Altimetry backscattering signatures at Ku and S bands over land and ice sheets

ABSTRACT

Satellite radar altimetry, initially designed for studying ocean surface topography, demonstrated a strong potential for the continuous monitoring of ice sheets and land surfaces over the last 25 years. If radar altimetry is mostly used for its capacity to determine surface height, the backscattering coefficients provide information on the surface properties. Spatio-temporal variations of radar altimetry backscattering over land and ice sheets were related to the nature of the surface and its changes against time. This study presents the results of an along-track analysis of radar altimetry echoes over land, Antarctica and Greenland at Ku and S bands from June 2002 to July 2003 using the ERS-2 and ENVISAT datasets on their nominal orbit during the tandem phase of the two missions. Temporal average and deviations are presented at global scale for ascending and descending tracks for the two missions.

Keywords: Radar altimetry, backscattering coefficient, dielectrical properties, land, ice sheets

1. INTRODUCTION

Spaceborne radar sensors provide global observation of continental surfaces at different frequencies, resolution, incidence angles and polarizations. Backscattering coefficients ($\sigma_0$) from radar scatterometers and Synthetic Aperture Radar (SAR) images are commonly used to monitor the dynamics of key variables characterizing the continental surfaces, such as vegetation density or surface soil moisture. Side-looking radar scatterometers, notably the C-band wind-scatterometer (WSC) onboard the European Remote Sensing satellites ERS-1 (launched in 1991) and ERS-2 (launched in 1995), already demonstrated a strong potential for the monitoring of surface dielectric properties related to soil moisture changes and vegetation dynamics at a spatial resolution of approximately 50 km. In addition, SAR images were widely used to map the temporal variation of surface soil moisture (SSM) over semi-arid environments such as Sahelian savannahs, land cover, and wetland extents along the hydrological cycle at C and L bands, for spatial resolutions lower than one kilometer and temporal resolution greater than one month.

Spatial and temporal variations of radar altimeter (RA) backscattering coefficients were related to the dynamics of surface properties over land and ice sheets. Surface characteristics of the ice sheets and their temporal variations were derived from altimetry observations. RA backscattering coefficients at C-band were used to detect flood in Siberia. Signatures of soil roughness and SSM changes in the deserts were identified at Ku band using ERS-1 and Topex/Poseidon data. A semi-empirical model was proposed to estimate SSM using RA backscattering coefficients over semi-arid surfaces. Backscattering coefficients from Topex/Poseidon were found to be decreasing as vegetation increase in Sahel. A comprehensive comparison of radar signatures acquired over West Africa (between 0° and 35°N
and 5°W - 25°E) at both C- and Ku- bands using nadir-looking altimeters (35-day orbital period ENVISAT RA-2 over 2003-2010 and 10-day orbital period Jason-2 over mid-2008-2012) that covers the major bioclimatic zones, soil and vegetation types encountered in this region was performed. A recent study also demonstrated the capability to retrieve SSM from ENVISAT RA-2 backscattering coefficients over Sahelian savannahs in the Gourma region of Mali. Preliminary results using the first of SARAL measurements at Ka-band showed the potential of Ka-band for detecting SSM changes and water even under forest canopy.

In this study, we present global maps of along-track average backscattering coefficients and associated standard deviation at Ku band using ERS-2 data and at Ku and S band using ENVISAT data for land and ice sheets during the tandem phase of the two missions. Then, we relate the resulting maps to the nature of the surface and its temporal evolution.

2. RADAR ALTIMETRY BACKSCATTERING

Over ocean-like surfaces, the altimeter echo can be described as the sum of the reflections from elementary surface facets distributed around the mean surface ordered by their arrival time or range. This radar altimetry echo (or waveform \( W(t) \)) results from the convolution of the impulse response shape (\( I \)) with the antenna pattern function (\( Ant \)) and the point distribution function (\( pdf \)):

\[
W(t) = I \otimes pdf \otimes Ant
\]  

Over land and ice sheets, the electromagnetic (EM) waves emitted by the altimeter are likely to penetrate most of the underneath surfaces. The resulting radar response can be composed of surface and volume echoes. Over ice sheets, it is the sum of surface and snowpack layers echoes. Over land, the resulting waveform can be the sum of echoes from the canopy, ground layers and possibly snow layers depending on the wavelength of EM wave, the nature and the water content of the soil and the vegetation. The echo shape is also affected by the surface topography slope and curvature. The echo shape is also affected by the surface topography slope and curvature. In these cases, it is necessary to take into account the scattering distribution (\( f_{scat} \)) that describes the vertical profile of the reflecting surfaces to model the waveform:

\[
W(t) = I \otimes pdf \otimes f_{scat} \otimes Ant
\]  

3. DATASETS

3.1 ERS-2

European Remote Sensing-2 (ERS-2) was launched in 1995 by ESA as ERS-1 follow-on mission. It was designed to study the Earth environment. The satellite carries, among other instruments, a radar altimeter (RA) operating at Ku-band (13.8 GHz) developed for measuring height over ocean, land and ice caps. ERS-2 orbits at an average altitude of 790 km, with an inclination of 98.54°, on a sun-synchronous orbit with a 35-day repeat cycle. It provides observations of the Earth surface (ocean, land, and ice caps) from 82.4° latitude north to 82.4° latitude south. This orbit was formerly used by ERS-1 mission, with an equatorial ground-track spacing of about 85 km. ERS-2 data are available from 17 May 1995 to 9 August 2010. After 22 June 2003, the dataset coverage is limited to ground station visibility.

