Snow surface albedo estimation using terrestrial photography

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Abstract

A flexible and inexpensive remote sensing tool for albedo estimation using conventional terrestrial photography and its validation on an Alpine glacier is described. The proposed technique consists in georeferencing oblique photographs to a digital elevation model (DEM), defining a mapping function between the information contained on a given pixel of the image and the corresponding cell of the DEM. This is attained by performing a perspective projection of the DEM after a viewing transformation into the camera coordinate system. Once the image is georeferenced, the reflectance values recorded by the film or digital camera are corrected for topographic and atmospheric influences and for the effect of the photographic process (lens-film-developing-scanning). Atmospheric transmittance is evaluated using the MODTRAN radiative transfer model. Diffuse and direct irradiation are estimated using a parametric solar irradiation model. The solar-ground geometry, anisotropy of reflected radiation, the effect of surrounding topography and the portion of visible sky are evaluated using terrain algorithms applied to the digital elevation model. The response of the camera-film-scanner system is evaluated using an empirical approach. The result is a geographically correct map of normalised reflectance values. By comparing these to a surface of known albedo, the spatial distribution of albedos is calculated. Comparisons to *in situ* measurements on the Mer de Glace glacier, French Alps, show good agreement. Sources of error are identified and ways of improvement addressed.

Nomenclature

Symbol	Definition
C	camera coordinates
T	target coordinates
F_{ms}	diffuse radiation due to multiple scattering between ground and sky
F_{sk}	diffuse radiation from the sky
F_t	correction term for the angle of incidence of sun on the slope
I_i	incoming solar radiation
I_r	reflected solar radiation
I_{sc}	solar constant (mean value: 1367 Wm^2)
R	Reflected radiation flux
R_e	earth radius (mean value: 6,367,450 m).
R_n	pixel reflectance
R_{ref}	reference pixel reflectance
f	focal length
f_{df}	ratio of diffuse to total incoming radiation
f_{rt}	ratio of direct to total incoming radiation
f_{sv}	ratio of snow covered to total visible surrounding terrain
f_s	ratio of snow covered to total surrounding terrain
f_v	skyview factor
h	film height (24 mm for 35 mm photography)
r	reciprocal of the square of the radius vector of the earth
w	film width (36 mm for 35 mm photography)
Ω	ratio of the solid angle of a receptor's pixel field of view to 2π
α	albedo
α_g	ground albedo
α_s	snow albedo
α_{sk}	atmospheric albedo
ϕ	half the vertical field of view of the camera
τ_i	transmittance function through the atmosphere
τ_t	transmittance functions through the atmosphere from the camera to the target
θ	solar zenith angle
θ_s	angle between sun and normal to surface or relative solar zenith angle
φ	half the horizontal field of view of the camera
$\vec{N}$	unit vector in the viewing direction
$\vec{U}$	near horizontal unit vector perpendicular to $\vec{N}$
$\vec{V}$	near vertical unit vector perpendicular to $\vec{N}$
$\vec{n}$	unit vector normal to the surface
$\vec{s}$	unit vector in the direction of the sun

1 Aim

The overall aim of this work is developing a practical and inexpensive remote sensing tool for the estimation of temporal and spatial variations of surface albedo on glacier and snow covered mountainous areas. Given that the maximum energy reflected by the snow lies on the visible band of the electromagnetic spectrum, and given the widespread use of photographic cameras, the good spectral response of modern films and the increasing availability of digital photography, the use of conventional photography was explored for this purpose.

2 Introduction

On low and mid-latitude glaciers and on high mountains, solar radiation is the main source of energy for the melting of ice and snow (e.g. de la Casinière 1974, Marks and Dozier 1992, Cline 1997). Thus an accurate measurement of the temporal and spatial variation of albedo, which is the ratio of incoming to outgoing hemispherical shortwave radiation, is necessary to estimate snow ablation, which consequently influences the glacier mass balance dynamics and runoff. Albedo is, therefore, a very important parameter for the study of the hydrological resources derived from snow and for the study of glacier behaviour and its climatic response. It is an essential input for the physically based estimation of the energy balance of glaciers and snow cover basins (e.g. Strasser et al. 2002).

In order to estimate the albedo distribution over a basin, a standard approach is the interpolation of values from a few point measurements. However, the high spatial variability of albedo may introduce a large error (Knap, Brock, Oerlemans and Willis 1999). Furthermore, *in situ* measurements may be difficult or even impossible due to avalanche risk, which makes remote sensing tools an attractive solution. Satellite remote sensing has the potential to provide the necessary information of spatial and temporal variations of albedo, and therefore considerable research is being done in this area (e.g. Dubayah 1992, Knap, Brock, Oerlemans and Willis 1999, Grover et al. 2000). Although satellite derived data is very cost effective it is still expensive in absolute terms. Additionally, in areas of high relief cloud cover and shadows may reduce the efficiency of satellite imagery in the optical band, and it is impossible to get a temporal resolution higher than the repeat coverage cycle of the satellite.

An economic and either alternative or complementary approach to satellite imagery is the use of oblique terrestrial photography, which allows high temporal and spatial resolution. Furthermore, the combination of both techniques, satellite and photography, may enhance the quality of the satellite data. By testing smaller sites at higher resolution the results can be validated for the the whole coverage area. The proposed technique is suitable for mountain regions where views at a steep incidence angle result in better precision and larger ground coverage. The technique was evaluated by using the Mer de Glace Glacier, in the French Alps, as a test site (figure 11).

3 Methodology

Firstly we describe the georeferencing of oblique photographic images, using a viewing transformation and perspective projection of a digital elevation model (DEM) and a mapping function between pixels in the photograph and cells in the DEM. In this section the mathematical approach to defining the camera coordinate system is explained, together with the geometric transformations needed for georeferencing oblique photography. Visibility analysis is performed and basic photo orientation and corrections for camera movements are considered. Problems arising from using non metric cameras and conventional film and scanner are addressed. Then we deal with the estimation of albedo from reflectance values recorded by the camera. This is done by obtaining the ratio between the reflectance normalised values of the georeferenced photograph and a surface of known albedo. The effect of topography on the global solar radiation arriving at the ground is studied, accounting for direct cast shadows, diffuse radiation from the sky and diffuse reflected radiation from the surrounding terrain, which can be important in snow covered areas. The attenuation of solar radiation reflected from the target pixels when traversing the intervening atmosphere is evaluated with the help of a radiative transfer model (MODTRAN) and a simple empirical relationship is found for the effect of the camera optics, scan and film developing on the final product, the digital reflectance values in the image of the studied area. Finally the preferred data storage format is justified.

3.1 Georeferencing terrestrial photography

In order to georreference terrestrial photographs we need to find a function relating two-dimensional pixels in the photograph to three-dimensional points in the digital elevation model. This is achieved by applying a perspective projection after transforming the coordinates of the DEM to camera coordinate system. In this way we produce a “virtual” photograph of the digital elevation model, that is, a two-dimensional representation of the relief information contained in the DEM, as seen from the point of view of the camera. By scaling this representation according to the resolution of the photograph, we can establish the necessary correspondence between pixels in the image, screen coordinates of the perspective projection of the DEM and their geographic location.

Simultaneous development of a similar technique has been carried out by different authors (Corripio 2000, Corripio 2001, Aschenwald et al. 2001). The details of the transformations are not explicitly given by Aschenwald et al. (2001), who derived them from classical photogrammetry theory (Slama et al. 1980). This paper follows computer graphics theory and, for completeness and repeatability, the detailed procedure is explained in the following paragraphs.

Firstly, we select the visible portion of the DEM according to the angular field of view. This is derived from the the focal length of the camera lens and the dimensions of the film. The angle ϕ in figure 1, is half the vertical field of view, and its value is:

$$\phi = \arctan \frac{(1/2)h}{f}, \tag{1}$$

where f is the focal length and h is the vertical dimension of the film, which is 24 mm for 35 mm photography. Similarly, the half value of the horizontal field of view, φ, is:

$$\varphi = \arctan \frac{(1/2)w}{f}, \tag{2}$$

where w is the horizontal dimension of the exposed film or 36 mm for this format.

Within this viewing window there are surfaces facing the observer and others facing away or hidden by nearer ground. These surfaces are, obviously, not seen by the camera, and in order to avoid duplicate or erroneous mapping of the photographic pixels to non visible DEM cells a viewshed analysis was performed with ArcInfo, a commercially available GIS package. Future work will be done toward the implementation of a viewshed algorithm by Wang et al. (2000), so that the whole procedure is a stand-alone routine coded in a single programming language.

