Technical Appendix: Snow Measurement Technology Summaries

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Manual Snow Measurements

About the Technology

There are a variety of manual snow measurements—snow courses, snow pits, and various citizen science efforts. Snow courses are the primary focus of this summary due to their legacy and use in operational snow monitoring programs.

Snow courses are locations where manual snow measurements are taken during the winter season to determine the depth and water content of the snowpack. Snow courses are permanent locations for long-term point specific periods of record and represent the snowpack conditions at a given elevation in a given area. Surveyor teams travel to a snow course which is a predetermined transect marked by signs on trees or steel posts. These transects are typically located on meadow or treeless areas.

Snow pits are similar to snow course but rather than extracting a sample of snow, a profile of the snow is exposed via digging a pit. Snow pits are not widely used in an operational sense and are more for studies and specific topics like dust on snow layers in snowpack.

Community Snow Observation (CSO) is a citizen science campaign to measure snow. The project aims to improve understanding of snow depth variability in mountainous regions by using community-based observers, including backcountry professionals and recreationists, to help gather snow observations. The measured snow depth data that are collected helps predict snow conditions and improve safety for mountain travelers

Temporal Resolution

Snow measurement data collected from snow courses is sampled several times each winter to observe changing conditions throughout the season and can be used in combination with other data available in a watershed. Snow courses may also contain snow pillows that transmit daily snow condition data. Data collected from snow pits and CSO

The surveyor team approaches a typical snow course marker. Photo courtesy of Natural Resources Conservation Service.

Snow data collected from snow courses for measuring snow depth and water content provide long-term periods of record for snowpack conditions.

Quantity Measured
Snow depth, SWE

Technology Readiness Level (TRL): 9

Availability
Operated in the Western United States.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

may be more sporadic but CSO project models snow distribution on a daily time step.

Spatial Resolution

Snow depth and snow water equivalent observations on snow courses are made at a fixed number of sample points along the transect, usually at a regular interval. Even at stations monitored automatically, data must be verified. An average snow course is 1,000 feet long. Most courses consist of about ten sample points to ensure sound statistical data. Two to six courses can be measured in a day—depending upon the severity of the weather and the remoteness of the location. CSO varies from year to year and are generally point measurements.

Verification Performance and Process

Verification is performed with available ground-based sensors or manual measurements. This may include snow pillows, snow courses, survey-specific manual measurement courses and snow pit, snow cameras (for weather verification purposes), and other ground-based observations.

Suitability

Snow courses technology has gradually improved with sophisticated new measuring devices, and an increasing number of snow stations being monitored automatically. Maintaining snow courses is a year-round job. Before the first snow of the season falls, special teams journey to the “snow country" to stock cabins with food and provisions for the winter months. Some of the cabins may be so remote that the only way to reach them is by horseback and pack animal.

Regional Performance/Strengths

Ground truthing data from snow courses are used to complement remote sensing data. Manual snow measurements via snow courses are the standard for calibrating and “ground-truthing” automated instrumentation and has the advantage that snow data can be obtained independent of most surface and weather conditions.

Suitability for Citizen Science

There is a limited role for citizen scientists for collection of ground-based observations to verify data products on ad-hoc snow courses.

CSO is a citizen science project that provides a platform for the larger community to upload snow depth measurements to smartphone apps that provide a time and location of the observation. These observations rely on backcountry recreationalists and education groups, which, unlike snow courses do not guarantee a consistent location is measured. CSO does provide more spatial coverage and possible access to challenging terrain, making these observations potentially useful for assimilating into high resolution snow models (Crumley et al. 2020).

Other Technologies

Snow data collected from snow courses provide valuable information, although typical schedules for snow data collection can result in weeks without information on snowpack conditions. Automated snow/weather stations, satellite products, and aircraft observations can provide additional complementary data.

Current and Future Planned Uses

Networks

California. The average depth of snow and water content data for each snow course are reported to the California Department of Water Resources (CA-DWR) Snow Survey office where the data are entered into CA-DWR's California Data Exchange Center (CDEC) database after being quality checked. The primary function of CDEC is to facilitate the collection, storage, and exchange of hydrologic and climate information to support real-time flood management and water supply needs in California. All of the snow courses within a watershed are in turn averaged to calculate a 'snow index' for each watershed. This index is used directly in the regression analysis for determining April through July runoff volume in acre-feet at the 15 major watershed forecast points. Preliminary runoff information is provided approximately one week after completion of the monthly snow surveys, and final results are provided in the monthly Bulletin 120.

Other Western States. The Natural Resources Conservation Service (NRCS) Snow Survey and Water Supply Forecast (SSWSF) Program's manual snow measurement network is composed of over 1,100 snow courses and aerial markers in the Western United States and Alaska. All the data collected at snow courses and aerial markers are entered into the Water and Climate Information System (WCIS) database and made available to its wide variety of users via an extensive internet delivery system.

Current and Future Use

California. California conducts snow data collection, relying on a wide variety of cooperating agencies to collect this information. CA-DWR is the coordinating agency of the statewide Cooperative Snow Survey Program (CCSS). CA-DWR currently lists 53 unique Federal, state, and county agencies that conduct snow surveys via snow courses and report the data to the state. Under the CCSS program, the various water agencies will take the snow measurements or reimburse the State or others who do. California is the only western state to perform this function on its own.

Other Western States. In the other Western States, NRCS collects snow data, and their program began in the mid-1930s. Both programs are similar and there is a high degree of cooperation between the two agencies. NRCS's SSWSF Program has grown into a network of more than 1,200 manually-measured snow courses and over 750 automated Snowpack Telemetry (SNOTEL) weather stations in 13 Western States, including Alaska. The SSWSF Program provides manual snow course data collected by NRCS conservation professionals, automated SNOTEL data, and modeled water supply/streamflow volume data as well as issues seasonal river flow volume (water supply) forecasts based on various snow and other data, using both data-driven and physics-based models, for over 600 locations in the Western United States.

Benefits

- Snow data collection using snow courses has been providing water managers and other interested parties good guidance on water supply for many years and have the longest climate records in many areas.
- The procedures used are designed to furnish reliable forecasts of runoff with minimal data from watersheds where winter access is difficult.
- Most snow courses contain snow pillows or other types of snow sensors, which can transmit daily data on snow conditions.
- Snow pits offer direct exposure to profile of snow and allows for ease of understanding snow/impurity layers.
- CSO uses the community working together to make more measurements than any one person or any scientific team.

Challenges

- Snow courses are manually tasking and can be costly.
- Snow courses are limited to terrains that are relatively flat and hazard-free.
- Snow courses are often conducted in remote locations and under the demanding conditions and safety and access must be considered.
- Snow pits are labor intensive, localized, and have limited network/data access.

Costs

Costs related to snow courses can be viewed as annual costs since snow data collection is for long-term point specific periods of record to represent the snowpack conditions at given elevations and areas. Annual costs take into account labor costs, travel, operation and maintenance of equipment, purchase of supplies to stock shelter cabins, and permitting needs for both equipment placement and ground disturbance coverage, since most snow courses are located in national parks or Federal forest lands. Average annual costs for snow courses can run between $10,000 - $20,000 per snow course, depending on the length and location and the type of equipment located in conjunction with the snow course.

References

Crumley, R.L., D.F. Hill, K. Wikstrom Jones, G.J. Wolken, A.A. Arendt, et al., 2020. Assimilation of citizen science data in snowpack modeling using a new snow dataset: Community Snow Observations. Hydrology and Earth System Sciences Discussions, 1-39.

The Resources Agency of California, 2018. Snow Survey Procedure Manual. Department of Water Resources, California Cooperative Snow Surveys. https://cawaterlibrary.net/wp-content/uploads/2017/12/SnowSurveyProcedureManualv20141027.pdf.

USDA, 2016. Manual Snowpack Measurement: Snow Courses and Aerial Markers. National Water and Climate Center and Natural Resources Conservation Service. https://www.wcc.nrcs.usda.gov/snotel/snowcourse_brochure.pdf.

Snow Tubes

About the Technology

Snow can be measured with an aluminum snow tube or sampler. The diameter of the snow tube has been designed so that one ounce of snow core is equivalent to one inch of water content. The snow tube is approximately 1.5 inches in diameter, with graduated markings on the outside. The sampler is threaded in sections of about 30 inches and can be shortened or lengthened by removing or adding sections as necessary to penetrate the entire snowpack.

A surveyor team uses a tube that is clear of all snow and soil before taking the snow core sample. The team uses a strong, light-weight, graduated aluminum tube and a weighing scale. One team member measures the snow depth while the other records data. Five to ten measurements are taken at regular time intervals along a snow course, usually on a monthly basis. In taking an accurate snow core sample, the team must verify that the tube has reached ground level by examining the base of the tube and finding soil. After clearing out the soil from the tube, the team determines the amount of water in the snowpack by weighing the tube with its snow core and subtracting the weight of the empty tube.

Temporal Resolution

Snow tubes are used to sample snowpack several times each winter to observe changing conditions throughout the season.

Spatial Resolution

Snow tubes measure a "core sample" which is assumed to represent that area on a snow course.

Verification Performance and Process

Verification is performed with available ground-based sensors.

A surveyor uses a snow tube at a sample point on a snow course to measure the snowpack depth and snow water equivalent. The remote location of this snow course requires the use of a helicopter.
Photo courtesy of Natural Resources Conservation Service.

Snow tubes are used with snow courses as an integral part in runoff forecasts.

Quantity Measured
Snow depth, SWE

Technology Readiness Level (TRL): 9

Availability
Widely used in the Western United States.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Ground truthing data from snow tubes is used to complement remote sensing data. Snow tube technology has gradually improved with sophisticated new measuring devices.

Regional Performance/Strengths

Manual snow measurements using snow tubes remains the standard for calibrating and "ground-truthing" automated instrumentation.

Suitability for Citizen Science

There is a limited role for citizen scientists for collecting ground-based observations to verify data products on ad-hoc snow courses.

Other Technologies

These ground measurements can be used in combination with and/or to verify remote sensing technologies such as those used on aircraft and satellite platforms and snow models.

Current and Future Planned Uses

Networks

Snow data collected from snow tubes provide valuable information; however, a typical schedule for manual surveys can results in weeks without information on snowpack conditions. Snow surveyors and water managers understand that timely forecasting and management decisions require more frequent measurements and additional information as well as a way to survey particularly remote and hazardous snowpacks. Manual surveys and the use of automated monitoring station data sensing can fill in data gaps.

Current and Future Use

The California Department of Water Resources' (CA-DWR) statewide Cooperative Snow Survey Program (CCSS) and the Natural Resources Conservation Service (NRCS) use snow tubes with snow courses.

Benefits

- Snow data from snow tubes have been providing water managers and other interested parties good guidance on water supply for many years, and these data are the longest climate records in many areas.
- Snow tube data are accurate with a well-trained crew.
- The procedures used are designed to furnish reliable forecasts of runoff with minimal data from watersheds.

Challenges

- Snow tubes are manually tasking and can be costly and may have poor time resolution.
- Measurements with snow tubes are often conducted in remote locations and under the demanding conditions of short days, steep terrain, high altitude, cold temperatures, towering winds, heavy precipitation, low visibility, and deep snow.

Costs

Snow tubes are relatively inexpensive (~$1,000). However, use of a snow tube not only includes cost for snow tube and related equipment, but also annual costs including survey team salaries, travel, supplies to stock shelter cabins, and equipment operation.

References

The Resources Agency of California, 2018. Snow Survey Procedure Manual. Department of Water Resources, California Cooperative Snow Surveys. https://cawaterlibrary.net/wp-content/uploads/2017/12/SnowSurveyProcedureManualv20141027.pdf.

USDA, Natural Resource Conservation Service. What is Snow Water Equivalent? (usda.gov).

Aerial Snow Markers

About the Technology

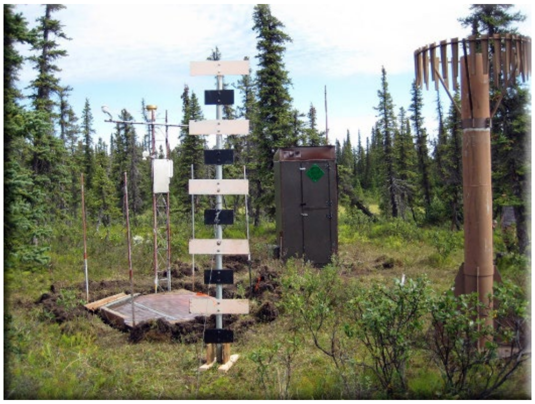
Aerial snow markers are tall vertical posts with horizontal cross-pieces at known intervals. These oversized rulers can be read from aircraft passing at a low altitude. Aerial snow markers were first used in the 1950s to complement snow courses. They would sometimes be co-located with existing snow courses or automated stations, but more often they would be located in areas that would be difficult to access by field personnel. Though not without risk, aircraft crews could either visually read or photograph several markers in a short period of time that were inaccessible or dangerous for ground personnel (Finnegan 1962, Miller 1962, and Natural Resources Conservation Service [NRCS] 2021). They might also be read and reported by passing recreational skiers or from a distance by ground personnel. Aerial snow markers expanded in use through the 1960s, especially in the Pacific states, then gradually fell out of use. The advent of unmanned aerial vehicles may renew the value of aerial snow markers, though little exploration has been undertaken (Gaffey and Bhardwaj 2020).

Temporal Resolution

Markers can be read at any time interval. Commonly, they were read at monthly intervals coinciding with manual snow courses.

Spatial Resolution

Aerial snow markers are a single-point measurement. They would typically be used to supplement snow courses, with one or more aerial snow markers being used within a typical watershed.



An aerial snow marker.
Photo courtesy of Natural Resources Conservation Service.

Aerial snow markers are a simple device to measure snow depth by passing aircraft, with fewer and fewer markers in use today. Yet, they may have utility in the future to supplement ground-based measurements, particularly if they can be reimagined with new technologies.

Quantity Measured

Snow depth

Technology Readiness Level (TRL): 9

Availability

Snow markers are inexpensive custom-built devices, with standard designs employed within a state or region, but differing between regions.

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Verification Performance and Process

When co-located with automated stations, aerial markers can be validated. The Central Sierra Snow Laboratory (CSSL) conducted a long-term study of their accuracy and utility (Miller 1962), though site-specific conditions will be important for determining their accuracy.

Suitability

Regional Performance/Strengths

Aerial snow markers can be used in any region.

Aerial snow markers are sporadically distributed in high mountain or remote areas, typically in Alaska, Washington, Oregon, Idaho, and California. Sites should have a safe approach and exist for aircraft, avoid turbulent zones, and have good lighting to see the marker with.

Suitability for Citizen Science

Aerial snow markers can be easily read by backcountry recreationalists or private pilots, but there is no formal reporting system for citizen scientists.

Other Technologies

Aerial snow markers can complement snow courses, particular at higher elevations that may not be safely accessible for ground personnel.

Current and Future Planned Uses

Networks

NRCS still maintains a few aerial snow markers as part of the Snow Survey and Water Supply Forecasting (SSWSF) Program; some state agencies still maintain a few markers in their respective programs.

Current and Future Use

Aerial snow markers have been removed or abandoned from many locations, though many markers that are co-located with snow courses or automated snow stations are still maintained. Markers based on non-visual sensing techniques (e.g., laser reflector) are possible but have not been explored.

Notable Use Cases

California built an extensive array of hundreds of aerial snow markers, typically at elevations above the snow courses where access is difficult.

NRCS still maintains some markers at sites outside of California.

Benefits

- The primary benefit of aerial snow markers is to capture snow depth data at high elevation or inaccessible sites to complement snow course information.
- Markers are inexpensive to construct and require modest maintenance.

Challenges

- Aerial snow markers are prone to drifting around the vertical support, and also prone to melting due to the marker material. Thus, the depth registered may be an over or underestimate of the surrounding area.
- In Wilderness Areas, markers require a review and permit as they create a visual intrusion, so they may not be suitable for some remote areas.
- Reading markers by aircraft requires substantial safety and cost considerations—similar to any aviation activity.

Costs

Costs for installation and maintenance are modest. The cost of reading the marker can be reasonable if multiple sites can be visited in a single flight; or if citizen scientists are used, the cost can be quite inexpensive.

References

Finnegan W.J. 1962. Snow Surveying with Aerial Photography. In Photogrammetric Engineering November 1962. Pp. 782-290.

Gaffey C. and A. Bhardwaj, 2020. Applications of Unmanned Aerial Vehicles in Cryosphere: Latest Advances and Prospects. In Remote Sensing, 12:948.

Miller R.W., 1962. Aerial Snow Depth Marker Configuration and Installation Considerations. In Western Snow Conference Proceedings.

NRCS, 2021. Snow Survey and Water Supply Forecasting (SSWSF) Program. https://www.nrcs.usda.gov/wps/portal/wcc/home/.

Snow Pillows

About the Technology

Snow pillows, also referred to as snow sensors, are devices that measure the weight of the water in the snowpack. Snow pillows are especially suitable for automated reporting stations such as Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) stations. A snow pillow generally consists of either one 10 to 12-foot diameter round or hexagonal bladder, or four flat 4-foot by 5-foot stainless steel tanks or rubber bladders, filled with anti-freeze and connected by manifold to a transducer (a device for converting fluid pressure into a proportional electric signal). The pressure created by water at rest provides information about how much water is present in the snowpack. Snow pillows are calibrated so that the equipment can measure the hydrostatic pressure as snow settles on the bladder and displaces the antifreeze.

Temporal Resolution

The electric signal from the pressure transducer connected to the snow pillow is stored in an electronic black box called a datalogger. Data are telemetered from remote sites via cellular modems and satellite radios. Most automated stations are be programmed to transmit hourly data, providing high temporal frequency (hourly) estimates of snow water equivalent (SWE). Snow pillow data are also very useful in assessing the melting snowpack to help determine the timing of snow melt runoff. This information can be crucial for reservoir operators in managing a potential flood due to melt from a heavy snowpack.

Snow pillow installation.
Photo courtesy of California Department of Water Resources.

Snow pillows provide information on the changes in overlying snow cover and an estimate of the snow water equivalent. Snow pillows are simple and inexpensive and allow for continuous unattended operation, but snow on the pillow must be maintained free of contact with its surroundings in order for mass changes to be accurately recorded.

Quantity Measured
SWE

Technology Readiness Level (TRL): 9

Availability
Several versions of this technology are commercially available.

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Spatial Resolution

The measurement area of a snow pillow varies by type of installation type (single vs multiple bladder), but generally represent an area of 80 to 256 square feet. They represent the general area where they are placed.

Verification Performance and Process

Verification is performed with available ground-based sensors or manual measurements. This may include snow courses, survey-specific manual measurement courses and snow pit, snow cameras (for weather verification purposes), and other ground-based observations.

Suitability

Ground truthing snow data from snow pillows is used to complement data collected from snow courses and snow tubes.

Regional Performance/Strengths

Manual snow measurements via snow courses are the standard for calibrating and "ground-truthing" automated instrumentation. Data from snow pillows can be obtained regardless of most surface and weather conditions.

Suitability for Citizen Science

There is a limited role for citizen scientists for collecting ground-based observations to verify data products on ad-hoc snow courses.

Other Technologies

Snow pillows are used in conjunction with snow courses and automated reporting stations.

Current and Future Planned Uses

Networks

The NRCS SNOTEL network and California Department of Water Resources (CA-DWR) California Cooperative Snow Survey Program (CCSS) are the primary two networks using snow pillows in the United States.

Current and Future Use

In addition to the SNOTEL and CCSS networks, snow pillows are used in some private, commercial, and research applications.

Benefits

- Snow pillows can be automated, and measurements can be transmitted by radio or satellite to a base station.
- Snow pillows can collect key information in remote areas that may be difficult or impossible to access in the winter months.
- Snow can be of varying density, and snow pillows can aid in determining the snow water equivalent in the snowpack.

Challenges

- Snow pillows require periodic maintenance to ensure the equipment is functioning as intended, which can be performed in the summer months when it is safe to enter remote areas.
- Snow pillow equipment can be compromised if tampered with from wildlife or vandalized through human activity
- The antifreeze solution in snow pillows can be hazardous to waters if equipment is ruptured or if leakage occurs.

Costs

The costs of snow data collection from snow pillows not only include snow pillow equipment costs (~ up to $10,000) but must also take into account installation, other equipment typically installed with snow pillows, and annual costs including salaries, travel, and operation and maintenance of equipment. As cooperative agencies can collect, verify, and maintain snow pillows within snow courses, costs may be shared among agencies.

