Postprint: Simulation Study of Mars Echoes for HF-Band Radar Altimeter Based on Layered Media Model

Authors: Xu Xiyu, Liu Heguang, Yang Shuangbao

Date: 2017-01-22T00:00:00+00:00

Abstract

Water detection in the Martian subsurface is one of the key issues in current deep space exploration. High-frequency (HF) radar altimeters, with strong penetration capability and the ability to simultaneously perform distance and power measurements, constitute an important means for Martian subsurface exploration. This paper introduces the principle and design of the HF radar altimeter system, and through analysis of the interaction between altimeter electromagnetic pulses and multilayer smooth media, derives a model for echo power variation with time while considering the effect of surface roughness on surface echo power. A typical Martian layered medium model is employed to simulate its dielectric constant characteristics and altimeter echo waveforms. Simulation results demonstrate that the HF radar altimeter system can achieve inversion of the vertical profile of dielectric characteristics in the Martian subsurface, playing a significant role in water identification on Mars.

Full Text

Study of Mars Echo Simulation for HF-Band Radar Altimeter Based on a Multi-Layer Media Model

XU Xi-Yu, LIU He-Guang, YANG Shuang-Bao
Key Laboratory of Microwave Remote Sensing, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100190

Abstract

The detection of water in the Martian subsurface is currently one of the most compelling issues in deep space exploration. HF-band radar altimeters possess strong penetration capabilities and can simultaneously obtain range and power measurements, making them powerful instruments for Mars subsurface detection. This paper first introduces the principles and design of the HF radar altimeter system, then derives the interaction between altimeter electromagnetic pulses and multi-layer smooth media, and extracts a model of echo power variation with time delay. The effects of surface roughness on surface echo power are also considered. Finally, several typical Martian multi-layer media models are adopted, and their dielectric constant characteristics and altimeter echo waveforms are simulated. The simulation results demonstrate that the HF radar altimetry system can retrieve the vertical profile of subsurface dielectric properties on Mars, which is crucial for identifying water on Mars.

Keywords
Radar altimeter; Mars; Multi-layer media model; Dielectric constant; Echo power

0 Introduction

The detection of water on Mars is currently one of the most prominent issues in deep space exploration. Numerous studies have shown that the Martian surface is covered by regolith composed of aeolian deposits, hard sedimentary layers, and other materials, with water molecules existing in solid or liquid form in the subsurface region [?, ?]. High Frequency (HF) band electromagnetic waves (3-30 MHz) possess strong penetration capabilities, making them particularly suitable for Mars subsurface exploration [?, ?]. This paper proposes that HF-band radar altimetry can enable the detection of dielectric properties of both the Martian surface and subsurface.

1 Principles and Design of the HF-Band Radar Altimeter

The HF-band radar altimeter for Mars surface/subsurface detection is a nadir-pointing radar that performs range measurement by transmitting pulses and measuring echo transmission time, and measures echo power by adjusting the receiver's Automatic Gain Control (AGC) [?, ?]. It can retrieve parameters such as regolith thickness on the Martian surface and the layered dielectric constant profile of the subsurface, thereby identifying subsurface water and mapping the along-track distribution of subsurface scattering echoes.

Based on scientific objectives and drawing on the design experience of Europe' s MARSIS system [?, ?] (Mars Advanced Radar for Subsurface and Ionospheric Sounding) and the United States' SHARAD system [?, ?] (SHAllow subsurface sounding RADar), we have designed an HF-band radar altimeter with system parameters listed in Table 1 .

Table 1 System parameters of HF-band radar altimeter

Parameter	Value
Operating frequency (MHz)	20

Parameter	Value
Altitude (km)	200–400
Pulse width (s)	100
Bandwidth (MHz)	10
Transmit power (W)	100 (conventional); 20 (SAR)
Pulse repetition frequency (Hz)	600
Antenna aperture (m)	10
Antenna beamwidth (°)	60
Antenna gain (dB)	2
Signal type	Linear frequency modulation

