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Advances in Space Research 50 (2012) 1150–1157

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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GNSS-R open-loop difference phase altimetry: Results from a bridge experiment

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Received 30 September 2010; received in revised form 15 October 2011; accepted 17 October 2011
Available online 4 November 2011

Abstract

The paper explores a method to obtain accurate lake surface heights using measurements of the Global Navigation Satellite System (GNSS) carrier phase reflected from the lake surface. The method is referred to as Global Navigation Satellite System-Reflection (GNSS-R) open-loop difference phase altimetry method. It consists of two key technologies: one is the open-loop tracking method to track the GNSS-R signals, where the direct GNSS signal's frequency is used as a reference frequency to obtain the carrier phases of the GNSS-R signals; the other key technology is time difference phase altimetry method to invert the lake surface heights using two or more carrier phases of GNSS-R signals received simultaneously. A validation experiment is carried out on the SANYING bridge over GUANTING lake using a GNSS-R receiver developed by the Center for Space Science and Applied Research (CSSAR), processing the data with GNSS-R open-loop difference phase altimetry method. The lake surface height results are consistent with the height results of GPS dual-frequency differential positioning altimetry. The results show that we can achieve centimeter level height in one minute average, by using 11 minutes carrier phase data of three GNSS-R signals received simultaneously.

Keywords: GNSS-R; Altimetry; Open-loop difference phase altimetry

1. Introduction

Global Navigation Satellite Systems reflected signal (GNSS-R) is a novelty and powerful technology for remote sensing with several advantages: wide coverage, passive, precise, long-term, all-weather and multi-purpose (Martín-Neira, 1993; Auber et al., 1994).

The bistatic radar using *L*-band signals transmitted by GPS as an ocean scatterometer was first addressed by Hall and Cordey (1988), while Martín-Neira proposed and described an altimeter system PARIS using ocean GPS reflections (Martín-Neira, 1993). Since then, GNSS-R technology as a remote sensing tool in marine applications has generated considerable attention during the last decade. Sea surface altimetry, which aims at retrieving mean sea level, is one class of GNSS-R applications which has rapidly emerged. The basic principle in GNSS-R altimetry is that direct and ocean-reflected signals are detected by GNSS-R receivers, and altimetric height information is extracted from the delays in arrival times of the reflected signals relative to the direct signals.

Altimetry in GNSS-R can be carried out in two ways (Ruffini, 2006): code altimetry and phase altimetry. The delays between direct and reflected signals, therefore, can be measured through two quantities: C/A code and carrier phase. Code altimetry is robust and applicable for ground, air and space applications. Code altimetry precision has

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doi:10.1016/j.asr.2011.10.019

been demonstrated in several experiments (Martín-Neira et al., 2001; Lowe et al., 2005, 2002; Rius et al., 2002; Ruffini et al., 2003, 2004). But code altimetry needs a long time average, so that results can be accurate up to several centimeters. Phase processing is severely affected by ocean roughness and dynamics, however, which render the reflected signal largely incoherent under rough conditions. Several experiments for GNSS-R phase altimetry on coastal locations (Ruffini et al., 2002; Belmonte and Martin-Neira, 2005) or lakes (Treuhaft et al., 2001) have also been performed for obtaining centimeter level results, and some proposed solutions to track GNSS-R signals are under study (Ruffini, 2006), e.g., using several frequencies to synthesize longer wavelengths as well as using a filtering approach to recover the coherent part of the signal (Ruffini et al., 2002; Caparrini et al., 2003), or working at low elevation angles (Beyerle and Hoche, 2001; Treuhaft et al., 2005).

Here we present a new approach, the GNSS-R open-loop difference phase altimetry, for the extraction and analysis of GNSS reflected signals to perform phase altimetry. The method consists of two key technologies: open-loop tracking method and time difference phase altimetry. The direct GNSS signal's frequency is used as a reference frequency to open-loop track GNSS-R signals. The approach just uses two or more single-frequence carrier phases of GNSS-R signals received simultaneously, and there is no need of ambiguity resolution. So the arithmetic of GNSS-R open-loop difference phase altimetry is simple and it is a computationally fast approach.

2. GNSS-R open-loop difference phase altimetry approach

GNSS-R open-loop difference phase altimetry approach consists of two key technologies: GNSS-R signal open-loop tracking method and time difference phase altimetry, the former solves the problem of tracking the phases of GNSS-R signals, the latter is a solution to altimetry using the tracked phases.

2.1. GNSS-R signal open-loop tracking

A GNSS-R receiver receives the direct and reflected GNSS signals in synchronization. The direct signal is processed using phase-locked loop (PLL) and delay-locked-loop (DLL), and then we obtain the direct signal's Doppler frequency, output phase ϕ_n^{direc} and the navigation code.

