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# Applications of remote sensing, GIS and GPS in glaciology: a review

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**Abstract:** Remote sensing has served as an efficient method of gathering data about glaciers since its emergence. The recent advent of Geographic Information Systems (GIS) and Global Positioning Systems (GPS) has created an effective means by which the acquired data are analysed for the effective monitoring and mapping of temporal dynamics of glaciers. A large number of researchers have taken advantage of remote sensing, GIS and GPS in their studies of glaciers. These applications are comprehensively reviewed in this paper. This review shows that glacial features identifiable from aerial photographs and satellite imagery include spatial extent, transient snowline, equilibrium line elevation, accumulation and ablation zones, and differentiation of ice/snow. Digital image processing (e.g., image enhancement, spectral ratioing and automatic classification) improves the ease and accuracy of mapping these parameters. The traditional visible light/infrared remote sensing of two-dimensional glacier distribution has been extended to three-dimensional volume estimation and dynamic monitoring using radar imagery and GPS. Longitudinal variations in glacial extent have been detected from multi-temporal images in GIS. However, the detected variations have neither been explored nor modelled from environmental and topographic variables. GPS has been utilized independent of remote sensing and GIS to determine glacier ice velocity and to obtain information about glacier surfaces. Therefore, the potential afforded by the integration of nonconventional remote sensing (e.g., SAR interferometry) with GIS and GPS still remains to be realized in glaciology. The emergence of new satellite images will make remote sensing of glaciology more predictive, more global and towards longer terms.

**Key words:** GIS, glaciers, GPS, remote sensing.

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## I Introduction

Owing to their synoptic view, repetitive coverage and up-to-datedness, remote sensing materials are an unprecedentedly powerful and efficient media by which to study glaciers that are usually located in remote, inaccessible and inhospitable environments. Sensors mounted on air- or space-borne platforms enable glaciers at various conditions to be captured. The launch of the first earth resources technology satellite (later renamed Landsat) in the early 1970s aroused tremendous interest in applying remote sensing to various sub-fields in glaciology. The advent of Geographic Information Systems (GIS) has further facilitated the detection of glaciers and evolution of their spatial extent from multi-temporal images. The introduction of GIS to modelling snowmelt runoff allows data from other sources to be incorporated. Recent developments in Global Positioning Systems (GPS) have provided renewed opportunities for rapidly and frequently monitoring the dynamic motion of glaciers and in estimating glacier mass balance. The speed and accuracy of GPS techniques make them particularly suitable for repeated glacier mapping.

Knight (1992) discussed the contribution geographers have made to studies of glaciers and reviewed papers published between 1987 and 1990. Since then many more applications have been carried out using remote sensing, GIS and GPS, either separately or integrated. These applications are reviewed comprehensively in this paper, which represents an attempt to update and drastically expand the review by Drewry (1979) on remote sensing of large ice masses, mostly carried out using coarse-resolution satellite data. This paper, however, is restricted to studies of terrestrial glaciers such as ice caps, ice sheets and ice shelves. Thus, those involving sea ice are beyond the scope of the paper. Literature on such applications can be found in Piwowar and LeDrew (1995) and Rees and Squire (1989).

This paper is divided into six sections. The following section discusses the feasibility of studying glaciers by means of remote sensing. The third section concentrates on the utility of various remote sensing data in glacier studies. It is followed by a discussion on glacier parameters identifiable using remote sensing. The applications of GIS and GPS in these identifications are also presented in this section. Section V discusses the future prospects of remote sensing of glaciology in light of new satellite images. Finally, the paper ends with a summary and conclusions.

## II Feasibility of remotely sensing glaciers

Whether a glacier can be successfully studied from remotely sensed materials depends upon its spectral uniqueness, spectral, spatial and temporal resolutions of the remotely sensed data, as well as the particular feature related to this glacier. The spectral property of glacier ice is examined in this section. The other two factors are discussed in the subsequent sections.

The spectral property or surface albedo of glaciers governs their separability from other covers on remote sensing images. In order for glaciers to be detected from remotely sensed materials, they must be spectrally discernible from the air or space. Figure 1 shows the spectral reflection/emission properties of glacier ice, fresh snow and firn in the visible/near infrared (IR) (VNIR), short-wave IR (SWIR) and thermal IR (TIR)

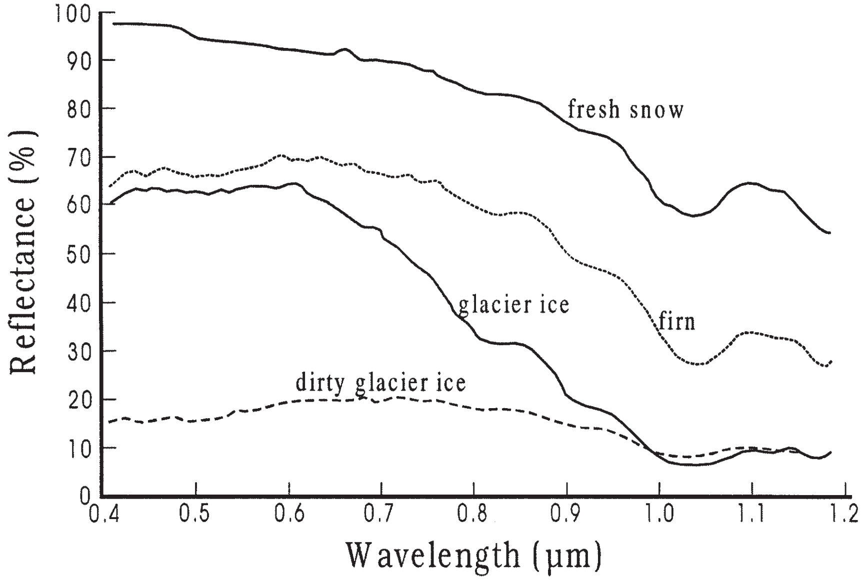


**Figure 1** Spectral reflectance curves between 0.4 and 1.2 μm for fresh snow, firn, glacier ice and dirty glacier ice (adapted from Zeng *et al.*, 1984)

regions of the spectrum. These curves suggest that some properties can be spectrally discriminated as long as the spectral resolution of the image is sufficiently narrow. Although surface albedo of glaciers shows a considerable short-term and spatial variability, these curves obtained in Northwest China should be applicable to other parts of the world. In addition, these curves differ considerably from those of covers commonly located next to glaciers, such as forest or denudated valleys. Theoretically, it is feasible to study glaciers by means of remote sensing.