Once visibility has been calculated, we apply a viewing transformation that maps points in the world coordinate system (that of the DEM) to points in the camera coordinate system, representing the viewing geometry of the camera in three-dimensional space, as shown in figure 2. A viewing transformation is parameterised by a viewing direction vector $\vec{N}$, a vector $\vec{V}$ indicating which way is up, a vector $\vec{U}$ positive in the direction of the X–axis and a viewing position C (Fiume 1989). This is a standard procedure for obtaining perspective views in computer graphics (e.g. Foley et al. 1990). Firstly, we apply a translation transformation to set the origin at C, the camera position. The transformation matrix, in homogeneous coordinates, representing this translation, T_t would be:

$$\begin{pmatrix} P_{tx} \\ P_{ty} \\ P_{tz} \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & -C_x \\ 0 & 1 & 0 & -C_y \\ 0 & 0 & 1 & -C_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} P_{wx} \\ P_{wy} \\ P_{wz} \\ 1 \end{pmatrix}, \tag{3}$$

where P_w is any given point in world coordinates and P_t is the translated point to a reference system with origin at C, the camera position.

Lastly, the viewing transformation is completed by multiplying the result of equation 3 by the following transformation matrix, which rotates the translated coordinates according to the viewing reference system:

$$\begin{pmatrix} P_{cx} \\ P_{cy} \\ P_{cz} \\ 1 \end{pmatrix} = \begin{pmatrix} U_x & U_y & U_z & 0 \\ V_x & V_y & V_z & 0 \\ N_x & N_y & N_z & 0 \\ 0 & 0 & 1/f & 1 \end{pmatrix} \begin{pmatrix} P_{tx} \\ P_{ty} \\ P_{tz} \\ 1 \end{pmatrix}, \tag{4}$$

where f is the focal length of the lens and P_c is the resulting coordinates of a point in camera coordinate system.

The calculation of the unit vectors defining the viewing geometry is as follows. The viewing direction or vector $\vec{N}$ is :

$$\vec{N}_0 = T - C, \tag{5}$$

$$\vec{N} = \frac{\vec{N}_0}{|\vec{N}_0|}, \tag{6}$$

where T is the coordinates of the the target (aim of the camera) and C the coordinates of the camera with respect to the DEM origin of coordinates.

From this vector, and applying a procedure slightly modified from that used by Fiume (1989) or Watt and Policarpo (1998), $\vec{U}$ and $\vec{V}$ are calculated using simple vector calculus, by finding the cross products:

$$\vec{U} = \begin{cases} \vec{N} \times \frac{\vec{N}_{xy}}{|\vec{N}_{xy}|} & \text{if } N_z > 0 \\ \frac{\vec{N}_{xy}}{|\vec{N}_{xy}|} \times \vec{N} & \text{if } N_z < 0 \end{cases} \tag{7}$$

$$\vec{V} = \vec{N} \times \vec{U}, \tag{8}$$

where $\vec{N}_{xy}$ is the projection of $\vec{N}$ onto the horizontal plane, or $(N_x, N_y, 0)$, and N_z the z coordinate of vector $\vec{N}$.

After the viewing transformation a perspective projection is applied. This is a mapping function of the points in three-dimensional space to a flat two-dimensional space representing the window of the camera vision. A simplified geometry of the projection is shown in figure 3. Following Watt and Watt (1992) the resulting x, y coordinates are calculated as:

$$P_{px} = \frac{fP_{cx}}{\frac{1}{2}wP_{cz}} \quad \text{and} \quad P_{py} = \frac{fP_{cy}}{\frac{1}{2}wP_{cz}}, \tag{9}$$

where $P_{p(x,y)}$ are the new x, y coordinates of the perspective projection of the point $P_{c(x,y,z)}$ onto the projection plane, which in this case is the film. The factor $1/2$ is introduced in the dividend to set the origin of coordinates in the projection plane to the centre of the film.

The resulting set of x and y coordinates after the perspective projection recreate, at a lower resolution and at a different scale, the terrain surface captured by the film (figure 4). It is, in fact, a virtual photograph of the digital elevation model. In order to map it to the original photograph it has to be scaled according to the resolution of the scanned picture. This is a simple linear transformation.

If the position of the camera and the viewing direction is correct, the projection of the DEM grid points should match the image in the photograph, as in figure 5, then the visual information of the picture can be extracted and mapped onto the digital elevation model. This is straightforward if, during the viewing and perspective transformation of the DEM, the link to the original coordinates of the grid cells is always preserved. When implementing the algorithm this is attained by constructing a five dimensional matrix with three dimensions (x, y, z) representing the original coordinates and two additional ones for those of the perspective projection.

Figure 4 shows the result of this perspective transformation, projection and scaling for a section of the Mer de Glace. Dots are the perspective projections of the original DEM grid cells, the frame is the camera field of view. The photograph in figure 5 shows the superposition of the projected DEM (red dots) onto the original photograph. Green crosses are ground control points (GCPs), used for fast photo orientation when the target coordinates are not precisely known and to assess the fitness of the match between the photography and the perspective projection of the DEM. If there were any uncertainty on the exact position of the point towards the camera is aiming (the target), the viewing direction vector will not be precisely defined, and this will result in a displaced perspective projection of the DEM. In order to avoid the more lengthy computation of the whole DEM, it is sufficient to compute only a few well defined GCPs to assess the accuracy of photo-orientation. Figure 9 shows a flow chart of the georeferencing process, where the first loop is done initially only for the ground control points in order to speed up the computation, and only when the match between GCPs and the corresponding points in the photograph is satisfactory, the computation is applied to the whole DEM.

The end result of this first process is a georeferenced image of reflectance values, shown in figure 6. Reflectance in the case of visible photography refers to the three optical bands in the red, green and blue to which the film is sensitive, though the technique is of application to any other ground based sensor able to record images in any spectral band. A more detailed georeferenced image, for the lower section of the glacier is shown if figure 7, in this case using a DEM resampled to 10 m resolution in order to show the potential of this technique to recognise and geolocate surface features.

3.1.1 Photo orientation

Unless the camera is mounted on a theodolite or a similar apparatus, it is very difficult to keep its X-axis (vector $\vec{U}$) in a strictly horizontal position at the time of taking the photograph, specially under adverse terrain and weather conditions. To cope with this problem a simple algorithm for correction of camera rotation is implemented.

The simplest correction is for the distortion due to roll of the camera around the the viewing direction axis. Figure 8 shows the calculation of the angle of rotation. The discontinuous line represents the projected terrain points for a viewing coordinate system rotated approximately 15 degrees anti clockwise (note that an anti clockwise roll of the camera results in a clockwise roll of the image). The continuous line would be the photographed terrain. By measuring the pixel positions of both, the actual image P_i and the projected elevation points P_p relative to the center of the image, we can calculate angles ψ and γ and their difference, which is angle ζ, the actual roll of the camera. By rotating the camera coordinate system $C\vec{U}\vec{V}\vec{N}$ an angle ζ, the distortion due to roll is corrected. As we are dealing with unit vectors, the operation is reduced to adding a vertical vector of magnitude $-\tan\zeta$ to$\vec{U}$ (recall from equation 7) and finding the unit vector in the resulting direction:

$$\psi = \arctan\frac{P_{iy}}{P_{ix}} \tag{10}$$

$$\gamma = \arctan\frac{P_{py}}{P_{px}} \tag{11}$$

$$\zeta = \psi - \gamma \tag{12}$$

$$\vec{u}_\zeta = (0, 0, -\tan\zeta) \tag{13}$$

$$\vec{U}' = \frac{\vec{U} + \vec{u}_\zeta}{|\vec{U} + \vec{u}_\zeta|} \tag{14}$$

$$\vec{V}' = \vec{N} \times \vec{U}' \tag{15}$$

The new, rotated camera coordinate system will be $C\vec{U}'\vec{V}'\vec{N}$.

The differences between expected (due only to rotation) and measured values of the displacement of P_p along the X-axis will give us information on the yaw of the camera, or horizontal displacement of the estimated target. Extensive work is been done toward the elaboration of precise photo orientation algorithms (e.g. Croitoru and Ethrog 2001), although it was found that the use of precise ground control points, for example, collected by differential GPS (global positioning system), allows fast manual photo orientation by trial and error.

