FREEZE/THAW RETRIEVAL OVER HIGH ALTITUDE AREAS WITH CYGNSS

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ABSTRACT

Soil Freeze/Thaw (F/T) transition monitoring is essential for quantifying climate change and hydrologic dynamics over cold regions. In this work, we investigated the use of Earth-reflected Global Positioning System (GPS) L-band signals as collected by the CYclone Global Navigation Satellite System (CYGNSS) mission for F/T retrieval over high altitude areas. CYGNSS can potentially detect the freezing and thawing of soil surface due to changes of dielectric constant when frozen, at an improved spatio-temporal sampling as compared to traditional microwave radiometry missions. A feasibility study has been performed over the Andes Mountains to further advance on this topic. Sensitivity in CYGNSS data to F/T transitions was demonstrated by comparing reflectivity differences between Summer and Winter to soil and snow temperature as provided by the European Centre for Medium-Range Weather Forecast (ECMWF) ERA 5-Land numerical reanalysis model. Finally, F/T retrievals with CYGNSS showed a better performance than those derived with the Soil Moisture Active Passive (SMAP) mission.

Index Terms— GNSS-R, CYGNSS, forward scattering, sensitivity, SMAP, Freeze/Thaw retrieval, Andes Mountains

1. INTRODUCTION

Spatial and temporal patterns of landscape F/T state transitions within the cryosphere are highly variable with impacts to climate, hydrological, ecological, and biogeochemical processes [1]. F/T state has a strong impact on the seasonal amplitude and partitioning of surface energy exchange, while ecosystem responses to seasonal thaw are rapid, with evapotranspiration, soil respiration, and plant photosynthetic activity accelerating with warmer temperatures and the availability of liquid water [1]. The annual thaw period also influences the vegetation growing season, while variability in F/T timing rules vegetation net primary production and Net Ecosystem CO2 Exchange (NEE) with the atmosphere [2].

More than one third of the Earth's land surface is covered by seasonal or permanent soil frost. Many agricultural, engineering, and environmental issues and applications are affected by F/T state. A frozen land surface

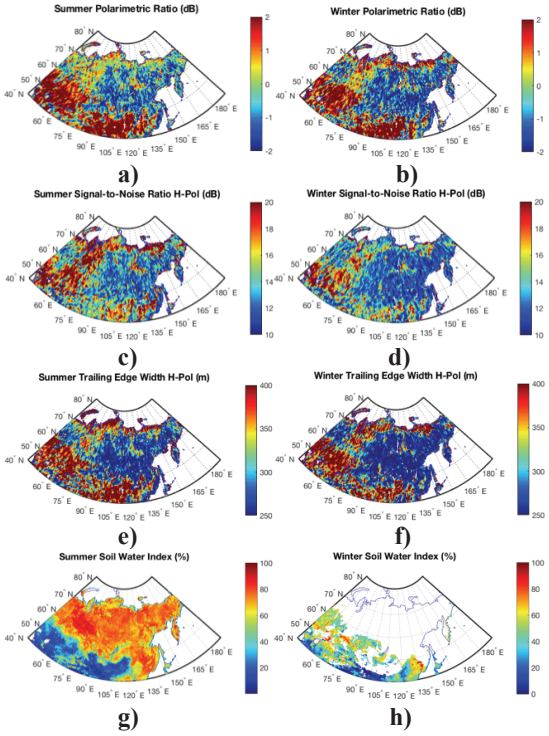


Fig. 1. Sensitivity study of SMAP GNSS-R mode to Freeze/Thaw (F/T) detection over Northern Asia [4]. Polarimetric Ratio (a) Summer; (b) Winter. Signal-to-Noise Ratio (c) Summer; (d) Winter. Trailing edge width (e) Summer; (f) Winter. Soil Water Index (g) Summer; (h) Winter.

tends to reduce or even to impede water infiltration, which may promote flooding, surface runoff, and soil erosion [3].

In this work, CYGNSS data were used to investigate the potential capability of Global Navigation Satellite Systems Reflectometry (GNSS-R) to determine the F/T state over regions of high altitude such as the Andes Mountains and the Tibetan Plateau, also known as the "third pole."

Some pioneering studies have shown a promising sensitivity to F/T transitions over high latitude regions (Fig. 1), including SMAP GNSS-R mode [4,5] and TechDemoSat-1 [6]; and also CYGNSS [7]. CYGNSS [8] was originally proposed for ocean surface winds speed

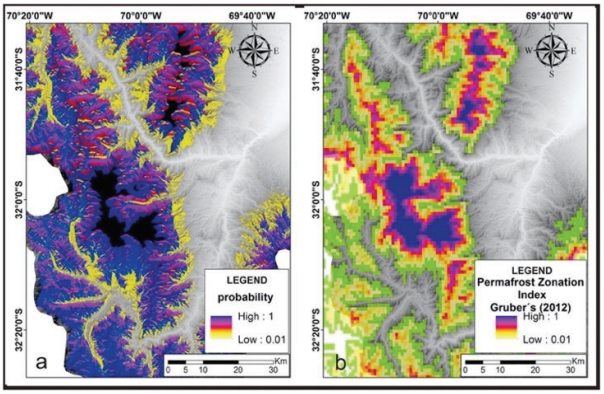


Fig. 2. Comparison of models over the Andes Mountains: (a) State-of-the-art permafrost distribution map, with a 30 m spatial resolution, (b) Permafrost Zonation Index (PZI) model of Gruber [12].

estimation over tropical cyclones using reflected L1 C/A code GPS signals at Left Hand Circular Polarization (LHCP). CYGNSS allows one to sample the Earth's surface along 32 tracks simultaneously, within a wide range of satellites' elevation angles. The unique sampling properties of CYGNSS could enable to further understand F/T dynamics.

