Snow Depth Estimation Using Interferometric Synthetic-Aperture Radar (InSAR) Technique

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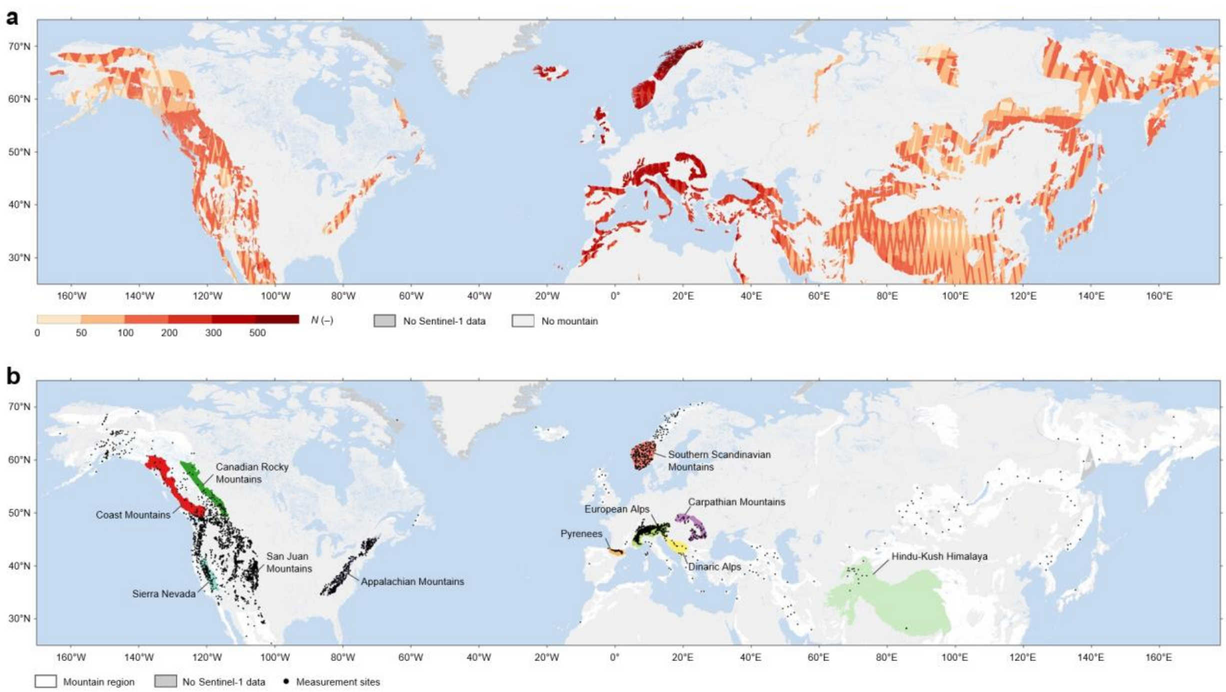
Final Report No. ST-2021-21108-01



Monthly snow depth retrieved by Sentinel-1. a Snow depth (m) over the Northern Hemisphere mountains. b Enlargement of a part of the western US and Canada. c As in panel b, but for a part of the Hindu-Kush Himalaya region. (Lievens-et-al. 2019).

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14. ABSTRACT
This research is aimed at evaluating the feasibility and value of using the InSAR technique to increase the detection accuracy of snow depth and quantify seasonal snow-melt water resources.

15. SUBJECT TERMS
Snow depth, SAR, Satellite remote sensing

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prepared by

Bureau of Reclamation
Technical Service Center
Jong Beom Kang, TSC, Civil Engineer

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Snow Depth Estimation Using Interferometric Synthetic-Aperture Radar (InSAR) Technique

JONG BEOM KANG   Digitally signed by JONG BEOM KANG
Date: 2021.09.30 11:18:40 -06'00'

Prepared by: Jong Beom Kang
Civil Engineer, Geotechnical Laboratory and Field Support, 86-68550

Peer Review: Scott Baker
InSAR Specialist, BOS Technologies

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Executive Summary

Spring snowmelt helps recharge and contribute around 80% of water storage into Western reservoirs. It is a critical element to evaluate how much snowmelt will enter the reservoirs to estimate proper release of water from dams, mitigate potential floods, maintain conservation pool storage, and manage water delivery volumes for the Reclamation's water management (Reclamation 2006).

Interferometric Synthetic-Aperture Radar (InSAR) technology application is growing rapidly and has significantly contributed to several areas with varying spatial resolutions. The spatial resolution is categorized as low (30m or more), medium (5m to 30m), high (1m to 5m), or very high (1m or less). Currently, global satellite imagery data accrued over four decades is available and InSAR satellite remote sensing technology has been broadly applied to various fields and produced an extraordinary range of applications including agriculture, disaster monitoring and mitigation, water resource management, environmental monitoring, mineral exploration, land use mapping, and coastal eco-system monitoring (Das et al., 2014; Fattahi et al., 2017). SAR satellite remote sensed imagery data have become an important tool to obtain earth image data by measuring electromagnetic radiation reflected from surface and subsurface materials. Satellites with SAR sensors can cover much larger areas and are highly effective in damage surveys since SAR can be used regardless of sunlight and weather conditions.

Thus, there is an ongoing need to evaluate the feasibility and value of using the Interferometric Synthetic-Aperture Radar (InSAR) technique to increase the detection accuracy of snow depth and density, quantify seasonal snow-melt water resources, and improve accuracy into river and reservoir operation models to better inform water allotments and planning efforts. Accurate understanding of seasonal snow cover is one of the most critical components in predicting water resources, supply planning, and parameters for hydrological water operation models.

The purpose of this research is to evaluate the feasibility and effectiveness of using the InSAR technique as a tool for measuring seasonal snow depth and inform snow-melt water resources for the Reclamation water information system. Snow depth estimation is a critical component for quantifying seasonal Reclamation water resources at reservoir areas, expanding the use of the hydrologic database across Reclamation regions, assisting other water facility operational decisions for hydrological applications with real-time data, and informing recreational reservoir water users of reservoir water conditions.

The strategy of this scoping-level study to answer the question – how to evaluate the feasibility and value of using the InSAR technique to increase the detection accuracy of snow depth and quantify seasonal snow-melt water resources - consisted of the following tasks: (1) conducting a literature review on how the SAR technique has been used to estimate snow depth or snow density, (2) understanding snow, snow accumulation, and snow reflectance/signal, (3) identifying research project sites and potential project partners, (3) collecting an evaluating Sentinel-1 snow depth retrievals are available online and the C-SNOW dataset for snow depth measurements of the mountains of Sierra Nevada between the Central Valley of California and the Great Basin and San Juan Mountains in the

Rocky Mountains in southwestern Colorado and northwestern New Mexico , (4) performing SAR data processing with time-series to estimate snow depth, (5) evaluating the applications and limitations of the SAR technique in detecting snow depths and snow densities for the Reclamation water resources management system, and (6) publishing the findings from this research effort.

The InSAR data processing and time-series analysis were performed to evaluate the applications and limitations of the InSAR technique to detect snow depths and snow density with the target year of September 2016 through August 2018 with the changes of SAR mean line-of-sight (LOS) velocity (mm/year) values obtained from timeseries analysis at the defined study areas of Sierra Nevada and San Juan Mountain ranges. The results indicated that InSAR technique could provide valuable information to Reclamation in snowmelt water resources evaluation in the future and result in better, faster, and cheaper solutions for efficient snow depth estimation and measurements of seasonal snowmelt water resources in reservoir areas.

1. Background

Snow depth estimation is a critical component for quantifying seasonal Reclamation water resources at reservoir areas, expanding the use of the hydrologic database across Reclamation regions, assisting other water facility operational decisions for hydrological applications with real-time data, and informing recreational reservoir water users of reservoir water conditions. This research could result in better, faster, and cheaper solutions for efficient snow depth estimation and measurements of seasonal snowmelt water resources in reservoir areas.

This research was conducted for the intent of evaluating the feasibility and effectiveness of using the SAR technique as a tool for measuring seasonal snow depth and inform snow-melt water resources for the Reclamation water information system. The following tasks were performed. The C-SNOW dataset for snow depth measurements over the defined study areas (Sierra Nevada and San Juan Mountain ranges) was evaluated. The dataset provides daily snow depth measurements at 1km spatial resolution for 2017-2019 from Sentinel-1 SAR imagery, with a weekly coverage for all northern hemisphere mountain ranges. The dataset utilizes dual-polarization Sentinel-1 SAR backscatter data, and the processing workflow for the C-SNOW dataset was evaluated. Sentinel-1 GRD and SLC datasets were downloaded over the Sierra Nevada and appropriate imagery data was acquired for snow depth measurements to determine the computing resources necessary for extending the 2017-2019 snow depth time series from the C-SNOW dataset. It is determined that the computing resources needed are largely dependent on the spatial resolution of the final data product, with more required at finer spatial resolutions.