References

The Resources Agency of California, 2018. Snow Survey Procedure Manual. Department of Water Resources, California Cooperative Snow Surveys. https://cawaterlibrary.net/wp-content/uploads/2017/12/SnowSurveyProcedureManualv20141027.pdf.

USDA, Natural Resource Conservation Service, 2021. What is Snow Water Equivalent? https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcseprd1314833.

Snow Depth Sensors

About the Technology

A snow depth sensor measures the depth of snow at a monitoring station. The sensor emits ultrasonic pulses and measures the travel time for the pulse to be reflected by the snow surface back to the sensor. Based on the travel time, the distance between the snow surface and the sensor can be determined. This information coupled with the height of the sensor above the ground surface provides snow depth.

Temporal Resolution

When installed at an automated monitoring station, these sensors can provide high temporal frequency (hourly) estimates of snow depth.

Spatial Resolution

Sensors are installed at point monitoring stations and data collected represent a relatively small area. Snow depth sensors are installed at most stations in major monitoring networks (e.g., Natural Resources Conservation Service [NRCS] Snowpack Telemetry [SNOTEL] stations). As such, data from snow depth sensors are available at over 1,000 locations across the West.

Verification Performance and Process

These sensors have been validated extensively and when properly installed are typically accurate within 1 centimeter of actual snow depth.

A snow depth sensor shown above a snow pillow.
Photo courtesy of Natural Resources Conservation Service.

Snow depth sensors are inexpensive sensors installed at most snow monitoring stations that provide accurate, automated measurements

Quantity Measured

Snow depth

Technology Readiness Level (TRL): 9

Availability

Several versions of this technology are commercially available.

Suitability

Regional Performance/Strengths

Performance is generally robust across a range of regions and environments. Performance can be impacted if the sensor is not installed perpendicular to the ground surface. Ice and snow build-up on the sensor can also impact performance. During snowfall, measurements can be affected by large

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snowflakes which can interfere with the ultrasonic signal and response off the snowpack. Shortly after snowfall, measurements can be impacted if recent snow is very low density which can affect the ultrasonic signal reflection off the snow surface. These issues are generally short-lived.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification

Other Technologies

A station using this technology would typically also have other instrumentation, which could include a snow pillow, meteorological sensors, and possibly a radiometer. Collectively these would provide a more complete characterization of the snowpack.

Current and Future Planned Uses

To date, this technology has been deployed extensively in operational and research snow monitoring applications. In particular, snow depth sensors are installed at NRCS SNOTEL and SNOw telemetry LITE (SNOLITE) stations, among other networks.

Benefits

- Low cost.
- Reliable and extensively used.
- Non-contact measurement.

Challenges

- Can be impacting if ice or snow accumulates around the sensor.
- Measurements can be impacted during and shortly after snowfall.

Costs

The costs of snow data collection from depth sensors not only includes the sensor costs (less than $1,000) but must also consider installation, other equipment typically installed at a station, and annual costs including salaries, travel, and operation and maintenance of equipment.

References

USDA. Idaho Snow Depth FAQs. Natural Resources Conservation Service Idaho Snow Survey. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/id/home/?cid=nrcs144p2_047777#q1.

USDA, 2016. Snow Telemetry (SNOTEL) Data Collection Network. National Water and Climate Center and Natural Resources Conservation Service. https://www.wcc.nrcs.usda.gov/snotel/snotel_brochure.pdf.

Fluidless Snow Pillows

About the Technology

A fluidless snow pillow (load cell) measures snow mass as an alternative to the traditional fluid-filled snow pillows coupled with a pressure transducer. They are typically a series of flat panels assembled on a rigid frame. Size and configuration can vary, but usually perimeter panels serve as a buffer to the center panel(s) where the measurement is made. This aims to reduce issues with bridging of snow— i.e., that the measurement under-represents the snow by virtue of its connectivity to adjacent snowpack.

Temporal Resolution

When installed at an automated monitoring station, these sensors can provide high temporal frequency (hourly) estimates of snow water equivalent (SWE).

Spatial Resolution

Sensors are installed at point monitoring stations and typically have a footprint that is roughly 100" x 100", although this can vary by design and manufacturer.

Verification Performance and Process

Verification is performed against traditional SWE measurement techniques (e.g., traditional snow pillows and manual SWE measurements).

Suitability

Regional Performance/Strengths

These provide an alternative to traditional snow pillows filled with anti-freeze. Especially in ecologically sensitive areas, avoiding the use of anti-freeze may be desirable. The

Natural Resources Conservation Service (NRCS) Oregon Snow Survey staff installing an experimental fluidless snow pillow.
Photo credit Allen Buckman/NRCS.

Fluidless snow pillows are a newer technology that offer an anti-freeze free alternative to traditional snow pillows for snow water equivalent measurement.

Quantity Measured
SWE

Technology Readiness Level (TRL): 8

Availability
Several versions of this technology are commercially available.

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technology requires limited site preparation but requires level ground for proper installation and function.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification

Other Technologies

A station using this technology would typically also have other instrumentation, which could include a laser snow depth sensor, meteorological sensors, and possibly a radiometer. Collectively these would provide a more complete characterization of the snowpack.

Current and Future Planned Uses

To date, deployment of this technology has largely been in testing and evaluation applications. Operational use tends to be outside of the United States. An assessment of this technology conducted by Smith et al. (2017) was carried out in at sites in Canada, Switzerland, and Finland.

Benefits

- Avoids the use of anti-freeze found in traditional snow pillows.
- Design uses several small panels installed together; panel size may have portability advantages over other available technologies.
- Requires limited site preparation if a level site is available.

Challenges

- Despite the multi-panel designs aimed at reducing snow bridging impacts on measurements, under-estimating SWE may still be an issue.
- Limited data on long-term durability and reliability are available.
- Cost is typically greater than for a traditional snow pillow.

Costs

The costs of snow data collection from load cells not only include load cell equipment costs (over $10,000) but must also consider installation; other equipment typically installed at a station; and annual costs including salaries, travel, and equipment operation and maintenance.

References

Smith, C. D., A. Kontu, R. Laffin, and J.W. Pomeroy, 2017. An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment, The Cryosphere, 11, 101–116, https://doi.org/10.5194/tc-11-101-2017.

In-Situ Gamma Radiation Sensors

About the Technology

Natural gamma radiation is emitted from potassium, uranium, and thorium radioisotopes in the upper soil layer, which can be measured by a sensor mounted above the ground. Water mass (regardless of phase) in the snow cover blocks a portion of these terrestrial radiation signals. The difference between radiation measurements made over bare ground and snow-covered ground can be used to estimate snow water equivalent (SWE).

Gamma radiation sensors are a non-contact technology for measuring snow water equivalent.

Quantity Measured
SWE

Technology Readiness Level (TRL): 8

Availability
Sensor is commercially available (e.g., Campbell Scientific 725).

Temporal Resolution

When installed at an automated monitoring station, these sensors can provide high temporal frequency (hourly) estimates of SWE.

Spatial Resolution

Sensors are installed at point monitoring stations and are generally able to characterize snow conditions of the surrounding 50 - 100 square meters (m).

Verification Performance and Process

Verification is performed against more standard SWE measurement technologies, such as snow pillows and manually SWE measurements. Performance is generally good although accuracy tends to be reduced as SWE increases. Once the majority of the radiation is blocked by the snowpack, differentiating between high and very high SWE levels can be challenging. Also, shallow soil moisture and presence of liquid water under the snowpack may result in artificially high SWE estimates; there is not a way to distinguish the water phase (solid/liquid) responsible for blocking the radiation.

Suitability

Regional Performance/Strengths

This sensor is relatively small compared to equipment associated with traditional SWE monitoring technologies (e.g., snow pillows). Consequently, it may be more suitable for remote areas where logistics of transporting equipment can be a factor. Proper siting is important. Generally, an open area clear of significant vegetation or structures for 50 m is needed, to not have other sources of radiation conflate measurements. If a fully suitable site is not available, additional equipment can be deployed to mitigate the influence of other radiation sources.

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Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

The basis for this technology was established decades ago. The National Oceanic and Atmospheric Administration (NOAA) has used the concept via aircraft to conduct SWE assessments along flight lines since the 1980s.

Current and Future Planned Uses

Current and Future Use

To date, deployment of this technology has largely been in testing and evaluation applications. Operational use tends to be mainly in Canada; the technology was developed by Hydro-Quebec as "GMON" (gamma monitoring) and is commercially produced by their partner, Campbell Scientific.

Benefits

- The sensor providies non-contact SWE measurements and involves limited site distrubance for installation.
- The size of the sensor is relatively compact, as compared to other technologies.
- The technology avoids the use of anti-freeze.

Challenges

- Sensor accuracy is reduced with higher SWE values.
- Sensor requires calibration, which may not be trivial.
- SWE estimates can be impacted by other radiation sources.
- The presence of liquid water or soil moisture can result in artificially high SWE estimate.
- Sensor is one of the more expensive options for *in-situ* SWE monitoring.

Costs

The costs of snow data collection from gamma radiation sensors include equipment costs (over $15,000) but must also consider installation; other equipment typically installed at a station; and annual costs including salaries, travel, and equipment operation and maintenance.

References

Campbell Scientific. CS725 Snow Water Equivalent Sensor. www.campbellsci.com/cs725.

Hydro-Quebec, 2009. GMON Automatic Snowpack Sensor. http://www.hydroquebec.com/innovation/en/pdf/2008G227-01A-GMON.pdf

Smith, C. D., A. Kontu, R. Laffin, and J.W. Pomeroy, 2017. An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment, The Cryosphere, 11, 101–116, https://doi.org/10.5194/tc-11-101-2017.

Ground Penetrating Radar

About the Technology

Ground Penetrating Radar (GPR) uses the two-way travel time of electromagnetic waves in the microwave band to identify boundaries in the subsurface and can be used to measure snowpack. The technique requires transmitting and receiving antennas that have been pulled behind skiers or snowmobilers or flown from a helicopter.

Antenna placement and configuration determines the accuracy of the measurement. The two-way travel time depends on the distance (or in this case snow depth) and velocity of the waves. In a dry snowpack, velocity is related to density; however, this relationship is complicated by liquid water in the snow. Snow depth is converted to snow water equivalent (SWE) using an appropriate density estimate, either directly from GPR (as in Holbrook et al. 2016) or other observational or modeling estimates.

Temporal Resolution

This technology captures data at a point in time, when pulled behind a vehicle. Another configuration used in avalanche studies is upward looking units installed prior to the season for continuous monitoring at a single location (e.g., Schmid et al. 2017).

Spatial Resolution

The spatial resolution is continuous along linear transects, spacing varies but is on the order of 2.5 centimeters (cm) (Holbrook et al. 2016).

Verification Performance and Process

GPR estimates are verified through comparison to snow pits and probed depth measurements. The GPR system configuration effects the accuracy of the measurements, with a 6 percent difference between manual SWE

The snowmobile-mounted ground penetrating radar system in use. (Holbrook et al. 2016, Creative Commons CC BY-NC-ND 4.0).

GPR provides an intermediate-scale, high-accuracy estimate of snow water equivalent and snow depth that is best used in dry snow.

Quantity Measured
Snow depth, snow density, SWE

Technology Readiness Level (TRL): 8

Availability
Demonstrations used MALA GPR equipment. These units are available to purchase or rent.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

measurements when the unit is mounted at the snow surface and a 3-21 percent difference when mounted on a snowmobile above the surface (Clair and Holbrook 2017). For snow depth, manual measurements were highly correlated to GPR measurements (correlation [r] = 0.89, $p < 0.0001$, root mean square error [RMSE] = 18 cm), although the median difference was minus 10 cm, which could also be related to error in the probe measurements (McGrath et al. 2019). GPR measurements were also well-correlated with remotely sensed measurements and had a median difference of -1 cm from Airborne Snow Observatory (ASO) lidar-derived snow depths and -3 cm from preliminary DigitalGlobe WorldView-3 satellite-derived snow depths (McGrath et al. 2019).

Suitability

Regional Performance/Strengths

GPR derived snow estimates work best in small areas of dry snow with access by skier or snowmobile, but helicopters can be used for harder-to-access areas.

Suitability for Citizen Science

Slow snowmobile speeds and heavy equipment limit collection by citizen scientists.

Other Technologies

GPR has been used as a validation dataset for airborne or satellite-based remote sensing products due to its accuracy and intermediate scale which can connect points estimates to gridded products.

Current and Future Planned Uses

This technology was used at SnowEx 2017 in Grand Mesa, Colorado (McGrath et al. 2019) as a verification dataset for snow depth and in the Medicine Bow Mountains of southeast Wyoming to demonstrate the ability to derive SWE from GPR measurements (Clair and Holbrook 2017). Known future usage is limited to research and testing applications.

Benefits

This approach has several benefits, including:

- High spatial resolution.
- Intermediate spatial coverage may be beneficial for specific local applications.
- GPR units have other uses, like subsurface imaging, that make them easy to obtain with a broad existing user group, even with Reclamation.

Challenges

This approach has some challenges as well, including:

- Limited spatial and temporal coverage for basin-scale water supply forecasting.

- Accessibility may be a challenge.
- 'Wet' snow adds additional complexity and introduces error in depth and SWE estimates.

Costs

Data Acquisition. Costs related to data acquisition include procurement of a GPR unit and snowmobile and crew time and travel for data collection and processing. GPR rental is on the order of $1,000/week; however, Reclamation and likely other agencies own this equipment as GPR is used in other types of analysis as well. Snowmobile rental is estimated to cost $500/day.

Data Storage. Data storage requirements could be considerable and would represent the only copy of the collected data. Data would not be able to be reproduced if the data are lost.

Data Processing. Data processing can be done on a desktop computer; however, dedicated hardware is recommended.

References

Clair, J.S. and W.S. Holbrook, 2017. Measuring snow water equivalent from common-offset GPR records through migration velocity analysis. The Cryosphere, 11(6), 2997-3009.

Holbrook, W.S., S.N. Miller, and M.A. Provart, 2016. Estimating snow water equivalent over long mountain transects using snowmobile-mounted ground-penetrating radar. Geophysics, 81(1), WA183-WA193. https://library.seg.org/doi/10.1190/geo2015-0121.1.

McGrath, D., R. Webb, D. Shean, R. Bonnell, H.P. Marshall, T.H. Painter, et al. 2019. Spatially extensive ground-penetrating radar snow depth observations during NASA's 2017 SnowEx campaign: Comparison with *in situ*, airborne, and satellite observations. Water Resources Research, 55(11), 10026-10036.

Schmid, L., A. Heilig, C. Mitterer, J. Schweizer, H. Maurer, R. Okorn, and O. Eisen, 2014. Continuous snowpack monitoring using upward-looking ground-penetrating radar technology. Journal of Glaciology, 60(221), 509-525.

Terrestrial Laser Scanning

About the Technology

Terrestrial Laser Scanning (TLS), also called ground based lidar, is a geodetic imaging technology that is positioned at the ground surface and measures the surrounding ground surface elevation. TLS uses similar technology to Airborne Laser Scans (ALS) from Airborne Snow Observatory (ASO) Inc. but with measurements taken from the ground. To calculate snow depth, a scan without snow must be taken first to provide a baseline ground surface map. This map is used to calculate the snow depth once a scan is taken with snow.

Temporal Resolution

TLS requires a person to move the instrument to the place they want to measure and take a scan that measures the ground surface at an instance in time. TLS could be permanently installed in a location and thus could be set up to run, but this has not been widely tested in snow science and would likely require frequent maintenance.

Spatial Resolution

TLS is extremely precise and can measure at a sub-centimeter resolution. The instruments usually measure a radius of 150 meters to 2 kilometers, though newer versions can measure farther. This distance is limited by line-of-sight and the angle of the terrain. If the instrument was placed on a flat surface, the incident angle would be too low for accurate measurements at longer distances, but if the instrument was measuring a slope farther away (e.g., across a valley) the measurement would be accurate.

Verification Performance and Process

SnowEX campaigns have used the TLS system to measure snow processes at field sites in the United States. At a field campaign in

Terrestrial Laser Scanning system being set-up, Grand Mesa SnowEX.
Photo courtesy of U.S. Army Corps of Engineers.

TLS is a ground based lidar that makes very precise measurements of the ground surface elevation. TLS is extremely precise, portable, and easy to operate. Due to its accuracy, TLS has been used to understand fine-scale snow processes such as wind drift snow and scouring.

Quantity Measured

Snow depth, snow cover

Technology Readiness Level (TRL): 8

Availability

Several versions of this technology are commercially available.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Grand Mesa, Colorado, TLS was compared to ALS, and TLS measurements corresponded well with ALS measurements and other manual measurements.

Suitability

Regional Performance/Strengths

TLS works best in regions that have sloping topography where the instrument can see far away. Flatter areas or complex topography may be more difficult for the instrument and would limit its area of measure.

Suitability for Citizen Science

Not suitable.

Other Technologies

TLS is similar to other lidar technologies (e.g., aircraft lidar) and could be used in the same way as these other technologies. Measurements could be used to validate models or observations made with other instruments.

Current and Future Planned Uses

Current and Future Use

TLS has been used for many geo-physical applications but has not been widely used in snow science.

Since TLS is so accurate, current use has been focused small studies researching fine-scale snow variability (i.e., snow drifting, preferential deposition, grain size) as well as large scale dynamics (i.e., avalanches). Examples of current snow studies using TLS include:

- SnowEx is a National Aeronautics and Space Administration (NASA) funded program to address gaps in remote sensing of snow through airborne campaigns and field work at various study sites. TLS has been used at various field sites throughout the campaign to explore its potential use and compare its measurements with other technologies (e.g., Currier et al. 2019).
- TLS has been used to measure fine scale variability due to snow drifting, preferential deposition, or variable radiation (Grunewald et al. 2010 and Schirmer et al. 2011).
- TLS was used to assist with avalanche control forecasting at Arapahoe Basin, Colorado (Deems et al. 2015).
- A continuously deployed TLS system is located at Mammoth Mountain, California. This site has been used in various studies to measure the snow variability and correct albedo measurements (Blair el al. 2012 and Hartzell et al. 2015). This location is near a gondola and can be maintained regularly.

Future use of TLS continues to be in the research realm, as small studies are being conducted to explore its potential utility.

Benefits

- The TLS instrument is portable, easy to operate, and has been used in a wide range of applications.
- TLS is highly precise with comparable accuracy to manual snow depth measurements.
- TLS is cheaper than ALS since ALS requires a plane to fly that is mounted with this technology. ALS flights are much more expensive, though the flights can cover a larger area than TLS measurements.

Challenges

- TLS requires a ground control point for the best accuracy which needs to be setup relatively far away from the measurement location (Currier et al. 2019).
- TLS also has a difficult time measuring snow depth in low vegetation and at an oblique angle and therefore needs to be setup in a location way from shrubs with an adequate incident angle (Currier et al. 2019).
- During a TLS scan, snow can compact causing errors in measurement. For example, the snow can sink during a reading which would cause errors in the ground surface depth being measured.
- Due to the limited range of TLS instruments, the equipment needs to be manually moved. Thus, it can be time consuming to measure over large areas.
- TLS measurements are data intensive as the measurements have such a high resolution.

Costs

Data Acquisition. TLS instruments are quite expensive, ranging from $100,000 to $300,000. Added costs include staff to set up and maintain the instrument. There would also need to be an initial field visit without snow present to provide a baseline to measure snow depth from.

Data Storage. As TLS is data intensive, storage costs will need to be considered.

Data Processing. Staff costs would be needed to ensure data were suitable for the models used.

References

Bair, E.H., R.E. Davis, D.C. Finnegan, A.L. LeWinter, E. Guttmann, et al. 2014. Can we estimate precipitation rate during snowfall using a scanning terrestrial LiDAR? In Proceedings of the 2012 International Snow Science Workshop, Banff, Alberta, 923-929.

Currier, W.R., J. Pflug, G. Mazzotti, T. Jonas, J.S. Deems, et al., 2019. Comparing Aerial Lidar Observations with Terrestrial Lidar and Snow-Probe Transects from NASA's 2017 SnowEx Campaign Water Resources Research, 55(7). Doi:10.1029/2018WR024533.

Deems, J.S., P.J. Gadomski, D. Vellone, R. Evanczyk, A.L. LeWinter, et al., 2015. Mapping starting zone snow depth with a ground-based lidar to assist avalanche control and forecasting. Cold Regions Science and Technology, 120, 197–204. https://doi.org/10.1016/j.coldregions.2015.09.0.