To achieve a good compromise between penetration depth and vertical resolution, the HF-band altimeter employs a center operating frequency of 20 MHz. To improve range resolution, the altimeter uses a linear frequency-modulated pulse (Chirp signal) as the transmitted pulse, with a pulse width of 100 s, bandwidth of 10 MHz, and compression ratio of 1000. The receiver employs full-deramp technology to achieve pulse compression [**?**]. The altimeter operates in both conventional and synthetic aperture modes. The synthetic aperture mode can significantly improve along-track resolution and enhance the effective signal-to-noise ratio. The two modes can be switched freely as needed. Based on system Doppler bandwidth requirements, the altimeter is designed with a 600 Hz pulse repetition frequency. Due to the long operating wavelength, a half-wave dipole antenna configuration is adopted [**?**]. Compared with ordinary dipole antennas, the half-wave dipole easily achieves resonance in its impedance characteristics and has no sidelobes in its radiation pattern. The length of a half-wave dipole is half the wavelength. Considering that the lowest operating frequency of the radar’ s linear frequency-modulated signal is 15 MHz (corresponding to a 20 m wavelength), the antenna aperture cannot be less than 10 m. The large antenna aperture is therefore designed as a deployable structure.

2 HF-Band Radar Altimeter Echo Model

Research indicates that the upper layers of the Martian surface are primarily formed by volcanic, alluvial, aeolian, and glacial processes. At large scales, this layer can be interpreted as porous weathered soil with exponentially decaying porosity. The porosity at depth z is given by [**?**]:

$$\Phi(z) = \Phi(0)e^{-z/K} \tag{1}$$

where $\Phi(0)$ is the surface porosity (typically between 0.2–0.5) and K is the decay constant (with dimensions of length).

The pores in Martian near-surface soil may contain large amounts of ice, with liquid water possibly present at greater depths. Figure 1 [Figure 1: see original paper] illustrates a Martian stratigraphic model, including the global distribution of water and ice. While Figure 1 shows only a typical distribution example, we will simulate several types of Martian subsurface structures through extensive examples below.

2.1 Flat-Interface Subsurface Model

As previously described, the subsurface beneath the Martian surface is basically layered. Therefore, this section first analyzes a flat-interface layered model. Consider the simplified layered model shown in Figure 2 [Figure 2: see original paper], which consists of three layers: an atmospheric layer of height H_0, a sedimentary layer of height H_1, and a basalt layer. The electrical properties of the three layers are as follows:

1. Atmospheric layer: dielectric constant ε_0, loss tangent $\tan\delta_0$ (≈ 0), permeability μ_0;
2. Sedimentary layer: dielectric constant ε_1, loss tangent $\tan\delta_1$, permeability μ_1;
3. Basalt layer: dielectric constant ε_2, loss tangent $\tan\delta_2$, permeability μ_2.

Except for a few ferromagnetic materials, the permeability of most media is close to μ_0; typically we can assume $\mu_1 \approx \mu_0$ and $\mu_2 \approx \mu_0$.

The signal transmitted by the altimeter penetrates the atmosphere to reach the Martian surface, producing two echoes (reflections beyond the second order are not considered because their energy is sufficiently low). The first is the direct reflection echo from the Martian surface, and the second is the echo received by the altimeter after the electromagnetic wave transmitted into the Martian surface sedimentary layer undergoes attenuation, reflects from the interface with the basalt layer, and transmits back through the sedimentary layer and atmosphere.

These two echoes can be distinguished by time delay. The time delay difference between the two echoes is:

$$0\epsilon_0 \tan\delta_0 \approx 0\mu_1\epsilon_1 \tan\delta_1\mu_2\epsilon_1 \tan\delta_2\mu_0\mu_{10}\mu\mu \approx 20\mu\mu \approx$$

From this equation, the altitude can be calculated. Calculating altitude from Equation (3) requires knowledge of the sedimentary layer' s dielectric constant ε_1, which can be obtained from the surface echo power.

The backscattering coefficient of a specular surface is completely coherent, and its radar equation takes the form of the Friis transmission equation:

$$\frac{P_r}{P_t} = \frac{G^2\lambda^2}{(4\pi)^2 H^2}\Gamma \tag{4}$$

where Γ is the reflection coefficient at the interface between two media:

$$\Gamma = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \tag{5}$$

where ε_1 and ε_2 are the dielectric constants of the two layers.

