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Remote Sensing of Cryosphere

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1. Introduction

The cryosphere is the frozen water part of the Earth's system. The word is derived from the Greek "kryos," meaning cold. Snow and ice are the main ingredients of the cryosphere and may be found in many forms, including snow cover, sea ice, freshwater ice, permafrost, and continental ice masses such as glaciers and ice sheets. Snow is precipitation made up of ice particles formed mainly by sublimation (NSIDC, 2011). Ice is the key element in glaciers, ice sheets, ice shelves and frozen ground. Sea ice forms when the ocean water temperature falls below freezing. Permafrost occurs when the ground is frozen for a long period of time, at least two years below 0^0 C, and varies in thickness from several meters to thousands of meters (NSIDC, 2011). Glaciers are thick masses of ice on land that are caused by many seasons of snowfall. Glaciers move under their own weight, the external effect of gravity, and physical and chemical changes. The cryosphere lowers the earth's surface temperature by reflecting a large amount of sunlight, stores fresh water for millions of people, and provides habitat for many plants and animals.

Apart from the Arctic and Antarctic regions, the cryosphere is mainly a high altitude phenomenon. It is found on Mount Kilimanjaro in Africa, the Himalayan mountain range, high mountains of United States, and in Canada, Russia, Japan, and China. Researchers in the cryosphere are often hindered by the lack of accessibility due to the rugged terrain. In such cases, remote sensing technologies play an important role in cryosphere research. These techniques are imperative for researchers studying glacial retreat and mass balance change in relation to global climate change.

The cryosphere has a significant influence on global climate and human livelihoods. Change in spatial and temporal distribution of the cryosphere influences the water flow in the world's major rivers. Among the various parts of the cryosphere, glaciers play the most important role in climate change studies since glacier recessions are indicators of global climate change (Oerlemans et al., 1998; Wessels et al., 2002; Ambinakudige, 2010). Retreating glaciers can pose significant hazards to people (Kaab et al., 2002). Glacier retreat often lead to the formation of glacial lakes at high altitudes, the expansion of existing lakes, and the potential for glacial lake outburst floods (GLOFs) (Fujita et al., 2001; Bajracharya et al., 2007). A GLOF is the sudden discharge of a huge volume of water stored in a glacial lake due to huge ice falls, earthquakes, avalanches, rock fall or failure of a moraine dam (Grabs & Hanisch, 1993). There are more than 15,000 glaciers and 9,000 glacial lakes in the Himalayan mountain ranges of Bhutan, Nepal, Pakistan, China and India (Bajracharya et al., 2007). All

these countries within the Himalayan region have at some time or another suffered a flood from a glacial lake outburst causing loss of property and lives, and these floods can be disastrous for the downstream riparian area (Richardson & Reynolds, 2000; Bajracharya et al., 2007). The significance of the glaciers as fresh water resources for millions of people is another reason to justify the continuous monitoring of these glaciers (Shiyin et al., 2003). Therefore, monitoring glaciers has significant importance both in understanding global climate change and in sustaining the livelihoods of the people downstream of the glaciers.

This chapter explores the use of remote sensing technologies in studies of the cryosphere and particularly in glaciers. First, we will discuss remote sensing sensors that are effective in monitoring glaciers. Then we will discuss the global effort to create glacier data, using remote sensing tools to delineate glacier areas, estimate volume and mass balance.

2. Remote sensors for monitoring glaciers

Remote sensing methods are more convenient than field methods to measure changes in glaciers. Studies have used Landsat (Ambinakudige, 2010), SPOT (Berthier et al., 2007), Terra ASTER (Rivera & Casassa, 1999; Kaab, 2007), IRS (Kulkarni et al. 2011), and ALOS (Narama et al., 2007) sensors successfully to measure glacial parameters. High-resolution satellite data such as IKONOS (Huggel et al., 2004) and Quickbird (Schmidt, 2009) have also been used in studies on glaciers. ASTER, SPOT5, IRS-1C, Resourcesat1 and 2, CORONA KH-4, KH 4A and KH 4B satellites have the capability to acquire stereoscopic images from which elevation data can be extracted for monitoring glacial surfaces in three dimensions (Racoviteanu, et al. 2008). Digital elevation models developed from these stereoscopic images can be used in measuring volume and mass balance change in glaciers.

2.1 Glacial mapping

Glacial mapping using remote sensing initially involved manual digitization of glacier boundaries on a false color composite (FCC) of Landsat MSS and TM images in Iceland (Williams, 1987) and Austria (Hall et al., 1992). Figure 1, is a picture taken by the astronauts in the international space station shows the snow and ice in Colonia glacier and its surroundings in Chile (International Space Station, 2000).

