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A subwaveform threshold retracker for ERS-1 altimetry: A case study in the Antarctic Ocean

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ABSTRACT

Based on a correlation analysis method, a subwaveform threshold retracker is developed and coded in FORTRAN for satellite altimetry to determine the leading edge and retracking gate, and to improve the precision of sea surface heights (SSHs) and gravity anomalies (GAs). Using ERS-1/ERM waveforms, the subwaveform threshold retracker outperforms full-waveform threshold retrackers at the tide gage Port Station. A direct comparison between retracked SSHs and in situ SSHs is made at tide gage Port Station. Here the subwaveform retracking improves SSH precision from 0.241 to 0.193 m, yielding an improvement percentage (IMP) of 20%. Using ERS-1/GM waveforms, the subwaveform threshold retracker outperforms the Beta-5 and full-waveform threshold retrackers over the Bellingshausen and Amundsen Seas (BAS) in the Antarctic Ocean. The standard deviations of raw and retracked SSHs are 0.157 and 0.070 and 1.836 and 0.220 m over the ice-free and ice-covered oceans, corresponding to IMPs of 54.4% and 88%, respectively. Use of retracking improves the precision of GAs by up to 46.6% when comparing altimeter-derived and shipborne GAs.

1. Introduction

Satellite altimetry has been widely used in many disciplines of Earth science. A summary of altimetric theories and applications is given by Fu and Cazenave (2001). For a pulse-limited radar, the return waveform is the basic measurement. The waveform is used to derive the range between the satellite antenna and the Earth's surface, which in turn yields surface topography at sea and land. Over oceans, the radar ranging accuracy can normally meet the mission-required accuracy due to the reflecting surface of the ocean that result in an ideal waveform, i.e., the Brown waveform (Brown, 1977; Sandwell and Smith, 2005). The ranging accuracy is quickly degenerated as the observation is near coasts or over nonocean surfaces, largely due to waveform contamination (Deng, 2003; Deng et al., 2003; Deng and Featherstone, 2006; Hwang et al., 2006).

Over oceans, the waveform contamination can happen not only near coastal areas, but also over areas covered with sea ice. A postprocessing technique, known as waveform retracking, can be used to retrack the corrupted waveform and in turn improve the ranging accuracy of altimeter-derived sea surface height (SSH). For geodetic and geophysical applications, SSHs from altimetry are often used to derive gravity anomalies (GAs). For example, Brooks et al. (1997), Sandwell and Smith (2005), Deng and Featherstone (2006), Hwang et al. (2006), and Sandwell and Smith (2009) show that waveform retracking can improve the accuracies of SSHs and GAs over both open and shallow waters.

Several algorithms have been developed to retrack waveforms over different reflecting surfaces, such as land/sea ice, land, and coastal waters (Gommenginger et al., 2011). For example, the Beta retracker (Martin et al., 1983), the threshold retracker (Wingham et al., 1986), and the surface/volume retracker (Davis, 1993) have been used over ice. A review of waveform retracking methods for different reflecting surfaces can be found in Deng and Featherstone (2006). These algorithms are based on either a statistical model or a deterministic model.

This paper presents a subwaveform retracker to compute range corrections for satellite altimetry. A FORTRAN computer program is developed to implement this retracker. This retracker first identifies the leading edge based on subwaveform correlation analysis, and then computes the retracking gate using a threshold method. This retracker will be compared with the Beta-5 and threshold retrackers to assess its performance in the Antarctic Ocean. Improvements in SSHs and GAs due to retracking by this method will be presented.

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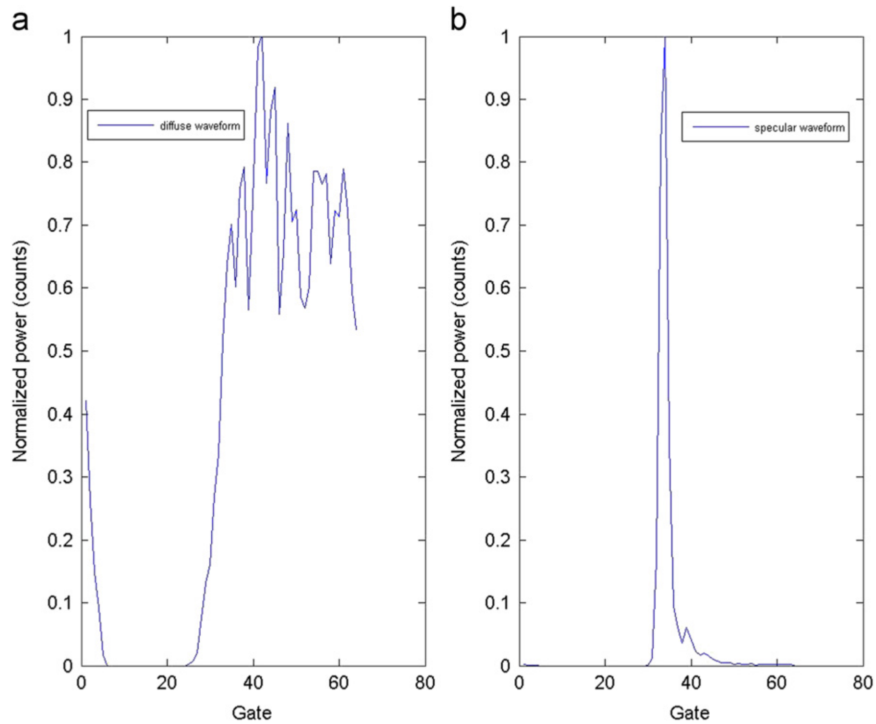

