



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

¹ **CLUSIM: A synthetic aperture radar clutter** ² **simulator for planetary exploration.**

Ya. A. Ilyushin,^{1,2} R. Orosei,³ O. Witasse,⁴ and B. Sanchez-Cano,⁵

¹ 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

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

³ Istituto di Radioastronomia, Istituto
Nazionale di Astrofisica, Via Piero Gobetti
101, 40129, Bologna, Italy
roberto.oroisei@inaf.it

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

⁵Radio 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.**

Abstract. In this paper we present the CLutter SIMulator (CLUSIM), a special program simulating radar side echoes from rough planetary surfaces using realistic topography data sets. A numerical model of realistic topography of the Martian surface, based on Mars Orbiter Laser Altimeter data, is developed. A specially developed computer routine for evaluation of wide band radar echoes reflected from rough surfaces, capable of aperture synthesis simulation, is described. A synthetic radargram for a portion of Mars Express (MEX) orbit 9466 is computed and validated against experimental data obtained by the MARSIS radar instrument. Finally, a previously developed ionospheric phase correction procedure is numerically tested with new simulated echo signals. **Impact of the surface clutter on the ionospheric correction procedure is investigated with a direct numerical comparison to a known benchmark result, which shows robustness of the correction algorithm with respect to the surface clutter.**

1. Introduction.

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

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

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

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

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

consist of the physical model of the object structure (surface) and algorithm for the numerical solution of the electromagnetic equations, ruling an interaction of the electromagnetic wave with the object.

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

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

2. Synthetic aperture radar clutter simulator.

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

Both the rough surface model and the approach to the electromagnetic equations itself can be deterministic or statistical. To validate the detection of subsurface interfaces, numerical electromagnetic models of surface scattering should be used to produce simulations of surface echoes, which are then compared to real echoes detected by the radar. A realistic model of the surface should be based on real observations.

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

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

2.1. Topography interpolation

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

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

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

(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, ε and μ 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 constant
198 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 standard 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

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

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

Practical success of this numerical approach therefore depends on the quality of the surface height approximation, discretization of the integral sum and approximation of the integrands by analytical expressions. [*Nouvel et al.*, 2004] adopted rectangular facet approximation of the rough surface. Such an approximation results in an analytical representation of the Kirchhoff integral over a single facet. Summing contributions of all the 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

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

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

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

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

3. Ionospheric model and correction algorithm tests.

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

For these simulations, we use a new developed empirical model for the dayside electron density of the martian ionosphere (primary and secondary layer), called NeMars [Sanchez-Cano *et al.*, 2013]. The model is largely based on MARSIS Active Ionospheric Sounding (AIS) mode data [Gurnett *et al.*, 2005a; Morgan *et al.*, 2013; Sánchez-Cano *et al.*, 2012] 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 ω_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.

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

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

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

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 ω_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.

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

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

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

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

6. Conclusions and remarks.

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

Acknowledgments.

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

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

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

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

References

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

552 *Electronics*, 53(5), 545–549, doi:10.1134/S1064226908050094.

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,

doi:10.1126/science.1165988.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