Snow has high reflectivity in the visible wavelength region and relatively less reflectivity in middle and shortwave infrared regions (Pellika and Rees, 2010). Freshly fallen snow has the highest reflectance in the visible and near-infrared wavelengths. Firn (partially compacted snow) has 25-30 % less reflectance than snow. Ice in glaciers has high reflectance in blue (400- 500 nm) and green (500 – 600 nm) wavelengths. However, in red (600-700 nm) the reflectance of ice is near zero. Debris in glaciers will significantly reduce the reflectance (Pellika and Rees, 2010). The spectral reflectance properties of snow also depend on time and season of the year. Sharp changes in the reflectance of snow can be seen when the melted snow recrystallizes to form firn and the density of snow changes. Similarly, albedo, which is the ratio of radiation reflected from a surface to the radiation incident on that surface, also varies among different cryospheric surfaces. Snow has high albedo (0.8 – 0.97) while dirty ice has low albedo (0.15-0.25). A high albedo value helps to reflect a huge amount of sunlight, which otherwise would have heated the earth's surface. Snow and ice reflectance is the main characteristic that is measured using remote sensing techniques. This

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Fig. 1. Astronaut photograph of Colonia Glacier, Chile. Photographer: International Space Station (2000).

characteristic assists in delineating glacier boundaries and classifying various cryospheric surface types (Pellika and Rees, 2010).

In figure 2, the Landsat TM bands 1 to 6, acquired on 25 April 2010, are shown to compare spectral characteristics of glaciers. This figure presents the area around the Imja glacier in the Sagarmatha National Park in the Himalayas of Nepal. TM1 (0.45 – 0.52 μm) is useful to distinguish snow/ice in cast shadow, and also in mapping glacier lakes. Snow and firn areas get saturated in TM1. TM2 (0.52 – 0.60 μm) and TM3 (0.63 – 0.69 μm) have very similar spectral reflectance. TM2 is also useful in distinguishing snow and ice in cast shadow. TM3 is used in band ratio such as the normalized difference vegetation index (NDVI), which helps in classification of ice and snow in areas of dense vegetation. TM4 (0.76-0.90 μm) in the near infrared wavelength region has less reflectance from snow than TM2 and TM3. The clean ice region looks darker in near infrared band, indicating lower reflectance due to the presence of water at the surface (Hall et al., 1988). In TM5, the snow-covered area absorbs nearly all radiation and appears almost dark. This band is also useful in identifying clouds. The thermal band TM6 (2.08-2.35 μm) registers thermal emissions from the surface. Debris has a higher temperature and thus brighter pixels. Thick debris on ice can be easily distinguished as it will have a higher temperature (Pellika and Rees, 2010).