From Equation (4), the echo power reflected from the atmosphere-sediment interface is:

$$P_{r0} = \frac{P_t G^2 \lambda^2}{(4\pi)^2 H^2} \Gamma_0 \tag{6}$$

where Γ_0 is the reflection coefficient at the atmosphere-sediment interface. The echo power reflected from the sediment-basalt interface is:

$$P_{r1} = \frac{P_t G^2 \lambda^2}{(4\pi)^2 H^2} (1 - \Gamma_0)^2 \Gamma_1 L \tag{7}$$

The echo includes one reflection, two transmissions, and two attenuations. $(1 - \Gamma_0)$ is the transmission coefficient at the atmosphere-sediment interface, Γ_1 is the reflection coefficient at the sediment-basalt interface, and L is the attenuation of the electromagnetic wave in the sedimentary layer, expressed as:

$$L = \exp\left[-2H_1 \cdot \frac{2\pi f}{c} \cdot \frac{\tan\delta}{\sqrt{\varepsilon_r}}\right] \tag{8}$$

where c is the speed of light in vacuum, ε_r' and μ are the relative dielectric constant and permeability respectively (with μ set to 1). The conversion between nepers (Np) and decibels (dB) is used in the above equation:

$$1 \text{ Np} = 20 \log_{10}(e) \text{ dB} = 8.69 \text{ dB} \tag{9}$$

Therefore, based on the power and relative time delay of echoes from the two interfaces, the dielectric properties of the two layers can be determined. For multi-layer flat media, the echo model for each layer' s reflection can be established using the same method.

2.2 Geometric Optics Model for Rough Surfaces

The previous section assumed a flat Martian surface, which is generally not realistic. This section establishes a rough surface model for Mars. The Martian surface exhibits both large-scale and small-scale roughness. Since this study concerns remote sensing measurements from Mars orbiters, a large-scale model suffices; small-scale models would be required for lander or rover subsurface radars.

The height probability density of Martian rough surface scattering elements follows a zero-mean Gaussian distribution [?]:

$$f(h) = \frac{1}{\sqrt{2\pi}\sigma_h} \exp\left(-\frac{h^2}{2\sigma_h^2}\right) \tag{10}$$

where σ_h is the RMS value of the local elevation distribution. The local RMS slope can be derived from the local RMS wave height and correlation length l:

$$\sigma_s^2 = \frac{2\sigma_h^2}{l^2} \tag{11}$$

The scattering field from large-scale rough surfaces is dominated by specular (quasi-specular) reflection. At scales of 200 m to 10 km, σ_s generally does not exceed 0.02 rad (1 degree).

According to the quasi-specular geometric optics model under classical Kirchhoff approximation, the scattering coefficient of the echo is:

$$\sigma^0 = \frac{|R(0)|^2}{2\sigma_s^2 \cos^4\theta} \exp\left(-\frac{\tan^2\theta}{2\sigma_s^2}\right) \tag{12}$$

where θ is the electromagnetic wave incidence angle. Letting R be the slant range from the nadir direction, the geometric relationship gives:

$$\cos\theta = \frac{H}{R} \tag{13}$$

Substituting Equation (13) into Equation (12) yields:

$$\sigma^0 = \frac{|R(0)|^2}{2\sigma_s^2} \left(\frac{R^2}{H^2}\right)^2 \exp\left(-\frac{R^2 - H^2}{2\sigma_s^2 H^2}\right) \tag{14}$$

Clearly, the transmission distance R is a function of time t:

$$R(t) = \frac{ct}{2} \tag{15}$$

Taking t_0 as the time origin, let:

$$t_p = t - t_0 \tag{16}$$

Substituting into Equation (12) and simplifying gives:

$$\sigma^0(t_p) \approx \frac{|R(0)|^2}{2\sigma_s^2} \exp\left(-\frac{c^2 t_p^2}{8\sigma_s^2 H^2}\right) \tag{17}$$

According to the radar equation, the corresponding peak echo power is:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma^0 A \tag{18}$$

where A is the illuminated area of the electromagnetic wave. According to the Walsh formula [**?**], the pulse-limited footprint diameter and illuminated area are:

$$D = \sqrt{\frac{4Hc\tau}{\cos(\arcsin(H/(H+R_m)))}} \tag{19}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi H c\tau}{\cos(\arcsin(H/(H+R_m)))} \tag{20}$$

where R_m is the radius of Mars. Substituting Equations (17) and (19) into Equation (18) yields:

$$P_r(t_p) = \frac{P_t G^2 \lambda^2}{(4\pi)^3 H^2} \cdot \frac{\pi c\tau}{\cos(\arcsin(H/(H+R_m)))} \cdot \frac{1}{2\sigma_s^2} \exp\left(-\frac{c^2 t_p^2}{8\sigma_s^2 H^2}\right) \tag{21}$$

This is the radar equation for rough surface altimetry, which can be used to extract surface echo power for HF-band altimeters.

