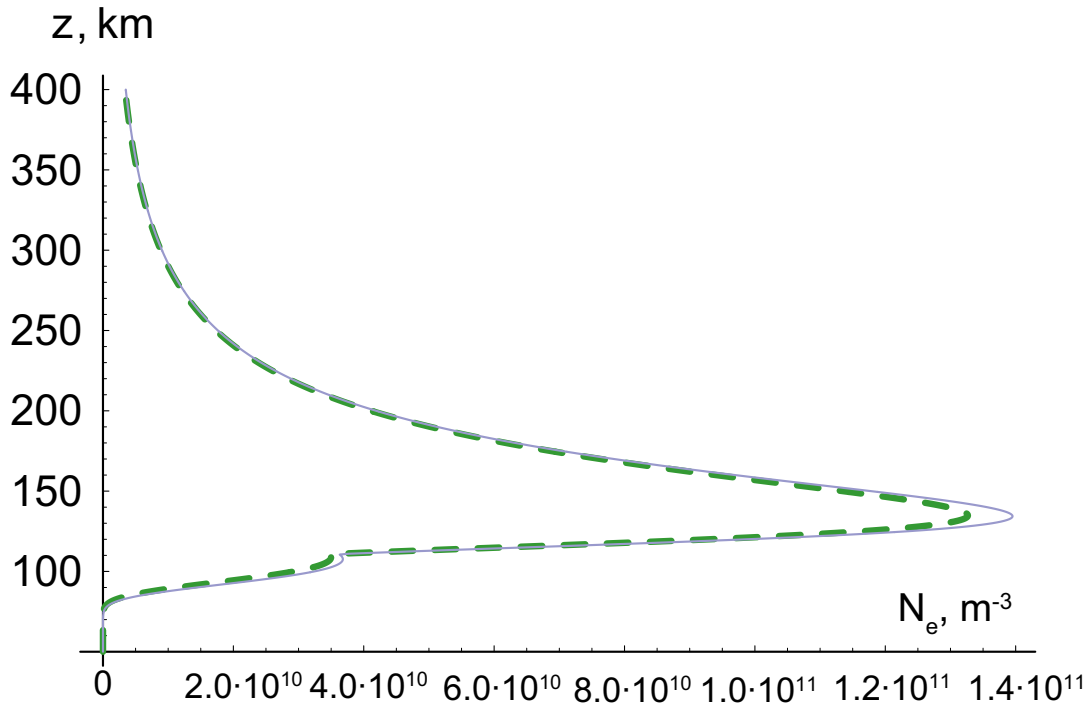
**Figure 3.** Facet approximation of the planetary surface topography (Martian crater at 22N 61E).



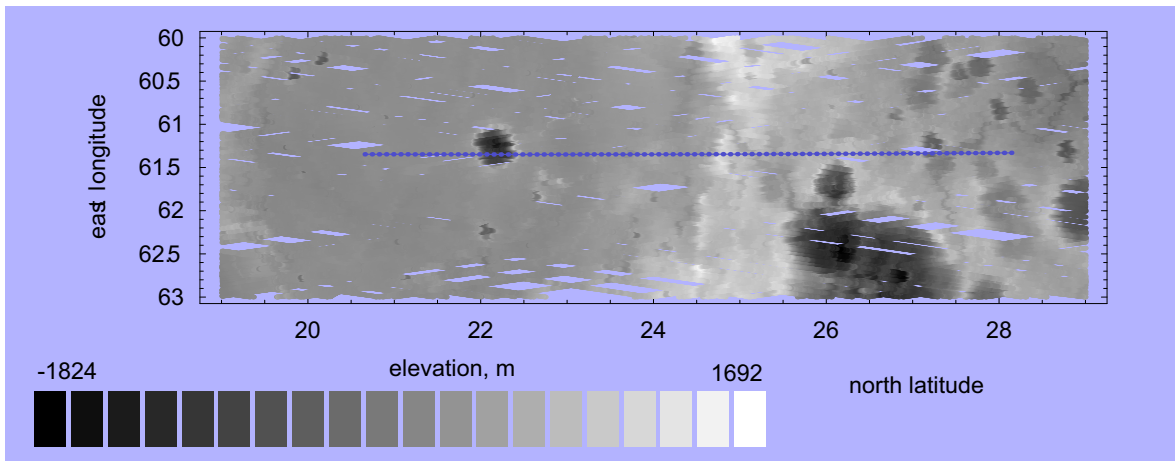
**Figure 4.** Piecewise-planar triangulation of the planetary surface topography (Martian crater at 22N 61E).