The high reflectance of the snow compared to the ice makes it easy to separate snow and ice. Snow and clouds are often difficult to distinguish when single imagery is used. Clouds and snow have similar reflectance at wavelengths below 1 μm in the near infrared region. The distinction between snow and ice is clearer near 1.55 and 1.75 μm. Therefore a ratio of two
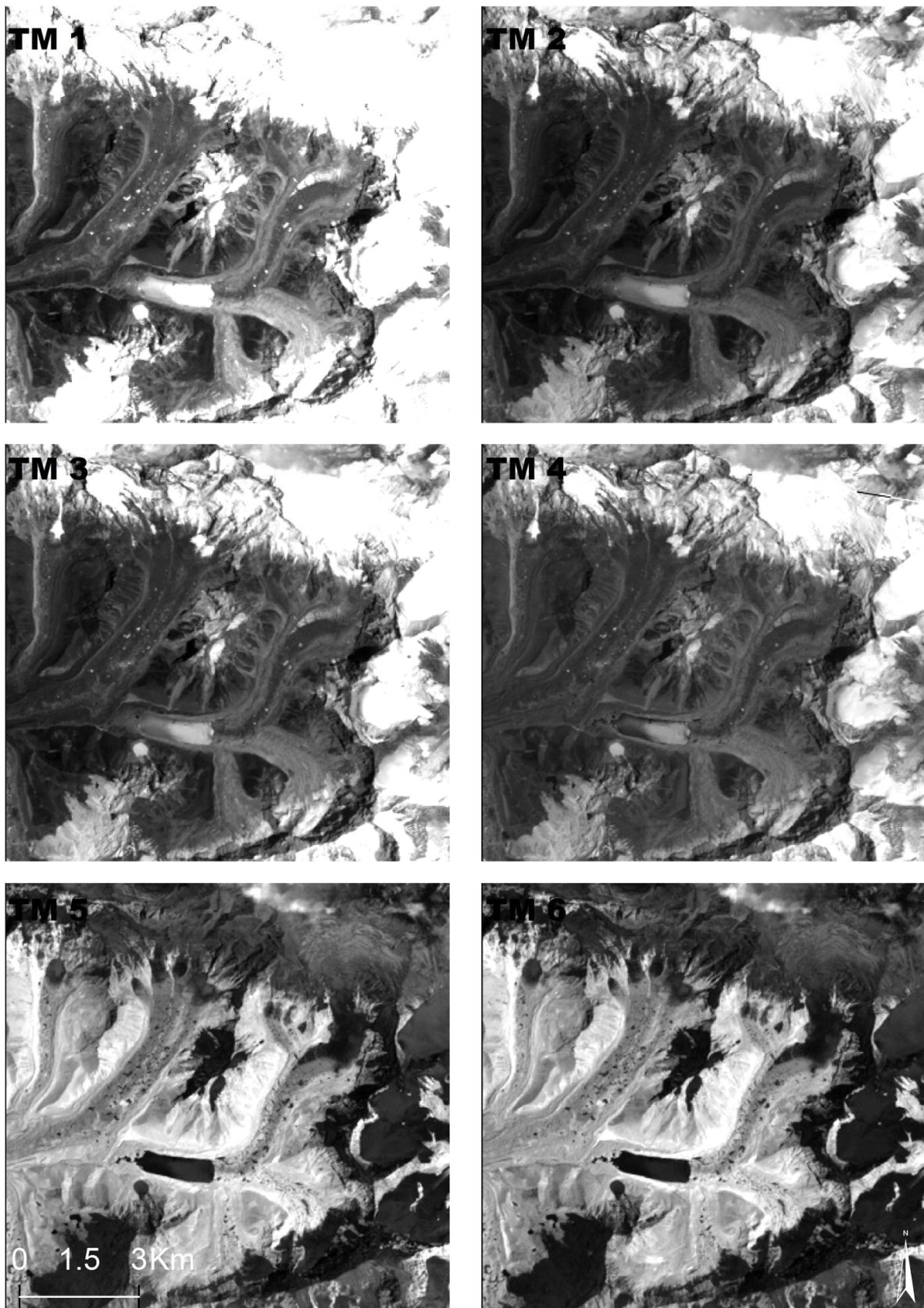
Fig. 2. Six Landsat TM bands showing Imja and surrounding glaciers in the Himalayas.

spectral bands in the visible (VIS) and shortwave near infrared (SWIR) regions are commonly used in automated mapping of snow and ice. A Normalized Difference Snow Index (NDSI) calculated as (VIS-SWIR)/(VIS+ SWIR) helps to separate snow and ice from darker areas such as rocks and soils. Whereas the visual spectrum band covers a wavelength of 0.57µm, the shortwave infrared band covers 1.65µm. If the NDSI value exceeds 0.4, it is assumed there is snow cover on the ground (Dozier 1984). However, seasonal variation in NDSI value for snow has also been observed. A threshold of 0.48 in July and 0.6 in September was observed as an optimal threshold during the field investigation in Abisko, Sweden (Vogel 2002). The Normalized Difference Water Index (NDWI) calculated as (NIR-VIS)/(NIR+VIS) is useful to differentiate water from snow, ice and other physical features. NDWI is very useful in detecting formation of new, as well expansion of existing, glacial lakes (Huggel et al., 2002).