2. METHODOLOGY

In a general scenario, Earth-reflected Delay Doppler Maps (DDMs) consist on a sum of two terms: coherent scattering term and incoherent or diffuse scattering term e.g. [9]. The relative portion of both components mainly depends on the observation geometry, and both the dielectric and structural properties of the scattering media. Both the reflectivity and the Normalized Bistatic Radar Cross-Section (NBRCS) are under evaluation to determine which is the most accurate observable for each type of surface in this study [10,11].

2.1 Target Areas

All available CYGNSS data (2017-present) are considered to generate a time-series of surface reflectivity and NBCRS over specific target areas of interest for a deeper understanding of land cover type, vegetation, and topography effects on CYGNSS sensitivity to F/T surface state, including at least:

- Andes Mountains: Permafrost occurs extensively in the Andes (Fig. 2). In the northern, tropical Andes it probably only occurs above ~ 5,000 m. This lower limit falls gradually southwards to about ~ 1,500 m in southern Chile and Argentina. The total area underlain by permafrost is at least ~ 30,000 km^2.

- Tibetan Plateau: The largest area of permafrost in mountains regions occurs in Middle and Central Asia, including the Tibetan Plateau, the Himalayas, Trans-Himalayas, Karakoram, Hindu Kush, Kunlun Shan, Pamirs, and the Tien Shan. In this vast area of complex mountain chains and high plateaus, permafrost occupies an estimated area of ~ 1,000,000 km^2. The Tibetan Plateau hosts the largest and thickest frozen ground at the middle and low latitudes, including permafrost and seasonally frozen ground. Recent research revealed that the area of seasonal frozen ground is larger than that of permafrost, accounting for ~ 55 % of the total area [13].

2.2 Sensitivity Analysis

Sensitivity of CYGNSS data to F/T transitions (freeze depth and freeze–thaw duration) was demonstrated by comparing reflectivity (and NBRCS) differences between Summer and Winter to soil and snow temperature as provided by the ECMWF ERA 5-Land numerical reanalysis model. Data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and meteorological stations are also under evaluation. Temperature of the soil in layer 1 (0 - 7 cm) of the ECMWF Integrated Forecasting System (IFS) model was used. The ECMWF IFS model represents snow as a single additional layer over the uppermost soil level. Temperature of the snow layer was calculated from the ground to the snow-air interface. Additional parameters are also under study, including Soil Moisture Content (SMC) in layer 1 and topographic roughness as derived from a Digital Elevation Model (DEM).

2.3 Retrieval Algorithm

The baseline approach in this project is based on a seasonal-threshold algorithm which examines the time series progression of CYGNSS-derived measurements (reflectivity, NBRCS) relative to signatures acquired during seasonal reference frozen and thawed states. A seasonal scale factor $\Delta(t)$ was defined for an observation acquired at time t as [14]:

$$\Delta(t) = \frac{\Gamma(t) - \Gamma_{fr}}{\Gamma_{th} - \Gamma_{fr}} \quad (1)$$

where $\Gamma(t)$ is the reflectivity measurement acquired at time t, for which a F/T classification is sought, and Γ_{fr} and Γ_{th}

