

GPS Snow Surface Thermometer: Surface Thermal Transmission and Estimation

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Abstract

The Global Positioning System (GPS) reflected signals are able to remotely sense the Earth surface characteristics, such as soil moisture, snow depth, vegetation growth and ocean wave height. Since the snow depth is coupling with surface temperature, it is possible to estimate the snow depth and surface air temperature by incorporating GPS-Reflectometry (GPS-R) in Greenland. In this paper, the ionosphere geometric free linear combination of GPS signal variability (GPS-L4) is employed to estimate the snow surface temperature (SST) by considering the physical thermal transmission which causing snow height (SH) variations thermodynamically. The results show that the estimated SST values extracted from the inversion of bootstrapping model have a good agreement to the in-situ meteorological observations in MARG site in Greenland. The mean bias for the estimated SST values during the 286 days from March 21 to December 31, 2010 is about 3.8 C with correlation coefficient of 0.69 between SST values from the inversion of bootstrapping model and observations at MARG station. Moreover, some uncertainties are further discussed.

Keywords-GPS-R; Thermometer; Multipath; Bootstrapping model; Thermal transmission.

1. Introduction

Recently, a number of GPS remote sensing applications and experimental cases have been applied and demonstrated the ability of GPS scattered and reflected signals for soil moisture estimation [1], the vegetation growth [2] and forest biomass monitoring [3]. Furthermore, the snow depth and snow water are estimated using GPS signal to noise ratio (SNR) recently [4], [5]. In addition, Ozeki and Heki [6] estimated snow depth using the geometry free linear combination of GPS signals. Therefore, it is possible to estimate the snow depth and surface air temperature by incorporating GPS-Reflectometry (GPS-R) over snow covered surface. The Greenland Ice Sheet (GrIS) is the second largest glacier in the world [8] and thus it is important to measure the snow and surface temperature variations [11-13].

In this paper, the ionosphere geometric free linear combination of GPS signals (GPS-L4) is obtained to characterize the surface changes of around ground GPS receivers, including the surface air temperature changes and thus leading to snow height (SH) variation. The physical surface heat exchange plays a critical role to bridge from the SH to estimate the snow surface temperature (SST) values from the GPS-L4 ones. Furthermore, the non-parametric bootstrapping model is developed to inverse and estimate the snow surface temperature. In the next parts, the theory and methods are discussed. Results and discussion are given in Section 3, and Section 4 presents the conclusion.

2. Theory and Methods

2.1 GPS Reflected Signals

The GPS reflected signals are related to the physical surface reflectivity and the chemical surface characteristics of the scattered and reflected surfaces. The former depends mainly on GPS satellite elevation angle and receiver antenna height and the latter is the function of signal frequency, surface conductivity and relative permittivity in different grazing angles [14],[15]. Here the multipath of ionospheric geometric free linear combination of GPS signals as Φ_{IF} is obtained with removing the effect of the ionosphere on the GPS signals. The ionosphere geometric free linear combination (GPS-L4) can be written as:

$$\text{GPS-L4} = \Phi_{IF} = -\frac{f_1^2}{f_1^2 - f_2^2} \times \Phi_1 + \frac{f_2^2}{f_1^2 - f_2^2} \times \Phi_2 \quad (1)$$

where Φ_1 and Φ_2 are the dual-frequency GPS carrier phase signals, f_1 and f_2 are GPS frequencies with $f_1=1575.42$, $f_2=1227.60$ MHz. According to [16], the highest noise increment is seen for the wide lane linear combination while the lowest is observed for the narrow lane one.