Band ratios such as Landsat TM3/TM5 or TM4/TM5 are also helpful in mapping glacial areas. The TM4/TM5 ratio is more appropriate for clean-ice glacier mapping (Paul and Kaab, 2001), whereas TM3/TM5 works better in areas of dark shadow and thin debris cover (Andreassen et al., 2002). Both NDSI and ratio methods have similar robust outcomes in glacier mapping and are recommended. NDSI and band ratio methods often misclassify debris-covered glacier ice because of the similarity in spectral signature to the surrounding debris Band ratio VIS/NIR also often misclassifies proglacial lakes. The band ratio NIR/SWIR is good for classifying only clean glacier ice (Bhambri and Bolch, 2009). Therefore, manual corrections have to be made after classifying glaciers using either NDSI or ratio methods. High resolution panchromatic images used in manual corrections can help to delineate the precise boundaries of glaciers. Similarly, figure 3 also indicates spectral responses of different types of snow and water.
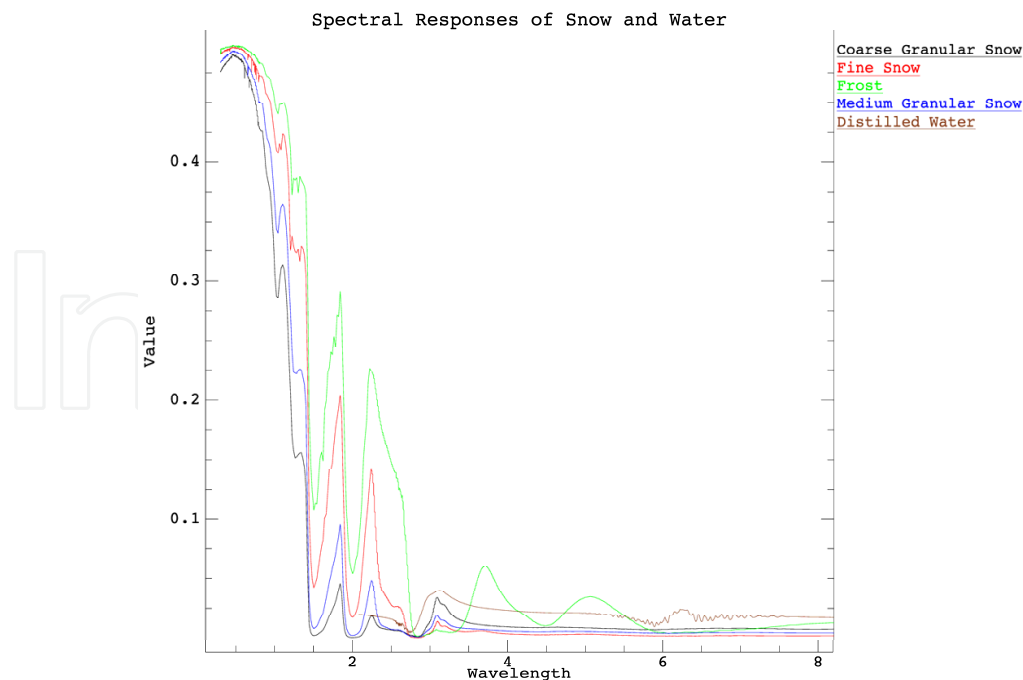
(Data Source: ENVI Spectral Library derived from John Hopkins University
http://asterweb.jpl.nasa.gov/speclib/)

Fig. 3. Spectral responses of different types of snow and water

3. Digital elevation models in glacier mapping

Debris-covered glaciers can be mapped effectively by using morphometric parameters derived from DEM and thermal bands (Ranzi et al., 2004). The surface temperatures of the debris on glacier ice are cooler than the debris outside the ice, which can be identified by a thermal image. AVHRR and MODIS satellites have coarse resolution thermal bands; the Landsat TM/ETM+ satellite, on the other hand, has a higher resolution thermal band. Using morphometric characteristics like slope can help to separate a debris-covered glacier from its surrounding moraines (Bishop et al., 2001). DEMs help in estimating morphometric characteristics such as slope, glacier profile curvature, and aspect. DEMs are most important for the estimation of volume change for inaccessible glacier regions (Bolch et al., 2008).

DEMs are generated from topographic maps, spaceborne optical stereo data, synthetic aperture radar (SAR) imagery, spaceborne radar and laser altimetry, such as LiDAR data. Terra ASTER optical stereo satellite data with a spatial resolution of 15 m has been used successfully in generating DEM to study glaciers (Kargel et al., 2005). SPOT-5, ALOS PRISM, CartoSat I and II, IKONOS, Quickbird and GeoEye-1 satellites also have stereo capability and can be used in creating DEMs. ASTER and ALOS PRISM produce along-track stereo images and are capable of simultaneous image acquisition. Other sensors provide across-track acquisition with a time lag, which causes problems in certain situations, such as under different atmospheric conditions (Bhambri & Boch, 2009). Measuring surface changes using DEMs, known as indirect geodetic methods, is a useful method to calculate a glacier's volume and mass balance changes (Etzelmüller & Sollid, 1997).