The satellite imagery data from InSAR can be collected at nighttime and through cloud cover. InSAR observations provide high-resolution measurements, and these measurements are more suitable for monitoring snow cover than data from optical or microwave sensors. Using this enhanced approach with historical and recent high-resolution SAR imagery data will provide a technique for effective snow depth estimation on a wide scale with rapid monitoring and give cost savings to reservoir and river Reclamation sites.

Without the understanding of seasonal snow cover, the prediction of water resources and hydrological water operations model may not be accurate in water supply planning and decisions. The specific benefits of InSAR data processing are that SAR imagery data and the time-series analysis results will be periodically collected. This information could provide valuable information to Reclamation in snowmelt water resources evaluation in the future.

2. Scope of Research

The project study areas are identified in the mountains of Sierra Nevada between the Central Valley of California and the Great Basin and San Juan Mountains in the Rocky Mountains in southwestern Colorado and northwestern New Mexico. Columbia Pacific Northwest (CPN) and California Great Basin (CGB), and Upper Colorado Basin (UCB) regions and offices will rely or being impacted by snowmelt water resources.

The strategy of this scoping study to answer the question how to evaluate the feasibility and value of using the InSAR technique to increase the detection accuracy of snow depth and quantify seasonal snow-melt water resources consists of the following tasks: (1) conducting a literature review on how the InSAR technique has been used to estimate snow depth or snow density, (2) understanding snow, snow accumulation, and snow reflectance/signal, (3) identifying research project sites and potential project partners, (3) Sentinel-1 snow depth retrievals are available online and the C-SNOW dataset for snow depth measurements of the mountains of Sierra Nevada between the Central Valley of California and the Great Basin and San Juan Mountains in the Rocky Mountains in southwestern Colorado and northwestern New Mexico was collected and evaluated, (4) performing InSAR data processing with time-series and sensitivity analysis to estimate snow depth and density, (5) evaluating the applications and limitations of the InSAR technique in detecting snow depths and snow densities for the Reclamation water resources management system, and (6) publishing the findings from this research effort.

3. Previous Work

Research has been done on the volume of stream flows from snowmelt in Colorado rivers for evaluating water supply and flooding forecasts. The research indicates that a major challenge in the forecasts has been a lack of detailed knowledge of the snow water equivalent (SWE) in the mountain study areas. The research has proposed to apply a new sophisticated modeling and data assimilation system to resolve the limitation for SWE, the Snow Data Assimilation System (SNODAS). SNODAS is a combined precipitation and snowpack measurement system that provides water managers with accurate and timely information about snowmelt water volumes and represents crucial decision support for Reclamation water operations managers (Reclamation, 2006).

Snowfall monitoring systems have relied on gauges to measure precipitation. The limitations using precipitation gauges are that (1) the gauge system provides sparsely distributed point measurements in mountainous areas and (2) the gauge data is more challenging to measure snow and rain separately in the mountains. The Snow Telemetry (SNOTEL) is a primary gauge system for snowfall measurements in the mountains, however, the SNOTEL gauges are not sufficiently installed in high elevations where snowpack needs to be observed. Therefore, it is a challenge to accurately measure snowfall, estimate the snow water equivalent (SWE), and track the melting of the snowpack in the mountains (Reclamation, 2006).

Accurate snow depth observations are important to estimate water resources because more than a billion people rely on water resources obtained from snow in the Northern Hemisphere mountain ranges. However, remote sensing techniques to observe snow depths in mountains are still lacking at the large scale. The research shows the ability of Sentinel-1 to map snow depth in the Northern Hemisphere mountains at 1 km^2 resolution using an empirical change detection approach. The research describes that the retrieval processes of the Sentinel-1 imagery data capture the spatial variability between mountain ranges and interannual differences. The research findings provide a good approach for quantifying the long-term vulnerability of mountain snow-water resources to climate change (Lievens et. al., 2019).

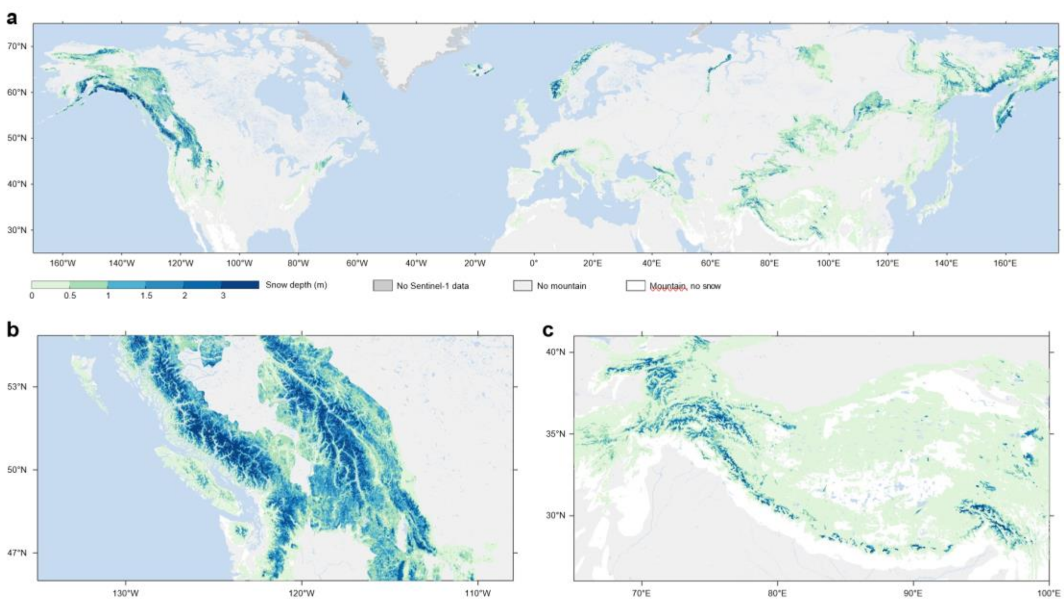

Figure 1. Sentinel-1 is the only SAR mission providing high-resolution backscatter measurements (at C-band; 5.4 GHz) with a revisit time of 6 days suitable for snow monitoring (Lievens et. al., 2019).

Synthetic Aperture Radar (SAR) satellite remote sensing technology has been broadly applied to various fields and produced an extraordinary range of applications including agriculture, disaster monitoring and mitigation, water resource management, environmental monitoring, mineral exploration, land use mapping, and coastal eco-system monitoring (Das et al., 2014; Fattahi et al., 2017). SAR technology application is growing rapidly and has significantly contributed to several areas with varying spatial resolutions.

SAR satellite remote sensed imagery data have become an important tool to obtain earth image data by measuring electromagnetic radiation reflected from surface and subsurface materials. Satellites with SAR sensors can cover much larger areas and are highly effective in damage surveys since SAR can be used regardless of sunlight and weather conditions.

Seasonal snow depth is one of the most important components in predicting water balance due to earth-system variability (Shi, 2008). Snow depth can dominate local and regional climate and hydrology. Snow Water Equivalence represents the total amount of water available if the snowpack were melted instantaneously. InSAR remote-sensing technique is a powerful tool that offers the ability to examine quantitatively the physical properties of snow in remote or otherwise inaccessible areas where obtaining measurements may be expensive and dangerous (Rango, 1989). InSAR remote-sensing practitioners have strived for many years to measure snow depth and SWE from satellite-based sensors but have had limited success (Nolin, 2011).

As opposed to optical sensors, active microwave sensors, especially Synthetic Aperture Radar (SAR), can be collected at nighttime and through cloud cover (Robinson et al., 1984). SAR observations provide high-resolution measurements that are comparable to the scale of topographical variation in mountainous areas, and these measurements are more suitable for monitoring snow cover than data from passive microwave instruments (Jiang et al., 2011; Storvold et al., 2006).

Snow depth estimation from SAR backscattering measurements requires very accurate inversion models and is a very complex process (Shi and Dozier, 2000). InSAR is the most notable application of spaceborne SAR for monitoring dynamic changes. It is achieved by using the repeat-pass pattern, in which two SAR images are acquired by the same antenna, and the area is revisited in a specific time interval. During past decades, spaceborne SAR interferometry has been successfully used to measure millimeter- to meter-level deformation on the surface due to earthquakes, landslides, glacier movements, and displacements on Earth's surface (Luzi, 2004), and the data has been used extensively to map snow cover, temporal snowpack conditions, and snow evolution, perform coherence analysis, and estimate snow depth and SWE (Kumar and Venkataraman, 2011).

4. SAR Processing Platform

The following SAR data processing platforms are described within this section: (1) Google Earth Engine (GEE), (2) SNAP (Sentinel Application Platform), and (3) ISCE/MintPy.

4.1 Google Earth Engine

Google introduced Google Earth Engine (GEE) to enhance the applications of satellite imagery for large scale applications in the 2010s. GEE is a web-based platform providing global-scale geospatial analysis with preprocessed Sentinel-1 backscatter images and the cloud computing infrastructure (Gorelick, et. al., 2017).