Since the radiation used for remote sensing must pass through the atmosphere, the spectral differences among these covers on the remote sensing media are subject to the attenuation of the atmosphere (Hall *et al.*, 1988). Thus, correction for atmospheric effects is essential. After correction the reflectance corresponds closely with *in situ* measured results in the nadir-viewing mode (Hall *et al.*, 1989). There is a good correlation between snow density and spectral reflectance within the wavelength range of 0.38–1.20 μm (Zeng *et al.*, 1984). The spectral reflectance gradually decreases from 95% to 60% within visible range while snow is metamorphosed to glacier ice. Atmospheric correction led to a 5–17% increase in reflectance value relative to the calculated at-satellite result (Hall *et al.*, 1990). The satellite-derived reflectance corresponded to within 6% of the *in situ* reflectance measured at nadir. On the other hand, Duguay (1993) cautioned that it is problematic to estimate surface albedo of snow from near-nadir satellite reflectance measured from TM imagery despite very encouraging results from preliminary analyses.

## III Utility of remote sensing materials in glaciology

Remote sensing materials that have found applications in glaciology are shown in Table 1. They fall into two broad categories: optical (including aerial photography and satellite imagery) and microwave remote sensing. Remote sensing in the emissive mode tends to result in images of a coarse spatial resolution that is inadequate for the detection of glaciers.

### 1 VNIR – camera

VNIR radiation can be captured by a film mounted in a camera. Vertical frame aerial photographs tend to have the finest spatial resolution owing to the low flight height and long focal lens of aerial cameras. Thus, they are suitable for accurately mapping small-scale glaciers (Agarwal, 1989; Rostom and Hastenrath, 1994) instead of monitoring glaciers over a broad region because each frame of photograph covers only limited ground area. The relatively large scale of photographs allows glaciers to be interpreted by image size, location and shape in addition to tone. Photographs recorded in visible light show glaciers in a form that is familiar to the human interpreters.

**Table 1** Remote sensing materials useful in glaciology

| Spectrum | Platform | Instrument | Sensor/band | Spatial Resolution[a] | Swath Width | Revisit Period |
|---|---|---|---|---|---|---|
| Optical | Airplane | camera | photographs | variable | variable | variable |
| | | scanner | AVIRIS | | | |
| | Satellite | Landsat | RBV | 79 m | 98 km | 16 days |
| | | | MSS | 79 m | 185 km | |
| | | | TM | 30 m | | |
| | | SPOT | PAN | 10 m | 60 km | 26 days[b] |
| | | | XL | 20 m | | |
| | | NOAA | AVHRR | 1.1 km | 2400 km | 12 hours |
| Microwave (imaging) | Shuttle | SIR-A, -B, -C[c] | X, C, L | 40 m | 50 km | variable |
| | Satellite | ESA ERS-1, -2 | C-band SAR | 30 m | 100 km | 35 days |
| | | JERS-1 | L-band SAR | 18 m | 75 km | 44 days |
| | | Seasat | L-band SAR | 25 m | 100 km | 3 days |
| | | Radarsat | C-band | 10–100 m | 45–500 km | 24 days |
| Radar/laser (nonimaging) | Airplane | Radar/laser altimeter | | – | – | variable |

**Notes:**
[a]Spatial resolution of all radar imagery varies with looking angle. Figures provided in the table are representative.
[b]Revisit period can be changed by tilting the scanning mirror.
[c]SIR-A parameters used here (swath width and range resolution of SIR-B imagery vary with looking angle).

Glaciers can be identified by inexperienced personnel with minimum training in photo interpretation.

Aerial photographs are advantageous in detailed studies of glaciers, such as delineation of glacier tongues (Espizua, 1986), determination of the position of glacial termini (Chinn, 1988), mapping of snowline (Krimmel and Meier, 1975), and detection of spatial fluctuations of glaciers over an area where satellite imagery is nonexistent (Dowdeswell, 1986). Such cirque morphometric parameters as area, length and width can only be measured using photogrammetric techniques (Aniya and Welch, 1981). Glacier boundaries can be mapped easily with an optical sensor (Shi *et al*., 1994). As a matter of fact, vertical aerial photographs, if taken on a repetitive basis, are still the most effective means of monitoring changes in the glaciers of Africa (Young and Hastenrath, 1991).

## 2 VNIR – air-borne scanning

Air-borne scanning imagery is similar to aerial photographs in that the sensor is mounted in an aeroplane. Unlike a camera, the scanner is able to acquire a great number of spectral bands of imagery during one scan. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) sensor is an example of air-borne scanning remote sensing. This hyperspectral system is able to record the radiation from glaciers in more than 124 channels whose bandwidth can be programmed. The spatial and temporal resolutions of AVIRIS imagery bear a striking resemblance to those of aerial photographs. Thanks to its spectral resolution, AVIRIS imagery is highly effective at detecting high clouds over snow- and ice-covered surfaces in the Arctic (Bo *et al*., 1999). Additionally, AVIRIS imagery also proves suitable for mapping snow cover in areas that are shaded or forested, even at the sub-pixel level (Nolin *et al*., 1993).

