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Remote Sensing of Mountain Environments

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INTRODUCTION

Remote sensing technologies provide powerful tools for observing mountain environments such as the UNESCO Mountain Biosphere Reserves (MBRs). Due to the difficult access to most mountain regions – difficult for physical and/or political reasons – remote sensing is often the only way for investigating large sections of the Earth's surface. The purpose of this contribution is to give a brief overview on how remote sensing can contribute to the mapping, monitoring and modelling of mountain environments.

In general, remote sensing methods can be classified according to the platform location (space, air, or ground) and according to the section of the electromagnetic spectrum covered by the sensor (visible and near infrared light, short-wave infrared, thermal infrared, and microwaves) (Figure 1). Together with the basic sensor types 'active' (sending and receiving signals) and 'passive' (receiving signals from a natural source) the combination of the above characteristics determines to a large extend the applicability of the data and the costs, expertise and analysis equipment required.

The typical data characteristics for the three platform types are:

- *Spaceborne platforms*: high acquisition frequency of up to some days; coverage of up to ten-thousands of km^2 by one scene; potential coverage of the complete Earth surface; spatial resolution from metres to hundreds of metres; decade-long time series already available; data costs in the order of 1 EUR/km^2 or much less.
- *Airborne platforms*: low acquisition frequency of (usually) years; coverage of a few or a few tens of km^2 by one scene; study areas have to be accessible by plane or helicopter; spatial resolution from centimetres to metres; decade-long time series partially available (mapping authorities); data costs from of a few EUR/km^2 (data reproduction) to hundreds of EUR/km^2 (original acquisition).
- *Terrestrial platforms*: very high acquisition frequency possible (hours and less for automatic systems); coverage of single points or a few hundred metres; study areas have to be directly accessible; spatial resolution from millimetres to metres; data costs from of a few EUR to hundreds of EUR/km^2.

According to the sections of the electromagnetic spectrum exploited, remote sensing data are characterised as follows:

- *Visible light and near infrared (VNIR)*: sensors collect the reflected sunlight (passive sensor); data content similar to what the human eye sees; multi- and hyper-spectral sensors split the light in separate sections of the spectrum, which facilitates automatic analysis; laser sensors (light detection and ranging, LIDAR; active sensor) apply often near infrared.
- *Short-wave infrared (SWIR)*: some surfaces show significantly different reflectivity in the SWIR compared to VNIR (e.g. ice, vegetation), or a high variability in reflectivity with wavelength (e.g. according to the mineral composition). These properties enable (automatic) multi- or hyper-spectral classification.
- *Thermal infrared (TIR)*: the long-wave emitted radiation is indicative for the surface temperature (e.g. helpful for energy balance studies or surface characterisation).
- *Microwaves*: the surface reflection of microwaves (wavelength in the order of millimetres to metres) depends on the di-electric (near-)surface properties, which are among others sensitive to roughness and humidity. Synthetic aperture radar (SAR) combines multiple radar returns to images. In contrast to optical sensors, which do not work through clouds, microwave sensors have all-weather (and day-and-night) capabilities.

(Entire section: Figure 1; Schowengerdt, 1997; Lillesand and Kieffer, 2000; Campbell, 2002; Bishop and Shroder Jr, 2004).

DIGITAL ELEVATION MODELS

From a topographic point of view, large relief defines mountains essentially. Thus, digital elevation models (DEM) usually form the base data for any mountain geoinformation system and any spatial model.

If not readily available (e.g. digitised from topographic maps), satellite-derived DEMs can be computed from optical satellite stereo and interferometric SAR (InSAR). Satellite stereo using sensors such as ASTER or SPOT5 provides DEMs with a spatial resolution in the order of some tens of metres, and with a vertical accuracy in the order of some metres to a few tens of metres (Kääb, 2005). InSAR-derived DEMs have similar resolutions and accuray, but are not limited by cloud-cover at the time of data acquisition (Toutin and Gray, 2000).

A unique DEM, which is available at no costs for the continents between 60° N and 54° S, was computed from the Shuttle radar topography mission (SRTM). The SRTM DEM has a spatial resolution of about 90 m and a vertical accuracy in the order of metres to a few tens of metres (e.g. Kääb, 2005) (Figure 2).

Another group of DEMs with better spatial resolution and vertical accuracy is derived from aero-photogrammetry (based on analogue or digital imagery), airborne InSAR, and laserscanning. Stereo-photogrammetry of air photos is one of the best-established methods for DEM generation. Such-produced DEMs have spatial resolutions of some metres to some tens of metres, and a vertical accuracy in the centimetre to metre range. Similar DEM characteristics are obtained from airborne InSAR. A slightly better vertical accuracy and a significantly higher DEM point density (metre-order) compared to aero-photogrammetric DEMs and airborne InSAR can be achieved by airborne laserscanning. If high resolution and accuracy is required this technique offers so far not known possibilities. (Entire paragraph: Kääb, 2004).