3.1.2 Additional corrections

Additional corrections to account for the curvature of the earth and the refraction of light through the atmosphere need to be taken into account in some cases. Curvature of the earth may be important for images taken from a long distance. Simple trigonometry shows that the the depression of the observed point or dip (Δz), is related to the distance to the observer by:

$$\Delta z = R_e - \frac{R_e}{\sqrt{R_e^2 + d^2}}, \tag{16}$$

where R_e is the radius of the Earth, (mean value: 6,367,450 m) and d is the distance to the observer. For a distance of 10 km the dip would be 7.85 m, which should be subtracted from the cells' heights at that range prior to the georeferencing process.

The refraction of light is only important for paths through the atmosphere where the target and the observer are at very different altitudes, and therefore at significantly different air densities. Refraction is evaluated using the MODTRAN radiative transfer model (Berk et al. 1989). In the present study, for typical atmospheric conditions and maximum difference in height, the cumulative bending of the light rays is about 0.012°, which for the maximum distance range within the DEM amounts to an error of 2 m. However, the photographs are taken for smaller areas and elevation ranges, which made refraction and curvature in this case negligible.

Radial distortions are highly variable depending on the quality of the lenses used. This type of distortion alters the geometry of the image, typically in an exponential way as we move away from the centre of the image. Access to this information is not easy, as manufacturers normally classify it as confidential, but typical values are in the range of up to tens of μm (Cooper and Robson 1996, Fryer 1996) . For a scanned digital image at 200 dots per cm (512 dpi), the radial distortion would be smaller than one pixel, and therefore negligible. An alternative solution if the radial distortion is expected to be high, is to discharge the margins of the photograph and cover the area with another photograph centered around the discharged area. Tangential distortion is typically small compared to radial distortion (Jacobson 1978).

Other errors due to coma, astigmatism, barrel and pincushion distortion of the lens, curvature of field (Jacobson 1978) and for film deformation due to unflatness (Fryer 1996) are minimised by using high quality lenses and cameras.

3.2 Conversion from reflectance to albedo

A pixel in a photograph contains information on the reflected radiation coming from a determined surface area. This reflected radiation will depend on the incoming global radiation, the albedo of the surface, the intervening atmosphere and the viewing geometry. The global radiation is the result of multiple interactions of the solar radiation field with the atmosphere, the target and the surrounding terrain. Thus, the main factors affecting the solar radiation falling on a surface are:

- Ratio of direct to diffuse radiation. - Angle of incidence of the solar beam on the surface.
- Local horizons to the surrounding ground and the nature of this ground.
- Fraction of visible sky in the upper hemisphere or skyview factor.
- Multiple scattering of solar radiation between the sky and the ground.

The main factors affecting the measurement and recording of reflected solar radiation arriving to the film are:

- Atmospheric transmittance between the object and the camera.
- Anisotropy of the reflected radiation.
- Input/output relationship between the incoming light and the response of the lens-camera-film-scanner system.

A photograph contains a large amount of information at a very high resolution, but it is not a system designed for retrieving quantitative information from the original incoming radiation. However, this work assumes that there is a direct relationship between the albedo of a surface and the camera output of the recorded reflected flux radiance. Then, by comparing the values of pixels in a photograph to a determined reference pixel corresponding to a surface of known albedo, we can estimate the albedo of the remaining surfaces, even when it is not possible to estimate the actual value of the radiative flux arriving to the film.

The surface albedo is defined as the ratio of the hemispheric reflected (I_r) and incoming (I_i) radiative fluxes (e.g. Knap and Reijmer 1998):

$$\alpha = \frac{I_r}{I_i}. \tag{17}$$

The incoming radiative fluxes are calculated as:

$$I_i = rI_{sc}\tau_i(F_t + F_{sk} + F_{ms} + F_{sn}), \tag{18}$$

where I_{sc} is the solar constant or 1367 Wm^2; r is the reciprocal of the square of the radius vector of the earth, or correction for the eccentricity of the earth's orbit, which here is calculated using Fourier series derived by Spencer (1971); and τ_i represents atmospheric transmittance functions, both for diffuse and direct radiation, which take into account Rayleigh scattering, transmittance by ozone, by uniformly mixed gases, by water vapour and by aerosols, and are computed following a parametric model by Iqbal (1983). The τ–functions incorporate the relative optical path length and pressure corrected air mass, depending on solar zenith angle and altitude. Further updates to Iqbal's model are introduced for the calculation of precipitable water, following Prata (1996), for ozone layer thickness, which is extracted from the NASA Total Ozone Mapping Spectrometer dataset (TOMS/EP 2001) and for increased transmittance with altitude, computed statistically after several runs of the model and in accordance with values recommended by Bintanja (1996).

The model has been tested successfully at high altitude in the Andes by the author (Corripio and Purves 2002) , where the differences between modelled and measured data were smaller than the error introduced by pyranometer accuracy (3%), and gives the best results in a comparative study of radiative flux parameterizations for shortwave radiation published by Niemelä et al. (2001).

The terms of the last factor in equation 18 represent the corrections for the influence of topography and diffuse radiation. These are:

$$F_t = f_{dt}\vec{n}\cdot\vec{s} = f_{dt}\cos\theta_s, \tag{19}$$

is a correction term for the angle of incidence of sun on the slope, where f_{dt} is the ratio of direct to total incoming radiation, $\vec{n}$ is the unit vector normal to the surface and $\vec{s}$ is the unit vector in the direction of the sun. This dot product is equivalent to the cosine of the relative solar zenith angle θ_s. F_t is computed only for cells in the sun, not in the shadow.

$$F_{sk} = f_{df}f_v \tag{20}$$

is diffuse radiation from the sky, f_{df} is the ratio of diffuse to total incoming radiation, calculated from Iqbal's model, and f_v is the hemispherical fraction of visible sky, or skyview factor. f_v and $\vec{n}$ are calculated from a digital elevation model of the area, these two terms and $\vec{s}$ are computed following Corripio (2002).

$$F_{ms} = \alpha_{sk}(f_s\alpha_s + (1 - f_s)\alpha_g)f_{sh} \tag{21}$$

is diffuse radiation due to multiple scattering between the ground and the sky, where α_{sk} is the albedo of the atmosphere, which depends on atmospheric conditions and is calculated according to Iqbal (1983); f_s is the fraction of surrounding terrain covered by snow with albedo α_s; the remaining terrain has an estimated albedo of α_g; and f_{sh} is a shadow factor:

$$f_{sh} = f_{dr}f_{st} + f_{df}, \tag{22}$$

where f_{st} is the ratio of cells in the sun to total number of cells.

A rigorous computation of reflected diffuse radiation will require an exhaustive evaluation of viewing geometry and illumination conditions of the surrounding terrain, which is computationally expensive. Therefore, a simplified approach is suggested in the form of the following equation:

$$F_{sn} = (1 - f_v)(f_{sv}\alpha_s + (1 - f_{sv})\alpha_g)f_{sh}, \tag{23}$$

where the term f_{sv} is the ratio of snow covered to total visible surrounding terrain. Following Greuell et al. (1997), a distinction is made between f_s and f_{sv}, as reflected diffuse radiation from snow will come from those surfaces which are visible, while the diffuse radiation due to multiple scattering with the sky might come from surrounding snow covered terrain which is not visible from the area under consideration.

The snow albedo is not isotropic, and variations might be important, especially at low relative solar zenith angles. It is generally agreed that the albedo of the snow is independent of θ_s for θ_s smaller than 50° (Wiscombe and Warren 1980, Brock et al. 2000). In any other cases, and for the albedo of the ice, bidirectional reflectance distribution functions should be applied (see for example: Greuell and de Ruyter de Wildt 1999, Knap and Reijmer 1998).

The reflected radiation arriving at the camera or recording device per pixel will be:

$$R = I_i\alpha\Omega\tau_t, \tag{24}$$

where Ω is the ratio of the solid angle of a receptor's pixel field of view to 2π (the whole hemisphere solid angle), and τ_t is a transmittance function to account for atmospheric attenuation between the target and the camera. τ_t is calculated using MODTRAN and general knowledge of the local atmospheric conditions. Running the MODTRAN model for all the cells would be extremely time consuming if not impossible. Thus, a feasible solution is to run the model for a set of points containing the boundaries of the DEM, clusters of points in the regions of more interest and randomly selected points. From the results of these runs an statistical fit is interpolated as a surface of minimum curvature passing through the given values. Transmittances for all the remaining grid cells are obtained by reference to this interpolated surface.

