Comment on essd-2021-432

Anonymous Referee #1

The authors proposed a comprehensive framework to process GNSS raw data under complex environment conditions to retrieve snow depth, and based on this, the authors produced a GNSS-based long-term snow depth data set over China from 80 stations. The topic is very interesting from a perspective different from traditional microwave remote sensing retrievals. As the authors' statement, this data set has a unique spatial resolution between point-scale and coarse grid-scale. The new data set is valuable to the science community from this point. I also have confidence in this GNSS-IR technique, which could be a helpful and complementary tool for producing more snow depth products with high spatial-temporal resolution using extended global GNSS networks, particularly from GNSS sites in polar regions or even on scientific expedition vessels. I recommend this work for publication after revisions. Several comments are listed below:

We thank this reviewer for her/his valuable time in reviewing our manuscript and providing thorough and insightful comments. We have carefully revised the manuscript to address the issues and comments raised by the reviewer. Point-by-point responses to the comments are listed below. Comments are shown in black, the authors' responses are shown in blue, and the revisions in the manuscript are shown in red. A revised manuscript will be uploaded during the subsequent "final response" stage according to the journal's review rules.

In addition, we have updated the data set during this round to reconsider several issues. The updates are described below. The results show that the quality of the data set has been improved. We have also revised the figures and the corresponding texts in the manuscript to match the updated data set. Some of the updates will be shown in the following responses, and the remaining will be shown in the revised manuscript during the subsequent "final response" stage.

- Added a new quality flag, i.e., the Signal Strength Indicator (SSI), to do the quality control (SSI >=2).
- Changed the strategy to deal with the non-repeating GLONASS tracks, i.e., used twelve azimuths separated by 30° as a basis to derive the snow-free surface reflector heights.
- Used a more accurate way to consider the penetration depth of the GNSS signal through bare soil, i.e., the penetration depths of each site for GPS L1/L2, GLONASS B1/B2, and BDS B1/B2/B3 were separately calculated using the prepared soil components and VSM parameters.
- Used the maximum snow depths during 2010-2020 as constraints to remove possible outliers of the raw GNSS snow values per track.

The updated GSnow-CHINA v1.0 data set has been uploaded at https://doi.org/10.11888/Cryos.tpdc.271839.

1. Vegetation and terrain are two significant issues that affect snow depth estimation. The authors only discussed vegetation in Section 5.1. How about terrain effects? I recommend adding in-depth discussions relevant to this issue.

We have added a paragraph to discuss the terrain effects. Please see below:

In practical applications, none of the planar surfaces is entirely horizontal. Small ground tilting angles translate into several tens of centimeters of bias due to the large horizontal distances involved (Larson and Nievinski, 2013). Figure 17 shows simulations for a 2-m antenna height with a variety of snow depth levels and positive terrain slopes using the open-source GPS multipath simulator provided by (Nievinski and Larson, 2014b). For slopes of 5° and less, the error in snow depth retrieval is below 10 cm, while for larger slopes (e.g., 8° in the figure), the residual effects are ~ 15 cm and higher. Fortunately, for GPS satellites with repeatable ground tracks, such a topographic bias remains stable over time. It thus could be canceled out when using Eq. (1) to estimate snow depth, most of which is the case in this study. While for GNSS satellites like GLONASS and BDS, whose ground tracks are non-repeatable, the terrain effect should be considered. Some previous studies investigated methods to eliminate the influence of terrain (Zhang et al., 2017; Zhang et al., 2020). We are also developing a new approach to consider the terrain effects, which will be demonstrated in a future study.

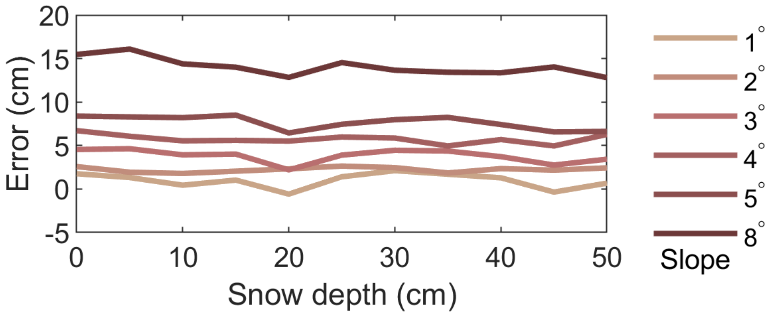


Figure 17. Simulations of the effects of terrain slopes on snow depth retrievals for a 2-m antenna height of GPS L1 (wavelength = 19 cm)

References:

Larson, K. M. and Nievinski, F. G.: GPS snow sensing: results from the EarthScope Plate Boundary Observatory, GPS Solutions, 17, 41-52, 10.1007/s10291-012-0259-7, 2013.

Larson, K. M. and Nievinski, F. G.: GPS snow sensing: results from the EarthScope Plate Boundary Observatory, GPS Solutions, 17, 41-52, 10.1007/s10291-012-0259-7, 2013.

Zhang, S., Wang, X., and Zhang, Q.: Avoiding errors attributable to topography in GPS-IR snow depth retrievals, Advances in Space Research, 59, 1663-1669, https://doi.org/10.1016/j.asr.2016.12.031, 2017.

Zhang, Z., Guo, F., and Zhang, X.: Triple-frequency multi-GNSS reflectometry snow depth retrieval by using clustering and normalization algorithm to compensate terrain variation, GPS Solutions, 24, 52, 10.1007/s10291-020-0966-4, 2020.