Grünewald, T., M. Schirmer, R. Mott, and M. Lehning, 2010. Spatial and temporal variability of snow depth and ablation rates in a small mountain catchment. Cryosphere, 4(2), 215–225. https://doi.org/10.5194/tc-4-215-2010.

Hartzell, P., P. Gadomski, C. Glennie, D. Finnegan, and J. Deems, 2015. Rigorous error propagation for terrestrial laser scanning with application to snow volume uncertainty. Journal of Glaciology, 61(230), 1147-1158. doi:10.3189/2015JoG15J031.

Schirmer, M., V. Wirz, A. Clifton, and M. Lehning, 2011. Persistence in intra-annual snow depth distribution: 1. Measurements and topographic control. Water Resources Research, 47, W09516. https://doi.org/10.1029/2010WR009426.

Solar Radiation Sensors

A pyranometer setup near a snowy field (Matsui et al. 2012; used by permission).

About the Technology

Solar radiation sensors measure the energy in the form of incoming and outgoing short-wave and long-wave radiation from sky reaching the Earth's surface. Solar radiation sensors can be used to measure the effects of solar radiation on the snowpack, which is useful for physical snow modeling. A few different types of sensors measure solar radiation, including net radiometers, pyranometers, and 4-component net radiometers. Each of these sensors measure different types of radiation. For example, the 4-component radiometer, which provides the most useful information for physical snow modeling, measures upward and downward. Solar radiation sensors are not widely deployed and are mainly located at snow research stations across the Western United States.

Solar radiation sensors are used to measure solar radiation, which is a useful parameter when modeling the energy balance of a snowpack. They are not widely deployed in the United States.

Quantity Measured
Solar radiation, albedo

Technology Readiness Level (TRL): 9

Availability
Pyranometers, net radiometers, and 4-component net radiometers are widely available from various manufacturers.

Temporal Resolution

Solar radiation sensors are typically used to measure radiation continuously. They can take readings every 10 seconds, but measurements are typically averaged to an hourly resolution.

Spatial Resolution

Solar radiation sensors measure the radiation observed at a single point location.

Verification Performance and Process

Instruments are relatively accurate, with a typical measurement resolution of 0.01 watts per square meter (W/m^2). Typical uncertainty in daily total measurements range from 1 to 10 percent, depending on the manufacturer and instrument type.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

Solar radiation sensors are suitable for all locations.

Suitability for Citizen Science

Not suitable.

Other Technologies

Since solar radiation sensors measure incoming energy from the sky and outgoing energy reflected back from the Earth's surface, their measurements would be useful in snow energy balance modeling.

Current and Future Planned Uses

Networks

Solar radiation sensors are one of the sensors that can be located at Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) stations across the Western United States, though most sites do not currently have these sensors.

Current and Future Use

Solar radiation sensors are typically located at snow science research sites that collect a wide variety of weather and snow related data. Future research seeks to study their use in measuring changes in albedo of dust-on-snow events in the Rocky Mountains. ". . . towers spread around Colorado and Utah currently take in data on the solar energy absorbed and reflected by the snow. Dust particles darken the snow's surface then absorb more energy than clean snow does. Such a process changes light frequencies recorded by the pyranometers. Researchers take these frequency data and run these data through models to quantify how much surface dust heats snow and speeds snowmelt." (Keltner-McNeil, 2021).

Benefits

- Solar radiation sensors are a relatively simple technology that has been in use for decades. Therefore, they are trusted, though their applications in snow science are still being explored.

Challenges

- Solar radiation sensors only measure at a single point, which cannot necessarily be generalized to a larger area. For example, the measurement site could be affected by tree cover—resulting in different readings that an adjacent site with fewer trees.

Costs

Cost of this instrument typically ranges from $2,000 to $4,000 per sensor, with only one sensor required per site. Additional costs may be incurred associated with installation and maintenance activities.

References

Keltner-McNeil, N. 2021.New dust-on-snow monitoring tech to be added to Steamboat lab, expanding a growing snowpack data network. Steamboat Pilot & Today, April 22, 2021. https://www.steamboatpilot.com/news/new-dust-on-snow-monitoring-tech-to-be-added-to-steamboat-lab-expanding-a-growing-snowpack-data-network/.

Matsui, N., C. Long, J. Augustine, D. Halliwell, T. Uttal, et al., 2012. Atmospheric Measurement Techniques Evaluation of Arctic broadband surface radiation measurements. Atmospheric Measurement Techniques. 5. 1-10. https://www.researchgate.net/publication/262222904_Atmospheric_Measurement_Techniques_Evaluation_of_Arctic_broadband_surface_radiation_measurements.

Snow Temperature Sensors

About the Technology

Snow temperature sensors are an arrangement of temperature sensors that measure the snow temperatures at various heights from a ground surface within the snowpack. They are normally arranged in a horizontal "fork" array (pronged) or as a vertical array (candles). This is a relatively simple technology—but it has not been widely implemented. The temperature information provided by the snow temperature probes has been shown to be a valuable input to snow energy balance models.

Temporal Resolution

Temperature sensors can measure continuously and normally record measurements every 30 to 60 seconds.

Spatial Resolution

Sensors make measurements at a single point location. Measurements are normally taken every 10 to 30 centimeters or are spaced as desired.

Verification Performance and Process

Temperature sensor performance is normally verified by manufacturers. They typically have a measurement tolerance of ±0.2 degrees Celsius.

Suitability

Regional Performance/Strengths

This technology can be used anywhere there is snow.

Suitability for Citizen Science

Not suitable unless a citizen wants to set up temperature sensors to measure the temperature profile of snow at their location.

Snow temperature sensor at the Center for Snow and Avalanche Studies site in Senator Beck Basin, Colorado (Center for Snow and Avalanche Studies, used by permission).

Temperature sensors are a relatively simple technology that can be used to measure snow temperature at various depth. This can be useful for snow modeling to help predict runoff quantity and timing, though these measurements are not widely available.

Quantity Measured

Snow temperature

Technology Readiness Level: 7

Availability

Temperature sensors are widely available and can be used to build a vertical arrangement of sensors. Alternatively, certain manufacturers also have designed profile temperature sensors.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Other Technologies

Snow temperature profiles could be a useful input to snow energy balance models. As these data become more widely available, more technologies may be able to ingest these data.

Current and Future Planned Uses

Current and Future Use

Senator Beck Basin study site has several of these sensors installed. Other research sites have also explored this technology (e.g., Snoqualmie Pass, Washington; Wayand et al., 2015). Natural Resources Conservation Service (NRCS) has been performing research and development work to operationalize these arrays at a subset of Montana and Idaho Snowpack Telemetry (SNOTEL) stations since 2017. While still in the development phase, 6 SNOTEL sites have been outfitted with in-situ snowpack temperature monitoring arrays. An additional 12 will be outfitted with new cable-based temperature monitoring technology as part of the SNOTEL Supersite Initiative to vet performance and assess integration into the SNOTEL network.

Benefits

- Snow temperature sensors are a simple technology that has a relatively low cost.

Challenges

- Snow temperature sensors have not been widely used. Therefore, they have not been thoroughly tested or implemented in a robust network. Since a snow temperature profile is a relatively unknown type of measurement, it could be challenging for people to know to use it in snow modeling.
- Current forecasting methods do not have an easy way to leverage this information.

Costs

Data Acquisition. The cost of the instruments themselves is relatively low as snow temperature profile sensors are a combination of a simple temperature sensors. Added costs would include installation and maintenance of the equipment.

Data Storage. There would be a cost to add this data source to a network.

Data Processing. The process for inclusion of this data into models is relatively unknown.

References

Center for Snow and Avalanche Studies, 2021. Senator Beck Study Plot. https://snowstudies.org/senator-beck-study-plot/ Accessed 6/21/2021.

Wayand, N.E., A. Massmann, C. Butler, F. Keenan, J. Stimberis, et al., 2015. A meteorological and snow observational data set from Snoqualmie Pass (921 m), Washington Cascades, USA, Water Resources Research. 51, 10092 - 10103, doi:10.1002/2015WR017773. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015WR017773.

GPS Receiver

About the Technology

Global Positioning System (GPS) technology can be used to measure snow depth using a GPS receiver on the ground that records the signal from a GPS satellite. When a GPS satellite has a path over the ground-based GPS receiver, the satellite signal is reflected off the ground and is then measured and recorded by the receiver. The change of this signal relative to the signal measured when there is no snow on the ground is used to estimate snow depth. Snow depth is averaged over one day with all available satellite tracks. This data is used to report uncertainty in the measurement, which can reflect potential changes in snow depth over a day due to diurnal changes or snow fall, and error. Snow water equivalent (SWE) can also be estimated using models and local Snowpack Telemetry (SNOTEL) data.

GPS receivers are used to measure snow depth over a relatively large area.

Quantity Measured
Snow depth

Technology Readiness Level (TRL): 9

Availability
GPS receivers are widely available from various manufacturers.

Temporal Resolution

Multiple measurements are needed to accurately estimate snow depth; therefore, measurements are typically reported at a daily resolution.

Spatial Resolution

GPSs can measure snow depth at a radius of 10 to 50 meters around the reciever location.

Verification Performance and Process

GPS measurements are relatively accurate, especially when multiple satellites are available for measurements. Since many measurements are taken during a day, some error represents true snow depth variability over a day. A study by Gutmann et al. (2011) reported an accuracy of 9 to 13 centimeters, though accuracy depends on the environmental conditions.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

GPS snow measurements are suitable for most locations.

Suitability for Citizen Science

Not suitable.

Current and Future Planned Uses

Networks

Sensors are installed as part of the Plate Boundary Observatory to measure plate tectonics. This network has over 224 measurement locations, though some of these locations may not be optimal for snow measurements.

Current and Future Use

GPS measurements of snow depth are generally limited to research applications at this time.

Benefits

- GPSs have a fairly large sensing area (i.e. a circle of radius 10 to 50 meters).
- The recievers are relatively robust and require minimal maintenance, even in extreme environements.

Challenges

- Receivers have larger errors than purpose built sensors (e.g., lidar or ultrasonic).
- Technology cost is more expensive than other comparable technology.
- Sites with surrounding trees make it difficult for the GPS receiver to track the reflected signal.
- Receivers may have challenges when snow or ice accumulate on top of the antenna, but can be determined and data can be excluded.

Costs

Cost of this instrument is typically around $10,000, though measurements may also be made using lower cost sensors that cost approximately $1,000. Additional associated costs include installation, operation, and maintenance costs.

References

Gutmann, E.D., K.M. Larson, M.W. Williams, F.G. Nievinski, and V. Zavorotny, 2012. Snow measurement by GPS interferometric reflectometry: an evaluation at Niwot Ridge, Colorado. Hydrol. Process., 26: 2951-2961. https://doi.org/10.1002/hyp.8329.

Larson, K. M., E.D. Gutmann, V.U. Zavorotny, J.J. Braun, M.W. Williams, and F.G. Nievinski, 2009. Can we measure snow depth with GPS receivers? Geophys. Res. Lett., 36, L17502, doi:10.1029/2009GL039430.

McCreight, J.L. and E.F. Small, 2014. Modeling bulk density and snow water equivalent using daily snow depth observations, The Cryosphere, 8, 521–536, https://doi.org/10.5194/tc-8-521-2014.

Sturm, M., B. Taras, G.E. Liston, C. Derksen, T. Jonas, and J. Lea, 2010. Estimating Snow Water Equivalent Using Snow Depth Data and Climate Classes, Journal of Hydrometeorology, 11(6), 1380-1394. https://journals.ametsoc.org/view/journals/hydr/11/6/2010jhm1202_1.xml.

UNAVCO. GPS Snow Depth. https://spotlight.unavco.org/how-gps-works/gps-and-the-water-cycle/gps-snow-depth.html.

Digital Snow Probes

About the Technology

Digital snow probes measure snow properties to determine density or hardness. Snow penetrometers are one example of a digital snow probe. Penetrometers measure the force required to push a probe through the snowpack to estimate mechanical snow properties. Examples of this probe include the SnowMicroPen from the Swiss Federal Institute for Snow and Avalanche Research and the SABRE Penetrometer from Himachal Safety Systems. This technique is often used to understand snowpack layers and stability for avalanche forecasting but can also provide useful information to estimate snow density. Another variation uses the capacitance of snow to infer snow density (e.g., the Multi-Parameter Snow Sounding probe from Capacitec, Inc). Probes can also be used to measure snow depth like a traditional snow depth probe.

SnowMicroPen about to take a measurement
Photo courtesy of J. Schweizer

Digital snow probes, including snow penetrometers, provide a portable way to estimate snow properties such as density.

Quantity Measured
Snow hardness, snow density, snow depth

Technology Readiness Level (TRL): 6

Availability
Digital snow probe data are not publicly available outside of individual research studies.

Temporal Resolution

Snow penetrometers are not currently used operationally for snow density measurements. Measurements may be taken as part of individual studies, resulting in sporadic temporal resolution.

Spatial Resolution

Like the temporal resolution, the spatial resolution of penetrometer measurements is limited to the locations where studies use this instrument because they are not part of an organized network in the Western United States.

Verification Performance and Process

Verification is performed against more standard measurements of snow hardness, such as hand hardness (e.g., Schneebeli and Johnson 1998) or density, such as snow tubes.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

These probes can be lightweight and easy to transport, making them suitable for areas that are hard to access with larger equipment.

Suitability for Citizen Science

With some additional development and training, snow penetrometers could play a limited role in snow data collection through a citizen science program, particularly when instruments are also being deployed for backcountry avalanche safety.

Other Technologies

Using snow penetrometers to estimate density relies on other density measurements, (e.g., from a snow tube) to develop empirical relationships between penetration resistance and density.

Current and Future Planned Uses

Current and Future Use

Snow penetrometers are not currently used operationally to support water supply forecasting in the Western United States. While they are used as part of some discrete studies, there are no known plans for consistent future use.

Benefits

- Penetrometer probes can be lightweight and easy to transport.
- Probes can take measurements with high vertical resolution for density estimates.
- Measurements are quick to make—allowing for more measurements that better capture the local spatial variability of snow properties.

Challenges

- Snow density needs to be inferred from hardness or capacitance signals, introducing error into the measurement.
- Probes must be calibrated regularly.
- Density is only representative of the small area that the probe penetrates.

Costs

Costs for snow penetrometers include the equipment purchase and the costs related to taking measurements, including labor and travel.

References

Schneebeli, M. and Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Annals of Glaciology, 26, pp.107-111.

Cosmic Ray Neutron Sensors

About the Technology

Cosmic ray neutron sensors (CRNS) detect naturally occurring neutrons that lose energy as they collide with other atoms in the soil, snow, or atmosphere. These interactions are highly sensitive to hydrogen, thus making CRNSs suitable for detecting the presence of water molecules in any form. CRNS can be installed above or below the snowpack; however, recent efforts focus on above ground installation, which collect neutron counts over a larger area—and therefore provide an integrated estimate of snow water content.

Temporal Resolution

CRNSs measure continuously but are aggregated over longer time periods (such as every 12 hours in Schattan et al. 2017) to increase the neutron count rates and decrease uncertainty.

Spatial Resolution

CRNSs installed above the snowpack provide snow information that represent several hectares around the installation location. Schattan et al (2017) approximated that one CRNS installation could represent the area within 230 meters of the sensor in a relatively flat alpine area.

Verification Performance and Process

Verification is performed with available ground-based sensors or manual measurements. This may include snow courses and snow pillows.

Illustration of Hydroinnova's SnowFox snow water equivalent sensor, installed below the snowpack.
Image courtesy of hydroinnova.com

CRNS provide estimates of snow water equivalent over larger areas than typical in-situ point measurements.

Quantity Measured

SWE

Technology Readiness Level (TRL): 5

Availability

Available CRNS data in the Western United States are limited to that available from the COSMOS for soil moisture at http://cosmos.hwr.arizona.edu/.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

CRNS are more suitable for areas of shallow snowpack but are most useful in areas with snow water equivalent (SWE) that varies a lot over short spatial scales, since this technology measures over a larger area than typical in-situ measurements. CRNS may also be useful for areas around the rain/snow line, to help identify when precipitation is falling as rain or snow.

Suitability for Citizen Science

There is a limited role for citizen scientists for collecting ground-based observations to verify data products.

Other Technologies

CRNS require site-specific equations to convert neutron counts to SWE. Other technologies (e.g., snow tubes / manual surveys) are needed to generate these relationships.

Current and Future Planned Uses

Networks

CRNS are installed worldwide as part of research and observatory networks; however, these instruments are not currently used operationally for snow applications in the Western United States. CRNS were deployed for soil moisture monitoring as part of a National Science Foundation (NSF)-funded project called the COsmic-ray Soil Moisture Observing System (COSMOS); however, these data were only processed for soil moisture, not SWE, and have not been updated since 2020 or earlier, depending on the site.

Current and Future Use

CRNS uses in the United States are currently limited to research activities or processing for soil moisture. A stationary and a mobile CRNS were deployed during SnowEx 2020 on Grand Mesa, Colorado. Testing is also underway at the United States Army Corps of Engineers to determine suitability for deployment for snow monitoring activities.

Benefits

- Offers continuous measurement at intermediate scales between typical ground measurements, such as snow pillows, and remote sensing. This scale may be particularly relevant for distributed modeling applications.
- Detects ice or snow and is not sensitive to bridging like snow pillows.
- Is smaller and easier to transport and install than a snow pillow, also allowing it to be installed on uneven terrain.
- Does not contain anti-freeze or other chemicals.

Challenges

- Data must be corrected for local atmospheric properties, including incoming neutron intensity, air pressure, and absolute humidity.
- Snow density and season (i.e., accumulation versus melting) can influence neutron behavior and require special consideration for developing relationships between neutron counts and snow properties.
- Uncertainty increases with increasing snowpack, making this method less suitable for measuring deep snowpack. For example, Schattan et al. (2017) suggested that for measuring more than 200 millimeters (mm) of SWE, these data should be aggregated to a 12-hour timestep to increase neutron counts and that the signal may fade entirely when SWE exceeds 600 mm.

Costs

The CRNS data collection includes equipment costs but must also account for annual costs including salaries, travel, and operation and equipment maintenance.

References

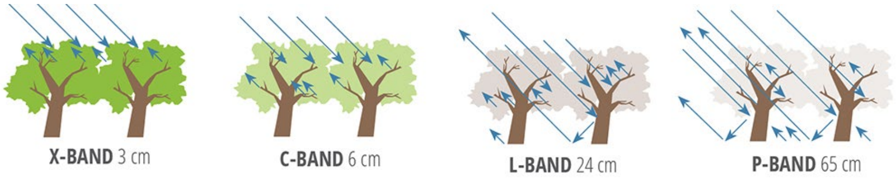
Schattan, P., G. Baroni, S.E. Oswald, J. Schöber, C. Fey, et al., 2017. Continuous monitoring of snowpack dynamics in alpine terrain by aboveground neutron sensing. Water Resources Research, 53(5), 3615-3634.

Synthetic Aperture Radar

About the Technology

Synthetic Aperture Radar (SAR) is an active remote sensing technology that captures the reflectivity of sensor-emitted microwave energy from a target scene. SAR uses a radar antenna on a platform (e.g., airborne or spaceborne) to transmit electromagnetic waves in specific frequency bands as pulses of microwave energy towards an object. SAR provides higher resolution imagery than passive microwave techniques that record the naturally emitted energy from the object. Backscatter and interferometric methods (primary types of retrieval algorithms) are used to convert SAR data into snow products.

Backscatter SAR: Using different processing algorithms, snow depth and snow water equivalent (SWE) can be estimated from the scattering response of radar through the snowpack. SWE estimates have been made using single bands, or combinations of bands of radar, such as K, X, and Ku, while snow depth has been estimated from Sentinel-1 C-band backscatter signatures (Lievens et al. 2019).



Microwave energy wavelengths change the penetration depth of the signal. For example, a C-band signal penetrates only into the top layers of a forest, while an L-band or P-band signal will have much deeper penetration and, therefore, experience strongly enhanced volume scattering as well as increasing amounts of double-bounce scattering caused by the tree trunk. Figure courtesy of National Aeronautics and Space Administration.

SAR approaches offer high resolution data collection of snow-covered regions that often are covered by clouds and the potential for remote snow water equivalent estimation.

Quantity Measured

SWE, snow depth, wet/dry snow mapping

Technology Readiness Level (TRL)

Satellite: TRL 8/9
TRL of derived snow products vary. More backscatter inversion methods are available at a higher TRL but with limited utility under some conditions. InSAR approaches for snow water equivalent are still in the research stage.

