Austrian Journal of Earth Sciences | Volume 105/2 | 63 - 77 | Vienna | 2012

The evolution of rock glacier monitoring using terrestrial photogrammetry: the example of Äusseres Hochebenkar rock glacier (Austria)

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KEYWORDS

Terrestrial photogrammetry
Deformation measurement
Äußeres Hochebenkar
Rock glacier
Ötztal Alps
Monitoring

Abstract

Rock glaciers are creep phenomena of mountain permafrost and have been the subject of research for over 100 years. Rock glaciers are lobate or tongue-shaped bodies of perennially frozen ice-rich unconsolidated material. Active rock glaciers creep downslope by force of gravity. Mean annual flow velocities are in the order of a few centimeters to several meters per year. Rock glacier surfaces typically show furrows and ridges which are visible expressions of active flow and cumulative deformation. The kinematics of rock glaciers can be determined by different measurement techniques. Terrestrial (ground-based or close-range) photogrammetry was one of the first successful methods for detecting and quantifying surface changes in rock glaciers. Flow velocity was a typical parameter derived from this. The 2D or even 3D kinematics of the rock glacier surface is needed for rheological models. In recent years, active rock glaciers have also become the focus of climate change research. Atmospheric warming is supposed to influence flow/creep velocity of rock glaciers, which can thus be seen as indicators of environmental change in mountainous regions. Melting of the subsurface ice causes surface lowering, which in the worst case may lead to active landsliding and even a total collapse of the rock glacier surface. The paper starts with an outline of the historical development of terrestrial photogrammetry applied to rock glacier research in awareness of the fact that the main developments were originally triggered by glacier studies and high-mountain topographic mapping. The work of three early pioneers of rock glacier monitoring in the Austrian Alps, i.e., Sebastian Finsterwalder and his son Richard, both from Germany, and Wolfgang Pillewizer from Austria, is briefly highlighted. These three personalities started and carried out various rock glacier monitoring projects in the Ötztal Alps, Austria. It was Pillewizer who commenced rock glacier monitoring with the application of terrestrial photogrammetry at Äußeres Hochebenkar rock glacier in 1938. Together with the Austrian mathematician Leopold Vietoris he laid the foundation of long-term monitoring at Äußeres Hochebenkar rock glacier. With the advent of airborne cameras the importance of terrestrial photogrammetry in high-mountain cartography declined significantly. The present paper, however, suggests a rebirth of terrestrial photogrammetry in high-mountain mapping, which also includes rock glacier monitoring, in the wake of cheap digital consumer cameras and powerful computer software. This is underpinned by practical work carried out at Äußeres Hochebenkar rock glacier. Terrestrial photogrammetric surveys were carried out at Äußeres Hochebenkar in 1986, 1999, 2003, and 2008. The following camera systems were used: analog cameras, i.e., Zeiss Photheo 19/1318, Linhof Metrika 45, and Rolleiflex 6006, and digital cameras, i.e., Hasselblad H3D-39, Nikon D100, and Nikon D300. Stereopairs from multiple baselines were acquired from the counter slope of Äußeres Hochebenkar rock glacier. The digital photogrammetric processing of the image data using modern techniques of computer vision, e.g., least-squares matching, is outlined. Three-dimensional flow vectors were computed for the whole area with high precision to reveal the spatio-temporal change in flow velocity. The paper also explains how surface change of a mountain slope can be detected and visualized by means of computer animation based on repeat terrestrial photography.