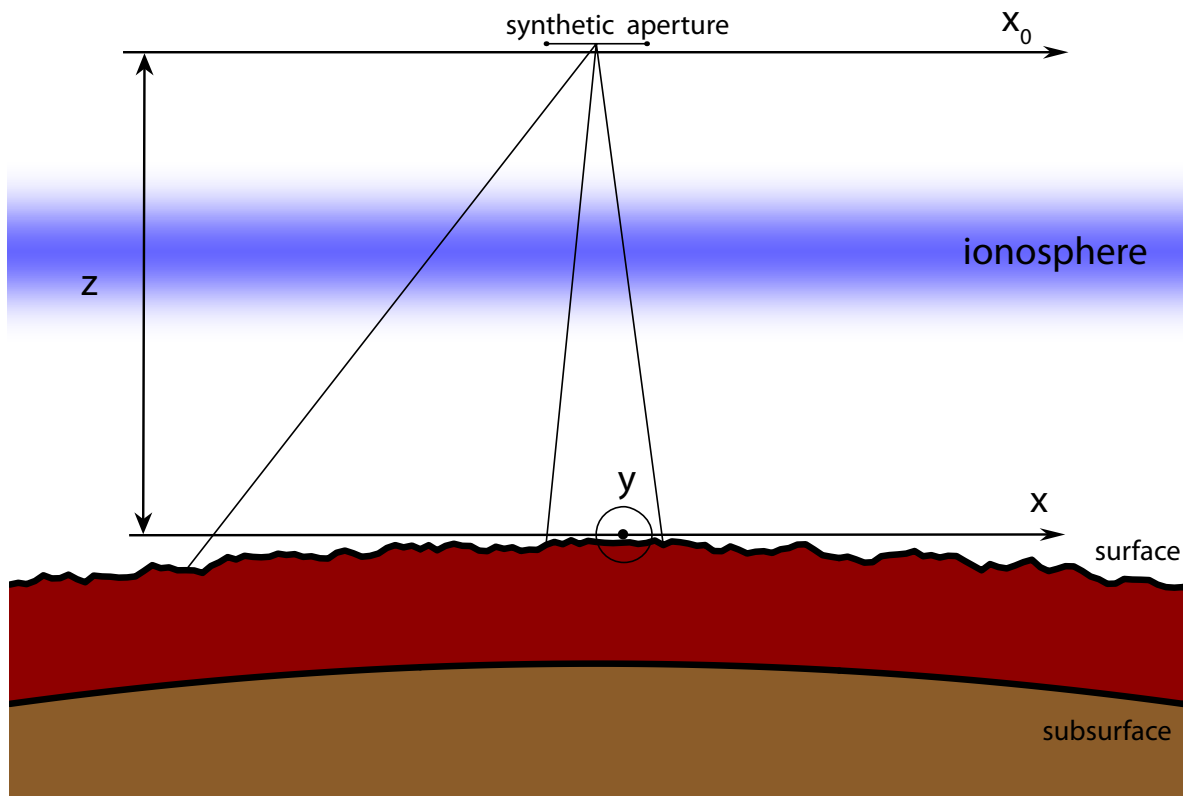


Figure 1. Schematic description of the subsurface radar sounding experiment.

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.

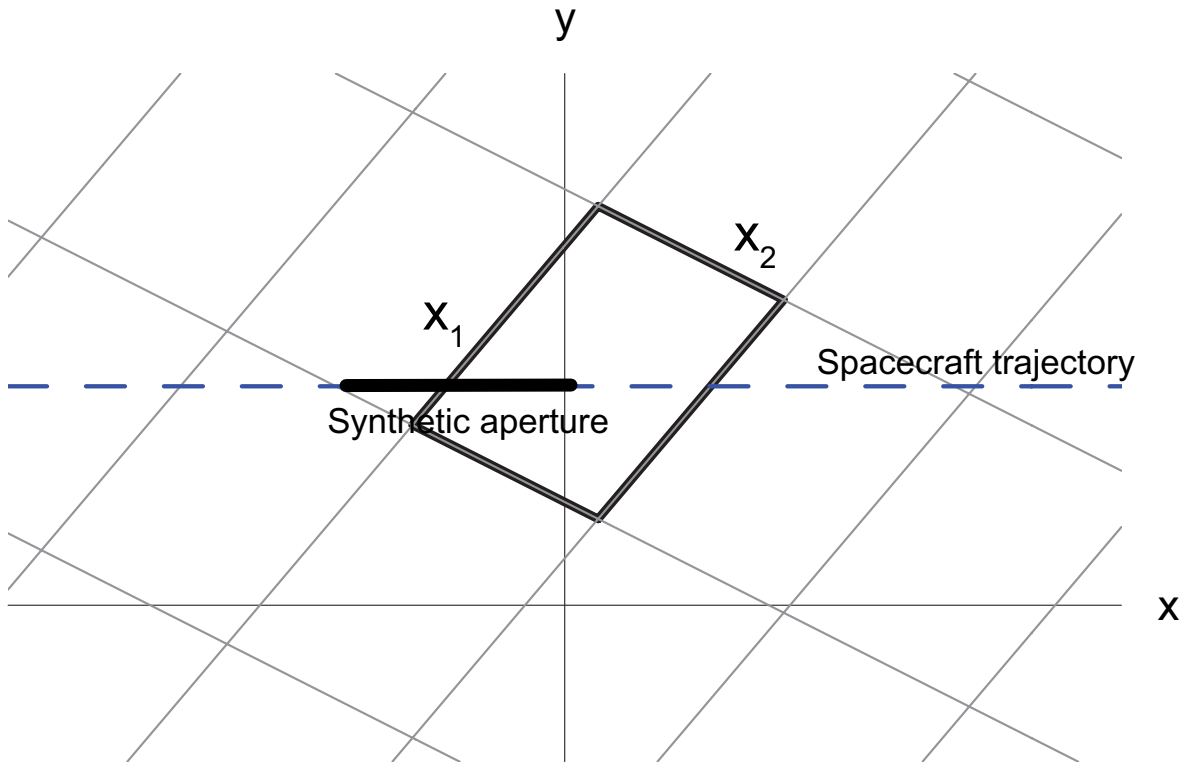


Figure 2. Schematic facet geometry.