3 Simulation of Layered Dielectric Properties of Martian Subsurface Media

Generally, Martian surface and subsurface media can be modeled as mixtures of air, water (ice), and soil. At frequencies above 100 kHz, the dielectric constant of this mixed medium can be expressed as [**?**]:

$$\varepsilon_m = \varepsilon_a^{\phi} \varepsilon_w^{s\phi} \varepsilon_s^{1-\phi} \tag{22}$$

where ε_m is the mixture' s dielectric constant, ε_a is air' s dielectric constant, ε_w is water' s dielectric constant, and ε_s is solid soil' s dielectric constant. In the equation, ϕ is porosity, representing the proportion of air, water, ice, etc. in the mixture (by volume), while the proportion of water in its various forms (ice, pure liquid water, brine, etc.) within the porosity is called saturation, denoted as s (shown in Figure 3). ε_a is approximately 1; ε_s is the solid soil’ s dielectric constant; and ε_w is water’s dielectric constant. According to the Debye equation [**?**]:

$$\varepsilon_w(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{23}$$

The Martian surface and subsurface media are rich in gravel and rubble. These fragments act as scatterers, creating more complex dielectric structures within the medium. Examining the scattering behavior at each fragment boundary individually would be too complex to calculate. However, if the fragments (scatterers) are uniformly distributed in the medium, these scatterers and the background medium can be equivalent to a single medium. Kong (1986) derived the effective dielectric constant for spherical scatterers [**?**]:

$$\varepsilon_{\text{eff}} = \varepsilon_b \left[1 + \frac{3v_f(\varepsilon_d - \varepsilon_b)}{\varepsilon_d + 2\varepsilon_b - v_f(\varepsilon_d - \varepsilon_b)}\right] \tag{24}$$

where ε_b is the background dielectric constant, ε_d is the scatterer (fragment) dielectric constant, v_f is the volume fraction of fragments, a is the scatterer radius, and λ is the electromagnetic wavelength. Although Equation (23) was derived for spherical scatterers, it is also applicable to generally smooth-shaped fragments. Martian surface fragments are basically randomly distributed, so Equation (23) can be used to model the dielectric constant of media containing fragments.

Based on the characteristics of Mars, we simulated layered media models under two scenarios and calculated the real part of the dielectric constant and loss tangent for each layer.

Scenario 1: Shallow seepage (basalt rich in liquid water below 100 m, containing brine below 160 m);

Scenario 2: Permafrost (ice lens between 50-200 m).

The simulation results are shown in Table 2 and Table 3 . The tables provide input parameters including porosity, saturation, water phase (0 for air, 1 for ice, 2 for liquid water, 3 for brine), and medium material for each layer. Output parameters are the real part of the dielectric constant and loss tangent. In the simulations, most media are assumed to have 10% ferrite content, with fragments of 0.1 m diameter and 5% volume fraction.

Table 2 Dielectric constant simulation results of Case 1 (20 layers)

Depth (m)	Porosity (%)	Saturation (%)	Water Phase	Medium Material	Real Part of Dielectric Constant	Loss Tangent
0–10	45	0	0	Sedimentary basalt	4.5	0.01
10–20	40	10	1	Dense basalt	5.2	0.008
…	…	…	…	…	…	…
100–110	35	80	2	Layered basalt	15.3	0.05
110–120	30	85	2	Layered basalt	16.8	0.06
…	…	…	…	…	…	…
160–170	25	90	3	Layered basalt	18.5	0.25
…	…	…	…	…	…	…

Scenario 1 represents shallow seepage, where the water phase below 160 m is brine. As can be seen, the loss tangent of the brine component is very large, significantly limiting electromagnetic wave penetration depth in this case.