The GEE cloud-based platform provides new options for researchers interested in geospatial data analysis as providing machine learning algorithms and massive computational capabilities of remote sensing data on various societal issues including drought, water management, disaster, disease, and climate monitoring.
The advantage of the GEE cloud-based platform is its computational speed as utilizing Google's servers. The GEE platform provides constantly updated datasets and the datasets can be accessed within the code editor (https://code.earthengine.google.com).

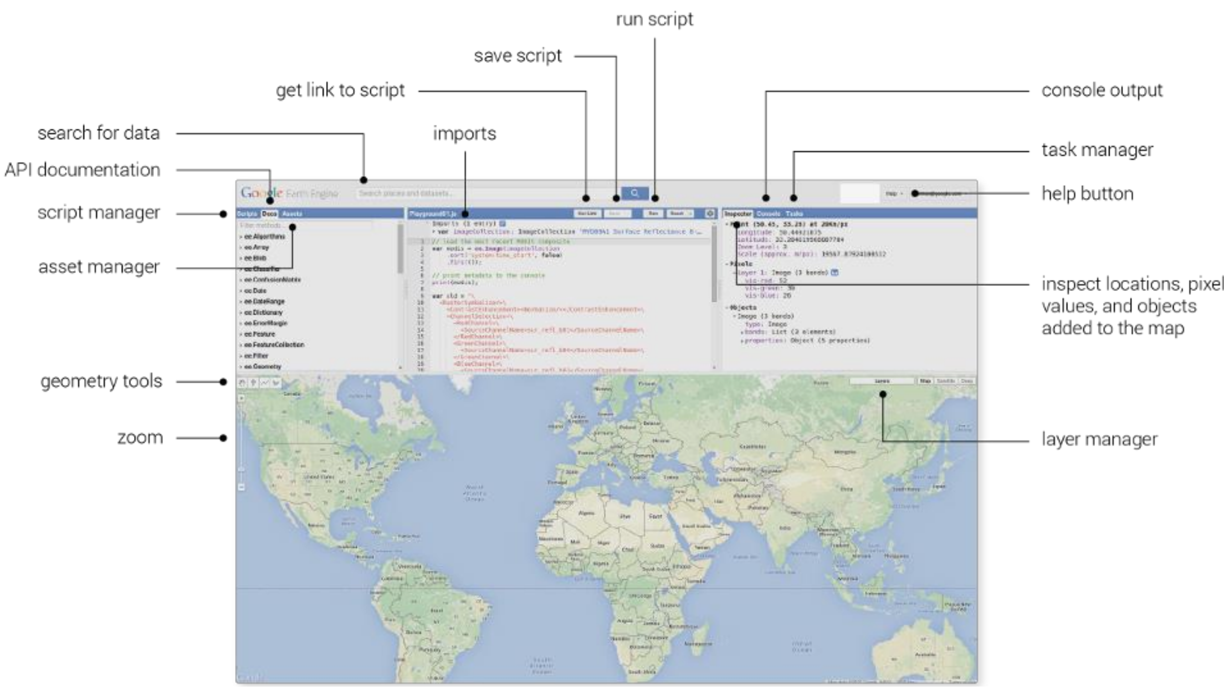

Figure 2. Earth Engine Code Editor with a web-based Integrated Development Environment (IDE) for the Earth Engine JavaScript Application Programming Interfaces (APIs).

The simplified procedure how to visualize different composites in Google Earth Engine is as follows.

Step 1. Preparation framework
The framework to prepare Sentinel-1 SAR backscatter Analysis Ready Data (ARD) is briefly described in Figure 15. The framework includes additional border noise correction, speckle filtering, and radiometric terrain normalization and can be applied to a Sentinel-1 GEE image collection. The additional preprocessing is optional and can be revised on application needs and specific requirements for the analysis. The framework is initiated in both the Python application programming interface (API) and GEE Java script (Mullissa et al. 2021).

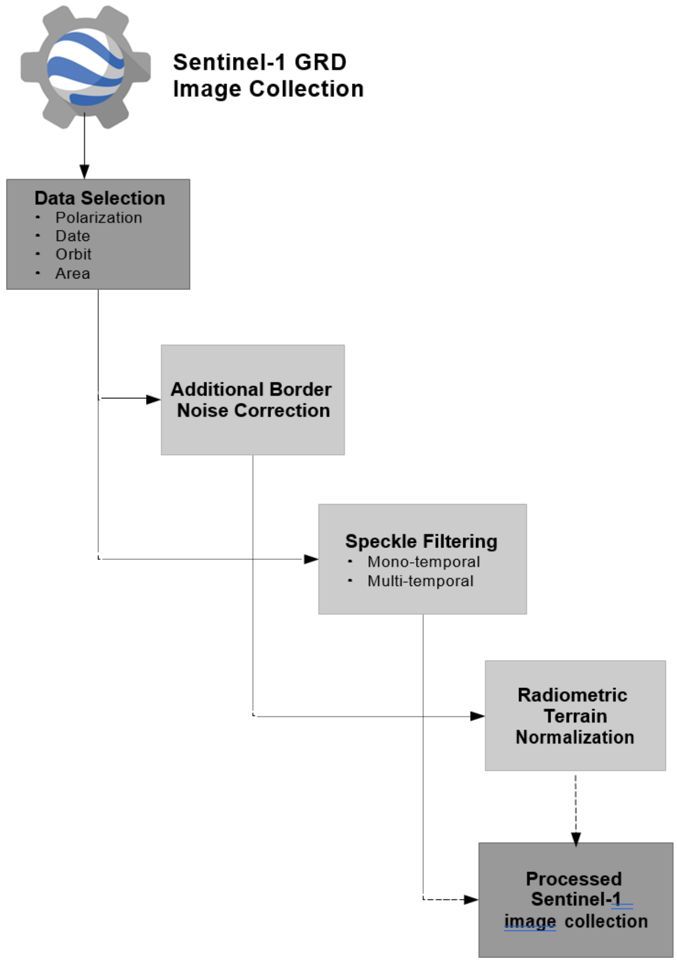

Figure 3. Preparation framework to create Sentinel-1 ARD in GEE. The dark and light grey boxes depict mandatory and optional preprocessing steps, respectively (Mullissa et al. 2021).

Step 2. Specify an area of interest and Sentinel-1 data selection

Selection of the location of the study area is necessary to specify the processing extent of the geospatial analysis and avoid redundant computations.

Sentinel-1 imagery data collection in GEE includes Sentinel-1 Ground Range Detected (GRD) scenes that are processed as using the Sentinel-1 Toolbox to generate a calibrated and ortho-corrected product.

The daily updated data collection includes all Sentinel 1-A and 1-B GRD image products acquired in both ascending and descending orbits in interferometric wideswath (IW) mode. The Sentinel-1 GRD images have a pixel spacing of 10 m at which the full information detail is guaranteed, and a spatial resolution

Sentinel-1 satellites provide temporally dense and high spatial resolution synthetic aperture radar (SAR) imagery and acquires images globally every 6 to 12 days. Sentinel-1 GRD data in the GEE catalogue can be collected as all the preprocessing steps require the data to be in linear scale. Sentinel-1 imagery in single polarization (i.e., VH or VV) or dual polarization mode (i.e., VV and VH) can be considered (Di Martino et.al., 2013).

Step 3. Time frame & sensor parameters selection

The user is required to setup time frame of pre- and post-event periods and Sentinel-1 imagery is acquired a minimum of every 12 days for each point globally. Sentinel-1 has different polarization options that "VV" means vertically polarized signal transmitted out and vertically polarized signal received, whereas VH refers to vertically polarized signal transmitted out, and horizontally polarized signal is received.

VV: single co-polarization, vertical transmit/vertical receive
HH: single co-polarization, horizontal transmit/horizontal receive
VV + VH: dual-band cross-polarization, vertical transmit/horizontal receive
HH + HV: dual-band cross-polarization, horizontal transmit/vertical receive

User also can select between 'VH' and 'VV' polarization to perform the analysis. 'VH' is widely used, since it is more sensitive to changes on the land surface, while 'VV' is rather susceptible to vertical structures and might be useful to delineate open water from land surface (e.g. a large water body).
User might choose between 'DESCENDING' and 'ASCENDING' pass direction, depending on the study area. It is necessary to select the same pass direction for the images being compared to avoid false positive signals caused by differences of the viewing angle when performing change detection.