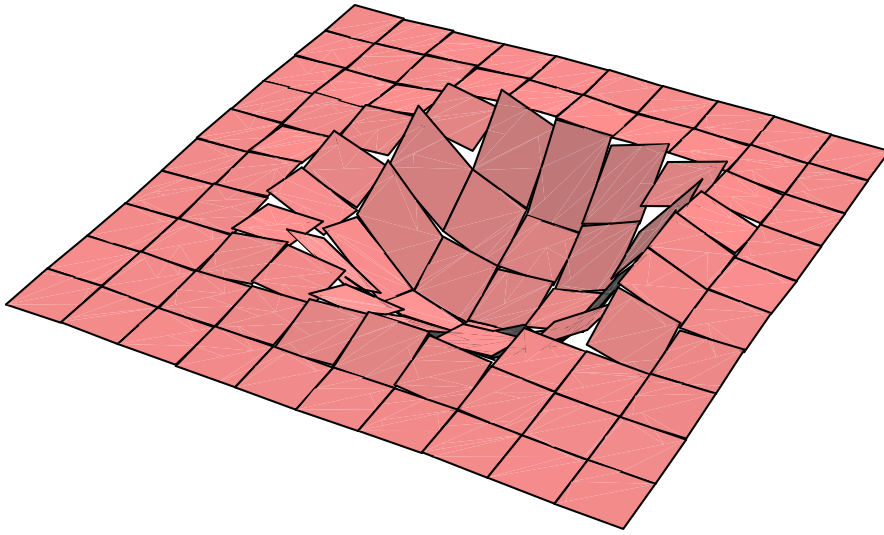


Figure 3. Facet approximation of the planetary surface topography (Martian crater at 22N 61E).

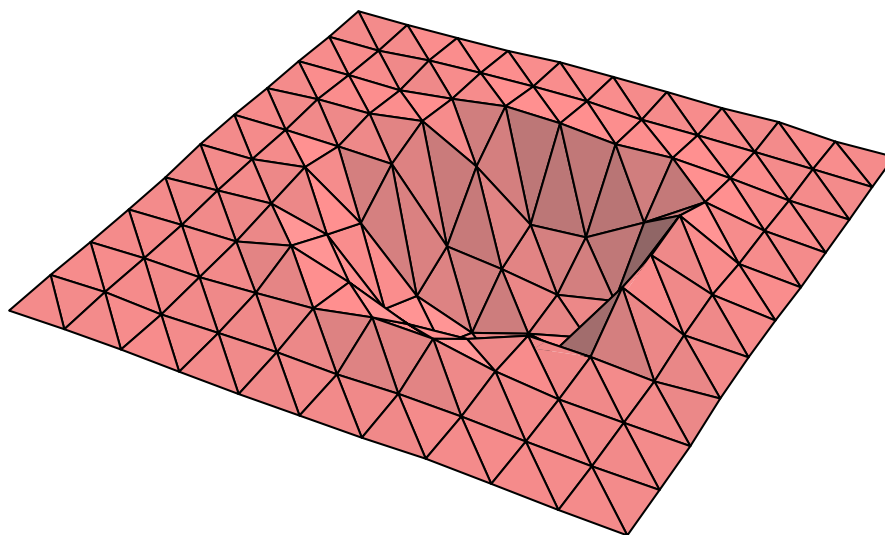


Figure 4. Piecewise-planar triangulation of the planetary surface topography (Martian crater at 22N 61E).