In the bridge-based experiment, the direct GNSS signal's frequency is used as a reference frequency to process the GNSS-R signal by open-loop tracking. The navigation data of the reflected GNSS signal can be removed by applying a data bit sequence recorded by the direct channel of the GNSS-R receiver, due to the small height provided by the bridge (about 18 m) as compared to the C/A-code chip length (300 m). The power contributions of the GNSS-R signal are mainly from the first Fresnel zone (an ellipse of almost 600 m diameter) reflection which takes place around the specular point, because the antenna footprint is beam-limited and the surface is smooth. So, we represent the reflected signal received at the antenna input as

$$u(t) = C(t) \cdot D(t) \cdot A(t) \cdot \cos(\phi(t) - \phi_0) \tag{1}$$

where $C(t)$ represents the C/A code, $D(t)$ is the navigation code, $A(t)$ is the direct signal amplitude, $\phi(t)$ is the $L1$ carrier phase, and ϕ_0 is the initialization phase.

The receiver tracks the signal $u(t)$ by correlating $u(t)$ with local replica in-phase and quad-phase replica signals:

$$\upsilon^i(t) = \cos(\phi^{Local}(t)) \tag{2}$$

$$\upsilon^q(t) = \sin(\phi^{Local}(t)) \tag{3}$$

In our process, the direct signal's phase is used as a model phase, the phase $\phi_n^{Local} = \phi_n^{direct}$ of the replicas $\upsilon^i(t)$ and $\upsilon^q(t)$ being the same as the direct signal's output phase, updated at a rate of 1 kHz. Aligned with the navigation bit of the direct signal, we perform circular correlation through Fourier transforms to demodulate the C/A code. The in-phase and quad-phase correlation integration can be written as (Beyerle et al., 2006)

$$\begin{aligned} I_n &= \frac{2}{T}\int_{t_n}^{t_n+T} u(t)\cdot \upsilon^i(t)\cdot dt + N_n^i \\ &\approx \overline{A_n}\cdot \sin c(\pi\overline{\Delta f_n}T)\cdot \cos(\pi\cdot \overline{\Delta f}_n\cdot T + \Delta\phi_n) \\ &+ N_n^i = \overline{A_n}\cdot \sin c(\pi\overline{\Delta f_n}T)\cdot \cos\left(\frac{2\cdot\pi\cdot\overline{\Delta f_n}\cdot T}{2} + \Delta\phi_n\right) + N_n^i \end{aligned} \tag{4}$$

$$\begin{aligned} Q_n &= \frac{2}{T}\int_{t_n}^{t_n+T} u(t)\cdot \upsilon^q(t)\cdot dt + N_n^q \\ &\approx \overline{A_n}\cdot \sin c(\pi\overline{\Delta f}_n T)\cdot \sin(\pi\cdot \overline{\Delta f}_n\cdot T + \Delta\phi_n) \\ &+ N_n^q = \overline{A_n}\cdot \sin c(\pi\overline{\Delta f_n}T)\cdot \sin\left(\frac{2\cdot\pi\cdot\overline{\Delta f_n}\cdot T}{2} + \Delta\phi_n\right) + N_n^q \end{aligned} \tag{5}$$

Here and in the following the subscript n denotes the corresponding function value at time t_n where the C/A code has been demodulated by the circular correlation method and navigation code has been removed using navigation bits of the direct signal, respectively, and $sin c(x) = sin(x)/x$. According to this equation, the loss of amplitude (SNR) due to errors in modelling of the frequency is small, because the frequencies, comparing direct signal's frequency with specular reflected signal's frequency, are very close. $\overline{\Delta f_n} = \overline{f_n} - \overline{f_n^{Local}}$ denotes the mean difference between the true frequency and the local replica frequency in time $t_n \leqslant t < t_n + T$. $\Delta\phi_n = \phi_n - \phi_n^{Local}$ denotes the initial phase difference at beginning time t_n between the true mean phase and the local replica phase. The local replica and true phases follow from $\phi_n^{Local} = 2\cdot\pi\cdot T\cdot\sum_{j=1}^{n-1} f_j^{Local}$ and $\phi_n = 2\cdot\pi\cdot T\cdot \sum_{j=1}^{n-1} f_j$.

N_n^i and N_n^q noise is added to the correlation sums. The coherent integration time T is 20 ms. From the in-phase (I) and quad-phase (Q) correlation sums, the signal raw residual phase φ_n^{raw} and output amplitude A_n^{out} is given by

$$\varphi_n^{raw} = \arctan 2\left(\frac{Q_n}{I_n}\right) = \frac{2\cdot\pi\cdot\overline{\Delta f_n}\cdot T}{2} + \Delta\phi_n \tag{6}$$

$$A_n^{out} = \sqrt{(I_n)^2 + (Q_n)^2} \tag{7}$$