Fig. 1. A typical diffuse waveform (left) and a specular waveform over an ice-covered oceanic surface in the Antarctic Ocean.

2. Algorithm for leading edge determination and retracking

2.1. Diffuse and specular waveforms

Since our case study will be carried out in the Antarctic Ocean, a waveform classification is presented here. A waveform can be specular over an ice-covered ocean and diffuse over an ice-free ocean. A specular waveform is characterized by an initial sharp rise, followed by a rapid fall off in power. For a diffuse waveform, the rise of the leading edge and the trailing edge depends largely on a significant wave height (SWH). Fig. 1 shows a typical specular waveform and a typical diffuse waveform of ERS-1. The peak power of a specular waveform can be up to 3 orders of magnitude greater than that of a diffuse waveform (Laxon, 1994; Peacock and Laxon, 2004). A waveform classification is to distinguish specular waveforms from diffuse ones. In the classification, the pulse peakiness (PP) is computed as (Peacock and Laxon, 2004; Lee, 2008)

$$\mathrm{PP}=\frac{31.5\times P_{max}}{\sum_{i=5}^{64}P(i)}, \tag{1}$$

where P_{max} is the waveform peak power, and $P(i)$ is the power of the ith gate. A waveform with PP <1.8 is regarded as a diffuse waveform (Peacock and Laxon, 2004); otherwise it is a specular one. Over oceans, this classification can be used to distinguish the ice-free area from the ice-covered area; see the case study in Section 4.

2.2. Brown waveform model and waveform correlation

The return power of a Brown waveform, $P(t)$, can be expressed as (Brown, 1977; Sandwell and Smith, 2005)

$$P(t)=\frac{A}{2}\left[\mathrm{erf}\left(\frac{t-\tau}{\sqrt{2}\sigma}\right)+1\right]\begin{cases}1 & t<\tau\\ \exp(-(t-\tau)/\alpha) & t\geq\tau\end{cases}, \tag{2}$$

where A is the amplitude of the power, σ is associated with the slope of the leading edge governed by SWH, t is the time of gate, τ is the center of the leading edge, α is an exponential decay parameter in the trailing edge, and erf is the error function. For the ERS-1 waveform, α can be regarded as a constant (137 ns) (Sandwell and Smith, 2005). Therefore, the parameters A, τ, and σ govern the shape of the waveform. The rise width σ is a convolution of the effective width of the point target response and the vertical distribution of ocean surface waves, usually parameterized in terms of SWH. For a theoretical ERS-1 waveform, τ is 32.5 in dimensionless unit of sample gate width and can be converted to time by 3.03 ns (Fu and Cazenave, 2001). Therefore, a waveform shape with $A=1$ is determined by the parameter σ.

Correlation is a statistical method used to describe the dependence between two observed arrays. This method is adapted to analyze the relationship between two waveforms. A correlation coefficient is computed as

$$r=\frac{S_{r'r}}{\sqrt{S_{r'}S_r}}, \tag{3}$$

with

$$S_{r'}=\frac{1}{k-1}\sum_{i=1}^{k}(P_{r'}(i)-\overline{P_{r'}})^2, \tag{4}$$

$$S_r=\frac{1}{k-1}\sum_{i=1}^{k}(P_r(i)-\overline{P_r})^2, \tag{5}$$

$$S_{r'r}=\frac{1}{k-1}\sum_{i=1}^{k}(P_{r'}(i)-\overline{P_{r'}})(P_r(i)-\overline{P_r}), \tag{6}$$

where $P_{r'}(i)$ and $P_r(i)$, $i=1,\ \ldots,\ k$ are the return powers of the reference waveform and an arbitrary waveform, respectively, $\overline{P_{r'}}$ and $\overline{P_r}$ are the average powers, $S_{r'}$ and S_r are the standard deviations of the powers, and $S_{r'r}$ is the covariance of the two time series of powers from the reference and arbitrary waveforms. For an ERS-1 waveform, k is 64. A waveform is composed of thermal noise, leading edge, and trailing edge. In these three parts, the samples of the leading edge are more accurate than the other