2. Around Line 185: "4) For high- and medium-quality sites, the model for deriving daily reflector height is established, and the raw snow depth for each GNSS satellite, each quadrant, and each GNSS frequency is subsequently calculated as the difference value of the referenced height in Step 3) and the height of this step". I am confused about the descriptions of "height." Which height was used as the referenced height? The authors should revise the texts to clarify this issue.

We have revised the texts to clarify this issue. Please see below:

1) The observables for snow depth retrieval, i.e., satellite Pseudorandom Noise (PRN) numbers, observation time, satellite elevation angle, satellite azimuth angle, pseudorange, carrier phase (CP), Signal-to-Noise Ratio (SNR), are extracted or calculated from the raw data.

2) The Lomb-Scargle Periodogram (LSP) analysis (Lomb, 1976) is executed on several non-snow days to determine the mean reflector heights for each GNSS satellite, each quadrant, and each GNSS frequency. For those high- and medium-quality sites which will be distinguished in the following Step 3), the mean reflector heights are used as reference heights when calculating snow depth.

3) A comprehensive evaluation of the quality of all the GNSS sites is done based on the data quality of the non-snow surface reflector heights in Step 2), and the sites are divided into high-, medium-, and low-quality accordingly.

4) For high- and medium-quality sites, the model for deriving daily reflector height is established, and the raw snow depth for each GNSS satellite, each quadrant, and each GNSS frequency is subsequently calculated as the difference value of the referenced height in Step 2) and the height of this step.

3. Line 350: "The 8-day MODIS NDVI is also involved as a quality flag in the data set to show the vegetation conditions of the site initially". The authors only gave this vegetation flag. How to use this flag? I recommend adding a few sentences to describe.

We have added descriptions of the NDVI flag in the manuscript. Please see below:

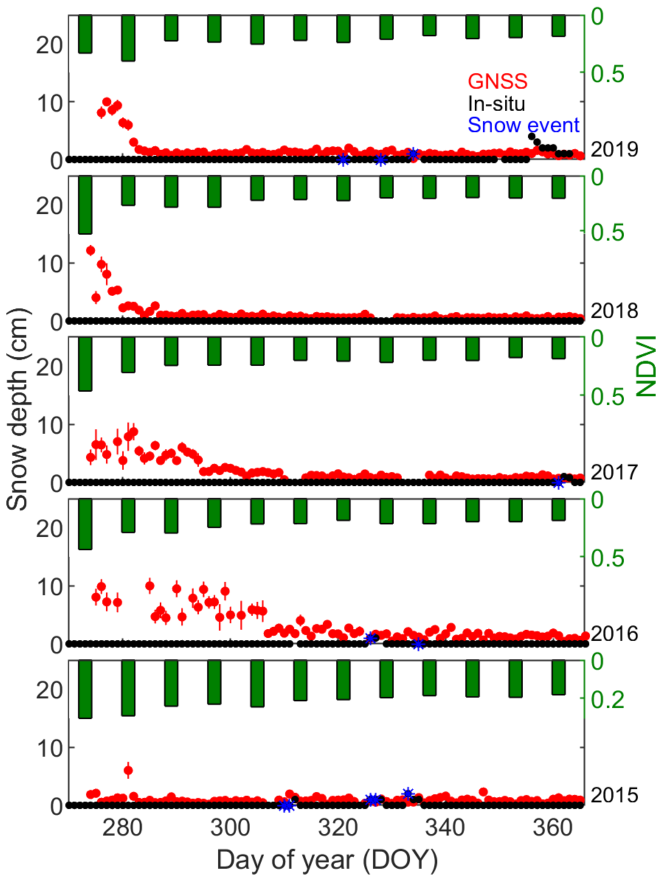
The 8-day MODIS NDVI is also involved as a quality flag in the data set to show the vegetation conditions of the site initially. The 8-day values are combinations of the MODIS MOD13Q1 and MYD13Q1 products. The NDVI flag can provide supplementary information for the users to identify the possible confusion of vegetation. However, due to the coarse resolution of MODIS data, it is not possible to use this flag to represent the actual vegetation cover around the GNSS station.

4. Should Section 4.4 be a separate section? I am afraid it is improper to put the data set descriptions inside Section 4.

We totally agree with the reviewer. We have changed Section 4.4 to a separate section, i.e., "Section 5. Data set descriptions".

5. Figure 17 x-label is not correct? Should it be the current number +10?

The x-label of this figure has been corrected. Please see below:



6. I am aware that the authors tried their best to reuse the data from the current GNSS networks. There are still limitations concerning the raw data. I look forward to seeing a longer-time series of snow depth products from more sites and systems (such as from China's Beidou). I also encourage the authors to find some way (e.g., making a website?) to maintain and share the methods and data sets to broader users?

We thank this reviewer for helping us considering to improve the potential value of this data set. We totally agree with the reviewer that we should involve more data once they are available in the future. We have added several sentences to address the reviewer's comments at the end of the manuscript. As below:

Finally, it should be noted that, although we tried our best to reuse the data from the current GNSS networks, there are still limitations concerning the raw data (e.g., limited site numbers and GNSS data types). We look forward to having more sites and data from more GNSS systems (such as from China's Beidou) from the CMA or other organizations to use in the future. Both the algorithm and the data set will be maintained and updated as more years of data become available.

In addition, both reviewers gave us comments on the easy sharing of the data set to a broader international community. We have put the data set on the TPDC website along with this paper which is freely available to the international community (see https://doi.org/10.11888/Cryos.tpdc.271839). We are also considering putting the extended data (e.g., every five years) in the future to some data-sharing websites or making an FTP or website to maintain and share the future data versions.