Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 46 (2010) 221–227
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Snow-covered lake ice in GPS multipath reception – Theory and measurement

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Received 28 July 2009; received in revised form 14 October 2009; accepted 15 October 2009

Abstract

Speculary reflected signals from the ground can significantly affect the performance of Global Positioning System receivers. For this type of multipath condition, the received powers are primarily the sum of the speculary reflected and direct signals. These reflected signals can provide useful information about the land-surface composition. In this paper, we discuss the special case of a snow-covered frozen lake, with incident energy at 1.57542 GHz with right-hand circularly polarization at elevation angles between 2° and 40°. The relative received powers are computed and measured for various thicknesses of lake ice. The received powers for both theory and measurement have the same behavior throughout a range of elevation angles. The potential for inferring lake ice thickness is explored for a snow-covered lake ice case study.

Keywords: Global Positioning System; Multipath interference; Snow; Lake ice thickness; Specular reflection

1. Introduction

Reflected signals from natural and man-made features affect the reception quality for land-base Global Positioning System (GPS) receivers. The sum of the direct line-of-sight (LOS) signal and the reflected signals constitute the total received signal at the receiver. These reflected signals can provide useful information about the land-surface composition such as soil moisture, ground electrical characteristics or snow depth (Grant et al., 2007; Jacobson, 2008; Katzber et al., 2006; Kavak et al., 1996, 1998; Larson et al., 2008a, 2008b, 2009). The surface roughness determines whether reflected signals arrive at GPS receivers either incoherently or coherently. Incoherent reflected signals are caused by rough surfaces and are called diffusely scattered signals. On the other hand, coherently reflected signals are caused by smooth surfaces and are called specularly reflected signals. Most of the reflected signals occur within the first Fresnel zone about the specular point.

Land parameter measurements using conventional remote sensing techniques can be extended to include ice thickness on frozen lakes and rivers (Arcone, 1991; Arcone et al., 1997; Cooper et al., 1976; Hall et al., 1981; Riek et al., 1990; Swift et al., 1972). Recently, GPS signal reflection techniques have been proposed for making ice thickness measurements (Komjathy et al., 2000a, 2000b; Lowe et al., 2002). In particular, Lowe et al. (2002) states "Ice thickness may be measured by looking at the amplitude of the reflected signal as a function of the incidence angle and/or relative amplitudes between different polarizations to see interference effects between the air–ice and ice–sea reflections – experiments that can be performed with this receiver." This paper follows up on this suggestion by locating a GPS receiver above a frozen lake. The relevance of lake ice thickness is examined next.

2. Lake ice thickness relevance

The U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory (GLERL) operates and

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doi:10.1016/j.asr.2009.10.013

manages the synoptic ice chart observations for the Great Lakes (Assel, 2005). For approximately 50 years, this system has provided critical lake ice information for this region. In particular, Assel (2004) states “Ice cover impacts the water balance of the lakes and lake Flora and fauna by affecting energy and mass transfers from lakes and to the lakes. Improved understanding of ice cover climatology is therefore needed for an improved understanding and forecasts of the winter lake ecosystem. The duration and extent of ice cover on the Great Lakes also has a major impact on the economy of the region by impeding and eventually stopping commercial navigation, interfering with hydropower production and cooling water intakes, and damaging shore structures.” During the winters of late 1965 through early 1977, GLERL collected weekly ice thickness and stratigraphy data up to 90 stations per year on the Great Lakes; these data are stored at the National Snow and Ice Data Center (Sleator, 1995). Data were acquired using augers and visual observations. The data are useful for site-specific shoreline engineering studies, winter navigation projects and remote sensing ground truth.

In addition to large frozen lakes, such as the Great Lakes, ice roads in the northern regions rely on accurate information about ice thickness (Finlay et al., 2008; Mala, 2007). These roads play a crucial role of supplying northern communities with medical and other supplies in the winter season. Furthermore, these ice roads fuel the economy by supplying machinery, tools and fuel to various work sites. These sites exist primarily for the exploration and extraction of oil, gas, and diamonds. With these critical wintertime infrastructures in the northern hemisphere, the control and monitoring of the ice thickness requires a quick and periodic remote sensing technique. Ground penetrating radars (GPR) are often used for measuring ice thickness on these roads (Finlay et al., 2008; Mala, 2007). GPR measurements provide the necessary ice thickness information in a much more cost-effective way compared with manual drilling. Two of these GPR frequencies (1.5 and 1.6 GHz) are very close to the GPS L1 frequency.