**Figure 5.** The CLUSIM program flow chart.



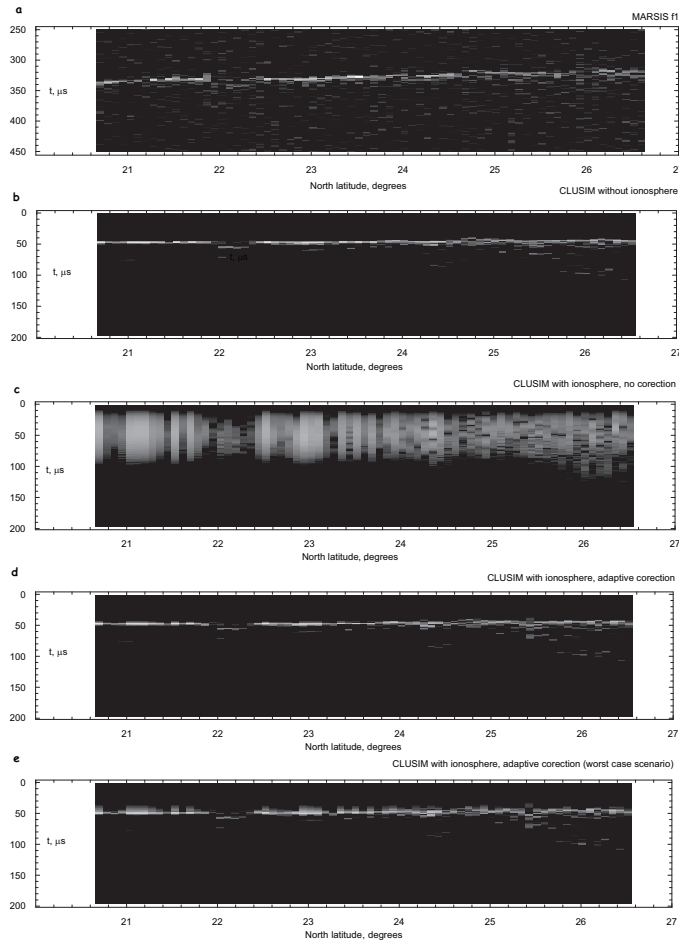
**Figure 6.** NeMars model ionospheric plasma density profiles for the ending points of satellite orbit portion. Solid line – SZA=61.293, LAT=20.658N, dashed line – SZA=64.95, LAT=26.554N.