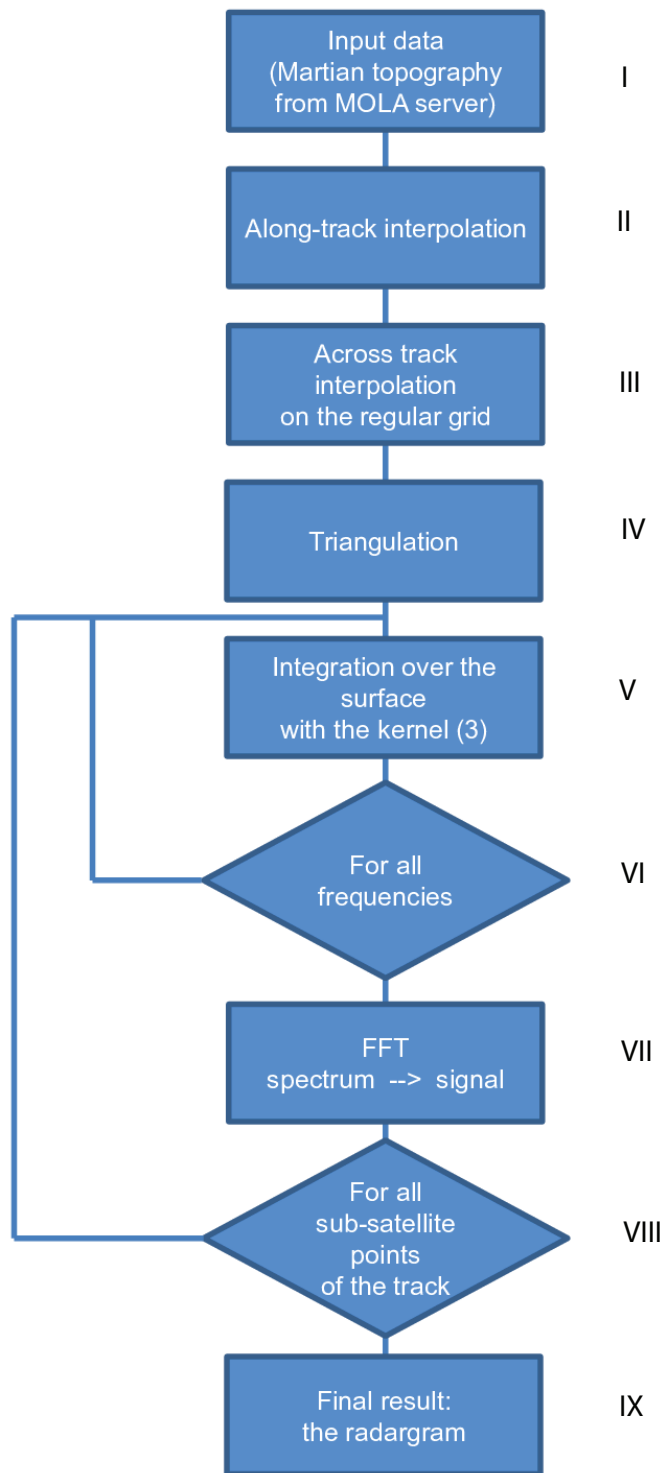


Figure 5. The CLUSIM program flow chart.