Another technology used to study the cryosphere is radar, which is an active microwave system composed of a transmitter and a receiver. Radar imagery is not confined only to daylight, cloud-free conditions, and thus has advantages in estimating glacial change. The first spaceborne SAR was the SEASAT satellite, launched in 1978. ERS-1/2, Envisat – ASAR, Radarsat-1, ALOS PALSAR, Radarsat-2 and TerraSAR-X are some of the satellites with spaceborne SAR launched after the initial success of SEASAT. Due to its all-day, all-weather imaging capabilities, large spatial coverage, and ability to measure minute changes on the earth's surface, SAR has a major advantage in glacier studies. Digital elevation models (DEM) created using SAR images are useful in measuring glacier mass balance, glacier velocity, and snow density.

Light Detection and Ranging (LiDAR) is also used in remote sensing of glaciers. High density measurement with a high vertical accuracy (10 cm) allows a very detailed representation of terrain in LiDAR imagery. LiDAR imagery also comes with accurate positional information because of the global positioning system receiver in the LiDAR instruments on aircraft.

4. The geodetic method of measuring glacier mass balance

The mass balance of a glacier is referred to as the total loss or gain in glacier mass at the end of a hydrological year (Cuffey and Paterson, 2010). Glacier mass balance is the link between climate and glacier dynamics (Kaser et al., 2002). Mass balance change is a direct reaction to

atmospheric conditions. The specific mass balance can be compared directly between different glaciers. This makes it easier than using length changes to establish a link to climate data (UNEP, 2008). Glacier mass losses affect local hydrology and are thus important for regional water supplies and assessing global sea level rise.

In the geodetic method, changes of glacier volume are measured from maps and elevation models, unlike the direct or glaciological methods that derive mass changes from ground-based spot measurements. With the development of remote sensing techniques, digital elevation models (DEM) are commonly used in the geodetic method. The difference in DEM values in two years is multiplied by the glacier accumulation area to obtain volume change (dV). The difference in volume (dV) multiplied by the density of ice, generally considered to be 850-900 Kg/m^3, would provide the mass balance (Cuffey & Paterson, 2010).

The accumulation and ablation area in a typical glacier is separated by an equilibrium line altitude (ELA). This line divides the accumulation zone (the higher reaches of a glacier where there is a net mass gain) and the ablation zone (the lower reaches where mass is lost). ELA is the elevation at which mass is neither gained nor lost through the course of a hydrological year. At the end of the season, the elevation at which there was no net gain or loss is identified as the ELA. The snow line altitude (SLA) divides the ice in the ablation zone from the snow in the accumulation zone. Since ice and firn have lower albedo, SLA can be determined using remote sensing images (Khalsa et al., 2004; Racoviteanu et al., 2007).

The geodetic approach has been used in several studies based on historical topographic maps and DEMs derived from SPOT imagery (Berthier et al., 2007), SRTM (Racoviteanu et al., 2007), ASTER (Rivera & Cassassa, 1999; Kaab, 2007). Studies have also used high resolution DEMs derived from ALOS PRISM and Corona (Narama et al., 2007) to estimate mass balances with the geodetic method.

The two bands in ASTER VNIR, 3N and 3B, generate an along-track stereo pair with a base-to-height (B/H) ratio of about 0.6. Studies have found that the DEM accuracy has a linear relation with terrain slopes (Toutin, 2008; Bolch et al., 2004; Racoviteanu et al., 2007). DEMs created using ASTER images on Mt. Fuji, Japan; in the Andes Mountains, Chile-Bolivia; at San Bernardino, CA and Huntsville, AL resulted an accuracy of ±5 m, ±10m, ± 6m and ± 1.5m respectively (Hirano, 2003). Therefore, accuracy, number and distribution of GCPs are required to create an accurate DEM.

The ALOS data have been available since January 2006. ALOS has three remote-sensing instruments. The Panchromatic Remote-Sensing Instrument for Stereo Mapping (PRISM) sensor of ALOS data is suitable for digital elevation mapping. It consists of three independent telescopes for forward, nadir and backward view, and each telescope provides 2.5m spatial resolution. The Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) sensor collects data with 10m resolution and is suitable for glacier mapping. The accuracy of elevation extracted from ALOS PRISM is 5 m (Racoviteanu et al., 2008).

The three images (forward, nadir and backward) that ALOS provides are required for creation of DEM (Ye, 2010). The base-to-height (B/H) of PRISM on ALOS is set to 1.0

(forward view + backward view) and 0.5 (sidelong view + nadir view). ALOS images have been used to produce highly accurate DEMS. The DEMs created for the northern slope of Qomolangma in the Mt. Everest region had a mean elevation difference of 1.7m with a DEM created using topographic maps in non-glaciated areas. The mean difference between Aster and ALOS images was found to be about 45m (Ye, 2010).