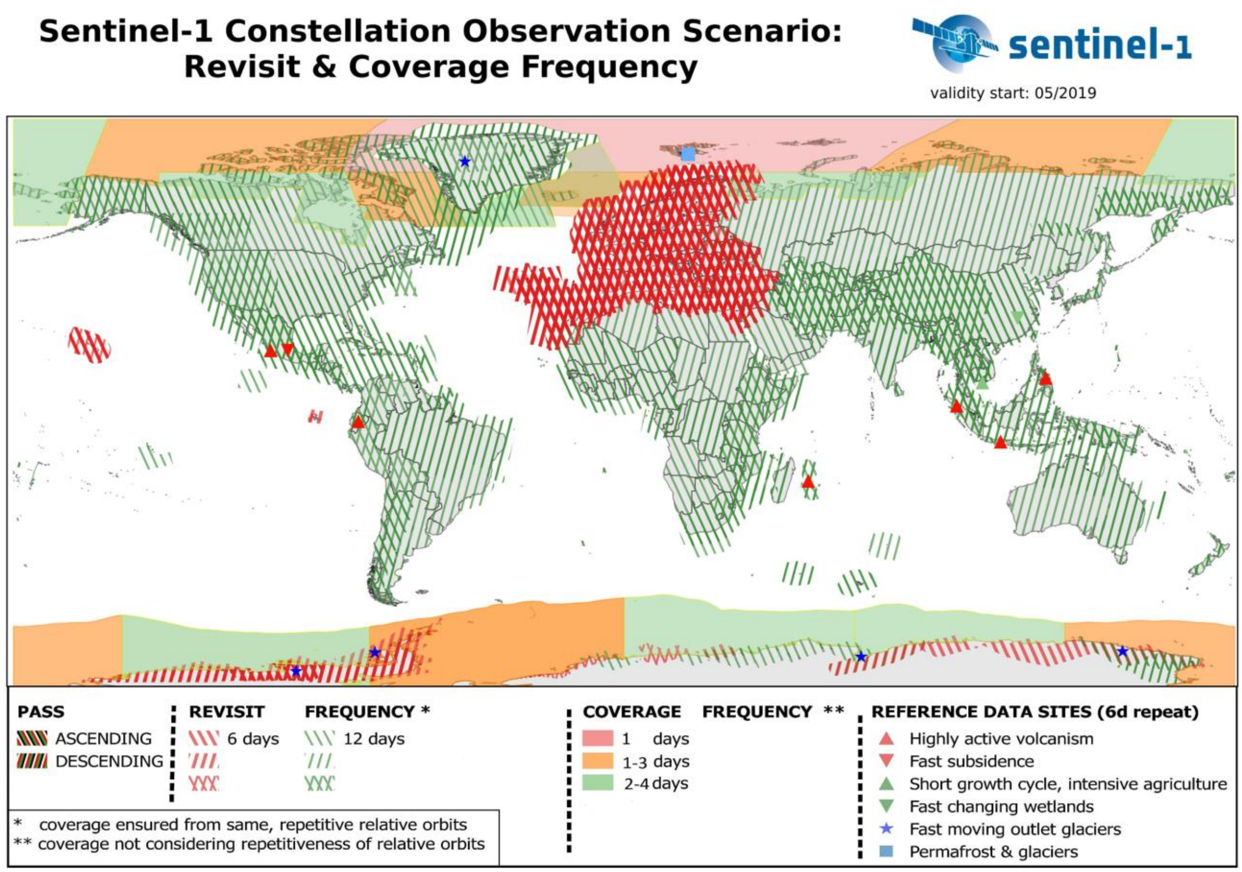

Figure 4. Revisit and coverage frequency of the Sentinel-1 constellation, showing which areas are mainly covered with descending or ascending imagery. Source: https://sentinel.esa.int/web/sentinel/missions/sentinel-1/observation-scenario

Entire Sentinel-1 GRD archive in Google Earth Engine is filtered by the instrument mode, the polarization, pass direction, and spatial resolution at the boundary of the area of interest.

Step 4. Preprocessing
Information from Sentinel-1 Level-1 Ground Range Detected (GRD) imagery in Google Earth Engine has already undergone the following preprocessing steps: (1) Apply-orbit-file (updates orbit metadata), (2) ARD border noise removal (removes low intensity noise and invalid data on the scene edges), (3) Thermal noise removal (removes additive noise in sub-swaths), (4) Radiometric calibration (computes backscatter intensity using sensor calibration parameters), (5) Terrain-correction (orthorectification), (6) Conversion of the backscatter coefficient ($\sigma°$) into decibels (dB).
Border noise artifacts were produced when transforming the raw data to level-1 products by the Sentinel-1 Instrument Processing Facility software (IPF). The presence of border noise in Sentinel-1 GRD products is one of the unwanted artifacts that should be removed before further analysis.

Speckle filtering is an important component of SAR image preprocessing as all SAR images are inherently affected by speckle. Users can evaluate the performance of speckle filters qualitatively by visually checking the speckle reduction in homogeneous regions and the preservation of subtle features, such as roads and point scatterers, in the filtered images or quantitatively using the equivalent number of looks (ENL) or coefficient of variation in homogeneous regions in the image.
Radiometric terrain normalization is important to mitigate the effect of topography on the SAR backscatter. Angular between the SAR image and the terrain geometry based radiometric terrain normalization implemented in GEE depends only on angles, from which a simplified relation between the image and terrain can be derived.
The implementation of speckle filters and radiometric terrain normalization in GEE gives the user options to use different parameters for preprocessing the Sentinel-1 images depending on the envisioned application and scale of processing.
The processing steps are performed automatically when running the Google Earth Engine script. It is useful to understand how the data is being processed, which datasets are used, and what limitations the analysis may have for each case.

Step 5. Visualize results in GEE and export products
When all parameters are selected, run the script and visualize results in GEE. The layers that the user is interested in can be checked or unchecked and a screenshot of the map can be taken as an overview. To export the generated products into a Google Drive account, click on 'Tasks' in the top-right corner of the code editor and hit 'RUN', and choose where to save the file.
The processed Sentinel-1 ARD image collection can be formatted to a linear power or dB scale. In the absence of radiometric terrain normalization, the data is processed in sigma naught (σ_0). To export the processed image collection, provided are the export-to-asset option so that every image in the collection can be exported to a GEE asset. To aid in visualization and interpretation, the output data format can be changed to a dB scale by the user.

4.2 Sentinel Application Platform (SNAP)

Sentinel Application Platform (SNAP) is a common architecture for all Sentinel Toolboxes, which is useful for earth observation processing and analysis. It is a software with incorporated utilities for interferogram generation and stacking.

Interferometric synthetic aperture radar (InSAR) processing exploits the phase signal difference between two complex radar SAR acquisitions/observations taken from slightly different sensor positions to extract information and analyze the shape and deformation of the earth's surface or objectives.

SAR is an active microwave imaging system obtained from active sensors to detect reflected responses from objectives irradiated by artificially generated energy sources.

The basic measurement from SAR signals includes amplitude and phase information of the complex image. The amplitude is the strength of the radar response of radio-frequency electromagnetic signal reflected from a target and the phase is the fraction of a single and multi-looked radar wavelength.

The Sentinel-1A and Sentinel-1B European radar imaging satellites launched on April 3, 2014 and April 25, 2016, respectively carries C-band SAR sensors, and delivers repeated many SAR acquisitions. InSAR technique, a remote sensing technique, using two or multiple SAR phase images performs time-series analysis to monitor ground deformation changes with many SAR acquisitions

The Sentinel-1 Toolbox (S1TBX) is being developed for European Space Agency (ESA) and called the Sentinel Application Platform (SNAP). The Sentinel-1 Toolbox (S1TBX) consists of (1) a collection of processing tools, (2) data product readers and writers and (3) a display and analysis application to support the large archive of data from European Space Agency (ESA) SAR missions. The Sentinel-1 Toolbox (S1TBX) includes various processing tools for calibration, speckle filtering, co-registration, orthorectification, mosaicking, data conversion, polarimetry and interferometry. The SNAP processing tools for earth observation and analysis could be run independently from the command-line as well as integrated within the graphical user interface. The common features of the SNAP tools include the followings: (1) very fast image display and navigation of giga-pixel images, (2) Graph Processing Framework (GPF) for creating user-defined processing chains, (3) advanced layer management allows adding and manipulation of new, (4) flexible band arithmetic using arbitrary mathematical expressions, (5) accurate reprojection and ortho-rectification to common map projections, (6) geo-coding and rectification using ground control points, (7) multi-threading and multi-core processor support, and (8) graph processing framework.

The steps for InSAR processing with a SNAP (Sentinel Application Platform) are as follows.

Step 1: Open raw data
Open raw data of the zipped Sentinel-1A or -1B Interferometric Wide (IW) Single Look Complex (SLC) or Ground Range Detected (GRD) products.

Step 2: View the products

Each Sentinel-1A or -1B product consists of metadata, vector data, tie-point grids, and bands. The bands contain the actual raster data, organized by polarization and sub-swaths of S1 IW products. The virtual intensity band is to assist in visualizing the complex data.

SAR images include the intensity of radar reflections from ground. The more reflection we have, the brighter the image. The intensity of radar reflections from ground is a measure of moisture and roughness in order to get soil moisture and roughness maps. A SAR image is very dark if we have low backscatter, and it is very bright if we have severe backscatter. Therefore, the brighter image indicates that something has changed on ground.

Step 3: Thermal noise removal (TNR) and apply orbit file

Sentinel Application Platform (SNAP) software provides a Thermal Noise Removal (TNR) module to remove thermal noise from the channel intensities of polarimetric Sentinel-1 data. To estimate the noise-free matrix, noise correction on the complex data is applied.