The ratio of the reflectance of any given pixel R_n to a reference pixel reflectance R_{ref} whose albedo is known, will be:

$$\frac{R_n}{R_{ref}} = \frac{(I_i\alpha\Omega\tau_t)_n}{(I_i\alpha\Omega\tau_t)_{ref}} \tag{25}$$

Rearranging terms, combining with equation 18 and noting that $\Omega_n = \Omega_{ref}$, as the camera pixels are uniform and their field of view solid angles are identical, we have:

$$\alpha_n = \alpha_{ref} \frac{R_n}{R_{ref}} \frac{(\tau_i \tau_t)_n (F_t + F_{sk} + F_{ms} + F_{sn})_{ref}}{(\tau_i \tau_t)_{ref} (F_t + F_{sk} + F_{ms} + F_{sn})_n}, \tag{26}$$

where $(\tau_i)_n$ and $(\tau_i)_{ref}$may cancel each other if altitudinal variations within the area under consideration are small.

The ratio R_n/R_{ref} is calculated directly from the digital numbers of the digitised (scanned) photograph. α_{ref} is known by direct measurement and the rest of terms are calculated following equations 18 to 23. Thus, it is sufficient to know a reference albedo, which is measured at one single point, in order to estimate the albedo of the whole area in the image. If no direct measurement of a reference point is possible, then a surface on known reflectance such as a Kodak grey card or a spectralon panel could be introduced at the time of taking the image and follow the same procedure to calculate the albedo of the remaining pixels.

3.2.1 Narrow band versus broadband albedo

The recording device used in this work is slide film for visible light, sensible to radiation in the range of 400 to 700 nm. However, the snow absorbs energy in the form of shortwave radiation in a wider spectrum, and the albedo is generally measured in the range 300 to 2800 nm. A conversion between the narrow visible band to the wide shortwave band is desirable.

Snow may present large variation in albedo in the near infrared, depending mainly on snow grain size (Wiscombe and Warren 1980, Dozier et al. 1981). However, the corresponding variations in the visible band are too small to detect with normal photographic film, therefore it is not possible to extend the visible albedo to a wider band using only information on the visible range. None the less, the actual energy inputs in the regions 300–400 nm and 700–2800 nm, for the usual atmospheric conditions in which we were working, are 10% and 25% respectively of the total shortwave energy, according to MODTRAN model outputs. The maximum range of albedo variation is very small in the ultraviolet and up to approximately 40% in some region of the infrared for varying snow grain size (Wiscombe and Warren 1980, figure 8). Thus, the maximum error in the estimation of energy inputs in the case of extreme variations of snow grain size, considering only the visible band, would be about 9% and typically smaller. During the present work snow grain size was practically uniform on the whole area except for the upper section of Mont Blanc de Tacul, above 4,000 m a.s.l. Ground above 4,000 m represented only 2% of the total surface and images used for the computation normally contains only one uniform type of snow. Therefore, the extension of albedo values derived from reflectance comparisons in the visible region band to broad band albedo is a reasonable assumption in this particular case. Further research will focus on ways of improving the estimation of albedo by using digital or spectral cameras sensitive to near infrared radiation.

3.2.2 Film-scanner input/output relationship

The relationship between incident light on the camera and film response depends on the emulsion used, the type of lens, the exposure, brightness of the object and film development. Additionally, the accurate response of the scanner to the light transmitted through the processed film is difficult to quantify, as scanner manufacturers normally do not provide the necessary information. These processes introduce uncertainties and non-linearities in the evaluation of the scanned digital image.

To deal with this problem an empirical approach was followed, to obtain a function that relates input (incoming light) to output (digital values produced by the scanner), for a given combination of lens-film-scanner. The procedure is similar to sensitometric analysis in photography (Jacobson 1978) and consists of finding a statistical fit between known illumination values and resulting output from the scanner.

In the present work a graded grey–scale card (Kodak Grayscale Q-13) was photographed and used as a calibration input. This card is a rectangle divided into 25 boxes of varying shades of grey, from near white to near black at 0.05 density steps, from nominal values of 0.05 to 1.95. Density is a magnitude normally used in photography, whose value is the logarithm of light flux intensity, either transmitted through the film, or reflected from a surface. Thus, the grey–scale card densities correspond to reflectance values between 1% and 89%. Values below 10% were ignored, as the response of the film in this area is non-linear and we are dealing with snow, which has always higher reflectance. Values for the scanned test photograph are plotted in figure 10. Most photographic films present characteristic response curves that shows a straight line between a toe of increasing slope in the darker region of the image and a shoulder of decreasing slope near saturation. Therefore, a correctly exposed film, with density values within these two thresholds, should present a linear response, although slightly modified by the development and scanning. For a film scanned at gamma = 1, figure 10 shows a linear relationship close to 1:1 (slope = 1.111, r^2=0.998) for digital numbers corresponding to reflectances in the snow region. This linear relationship simplifies the correction between original reflectance values and the DN values produced after scanning the film. It is sufficient to solve for the x in the regression equation and apply it to the reflectance values.

3.3 Data format

To facilitate data portability and to integrate digital elevation models and image files, the GeoTIFF data format was chosen for digital analysis and storage. GeoTIFF represents an effort by over 160 different remote sensing, GIS, cartographic, and surveying related companies and organizations, to establish a TIFF based interchange format for georeferenced raster imagery (Ritter and Ruth 1997, Ritter and Ruth 2000).

4 Experimental set up

Photographs and direct albedo measurements were taken on the Mer de Glace on different days from the 6th to the 26th of June 2000. The Mer de Glace is the largest glacier in the French Alps and the third largest in the whole Alps (figure 11). It is located east of the Mont Blanc, with a length of 12.3 km, and a surface area of 32.09 km^2 (Hoelzle and Haeberli 1999). The altitude ranges from 4,248 m above sea level to 1,470 m a.s.l. The location was selected taking into account the variability of snow and ice surface albedos, different orientations, accessibility, safety and efficiency of time allocation.

The orientation of the principal glacier slopes range from 0 to 180 degrees, with the largest sections of the glacier facing S, SE and N. This range of orientations makes possible studying the glacier at different times and with different solar illumination conditions. The upper section of the glacier, above 4000 m, had fresh snow that had not suffered intense metamorphism processes, and consequently had a higher albedo. However, most of the glacier was covered in well metamorphosed granular snow. The lower section was bare glacier ice partially covered in debris.

Albedo measurements were taken using a Kipp & Zonen CM 7B albedometer, which consists of two opposed pyranometers sensitive to hemispherical incoming and reflected short-wave radiation in the range 300–2800 nm. The albedometer was attached to a photographic camera tripod, as shown in figure 12, and positioned parallel to the surface to minimise measuring errors due to the inclination of the surface (Mannstein 1985, Sicart et al. 2001). Measurements were taken on the widest possible range of surface types, orientations and time of the day. The location of every site was determined using a GPS with a nominal precision of 15 m. The actual precision, especially at the bottom of the valleys with poor satellite visibility an geometry was estimated in the range of 25 to 100 m by comparison of actual readings on the GPS receiver with points whose location was well known.

A digital elevation model at 50 m grid resolution was purchased from the French Institute Géographique National. Photographs were taken with a Nikon F4 camera and lenses in the range 35–80 mm. The film used was Kodak Ektachrome E100SW for visible light, which shows a good overlapping of spectral bands and extended linear response over its sensitivity range (Kodak 2001). A Kodak grey card was used as a reference card, both for the intensity of reflected light and for spectral balance. Although the grey card is not a perfectly diffuse reflector, it has small variations in reflectance over the optical wavelengths according to Milton (1989) and to tests with a GER 3700 spectrometer performed by the author.

5 Results and discussion

The result of the georeferencing process for this test site have already been introduced in section 3.1, figures 6 and 7. The accuracy of the georeferencing process decreases with shallow viewing angles (areas of closely packed red dots in figure 5), and is better for viewing directions approaching the normal. This fact makes the technique more appropriate for mountain terrain, where images can be taken from ridges and peaks with steep viewing angles to the valley.

The final result of the albedo estimation is shown in figure 13 as a color coded georeferenced composite image of estimated albedo values derived from three different photographs of the Mer de Glace. Coloured crosses representing the measured values are superimposed, so that discrepancies can be easily highlighted, although none is obvious in this case. The inset, extracted from a resampled DEM at higher resolution, is a detail of the lower section, showing the albedo variations among the glacier ojives. Black areas are either areas non visible from the photo or with relative solar zenithal angles higher than 60°. Figure 14 shows the differences between estimated and measured albedo values. The maximum error in the estimation of albedo is 6.5%, while the average error is only 2.2%.