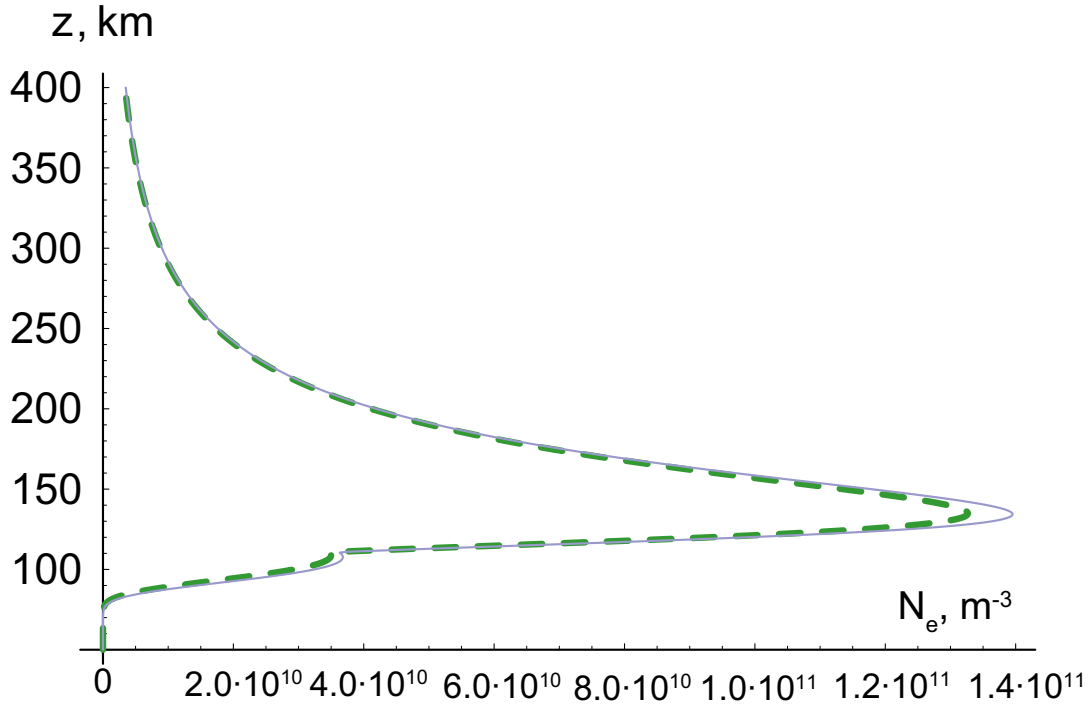


Figure 6. NeMars model ionospheric plasma density profiles for the ending points of satellite orbit portion. Solid line – SZA=61.293, LAT=20.658N, dashed line – SZA=64.95, LAT=26.554N.

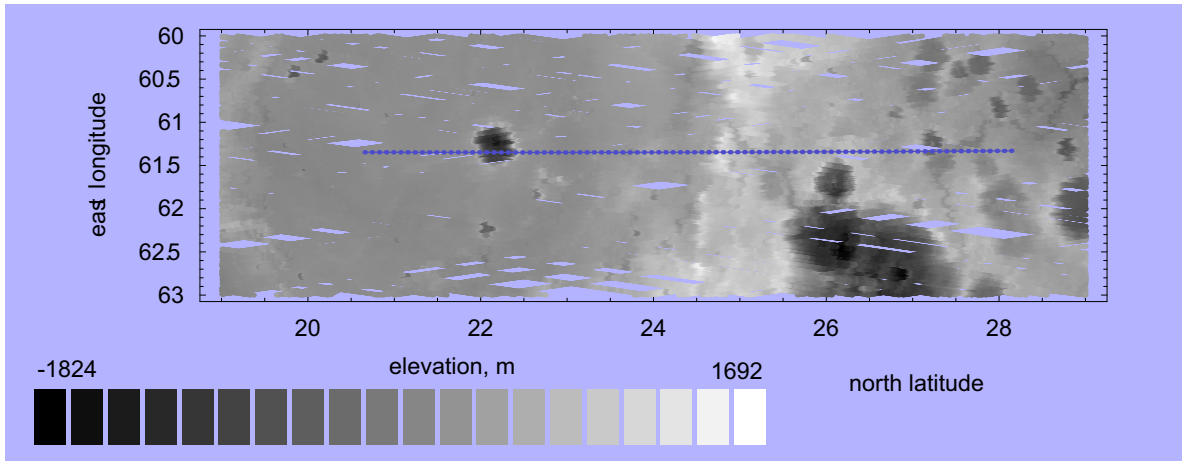


Figure 7. MOLA topography of the martian underlying surface landscape. Blue dotted line – the southmost part of the MEX orbit 9466 subsatellite track.

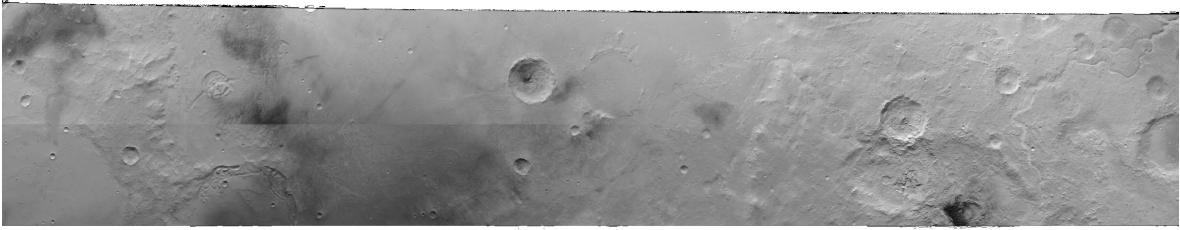


Figure 8. Mosaic of HRSC images H5191_0000_ND3 and H7357_0000_ND3 [*Neukum and Jaumann, 2004*] depicting the subsatellite landscape of the portion of MEX orbit 9466 under investigation. North is the right of the image.