Apply precision orbit correction with Apply-Orbit-File (AOF). Orbit file data can be downloaded by S1TBX and include information about the accurate position of the satellite image during the acquisition of SAR data. The Precise Orbit Ephemerides (POE) orbit files cover approximately 28 hours and contain orbit state vectors at fixed time steps of 10-second intervals. The POE files are generated every day and delivered within 20 days after data acquisition.

Step 4: Perform Border Noise Remove (BNR) and radiometric correction

The Sentinel-1 Ground Range Detected (GRD) product generated by the Instrument Processing Facility of the European Space Agency (ESA) has noise artifacts at the image borders of both left and right sides of the satellite's cross track. The Sentinel-1 border noise removal is important to mitigate backscatter from Sentinel-1 SAR data for time-series analysis and control SAR data quality for the large-scale data processing.

Radiometric calibration or radiometric correction is to convert the raw digital image data recorded by satellite sensors into common physical scales based on known reflectance measurements taken on the ground's surface and avoid radiometric errors or distortions.

Step 5: Co-register the images

Image co-registration is conducted for the comparison of two or more images in a series to understand any change. For interferometric processing, multiple images must be co-registered into a stack. One image is selected as the reference or master and the other images are the slaves that all other images are aligned. The rationale of co-registration is to ensure that each ground target or image become aligned to the same range and azimuth pixel in both the master and the slave images.

Step 6: Multi-Temporal speckle filter

Radar image brightness is normally expressed in σ^o (sigma-nought) which is the radar backscatter per unit area. The unit of σ^o is $[m^2/m^2]$, expressed in decibel (dB). Radar backscatter amplitude is provided as two separate images for the Horizontal- Horizontal (HH) and Horizontal-Vertical (HV) polarizations.

In order to accurately interpret the content of a SAR image, the radar polarization is a parameter to affect the strength of the backscatter. Current spaceborne radar systems operate with linear polarization where the radar signals are transmitted and received at horizontal (H) and/or vertical (V) polarization.

In general, speckle filtering allows a clear increase in the Equivalent Number of Looks (ENL) according to the filtering spatial resolution through a progressive smoothing of the speckle. Speckle filtering allows to improve slope estimation at the pixel scale. However, it implies a degradation of the multi-look pixel size.

Step 7: Terrain correction

Terrain correction removes the effect of variations in the observations due to the topography near observation sites and corrects geometric distortions that lead to geolocation errors. Topographic phase contributions are typically removed using a known Digital Elevation Model (DEM) to emphasize phases related to deformation. S1TBX will automatically find and download the DEM segment required for correcting your interferogram of interest.

Step 8: Export Data

The final geocoded data can be exported from S1TBX in a variety of formats with GeoTIFF, KMZ and various specialty formats.

4.3 InSAR Scientific Computing Environment (ISCE)

For this research, the InSAR data processing was performed using the InSAR Scientific Computing Environment (ISCE) platform and MintPy time-series software was used for the InSAR time-series analysis in the project site to evaluate the feasibility and value of using the InSAR technique to increase the detection accuracy of snow depth and quantify seasonal snow-melt water resources.

MintPy is the Miami INsar Time-series software in Python. It is an open-source package for InSAR time series analysis. It reads the stack of interferograms (co-registered and unwrapped) in ISCE, ARIA, FRInGE, HyP3, GMTSAR, SNAP, GAMMA or ROI_PAC format, and produces three-dimensional (2D in space and 1D in time) ground surface displacement in line-of-sight (LOS) direction.

MintPy reads a stack of interferograms (unwrapped interferograms, coherence and connected components from SNAPHU if available) and the geometry files (DEM, lookup table, incidence angle, etc.). MintPy is modulized in Python with utilities classes and functions and well commented in the code level.

The InSAR Scientific Computing Environment (ISCE) is a framework designed for the purpose of processing Interferometric Synthetic Aperture Radar (InSAR) data. The framework aspects of ISCE have been designed as a general software development framework. The ISCE is an open source with a modular software framework capable of supporting the geophysical research, InSAR data processing, and data modeling communities.

Applications of SAR are various and one of the principal applications of the SAR technology is represented by the interferometric SAR (InSAR) technique. The InSAR technique depends on the measurement of the phase difference between two or more complex SAR images acquired from different orbital positions and times.

The phase of the SAR image is a function of the distance between the satellite and the ground. It is determined primarily by the distance between the satellite antenna and the ground targets. The phase of each SAR image pixel carries range information to a small fraction of the SAR wavelength. The amplitude corresponds to the degree of strength of the radar backscatter and the phase corresponds to the position on a map where the data come from.

The SAR data processing consists of five major steps although not always in the following order: (1) SAR data collection, (2) data pre-processing, (3) interferogram generation, (4) phase unwrapping, and (5) geocoding.

Step 1. SAR data collection
Historical multiple-year L-band and C-band satellite image data archived from the ALOS-1(L-band) and Sentinel-1A/B (C-band) can be searched, accessed, and collected from the Seamless SAR Archive (SSARA) Federated Data Search and Access link.
(https://web-services.unavco.org/brokered/ssara/gui)

Step 2. Data pre-processing
Orbit data are used to compute offset vectors at pixel level from Single Look Complex (SLC) images. The effects of orbit positions and earth curvature are removed. Because the satellite is in different orbit positions for the two acquisitions, the distance between satellite and ground will vary across the image.

The processed image is resampled to the master grid. Two images from the same track and frame will be separated in time and still shifted slightly. Cross-correlate subsets of the two images using amplitude correlation to estimate the shift between the images.

Co-registered stacks of single-look complex (SLC) data can be created to generate surface displacement time-series followed by further analysis of the phase and amplitude. The process of multi-looking is applied to reduce phase noises by the averaging of adjacent samples or low pass filtering of interferogram and to improve the SAR image quality by reducing the speckle.

Step 3. Interferogram generation
An interferogram is formed by multiplying one SLC image (master image) by the complex conjugate of the other SLC images (slave images). Interferometric products are computed to generate the complex interferogram and the coherence images. The interferometric phase can be corrected for the phase of a ground control reference point and coherence changes can be compared through time. Interferometric phase at each SAR image pixel, depends on the difference in the travel paths from the SAR sensor to the considered resolution cell during the acquisition of each image.

Step 4. Phase unwrapping
Unwrapping is the process of converting the cyclical phase signal from the interferogram into a smooth deformation signal. Several different algorithms exist for unwrapping. Original phase from the wrapped phase representation is reconstructed with a sophisticated phase unwrapping algorithm. The interferogram is filtered and unwrapped.

Step 5. Geocoding

Unwrapped phase is converted to a height and the pixel coordinates are georeferenced. Interferogram is registered to a Digital Elevation Model (DEM) with forward or backward mapping to apply a topographic correction. The processing data are converted from radar coordinates of range and azimuth to geographic coordinates for the final processing step. The generated products can be modified for contouring and layering with geographic information system (GIS) programs.

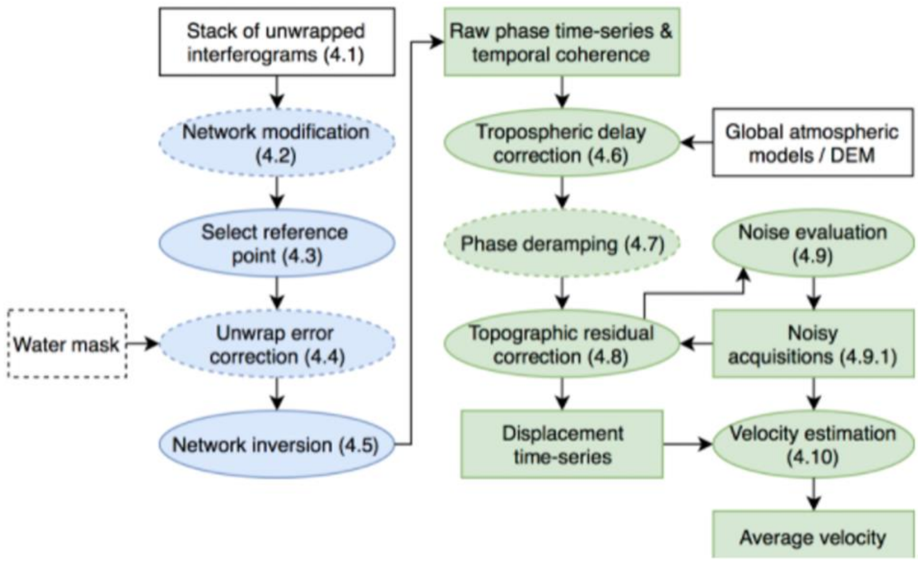

Figure 5. The routine processing workflow of InSAR time series analysis: (blue ovals) correcting unwrapping errors and inverting for the raw phase time-series and (green ovals) correcting for noise from different sources to obtain the displacement time-series (Yunjun et. al., 2019).