3.2 ENVISAT

Environment Satellite (ENVISAT) mission was launched on March 1st 2002 by ESA. It carried 10 instruments including the advanced radar altimeter (RA-2). It was based on the heritage of sensor on-board the ERS-1 and 2 satellites. RA-2 was a nadir-looking pulse-limited radar altimeter operating at two frequencies at Ku- (13.575 GHz), as ERS-1 and 2, and S- (3.2 GHz) bands. Its goal was to collect radar altimetry over ocean, land and ice caps. ENVISAT remained on its nominal orbit until October 2010 and its mission ended 8 April 2012. Its initial orbital characteristics are the same as for ERS-2 (see 3.1).
3.3 Altimetry backscattering coefficients

Altimetry data used in this study are the backscattering coefficients estimated using the Ice-1 and the Ice-2 retracking algorithms from the ENVISAT Geophysical Data Records (GDRs) v2.1 and the ERS-2 GDRs from Centre de Topographie de l’Océan et de l’Hydrosphère, that were recently made available after the reprocessing of ERS-2 Waveform Altimeter Products (WAP). Backscattering coefficients derived from these retracking algorithms are commonly used for characterizing land and ice sheets surface properties. These datasets were made available by the CTOH (http://ctoh.legos.obs-mip.fr/).

4. METHODS

Along-track altimetry data were first sorted using an average track defined using the mean location of altimetry data for each mission during its nominal orbit (Figure 1). This mean track is defined by four parameters: the mean longitude and latitude of each cell composing the mean track, and its size given by its dimensions along (δ_{along-track}) and cross track (δ_{Cross-track}). If δ_{Cross-track} is chosen arbitrarily (equals two kilometers in this study as this distance corresponds to the maximum cross-track variations along the orbit of ERS-2 and ENVISAT missions), δ_{along-track} is given by:

\[ \delta_{along-track} = \frac{V_{sat}}{\delta t} \]  

where \( V_{sat} \) is the velocity of the satellite along the orbit equals to 7.45 km.s\(^{-1}\) and \( \delta t \) is chosen equals to 1 second, that mean that every cell contains, each cycle a maximum of 20 measurements.

Figure 1. Average altimetry track (black arrow) obtained as the average of all altimetry data acquired during the life time of an altimetry mission. Altimetry track for a given cycle (red arrow). Altimetry measurements are represented using dots, each color representing a cycle. Rectangles represent the cells along the altimetry track defined by δ_{along-track} and δ_{Cross-track} for a given location (\( \lambda_{cell} \), \( \phi_{cell} \)) (yellow and black star).
In each cell, every cycle, the mean backscattering coefficient and the associated standard deviation were computed as follows:

\[
<\sigma_0>_{dB} = 10 \log_{10} \left( \frac{1}{h} \int h \sigma_0^n dh \right)
\]

and

\[
\text{std}(\sigma_0)_{dB} = 10 \log_{10} \left( 1 + \frac{\text{std} \sigma_0}{<\sigma_0>_{dB}} \right). \]

where \(<\sigma_0>_{dB}\) and \(\text{std}(\sigma_0)_{dB}\) stand for the average of \(\sigma_0\) in dB and its associated standard deviation in dB, respectively. As the backscattering coefficients of the different altimetry missions are provided in dB in the GDRs, they were first converted into their natural values as expressed in (4) and (5).

Using the mean backscattering value per cycle, average backscattering coefficients and associated standard deviations were computed for the whole observation periods of ERS-2 at Ku-band (cycles 75–85 from June 2002 to July 2003) and ENVISAT at Ku and S-bands (cycles 7–17 from June 2002 to July 2003) using (4) and (5) over land and ice sheets.

5. RESULTS

Maps of average backscattering coefficients and associated standard deviation were computed at Ku-band using ERS-2 data and at Ku and S bands using ENVISAT from June 2002 to January 2003, during the tandem phase of the two missions, from both Ice-1 and Ice-2 retracking algorithms, over Antarctica, Greenland, and land, for both ascending and descending tracks. In the followings, only maps obtained using Ice-2, for ascending tracks will be presented.

5.1 Radar altimetry backscattering over ice sheets

Altimetry backscattering exhibit large variations over ice sheets ranging from 0 to 15 dB at Ku-band from 0 to 20 dB at S-band with standard deviation reaching 1.5 to 2 dB respectively (Figs. 2 and 3). Very similar results are obtained at Ku-band for ERS-2 and ENVISAT flying the same orbit 30 minutes apart from each other during their tandem mission. However, slight differences in mean backscattering (Figs. 2a and c, 3a and c) and associated standard deviation (Figs. 2b and d, 3b and d). They can be attributed to the intermission bias, and also related to differences in orientation of the antennae of the two missions due to the directivity of the radar altimeter gain pattern.