Availability

ALOS PALSAR-2
TerraSAR-X
Sentinel-1 (data at: https://ees.kuleuven.be/project/c-snow)
NISAR (set to launch later this decade)
Capella X-SAR (commercial satellite constellation launched in 2020)
GLISTIN-A (airborne)
SWESARR (airborne)
UAVSAR (airborne)

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Backscatter-based approaches are also well suited for the detection of the onset of snowmelt. Multiple approaches have been evaluated to calculate snow properties from backscatter measurements but are complex and limited by snow microstructure, vegetation, and terrain effects that reduce performance and accuracy.

Interferometric SAR (InSAR): By measuring shifts in the phase of the signal between repeat passes, interferometry can determine a property of the ground or snow cover, with potential for estimating SWE or changes in SWE. At high frequencies, (e.g., Ka-band), InSAR methods use reflections from the upper part of the snowpack to develop elevation surfaces that can be compared to a snow-free surface to calculate snow depth (e.g., Moller et al. 2017), similar to other altimetry approaches that use lidar. These methods show promise to address the limitations of backscatter inversion techniques (Du et al. 2019); however, those are replaced by new limitations such as signal penetration that leads to an unknown bias. At lower frequencies, for example, L-band, the signal travels through the snowpack, reflects off the ground and experiences phase changes depending on the SWE change between successive passes. InSAR applied to these phase changes is sensitive to SWE.

Temporal Resolution

SAR sensors mounted on aircrafts can be flown on demand through programs such as SWESARR and UAVSAR/GLISTIN-A (https://uavsar.jpl.nasa.gov/). However, no operational program is currently in place to provide regular measurements. Satellite-based SAR is available with typical revisit times of 6 - 14 days, depending on the satellite. For example, the two satellites that comprise the Copernicus Sentinel-1 constellation have a combined revisit time of 6 days, while ALOS PALSAR-2 has a revisit time of 14 days. Commercially available satellite products can also be tasked for on-demand imagery.

Spatial Resolution

SAR sensors mounted on aircrafts have very high resolutions, on the scale of meters.

Satellite-based collection provides global coverage. Existing and proposed satellite-based SAR instruments have high spatial resolution, typically less than 40 meters (m). This high resolution makes satellite-based SAR data useful for capturing the spatial heterogeneity of SWE across complex terrain; however, spatial resolution is mode-dependent and may not reflect the resolution of the processed snow products. Commercially available SAR imagery from Capella provides even higher resolution with 50-centimeter (cm) pixels, however retrieval accuracy decreases with smaller pixel sizes.

Verification Performance and Process

Despite the lack of operational, satellite-based SAR missions processed for snow observations, continued efforts evaluate their potential and performance, compared to measurements taken from the ground and space. Most notably, the National Aeronautics and Space Administration (NASA) SnowEx program (https://snow.nasa.gov/campaigns/snowex) specifically compares snow sensing technologies, including SAR, on the ground and in the air to prepare for a possible future snow-focused satellite mission.

Other examples of SAR evaluation are summarized in recent reviews such as those by Tsai et al. 2019 and Liang and Wang 2020. A few highlights are also provided here as examples of the verification process and SAR performance.

- Research at Mammoth Mountain compared Space-borne Imaging Radar-C and X-band Synthetic Aperture Radar (SIR-C/X-SAR) back-scattering derived snow depth to field measurements, resulting in a root mean square error (RMSE) of 34 cm for snow depth and 42 kilograms per square meter (kg/m^2) (or 13%) for snow density (Shi and Dozier 1997, 2000a,b)
- Cold Regions Hydrology High-resolution Observatory (CoReH2O, Rott et al. 2010), an unfunded mission of the ESA Earth Explorer Program, proposed a dual frequency Ku- and X-band SAR mission to estimate SWE using a backscattering approach. Validation of the approach using a ground-based radar system with similar operating parameters resulted in an SWE RMSE of 16.59 millimeters (mm) and 19.70 mm across two seasons.
- Lievens et al (2019) used Sentinuel-1 data with a backscattering approach to determine snow-depth at a 1 square kilometer (km) spatial resolution. Sentinel-1 has the benefit of continuing a long record of C-band radar satellite data collection (over 20 years). The reported mean absolute error was 0.18 m, compared to thousands of *in-situ* measurements.
- Moller et al. (2017) evaluated the use of Ka-band single-pass InSAR from an auto-piloted jet (GLISTIN) over rugged and forested terrain. The standard deviation of results was less than a meter, when compared with lidar data from ASO.
- A demonstration of using Sentinel-1 InSAR to derive SWE with 20 m resolution in Finland indicated that sub-centimeter accuracy on changes in SWE between 6-day overpasses relative to *in-situ* measurements (Conde et al 2019).
- Zhu et al (2018) demonstrated the use of a backscattering algorithm using X- and Ku-band airborne SnowSAR data to determine SWE. The resulting RMSE was below 30 mm.

Suitability

Regional Performance/Strengths

Different bands of radar have different strengths and weakness, as described in the challenges section below, and it is generally agreed upon that no single sensor will provide the optimal global solution. See the SnowEx Science Plan v1.6 for a discussion of remote sensing applicability for snow measurements in diverse areas (e.g., dense forests, mountains, tundra, prairies, and maritime).

Suitability for Citizen Science

Citizens can provide other data to validate the technology or to include in data assimilation and inversion techniques; however, processing SAR data is a complex process that requires specific expertise.

Other Technologies

SAR data relies on ground measurements for validation and for some inversion approaches.

Current and Future Planned Uses

The applications of SAR are numerous, providing measurements of solid Earth, ice masses, and ecosystems, as well as the snow-related research demonstrations, such as those described under the verification section. Despite this research, there is currently no operationally produced snow product from SAR data. The NASA–Indian Space Research Organisation Synthetic Aperture Radar (NISAR) mission is set to launch later this decade and will combine L-Band and S-Band radar sensors that could estimate changes in SWE. NISAR is expected to improve forecasts and assessment of changing ecosystems, response of glacier and ice sheets, and natural hazards (NISAR Mission Handbook 2019) and shows promise for estimating SWE—although this is not one of the expected early products and the algorithm is still in relatively early stages of development.

Benefits

- One of the biggest strengths of radar approaches is the ability to continuously monitor the planet during day or night/rain or shine, because radar sensors do not require a light source (like optical sensors) and can penetrate cloud cover (unlike lidar and optical sensors).
- Most platforms also have adequate spatial resolution and coverage for snow monitoring.
- Some frequencies of radar are suitable for a variety of snow conditions. Combining the strengths of different sensor bands may help overcome some challenges of using SAR data for snow applications.

For a summary of the strength of the demonstrated capabilities of different radar and remote technologies for snow property estimation, see Table 1 in the SnowEx Science Plan v1.6: https://snow.nasa.gov/sites/default/files/SnowEx_Science_Plan_v1.6.pdf.

Challenges

- The primary challenge with SAR is the high level of complexity working with the data. Interpretation and analysis of SAR images requires advanced knowledge of remotely sensed data and tools, as well as an understanding of how these data should be used for specific applications. For example, the TerraSAR-X sensor is suitable for digital terrain model generation—whereas other SAR sensors may not be tuned for this purpose.
- Different bands of radar and retrieval approaches for snow properties present different challenges and require corrections, including other observations to ensure reasonable accuracy, particularly in areas of very shallow or deep snowpack, wet snow, and dense vegetation, depending on the sensor. For example, for Ka-band InSAR techniques, penetration of up to a meter in dry snow creates an unknown bias and swath width over which the required phase accuracy is available can result in narrow swaths. Combining the strengths of different sensor bands may help to overcome some of the challenges of using SAR data for snow applications, but currently, snow products are largely experimental—and are not yet produced operationally.

- Even after deployment, satellite-based retrievals will require testing and validation for use in water supply forecasting.
- Temporal resolution can also introduce challenges as revisit times of many spaceborne SAR sensors approaches weekly or longer. Upcoming commercial SAR sensors (e.g., Capella) will provide high temporal resolution but at significant costs. InSAR retrieval techniques also require repeat pass of the same location necessitating control of orbital positioning and precise geo-location for accurate measurements (Alvarez-Salazar et al. 2014), which increases mission cost and complexity.

Costs

Data Acquisition. Satellite data collection is supported by Federal and other government space agencies, making the raw data freely available. Assuming that the responsible agencies are maintaining satellite programs, the incremental costs of using SAR technology to obtain snow measurements for water forecasting is related to processing the SAR data to the desired snow variable and incorporating the snow variable(s) into forecast models. Commercially available products from Capella Space can provide higher resolution SAR data that can be tasked nearly on demand for a specific location. These data could be processed into SWE or snow depth—but comes with added cost.

Data Storage. Data are publicly available, so storage needs are limited to what is needed to for specific applications. Due to the high-resolution of SAR data, storage requirements could be considerable for larger domains.

Data Processing. Additional data processing costs could arise to employ newer inversion or data assimilation approaches for specific applications and could require considerable computational processing power.

References

Alvarez-Salazar, O., S. Hatch, J. Rocca, P. Rosen, S. Shaffer, et al., 2014. Mission design for NISAR repeat-pass interferometric SAR. Proceedings of SPIE - The International Society for Optical Engineering. 9241. 10.1117/12.2074162.

Conde, V., G. Nico, P. Mateus, J. Catalão, A. Kontu, and M. Gritsevich, 2019. On the estimation of temporal changes of snow water equivalent by spaceborne SAR interferometry: a new application for the Sentinel-1 mission. Journal of Hydrology and Hydromechanics.

Du, J., J. Watts, L. Jiang, H. Lu, Hui, X. Cheng, et al., 2019. Remote Sensing of Environmental Changes in Cold Regions. Remote Sensing, Volume 11, Issue 16, https://www.mdpi.com/2072-4292/11/16/1952.

Liang, S. and J. Wang, J. (Eds.), 2020. Advanced remote sensing: terrestrial information extraction and applications. Second Edition. Chapter 19 – Snow water equivalent. Academic Press. Pp 713-763.

Lievens, H., M. Demuzere, H.P. Marshall, R.H. Reichle, L. Brucker, et al., 2019. Snow depth variability in the Northern Hemisphere mountains observed from space. Nature communications, 10(1), 1-12.

Moller, D., K.M. Andreadis, K.J. Bormann, S. Hensley, and T.H. Painter, 2017. Mapping snow depth from Ka-band interferometry: proof of concept and comparison with scanning lidar retrievals. IEEE Geosci. Remote Sens. Lett. 14, 886e890. https://ieeexplore.ieee.org/document/7915678.

NISAR, 2019. NASA-ISRO SAR Mission Science Users' Handbook. August 2019, Version 1. https://nisar.jpl.nasa.gov/system/documents/files/26_NISAR_FINAL_9-6-19.pdf.

Rott, H., S.H. Yueh, D.W. Cline, C. Duguay, R. Essery, et al., 2010. Cold regions hydrology high-resolution observatory for snow and cold land processes. Proc. IEEE 98 (5),752e765.

Shi, J. and J. Dozier, 1997. Mapping seasonal snow with SIR-C/X-SAR in mountainous areas. Remote Sens. Environ. 59,294e307.

Shi, J. and J. Dozier, 2000a. Estimation of Snow Water Equivalence Using SIR-C/X-SAR, Part I: inferring snow density and subsurface properties. IEEE Trans. Geosci. Remote Sens. 38 (6), 2465e2474.

Shi, J. and J. Dozier, 2000b. Estimation of Snow Water Equivalence Using SIR-C/X-SAR, Part II: inferring snow depth and particle size. IEEE Trans. Geosci. Remote Sens. 38 (6), 2475e2488.

Tsai, Y., A. Dietz, N. Oppelt, and C. Kuenzer, 2019. Remote Sensing of Snow Cover Using Spaceborne SAR: A Review. Remote Sens, 11, 1456. https://doi.org/10.3390/rs11121456.

Zhu, J.S., Tan, J. King, C. Derksen, J. Lemmetyinen, et al., 2018. Forward and inverse radar modeling of terrestrial snow using SnowSAR data. IEEE Trans. Geosci. Remote Sens. 56, 1–11. https://ieeexplore.ieee.org/document/8412144.

Aircraft Lidar Platforms

About the Technology

Airborne Light Detection and Ranging (lidar) platforms that are typically used for mapping ground surfaces can also be deployed to monitor snow. The lidar laser scans back and forth across the ground during flight, capturing precise elevations. Snow depth can be measured by comparing the ground surfaces with and without snow cover. Lidar instruments are commonly mounted on Unmanned Aerial Vehicles (UAVs) and small airplanes, resulting in a range of potential resolutions and coverage areas. Spatial coverage of aircraft-based lidar can be extended anywhere equipped aircraft can reach.

The National Aeronautics and Space Administration (NASA) developed the Airborne Snow Observatory (ASO), which pairs a scanning lidar instrument with an imaging spectrometer, spatial snow density model, and other refinements tailored for snow measurement in mountainous terrain to produce snow depth and snow water equivalent (SWE). Refinements include using the most modern lasers able to reach the ground from high altitude, analysis of the full waveform reflection from the ground, integration with the imaging spectrometer, and rapid data processing. ASO's imaging spectrometer provides estimates of snow reflectance across visible and near-infrared bands, with planned upgrades to include short-wave infrared measurements. With proper instrument calibration, subtle differences in reflectance between discrete bands in the infrared can determine snow grain size, reflectance (albedo), and impurity content—and thus can quantify absorption of solar radiation, the dominant driver of snowmelt in the majority of western mountains (Painter et al. 2016).

NASA also flies the Land, Vegetation, and Ice Sensor (LVIS; Blair et al. 1999), an airborne full-waveform imaging lidar with

An aircraft lidar survey over the California Sierra Nevada.
Photo courtesy of National Aeronautics and Space Administration Jet Propulsion Laboratory.

Airborne lidar platforms such as ASO can be the most definitive snowpack measurement that can currently be made across a mountainous watershed. When integrated with physically based snow modeling, it can inform water management and making existing snowpack monitoring networks more efficient.

Quantity Measured

Snow depth. When coupled with modeling and other data, SWE can be produced.

Technology Readiness Level (TRL): 8

Availability

Aircraft lidar platforms are widely available, though less commonly used to measure snow depth. ASO 's processing workflow is exclusively licensed.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

a long track record of developing many of the techniques that are later employed by other airborne lidars. While normally used to observe vegetation, LVIS could be used for snow observations and has been considered for use in NASA snow campaigns.

LVIS currently operates from a higher-altitude, faster platform than other lidars, enabling more extensive and cost-efficient mapping, in addition to longer-range deployment capability. LVIS has operating modes that simulate satellite lidar measurements to test satellite algorithms and to provide post-launch validation measurements.

Airplane-based lidar platforms and processing workflows are commercially available for surveying snow. The enhanced ASO suite of technologies was licensed by NASA to Airborne Snow Observatory, Inc. The ASO license covers image registration and lidar point cloud analysis, as well as software for efficient and rapid data processing.

Additional advancements allow the technology suite to perform well over extremely rough terrain and variable vegetation cover, including under forest canopies.

Temporal Resolution

Airborne lidar platforms can capture a snapshot in time of snowpack conditions. Surveys can be flown whenever there are no clouds, fog, rain, or smoke below the aircraft altitude. Typically, surveys are conducted multiple times during both accumulation and melt periods (monthly or more frequently), though the timing can be tailored to water management needs such as pre- and post-storm events. An integrated snowpack model can provide estimated snow depth estimates and other data between lidar flights.

Seasonal preparation for the first flight requires several weeks of advanced planning, which includes staging the aircraft, calibrating instrumentation, adapting to airspace restrictions, and weather. Subsequent flights can be acquired with shorter lead-times once deployed for an area.

Spatial Resolution

Spatial resolution depends on the characteristics of the aircraft and lidar instrumentation. ASO is can now capture upwards of 150,000 acres per hour—although several factors can influence that rate. For example, the typical ASO deployment captures approximately 10 laser points across a 3x3 meter (m) area on the ground, which is repeated across an entire mountain basin, resulting in about 5 centimeters (cm) snow depth accuracy. Calculations of SWE are performed over a 50 m pixel, where the accuracy of the snow depth measurements is generally about 1 cm with averaging.

Verification Performance and Process

Verification is performed with available ground-based sensors or manual measurements. These include snow pillows, snow courses, survey-specific manual measurement courses, and snow pit measurements, as well as other ground-based observations. ASO specific verification is well documented, as described in Painter et al. (2016).

Suitability

Regional Performance/Strengths

Airborne lidar platforms are most appropriate for basins where snow is a major contributor to runoff. Airborne lidar platforms are most readily implemented in regions where there are periods of clear weather between winter storms and where multiple watersheds can be aggregated into a single survey domain to make best use of aircraft deployment and efficient flight planning. ASO is optimized for mountainous terrain, though the ASO technology suite can be applied to any snowmelt-dominated region worldwide. ASO's lidar and imaging spectrometer require cloud-free weather conditions; however, NASA has investigated supplementing ASO instruments with a radar to allow snow measurement through cloud cover (Moller et al., 2017). This is an area of active development.

Suitability for Citizen Science

The limited role for citizen scientists might be the collection of ground-based observations to verify data products (e.g., snow pits and ad-hoc snow courses synchronized with ASO surveys).

Other Technologies

Airborne platforms such as the ASO data processing and production process makes extensive use of existing ground-based snow measurement networks. ASO uses these networks for validation and model input in a way that is quite different than the networks' intended application as index locations. This use case extends the utility of these networks and renews their value in an environment where index and statistical forecasting are challenged by climate and land cover changes.

Modeling paired with information from these airborne platforms can fill in data needs between flights, giving more continuous temporal data. Such models can draw upon satellite-based measurements and imagery, ground-based stations, or high-resolution forecast models; periodic calibration with these measurements prevents large bias drift which is a known weakness of models.

Current and Future Planned Uses

Networks

Airborne lidar platforms are not part of any major snow monitoring network. ASO, the most common application of airborne lidar to measure snow, has been deployed on an ad-hoc or supplementary basis in the Central Rockies, Pacific Northwest, European Alps, and most extensively in the Sierra Nevada of California. In California, an informal working group led by the California Department of Water Resources (CA-DWR) guides ASO deployment. Data from existing ground-based observations are used to validate ASO snow depth measurements and to constrain the snow density model.

Current and Future Use

ASO is flown in the Sierra Nevada of California from the Tuolumne south through the Kings and Kaweah River basins. In water year 2022, the Truckee and Carson River basins will be added, and potential state legislation may markedly expand the extent throughout California's mountain areas. A 2019 California senate bill calling for CA-DWR to expand ASO operationally across many California watersheds passed both houses unanimously; but the governor vetoed it and instructed the legislature to provide sustained funding. COVID-19 interrupted the 2020 funding process for the full State of California ASO program.

ASO is also flown in the Colorado Rocky Mountains in the Gunnison, Blue River, Dolores, Animas, Rio Grande, and Conejos River basins, with several new basins being added in 2022 via collaborations with U.S. Geological Survey and Department of Energy projects. An ongoing effort in Colorado will assimilate ASO data into Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro) in near-real time—this combination has demonstrated good results in retrospective studies elsewhere in Colorado. A consortium of water management entities led by Denver Water has organized themselves as the Colorado Airborne Snow Observatory program (CASO) to coordinate a Colorado state-wide program akin to that in California.

Notable Use Cases

ASO has been deployed in the Tuolumne basin of the Sierra Nevada since 2013. These data enable San Francisco Public Utilities Commission to better forecast minimum-expected inflows into Hetch Hetchy Reservoir. This information helps the utility maximize power generation and water supply while meeting environmental flow requirements in Yosemite National Park.

In the snowy spring of 2019, ASO measurements demonstrated a higher-than-expected snowpack for the Kings River basin, in contrast with the more modest runoff forecast. The Kings River Water Authority reports that this information allowed early action to avoid reservoir flood spills, potentially saving as much as 100,000 acre-feet of water ($75 to $100 million market value).

On the San Joaquin River of California, ASO has been used since 2017 to improve water management during wet years (like the Kings River basin), minimize downriver flood impacts, as well as more accurately release environmental flows during all years for a Reclamation-led Federal Chinook salmon restoration effort.

Under contract with Denver Water in Colorado, ASO data were collected in the Blue River basin (Upper Colorado Basin) in 2019. In particular, the ASO data were collected as the basin SNOTEL sites became snow-free. Denver Water reports that ASO data informed their release operations, allowing the management of a second (higher) peak in snowmelt-driven streamflow without endangering downstream infrastructure with flooding flows.