In general errors are small and most of them are derived from displacements between photograph and DEM during the georeferencing process, especially in areas where there is an abrupt change of slope. This is because the angle between the sun and the normal to the slope is the most important parameter affecting the conversion between reflectance values and albedo. Thus, a small displacement may cause a relatively flat pixel being corrected for an excessively steep slope. This type of error can be avoided improving the georeferencing process by providing more precise and a larger number of ground control points. Uncertainties in the exact geolocation of the photo-pixels, together with ambiguous assignation of image pixels to DEM cells, specially for low resolution DEMs, may lead to errors due to high albedo variability over the glacier. As figure 15 shows, inter–pixel variability of albedo values is in the same range as the maximum error in the albedo estimation. This variability is maximum in areas partially covered with debris and on patchy surfaces, with intermixing of snow and glacier ice. The date of DEM production is important too, given the fast retreat and thinning rate of some Alpine glaciers.

When using normal film and additional scanning of the image on non metric cameras, there is always some mismatch between the actual borders of the film and the origin of the image. If the film is scanned from a framed slide, there may be some additional inaccuracies due to internal displacements of the film inside the slide mount. Additionally, the corners of the photographic emulsions are not perfectly square (Croitoru and Ethrog 2001), which may add an uncertainty of a few pixels, reducing the accuracy of the georeferencing step. This problem can be easily solved using digital photography.

As there was limited information on the anisotropy of the reflected solar radiation over the snow, the traditional rule of thumb considering albedo independent of the relative solar zenith angles for angles smaller than 50° (Wiscombe and Warren 1980) was applied, and cells falling outside this condition where masked out. Work by Greuell (2002) shows that there is still insufficient knowledge about the angular distribution of the reflected radiation over the snow and that bidirectional reflectance distribution functions (BRDFs) may not be of universal application. Therefore the masking out option was considered safer than applying corrections from BRDFs derived at other locations and with different snow characteristics. A further project using a modified application of the photographic technique described in this paper for the derivation of suitable BRDFs is under consideration. Albedo was estimated only for the visible part of the spectrum, which may lead to some errors (see section 3.2.1), although the uniformity of grain size in the case study suggests that these errors are likely to be small.

Further work would be desirable using a higher resolution DEM and GCP collection with differential GPS in order to assess the precision of the georeferencing process and to minimise the errors in albedo estimation due to geolocation. The use of a spectral digital camera may produce enough data to find a suitable algorithm for the conversion of narrow band photography to broad band albedo, similar to those applied to satellite derived albedos (Knap, Reijmer and Oerlemans 1999). Finally it would be desirable to perform tests with a narrow field of view, but the same photographic sensor, and at different solar elevation angles in order to assess the effects of viewing direction and illumination angles on the reflectance of the snow. In this way suitable bidirectional reflectance distribution functions could be implemented to correct for the anisotropy of the reflected solar radiation field.

6 Conclusions

Two complementary techniques are described in this paper. The first one, georeferencing of terrestrial photography, is a flexible and inexpensive remote sensing tool that has potential applications in many environmental and monitoring fields, such as: snow mapping, vegetation surveys, erosion monitoring, geomorphological mapping and visualisation in GIS, and may improve previous applications of photography to land cover mapping and change monitoring (e.g. Christiansen 2001). It provides an economical tool to assess any kind of land cover change at a high temporal resolution, with a spatial resolution and accuracy limited only by the scale and quality of the available digital elevation model. It is, in a summary, a flexible and inexpensive remote sensing tool.

The second technique is a simple and effective way of estimating the distribution of snow surface albedo from one single reference measurement. This may improve the implementation of distributed snow energy balance models, and in glaciated areas reduces the exposure of fieldworkers to potential risks such as crevasses and avalanches. The present work has some limitations due to the limited spectral sensitivity of the photographic film and the uncertainties in the anisotropy of the albedo. These limitations could be overcome, using digital spectral photography and building suitable BRDFs for the observed spectral bands.

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7 Figures

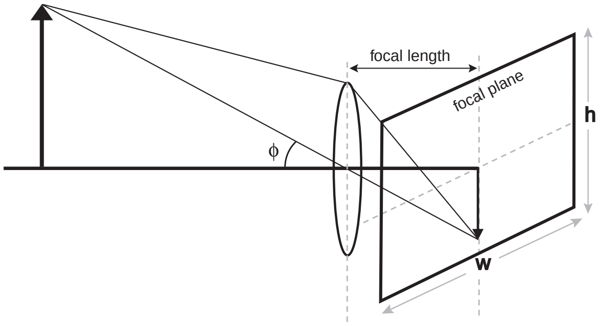

Figure 1: Simplified scheme of image formation in the camera. ϕ is half the angle of the vertical field of view, w is the width of the film (36 mm) and h is its height (24 mm).

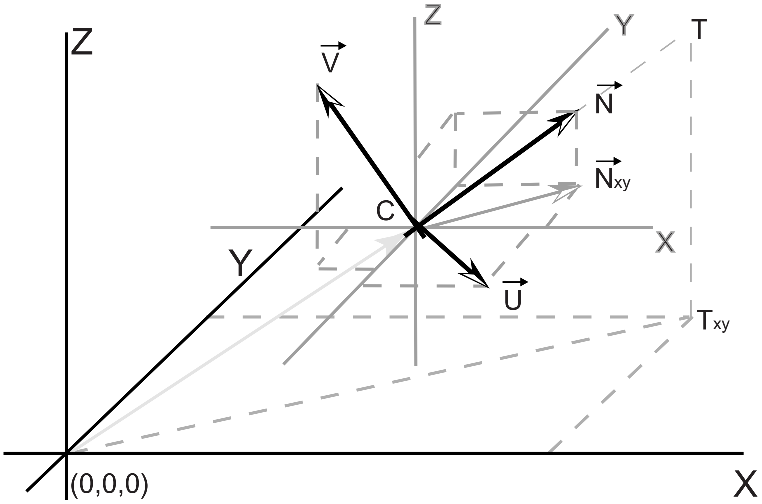

Figure 2: Change from world to camera coordinate system. DEM coordinates are referenced to the main reference system XYZ in the figure, while the image taken by camera at point C is referenced to the coordinate system defined by the three orthogonal unit vectors$\vec{U}\vec{N}\vec{V}$. $\vec{N}$ is the viewing direction of the camera, calculated from the camera and target positions. $\vec{U}$ is the unit vector of the cross product of $\vec{N}$ and $\vec{N}_{xy}$, which is the projection of $\vec{N}$ on the horizontal plane. $\vec{V}$ is $\vec{U} \times \vec{N}$. See section 3.1.

precision

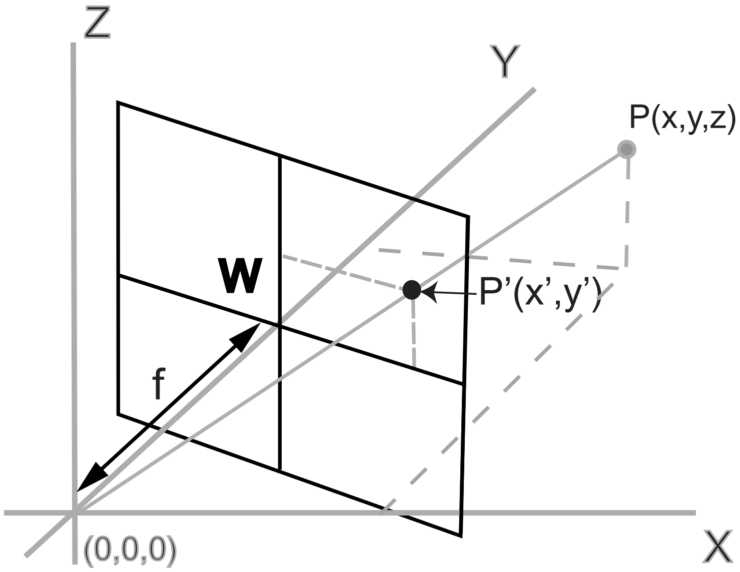

Figure 3: Simplified geometry of the perspective projection for one single point. A point P in tridimensional space is mapped (projected) to a point P' in a two-dimensional viewing window representing the camera film. The distance f to the origin of coordinates C in camera coordinate system is equivalent to the lens focal length. This perspective projection produces a virtual photograph of the DEM, which is then mapped to the pixels in the photograph. By conserving the link between P and P' the information in the flat two dimensional photograph can be mapped to the original three-dimensional points in the DEM. See section 3.1 for details.