Table 3 Dielectric constant simulation results of Case 2 (8 layers)

Depth (m)	Porosity (%)	Saturation (%)	Water Phase	Medium Material	Real Part of Dielectric Constant	Loss Tangent
0–10	50	0	0	Sedimentary basalt	4.2	0.01
10–20	45	5	1	Dense basalt	4.8	0.009
…	…	…	…	…	…	…
50–60	30	95	1	Sedimentary basalt	3.5	0.0012
60–70	25	90	1	Alluvial deposit	3.8	0.0015
…	…	…	…	…	…	…
150–160	20	85	1	Layered basalt	4.0	0.002

Scenario 2 represents typical permafrost regions, whose most significant feature is a deep ice lens below 50 m, manifested as pure ice. Its loss tangent is smaller than that of segregated ice (0.0012), allowing electromagnetic waves to penetrate deepest in this layer. Both ice lenses and segregated ice are important solid water detection elements in Mars exploration.

4 Echo Simulation Results

Using Scenario 2 as an example, we simulated the altimeter echo based on the models derived in Section 2. The resolution of each layer for the HF-band altimeter is shown in Figure 4 [Figure 4: see original paper]. As can be seen, the resolution of each layer is between 5-10 m, with the resolution of Layer 6 (ice lens) being 8.39 m. The attenuation of each layer is shown in Figure 5 [Figure 5: see original paper], where it is evident that the attenuation of Layer 6 (ice lens) is much lower than other layers (approximately 0.01 dB/m), allowing the altimeter electromagnetic waves to penetrate deeper into the ice layer.

Based on Equation (2), the delay corresponding to reflected echoes between each pair of layers can be calculated. Generalizing Equations (6) and (7), the echo power corresponding to interface reflections between layers can be obtained. By correlating these delays and powers, the echo waveform is obtained, as shown in Figure 6 [Figure 6: see original paper]. The power values on the vertical axis have been converted to dBm, and the horizontal axis has been normalized using the system' s compressed pulse width (1/10 MHz = 100 ns), corresponding to echo time resolution cells.

The simulation in Figure 6 treats the altimeter pulse as an impulse, without considering the radar system' s point target response (PTR) effects. The reflection from an infinitely smooth plane can be treated as a point target, while the altimeter system uses full-deramp pulse compression technology, whose PTR corresponds to a sinc function [**?**]. For mathematical convenience, it can be expressed as a Gaussian function:

$$S_r(t) = A\exp\left(-\frac{t^2}{2\sigma_p^2}\right) \tag{25}$$

where A is the normalized amplitude, $\sigma_p = k\tau$, τ is the system' s compressed pulse width (the reciprocal of bandwidth, 100 ns), and k is the scaling factor for the PTR equivalent Gaussian function. Based on research by the Jason altimeter team, $k = 0.513$ [**?**].

Therefore, the total echo power received by the altimeter is:

$$P(t) = \sum_{i=0}^{n-1} P_{r,i}\exp\left[-\frac{(t-t_i)^2}{2\sigma_p^2}\right] \tag{26}$$

where n is the number of medium layers, $P_{r,i}$ is the reflected power from the bottom of layer i, and t_i is the delay corresponding to the echo from the bottom of layer i.

The altimeter echo waveform obtained from Equation (26) is shown in Figure 7 [Figure 7: see original paper]. It can be seen that due to system resolution limitations, Layers 1-3 and Layers 4-5 effectively appear as single peaks. The ice layer is located between echo cells 10–25. The reflected power below the ice layer is significantly reduced because the reflection coefficient below the ice layer decreases markedly and attenuation increases. Therefore, the distribution of the ice layer can be identified through the magnitude of echo power drop and the sustained delay.

The above discussion concerns echoes from ideally smooth layered interfaces. When the surface or interfaces between layers are rough, parameters such as roughness shown in Equation (10) must be considered, and the actual echo power will decrease. However, we have simulated single-pulse echo power. For multi-pulse echo power, accumulation can be performed, with echo power multiplied by the square root of the number of accumulated pulses. For conventional mode, echo power accumulation is non-coherent; for synthetic aperture mode, accumulation is coherent, and echo power is multiplied by the number of accumulated pulses.

5 Conclusion

This paper introduced the principles and system parameter design of the HF-band radar altimeter system, derived the interaction between altimeter electromagnetic pulses and multi-layer smooth media, extracted a model of echo power variation with time delay, and considered the effects of surface roughness on surface echo power. Finally, two typical Martian layered media models were selected, and simulations were performed on the dielectric constant characteristics of each layer and the altimeter echo time delay, power attenuation, and waveform shape. The simulation results demonstrate that the HF-band radar altimeter system can retrieve the vertical profile of subsurface dielectric properties on Mars, thereby enabling the identification and detection of water on Mars (including solid and liquid water). Therefore, HF-band altimetry is significant for Mars subsurface detection and should be considered as a payload for China’s future independent Mars exploration missions.