## 3 VNIR – space-borne scanning

Unlike air-borne data, space-borne satellite data are recorded repeatedly over a long period. Such data make the long-term monitoring of glaciers possible. Satellite imagery is a valuable data source for mapping glaciers when aerial surveys are impossible to carry out or where glaciers change rapidly (Rott, 1988). Since satellite data are already in digital form, they can be manipulated and integrated with data from other sources readily. Compared with aerial photographs, space-borne satellite imagery provides a large areal coverage. Subsequently, an extensively distributed glacier can be captured by one scene, reducing the number of images and hence processing time. The extensive coverage also enables previously undetected subtle slope changes that may be manifestation of subglacial topography to be revealed (Krimmel and Meier, 1975). Very faint dust bands and medial moraines on the Bagley Ice Field in southern Alaska revealed directions of ice flow that it was not possible to detect on aerial photographs (Meier, 1973).

Space-borne scanning can be categorized into earth resources and meteorology by image spatial resolution. Earth resources satellite imagery such as Landsat and SPOT has an intermediate spatial resolution on the order of 10 to 79 m. Landsat series of satellites contain three types of sensors: Return Beam Vidicon (RBV), Multi-Spectral

Scanner (MSS) and Thematic Mapper (TM). RBV is not widely used in glacier studies because only limited frames of RBV imagery were recorded as a consequence of system malfunctioning (later dropped altogether). By comparison, Landsat MSS imagery is much more valuable in glaciology. The accurate map projection of MSS imagery allows quick and easy comparison of glacier extents with those depicted in topographic maps at a scale of 1:250 000 or 1:1 000 000. Glacier outlines mapped from Landsat imagery may be used to update old or inaccurate maps (Williams *et al*., 1975; MacDonald, 1976; Williams, 1976). The 79-m resolution of MSS can be used to identify and classify glaciers as small as 100 m $\times$ 200 m (Higuchi, 1975), and to detect changes in snow-covered areas as small as 6 $km^2$ easily (Krimmel and Meier, 1975). This spatial resolution, coupled with the overlapping orbits in the Polar Regions, makes MSS imagery highly suited to the study of glaciers on a global scale.

Nevertheless, the 79-m spatial resolution of MSS imagery may be too coarse to study small alpine glaciers and identify glacier boundaries (Rott, 1988). Such a spatial resolution is of little value in studying glaciers smaller than 1–2 $km^2$ in size and in observing glacial retreat because the magnitude of recession may be small relative to the image resolution (Chinn, 1988). Thus, the accurate delineation of glacier margins from Landsat images must rely on 'local knowledge' of glaciers (Williams *et al*., 1997).

With an improved spatial resolution of 30 m and a spectral resolution of seven bands, TM imagery is suitable for snow/cloud discrimination (Dozier, 1985). Snow reflectance in bands 4, 5 and 7 is sensitive to grain size. TM images can be used to distinguish between blue ice and snow (Boresjo-Bronge and Bronge, 1999) and to differentiate various types of ice (Frezzotti, 1993). Combination of TM bands in the visible portion of the spectrum facilitates the differentiation between clouds, fog and the ice below (Ormsby and Hall, 1991). Recently, a new spectral band called ETM+ (enhanced TM) band has been added to the system. This band has not yet found applications in glacial studies.

In comparison with Landsat data, SPOT imagery has neither the broad areal coverage per scene (a swath width of only 60 km instead of Landsat's 185 km) nor the high spectral resolution (only three spectral bands) (Table 1). Consequently, SPOT data have rarely been taken advantage of in glaciology. Two cases of application found in the literature are mapping of different surface states of the Arctic glacier (Parrot *et al*., 1993) and ice sheet margins (Sohn and Jezek, 1999).

Exemplified by the Advanced Very High Resolution Radiometer (AVHRR) sensor, meteorological satellite imagery has the coarsest spatial resolution on the order of kilometres, but most extensive ground coverage per scene among all images listed in Table 1. These features make it highly suited to maping and identifying the systematic patterns left on the landscape by glaciation on the continental scale (Johnston *et al*., 1989), and monitoring the dynamics of snow cover in the high mountainous area of northwestern China (Chen *et al*., 1991). Of the five spectral bands, band 2 is particularly useful for the recognition of lineation patterns, band 3 for identifying major morainic features (Johnston *et al*., 1989).

## 4 Microwave remote sensing

Microwave remote sensing, commonly known as radar, falls into two broad categories, imaging and nonimaging. Much more useful than nonimaging radar in glaciology, imaging radar includes Shuttle Imaging Radar (SIR), European Space Agency (ESA) ERS-1 and ERS-2, Japanese J-ERS1, Seasat Synthetic Aperture Radar (SAR) and Canadian Radarsat. The spectral bands commonly used in these systems are X, C and L (Table 1), all of which provide valuable glaciological information. In particular, X and C bands are useful for mapping wet snow packs (Rott, 1984).

As an active remote sensing system, radar imagery is invaluable in studying glaciers over areas that are frequently obstructed by clouds thanks to microwave's ability to penetrate cloud. Radar remote sensing is an efficient, cost-effective, and even indispensable means of monitoring glaciers, where perennial cloud cover hampers other means of data collection (Friedman *et al.*, 1999). Operational under all weather conditions, radar sensors can differentiate snow and glacier from other targets at a spatial resolution compatible with the topographic variation in alpine regions (Sidjak and Wheate, 1999). SAR has advantages over passive remote sensing in monitoring snow and ice and in differentiating moraine relative ages. SAR data at 5.3 GHz (C-band) can discriminate snow- from nonsnow-covered areas (Shi *et al.*, 1994). However, they are neither suited to discrimination of glacier ice from snow and rock, nor effective at discriminating glaciers from rocks. After evaluating the capability of Radarsat for mapping snow-line/accumulation area for a temperature alpine glacier, Demuth and Pietroniro (1999) found that Radarsat can discriminate between firm and bare ice facies in agreement with other orbital C-band SAR studies. Together with ERS-1 data, Radarsat imagery has been used to monitor retreating glaciers (Friedman *et al*. 1999). As a distance-based sensing system, radar imagery is severely disadvantaged by its inherent geometric distortions. Such distortions may be remedied through ortho-rectification using a Digital Elevation Model (DEM) and satellite orbital and ephemeris data (Adam *et al*., 1997).