InSAR and laserscanning provide not only terrain elevations, but can also be used to derive forest tomography, a valuable tool for forest and fire management. The vertical structure of the forest can be resolved if several return pulses from different heights of the vertical vegetation column are recorded, and if the signal amplitude (varying with the leaf size and density) is analysed in addition (e.g. Lefsky et al., 1999). Similarly, different radar wavelengths penetrate differently into the canopy. Thus, multifrequency SAR systems are also able to resolve the vertical forest structure (Figure 3).

For detailed and local studies, also terrestrial methods can be used for DEM generation. Global navigation satellite systems (GNSS, e.g. the GPS) and optical levelling require direct access to the DEM points but provide centimetre to millimetre accuracy. Touch-less close-range techniques are available for polar survey with laser rangers. Terrestrial laserscanning is an upcoming technology providing nearly continuous descriptions of object surface geometries.

TERRAIN MOVEMENT

Mass movement systems are particularly effective in mountains and form, therefore, important drivers of mountain landscape evolution and related processes.

Vertical changes, e.g. glacier thickness changes or different types of accumulation/erosion, can often be derived as differences between repeat DEMs (Kääb, 2004) (Figure 4). Horizontal glacier movement can under certain circumstances be measured from matching of repeat satellite imagery, at a horizontal accuracy in the order of ten metres (Kääb, 2002). Similar techniques are applied to air and terrestrial photos, providing horizontal terrain displacements on land slides, glaciers and rockglaciers with some centimetres to decimetres accuracy. The surface movement of dry and open terrain can be determined with millimetre accuracy through spaceborne repeat application of InSAR (differential InSAR, DInSAR) (Strozzi et al., 2004). This technique is for the most part used for land-slide monitoring.

Classical terrestrial methods for observing the movement of single terrain points are GNSS and polar survey.

SURFACE COVER

One of the most common applications of remote sensing is mapping and characterising the surface cover. Manual and semi-automatic segmentation of optical images for vegetation, open water, snow, ice, rock, human objects, etc. can be based on panchromatic or colour images. Multi-spectral remote sensing offers the opportunity for automatic classification of surface cover utilising the variation in reflectivity with wavelength, which differs for most surface types. Besides such purely spectral classification methods, spectral-spatial methods are in particular promising involving e.g. also DEMs or neighbourhood relations. Inclusion of not only VNIR data, but also SWIR and TIR in the spectral analysis allows for discriminating and describing surface types in a way, which cannot be accomplished by the human eye. Multispectral analysis techniques are particularly powerful (and of special interest for MBRs) if applied on repeat imagery (change detection). Thus, land cover/use change can be detected very efficient (Figure 5). (Entire paragraph: Schowengerdt, 1997; Lillesand and Kieffer, 2000; Campbell, 2002; Kääb, 2004).

Another class of surface characterisations, which is very different compared to the above optical methods, stems from the analysis of SAR backscatter, possibly even polarimetric or multi-frequency. These techniques are present research level and thus much less established than multi-spectral ones (Curlander and McDonough, 1991). Similarly, utilising hundreds of different, very narrow spectral bands (hyperspectral remote sensing) instead of some broad bands in multi-spectral imaging allows for much more detailed but more complicated surface characterisation (e.g. vegetation, lithology, open water composition, etc.) (Schowengerdt, 1997).

In general, the accuracy of spectral or SAR derived classifications and mappings is in the order of the applied image pixel size, i.e. ranging from metres to tens or hundred of metres for spaceborne sensors, and centimetres to metres for airborne sensors.

REMOTE SENSING OF MOUNTAIN BIOSPHERE RESERVES – A PROPOSAL

The possible applications of remote sensing to mountain environments, and UNESCO MBRs in particular, are too manifold to be listed here and depend largely on the human, technical and financial resources, and the knowledge level available to the individual MBRs. Focus should therefore be to establish a minimum but global set of data, methods and expertise with respect to remote sensing application in/to MBRs. The potential outcome of such strategy is a, to some extent, standardised, and

thus compatible set of data, methods and results, which facilitates inter-MBR knowledge sharing and support. The latter can help to make remote sensing a sustainable part of MBR mapping, monitoring and modelling. First steps towards the proposed strategy are (1) a representative set of pilot studies, (2) a survey of needs, and GIS and remote sensing resources existing in the MBRs, (3) selection of sophistication levels (*, **, ***, etc.; see Figure 1), and (4) selection of related sets of data and methods.