2.2 Thermal Behavior of Snow (Heat Exchange)

In order to bridge from SH to SST, understanding the thermal behavior of snow layer is very important. In fact, the key to assess the SST by considering the snow depth changes in the GPS-R technique is referring to thermodynamic characteristic of snow as a non-isolated medium. If there is no water in the snow and the snow is considered as a completed shaped snow [17],[18], the heat transfer is related to heat conduction as follow:

$$H = -L_{ik} S \quad (2)$$

where H is the thermal source term, S stands for melt or freeze phase change and eventually L_{ik} is defined as the following two terms on occasion:

- in snow accumulation; L_{ik} as L_{il} is the latent heat of fusion,
- in snow melting; L_{ik} as L_{iv} is the latent heat of sublimation.

It is good to note that if the fluid (air or water) flows through the snow layer, the heat transport will take place as a function of advective and diffusive processes, which makes it a very convoluted issue. In this study, we assume that the snow type is a complete created snow without any water or any other extraneous elements inside it. According to Eq. 2, the decrease in snow depth will be resulted from the increase in the near surface air temperature and vice versa. In the other words, the only reason to affect on decreasing (increasing) snow depth is originated from the decrease (increase) in near surface air temperature degree.

2.3 Non-parametric Bootstrapping Model

Since there is no enough information about the physical relation between the SST and GPS-L4 values, the non-parametric bootstrapping model is proposed. This bootstrapping model establishes a sampling distribution by resampling the existing data to perform the empirical distribution function (EDF) with probability density function (PDF) in a nonparametric bootstrapping functions library. It is good to note that both EDF and PDF are the most absolutely necessary functions to construct the origin shape of the model which will be used for the inverse modeling of bootstrapping. Moreover, the EDF tries to estimate the unknown cumulative distribution function (CDF) precisely through giving equal probabilities to the original values (GPS-L4 values) and thus each output value (SST) is independently modeled. Based on this, the modeled bootstrap output's trend is essentially an empirical normalized sample modeling with required replacement from the original trend.

3. Results and Discussion

The MARG station of International GNSS Service (IGS) GPS station is used in Greenland (lon: -65.69°, lat: 77.19°, altitude: 657.13 m) in this study. The IGS-GPS station can receive dual-frequency observations at 30-second continuously and the average daily 2880 epochs observations for 32 satellites are used during 286 days from March 21, 2010 to December 31, 2010. Furthermore, the mean daily SH (m) and SST (°C) meteorological observations of co-located GPS stations are used from the Greenland Climate Network Automated Weather Station (GC-NET-AWS) established by Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, USA. The GPS-L4 and SST daily values for the day 80 to 385 of 2010 at MARG site are presented in Fig. 1.

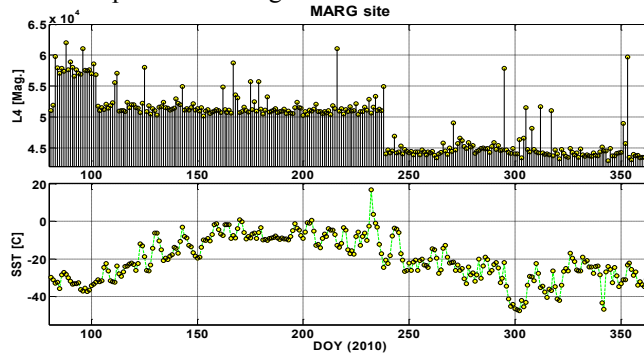


Figure 1. GPS-L4 and SST variation in MARG site (Greenland).

Fig. 1 shows a good homogeneous trend between the GPS-L4 values and the SST variations. The SST values for day 80 to 100, 100 to 235 and 235 to 365 are following the exact changes in GPS-L4 values in the same time. To model the relationship between SST and GPS-L4 variations, the non-parametric bootstrapping model based on Fourier transform and

local regression is proposed. Fig. 2 shows the GPS-L4 variations versus SST, which has been modeled by non-parametric bootstrapping model with two upward and downward confidence intervals.