A recent trend in radar remote sensing of glaciology is the introduction of radar interferometry that is able to generate 3-D surface ice flow patterns by calculating the interference pattern caused by the difference in phase between two passes at two distinct times or positions (Massonnet and Feigl, 1998). The resulting interferogram is a contour map of the change in distance between the ground and the radar instrument. Massonnet and Feigl (1998) reviewed the applications of radar interferometry on ice sheets using ERS-1 data. SAR interferograms data of ERS-1 and ERS-2 have been used to study ice flow (Jonsson *et al*., 1998) and to measure surface velocity and topography (Fatland and Lingle, 1998). The greater promise of radar interferometry seems to lie in determination of surface flow velocity of glacier ice (Forster *et al*., 1999), surface topography and even approximate state of balance (Joughin *et al*., 1999). If coupled with GPS receivers, radar interferometry can acquire submetre topographic profiles of glaciers (Garvin and Williams, 1993). Radar-based flow models constructed from differential radar viewing angles showed good agreement with *in situ* GPS reference data (Mohr *et al*., 1998). These radar measurements have the potential to substantially enhance our understanding of glacier dynamics and ice-sheet flow, and improve the accuracy of glacier mass-balance estimates.

Nonimaging radar systems such as airborne laser altimeter (ALA) and radio echo sounding offer great potential for remote sensing of glacier microtopography, such as crevasse morphology, spatial density and spacing, metre-scale local slopes, long-wavelength gradients and derived strain rates. Jezek and Thompson (1982) used mono-pulse radar sounding to determine ice thickness, and estimate glacier temperature and the character of glacier beds using the measured amplitudes and phases of radar data. Radio echo sounding is able to yield information on ice thickness. Because it has been reviewed by Drewry (1979) and covered comprehensively by Hall and Martinec (1985), the topic is not repeated here.

## IV Glacier features identifiable from remotely sensed images

A number of glacial features, such as glacial frontal termini, summer snowline, accumulation and ablation zones have been detected from remotely sensed imagery. Some of them can be determined to a usefully high precision even from satellite images (Rees and Squire, 1989). The glaciological features that have been successfully studied using remote sensing are mapping of glaciers, monitoring of their spatial variations, determination of flow velocity, estimation of mass balance and modelling of snowmelt runoff.

### 1 Inventory and mapping of glaciers

Glacier inventory provides an indicator of climate variability and is a prerequisite to estimates of freshwater storage. Inventory of glaciers requires detection of icepack at a time when the seasonal snow cover is minimal. This task is ideally accomplished from space-borne satellite imagery (Chen *et al.*, 1991). Variations of some surging glaciers (Krimmel and Meier, 1975) and small icecaps (Williams, 1976) have been successfully measured using satellite imagery. Such features as cirque glacier, niche glacier, icecap and snowfield can be mapped from TM images and aerial photographs (Allen, 1998). A Landsat TM mosaic of the Southern Patagonia Icefield, South America allowed its outlet glaciers to be inventoried (Aniya *et al.*, 1996). Nagler and Rott (1997) developed a methodology for mapping snow cover of glaciers in mountain areas from SAR images on a repeated basis. The identifiability of glaciological features from SAR backscatter is affected by seasonality (Engeset and Weydahl, 1998). Changes in snow cover distribution could be identified in the summer images whereas winter images allowed glaciers representing snow, firn/superimposed ice, and glacier ice to be detected.

If manually mapped from satellite imagery, glaciers are identified through the intensity values of visible images combined with clearness conditions related to exposure, slope and surface homogeneity (Della Ventura *et al.*, 1987). Digital image analysis (e.g., maximum likelihood classification) can map glacier extent and discriminating glacier zones (Sidjak and Wheate, 1999). Automatic methods offer improved efficiency and repeatability while retaining sufficient accuracy and precision. Automatic mapping of glaciers, however, is constrained by topographic shadow in hilly regions. Digital classification of satellite data, which is based solely on the spectral properties of glaciers, is unable to map glacier extent in the alpine environment at a satisfactorily accurate level (Howarth and Ommanney, 1986) because of topographic shadow.

The effect of topographic shadow may be eliminated through the use of DEM. A DEM can be used to compensate for the impact of solar elevation and azimuth in mapping glaciers located in shaded areas (Duguay, 1993; Parrot *et al*., 1993). High-resolution DEMs combined with thematic maps allowed glacier attributes to be derived (Sidjak and Wheate, 1999). After the impact of solar elevation and azimuth had been corrected with DEM, SPOT reflectance values revealed surface states of Arctic glacier in even shaded zones (Parrot *et al*., 1993). The other two processing techniques able to remove shadow effect are image enhancement and spectral mixture analysis. Digital enhancements provide considerable interpretative detail of glaciers (Howarth and Ommanney, 1986). Ratioing of TM-4 to TM-5, combination of principal components and the normalized difference snow index all produced accurate glacier extent (Sidjak and Wheate, 1999). Spectral ratioing of TM bands 3 to 5 compensates for topographic effects (Rott and Markl, 1989). A technique of spectral mixture analysis devised by Nolin *et al*. (1993) showed great promise in mapping snow cover over the Sierra Nevada, California.