Blockgletscher sind Kriechphänomene des Hochgebirgspermafrosts und werden schon seit über 100 Jahren wissenschaftlich untersucht. Blockgletscher sind ein Gemenge aus Schutt und Eis und bewegen sich der Schwerkraft folgend talabwärts. Die mittleren jährlichen Fließgeschwindigkeiten von aktiven Blockgletschern liegen bei wenigen Zentimeter bis mehreren Metern pro Jahr. Fließwülste und Gräben spiegeln das Fließverhalten und die Oberflächendeformation wider. Die Blockgletscherbewegung kann durch verschiedene Messverfahren erfasst werden. Die terrestrische Photogrammetrie war jenes Verfahren, mit dem man die Blockgletscherbewegung erstmals in Österreich messtechnisch erfassen konnte. Von besonderem Interesse ist die Bestimmung der Fließgeschwindigkeit. 2D und 3D Bewegungsvektoren finden nicht nur Eingang in blockgletschermechanische Modelle, sondern können in ihrer zeitlichen Änderung auch als Indikatoren der Klimaveränderung angesehen werden. Das Ausschmelzen von Eis aus dem Permafrostkörper führt weiters zur Absenkung der Blockgletscheroberfläche. Auch wurden in jüngster Zeit vermehrt Rutschungen und der Verfall von Blockgletscherkörpern beobachtet. Der Aufsatz beschreibt im ersten Teil die historische Entwicklung der terrestrischen Photogrammetrie in der frühen Blockgletscherforschung und beleuchtet die diesbezüglichen Arbeiten von Sebastian und Richard Finsterwalder (Deutschland) und Wolfgang Pillewizer (Österreich) in den Ötztaler Alpen, Österreich. Pillewizer startete 1938 mit einer terrestrisch-photogrammetrischen Aufnahme am Blockgletscher im Äußeren Hochebenkar ein Langzeit-Monitoring, das bis heute unter Einsatz von verschiedenen Messverfahren erfolgreich andauert. Schon in der ersten Hälfte des 20. Jahrhunderts sank die Bedeutung der terrestrischen Photogrammetrie für Hochgebirgsanwendungen durch den aufkommenden Bildflug. In jüngster Zeit jedoch eröffneten sich durch kostengünstige Digitalkameras und leistungsfähige Computerprogramme völlig neue Möglichkeiten für den Einsatz der terrestrischen Photogrammetrie in Hochgebirgsanwendungen, insbesondere auch in der Blockgletscherbeobachung. Der vorliegende Aufsatz zeigt das Potenzial der modernen terrestrischen Photogrammetrie am Beispiel des Blockgletschers im Äußeren Hochebenkar anhand von praktischen Arbeiten auf. Es liegen terrestrisch-photogrammetrischen Aufnahmen von mehreren Basislinien aus den Jahren 1986, 1999, 2003, und 2008 vor. Zum Einsatz kamen folgende Kamerasysteme: Zeiss Photheo 19/1318, Linhof Metrika 45, Rolleiflex 6006 (alles analoge Kameras) und Hasselblad H3D-39, Nikon D100 und Nikon D300 (alles Digitalkameras). Die digital-photogrammetrische Prozessierungskette der vorliegenden Bilddaten wird im Detail dargestellt. Als Ergebnis wurden flächendeckend dreidimensionale Bewegungsvektoren der unteren Blockgletscherzunge mit hoher Genauigkeit ermittelt. Somit konnte das raum-zeitliche Bewegungsmuster des Blockgletschers für den angegebenen Zeitraum erfasst werden. Der Aufsatz beschreibt auch, wie man Blockgletscherkriechen bzw. sonstige Oberflächenveränderungen von Berghängen mittels Computeranimation von Zeitrafferaufnahmen (wiederholte photographische Aufnahmen) qualitativ detektieren und visualisieren kann.

1. Introduction

Rock glaciers (Barsch, 1996; Haeberli et al., 2006) are prominent landforms of mountain permafrost and have already been the focus of research for over 100 years. Frozen ground and permafrost have been summarized recently in Barry and Gan (2011), and Shur et al. (2011), respectively. Rock glaciers are composed of angular rock debris and subsurface ice, and exhibit lobate or tongue-shaped forms. Active rock glaciers creep downslope by force of gravity mostly due to internal deformation of the ice and thus look like lava flows from a bird's eye view. Non-moving rock glaciers are called inactive. Relict rock glaciers contain no ice nor do they show any movement, and their surfaces look shrunken.

Rock glaciers belong to the periglacial environment (French, 2011), and being part of the cryosphere, they also react to global warming. Due to their larger thermal inertia changes of the permafrost body are presumably smaller, hardly detectable with the naked eye, even for a time interval of one year or more. Mean annual creep velocities are typically in the range of centimeters to decimeters, up to maximum of a few meters a year. Surface lowering of rock glaciers due to permafrost degradation (ice melt) is estimated to be in the centimeter range (Kaufmann, 1996).

Various authors (e.g., Kääb, 2011 and Embleton-Hamann, 2007) have reported that mountain permafrost degradation due to atmospheric temperature rise can cause natural hazards. Destabilized rock glaciers may cause rock fall and landslides (Roer et al., 2008).

Delaloye et al. (2008) have analyzed the inter-annual variations of flow velocity of several rock glaciers in the European Alps and found out that the variations appear to be primarily related to external climatic factors rather than to internal characteristics of the rock glaciers. For reasons of comparison see also Kellerer-Pirklbauer and Kaufmann (this volume).