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Platform:	**Space**		**Air**			**Ground**			
Sensor:	Optical	SAR	Optical	SAR	LIDAR	Polar survey	Terrestrial photography	Laser-scanning	SAR
Resolution:	100-1 m	100-10 m	1-0.01 m	1-0.1 m	0.1 m	0.01 m	10-0.01 m	0.01 m	0.1 m
Data:									
Digital elevation model	** Stereo photogrammtry	* SRTM **/*** Inter-ferometry	**/*** Stereo photogrammetry	*** Inter-ferometry *** Multi-frequency tomography	**/*** Laser-scanning **-*** tomo-graphy from multi-pulse	** 3D point positions	*** Stereo photo-grammetry	*** 3D point cloud	-
Vertical and horizontal terrain movement	** Repeat DEM **/*** Image matching, (image algebra)	**/*** Repeat DEM *** Differential InSAR	**/*** Repeat DEM *** Image matching	*** Repeat DEM (Differential InSAR)	**/*** Repeat DEM *** DEM matching	** Repeat measurement	*** Repeat DEM *** Image matching	*** DEM matching	- *** Diff. InSAR
Surface cover and change	*/**/*** Multispectral segmentation and analysis *** Hyper-spectral analysis *** Thermal IR */**/*** change detection techniques	**-*** Backscatter, polarimetry, multifrequency	*/** (Multi-) spectral segmentation and analysis *** Hyper-spectral analysis *** Thermal IR */**/*** change detection techniques	*** Backscatter, polarimetry, multifrequency	*** Laser intensity, surface roughness	-	*/** Segmentation	*** Laser intensity, surface roughness	-
Atmosphere (selection)	*/**/*** cloud cover, water vapor, aerosols, etc.	**/*** rain cells, etc.	*/**/*** cloud cover, water vapor, aerosols, etc.	*** rain cells, etc.	*** water vapor, aerosols, etc.	-	*/**/*** cloud cover, etc.		-

* *basic knowledge; simple (free) GIS and remote sensing software; cheap or free data*
** *expert knowledge; advanced GIS and remote sensing software*
*** *research institute level; sophisticated GIS and remote sensing software; expensive data / campaigns*

Figure 1: Overview of selected remote sensing methods suitable for mapping, monitoring and modelling of MBRs. The methods are sorted according to the platform/sensor-type used (horizontal) and the data-type needed (vertical). A rough estimation on the applicability of the methods to MBRs is also given, in terms of expertise required, costs, equipment, etc.

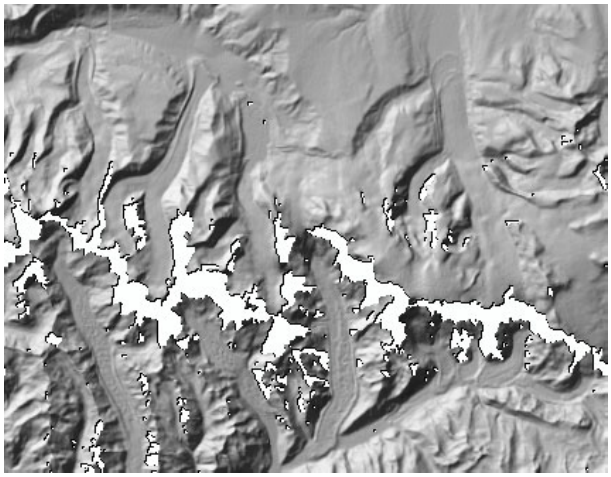

Figure 2: Hillshade of an approximately 40 × 30 km section of the SRTM digital elevation model in the Bhutanese Himalayas. White areas indicate data gaps. This data set has a spatial resolution of 90 m and is freely available for large parts of the continents.

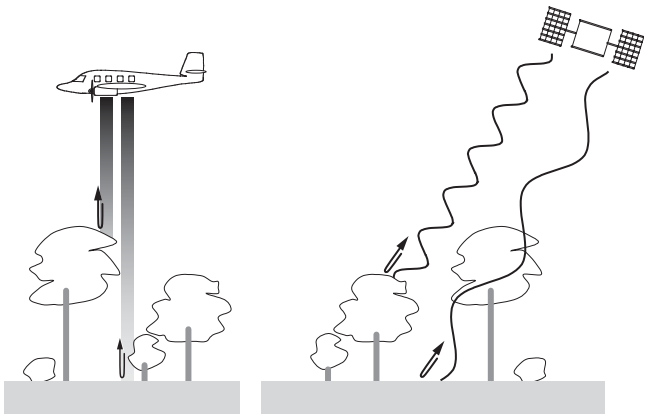

Figure 3: Laserscanning combined with laser intensity measurements (left) and multi-frequency synthetic aperture radar (SAR; right) allow to resolve the vertical structure of forest (so-called tomography), a valuable prerequisite for forest and fire management.