Automatic mapping of glaciers by means of remote sensing is also hindered by the presence of cloud. The acquisition of cloud-free imagery is worsened in the maritime climate. Difficulties in accurate discrimination between snow and cloud have handicapped the use of satellite data in operational glacier mapping because both snow and cloud share a similar spectral response, especially in the visible and IR wavelengths. The presence of fog further complicates the problem. Fog bears spectral reflectance characteristics similar to the ice below in the VNIR wavelengths (Ormsby and Hall, 1991).

There are several approaches to circumventing the problem. One solution is to use microwave remote sensing that can minimize the effects of cloud cover, but its lower spatial resolution and less reliable geometric property may impose more limitations. Another solution is to spectrally discriminate the two using hyperspectral data such as AVIRIS. The water vapour absorption channel at 1.38 μm is effective at detecting high clouds over snow- and ice-covered surfaces (Bo *et al*., 1999). Low-level clouds can be separated from surface snow using a channel centred at 1.5 μm. The NIR band of TM 5 also improves snow–cloud discrimination (Dozier, 1984).

Better spectral separability has to rely on digital image processing. With specially designed algorithms, snow extent in scenes partly covered by clouds may be estimated based on the altitude distribution of the different surface classes in the cloud-free areas (Rott and Markl, 1989). Unsupervised clustering procedure is able to remove cloud and accurately delineate snow extent from AVHRR data, provided that the required snow conditions are specified (Harrison and Lucas, 1989).

The accuracy of mapping glaciers reported in the literature varies between around 70% and over 90%. Hall *et al*. (1998) achieved 96.41% in areas where vegetation density was below 50%, but only 71.23% in areas where the vegetative cover exceeded 50%, the overall accuracy being 87.41%. The combination of visually and automatically classified covers increases the classification accuracy of MSS and TM data by 24% (kappa 0.61–0.85) and 13% (kappa 0.74–0.87), respectively, in subdivision of glacier basin covers into physiographic units (Gratton *et al*., 1990). The accuracy achieved by Shi *et al*. (1994) was 74% from VV polarization with topographic information, 76% from polarimetric SAR without topographic information and 79% from polarimetric SAR with topographic information. This accuracy level of 74% in mapping glacier areas from SAR data justifies the use of SAR data in areas so plagued by cloud cover that useful data such as Landsat TM are unattainable (Shi and Dozier, 1993).

## 2 Monitoring of glacier evolution

The state of a glacier is not stagnant but dynamic. Its physical condition and size are subject to constant climate impacts. Precipitation in the form of snow augments its mass while its mass is depleted through surface melting, sublimation and calving of icebergs. In response to these variations, a glacier redistributes its mass through downslope motion in order to reach an equilibrium state (Hall and Martinec, 1985). The detection of temporal evolution of a glacier requires multi-temporal images. Satellite imagery is very effective at the detection owing to its moderate spatial and temporal resolutions. For instance, glaciers in the remote Himalaya can be regularly monitored easily on a seasonal basis with satellite images (Krishna, 1996). Multi-temporal aerial photographs enable the tongue of glaciers (Espizua, 1986) and outlet glaciers (Aniya and Enomoto, 1986) to be mapped and compared with one another to detect glacial recession/surging. Apart from vertical aerial photographs, Holmlund and Fuenzalida (1995) also used oblique photographs in monitoring the frontal glacial changes in Darwin Cordillera, southern Chile. Rostom and Hastenrath (1994) used topographic maps and recent aerial photographs to identify variations of Mount Kenya's glaciers between 1987 and 1993.

Monitoring of glacial evolution is virtually detection of variations in the spatial extent of glaciers (Josberger *et al.*, 1993; Bayr *et al.*, 1994). Since satellite imagery did not come into existence until after the early 1970s, the detection is rarely based on the same types of imagery if the detection period extends earlier than the 1970s (Sohn *et al.*, 1998). Rather, the images used in a detection are likely of diverse types, including Landsat, SPOT and even aerial photographs (Dowdeswell, 1986; Zeng *et al.*, 1992; Frezzotti, 1993; Skvarca, 1993). Predictably, satellite data yielded larger residuals (± 150 m) because of their coarser spatial resolution and lower geometric reliability, whereas aerial photographs achieved a higher accuracy (± 25 m) (Dowdeswell, 1986). Similarly, Williams *et al*. (1997) achieved a positional accuracy of 42 m from Landsat TM, but only 112 m from MSS images. Occasionally, satellite-derived results had to be compared with those from field observations to fulfil the detection (Williams *et al*., 1997). Besides aerial photographs and field measurements of snowpack properties, Smith *et al*. (1997) also used temperature and runoff data in monitoring glacier zones at an alpine icefield in British Columbia, Canada.

Whether the variations in glacier extent are detectable by means of remote sensing is subject to their magnitude, the spatial and temporal resolutions of images used. Satellite imagery such as Landsat MSS cannot be used to detect rapid changes in small, steep and very active alpine glaciers (Chinn, 1988). If the variations are so small, the change in one glacial year may not be resolved on satellite images. Conversely, glacier motion can be measured if it is rapid enough to exceed the inherent positioning error of about 100 m for Landsat type images, or about 1000 m for meteorological satellite images (Krimmel and Meier, 1975).

The spatial-based detection of variations in glacial extent requires co-registration of multi-temporal images with one another, a task easily achievable in GIS. GIS is an efficient tool for analysing current state and changes in glaciers (Li *et al*., 1998). Other analyses such as classification and detection can also be carried out in GIS, as can calculation of glacier area and fluctuation in glacier termini. A database within a GIS may be manipulated to yield information on changes in glacier movements and size (Garelik *et al*., 1996). The detection of glacier temporal displacement may be preceded by image processing such as edge enhancement, dynamic thresholding, region growing, edge detection and edge following (Sohn and Jezek, 1999). Parameters related to glaciers may be automatically updated in an integrated GIS devoted to glaciology based on classification results (Binaghi *et al*., 1993). The accuracy of glacial detection is seldom provided quantitatively in the literature. Brecher and Thompson (1993) only mentioned that their findings are consistent with the behaviour of glaciers in the study area.

