Earth and Planetary Science Letters 482 (2018) 334–341

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Assessing the potential for measuring Europa's tidal Love number h_2 using radar sounder and topographic imager data

G. Steinbrügge[a,*], D.M. Schroeder[b], M.S. Haynes[c], H. Hussmann[a], C. Grima[d], D.D. Blankenship[d]

[a] German Aerospace Center, Institute of Planetary Research, Berlin, Germany
[b] Department of Geophysics, Stanford University, Stanford, CA, USA
[c] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[d] Institute for Geophysics, University of Texas at Austin, Austin, TX, USA

ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form 10 November 2017
Accepted 12 November 2017
Available online 24 November 2017
Editor: F. Moynier

Keywords:
Europa
solid body tides
radar altimetry
h_2

ABSTRACT

The tidal Love number h_2 is a key geophysical measurement for the characterization of Europa's interior, especially of its outer ice shell if a subsurface ocean is present. We performed numerical simulations to assess the potential for estimating h_2 using altimetric measurements with a combination of radar sounding and stereo imaging data. The measurement principle exploits both delay and Doppler information in the radar surface return in combination with topography from a digital terrain model (DTM). The resulting radar range measurements at cross-over locations can be used in combination with radio science Doppler data for an improved trajectory solution and for estimating the h_2 Love number. Our simulation results suggest that the absolute accuracy of h_2 from the joint analysis of REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) surface return and EIS (Europa Imaging System) DTM data will be in the range of 0.04–0.17 assuming full radio link coverage. The error is controlled by the SNR budget and DTM quality, both dependent on the surface properties of Europa. We estimate that this would unambiguously confirm (or reject) the global ocean hypothesis and, in combination with a nominal radio-science based measurement of the tidal Love number k_2, constrain the thickness of Europa's outer ice shell to up to $\pm$15 km.

1. Introduction

The potential habitability of a subsurface ocean of Europa makes the second moon of Jupiter a high-priority target for planetary exploration. The National Aeronautics and Space Administration (NASA) plans to observe the icy satellite with a dedicated flyby tour over a period of several years. One of the top priorities of the Europa Clipper is the characterization of the structure of the ice shell (Pappalardo et al., 2015). It is a key measurement for future exploration and provides insights into the thermal state and interior dynamics of the moon. However, in order to effectively constrain the interior structure a combined analysis of multiple measurements will be necessary. Previous publications have already pointed out the importance of measuring both tidal Love numbers h_2 and k_2 to constrain the ice thickness, e.g. Wahr et al. (2006) and Wu et al. (2001). The tidal Love number k_2 describes the secondary potential induced by the mass redistribution as a consequence of the external forcing by Jupiter and the tidal Love number h_2 expresses the corresponding radial amplitude of the tidal deformation. While k_2 can be measured by radio science experiments, the assessment of h_2 requires altimetric measurements.

One of the instruments onboard the Europa Clipper is the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON). While its primary focus will be the direct detection of subsurface water reservoirs, we will show that it also has the potential to deliver altimetric measurements which can be used for the detection of solid body tides and therefore make an enhanced contribution to the characterization of Europa's outer ice shell. Further, with magnetometer, imaging and radio science data it constitutes a broader geophysics package for revealing Europa's interior structure.

In the following section we will give an overview of the instrument and describe the proposed concept for altimetry measurements by combined stereographic camera and radar observations. This concept will be quantified by an analytic performance model and a variety of influences on the range measurement accuracy will be discussed in section 3. The resulting predictions for the ranging errors will then be incorporated in a numerical simulation

* Corresponding author.
E-mail address: gregor.steinbruegge@dlr.de (G. Steinbrügge).

https://doi.org/10.1016/j.epsl.2017.11.028

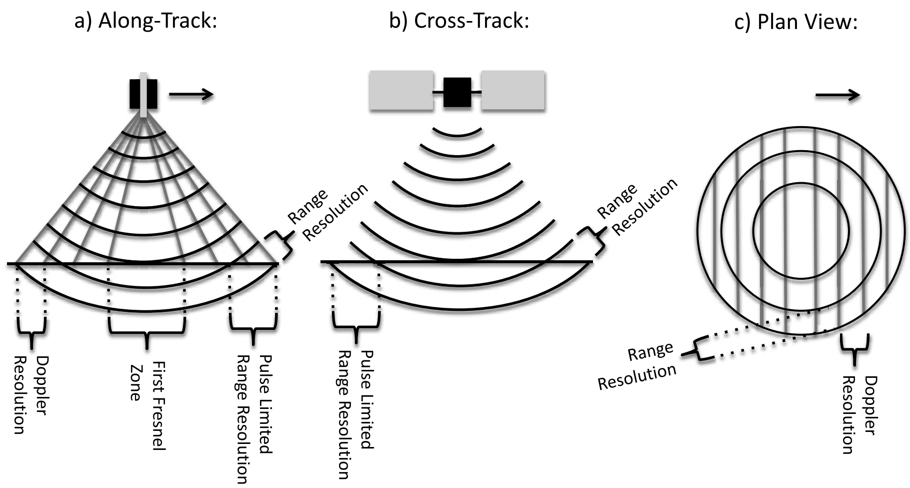

Fig. 1. a) In along-track direction the pulse can be discriminated by the Doppler phase. b) Each pulse-limited footprint is delimited by the range resolution (one range-bin) and can be distinguished in the return signal by the respective time delay. c) Top view on the cross-over plate composed of multiple delay/Doppler cells. Each cell contributes as a statistically independent range measurement to the differential average height of the plate between the two flybys.

of the flyby tour in section 4. Finally, the results and their potential contribution to the reconnaissance of Europa's interior will be discussed in section 5.