To date the direct integration of ASO data into operational runoff forecasts has been limited, primarily due to challenges with integration in operational models. Efforts to integrate ASO data more directly and update the water supply models to take advantage of such higher resolution are in development.

Benefits

- Provides high-resolution, spatially distributed snowpack information over an entire domain with precision and accuracy similar to ground-based solutions.
- Quantifies snow in steep and rugged mountainous terrain and provides a definitive estimate of SWE for any area of interest, even under forest canopies—a crucial need in the Western United States.
- Can verify and calibrate snow models, thereby enhancing other snow measurement tools and networks.
- Tends to produce a more favorable mix of traits than other platforms and methods for calculating snow depth technologies (e.g., accuracy under snow canopies, ability to survey large areas, and unconstrained by satellite orbital dynamics).
- Aerial lidar and spectrometry data have many ancillary benefits, such as monitoring tree mortality and wildfire risk, reconstructing glacial positions in the last ice age, and tracking glacial retreat, as has been done in Yosemite National Park.

Challenges

- ASO has a higher cost than other spatial snow monitoring tools. Optimization of the timing of surveys, using complementary technologies to reduce the frequency of surveys, and surveying larger areas at once can reduce the overall cost.
- ASO relies on modeled snow density to produce snow water equivalent. Snow density is well modeled in some regions but can be a source of greater uncertainty in other areas—decreasing the accuracy of ASO SWE estimates (but ASO depth measurements are still highly accurate and capture the majority of the variation in SWE).
- ASO requires cloud-free conditions. ASO deployment in cloudier areas, such as the Pacific Northwest, should continue to develop a complementary instrument, such as radar, which can mitigate the impact to survey schedules.

Costs

The cost of ASO is comprised of about 40% fixed costs and 60% of operational costs. Operational costs are \$0.20 – \$0.50 per acre per survey (for large areas). Fixed costs include instrument installation and calibration (performed once per season per aircraft), aircraft stand-by costs between surveys, and upkeep of model to track snow density. An individual survey typically covers 250,000 to 370,000 acres (1,000 to 1,500 square kilometers). Consequently, single survey costs are usually greater than \$100,000. Additionally, a bare ground lidar survey is required prior to ASO deployment and is thereafter only necessary when there is significant vegetation change (e.g., fire or years of growth). This cost could be shared or obviated by collaboration with the U.S. Geological Survey 3DEP, the Federal Emergency Management Agency, or state-level lidar mapping programs. Total costs for isolated small basins would be proportionally very high, however economy of scale savings can be realized by flying larger and connected survey domains to minimize aircraft standby cost. Costs could also be defrayed through multi-disciplinary interests, such as using ASO data for forest health surveys, biomass measurement, transportation and recreation management, hydropower planning, and other interests in the watershed.

References

Blair, J.B., D. L. Rabine, and M.A. Hofton, 1999. The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. ISPRS Journal of Photogrammetry and Remote Sensing 54(2-3), 115-122.

Moller, D., K M. Andreadis, K.J. Bormann, S. Hensley, and T.H. Painter, 2017. Mapping snow depth from Ka-band interferometry: Proof of concept and comparison with scanning lidar retrievals. IEEE Geoscience and Remote Sensing Letters.https://ieeexplore.ieee.org/document/7915678.

Painter, T.H., D.F. Berisford, J.W. Boardman, K.J. Bormann, J.S. Deems, et al., 2016. The Airborne Snow Observatory: scanning lidar and imaging spectrometer fusion for mapping snow water equivalent and snow albedo. Remote Sensing of Environment. https://www.sciencedirect.com/science/article/abs/pii/S0034425716302577.

Passive Microwave

About the Technology

Satellite mounted radiometers measure the microwave energy naturally emitted by the Earth's surface and report it as brightness temperature. Passive microwave approaches for measuring snow water equivalent rely on the difference in brightness temperature between high and low frequency emissions.

A range of inversion methods exist to translate the observed brightness temperature to snow water equivalent (SWE) or snow depth. These methods range in complexity from simple linear regressions to more complex machine-learning based and physics-based approaches. Inversion methods also have a variety of input needs, often including ground-based or other satellite-based observations of snow and land cover properties to account for the impacts of these properties, such as snow grain size and forest canopy coverage, on brightness temperature.

Temporal Resolution

Satellite passive microwave observations have daily data available from the National Snow and Ice Data Center (NSIDC) dating back to 1979.

Spatial Resolution

Satellite-based collection provides global coverage, but resolution from passive microwave sensors is too coarse for most snow observations to support water supply forecasting. Typical snow-product grid spacing is 25 kilometers.

Verification Performance and Process

Verification and validation of different inversion methods is typically performed against ground-or air-based measurements. Example efforts include a

AMSR-E instrument on Aqua satellite. Photo courtesy of National Aeronautics and Space Administration.

Passive microwave satellite technology can provide an estimate of snow water equivalent but is at a course resolution that is likely only applicable for water supply forecasting in flat areas with relatively uniform vegetation.

Quantity Measured
SWE, snow depth

Technology Readiness Level (TRL): 9

Availability
Data are publicly available from the NSIDC for these satellite-based sensors:

- SMMR
- SSM/I
- AMSR-E
- AMSR2

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

comparison of an inversion method that considers land cover in Canada where SWE was within +/-20 millimeters of manual *in-situ* measurements; however, the NSIDC published dataset from AMSR-E SWE reports a root mean square error (RMSE) of 10-32 centimeters (cm) compared to ground-based measurements (NSIDC). Evaluation of another snow depth algorithm in China used satellite derived snow-covered area estimates in addition to land cover information to reduce error, resulting in a RMSE of 5.6 cm. For additional examples of inversion approaches and their performance, see Liang and Wang (2020) and references therein.

Suitability

Regional Performance/Strengths

As the pixel size is large, variations in topography and land use will not provide detailed data. Thus, with careful consideration of inversion method and other limitations (such as snow depth), this technology is more suitable for homogeneous terrain, especially for vegetation (e.g., open plains) and topography (e.g., flat areas).

Suitability for Citizen Science

Citizens can provide other data to validate the technology or to include in data assimilation and inversion techniques.

Other Technologies

The inversion of passive microwave-derived brightness temperature to snow depth or SWE commonly relies on other observations. For example, one technique to estimate snow depth also uses Moderate Resolution Imaging Spectroradiometer (MODIS) based snow-covered fraction (Chang et al. 2009), while one to estimate SWE relies on ground-based measurements of snow depth (GlobSnow, see description in this appendix).

Current and Future Planned Uses

Passive microwave approaches are produced at large scales and not commonly used for water supply forecasting. The European Space Agency Climate Change Initiative produces one example of an operationally produced product that uses passive microwave data (formerly GlobSnow); however, the goal of this product is to provide long time series of consistently developed snow information, not generally to inform water managers.

While the spatial resolution of existing snow products derived from passive microwave measurements limits its current use, sensors have improved in their ability to capture higher resolutions (NASA 2016). Research to improve processing methods to account for both scale and sensor sensitivities to snow and land-cover properties continues and should continuously be evaluated for their ability to inform water supply forecasting.

Benefits

- This provides a long period of record (about 40 years for model calibration and to analyze long-term patterns.
- Microwave sensors can take data measurements without a light source, so this can operate day and night.
- Microwave sensors can penetrate clouds, so this can be used in any weather conditions.

Challenges

Snow and land cover properties such as snow microstructure (grain size, layering, water content, and snowpack depth) and forest canopy characteristics affect the emissions signal and complicate estimation of SWE and snow depth. To reduce these errors, estimates should assimilate surface observation from *in-situ* or other remote sources. The large pixel size further complicates the issue by introducing what is commonly referred to as "the mixed-pixel problem" in that any given pixel likely represents a combination of a variety of snow characteristics and land cover types. This large pixel size limits the utility of passive microwave measurements for water supply forecasting in complex topography, including the mountains of much of the Western United States.

Costs

Data Acquisition. Satellite data collection is supported by United States and other government space agencies, making the brightness, temperature, and some processed snow depth and SWE estimates freely available. Assuming that the responsible agencies are maintaining satellite programs, the incremental costs of using microwave technology to obtain snow measurements for water forecasting is related to ensuring the product is appropriate for the desired application and incorporating it into forecast models.

Data Storage. NSIDC hosts these data, so storage needs are limited to what is needed to for specific applications. Due to the coarse nature of current passive microwave snow products, storage requirements are small.

Data Processing. Additional data processing costs could arise to employ newer inversion or data assimilation approaches for specific applications and could require considerable computational processing power for more advance machine learning and physically based modeling approaches.

References

Chang, S., J. Shi, L. Jiang, L., Zhang, and H. Yang, 2009. Improved snow depth retrieval algorithm in China area using passive microwave remote sensing data. In: Proceedings of IEEE International Geoscience and Remote Sensing Symposium, 2. IGARSS, pp. II614eII617, 2009 IEEE International.

Liang, S., and J. Wang, J. (Eds.), 2020. Advanced remote sensing: terrestrial information extraction and applications. Second Edition. Chapter 19 – Snow water equivalent. Academic Press. pp 713-763.

NASA, 2016. NASA SnowEx Science Plan: Assessing Approaches for Measuring Water in Earth's Seasonal Snow. V. 1.6. https://snow.nasa.gov/sites/default/files/SnowEx_Science_Plan_v1.6.pdf.

National Snow and Ice Data Center, 2014. AMSR-E/Aqua Data Quality and Data Uncertainty. National Snow and Ice Data Center, University of Colorado, Boulder, https://nsidc.org/sites/nsidc.org/files/technical-references/AMSRE-DataQuality-DataUncertainty.pdf.

Signals of Opportunity

About the Technology

The signals of opportunity (SoOp) approach uses two sensors to detect P-band signals from already orbiting telecommunications satellites. One sensor measures the signal directly emitted from the satellite and the other detects the reflected signal from the Earth's surface. The phase change can be used to determine snow water equivalent (SWE), for dry or mostly dry snow (<6% liquid water) or snow depth for wet snow.

The National Aeronautics and Space Administration (NASA) selected Purdue University's SigNals of Opportunity: P-band Investigation (SNoOPI) mission to be part of the CubeSat Launch Initiative (CSLI) and Educational Launch of Nanosatellites (ELaNa) program. This demonstration mission will test the feasibility of P-band SoOp technology for snow and soil moisture collection from space over a range of different land surface conditions (Garrison et al. 2019).

Temporal Resolution

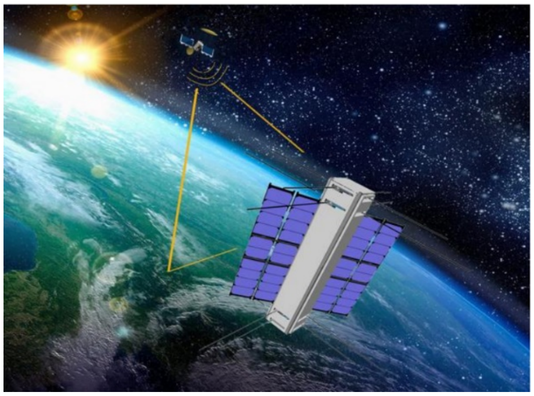
This technology is not yet produced with a consistent temporal resolution. The SNoOPI mission will inform future potential.

Spatial Resolution

Satellite-based collection provides global coverage, but with resolution of a future science mission is unknown.

Verification Performance and Process

The SNoOPI mission will be the first satellite-based demonstration of the SoOp approach using P-band radar for snow measurements and plans to compare to



Conceptual rendering of SigNals of Opportunity: P-band Investigation mission interacting with a telecommunications satellite.
Image courtesy of National Aeronautics and Space Administration.

The Signals of Opportunity approach leverages existing telecommunications satellites that transmit signals in the P-band to reduce the cost of satellite hardware to commercially available antennas. This approach may provide valuable snow measurements, but the feasibility from space is unknown until the results of an upcoming demonstration mission are available.

Quantity Measured

SWE, snow depth

Technology Readiness Level (TRL): 7 with the success of SNoOPI, but until proven, TRL 5

Availability

SNoOPI data will be housed at Purdue University's Science Operation Center.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

ground observations to validate the retrieval approach (Garrison et al. 2019).

UAS-based P-band SoOp technology was also tested as a proof-of-concept in the Fraser Experimental Forest in Colorado. The tests generated 10-meter SWE over the flown area, but performance statistics to ground-based measurements were not reported (Yueh et al. 2018).

Suitability

Regional Performance/Strengths

The use of P-band radar that can penetrate cloud and forest cover makes this product widely useful within the coverage areas of existing telecommunications satellites.

Suitability for Citizen Science

Citizens can provide other data to validate the technology or to include in data assimilation and inversion techniques.

Other Technologies

As this is a new technology, it is not currently used in combination with other snow technologies, beyond validation against other measurements types.

Current and Future Planned Uses

Current and Future Use

SoOp is not currently used in operational water supply forecasting, although it is being tested as part of the SNoOPI mission, originally set to launch in 2021 (Piepmeier 2019) to determine if SWE retrievals are feasible.

UAV applications also hope to provide high resolution hydrologic observations in support of water management and other applications such as natural hazard detection (Yueh et al. 2018). Results indicated a root mean square deviation of 7.5 millimeter between the measured phase and in-situ SWE (Shah et al. 2017).

Benefits

The SoOp approach offers a reduced cost relative to other satellite missions, from the use of existing hardware components, strong signals that reduce antenna and—ultimately—satellite size, and reliance on existing telecommunications transmitters.

The use of P-band radar provides the ability to penetrate cloud cover and dense forest canopy for thorough spatial coverage.

Challenges

This technology has not yet been proven from space and requires extensive testing and validation before operation snow products are available. As a result, many of the challenges could limit the applicability of this product are yet to be determined.

Costs

Data Acquisition. SNoOPI is part of NASA's CubeSat program, which uses small satellites and hardware that is commercially available. The lack of engineering and validation of new hardware significantly reduces the cost of satellite development and deployment and, therefore, the overall cost of data acquisition.

Data Storage. Data from the SNoOPI demonstration mission will be hosted by Perdue University. Future science missions are not yet planned, so storage approach and local storage needs are unknown.

Data Processing. Data from the SNoOPI demonstration mission will be processed by the University of Perdue. Future science missions are not yet planned, so processing needs are unknown.

References

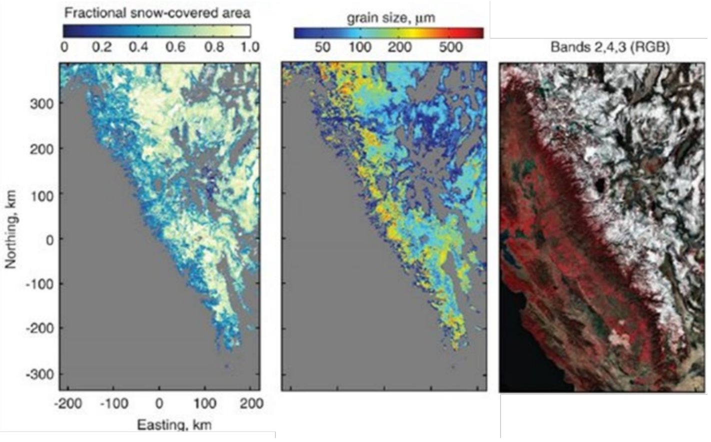
Garrison, J.L., J. Piepmeier, R. Shah, M.A. Vega, D. Spencer, R. Banting, et al., 2019. SNOOPI: A technology validation mission for P-band reflectometry using signals of opportunity. In IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium (pp. 5082-5085). IEEE.

Piepmeier, J., 2019. SNoOPI: A flying ace for soil moisture and snow measurements. Cutting Edge, A Goddard Space Flight Center publication. Available at: https://www.nasa.gov/sites/default/files/atoms/files/winter_2019_final_web_version.pdf.

Shah, R., X. Xu, S. Yueh, C.S. Chae, K. Elder, et al., 2017. Remote sensing of snow water equivalent using P-band coherent reflection. IEEE Geoscience and Remote Sensing Letters, 14(3), 309-313.

Yueh, S., R. Shah, X. Xu, K. Elder, S. Margulis, et al., 2018. UAS-based P-band signals of opportunity for remote sensing of snow and root zone soil moisture. In Sensors, Systems, and Next-Generation Satellites XXII (Vol. 10785, p. 107850B). International Society for Optics and Photonics.

Optical Sensors for Snow Extent



Fractional snow-covered area and related data. Modified from: Painter et al 2009

About the Technology

Optical sensors on many of the currently active satellites passively measure reflected sunlight in the visible, near-infrared, and short-wave infrared bands of the electromagnetic spectrum. These measurements can be used to estimate snow covered area, grain size, and albedo. The simplest snow-cover area retrievals are binary—either indicating the presence or absence of snow in a pixel and differentiating snow from clouds based on the characteristics of reflected radiation. Snow reflects high visible (VIS) and very low shortwave infrared radiation (SWIR), while clouds generally reflect visible and near infrared radiation (NIR).

The National Aeronautics and Space Administration (NASA) currently uses reflectance signatures with the Normalized Difference Snow Index (NDSI) approach to generate the MOD10A1 and MYD09GA products from Moderate Resolution Imaging Spectroradiometer (MODIS) data and the standard snow cover product from VIIRS data. These products, available for download from the National Snow and Ice Data Center (NSIDC), provide the NDSI, which can be used with a threshold to make binary maps of snow-covered extent, or snow-covered area (SCA), or with a regression based on higher resolution satellite imagery (e.g., Landsat) to get an estimate of the fraction of the pixel that is snow covered, or fractional snow-covered area (fSCA). MODIS thermal infrared bands are also used to correct for

Optical sensors provide fractional snow-covered area at a range of spatial and temporal scales and are produced operationally.

Quantity Measured
SCA and fSCA

Technology Readiness Level (TRL): 8-9

Availability
SCA/fSCA products have been tested or applied to data from these government supported satellites:

- Landsat 8 (Operational Land Imager, OLI)
- TERRA/AQUA (MODIS)
- Sentinel-2 (MultiSpectral Instrument, MSI)
- GOES-R (Advanced Baseline Imager, ABI)
- Visible Infrared Imaging Radiometer Suite (VIIRS)

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

erroneous snow detection by enforcing surface temperature thresholds for snow.[1] Research also shows that thermal snow indices can be used with thermal imagery directly to determine snow covered area, but these indices do not appear to be produced operationally (e.g., see Kour et al. 2016). Thermal infrared imagery also has potential to determine surface temperatures to inform energy balance models if the pixels can be adequately separated by land cover type (Lundquist et al. 2018).

The MODIS snow covered area and grain size (MODSCAG) algorithm uses the MOD09GA surface reflectance from the MODIS sensor on NASA's Terra satellite. In contrast to MODIS's MOD10A1 snow cover product, which relies on absolute reflectance and indicates if a pixel is snow covered or not, MODSCAG uses a spectral mixing approach to estimate the fraction of each pixel that is covered with snow. The algorithm also solves for the grain size of the snow-covered area, which is necessary because spectral reflectance is sensitive to grain size. Albedo estimates are provided only over the snow-covered fraction of the pixel (Painter et al. 2009).

While the MODIS products described above are the most used, similar approaches can be applied to other satellites that measure reflected shortwave radiation in the visible through shortwave infrared bands and the spectral signature of snow. SCA products available from Landsat 8 and Sentinel-2 data also rely on the NDSI approach using thresholds to indicate snow cover. Both of these satellites have a higher spatial resolution than MODIS but a longer temporal resolution and shorter record (since 2013 and 2017 for Landsat and Sentinel-2 respectively). Research suggests the spectral mixing approach produces less bias in fSCA estimates (Aalstad et al. 2020). The MODSCAG product is the only readily available spectral-mixing product. However, a similar spectral mixing algorithm was tested for use with the GOES-R satellite (GOESRSCAG; Cline et al. 2010) and VIIRS data (VIIRSSCAG; Rittger et al. 2021).

Temporal Resolution

The MOD09GA product has a daily temporal resolution back to February 2000. MODSCAG is available at the same temporal and spatial resolution and is hosted on NASA's Jet Propulsion Laboratory's (JPL) servers with approximately a day lag time. Other sensors that are, or could be, similarly used for SCA are summarized in Table 1.

Table 1 - Resolution of satellite-derived products used for estimating snow extent.

Satellite	Temporal Resolution	Spatial Resolution (meters)
GOES - R	Sub-daily	2,000
Landsat – 8	16 days	30
TERRA/AQUA	1 day	500
VIIRS	1 day	742-1,000
Sentinel - 2	5 days	10-20

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[1] https://modis.gsfc.nasa.gov/data/atbd/atbd_mod10.pdf

Spatial Resolution

The MOD09GAand MODSCAG fSCA products are available at 500 m spatial resolution from the TERRA-mounted MODIS instruments. Table 1 provides the spatial resolution of other satellite-derived estimates of SCA or fSCA.