InSAR technique has solved various geodetic applications and ground deformation measurements. A new challenge is to monitor global surface deformation with high precision and large computing power. Figure 5 shows the routine processing workflow of InSAR time series analysis. The MintPy script takes a stack of co-registered and unwrapped interferograms and generates the displacement time-series. The workflow consists of two main blocks: correcting unwrapping errors and inverting for the raw phase time-series (blue ovals) and correcting for noise from different sources to obtain the displacement time-series (green ovals).

Figure 6 shows a flowchart of the Sentinel-1 processing with standard backscatter processing techniques, further processing steps, and application of the retrieval algorithm (Lievens et. al., 2019).

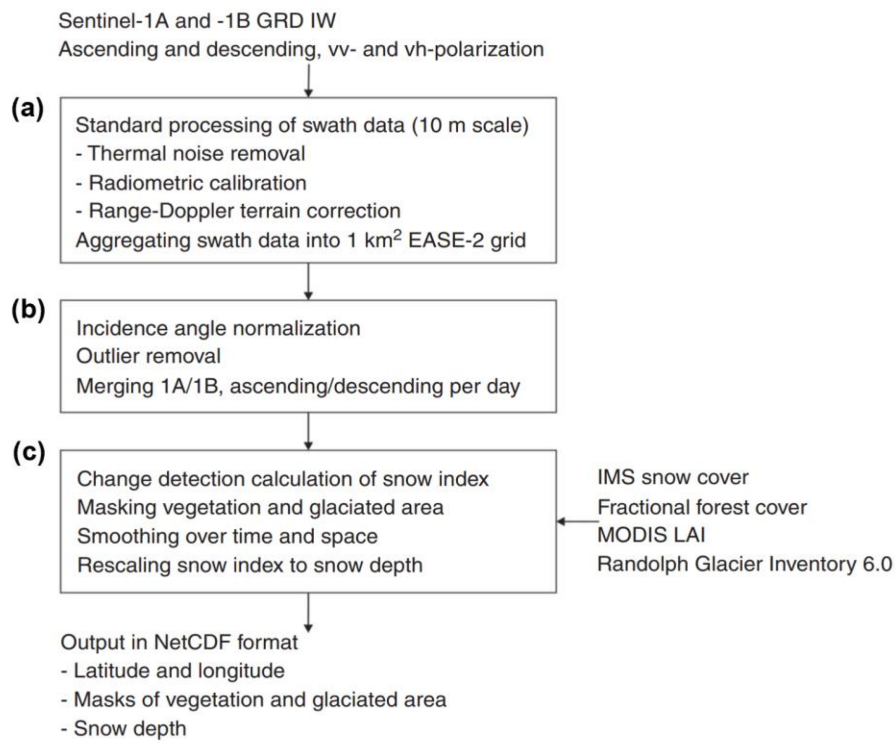

Figure 6. Flowchart of the Sentinel-1 processing. (a) The standard backscatter processing techniques are performed, (b) Further processing steps, and (c) the application of the retrieval algorithm are performed offline (Lievens et. al., 2019).

5. Snow Depth Validation Sources

The following validation data sources are described in this section: (1) NASA Airborne Snow Observatory (ASO) data of NASA Distributed Active Archive Center (DAAC) at National Snow & Ice Data Center (NSIDC), (2) Snow Telemetry (SNOTEL) and Snow Course Data and Products at Natural Resources Conservation Service (NRCS), (3) PBO H2O using GPS reflection data from National Science Foundation (NSF)'s Plate Boundary Observatory (PBO), and (4) Snow Data Assimilation System (SNODAS).

5.1 NASA Airborne Snow Observatory (ASO)

NASA Airborne Snow Observatory (ASO) program was performed in a collaboration with NASA's Jet Propulsion Laboratory, the California Department of Water Resources, and other state and local entities and supported by NASA’s Terrestrial Hydrology and Applied Sciences programs. ASO was a combined system between an airborne imaging spectrometer and scanning Light Detection and Ranging (LiDAR) developed for monitoring snow and water resources.

The Sentinel-1 snow depth estimation data can be validated using in-situ measurements of NASA ASO archive data. The NSIDC DAAC ASO data collection includes snow depth and snow water equivalent data sets, and LiDAR point cloud terrain models derived from airborne remote sensing efforts performed over the western United States. NASA ASO collected LiDAR data of snow melt in Colorado, California, Oregon, and Washington in late winter and late summer (2017 to 2019) to facilitate comparisons of snow-covered and snow-free conditions. The LiDAR observation measures snow depth relative to snow-free data sets and the LiDAR measurements are served as a basis for data sets in this NSIDC collection.

The primary objectives of ASO include: (1) quantifying snow water equivalent and snow albedo for entire mountain watersheds, (2) improving knowledge of snow properties and their spatial and temporal variability, (3) providing input data for future water-management models and systems

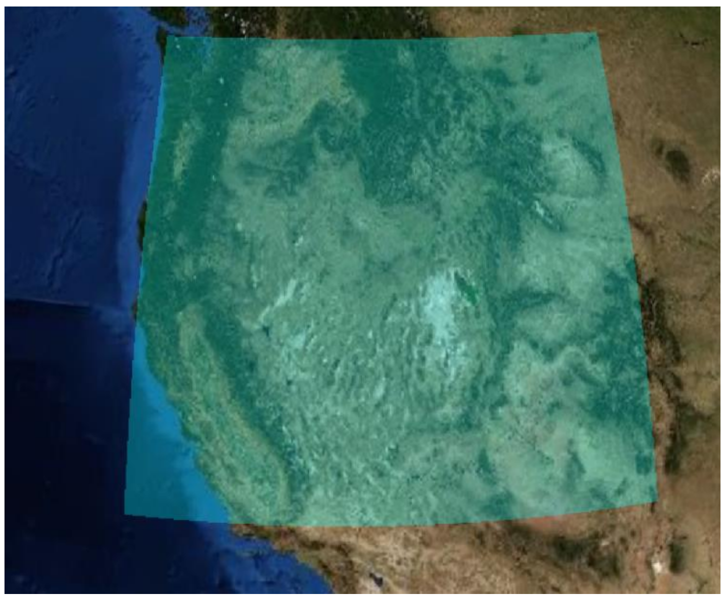

Figure 7. An example of snow-covered and snow-free conditions from AOS

This ASO data set provides 3 m gridded, bare ground elevations used as the baseline for the ASO snow outputs. The data are collected during snow-free conditions as part of the NASA/JPL ASO aircraft survey efforts.

5.2 Snow Telemetry (SNOTEL)

The Snow Telemetry (SNOTEL) program consists of over 900 automated and semi-automated data collection sites located in high-elevation mountains across the western U.S to monitor snowpack, precipitation, temperature, and other climatic conditions. The data collected at SNOTEL sites are transmitted to the Water and Climate Information System central database to make water supply forecasts.

A typical SNOTEL remote site consists of measuring sensors and devices, a shelter for the radio telemetry equipment, and an antenna that supports the solar panels to operate without maintenance for about a year. A typical sensor includes a snow pillow, a storage precipitation gage, and a temperature sensor. The snow pillow measures how much water is in the snowpack by weighing the snow with a pressure transducer. Automatic measuring devices in the shelter house convert the weight of the snow into an electrical reading of the snow water equivalent that is the actual amount of water in a given volume of snow.

SNOTEL stations collect data on daily maximums, minimums, and averages of snow depth, all-season precipitation accumulation, and air temperature. Many enhanced SNOTEL sites are equipped to take soil moisture and soil temperature measurements at various depths, as well as solar radiation, wind speed, and relative humidity. The data collected at SNOTEL sites are generally reported multiple times per day.

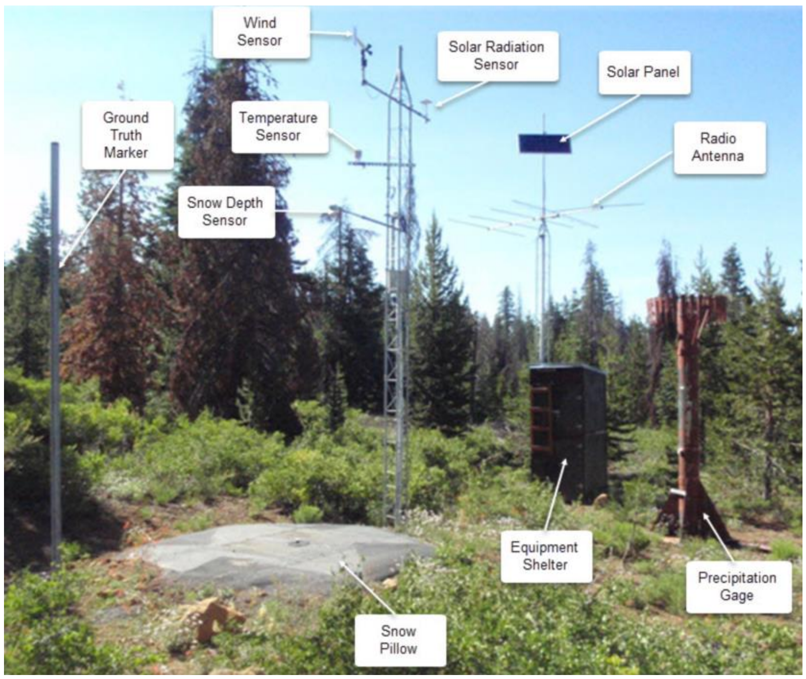

Figure 8. Typical SNOTEL automated data collection site. (https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms/automatedSnowMonitoring/)