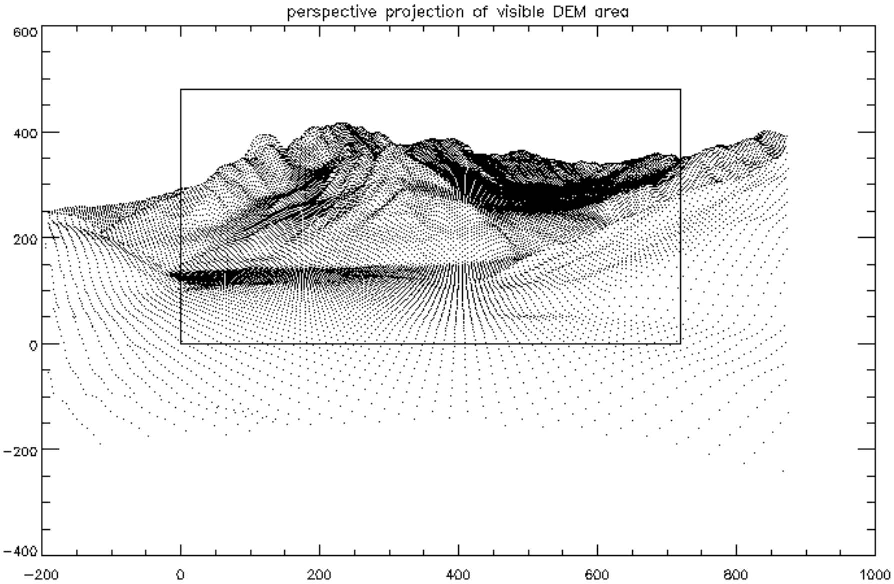

Figure 4: Perspective projection of a DEM of the lower section of the Mer de Glace, Mont Blanc. Every dot represent a grid cell after a viewing transformation and perspective projection. The frame is the camera field of view. Axis units are pixels in the original photograph: 720x480 within the frame, at a resolution of 200 dots per cm.

Figure 5: Super imposition of the perspective projection of a DEM of the Mer de Glace glacier (figure 4) over a photograph of the area. Red dots are the perspective projections of the original DEM grid cells, green dots are ground control points. The photograph is taken from the Refuge du Requin looking east-northeast.

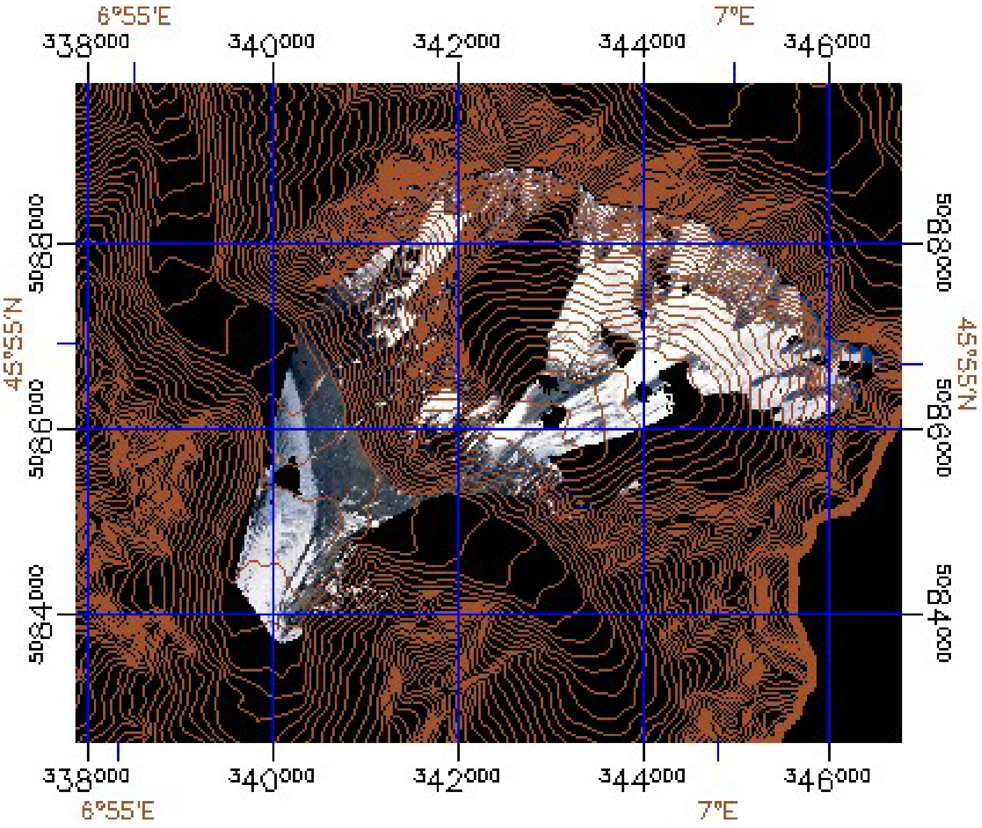

Figure 6: Georeferenced image of the lower middle section of the Mer de Glace. Reflectance values are extracted from photograph in figure 5. Black areas (holes) are not visible from the camera position.

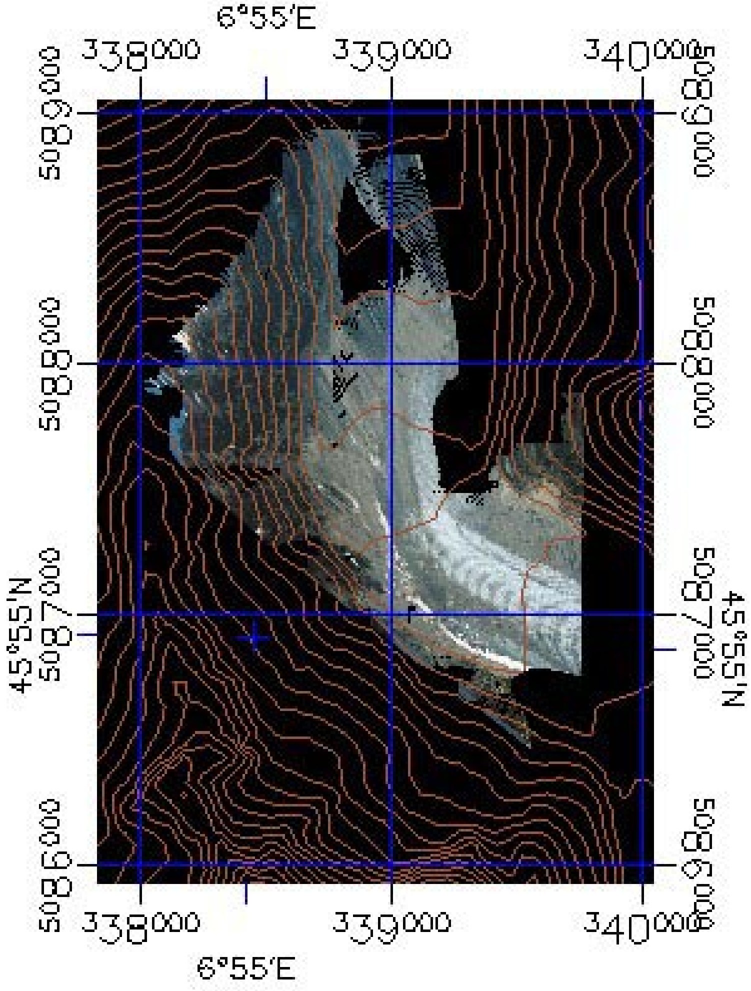

Figure 7: Detail of lower section of Mer de Glace. Georeferenced image using a resampled 10 m resolution DEM to show the potential of this technique for landform and pattern recognition. Note the dark and white ojives or Forbes bands on the glacier, which are characteristic of the lower tongue of the Mer de Glace.