Verification Performance and Process

Coarser fSCA products, such as MODSCAG, are often verified with widespread coverage against products derived from higher resolution satellites, such as Landsat. Painter et al. (2009). found MODSCAG had a 5 percent root mean square error (RMSE) compared to Landsat data across 31 scenes. Subsequent studies suggest MODSCAG consistently has less error than the MOD10A1 over a variety of locations and times of the season (Rittger et al. 2013). Similarly, Steele et al. (2017) found that canopy-corrected MODSCAG outperformed the raw MOD10A1, and further concluded it was more appropriate for simulating snow runoff from small basins than the freely availably MOD10A1 product.

Suitability

Regional Performance/Strengths

MODSCAG is available west wide and is regularly produced. Due to the lack of snow depth or water content information, it may be more useful directly for operations in areas with less variable snow depth.

Suitability for Citizen Science

Citizens can provide other data to validate the technology.

Other Technologies

Fractional snow-covered area can be assimilated into snow models or used in snow reanalysis workflows to provide estimates of snow water equivalent.

Current and Future Planned Uses

Current and Future Use

Fractional snow-covered area is most useful for water supply forecasting when used with other modeling efforts. A variety of efforts have explored incorporating SCA data into snow and hydrology modeling over the past decade. Ongoing research is looking into assimilation or use of MODSCAG or other SCA products into Snow-17 for the River Forecast Centers. Other examples of current uses of satellite-derived SCA include:

- Constraining high resolution snow modeling, such as SnowModel. Ongoing Reclamation-funded U.S. Geological Survey snow modeling efforts[2] use a canopy-adjusted merged Landsat-Sentinel SCA product that leverages the high spatial resolution of these satellites but

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[2] https://www.usbr.gov/research/projects/detail.cfm?id=21041.

combines the products to account for the lower revisit times and missing data from cloud-covered days.

- SWE reconstructions (e.g., Guan et al. 2013, and Molotch et al. 2009).
- Improved processing formulations to account for sensor challenges, such as vegetation (e.g., STC-MODSCAG, Rittger et al. 2020)

Operators can also view the images directly through products such as the NSIDC's Snow Today (https://nsidc.org/reports/snow-today) for a qualitative look at the snowpack across their watersheds.

Benefits

One of the biggest benefits of snow covered area datasets is that they rely on satellite missions that have broader support beyond snow activities—resulting in freely available products that are expected to be supported with future missions. These satellites also provide a range of spatial and temporal resolutions, many of which are useful for water supply information.

Challenges

Satellite-derived SCA does not provide snow depth or density without assimilation into other models, thereby limiting the utility for quantifying how much snow and water content is present. Optical sensors are also limited by satellite view, producing data gaps on cloudy days and in dense vegetation, although new approaches, such as STC-MODSCAG (Rittger et al. 2020), account for vegetation effects.

Costs

Data Acquisition. Satellite data collection is supported by the United States and other government space agencies, making the raw data freely available and in some cases already processed for SCA of fSCA. Assuming that the responsible agencies are maintaining satellite programs, the incremental costs of using satellite-derived SCA is limited to the cost of incorporating the information into forecast models.

Data Storage. Data are publicly available, so storage needs are limited to what is needed for specific applications. Due to the high-resolution of some optical data, storage requirements could be considerable for larger domains.

Data Processing. Additional data processing costs could arise to employ newer processing approaches for specific applications and could require considerable computational processing power.

References

Aalstad, K., S. Westermann, and L. Bertino, 2020. Evaluating satellite retrieved fractional snow-covered area at a high-Arctic site using terrestrial photography. Remote Sensing of Environment, 239, 111618.

Cline, D., A. Rost, T. Painter, and C. Bovitz, 2010. NOAA NESDIS Center for Satellite Applications and Research Algorithm Theoretical Basis Document: Snow Cover. Version 2.1. September 20, 2010. Available: https://www.goes-r.gov/products/ATBDs/option2/Cryosphere_SnowCover_v2.0_no_color.pdf.

Hall, D.K., G.A. Riggs, N.E. DiGirolamo, and M.O. Román, 2019. Evaluation of MODIS and VIIRS cloud-gap-filled snow-cover products for production of an Earth science data record. Hydrology and Earth System Sciences, 23(12), 5227-5241.

Kour, R., N. Patel, and A.P. Krishna, 2016. Development of a new thermal snow index and its relationship with snow cover indices and snow cover characteristic indices. Arabian Journal of Geosciences, 9(1), 71.

Lundquist, J.D., C. Chickadel, N. Cristea, W.R. Currier, B. Henn, et al., 2018. Separating snow and forest temperatures with thermal infrared remote sensing. Remote Sensing of Environment, 209, 764-779.

Painter, T.H., K. Rittger, C. McKenzie, P. Slaughter, R.E. Davis, et al., 2009. Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. Remote Sensing of Environment, 113(4), 868-879.

Rittger, K., T.H. Painter, and J. Dozier, 2013. Assessment of methods for mapping snow cover from MODIS. Advances in Water Resources, 51, 367-380.

Rittger, K., M.S. Raleigh, J. Dozier, A.F. Hill, J.A. Lutz, et al., 2020. Canopy adjustment and improved cloud detection for remotely sensed snow cover mapping. Water Resources Research, 56(6), e2019WR024914.

Rittger, K., K.J. Bormann, E.H. Bair, J. Dozier, and T.H. Painter, 2021. Evaluation of VIIRS and MODIS snow covered fraction in High Mountain Asia using Landsat 8. Frontiers in Remote Sensing, 2, 8.

Steele, C., J. Dialesandro, D. James, E. Elias, A. Rango, et al., 2017. Evaluating MODIS snow products for modelling snowmelt runoff: Case study of the Rio Grande headwaters. International Journal of Applied Earth Observation and Geoinformation, 63, 234-243.

Moderate Resolution Imaging Spectroradiometer Dust Radiative Forcing in Snow

About the Technology

Deposition of light absorbing particles (LAP), primarily dust and carbonaceous particles from incomplete combustion, can result in increased absorption of solar radiation and faster snowmelt. Albedo is the property of a surface that describes the proportion of incoming solar radiation that the surface reflects. Fresh snow's albedo is very high—indicating low solar radiation absorption. Darker LAPs deposited on the surface absorb more radiation than clean snow—resulting not only in direct increases in melt rate but also faster melt from accelerated snow grain growth and earlier exposure of darker buried features such as rocks or vegetation.

The Moderate Resolution Imaging Spectroradiometer (MODIS) Dust Radiative Forcing in Snow (MODDRFS) algorithm estimates the instantaneous at-surface radiative forcing (in watts per square meter [W/m^2]) from LAP on snow for the portion of the pixel that is not classified as vegetation. MODDRFS relies on the surface reflectance from the MODIS sensors on the National Aeronautics and Space Administration (NASA)Terra and Aqua satellites (MOD09GA and MYD09GA respectively, but collectively called MOD09GA in this writeup) and the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model. The underlying MODIS products used in MODDRFS are consistent with those used to develop fractional snow-covered aread (fSCA) products such as MODSCAG. See the Optical Sensor technology description for additional details on the satellite and sensors.

Dust-laden snowpack reduces reflections (albedo). (Reclamation).

MODDRFS provides a daily estimate to quantify the impact of dust and other light absorbing impurities on the radiative forcing that drives snowmelt.

Quantity Measured
Surface radiative forcing

Technology Readiness Level (TRL): 8

Availability
MODDRFS is freely available by request from NASA JPL.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Temporal Resolution

The MODIS data products are avaialble at a daily temporal resolution back to February 2000. MODDRFS is available at the same temporal resolution and is hosted on NASA Jet Propulsion Laboratory (JPL) servers.

Spatial Coverage and Resolution

The underlying MODIS data are available as a 500 x 500 meter (m) gridded product. MODDRFS is available at the same spatial resolution and is hosted on JPL servers.

Verification Performance and Process

Validation of MODDRFS with a 7-year record of *in situ* measurements indicates the radiative forcing retrieval has positive bias at lower values and slight negative bias above 200 W/m^2, subject to mixed pixel uncertainties. With bias-correction, MODDRFS has a root mean squared error of 32 W/m^2 and mean absolute error of 25 W/m^2 (Painter et al. 2012).

Suitability

Regional Performance/Strengths

The MODDRFS product is best suited for areas that rely on snowmelt for water supply and also experience dust deposition on the snowpack. In North America, the impacts of dust on snowmelt are the largest in the mid- to southern Rockies (Skiles et al. 2018). One notable example of such a region is in the San Juan Mountains in southwestern Colorado.

Suitability for Citizen Science

Citizens can help validate data.

Other Technologies

MODDRFS relies on the MODSCAG fSCA product to identify the portion of snow cover in a cell. MODDRFS can be used to force physically based snowmelt models that require radiation or albedo as an input, or to manually adjust more conceptual models (like SNOW-17). These inputs or manual adjustments can improve snowmelt timing in areas of high dust deposition.

The approach would benefit from a hyperspectral sensor, which is a sensor with more continuous band spacing. Hyperspectral sensors are similar to multispectral imaging sensors, such as MODIS, but contain many narrowly defined spectral bands and can detect more subtle changes in reflectance signature—which is particularly useful for characterization of snow grain size and dust or soot content. Hyperspectral sensors are currently flown on aircraft, including in the Airborne Snow Observatory (ASO) workflow. NASA is currently studying a similar sensor as part of the Hyperspectral Infrared Imager (HyspIRI) mission, which was recommended in the 2007 National Research Council Decadal Survey[1].

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[1] https://hyspiri.jpl.nasa.gov/.

Current and Future Planned Uses

Current and Future Use

Research efforts have evaluated the MODDRFS product in the Senator Beck Basin in the San Juan Mountains of Colorado and Hindu Kush-Himalaya Mountains in Asia (Painter et al. 2012). The Colorado Basin River Forecast Center's SNOW-17 model (see description) does not have an albedo or radiation parameter where this product could be input directly, but they use MODDRFS to adjust the model's temperature inputs to better simulate runoff.[2] Looking forward, as the satellites that support MODIS data reach the end of their lives, data from Visible Infrared Imaging Radiometer Suite (VIIRS[3]) may be an option for sustainability of current MODIS-derived products.

Benefits

- Little information is available to quantify the effects of impurities on snow albedo, other than the MODDRFS product or point observations of albedo. MODDRFS, therefore, provides a critical dataset to understand how snow melts in response to radiation, particularly in areas prone to dust deposition.
- The approach may also be applied to other satellites, but it has stricter spectral requirements than MODSCAG.

Challenges

- The MODDRFS has some of the same limitations of MODIS derived snow data as described for MODSCAG, notably that the sensors cannot penetrate cloud cover or vegetation resulting in data gaps.
- Uncertainties also arise from sub-pixel terrain heterogeneity, atmospheric correction, and sensor angle. As a result, it may require bias correction using in-situ estimates. While the product has a suitable temporal resolution with daily revisit times, the values are instantaneous, not average which does not describe the radiative forcing over the whole day. Research into better daily-average estimates is needed (Miller et al. 2016).

Costs

Data Acquisition. Satellite data collection is supported by Federal and other government space agencies, making the raw data freely available and processed by JPL for MODDRFS. Assuming that the responsible agencies are maintaining satellite programs, the incremental costs of using satellite-derived radiative forcing is limited to the cost of incorporating the information into forecast models.

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[2] https://www.coloradomesa.edu/water-center/documents/2-kormoscbrfc_ucrbwf_nov2019.pdf.

[3] https://www.jpss.noaa.gov/viirs.html

Data Storage. Data are publicly available, so storage needs are limited to what is needed to for specific applications. Due to the high-resolution of some optical data, storage requirements could be considerable for larger domains.

Data Processing. Additional data processing costs could arise to employ newer processing approaches for specific applications which could require considerable computational processing power.

References

Miller, S.D., F. Wang, A.B. Burgess, S.M. Skiles, M. Rogers, et al., 2016. Satellite-based estimation of temporally resolved dust radiative forcing in snow cover. Journal of Hydrometeorology, 17(7).

Painter, T.H., A.C. Bryant, and S.M. Skiles, 2012. Radiative forcing by light absorbing impurities in snow from MODIS surface reflectance data. Geophys. Res. Lett., 39, L17502, doi:10.1029/2012GL052457.

Skiles, S.M., M. Flanner, J.M Cook, M. Dumont, and T.H. Painter, 2018. Radiative forcing by light-absorbing particles in snow. Nature Climate Change, 8(11), 964-971.

Aircraft Gamma Surveys

About the Technology

Natural gamma radiation is emitted from the potassium, uranium, and thorium radioisotopes in the upper soil layer. This radiation can be measured from a low-flying aircraft (500 feet [ft] above the ground). Water mass (regardless of phase) in the snow cover blocks a portion of the terrestrial radiation signal. The difference between radiation measurements made over bare ground and snow-covered ground can be used to calculate a mean areal snow water equivalent (SWE) estimate.

Temporal Resolution

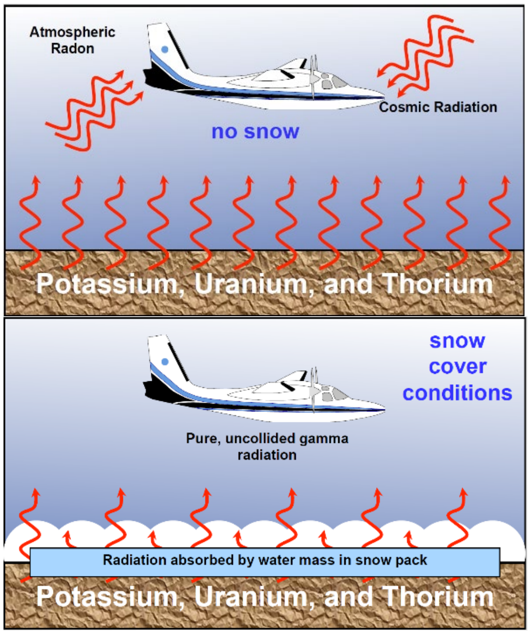
Established flight lines are flown with varying frequencies. Some may be flown multiple times a year, others only once every few years. Aircraft availability, weather, and regional conditions/priorities factor into the flight plans for a given year.

Spatial Resolution

Each flight line is approximately 10 miles long and 1,000 ft wide and results in a mean areal SWE estimate.

Verification Performance and Process

Verification is performed against ground-based monitoring data. Performance is generally good, although accuracy tends to be reduced as SWE increases. With very high SWE conditions, SWE measured is an “at minimum estimate”, but may be greater as the snow effectively blocks all gamma radiation.



Depiction of aircraft gamma survey. Graphics courtesy of National Oceanic and Atmospheric Administration.

Aircraft gamma radiation surveys are conducted each year by NOAA NWS NWC. In some locations, data have been collected since the 1980s.

Quantity Measured

SWE

Technology Readiness Level (TRL): 9

Availability

Data are collected each year and available from NOAA.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

Effective use of this technology requires an aircraft to fly relatively low (500 ft above the ground). Suitable flight conditions are important to be able to fly safely; complex topography and poor weather can limit these opportunities. This, along with other factors have resulted in many of the regularly flown flight lines being outside of the inter-mountain west. Flights are primarily made in the mid-west and northeast United States.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

Ground based gamma radiation sensors have recently been developed; their use is somewhat limited, with the majority having been deployed in Canada.

Current and Future Planned Uses

Current and Future Use

Since the early 1980s, the National Oceanic and Atmospheric Administration (NOAA) has conducted aircraft gamma snow surveys. Each year, dozens of flights are flown across the country. These data provide a rich record for operational and research applications. In winter of water year 2021, flights are planned in the Upper Colorado River Basin as part of NOAA's Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology (SPLASH).

Benefits

- Surveys provide SWE estimates over a relatively large area compared to ground-based monitoring.
- There is a long record of these surveys, in some places going back to the early 1980s.
- Data are operationally collected by NOAA and freely available. They are assimilated into the National Weather Service (NWS) National Water Center's (NWC) operational distributed snow product, Snow Data Assimilation System (SNODAS).

Challenges

- SWE estimate accuracy is reduced with higher SWE values.
- Baseline radiation surveys must be repeated each year as natural background radiation can change over time.

- Spatial coverage is limited to flight lines. Most flight lines flown regularly are outside the Western United States.
- The presence of liquid water or soil moisture can result in artificially high SWE estimate.
- Other priorities within NOAA's aviation program can impact the data collected each year.

Costs

Costs for aircraft data collection are significant. Annual data collection costs include instrument calibration and maintenance but are primarily driven by the number of flights conducted. While these costs are significant, they are funded by NOAA, so data is available at no cost to users.

References

Carroll, T., 1981. Airborne Soil Moisture Measurement Using Natural Terrestrial Gamma Radiation. Soil Science. 132 (5). https://www.nohrsc.noaa.gov/technology/pdf/1981_Airborne_soil_moisture_using_gamma.pdf.

Carroll, T., 2001. Airborne Gamma Radiation Snow Survey Program. NOAA, National Operational Hydrologic Remote Sensing Center. www.nohrsc.noaa.gov/special/tom/gamma50.pdf.

Stereo Satellite Imagery

About the Technology

Photogrammetric imagery can be used to develop digital surface models (DSM). Differencing the DSMs between times with and without snow cover produces snow depth maps at reasonably high resolution (<10 meters [m]), depending on the how the imagery is collected and processed. Satellite-, airplane-, unmanned aerial vehicle (UAV)- and terrestrially-based instruments can collect the photogrammetric images used to generate snow depth maps. Snow depth derived from stereo satellite imagery has a higher error than lidar estimates, but relatively low overall bias. Satellite-based stereo optical estimates of snow depth show a lot of promise for their cost-effectiveness and ability to be collected nearly on demand to fill between other estimates, such as lidar flights.

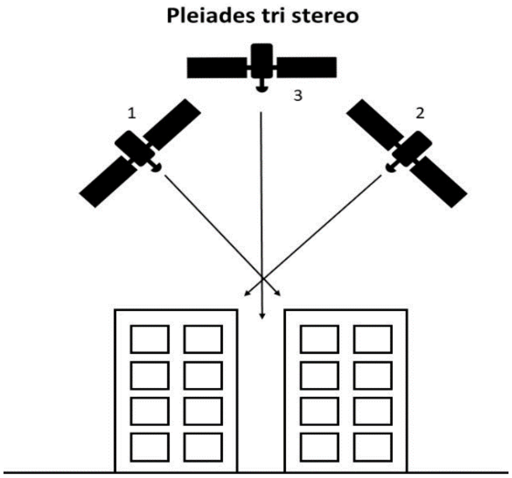
Many satellites provide high resolution imagery for military and civil applications. Researchers have tested several for stereo-optical snow depth estimation, including the Pléiades satellite constellation operated by the Space Agency of France (Marti et al. 2016 and Deschamps-Berger et al. 2020) and the WorldView-3 satellite operated commercially by DigitalGlobe (McGrath et al. 2019).

Temporal Resolution

The temporal resolution is based on the revisit time of the desired satellite, and most can be tasked to provide imagery nearly on demand.

Spatial Resolution

The spatial resolution is also based on the selected satellite and choices made during the processing



Tri-stereo view of the Pleaides 1 mission, showing areas covered (Panagiotakis et al. 2018. Used under Creative Commons license).

Satellite-based stereo optical estimates of snow depth show a lot of promise for their cost-effectiveness and ability to be collected nearly on demand. This technology has a larger error than lidar, is still limited to targeted areas, and can't provide information under the trees.

Quantity Measured

Snow depth

Technology Readiness Level (TRL): 7

Availability

Imagery available from the following satellite platforms may be suitable:

- Pléiades (Marti et al. 2016)
- DigitalGlobe/Maxar WorldView-1/2/3 (Shean et al. 2016)
- GeoEye-1 (WorldView predecessor)
- ASTER (Girod et al. 2017)

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

workflow. Imagery from the Pléiades satellite constellations has been tested with a 2-3 m resolution, although the accuracy improves at coarser resolution (Deschamps-Berger et al. 2020).