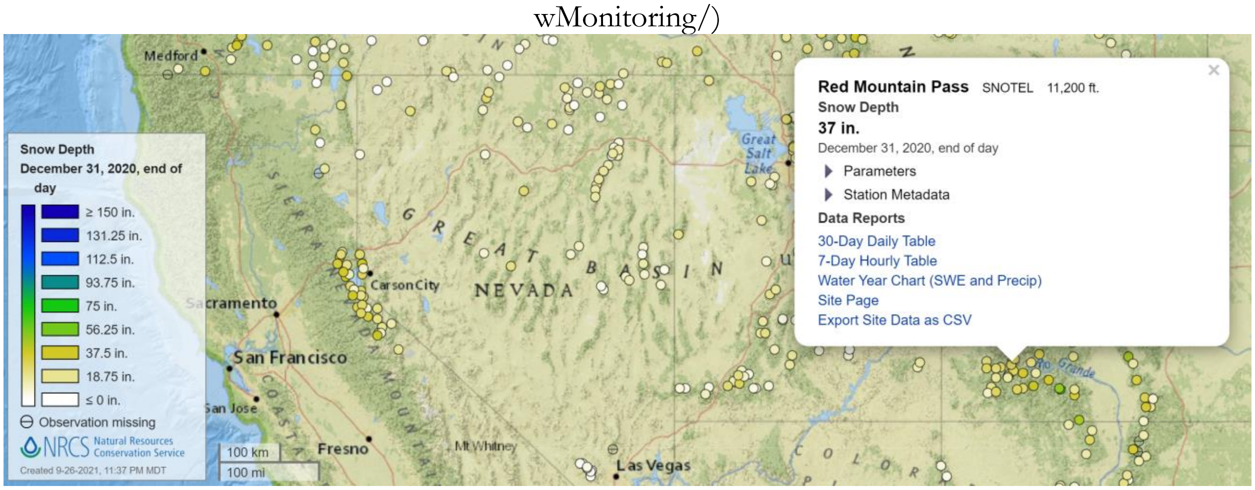

Figure 9. Historical snow depth collected at the Red Mountain Pass station from SNOTEL.

5.3 Plate Boundary Observatory (PBO) H_2O

PBO H_2O provides daily snow depths and SWE from GPS signal-to-noise ratio reflection data from National Science Foundation (NSF)'s Plate Boundary Observatory (PBO) to study the water cycle and is available from the NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC).

The datasets consist of daily snow depth and snow water equivalent (SWE) at 223 stations located primarily in the western United States including Alaska. Additional sites are in Hawaii, Indiana, Iowa, Kansas, Minnesota, Ohio, and Wisconsin, plus seven locations in Canada, one in Greenland, and one in Sweden.

Snow depth is determined by calculating the relative change of the effective multipath reflector height of the snow surface with respect to the snow free surface. SWEs are determined using GPS snow depths and, when available, density observations from nearby SNOpack TELemetry (SNOTEL) stations. When a nearby SNOTEL station is not available, density is estimated using GPS snow depth and climate classes, which account for variables such as location and time of the year.

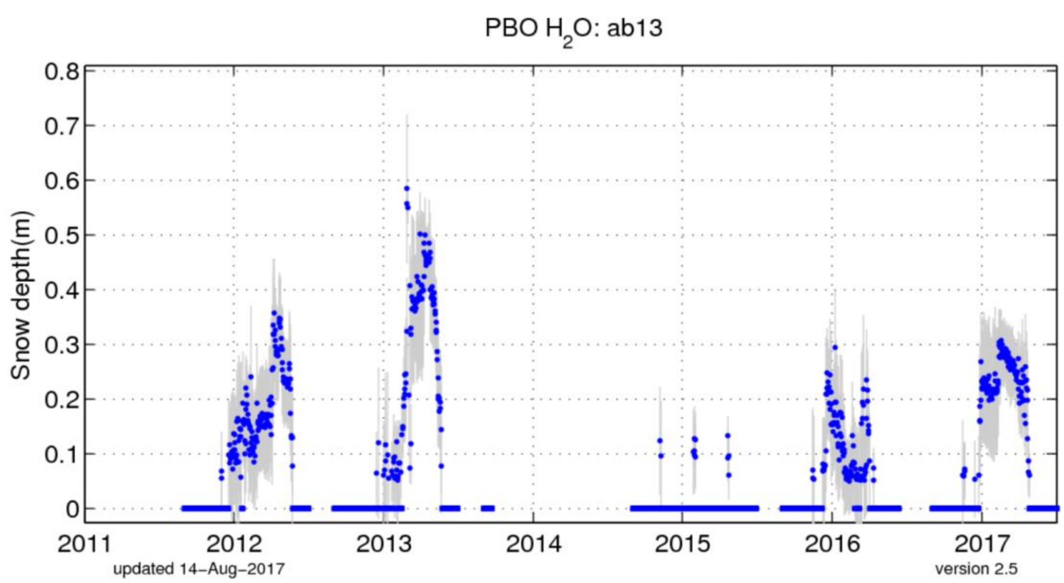

Figure 10. An example of snow depth output from PBO H_2O

5.4 Snow Data Assimilation System (SNODAS)

The Snow Data Assimilation System (SNODAS) has been developed by the National Operational Hydrologic Remote Sensing Center (NOHRSC) to provide reasonable estimates of snow cover and associated parameters to support hydrologic modeling and analysis (https://nsidc.org/data/G02158/versions/1).

SNODAS includes datasets of snowpack properties of snow depth and snow water equivalent (SWE) from the NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNODAS).

SNODAS has three components: (1) a data quality control and downscaling component for meteorological information from numerical weather prediction models, (2) a snow mass and energy balance model, and (3) data assimilation routines to update snow model estimates of snow pack parameters with satellite, airborne, and ground-based observations of snow covered area, snow depth and snow water equivalent. The snow mass and energy balance model is the core of the system.

The SNODAS system provides parameters of snow depth and snow water equivalent (SWE) measurements at 1km spatial resolution with a daily coverage from September 28, 2003 to present. The SNODAS is aimed to provide a physically consistent framework to integrate snow data from satellite and airborne platforms, and ground stations with model estimates of snow cover (Carroll et al. 2001).

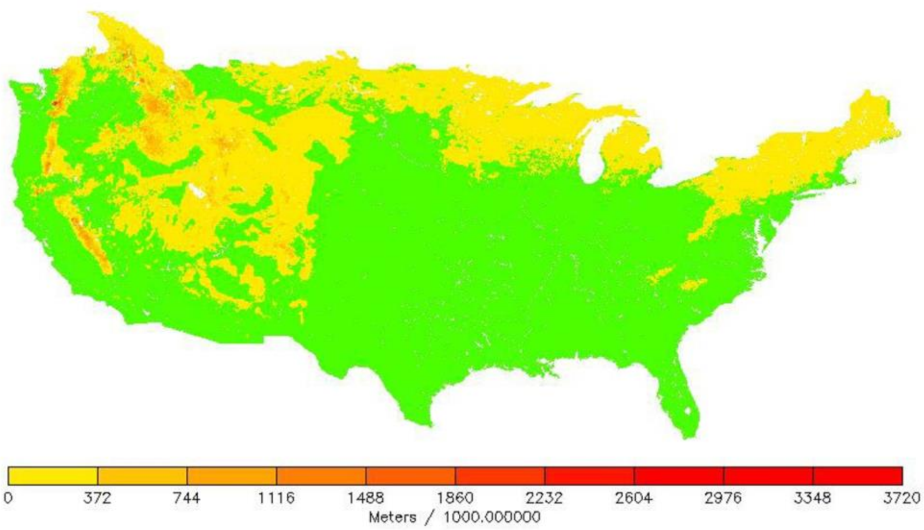

Figure 11. An example of snow water equivalent output from SNODAS

6. Results

The C-SNOW dataset for snow depth measurements of the mountains of Sierra Nevada between the Central Valley of California and the Great Basin and San Juan Mountains in the Rocky Mountains in southwestern Colorado and northwestern New Mexico was collected and evaluated. The Sentinel-1 snow depth retrievals are available online at https://ees.kuleuven.be/ project/c-snow.

Sentinel-1 GRD and SLC datasets from Sierra Nevada were downloaded to use newly acquired imagery appropriate for snow depth measurements to determine the computing resources necessary for extending the 2017-2019 snow depth time series from the C-SNOW dataset. We determined that the computing resources needed are largely dependent on the spatial resolution of the final data product, with more required at finer spatial resolutions.