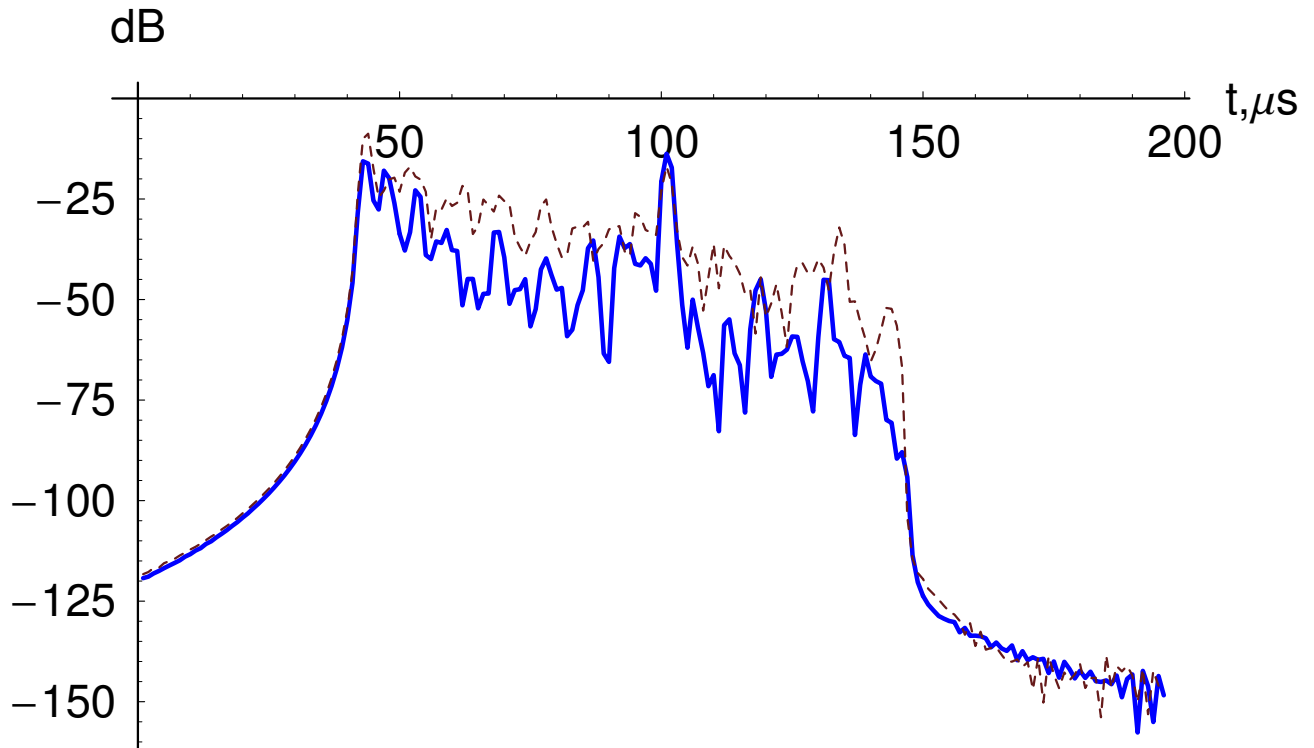
**Figure 7.** MOLA topography of the martian underlying surface landscape. Blue dotted line - the southmost part of the MEX orbit 9466 subsatellite track.