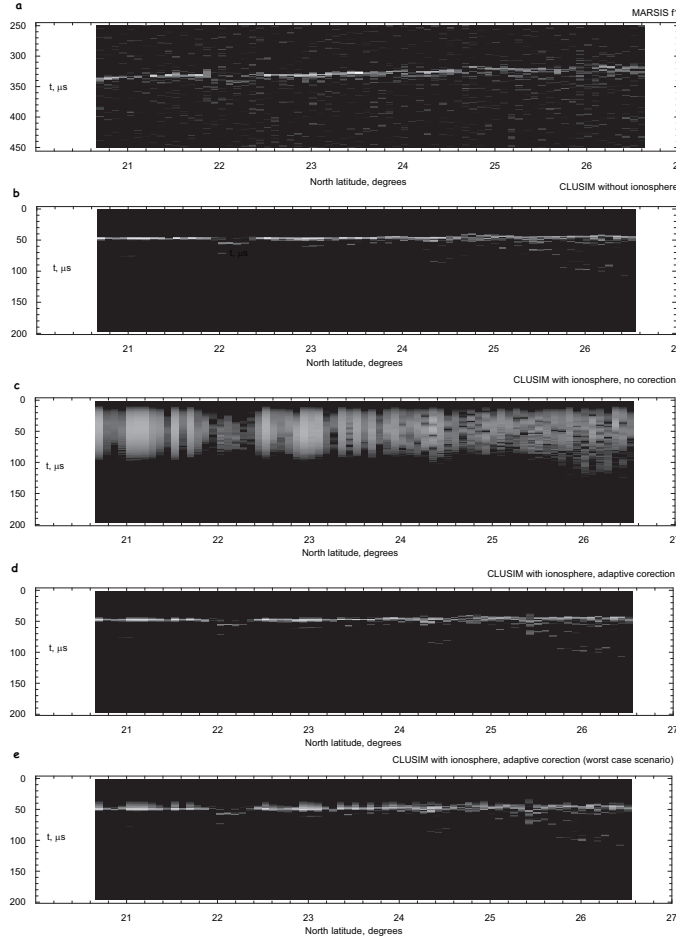


Figure 9. MARSIS radargrams of 9466 MEX orbit. MARSIS Band 4 (4.5 -5.5 MHz). *a* – experimental MARSIS radargram, doppler filter 0, working frequency $f = 5$ MHz (MARSIS band IV), *b* – simulated MARSIS radargram (CLUSIM) without any ionospheric phase shifts, *c* – simulated MARSIS radargram (CLUSIM) 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).