Surface responses at both Ku and S bands exhibit similar patterns with some exceptions that will be detailed below. Due to the larger antenna pattern at S-band, the backscattered signal is less sensitive to surface slope. The penetration depth into the snowpack is higher than at Ku-band. The contribution of volume echo from internal icy layer to the total backscattering is hence higher. As previously observed, lower backscattering are present in the low elevation coastal regions characterized by high surface slopes, especially at Ku-band. The eastern part of Antarctica also exhibits low backscattering response due to the conjugate effects of the intense katabatic winds carving the surface and of snow accumulation that cause an increase in surface roughness. Backscattering values are larger at higher altitude as the surface is smoother due to the lower intensity of the wind. Similar results are found over Greenland even if the effect of the wind on surface roughness is much lower. The second difference is the low and variable backscattering at Ku-band in the coastal areas all around Greenland. It is due to the phases of melting and refreezing of the ice sheet producing specular non-nadir reflection of the EM wave on the steep surfaces. If the surface slope is larger than the antenna aperture then the signal received is very low.
Higher backscattering values are observed at S than at Ku-band over the east of Antarctica and the south of Greenland. These differences are respectively due to a larger volume reflection at S-band as the EM wave is less attenuated in this very stratified region of low snow accumulation of Antarctica and in the percolation zone of Greenland. On the contrary over windy regions with large snow accumulation in Antarctica, radar signal at S-band is more attenuated than at Ku-band leading to lower radar backscattering values.

Figure 3. Maps of average radar altimetry backscattering coefficients and standard deviation over Greenland from ERS-2 at Ku-band (a, b), from ENVISAT at Ku-band (c, d), and from ENVISAT at S-band (e, f) during their tandem phase period.

5.2 Radar altimetry backscattering over land

Radar altimetry backscattering values averaged over the 10 common cyles of the ERS-2 and ENVISAT tandem phase range between 0 and 25 dB at Ku-band (Figs. 4a and c for ERS-2 and ENVISAT respectively) and between 0 and 30 dB at S-band (Fig. 4e). Altimetry backscattering is low (< 5 dB at Ku-band and < 7 dB at S-band) over mountainous regions (Himalaya, Andes, Rocky Mountains) as the power returned to the altimeter decreases with the angle of incidence and lower at Ku than at S-band as the antenna aperture increases (Eq. 2). Largest values, that can reach 20 dB at Ku-band and 25 dB at S-band are found over flat areas such as deserts and large river basins with extensive wetlands, as well as in large irrigated zone where specular returns occur. For example, this is clearly visible in large regions of the Sahara, in Arabian, Gobi and Australian deserts, along the Ganges, and especially in the Ganges-Brahmaputra-Meghna delta, the Plata or the Ob’, a large peri-arctic river. Along the Ganges and in the Mekong basins, the large backscattering values are also due to the inundated rice paddies. Similar patterns were found at Ku and C bands using Topex/Poseidon data. Over rivers with extensive floodplains covered with forest, as in the Amazon Basin, the mean backscattering coefficient is low due to the presence of the forest once averaged on 7 km along the track.

Figure 4. Maps of average radar altimetry backscattering coefficients and standard deviation over land from ERS-2 at Ku-band (a, b), from ENVISAT at Ku-band (c, d), and from ENVISAT at S-band (e, f) during their tandem phase period.

The standard deviations are lower at S-band than at Ku-band. They are low (< 1 dB) over areas presenting small variations in surface dielectric properties as deserts (e.g., Sahara, Arabic Peninsula, Gobi desert, Australian desert) as already observed in previous studies (Figs. 4b, d, f). Larger differences are present in tropical river basins covered with extensive floodplains (e.g., Amazon, Congo, Ganges, Mekong), rice paddies in Asia, and the boreal regions. This is mostly due to the presence of open water (and snow over boreal regions) that changes the dielectrical properties of the surface.

6. CONCLUSION

Altimetry radar signatures from ERS-2 (Ku-band), and ENVISAT (Ku and S bands) were analyzed over Antarctica and Greenland ice sheets and over land surfaces during the tandem mission of the two altimeters on a one year time span. The altimeter backscattered responses at Ku-, and S- bands exhibit a wide range of spatial and temporal variations over these different areas. The backscattered energy by each surface can be related to its soil roughness and soil dielectric constant and their variations against time. This study points out the interest of using nadir-pointing radar observations for the monitoring of land and ice sheets surfaces and their temporal evolution. If the use of radar altimetry for the monitoring of land surfaces currently suffers from its low spatial and temporal resolutions, the launch of the Surface Water and Ocean Topography (SWOT) mission in 2020 will permit to overcome the limitations. Using the SAR interferometry technique at near nadir incidences, SWOT will provide backscattering coefficients in a swath of ~120 km with a spatial resolution of 100 m over land.
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REFERENCES