2. Instrument description and measurement principle

REASON is a dual-band, nadir-pointed, interferometric radar sounder. It has a VHF band operating at 60 MHz with a 10 MHz bandwidth and an HF band operating at 9 MHz with a 1 MHz bandwidth. The chirp length is adjustable between 30 and 100 μs. The radar is designed to characterize the surface and subsurface of Europa's ice shell by means of sounding, reflectometry, and altimetry (Blankenship et al., 2009; Moussessian et al., 2015). The instrument is composed of a two elements HF antenna mainly dedicated to penetrate the surface up to a depth of 30 km and four VHF antennas which allow to examine the upper ice layers and to perform altimetric measurements. The radius of the first pulse-limited footprint of the VHF is about 2.2 km from an altitude of 1000 km.

Over the Earth's oceans, radar instruments routinely achieve resolutions one magnitude better than their inherent range resolution (Garcia et al., 2014). However, the ocean is a generally flat surface which is well understood and therefore allows precise re-tracking of the altimeter waveforms. In application to planetary surfaces the topography can include much more complex structures making it difficult to discriminate the nadir return from surface clutter. However, this effect can be mitigated by utilizing additional knowledge of the topography at the footprint scale, e.g. from a stereo imagery derived digital terrain model (DTM) and by exploiting both the delay and Doppler information, in the surface return signal (Raney, 1998). In delay space, the principle uses the fact that on a flat surface a return from the n-th pulse-limited footprint will arrive before the return of the $(n+1)$-th pulse-limited footprint allowing them to be distinguished in the return signal. In the Doppler dimension footprints in along-track direction can be separated according to their azimuth Doppler bin (Fig. 1a, b). The size of such a delay/Doppler cell is typically in the order of several hundreds of meters to a few kilometers.

Utilizing this information to map returns in delay/Doppler space to a known surface geometry or DTM simultaneously reduces any directional ambiguity in the rough-surface return and increases the number of usable "looks" or statistically independent observations of the surface (Raney, 2012). This allows the topography in each delay/Doppler cell to be seen as an individual range measurement (Fig. 1c). The accuracy of the range measurement on one delay/Doppler cell can then estimated as

$$\sigma_z = \sqrt{\left(\frac{c}{2B}\right)^2 + \sigma_r^2 + \sigma_c^2}, \quad (1)$$

where σ_r and σ_c are the root mean square (rms) roughness within a delay/Doppler cell and the vertical resolution of the camera-derived, digital terrain model (DTM) respectively, c is the speed of light and B is the analog bandwidth of the radar. Because nadir-looking radar altimeters are nearly always limited by multiplicative (e.g. speckle, side-lobes, clutter) rather than additive noise, for the purposes of range estimate precision, the range error is constrained by the number of looks rather than by the signal to noise ratio (SNR) as long as the latter is above 1 (Raney, 2012). However, in case of a very rough surface the SNR can possibly drop with $1/R^4$ (see section 3.1) leading to a maximum useful altitude R of about 200 km. In contrast, on a flat surface the SNR can be very strong but only nadir returns are observed, eliminating azimuth processing and therefore multi-looking performance gains. Since precise information about the surface properties at the wavelength scale is lacking, both cases will be treated as separate possible end members bounding the likely performance over a realistic surface.

Here, we are mainly interested in retrieving a tidal signal of specific surface elements by measuring the differential ranges to a single area on the surface between two distinct points in time. A cross-over surface element is then defined by the geometry given by two spacecraft flybys over the same area. In order to measure tidal deformations cross-over based techniques are the method of choice since they cancel out any large scale topography effects (e.g. Mazarico et al. (2014); Steinbrügge et al. (2015)). In the case of a radar sounder altimeter the cross-over surface element is a cross-over plate containing multiple delay/Doppler cells, rather than a point (as it is the case in laser-altimeter based cross-over approaches). Since the two passes can occur at different altitudes the contributing radar footprints and DTMs may be significantly different in size. However, using forward simulated radar data from a DTM allows our technique to fit the specific sub-set of the returns to selected cross-over areas within the DTM and therefore compare the same area on the surface even though observations are made from different altitudes (Garcia et al., 2014). Each delay/Doppler cell inside the selected area will then be considered as one look (i.e. as a statistically independent observation). Having N uncorrelated looks on the surface, the total range measurement error of the cross-over plate would be $\sigma_z/\sqrt{N}$ (Raney, 2012).