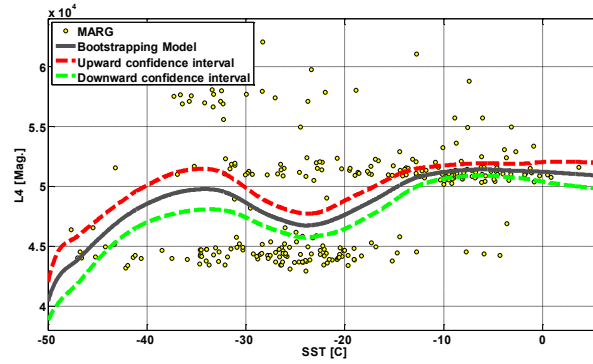


Figure 2. Nonparametric bootstrap model of GPS-L4 variations versus SST in MARG site.

Furthermore, the inverse model of bootstrapping model is employed to retrieve the SST values from GPS-L4 variations. Fig. 3 presents the SST from the meteorological observations at co-located MARG GPS station and the inversion of bootstrapping model.

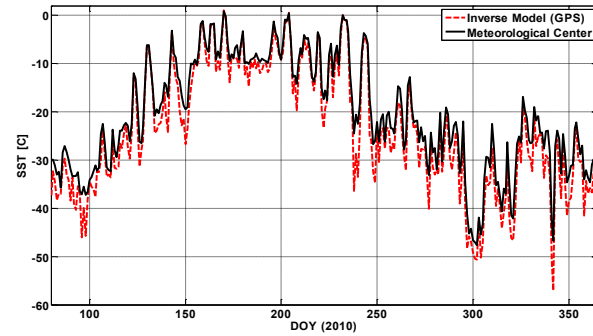


Figure 3. SST and SH from the inversion of bootstrapping model (GPS-L4) and meteorological observations at MARG site.

The outputs precision from the inversion of bootstrapping model depends on several factors: the homogeneity of SST and GPS-L4 distribution, the chosen confidence level (which here is considered as 63%) and the degree of freedom in Fourier approximations. The Pearson correlation coefficient between these two types of SSTs is 0.69 at MARG site. Thus, there is a good agreement between the resulted SST and the in-situ SST observations. The daily uncertainty of SST from the inversion of bootstrapping model with respect to the meteorological observations is given in Fig. 4. The mean bias value for SST is about 3.8 °C. Although the inversion of bootstrapping model uses a range of approximation to model the distribution of SST and GPS-L4 values, but the trend for these two parameters are generally following each other (Fig. 3 and Fig. 4).

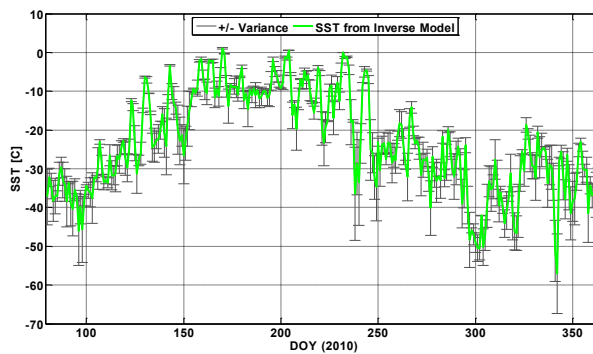


Figure 4. Uncertainty of inversed SST from the bootstrapping model with GPS-L4 at MARG site.

4. Conclusion

In this study, the SST is estimated based on the thermal relationship between SH and SST using GPS reflected signals (GPS-L4) at MARG site in Greenland during 286 days from March 21 to December 31, 2010. The Pearson correlation between two SST values derived from the inversion of bootstrapping model and the meteorological observations show that the estimated SST values based on GPS-L4 variations have a good accuracy. Moreover, the proposed non-parametric bootstrapping model has a good performance to connect the variability of GPS-L4 and SST values. The estimated SST values by applying the inversion of bootstrapping model reflect climate dynamics conditions, and the GPS reflected values can be initially used for the near surface air temperature estimates for the snow-covered surfaces. However, more works and tests are further needed in the future.

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