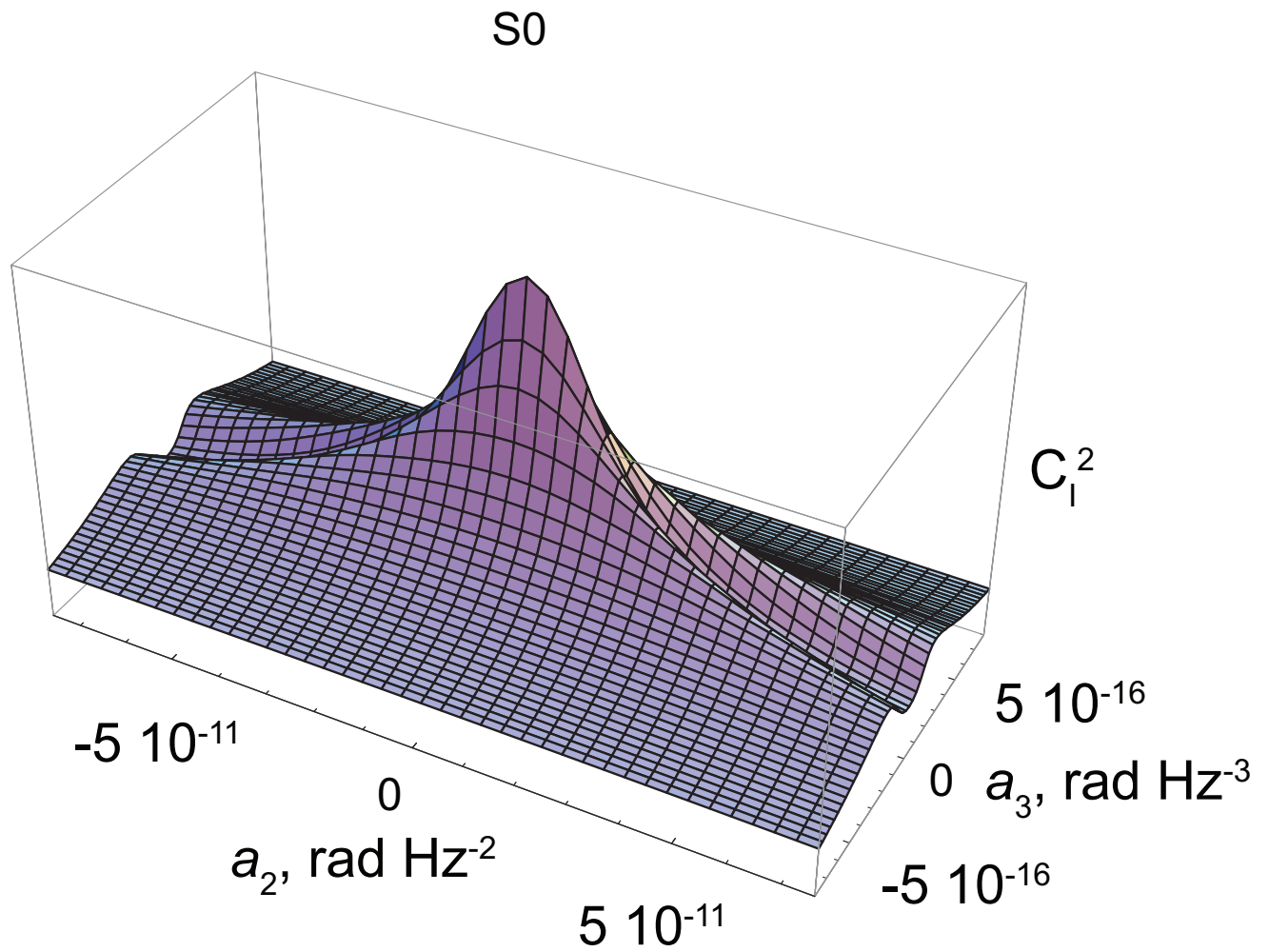
**Figure 8.** Mosaic of HRSC images H5191\_0000\_ND3 and H7357\_0000\_ND3 [*Neukum and Jaumann, 2004*] depicting the subsatellite landscape of the portion of MEX orbit 9466 under investigation. North is the right of the image.