## 3 Determination of glacier velocity

The motion of a glacier occurs in three dimensions in space. There are three methods by which the velocity of the motion may be determined from multi-temporal imagery: feature tracking with or without GPS (Frezzotti *et al*., 1998; Rosanova *et al*., 1998), and through radar interferometry (Joughin *et al*., 1999). Surface ice patterns of smaller glaciers may be tracked on sequential images (Rosanova *et al*., 1998). Crevasses and other patterns moving with the ice are some of remaining features that may be tracked in two sequential satellite images (Frezzotti *et al*., 1998). Apart from feature tracking, velocity may be derived by co-registering multi-temporal images. Co-registration of RBV, MSS and TM images revealed that northern glaciers in the middle section of Kunlun Mountains advanced while the southern glaciers retreated at a velocity between 50 and 105 ma$^{-1}$ (Li *et al*., 1999). Compared with sequential satellite images, GPS is more advantageous when only small features are available for tracking in a study area because these features may not be discernible on the images (Forster *et al*., 1999). On the other hand, GPS is disadvantaged by the problem of accessibility.

It must be noted that feature tracking from and co-registration of multi-temporal images are able to reveal glacier velocity in the down-slope direction only. However, the velocity direction can be extended to three with the assistance of an external DEM (Mohr *et al*., 1998) or radar interferometry (Joughin *et al*., 1998). Radar interferometry may be used in conjunction with ice-penetrating radar profiles and a DEM to derive the velocity fields of outlet glaciers (Joughin *et al*., 1999). Glacier velocities can be measured and calculated from ERS tandem INSAR data using existing and newly implemented modules in Arc/Info (Wangensteen *et al*., 1999). Satellite radar interferometry can measure the radar line-of-sight component of ice-flow vectors (Mohr *et al*., 1998). Conventional interferometric measurements made from a single-track direction are sensitive only to a single component of the velocity vector. This technique can be perfected to detect the three-component velocity vector from data acquired along ascending and descending orbits (Joughin *et al*., 1998).

The accuracy of velocity determination varies with the method and the remote sensing data used. Forster *et al.* (1999) achieved an accuracy of higher than 2 cm d$^{-1}$ in producing phase-coherence maps and ice-velocity from co-registration of three L-band SIR-C images. Frezzotti *et al*. (1998) assessed the accuracy of feature tracking from sequential satellite images through comparison with GPS results. It was found that the feature tracking method produced errors in the measured velocity as low as ±15–20 m $a^{-1}$ in areas close to image tie-points, but about ±70 m $a^{-1}$ in areas far from tie-points.

## 4 Snow/ice differentiation

It is possible to differentiate various types of ice from Landsat MSS, TM and SPOT images (Frezzotti, 1993). Rundquist and Samson (1980) tested the feasibility of distinguishing certain glacier parameters in the Khumbu ice mass in the Mount Everest region. They found that MSS-5 was the most useful channel for depicting snow, firn, clean ice, debris-covered snow and moraine. In comparison with these earth resources satellite images, microwave remote sensing is more capable of differentiating snow from ice. Clear differences existed between glaciers and unglaciated (e.g., snow-covered) surfaces on SIR-C imagery (Matzler *et al.*, 1997). Scree/talus, dry snow, dry snow-covered glacier, wet snow-covered glacier and rock-covered glacier on the rugged north slope of Mount Everest can be successfully identified and mapped from SIR-C images (Albright *et al.*, 1998). Even single polarization, C-band (5.3 GHz) SAR data can discriminate areas covered by wet snow from those that are ice-free, but do not easily separate glacier ice from snow and rock (Shi and Dozier, 1993). Snow and ice facies can be distinguished from SAR's response to surface roughness, liquid water content and grain size distribution (Anonymous, 1993).

The separation of snow from ice is made easier through simple digital processing. Ratioing of TM-3 to TM-4 distinguishes between blue ice and snow of various characters while the TM-3/TM-5 ratio enhances snow grain-size variations (Boresjo-Bronge and Bronge, 1999). Maximum likelihood classification enhances the detectability of blue ice and snow of various degrees of metamorphosis. Lesaffre *et al.* (1998) developed a semi-automatic procedure that allowed snow grain characteristics (such as type or size) to be mapped at an accuracy of 97%.

The differentiation of snowpack from icecap is impeded in melting conditions when the former becomes wet. Difficulties arise for those glaciers within which appreciable melt water is refrozen as internal accumulation or as superimposed ice. The internal accumulation probably cannot be measured using remote sensing (Meier, 1973), but it does appear to be possible to delineate the glacier ice/superimposed ice boundary. In order to overcome this obstacle, Walker and Goodison (1993) developed a wet snow index using Special Sensor Microwave Imager (SSM/I) 37 GHz dual-polarization data for the open prairie region of western Canada. The addition of this indicator to the current SSM/I snow water equivalent algorithm provided a more accurate representation of spatial snow coverage. The boundary between wet snow and glacier ice surfaces and the glacier boundary obtained through supervised classification on the rectified images was within 75 m horizontally of the snow line obtained from field data (Adam *et al.*, 1997).

## 5 Determination of TSL and ELA

Transient Snow Line (TSL) refers to the lower margin of the previous winter's snowpack. It can be easily distinguished on aerial photographs based on tone (Østrem, 1975). Glacier ice or firn is discoloured by dust while previous winter's snow is white. Closely correlated with the net mass balance of a glacier, TSL serves as a sensitive indicator of the amount of snowmelt runoff, and has been studied using remote sensing directly. The end-of-summer snowlines are easily mapped from low-altitude, oblique aerial photographs (Chinn and Salinger, 1999). Benson and Follett (1986) detected variations in the termini of glaciers radiating from the summit of Mount Wrangell, Alaska from orthophoto maps prepared from controlled aerial photographs.