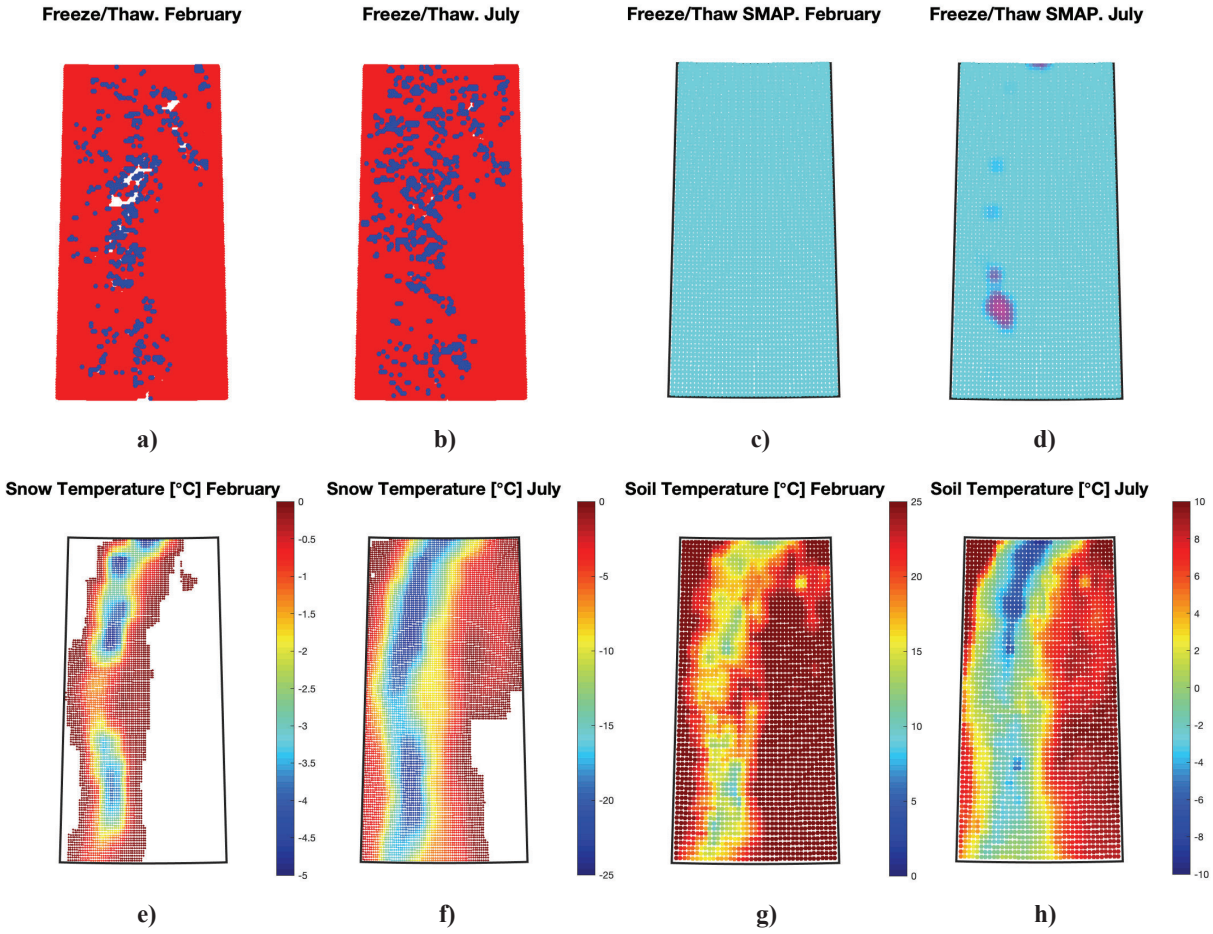


Fig. 3. Study of surface F/T retrieval over the Andes Mountains using CYGNSS. February (Summer), July (Winter). CYGNSS F/T state [red-thaw, blue-freeze]: a) February, b) July. SMAP F/T state [blue-thaw, pink-freeze]: c) February, d) July. ECMWF snow temperature: e) February, f) July. ECMWF soil temperature: g) February, h) July.

are reflectivity measurements corresponding to frozen and thawed reference states, respectively.

A threshold level T was then defined such that:

$$\Delta(t) > T \tag{2}$$

$$\Delta(t) < T \tag{3}$$

defines the thawed and frozen landscape states, respectively. The threshold level was defined using the optimum operational point of the Receiver Operating Characteristic (ROC) curves considering the ECMWF ERA 5-Land temperature as proxy data. It is expected to find different thresholds for different land cover types, including glacierized and non-glacierized surfaces.

3. PRELIMINARY RESULTS

First preliminary results using this approach are depicted in Fig. 3. It can be observed that CYGNSS-derived F/T state is more consistent with ECMWF ERA 5-Land snow and soil temperature than SMAP. On the other hand, CYGNSS F/T maps show relatively high scatter in the detection of frozen soil due to the impact of outliers in the reflectivity, which are non-linked with geophysical parameters. The inverse Cumulative Distribution Function (CDF) of the reflectivity will be computed over the range for which the percentage of samples (p) goes from 0% to 5% and from 95% to 100%. Then, a best fit power series will be computed using all the samples of the inverse CDF in the range of p which is linked with geophysical parameters. Finally, the inverse CDF will be extrapolated to the 100% fraction while ignoring the behavior where the outliers are present (potentially, they should show a sharp increase in the inverse CDF). The same approach will be applied to the NBRCS. The retrieval algorithm will be validated at specific test sites.

4. CONCLUSIONS

In 2012, NASA selected the CYGNSS mission coordinated by the University of Michigan (UM), as a low cost and high science Earth Venture Mission. CYGNSS, an eight-microsatellite fully operational constellation, was

launched on December 15th, 2016. Following the Earth Science Division 2020 Senior Review, NASA announced recently it is extending the CYGNSS mission through September 30th, 2023.

In this scenario, we are further expanding the scientific use of CYGNSS, with focus over land surfaces. Our first results within this investigation demonstrated the feasibility to capture F/T transitions over high altitude areas. At present, we are working so as to optimize the performance of several F/T retrieval algorithms.

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