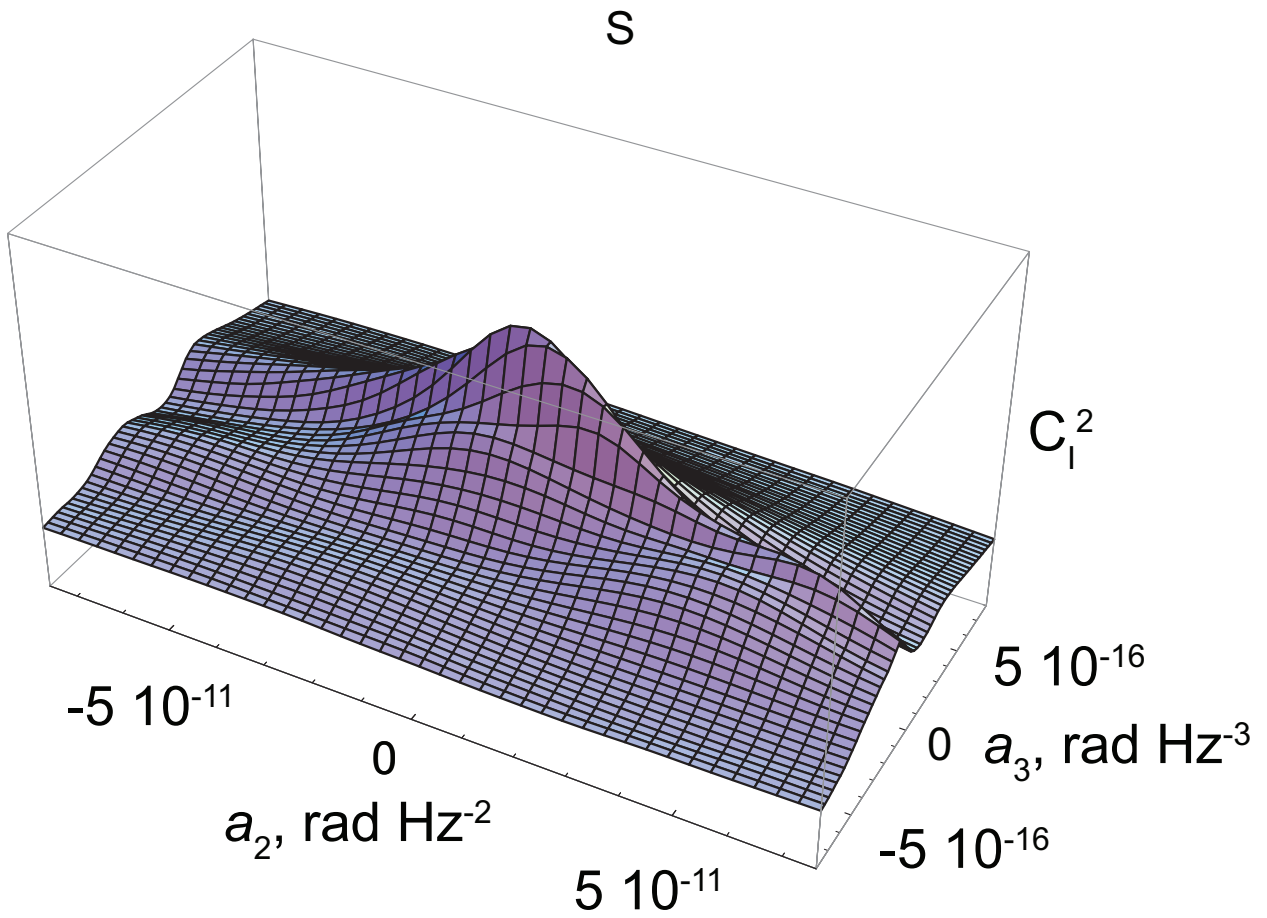
**Figure 9.** MARSIS radargrams of 9466 MEX orbit. MARSIS Band 4 (4.5 -5.5 MHz). *a* – experimental MARSIS radargram, doppler filter 0, working frequency  $f = 5$  MHz (MARSIS band IV), *b* – simulated MARSIS radargram (CLUSIM) without any ionospheric phase shifts, *c* – simulated MARSIS radargram (CLUSIM) with ionospheric phase distortions and no correction, *d* – simulated MARSIS radargram (CLUSIM) with ionospheric phase distortions superimposed and corrected by the maximal contrast adjustment, *e* – simulated MARSIS radargram (CLUSIM) (the same as *e* for the hypothetical ”worst case” scenario).



**Figure 10.** Single pulse MARSIS echo simulation. Solid curve – aperture synthesis is applied (the Doppler filter 0), dotted curve – single pulse echo. Subsatellite point is about  $26^{\circ} N$  along the 9466 MEX orbit.



**Figure 11.** Intensity contrast of the distorted radar reflection from the ideally flat surface (arbitrary units).



**Figure 12.** Intensity contrast of the distorted radar reflection from the realistic surface terrain (arbitrary units).