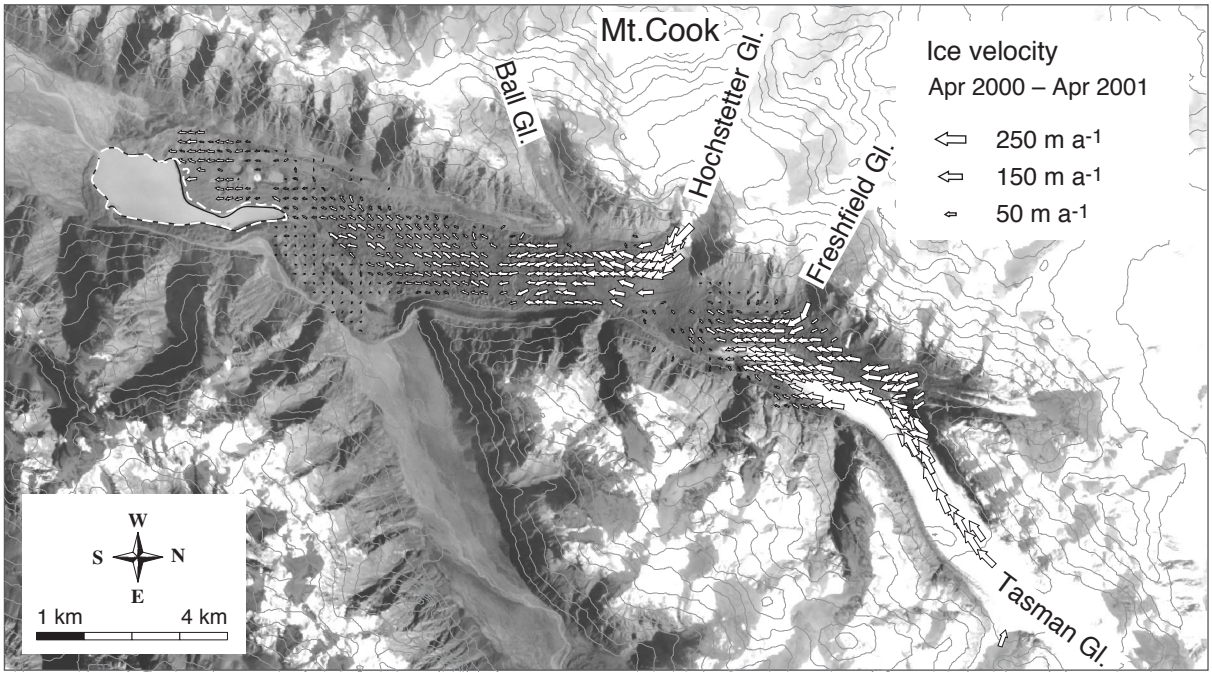

Figure 4: Glacier flow field of Tasman Glacier, New Zealand as derived from repeat images from the ASTER satellite sensor. Similarly, many types of high-mountain terrain movement can be investigated through optical and microwave techniques.

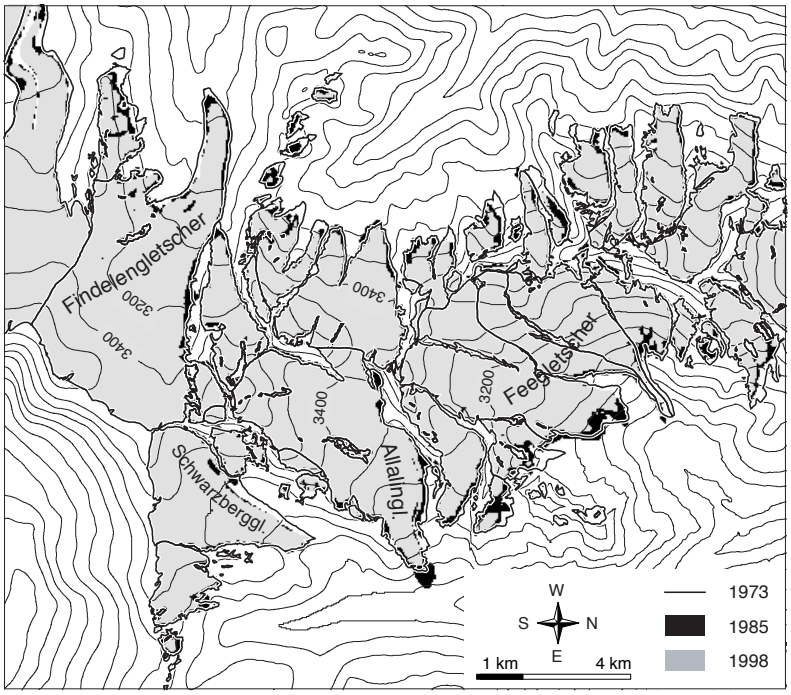

Figure 5: Glacier change in the Mischabel range, Swiss Alps, derived from a 1973 inventory based on maps and air photos, and satellite imagery of 1985 and 1998. Repeat satellite imagery offers a simple and effective method for detecting many kinds of land cover change.