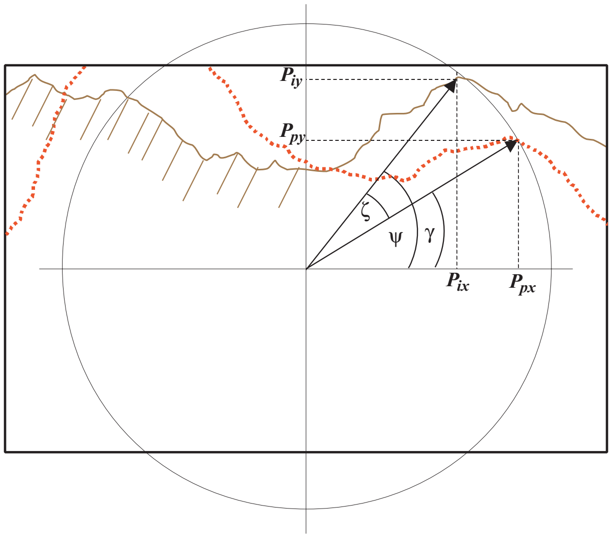

Figure 8: Example of mismatch between the perspective projection of the DEM (dotted line) and the photographic image (continuous line) due to roll of the camera. The correction for this displacement is explained in section 3.1.1

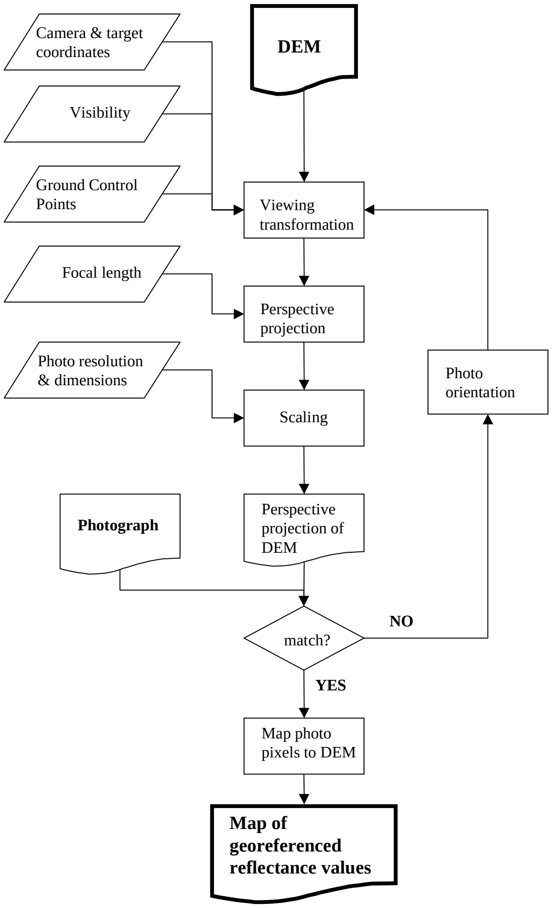

Figure 9: Flow chart of the georeferencing process.

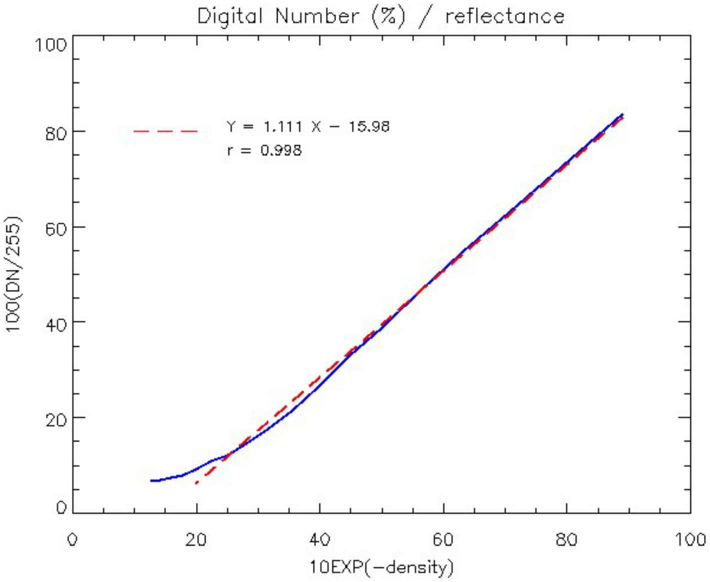

Figure 10: Digital Number (DN) versus reflectance. The output of the scanned photographic image is conditioned by the whole photographic process, camera, lenses and scanner characteristics. In order to relate the input light to the output values an empirical approach was followed. Solid line shows the relationship between input light and output DN values and dashed line is a regression fit excluding areas of very low reflectance. The regression is then linear, and the exclusion of very low (dark) values is justified as we are dealing with snow, which high reflectance values, in the region where the function is linear.

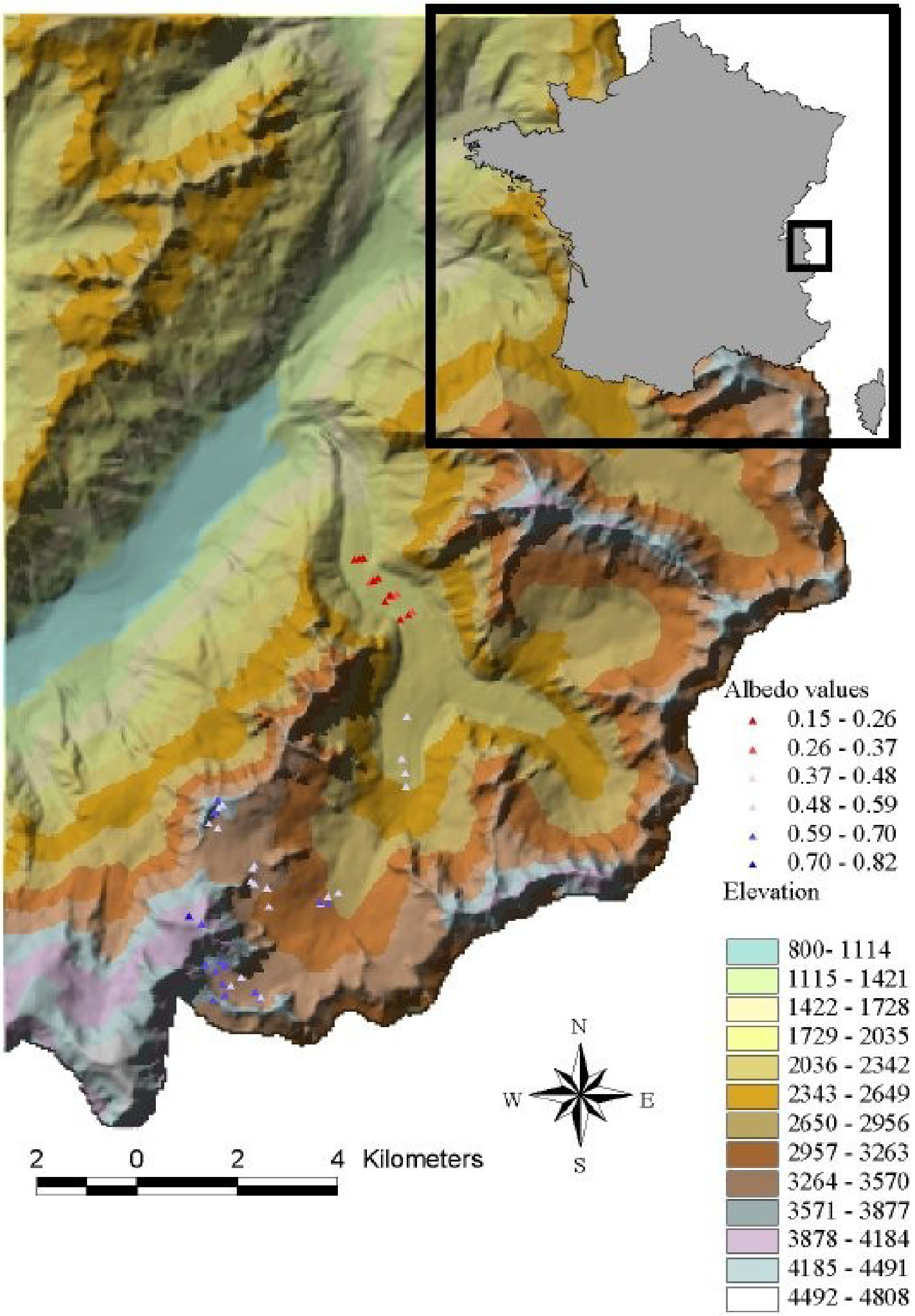

Figure 11: Map of the area of study in the French Alps, 45° 50′ N, 7° E. Mer de Glace glacier is the inverted Y-shaped glacier in the lower centre of the image. Coloured dots are albedo measurements. The DEM only covers the French side of the area, with no values for Italy and Switzerland.

Figure 12: Albedometer setting. The white oval, above and left the camera tripod is the albedometer, made up of two Kipp & Zonen opposed pyranometers. The output is read in two voltmeters connected at the extreme of the cable, hold by the skier-operator in the image.