Once the outlines of the glaciers are delineated, they can be combined with DEM to derive glacier parameters such as length, termini elevations, and volume. DEMs derived from SPOT5, ASTER, CORONA or ALOS PRISM can be used in mass balance studies.

5. Global Land Ice Measurements from Space (GLIMS)

In an effort to analyze the glacial change throughout the world, a global-level consortium, the Global Land Ice Measurements (GLIMS), has established a database at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado (Raup et al., 2007). Under GLIMS, 12 regional centers are working to acquire satellite images, analyze them for glacial extent and changes, and assess change data for causes and implications for people and the environment.

GLIMS is an international consortium established to monitor the world's glaciers. Although GLIMS is making use of multiple remote-sensing systems, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images are the major data input in GLIMS database. The GLIMS team has put together a network of international collaborators who analyze imagery of glaciers in their regions of expertise. Collaborators provide digital glacier outlines and metadata. Data also include snow lines, center flow lines, hypsometry data, surface velocity fields, and literature references. The National Snow and Ice Data Center archives the data provided by the regional centers.

The GLIMS team also developed tools to aid in glacier mapping, such as GLIMSView, which is an open-source, cross-platform application designed to support and standardize the glacier digitization process. It allows regional centers to transfer data to the National Snow and Ice Data Center for incorporation into the GLIMS glacier database. Users can view various types of satellite imagery, digitize glacier outlines and other material units within the images, attach GLIMS-specific attributes to segments of these outlines, and save the outlines to ESRI shapefiles. GLIMSView is free and available at http://www.glims.org/glimsview/.

6. Conclusions

Satellite remote sensing of the cryosphere has progressed over the last five decades. It has helped us to understand the global distribution of the cryosphere, variation and trends in snow cover, sea ice, and glaciers. We have a pretty decent map of the cryosphere. Remote sensing has helped in rapid assessment of glaciers in hostile ground conditions in areas such as Antarctica, the Artic and alpine glaciers.

There are several challenges in remote sensing of the cryosphere. Acquiring cloud-free satellite imagery is still challenging. Synthetic aperture radar (SAR) imagery has received a great deal of attention in recent years as it can provide cloud-free data. SAR interferometry has been used successfully in areas such as glacier motion and topographical mapping. The

use of radar has been gaining more attention recently. Ground penetrating radars are being used to study the internal structure and bedrock configuration of glaciers.

For most part, *in situ* measurement of the cryosphere is often not a viable option, so the focus of cryosphere study remains on the use of remote sensing techniques. The World Glacier Monitoring Service (WGMS) coordinates the global glacier observation strategy with the help of the Global Land Ice Measurement from Space project and the European Space Agency's Global Glacier Project.

Spaceborne remote sensing techniques in the last five decades have shown tremendous advancement. From Landsat to InSAR imagery, the remote sensing technology has helped in understanding and mapping the cryosphere. Many of these data are available free or for low cost; some of them are very expensive, and using them requires specialized skill. With the increase in computer processing power, the potential for the collection, storage, transmission and processing of remotely sensed data on the cryosphere has improved.

Changes in glaciers provide evidence of climate change, and therefore glaciers play a key role in early detection of global climate-related observations (WGMS, 2011). Glacier change will impact global sea level fluctuations and other natural hazards. These environmental changes require international glacier monitoring efforts to make use of remote sensing and geo-informatics along with the more traditional field observations.

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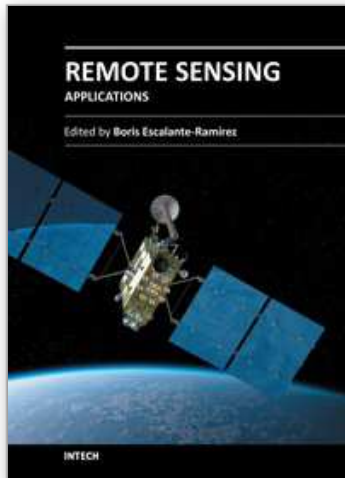
Remote Sensing - Applications

Edited by Dr. Boris Escalante

Nowadays it is hard to find areas of human activity and development that have not profited from or contributed to remote sensing. Natural, physical and social activities find in remote sensing a common ground for interaction and development. This book intends to show the reader how remote sensing impacts other areas of science, technology, and human activity, by displaying a selected number of high quality contributions dealing with different remote sensing applications.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

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