Clearly, with the above applications, lake ice thickness measurements are important. In this paper, we explore the possibility of estimating lake ice thickness by using the GPS L1 frequency. In particular, a GPS receiver is located above a frozen reservoir. With this setup, the received power variations with respect to the changing satellite elevation angle are calculated and measured. A case study shows potential for inferring lake ice thickness by fitting the theory to the measurements.

3. Theory

A simple model depicting a water surface covered by dielectric layers is used to determine the relative received power at a GPS receiver. This model includes a vertically mounted hemispherical directional antenna with no sidelobes, a flat dielectric layer(s) of infinite extent above water, and uniform plane waves with a monochromatic frequency. Fig. 1 shows the total field received by the GPS antenna. The total field is the sum of the direct and specularly reflected signals. The relative received power at the right-hand circularly polarized antenna (Stutzman, 1993) is

$$P = \left|1 + \frac{(r_h - r_v)}{2} \exp(i\phi)\right|^2 \tag{1}$$

where r_h is the field reflection at horizontal polarization, r_v is the field reflection at vertical polarization, $\phi = \frac{4\pi h \sin\theta}{\lambda_0}$ is the phase shift difference in physical path length between the direct and reflected paths (Beckmann and Spizzichino, 1987), $i = \sqrt{-1}$ by definition, h is the height of the antenna above the top dielectric layer (in meters), θ is the elevation angle (in degrees), $c = 2.997925 \times 10^8$ m/s is the speed of light in a vacuum, $f = 1.57542$ GHz is the GPS L1 frequency, and $\lambda_0 = c/f = 0.1902937$ m is the GPS L1 free-space wavelength.

We compute r_h and r_v by using either a ray diagram (Jacobson et al., 1986; Johnk, 1975) or a transmission line equivalent circuit (Adler et al., 1960). The dielectric identifier, j, has the following values in this model: 1 for the top layer, 2 for the bottom layer, and 3 for the water. For a single-layer dielectric ($j = 1$) above water ($j = 3$)

$$r_x = \frac{W_{xj} - 1}{W_{xj} + 1}, \quad \text{for } x = h \text{ or } v \tag{2}$$

where

$$W_{xj} = \frac{Z_{x3} + iZ_{xj} \tan\psi_j}{1 + i\frac{Z_{x3}}{Z_{xj}} \tan\psi_j} \tag{3}$$

$$Z_{hj} = \frac{\sin\theta}{\sqrt{\varepsilon_j - \cos^2\theta}} \tag{4}$$

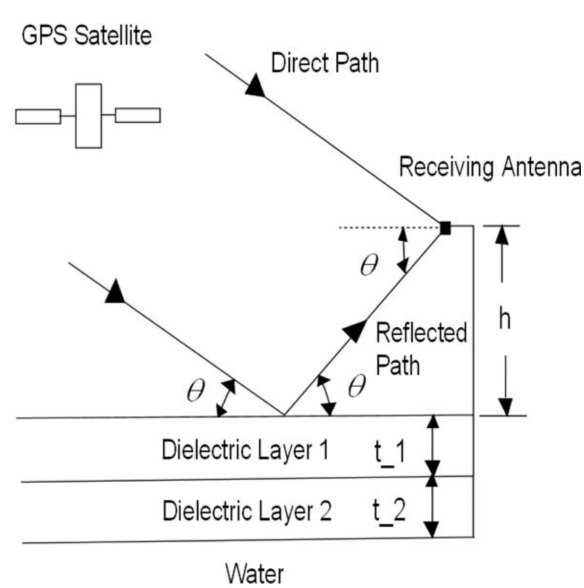

Fig. 1. Geometry of the total GPS L1 signal at the receiving antenna with a height h above dielectric layer 1. Dielectric layers 1 and 2 have thicknesses of t_1 and t_2, respectively. The elevation angle is given by θ.