Verification Performance and Process

Satellite-derived photogrammetric snow depth estimates have been compared to other snow depth measurements, including manual measurements (snow probes), geophysical methods (GPR), and aerial measurements (lidar). When compared to 451 probe measurements, Pléiades-derived snow depth had a median residual of -0.16 m at a 2-m grid size in the Pyrenees mountain range (Marti et al. 2016). Compared to ASO lidar-derived snow depth in the Tuolumne, Pléiades-derived snow depth had a positive bias of 0.08 m, a root-mean-square error (RMSE) of 0.80 m and a normalized median absolute deviation of 0.69 m for the 3-m grid size (Deschamps-Berger et al. 2020). McGrath et al. (2019) compared a variety of snow technologies to ground penetrating radar, including 8-m DigitalGlobe WorldView-3 derived snow depth. Here, the median difference was -3 centimeters (cm) and RMSE was 24 cm.

Suitability

Regional Performance/Strengths

Photogrammetric snow depth is good for remote areas with limited coverage of ground measurements, especially if it has high satellite coverage. It is not suitable for densely vegetated areas or areas and times with high cloud coverage.

Suitability for Citizen Science

This approach is not suitable for citizen science, other than validation data collection.

Other Technologies

This technology presents an opportunity to fill the gaps between Airborne Snow Observatory (ASO) flights with a lower-cost product. It would also benefit from ASO or station data to fill under-canopy, cloud, or terrain-based gaps.

Current and Future Planned Uses

Current and future usage is limited to research applications, as described under the verification section.

Benefits

This approach has several benefits, including:

- The method is relatively inexpensive as it leverages existing satellites.
- Required data have broad spatial coverage.

- Potential for close to "On demand" availability, particularly in areas with high satellite coverage (higher latitudes) and expected increase in launch of stereo satellites.
- Does not require "snow-specific" satellite launch for continued program support.
- Open-source processing tools offer high potential for automation.

Challenges

This approach has some challenges as well, including:

- Less accurate in high slope areas (Shean et al. 2016).
- Cannot "see" below the tree canopy.
- Cloud coverage can prevent suitable image acquisition.
- Reduced accuracy in shaded areas.
- High-resolution sensors have narrower swaths (20 kilometer for Pléiades) so large areas are challenging to revisit frequently to obtain a stereo pair.
- Does not address snow density to get to snow water equivalent (SWE).

Costs

Data Acquisition. Some imagery is available freely online for the public (e.g. WorldView-3 from the European Space Agency[1]) or for researchers (e.g. Pléiades). Commercial contracting for new stereo-optical images from DigitalGlobe (WorldView) or Airbus (Pléiades) is estimated to cost about $60 per square kilometer per stereo collection. However, government access to these and similar imagery can be at a significant discount or no cost.

Data Storage. Data storage requirements could be considerable for larger domains.

Data Processing. Open-source data processing workflows such as the Ames Stereo Pipeline (ASP; Shean et al. 2016) can reduce data processing costs, although tools should be used by trained experts.

References

Deschamps-Berger, C., S. Gascoin, E. Berthier, J. Deems, E. Gutmann, et al. 2020. Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data. The Cryosphere, 14(9), 2925-2940.

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[1] https://earth.esa.int/eogateway/missions/worldview-3.

Eberhard, L.A., P. Sirguey, A. Miller, M. Marty, K. Schindler, et al., 2021. Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping. The Cryosphere, 15(1), 69-94.

Girod, L.M.R., C. Nuth, A. Kääb, R.W. McNabb, and O. Galland, 2017. MMASTER: Improved ASTER DEMs for elevation change monitoring. Remote Sensing. ISSN 2072-4292. 9(7) . doi: 10.3390/rs9070704 Full text in Research Archive. https://www.duo.uio.no/handle/10852/70873.

Marti, R., S. Gascoin, E. Berthier, M. de Pinel, T. Houet, et al., 2016. Mapping snow depth in open alpine terrain from stereo satellite imagery, The Cryosphere, 10, 1361–1380, https://doi.org/10.5194/tc-10-1361-2016.

McGrath, D., R. Webb, D. Shean, R. Bonnell, H.P. Marshall, et al. 2019. Spatially Extensive Ground-Penetrating Radar Snow Depth Observations During NASA's 2017 SnowEx Campaign: Comparison with *In Situ,* Airborne, and Satellite Observations, Water Resour. Res., 55, 10026–10036, https://doi.org/10.1029/2019WR024907.

Panagiotakis, E., N. Chrysoulakis, V. Charalampopoulou, and D. Poursanidis, 2018. Validation of Pleiades Tri-Stereo DSM in Urban Areas. International Journal of Geo-Information. 7. 10.3390/ijgi7030118.

Shean, D.E., O. Alexandrov, Z.M. Moratto, B.E. Smith, I.R. Joughin, et al., 2016. An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery. ISPRS Journal of Photogrammetry and Remote Sensing, 116, 101–117. https://doi.org/10.1016/j.isprsjprs.2016.03.012.

GlobSnow

About the Technology

GlobSnow uses a data-assimilation based method that combines satellite passive microwave radiometer data with ground-based synoptic weather stations to produce snow covered area and snow water equivalent (SWE) data. The project is funded by the European Space Agency (ESA) and is coordinated by the Finnish Meteorological Institute (FMI). Other project partners involved are NR (Norwegian Computing Centre), ENVEO IT GmbH, GAMMA Remote Sensing AG, Finnish Environment Institute (SYKE), Environment Canada (EC), Northern Research Institute (Norut), University of Bern, Meteoswiss, and the Central Institution for Meteorology and Geodynamics (ZAMG).

GlobSnow provides long-term records of satellite based gridded snow information for the Northern Hemisphere.

Quantity Measured

SWE, snow covered area

Technology Readiness Level (TRL): 8

Availability

Data are available from the GlobSnow website.

Temporal Resolution

Data are available on daily and monthly timesteps. SWE data are available from 1979 - present. Snow covered area data are available from 1995 - 2018.

Spatial Resolution

SWE data are produced on a 25 x 25-kilometer (km) grid for the northern hemisphere, covering all land surface areas except for mountainous regions, glaciers, and Greenland. Snow extent (SE) or snow-covered area (SCA) data are produced on a grid of 0.01 x 0.01 degree (~11 x 11 km). These data cover the Northern Hemisphere from 25°N to 84°N, which corresponds to the seasonally snow-covered land areas of the Northern Hemisphere.

Verification Performance and Process

Data have been validated against several independent ground-based datasets collected from the Former Soviet Union, Russia, Canada and Finland. Across a range of biomes, a low SWE bias persists, with largest bias and error being reported for northern boreal forests.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

SWE data is limited to non-mountainous regions. Microwave radiometer observations perform best for dry snow conditions. Areas with wet snow or a thin snow layer are not reliably detected and typically are not present on the SWE product.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

GlobSnow leverages a variety of satellite data, notably passive microwave radiometer data.

Current and Future Planned Uses

Current and Future Use

The objective of the GlobSnow project is to generate long-term records of snow cover information at the global scale intended primarily for climate research purposes. The World Meteorological Organization (WMO) has used GlobSnow to track snow conditions. The data have also been used in climate studies such as *Climate change, impacts and vulnerability in Europe 2012*, a European Environment Agency report.

Benefits

- SWE begin in1979 and continue to be produced in near real time.
- Snow covered area data being in 1995 and were produced through 2018.
- Data are available for a significant portion of the northern heisphere.

Challenges

- At ~11 km resolution, snow covered area data is coarser than other available products.
- At 25 km resolution, SWE data is coarse compared to many other spatially distributed snow products.
- SWE data is limited to non-mountainous regions.
- Technology has difficulty in areas with wet snow or a thin snow.

Costs

GlobSnow data is available free of charge as the project is funded by ESA. Costs associated with the project include, but are not limited to, staff labor to support producing the data products, research activities, and computational resources.

References

Pulliainen, J., K. Luojus, and S. Pinnock, 2014. "Newsletter 4", Globsnow-2 newsletter, Finnish Meteorological Institute. https://www.globsnow.info/newsletters/GlobSnow-2_final_newsletter.pdf.

Takala, M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P. Kärnä, J. Koskinen, and B. Bojkov, 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment, Vol. 115 No. 12, December 2011, pp. 3517-3529, doi: 10.1016/j.rse.2011.08.014. https://www.cen.uni-hamburg.de/en/icdc/data/cryosphere/docs-cryo/takalaetal-rse-2011.pdf.

Snow Water Artificial Neural Network

About the Technology

The Snow Water Artificial Neural Network (SWANN) snow modeling technology was developed at the University of Arizona. The technique uses ground-based snow monitoring station data and gridded weather data in a machine learning framework to produce spatially distributed estimates of snow water equivalent (SWE), snow depth, and snow-covered area. Data can be viewed and compared with the National Oceanic and Atmospheric Administration's (NOAA) Snow Data Assimilation System (SNODAS) data at the University of Arizona's SnowView Portal.

SWANN provides 4-kilometer daily gridded SWE data for the contiguous United States.

Quantity Measured
Snow water equivalent, snow covered area

Technology Readiness Level (TRL): 8

Availability
Data are produced by the University of Arizona and available from their site as well as the National Snow and Ice Data Center.

Temporal Resolution

SWANN data can be updated, and updates are typically governed by acquisition of suitable satellite data. Typically, this rhythm results in updates occurring every 2 weeks.

Spatial Resolution

Data are produced on a 4 x 4-kilometer (km) grid.

Verification Performance and Process

Data have been evaluated against other spatially distributed snow data (e.g., SNODAS and Airborne Snow Observatory [ASO] SWE data) as well as point snow monitoring station data. Comparison of 4 km gridded data to point data can be challenging due to the significant difference in area represented.

Suitability

Regional Performance/Strengths

As the method assimilates ground-based station data, performance is likely enhanced in areas with robust in-situ observations.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

The SWANN framework is flexible and has potential to leverage other snow information that may be locally available. In the Salt River Project (SRP) domain, the SWANN method was combined with aircraft based lidar snow depth surveys to produce enhanced estimates of SWE in that area.

Current and Future Planned Uses

Current and Future Use

SWANN data have been retrospectively generated going back to 1981 for the contiguous United States. Data are produced daily and SnowView provides data vizualization and comparison with SNODAS and station data. SRP has evaluated downscaled SWANN data in their runoff forecasting workflow and found that using SWANN data improved their skill, as compared with using only station-based snow monitioring data.

Benefits

- Data are generated daily with minimal latency for the contiguious United States.
- The method has flexibility to take advantage of other data sources.
- The method has been applied retrospectively to produce data going back to 1981.

Challenges

- 4 km spatial resolution limits the ability to represent complex topography.
- Input weather data contain uncertainty associated with station interpolation assumptions, which may impact accuracy of SWE estimates.

Costs

SWANN data are freely available. Most data and inputs for this method are freely available or low cost. Costs are primarily driven by staff labor to apply the method. Computational resources to support the application of this modeling technology are primary considerations related to the cost and sustainability of the product.

References

Broxton, P.D., 2020. SnowView: A Satellite Data and Model Driven Decision Support Tool for monitoring snowpack, precipitation, and streamflow. https://storymaps.arcgis.com/stories/28b6f41ba4934867873c1131c37237fd.

Broxton, P.D., W.J.D. van Leeuwen, and J.A. Biederman, 2019. Improving snow water equivalent maps with machine learning of snow survey and lidar measurements. Water Resources Research, 55, 3739– 3757. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018WR024146.

Zeng, X., P. Broxton, and N. Dawson, 2018. Snowpack change from 1982 to 2016 over conterminous United States. Geophysical Research Letters, 45, 12,940– 12,947. https://doi.org/10.1029/2018GL079621.

Snow Data Assimilation System

About the Technology

The Snow Data Assimilation System (SNODAS) is a national domain snow product from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) National Water Center (NWC). It uses a physically based, spatially distributed, energy- and mass-balance snow model to integrate snow data from satellite, airborne platforms, and ground stations with output from the numerical weather prediction (NWP) models.

Temporal Resolution

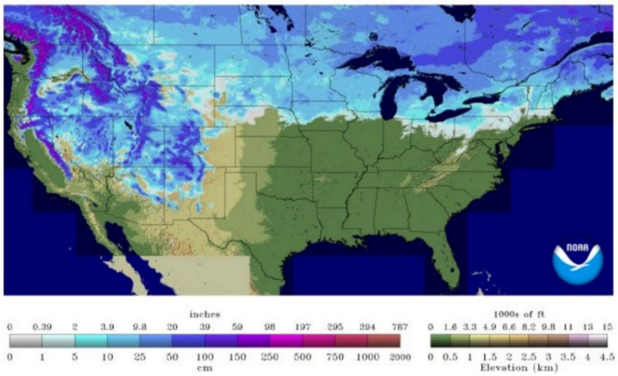
Data are updated hourly.

Spatial Resolution

Data are produced on a 1 square-kilometer (km) grid for the United States and portions of Canada.

Verification Performance and Process

A variety of SNODAS evaluations have been conducted over the years, including the potential for SNODAS to improve forecasts. Clow et al. (2012) evaluated SNODAS in the Rocky Mountains of Colorado. Results found that SNODAS performed well in forested areas for both snow depth and snow water equivalent (SWE). However, in alpine areas, correlation of SNODAS with observed snow depth and SWE was substantially reduced.



Sample snow depth output from Snow Data Assimilation System for January 15, 2015. Image courtesy of the National Oceanic and Atmospheric Administration.

SNODAS is an operational, national domain snow product generated by NOAA NWS NWC.

Quantity Measured

SWE, snow depth, snow covered area

Technology Readiness Level (TRL): 9

Availability

Data are available from NOAA NWS NWC as well as the National Snow and Ice Data Center.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

SNODAS is produced for the United States and portions of Canada. In areas with limited *in-situ* snow monitoring, SNODAS is often relied on for information about snowpack conditions. Gamma aircraft snow water equivalent (SWE) surveys are assimilated in SNODAS when and where they are available. Most of these flights are conducted in the Midwest and Northeast United States.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

SNODAS assimilates a variety of snow monitoring data. In particular, NWC's aircraft gamma SWE surveys are incorporated into SNODAS.

Current and Future Planned Uses

SNODAS data are publicly available and used by entities across the Unites States and Canada. Use of SNODAS by NOAA River Forecast Centers (RFC) varies regionally. Most use tends to be in the Midwest and Northeast United States where robust *in-situ* snow monitoring is not available.

Benefits

- SNODAS is an operationally supported product, produced daily.
- The SNODAS framework blends a variety of data sources.
- SNODAS has an almost 20-year record going back to 2003.

Challenges

- Performance varies regionally; challenges have been documented in alpine/high elevation regions.

Costs

SNODAS data are available free of charge as NOAA funds this program. Costs to NOAA associated with generating SNODAS include staff labor to support producing an operational product, computational resources required, and data collection such as the aircraft gamma SWE surveys.

References

Barrett, A. 2003. National Operational Hydrologic Remote Sensing Center SNOw Data Assimilation System (SNODAS) Products at NSIDC. NSIDC Special Report 11. Boulder, CO, USA: National Snow and Ice Data Center. https://nsidc.org/sites/nsidc.org/files/files/nsidc_special_report_11.pdf

Clow, D.W., L. Nanus, K. L. Verdin, and J. Schmidt, 2012. Evaluation of SNODAS snow depth and snow water equivalent estimates for the Colorado Rocky Mountains, USA. Hydrol. Process., 26: 2583-2591. https://doi.org/10.1002/hyp.9385.

Snow Cover Energy and Mass Balance Model (iSnobal)

About the Technology

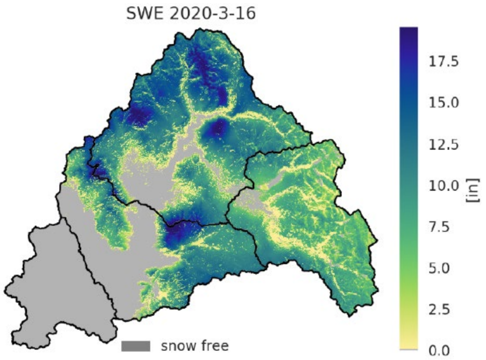
iSnobal is a physically based distributed snow model that characterizes snowpack conditions for each grid cell across a basin. Required model inputs include: air temperature, vapor pressure, wind speed, solar radiation, and precipitation. Using such hourly weather data inputs to drive the model, iSnobal solves the energy and water balance for each grid cell, resulting in snowpack mass, density, temperatures, and any melt water produced (Marks et al. 1999). With the advent of more powerful computer resources and available forcing data at high resolution, iSnobal has been successfully deployed in an operational nature in many locations (Havens 2016) and modified for user-friendliness (Havens et al. 2020). The model can directly ingest measured snow depth from the Airborne Snow Observatory (ASO) and other spatial snow surveys, which has been shown to improve model accuracy and compensate for uncertainty in forcing data (Hedrick et al. 2018). iSnobal is in continuous development by the Agricultural Research Service (ARS).

Temporal Resolution

iSnobal is run at an hourly time step and can be run on either looking at past conditions leading to the present or can be run forward using forecasted forcing data. Using intermediate-range gridded forecasts to estimate future snow accumulation and melt was successfully deployed in Idaho (3-day forecast; Havens et al. 2016) and for a 10-day forecast provided to Reclamation in the San Joaquin Watershed, California.

Spatial Resolution

While iSnobal can be run at different spatial resolutions, with success at resolutions as fine as 2.5 meters (m) for research applications, the model is typically run at 50 m per grid cell for operational, real time use (Hedrick et al. 2018). Forcing data from atmospheric models are typically available at resolutions of 1 kilometer (km) to 3 km (i.e., much coarser than model resolution).



Snow water equivalent results from iSnobal in the San Joaquin, California, watershed.

iSnobal is a flexible modeling tool for snow water resources that integrates modeling and remote sensing by updating snow conditions with snowpack measurements. It is one of a growing number of physically based distributed snow models.

Quantity Measured

Snow depth, snow density, SWE, surface water input, snowpack temperatures

Technology Readiness Level (TRL): 8

Availability

iSnobal is in the public domain, available at https://github.com/USDA-ARS-NWRC/.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Verification Performance and Process

When model inputs are driven by high-resolution atmospheric forecasts, such as Weather Research and Forecasting Model (WRF) or High-Resolution Rapid Refresh Model (HRRR) output, ground-based stations (e.g., Snow Telemetry [SNOTEL]) or snow courses are typically used to verify snow depth and snow water equivalents. Model output can also be verified and updated with ASO snow depth data to improve the performance of the model results between ASO flights (Hedrick et al, 2018).

Suitability

Regional Performance/Strengths

iSnobal has been applied in maritime, intermountain, continental, and artic snowpacks with success. The ability to quantify snowpack conditions during intense storms where cloud cover obscures remote sensing methods (lidar, Moderate Resolution Imaging Spectroradiometer [MODIS], etc.), make iSnobal particularly valuable in stormier areas or wet years that can lead to flood conditions.

Suitability for Citizen Science

The limited role for citizen scientists might be collecting ground-based observations to verify model output (e.g., snow depth, snow pits, ad-hoc snow courses) using avenues such as the Community Snow Observations [CSO] network).

Other Technologies

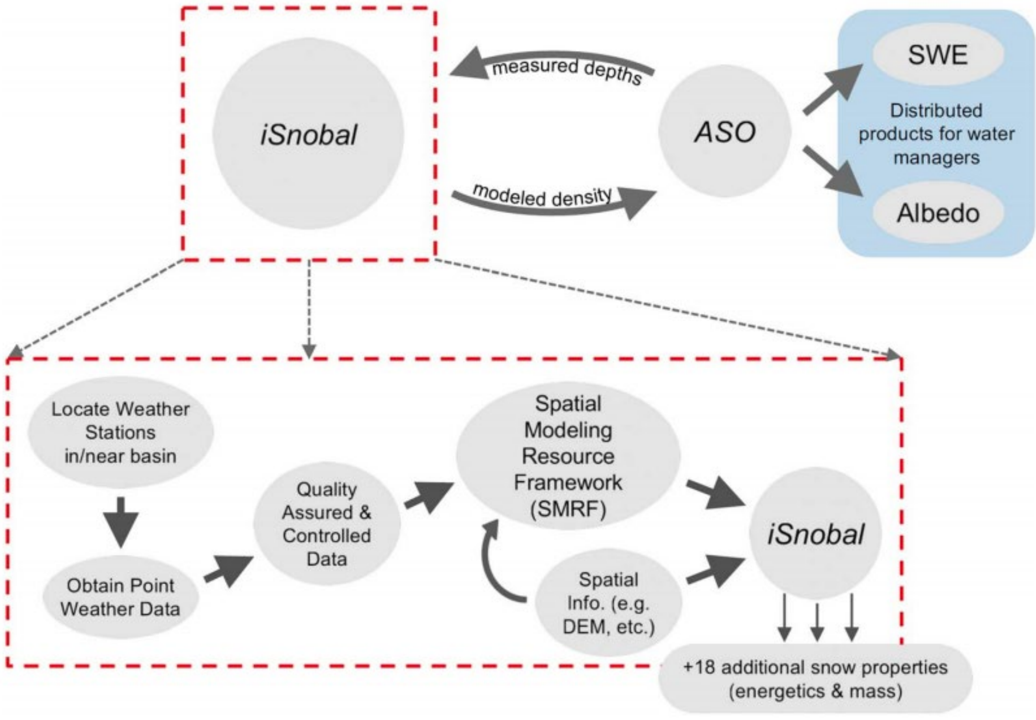
iSnobal integrates modeling and remote sensing to take advantage of each technology's strengths. iSnobal has the ability to ingest gridded snowpack data from other snow measurement technologies (e.g., lidar snow depths) and provide updates of snowpack conditions and surface water input at any required interval, past or future. The cost of operating an iSnobal model is less than some other aerial remote sensing technologies and can thus complement those technologies by continuously tracking conditions between surveys.