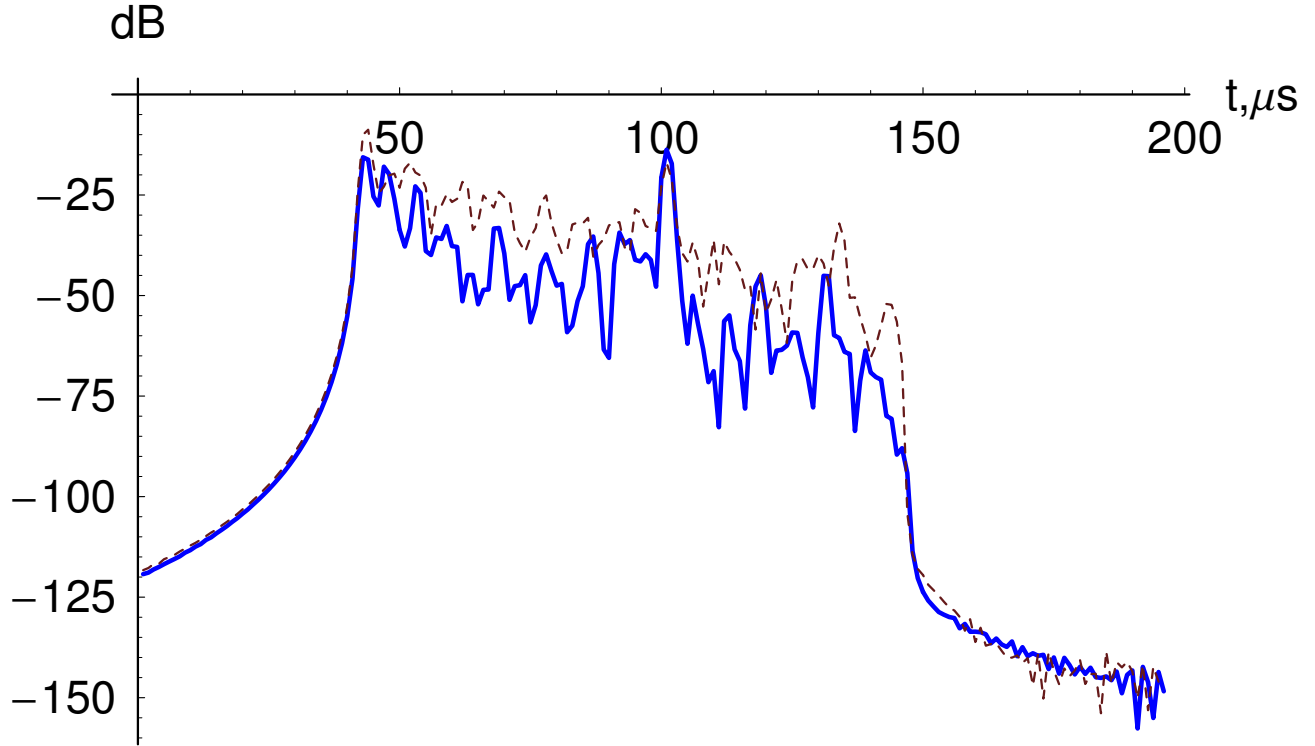


Figure 10. Single pulse MARSIS echo simulation. Solid curve – aperture synthesis is applied (the Doppler filter 0), dotted curve – single pulse echo. Subsatellite point is about $26^\circ N$ along the 9466 MEX orbit.

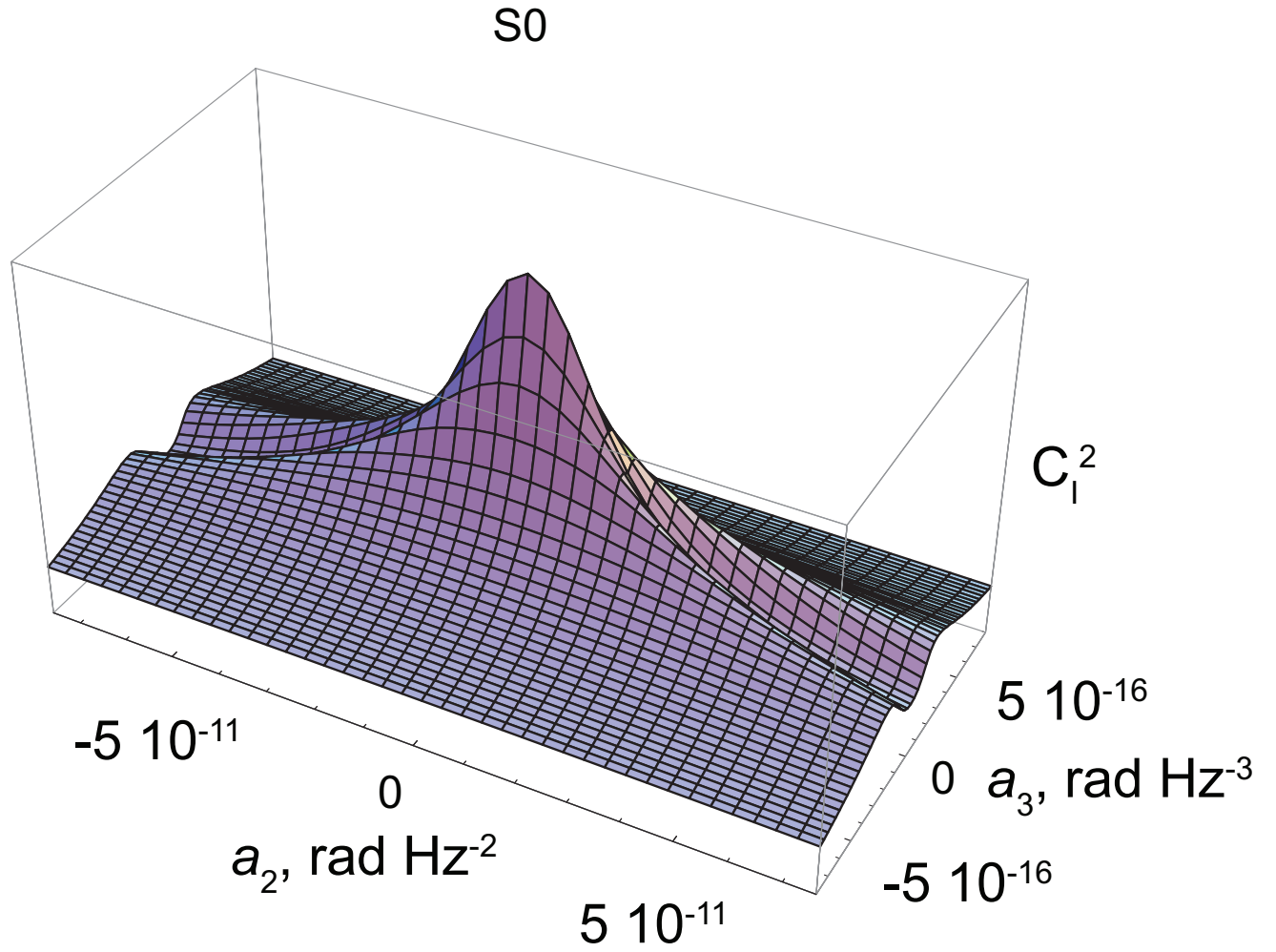


Figure 11. Intensity contrast of the distorted radar reflection from the ideally flat surface (arbitrary units).