References

[1] JIN Yaqiu, FA Wenzhe, XU Feng. Overview of the Advance for Mars Exploration Using Microwave Remote Sensing[J]. China J. Space Sci., 28 (3), 2008: 264-272, In Chinese (金亚秋，法文哲，徐丰. 火星探测的微波遥感技术 [J]. 空间科学学报，28 (3)，2008:264-272)

[2] Jiao Weixin, Zou Hong. Planetary Sciences [M]. Beijing: Peking University Press, 2009, In Chinese (焦维新，邹鸿. 行星科学 [M]. 北京：北京大学出版社，2009)

[3] Panel on Frequency Allocations and Spectrum Protection for Scientific Uses Committee on Radio Frequencies Board on Physics and Astronomy Division on Engineering and Physical Sciences. Handbook of frequency allocations and spectrum protection for scientific uses [M]. Washington: the National Academies Press, 2007

[4] Chelton D. B., Walsh E. J., MacArthur J. L. Pulse compression and sea level tracking in satellite altimetry[J]. Journal of Atmos. Oceanic Technology. 1989, (6): 407-438

[5] Xu Xi-Yu, Liu He-Guang, Liu Peng. Engineering Design of the Rain Mode on an Ocean-dedicating Radar Altimeter [J]. IEEE ICMMT 2010 Proceedings: 1719-1722

[6] Picardi G., et, al. MARSIS, a radar for the study of the Martian subsurface in the Mars Express mission [J]. Mem. S.A.It. Suppl. Vol. 11, 2007: 15-25

[7] Picardi G., et, al. Radar soundings of the subsurface of Mars [J]. Science 310, 2005:

[8] R. Seu, et, al. SHARAD: The MRO 2005 shallow radar [J]. Planetary and Space Science, vol. 52, iss. 1-3 [Special Issue], 2004: 157-166.

[9] Seu, R. et al. SHARAD sounding radar on the Mars Reconnaissance Orbiter [J]. J. Geophys. Res. 112 (E5), 2007: 1–18

[10] Harry M. J. Ground Penetrating Radar: Theory and Application [M]. Singapore: Elsevier, 2009

[11] Squyres, S. W. et al. Ice in the Martian regolith [M]. in Mars, edited by Kieffer H. H., et al. Tucson: University of Arizona Press, 1992: 557-593.

[12] Iain H. Woodhouse. Microwave Remote Sensing [M]. Taylor & Francis, 2006

[13] Brown, G.S. The average impulse response of a rough surface and its applications [J]. IEEE Trans. Anten. Propag [J]., AP-25, 1977: 67–74

[14] Kong J. A. Electromagnetic Wave Theory [M]. New York: John Wiley and Sons,

[15] Yin Zhiwen. Physics [M]. Beijing: Science Press [M], 2003. In Chinese. (殷之文. 电介质物理学 [M]. 北京：科学出版社，2003)

[16] Xu Xi-Yu, Xu Ke, Wang Zhen-Zhan. Generation of the HY-2 Satellite Altimeter Look-Up Table to Account for the PTR and LPF Features[J]. IGARSS Proceedings 2013:

[17] Thibaut, P., L. Amarouche, O. Z. Zanife, N. Stunou, P. Vincent, and P. Raizonville. Jason-1 altimeter ground processing look-up correction tables [J]. Marine Geodesy, 27 (3-4), 2004: 409-431

XU Xi-Yu (Corresponding Author): Associate researcher, main research areas include spaceborne radar altimeters and other active microwave remote sensing technologies; altimeter calibration and its applications in ocean remote sensing and planetary exploration.

Correspondence address: Room B0409, Center for Space Science and Applied Research, Chinese Academy of Sciences, No. 1 Zhongguancun South Sec-

ond Street, Haidian District, Beijing (P.O. Box 8701, Beijing); Phone: 010-62582851; Mobile: 13520179281; ID Number: 412926197908150053.

LIU He-Guang: Researcher, main research area is spaceborne radar altimeter system design.

YANG Shuang-Bao: Associate researcher, main research areas include spaceborne radar altimeter signal processing and new system altimeter research.

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