Current and Future Planned Uses

iSnobal has been successfully transitioned from research applications to operations, providing immense value to water management agencies.

Networks

iSnobal is not part of any formal monitoring network. The model is used operationally in basins in California and Idaho, and it is typically used with ASO for determining snowpack density but can also be run in watersheds without ASO measurements.



The iSnobal workflow and the integration of Airborne Snow Observatory (ASO) data, showing how ASO's lidar-derived snow depths are integrated into the model (Hedrick et al. 2018).

Current and Future Use

iSnobal is used to track snowpack conditions in a number of watersheds in the Sierra Nevada, Pacific Northwest, and Rocky Mountains. It is often integrated with ASO measurements to track snow conditions between ASO flights.

Recent iSnobal development has focused on more efficient processing of data, reporting, and visualization; with ongoing efforts to model future conditions and predict snowpack conditions across days to weeks. ARS is working with the Colorado Basin River Forecast Center (RFC) to assess future iSnobal modeling at RFCs. ARS is working with the Natural Resource Conservation Service's (NRCS) National Water and Climate Center (NWCC) to develop a 30-year model simulation to build upon the current statistically methodology of relating SNOTEL sites to streamflow but using model output. Another nascent area of research is the influence of forest fire upon iSnobal model behavior and accuracy.

iSnobal is one of a growing handful of snow models that can handle higher spatial resolutions, incorporate remotely sensed snow measurements, and can be accurately tuned to a specific region or watershed.

Notable Use Cases

iSnobal has been used extensively in the Reynolds Creek Experimental Watershed in Idaho. Additionally, the model has been deployed successfully in many different types of snowpack settings around the world ranging from the Canadian Arctic to the Sierra Nevada in California, and more recently in many other small and large watersheds, such as the Gunnison River watershed in Colorado. In water years 2019 and 2020, iSnobal simulations were run which covered over 14,000 km^2 of area in real time, providing over 100 snowpack summary reports to multiple watershed stakeholders in California.

Benefits

- iSnobal is a proven model environment that can be flexibly adapted to user needs and to various data sources. It can provide a high-resolution characterization of snowpack properties (e.g., snow depth, density, and water content) and surface water input and can work with a wide range of forcing data.
- Spatially distributed physically-based models such as iSnobal have some of the lowest cost solutions for monitoring snowpack and are especially well suited for large areas.
- iSnobal can be set up at coarse or fine spatial resolution to match the available computing power.
- iSnobal is well suited for using spatial snow measurements to calibrate and update the model (e.g., ASO data, satellite snow depth or coverage information, or other model output).
- iSnobal is available wherever there is adequate weather forcing data. The current atmospheric model has a spatial coverage over the entire continental United States (and Alaska), enabling future applications of iSnobal wherever snowpack estimates are needed.

Challenges

- iSnobal requires intensive set-up and tuning for new areas, but once set up, operational costs decrease.
- Like any model, verification of output and regular calibration is necessary for producing accurate synthetic snow measurements (i.e., accurate model output).
- Like all spatially distributed models that characterize the interaction between snowpack and vegetation, burned forest areas may require a period of recalibration, although this has not been fully explored.
- The suitability of the iSnobal model to an area is mainly limited to the availability of high-resolution gridded weather data inputs to drive the model.

Costs

iSnobal model cost for a basin is higher at initial start-up and calibration and declines somewhat once fully operational for a basin. The modeling cost scales with the size of the basin, the frequency of model reporting, and the availability of congruent forcing and validation data. Costs for large basins (for example basins of 1 million acres) are in the range of $90,000 per year.

References

Havens, S., D. Marks, and E. Rothwell, 2016. Application of a Physically-based Distributed Snowmelt Model in Support of Reservoir Operations and Water Management. Research and Development Office, Science and Technology Program, Final Report: ST-2016-2157-1. https://www.usbr.gov/research/projects/detail.cfm?id=2264.

Havens, S., D. Marks, M. Sandusky, A. Hedrick, M. Johnson, et al., 2020. Automated Water Supply Model (AWSM): Streamlining and standardizing application of a physically based snow model for water resources and reproducible science. Computers & Geosciences, Volume 144, https://doi.org/10.1016/j.cageo.2020.104571.

Hedrick, A. D. Marks, S. Havens, M. Robertson, M., Johnson, et al., 2018. Direct Insertion of NASA Airborne Snow Observatory-Derived Snow Depth Time Series into the iSnobal Energy Balance Snow Model. Water Resources Research, 54.

Marks, D., J. Domingo, D. Susong, T. Link, and D. Garen, 1999. A spatially distributed energy balance snowmelt model for application in mountain basins. Hydrological Processes, 13(12-13), 1935-1959.

University of Colorado Real Time Spatial Estimates of Snow Water Equivalent

About the Technology

University of Colorado real-time spatial estimates of snow water equivalent (CU-SWE) uses a statistical approach that blends satellite data, physiographic properties, ground-based snow monitoring station data, and analog historical snow patterns to produce spatially distributed estimates of snow water equivalent (SWE), snow depth, and snow-covered area. Latency to produce the data is approximately 1 week from satellite data acquisition. Data are typically accompanied by a summary report.

Temporal Resolution

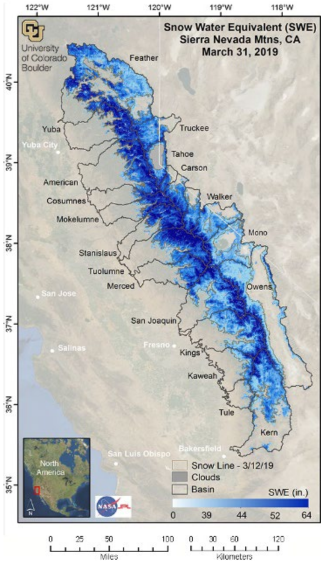
The frequency with which this data can be updated is typically governed by acquisition of suitable satellite data. Typically, this rhythm results in updates occurring every 2 weeks.

Spatial Resolution

Data is produced on a 500 x 500-meter (m) grid, which is the resolution of the MODIS data that the method relies upon.

Verification Performance and Process

Verification is performed using leave-out cross validation for 10 percent of SNOTEL data in a region being modeled. Additionally, the method has been verified against manual field measurements that were not used in model training. Based on this, SWE estimates are reported to have sub-meter SWE error. Validation of 500 m gridded snow data against point SNOTEL data can have challenges.



March 31, 2019 Sierra Nevada snow water equivalent.
Image courtesy of University of Colorado Mountain Hydrology Group

CU-SWE provides 500 meter gridded snow information the blends satellite and in-situ data using a statistical framework.

Quantity Measured

Snow water equivalent, snow depth, snow covered area

Technology Readiness Level (TRL): 7

Availability

Data are produced by the University of Colorado Mountain Hydrology Group.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Suitability

Regional Performance/Strengths

The method has potential for extensibility across much of the Western United States, although certain considerations may make some regions less conducive. Of note, the method uses Moderate Resolution Imaging Spectroradiometer (MODIS) optical imagery data.

Regions like the Pacific Northwest that have frequent cloud cover may make acquiring suitable satellite data challenging. Further, the method leverages ground-based snow monitoring station data. If these data aren't sufficiently available (in number of stations and length of record), accuracy may be negatively impacted.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

The CU-SWE framework is flexible and has potential to leverage other, less regular snow information such as aircraft-based snow surveys.

Current and Future Planned Uses

To date, CU-SWE has been produced in the Sierra Nevada of California and in the Upper Colorado River Basin. Work is currenlty underway to apply the metthod retrospecively and generate historical SWE estiamtes for 2001-2021 in both the Sierra Nevada and Upper Colorado River Basin. Califronia Department of Water Resouces (CA-DWR) considers these data in generating their Bulletin 120 water supply forecasts. The Colorado Basin River Forecast Center will be evaluating these data in the coming year for forecast improvement potential.

Benefits

- The data are accompanied with a summary report that includes graphical presenation of the data along with a narrative discussion.
- The method has flexibility to take advantage of other data sources.
- The method can be applied retrospectively to produce (~ 20-year records).

Challenges

- Latency is about 1 week from satellite data acquisition. This may or may not be a challenge, depending on needs and how quickly conditions are changing.

- Quality/availability of satellite data can be impacted by cloud cover and satellite angle.
- Error can be higher in situations with significant low elevation snow or when only very high elevation snow remains.

Costs

Most data and inputs for this method are freely available. Costs are primarily driven by staff labor to apply the method and generate the accompanying reports. Computational resources to support the application of this modeling technology must also be considered. Costs are also a function of the spatial extent for which the data are generated, and the number of times estimates are produced during a given snow season.

References

Molotch, N, L. Lestak, D. Schneider, and K. Musselman, 2018. Real-Time Spatial Estimates of Snow-Water Equivalent (SWE). http://instaar.colorado.edu/uploads/research/labs-groups/mountain-hydrology-group/RT_SWE_Report_methods.pdf.

Schneider, D. and N. Molotch, 2016. Real-Time Estimation of Snow Water Equivalent in the Upper Colorado River Basin Using MODIS-Based SWE Reconstructions and SNOTEL Data. Water Resources Research 52, 7892–7910.

SNOW-17

About the Technology

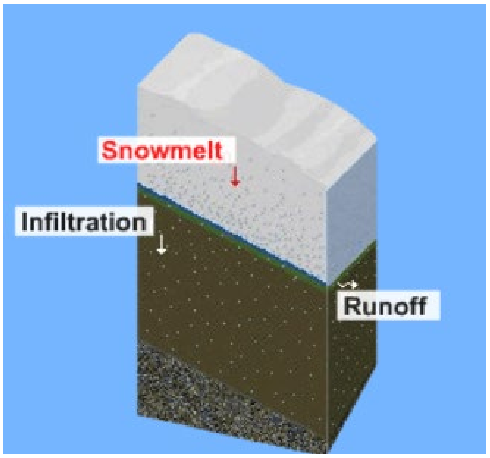
SNOW-17 is the snow model that is typically paired with the Sacramento Soil Moisture Accounting (SAC-SMA) hydrology model at National Oceanic and Atmospheric Administration (NOAA) River Forecast Centers (RFCs) and is used in operational streamflow forecasting. SNOW-17 is a relatively simple snow model compared to new models that simulate the entire energy balance of the snow. SNOW-17 is a temperature index model that estimates snow water equivalent (SWE) using observed precipitation and temperature from Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) and California Cooperative Snow Surveys (CCSS) locations, along with Parameter-elevation Regressions on Independent Slopes Model. (PRISM) climatology. The framework simulates snowpack accumulation, and ablation is simulated using temperature, precipitation, and freezing level information. The model is, therefore, a relatively simple conceptual model compared to newer, computationally and data intensive energy balance models.

Temporal Resolution

The SNOW-17 model is normally updated with new snow conditions and run every day (though this could also be every few hours). The model then solves for new snow conditions every 6 hours, though it can be refined to other frequencies (e.g., every 1, 2, 3, 4, 6, 8, 12, and 24 hours).

Spatial Resolution

In SNOW-17, a large river system is split up into watersheds. Each watershed is split into two or three segments based on the elevation of the different parts of the watershed. Snow conditions are then solved at each watershed.



Relationship between snowpack and runoff.
Image courtesy of COMET MetEd.

SNOW-17 is the most commonly used snow model at RFCs in the Western United States to simulate snowpack conditions. The model simulates outflow from snow using a relatively simple algorithm that does not require many inputs.

Quantity Measured

SWE, snow depth, snow covered area, outflow

Technology Readiness Level (TRL): 9

Availability

RFCs use SNOW-17 as their primary snow model for forecasting water supply.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Verification Performance and Process

For the computational and data requirements, SNOW-17 does very well and often compare similarly with other more robust energy-based snow models, though results are variable, and this is an active area of research. Researchers are looking for ways to improve the energy balance snow models, which may improve their results.

Suitability

Regional Performance/Strengths

SNOW-17 is typically used where seasonal runoff is driven by snowmelt, such as mountainous regions in the Western United States, though can be used in flatter areas.

Suitability for Citizen Science

Not suitable.

Other Technologies

Other technologies or snow products cannot be easily ingested into SNOW-17. Forecasters can change snow conditions in SNOW-17 based on snow data (e.g., satellite, Airborne Snow Observatory [ASO], etc.), but this would require manual input from forecasters.

Current and Future Planned Uses

RFCs in the Western United States use SNOW-17 as their snow model to produce operational streamflow forecasts. They do not have plans to move away from SNOW-17. If snow energy balance models become more accurate and less data intensive, RFCs could move towards an alternative snow model.

Benefits

- SNOW-17 is a relatively simple model that only requires two variables (temperature and precipitation) to run. These variables are readily available with a long historical record, which is needed for model calibration.
- SNOW-17 meshes well with RFCs’ operational hydrology model, SAC-SMA.

Challenges

- SNOW-17 is calibrated based on historical conditions in a watershed and may encounter challenges simulating conditions not experienced in the historical record.
- SNOW-17 may require forecasters to manually adjust the initial snow information inside the model to ensure that an accurate runoff will be being simulated.

Costs

Cost is generally low to set up and maintain.

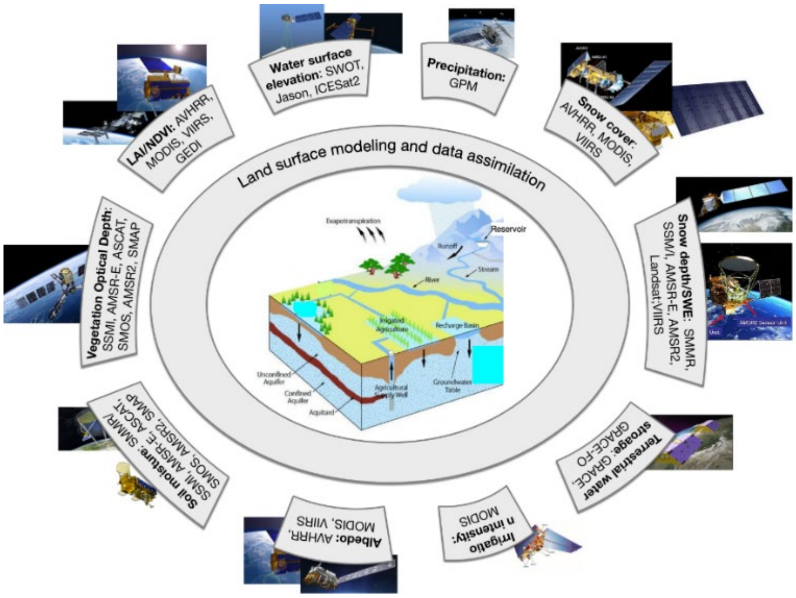
References

Anderson, E. A., 2006. Snow Accumulation and Ablation Model – SNOW-17, Nat. Weather Serv., 44 pp., https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcseprd1805290&ext=pdf.

Land Data Assimilation Systems

About the Technology

Land data assimilation systems (LDAS) ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes (Rodell et al. 2004). Snow water equivalent (SWE) is one of these land surface states. The National Aeronautics and Space Administration (NASA) Land Information System (LIS) is a software framework that enables users to drive multiple, offline (not coupled to the atmosphere) land surface models with a variety of different meteorological forcing inputs and other configuration options (Kumar et al. 2006). It also can integrate satellite observations of various land surface states, using ensemble Kalman filter data assimilation, leading to more accurate representations of these states (Kumar et al. 2019). Various instances of LIS now run routinely. In particular, the Global LDAS (GLDAS; Rodell et al. 2004) includes a simulation of the Catchment land surface model, into which observations of terrestrial water storage anomalies from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On (GRACE-FO) satellite missions are assimilated (GRACE-DA; Li et al. 2020), resulting in improved estimates of SWE. Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data assimilation (Rodell and Houser 2004) will be incorporated into this simulation in the near future.



Satellite-based datasets that can be integrated into land data assimilation systems to generate timely, spatially continuous, observation-constrained outputs, including gridded fields of snow water equivalent.
Image courtesy of C. Peters-Lidard/ National Aeronautics and Space Administration.

Land Data Assimilation Systems integrate data from various sources to produce spatially and temporally continuous, gridded fields of snow water equivalent, among other variables.

Quantity Modeled

SWE

Technology Readiness Level (TRL): 9

Availability

GLDAS GRACE-DA output are freely available from GES DISC.

Note: Reclamation developed this technology description in 2021 based on available information. Mentions of product names does not constitute an endorsement. See the main Report to Congress for an overall summary.

Temporal Resolution

LDAS land surface models typically run on a 15-minute timestep and produce hourly, 3-hourly, or daily output fields. These are often available within 48 hours to 2 months of real time, depending on the product.

Spatial Resolution

The GLDAS GRACE-DA products are available on a 0.125 degree grid over the contiguous United States and on a 0.25 degree grid globally.

Verification Performance and Process

LDAS outputs have been evaluated by numerous investigators using ground and satellite-based observations and through model intercomparisons. Uncertainty in the output fields is often estimated using the standard deviation across outputs from multiple model configurations as a proxy (Kato et al. 2007).

Suitability

Regional Performance/Strengths

Owing to their global availability, LDAS simulated SWE fields are particularly valuable where direct observations are scarce. They are more accurate where meteorological network observations, particularly precipitation, are dense.

Suitability for Citizen Science

There are limited opportunities for citizen science related to this technology. Citizen science measurements may support validation/verification.

Other Technologies

LDASs rely on numerous ground and space-based observation technologies, associated retrieval algorithms, and atmospheric analysis models that also contribute meteorological forcing inputs.

Current and Future Planned Uses

The Land Information System has been operationally implemented by the Air Force 557th Weather Wing, the United Kingdom Met Office, and National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP), among others. Output from the GLDAS GRACE-DA simulation are incorporated into the weekly U.S. Drought Monitor maps. GLDAS output is routinely downloaded from Goddard Earth Sciences Data and Information Services Center (GES DISC) by 800 or more unique users each month.

Benefits

- Globally continuous, gridded fields.
- GLDAS GRACE-DA output are available within 2-8 days of real time.
- Data are publicly available and may be visualized on the GES DISC website.

Challenges

- Land surface models aim to simulate physical processes based on our incomplete understanding of these processes, in a computationally economic manner. Hence errors are common, particularly over complex terrain.
- Uncertainty in LDAS simulated SWE is directly related to uncertainty in the input meteorological fields, particularly precipitation and temperature. Where these are poorly observed, simulated SWE is likely to suffer.

Costs

GLDAS data are freely available. Most data and inputs are freely available. Costs are primarily driven by manpower. Supercomputing resource costs must also be considered.

References

Kato, H., M. Rodell, F. Beyrich, H. Cleugh, E. van Gorsel, et al., 2007. Sensitivity of land surface simulations to model physics, land characteristics, and forcings at four CEOP sites. J. Meteorol. Soc. Jpn. Ser. II, 85, pp.187-204.

Kumar, S.V., C.D. Peters-Lidard, Y. Tian, P.R. Houser, J. Geiger, et al., 2006. Land information system: An interoperable framework for high resolution land surface modeling. Environ. Model. Softw., 21(10), 1402-1415.

Li, B., M. Rodell, S. Kumar, H.K. Beaudoing, A. Getirana, et al., 2019. Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. Water Resour. Res., 55(9), 7564-7586.

Rodell, M. and P.R. Houser, 2004. Updating a land surface model with MODIS-derived snow cover. J. Hydrometeor., 5(6), 1064-1075.

Rodell, M., P.R. Houser, U.E.A. Jambor, J. Gottschalck, K. Mitchell, et al., 2004. The global land data assimilation system. Bull. Amer. Meteorol. Soc., 85(3), 381-394.