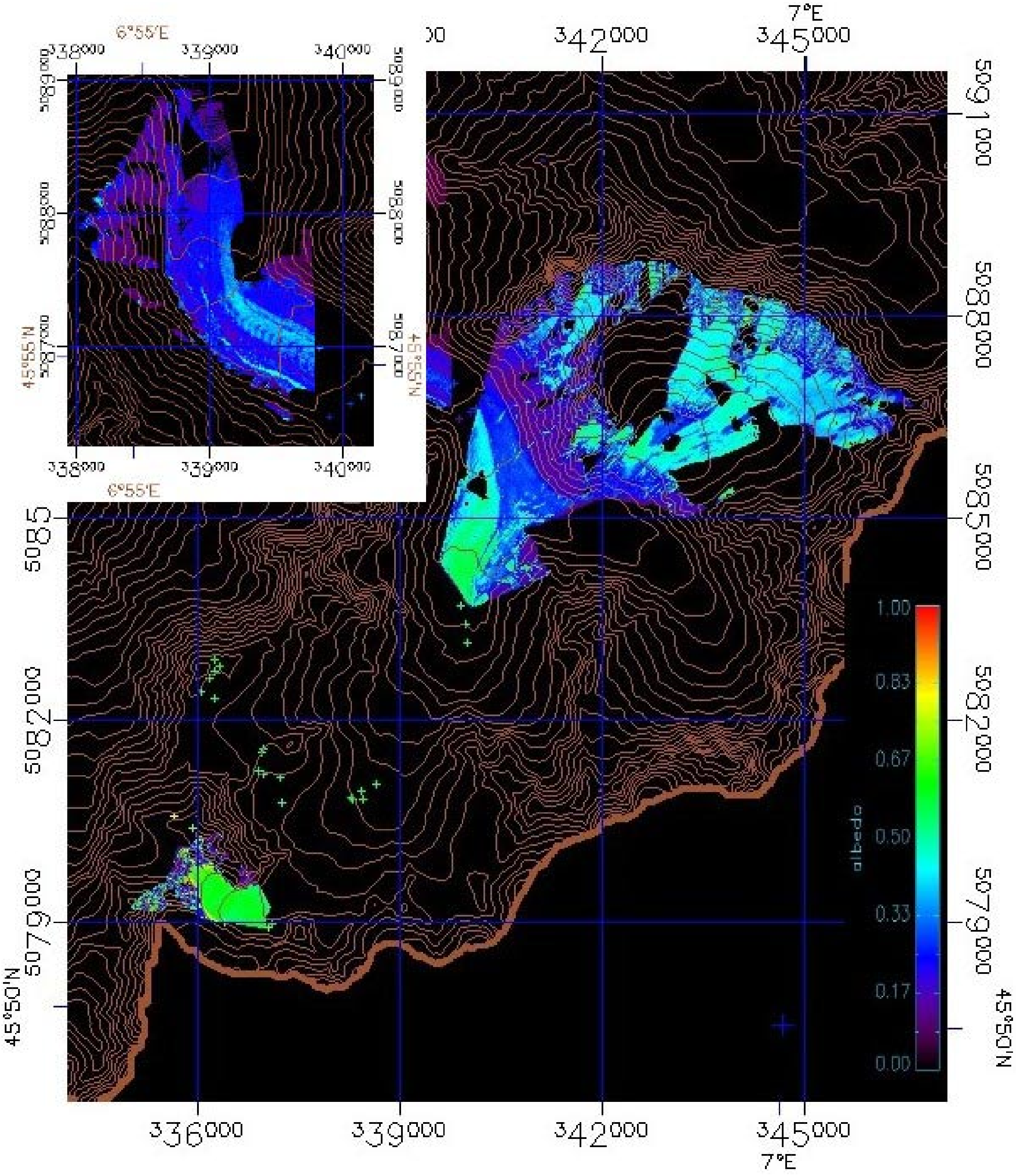

Figure 13: Colour coded composite map of albedo values derived from three georeferenced photographs of the Mer de Glace. Coloured crosses are measured values, a first inspection reveals good agreement between measured and estimated values. Actual values are plotted in figure 15. The inset is a detail of the lower section of the Mer de Glace, corresponding to figure 7, showing the albedo variability among the glacier ojives.

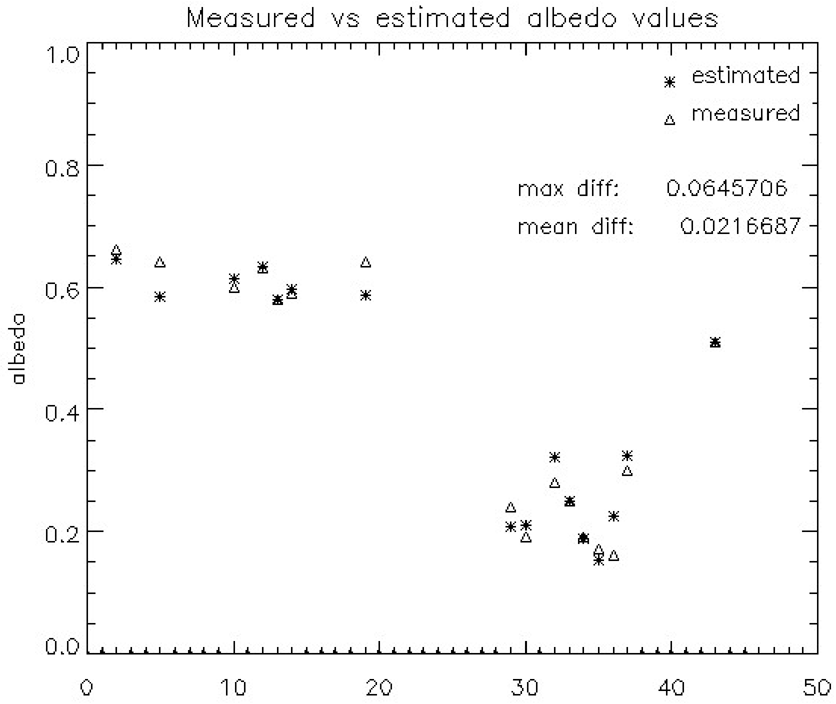

Figure 14: Measured versus estimated albedo values for areas in figure 13. The maximum difference is 6.5%, while the average is 2%, which is less than the of the albedometer. Measured points on the X-axis are ordered from west to east.

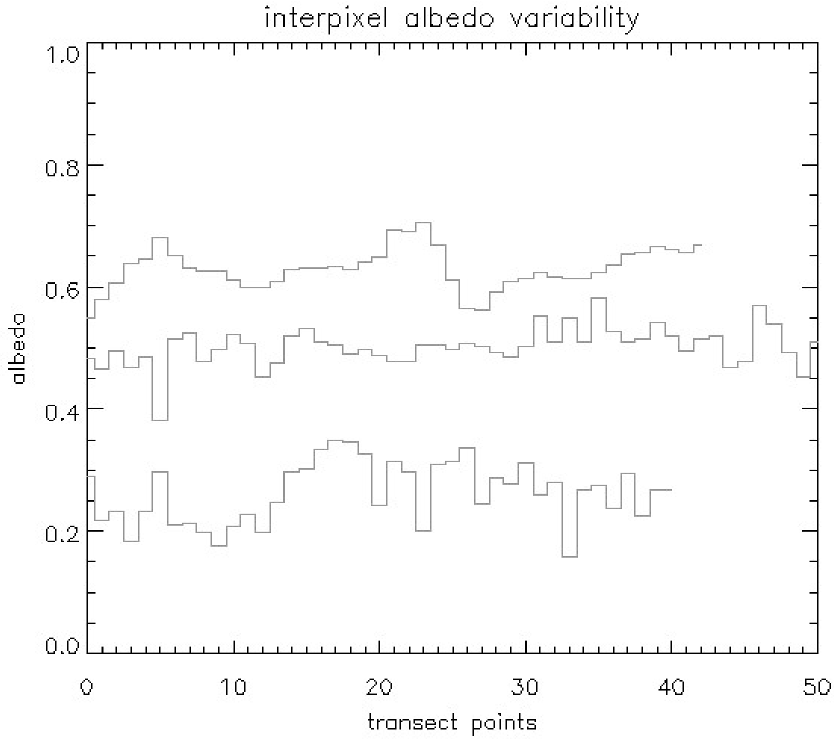

Figure 15: Inter-pixel variability of the albedo values for three arbitrary transects on the upper, medium and lower (ice covered) areas of the glacier. High variability in a relative small space is a large source of errors in the photography derived albedos.