6.1 C-SNOW Dataset

C-SNOW program is for observing snow mass in the Northern Hemisphere mountain ranges maintaining two major objectives: (1) to map snow mass in the Northern Hemisphere mountains using satellite observations from the C-band Sentinel-1 radar mission and (2) to improve understanding of radar interactions with snow by analyzing snowmobile-mounted radar measurements with local observations of snow properties.

Main C-SNOW consists of three steps: (1) Sentinel-1 observations, (2) field experiments, and (3) validation.

For the Sentinel-1 observations activity, the Sentinel-1 algorithm for estimating snow mass converts changes in Sentinel-1 radar measurements at C-band (5.4 GHz) into snow accumulation, depletion, or ablation over time. This results in weekly coverage and 1 km resolution observations of snow depth or snow density. Sentinel-1 algorithm developments are improved based on field experiments.

For the field experiments activity, field tower- and snowmobile-mounted radar measurements are collected at three sites in Idaho and Colorado, USA. The radar measurements are analyzed with snow properties of snow depth, snow mass, snow density, snow layering, and snow wetness to provide fundamental understandings on the interactions of radar measurements with snow.

For the validation activity, Snow depth and snow mass observations from Sentinel-1 are compared with validation data sets. The validation data sets include point-scale data of in-situ measurements, grid-scale data of regional and global model simulations, or aircraft observations. The validation is necessary to evaluate the accuracy of the Sentinel-1 snow estimates.

The C-SNOW system provides daily Sentinel-1 snow depth measurements at 1km temporal resolution from Sentinel-1 SAR imagery, with a weekly coverage for all northern hemisphere mountain ranges. The dataset utilizes dual-polarization Sentinel-1 SAR backscatter data, and the processing workflow for the C-SNOW dataset was evaluated.

6.2 C-SNOW and SNOTEL Comparison

The InSAR timeseries analysis at a few locations to evaluate snow depth in the mountains of Sierra Nevada and San Juan Mountains were performed. The results are compared with historical SNOTEL data and plotted along with the Sentinel-1 C-SNOW data to validate the Sentinel-1 snow depth retrievals using in situ measurements.

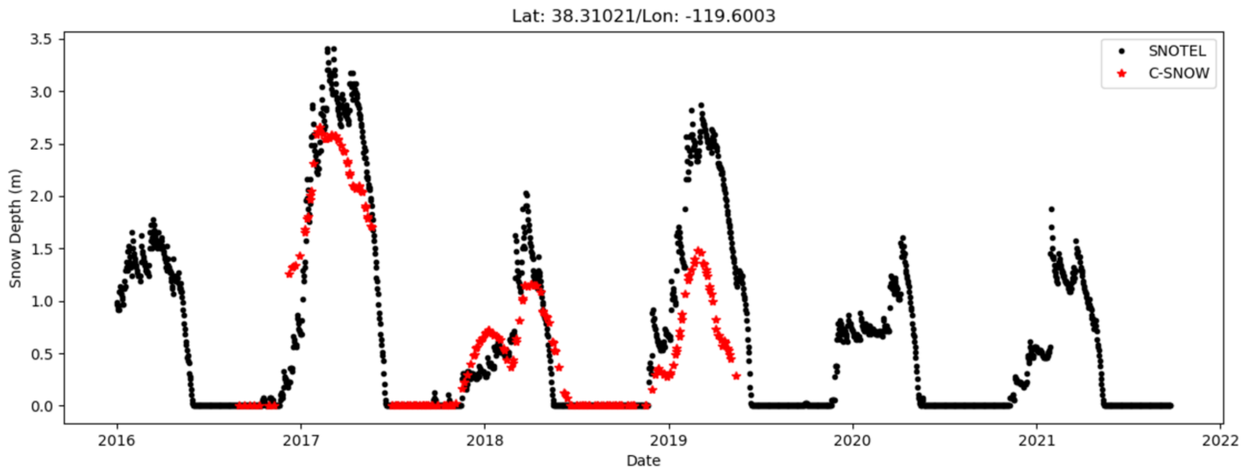

Figure 12. Time series of snow depth measurements and comparison between the Sentinel-1 C-SNOW snow depth retrievals and historical SNOTEL data at the Red Mountain Pass site in Colorado.

Figure 12 shows the comparison between the Sentinel-1 C-SNOW snow depth retrievals and historical snow depth data collected from SNOTEL over three consecutive winters in 2017, 2018, and 2019 at the Red Mountain Pass site in Colorado

The historical snow depth data collected from SNOTEL are downloaded from this link (https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=713).

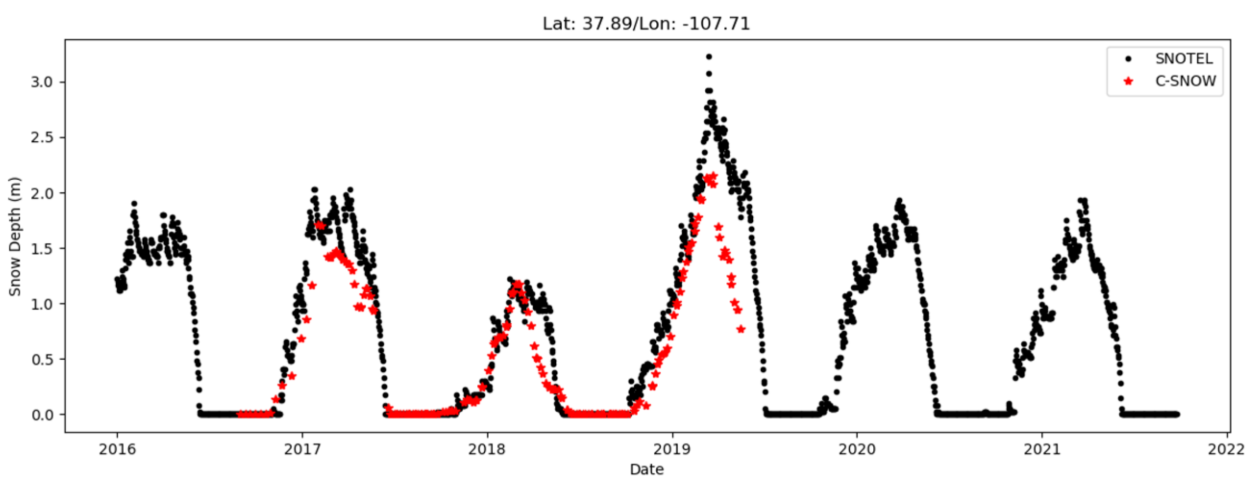

Figure 13. Time series of snow depth measurements and comparison between the Sentinel-1 C-SNOW snow depth retrievals and historical SNOTEL data at the Sonora Pass in California.

Figure 13 shows the comparison between the Sentinel-1 C-SNOW snow depth retrievals and historical snow depth data collected from SNOTEL over three consecutive winters in 2017, 2018, and 2019 at the Sonora Pass in California. The historical snow depth data collected from SNOTEL are downloaded from this link (https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=771).

The Sentinel-1 C-SNOW snow depth retrievals in Figures 12 and 13 match the accumulation of dry snow that occurs when the surface air temperature is below freezing, whereas some underestimation is observable during snow ablation from spring season. This underestimation is likely caused by wet snow conditions that occur when the air temperature near the surface is above freezing. The wet snow condition is partly reflecting and absorbing the radar signal.

7. Conclusions and Recommendations

About 1.5 billion people rely on snowmelt water resources. Snow depth estimation is a critical element for quantifying seasonal water resources at reservoir areas, expanding the use of the hydrologic database across Reclamation regions, assisting other water facility operational decisions for hydrological applications with real-time data, and informing recreational reservoir water users of reservoir water conditions. Therefore, enhanced and accurate evaluation techniques of snowpack in mountains is crucial for water management nationally and globally.

The Sentinel-1 C-SNOW snow depth retrievals indicate some underestimation, and it can be explained by wet snow conditions during snow melting season in spring. The wet snow condition reflecting and absorbing the radar signal need to classify for future analysis from historical snow depth data collected from SNOTEL and other validation data sources. The results indicate that InSAR technique could provide valuable information as an efficient solution of snow depth estimation and measurements of seasonal snowmelt water resources in reservoir areas.

The SAR data processing technique with the time-series analysis could provide an alternative snow depth estimation approach to the Reclamation water resources area offices and other agencies. Since SAR data and the time-series analysis results will be periodically collected, this information could provide valuable information to Reclamation in snowmelt water resources evaluation in the future. Seasonal snow depth estimation using SAR technique will provide enhanced quality of snow depths with historical and recent high-resolution SAR imagery data. This technique will quantify snow depth and density on a wide scale, with rapid real-time analysis, efficient cost savings, and without field measurements.

The snow depth estimation system using SAR could be used in any part of Reclamation's water delivery reliability, water supply and forecasting, water operations models, and planning. The applications have broad use and results could allow for a better quantification technique on Reclamation water resources and more accurate operation management. The alternative snow depth estimation approach using SAR technique will directly benefit the reservoir water operations as it could accurately quantify snow-melt water resources for the Reclamation water information system, including all water users upstream and downstream.

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