At the end of the summer TSL retreats to a maximum altitude where snow accumulation is exactly equal to snow depletion within a given year (Paterson, 1981). This elevation is commonly known as Equilibrium Line Altitude (ELA). Located somewhere in the middle of a glacier, ELA's determination requires discrimination of the ablation and accumulation zones. This differentiation can be made from remotely sensed imagery thanks to differential spectral responses of glacial areas (Frezzotti, 1993). The angular dependencies of the backscattering of glacial surfaces on SIR-C imagery were useful in distinguishing between the accumulation and ablation areas (Matzler *et al.*, 1997). Landsat MSS imagery allows a vegetation trim line that marks the position of the western ice margin of the Greenland ice sheet to be accurately identified (Knight *et al.*, 1987). It is even possible to delineate glacier margins and their temporal change from sequential satellite images if the magnitude of motion exceeds the image pixel size (Williams *et al.*, 1997). For instance, through mapping modern glacier terminus positions from Landsat MSS imagery in central Nepal, Duncan *et al*. (1998) estimated ELAs for both historic and modern glaciers. Using a supervised classification of Landsat TM mosaic, Aniya *et al*. (1996) divided glacier drainage basins into accumulation and ablation areas, thus mapped ELA position indirectly. Allen (1998) derived ELA through overlay of detected glacier boundaries with DEMs within a GIS. ELA can also be derived from winter SAR image (Engeset and Weydahl, 1998) as well as composite of multi-temporal Landsat images (Lucchitta and Rosanova, 1998).

Nevertheless, Demuth and Pietroniro (1999) cautioned that using the transient snowline to define the equilibrium line by means of radar remote sensing may encounter difficulty if traditional ground measurements used in the direct glaciological method are absent. The accuracy of estimating ELA varies with the accuracy of the reference digital elevation information.

## 6 Mass balance and snowmelt runoff

The precise estimation of icepack volume and modelling of snowmelt runoff requires two parameters, areal extent of snow cover and icepack depth. In recent years the areal extent of snow cover has become operationally available by means of remote sensing. In particular, remote sensing-derived snow cover extent has been fed to the snowmelt runoff model (SRM) as a major input variable. Discharge forecasts based on SRM were operational by 1978 in many basins in the western USA for the purposes of irrigation (Hall and Martinec, 1985). Nagler and Rott (1997) verified the SAR-derived snow maps for daily runoff modelling for two drainage basins in the Austrian Alps. Good agreement was found between simulated and measured runoff. This study clearly indicates the high value of SAR imagery for snow and glacier hydrology. Employing satellite-derived snow cover and actual hydrometeorological data, Zeng *et al*. (1992)

developed spring-runoff models to forecast inflow to a reservoir at an accuracy of ±15% of the actual observation.

Owing to its ground penetration capability, radar remote sensing has found wide applications in estimating icepack depth. Forster *et al*. (1991) demonstrated the feasibility of high resolution X-band radar imagery in observing annual snow-accumulation layers in Antarctica. The thickness of polar ice sheets (no liquid water present) can be determined using conventional air-borne radar (Gudmandsen, 1970). With a radar unit Driedger and Kennard (1986) obtained point measurements of ice thickness from which subglacial contour maps were produced. The estimation of glacier volume using this nonimaging system required knowledge of glacier slope, altitude and area, as well as basal shear stress. Nevertheless, changes in mass balance from one year to another were difficult to detect using only SAR backscatter data because they contained signals from both accumulation and ablation integrated over several years (Engeset and Odegard, 1999).

Two trends have recently emerged in monitoring glacial surfaces. The first is to acquire elevational information about glaciers to calculate ice discharge (Rignot *et al*., 1997). The combination of SAR with a co-registered high-resolution DEM (TOPSAR) provides a promising tool for measuring glacier change in three dimensions, thus allowing ice volume change to be measured directly. The second is to sense glaciers from above the ground using GPS and scanning ALA. Gandolfi *et al*. (1997) evaluated the feasibility of using GPS to monitor small glaciers in Antarctica. After comparing surface profiles surveyed using GPS and conventional methods, they concluded that kinematic GPS is a useful method of monitoring glacier surfaces. Jacobsen and Theakstone (1997) logged 2228 GPS points from which a DEM was constructed in a GIS for the Austre Okstindbreen Glacier in Norway. The comparison of this DEM with those from other sources shed light on the mass balance of the glacier. Scanning ALA is ideally applied to smooth snow-covered glaciers because they are highly reflective (Kennett and Eiken, 1997). Its low levels of noise (around 2 cm), repeatability between overlapping swaths (approximately ±10 cm), and over 1 km swath width make them highly suited to small and medium-sized glaciers. The high accuracy and dense, even coverage (about 20 000 points per km$^2$) enables reliable measurement of glacier volume change.

## V Prospects of remote sensing of glaciology

The success of remote sensing of glaciers depends, to a large degree, upon the availability of suitable data. The launch of NASA's Earth Observatory Satellites (EOS) Terra on 18 December 1999 will markedly enrich the availability of quality remote sensing data for studying glaciers from space. This satellite started to collect data on a global scale in 14 spectral bands (Table 2) from 24 February 2000. The EOS Terra spacecraft carries a payload of five state-of-the-art sensors, one of which is named Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). This sensor collects data at a spatial resolution of 15 m in the VNIR spectrum, much finer than that of SPOT multispectral bands. Such a high spatial resolution and near-global coverage will enable ASTER to become a vital information source for monitoring and mapping of the spatial extent, velocity fields and other parameters of glaciers around the world, as well