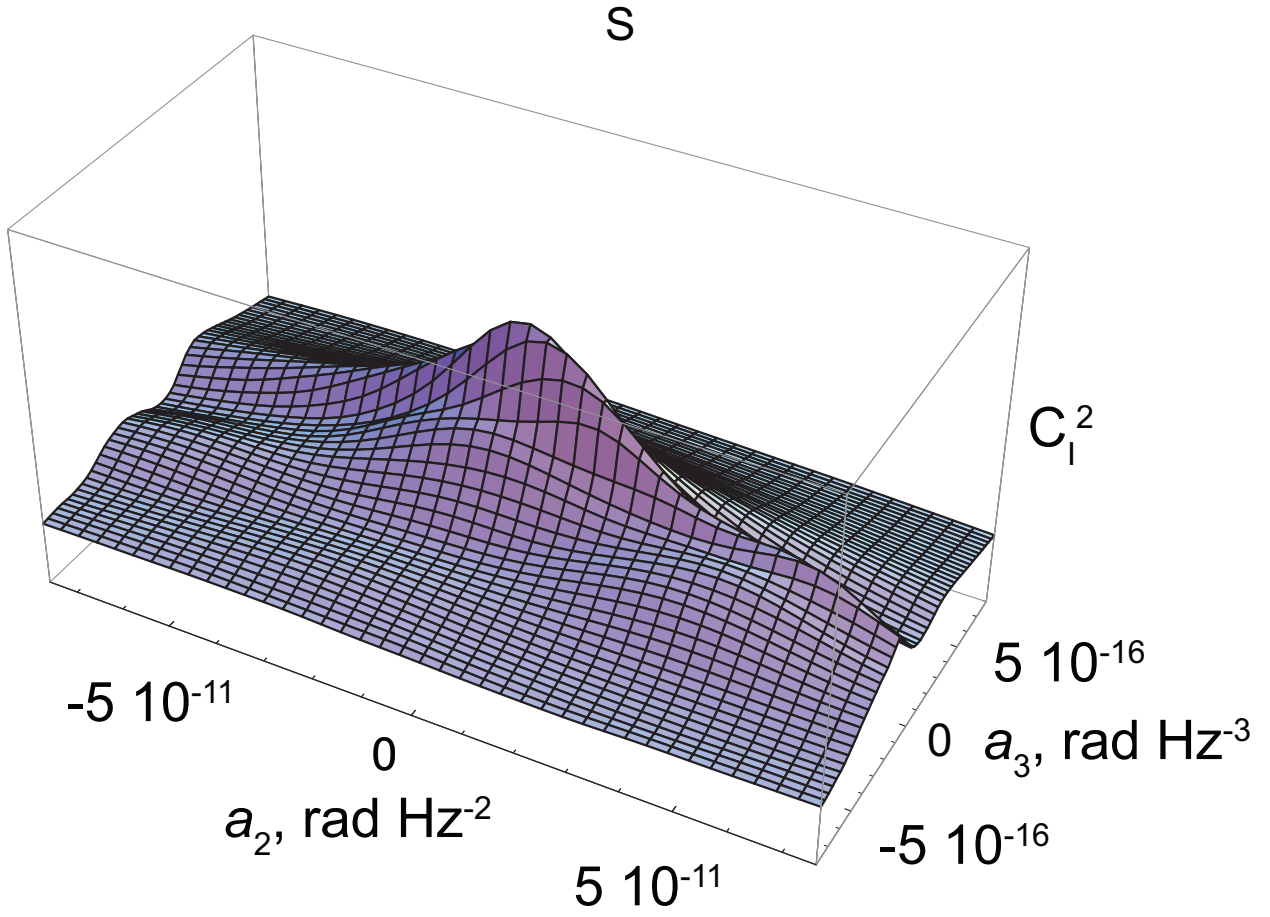


Figure 12. Intensity contrast of the distorted radar reflection from the realistic surface terrain (arbitrary units).