**Table 2** ASTER instrument characteristics

| Characteristics | VNIR | SWIR | TIR |
|---|---|---|---|
| Spectral band and range (μm) | 1: 0.52 – 0.60<br>2: 0.63 – 0.69<br>3: 0.76 – 0.86 | 4: 1.600 – 1.700<br>5: 2.145 – 2.185<br>6: 2.185 – 2.225<br>7: 2.235 – 2.285<br>8: 2.295 – 2.365<br>9: 2.360 – 2.430 | 10: 8.125 – 8.475<br>11: 8.475 – 8.825<br>12: 8.925 – 9.275<br>13: 10.25 – 10.95<br>14: 10.95 – 11.65 |
| Ground resolution at nadir (m) | 15 | 30 | 90 |
| Swath width (km) | 60 | 60 | 60 |
| Data rate (Mbits/sec) | 62 | 23 | 4.2 |
| Cross-track pointing (deg.) | ±24 | ±8.55 | ±8.55 |
| Cross-track pointing (km) | ±318 | ±116 | ±116 |
| Quantization (bits) | 8 | 8 | 12 |

as their advance and retreat. All three ASTER telescopes can be rotated up to 24° in the cross-track direction. The combination of its high resolution with its ability to change viewing angles will enable ASTER to produce stereoscopic images and detailed terrain height models over glacial areas. Thus, it may be possible to study the change in glacier ice volume.

Like ASTER, Terra's Multi-angle Imaging Spectroradiometer (MISR) instrument can also observe the Earth from nine different angles. Designed primarily for studying clouds, MISR will prove to be of limited utility in glaciology except in monitoring ice sheets on the continental scale owing to its coarse spatial resolution.

The ESA scheduled the launch of another satellite called Envisat in June 2001. This polar-orbiting Earth observation satellite will provide measurements of the land and ice. Its innovative payload will ensure the continuity of the data measurements of the ESA ERS satellites. In Image Mode the Advanced SAR (ASAR) will generate high spatial resolution (30 m) products similar to the ERS SAR. It will image one of the seven swaths located over a range of incidence angles spanning from 15° to 45° in HH or VV polarization. The emergence of this kind of satellite data will make the long-term monitoring of glaciers possible.

At present, Radarsat shows only limited potential in radar interferometry because of its variable spatial resolutions and incidence angles. The launch of Radarsat 2 planned in 2001, which has an improved spatial resolution, will offer some interferometric capabilities with Radarsat 1 data.

Thus, the collection of remotely sensed data on a continuous basis will ensure the availability of the same or similar types of data over a long period of time. These satellite data provide excellent opportunities to monitor the long-term evolution of glaciers and examine the potential impact of climate on them at the global scale. Also, the satellite data collectable at the global scale will facilitate the establishment of a worldwide database for glaciers. The dynamic monitoring and modelling of glaciers around the world can be applied to both small and large glaciers alike.

## VI Summary and conclusions

Glaciers have been intensively studied from both airborne and space-borne remotely sensed materials. Aerial photographs are used mainly for highly accurate mapping of glaciers and for acquiring detailed glacial parameters. They are especially valuable in studying alpine glaciers that are too small to be detected from satellite imagery. The medium spatial resolution of satellite imagery restricts their applications to the mapping and monitoring of glacial features at a broad scale. Both aerial photographs and satellite images have been used to map TSL, ESL and areal extent of glaciers and monitor their temporal evolution. A huge portion of the mapping efforts has gone to differentiation of ice and snow, and elimination of the impact of clouds. These two tasks are better achieved using microwave remote sensing than VNIR remote sensing. Simple image processing techniques such as enhancement, spectral ratioing and automatic classification have been employed to improve the ease and accuracy of the mapping. Auxiliary data such as DEM have been incorporated into the mapping to compensate for the effect of topographic shadow in mountainous terrains.

Aerial photographs and satellite imagery recorded in the VNIR spectrum are able to reveal two-dimensional glacial phenomena (e.g., spatial distribution). The determination of the third dimension (icepack depth) has to rely on imaging radar or nonimaging methods such as radio echo sounding. Radar SAR images are able to provide depth information, but are inadequate for measuring glacier mass balance within a glacial year alone. Ground penetration radar appears to be a useful method. Point measurements of icepack thickness need to be spatially interpolated to create a surface representation. A recent trend in estimating the third dimension is to study glacier surfaces from above the ground using radar interferometry, GPS and laser altimetry. The elevational accuracy of GPS may not be adequate in monitoring glacial surfaces that experience only subtle temporal variations. Airborne scanning laser altimetry can solve this dilemma. However, its narrow swath width means that only small glaciers can be effectively studied using this method. Thus, the solution seems to lie in interferometry using SAR images from the yet-to-be launched ESA Envisat.

Increasingly, temporal evolution of glaciers has been detected with the assistance of GIS. Nevertheless, the use of GIS in glaciology has been of limited scope. The detected changes in glacial extent have not been linked to other topographic or environmental variables, let alone modelled from them and other factors stored in a GIS database. At present, modelling of snowmelt runoff simply reduces to feed remotely sensed snow cover to the SRM. Thus, the full potential of GIS in manipulating glacial variables acquired from digital analysis of remotely sensed data has not been realized. Allen (1998) is the only author who attempted to predict the type of glacier morphology from factored variables of glacier shape, elevation range and upslope area.

To conclude, remote sensing of glaciers remains highly descriptive so far. The impact of environmental and topographic variables on the variations in the spatial extent of glaciers detected from multi-temporal images still remains to be explored and modelled in a GIS. The power of combining GIS and GPS in glaciology has been exploited only to a highly limited degree. The potential afforded by the integration of remote sensing, GIS and GPS in acquiring, manipulating and displaying glacial data is yet to be realized. It is anticipated that with the increasing integration of remote sensing and GIS, glaciers will be monitored and modelled more accurately in the future. The integration of recently emerged or forthcoming remote sensing imagery with GIS and GPS will make glaciology more dynamic, more analytical, more global, more exploratory and more predictive in the future.

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