The kinematic state of a rock glacier can be deduced either from qualitative observations, which are not very reliable at all, or from exact measurements of different kinds as outlined in Kääb (2005). Terrestrial photogrammetry was one of the first measurement techniques to reliably measure flow velocities of rock glaciers. Terrestrial (ground-based or close-range) photogrammetry for high-mountain applications has experienced a varied development over time as outlined in Mayer (2010). Austria has always been an excellent hotbed for new developments in photogrammetry. In this paper we want to briefly highlight the historical background of terrestrial photogrammetry applied to rock glacier monitoring from an Austrian perspective. In the early days of terrestrial photogrammetry in high-mountain areas the applications were primarily in topographic mapping and glacier studies (Rinner & Burkhardt, 1972). The techniques and methods developed in this context were then transferred directly to rock glacier applications. In this paper we present the work of three pioneers who were interested in rock glaciers. Finally, after the Second World War airborne photogrammetry superseded terrestrial photogrammetry in high-mountain mapping. The camera type was still analog. Today, however, cheap digital consumer cameras and modern techniques of digital photogrammetry and computer vision give rise to a revival of terrestrial (close-range) photo-

Figure 1: Pioneers of terrestrial photogrammetry in glacier and rock glacier mapping. a) Sebastian Finsterwalder (1862-1951), b) Richard Finsterwalder (1899-1963), c) Wolfgang Pillewizer (1911-1999). Source of photographs: Technical University Munich; Brunner and Welsch, 1999; Pillewizer, 1986.

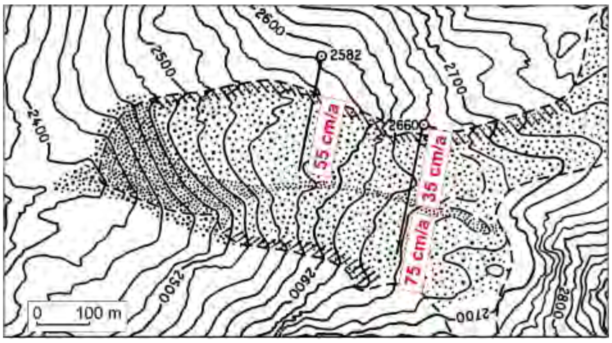

Figure 2: This map shows the maximum mean annual flow velocities obtained at Ölgruben rock glacier, Ötztal Alps, for the time period 1938-1939 for the lower motion profile and for 1938-1953 for the upper motion profile. These measurements were done by Wolfgang Pillewizer applying terrestrial photogrammetry. Earlier measurements of Sebastian Finsterwalder for a profile close to the lower profile for the time period 1923-1924 are in good accordance with the results obtained by Pillewizer. The base map of this Figure is a clip of the 1:20,000 Gepatschferner map, which was compiled by Sebastian Finsterwalder and co-workers by means of terrestrial photogrammetry in 1922. Source of map reproduction and thematic information: Pillewizer, 1957.

grammetry for topographic applications (Triglav-Èekada et al. 2011; Kajuutti et al. 2010; Kaufmann and Ladstädter, 2008). This might also be true for rock glacier mapping/monitoring. The main tasks to be solved are: (1) detection of surface change of rock glaciers, (2) computation of 2D or even 3D displacement vectors, and (3) visualization of surface change. The byproducts will be digital elevation models (DEMs) and orthophotos, if applicable. A significant amount of automation is envisaged.

Currently, aerial photogrammetry is the most powerful technique for area-wide monitoring of rock glacier surfaces in space and time. Its applications are manifold as shown in Kääb (2005) and Kääb et al. (2007). Modern digital aerial photogrammetry is characterized by ease of use, high precision, and high degree of automation. Other promising techniques in rock glacier monitoring are radar interferometry and airborne laser scanning (Bollmann et al., 2012).

2. Pioneers of terrestrial photogrammetry in rock glacier mapping

A first overview has already been published by Kaufmann (1996).

2.1 Sebastian Finsterwalder (1862-1951)

Sebastian Finsterwalder (Figure 1a) was one of the pioneers of photogrammetry. He made substantial contributions to terrestrial applications and to the mathematical fundamentals (Albertz, 2010). Sebastian Finsterwalder is also called the "father of glacier photogrammetry" (Rinner and Burkhardt, 1972; see also Brunner, 2006). Finsterwalder constructed a first lightweight and also highly accurate phototheodolite for high-mountain applications based on the prototype phototheodolite developed by Albrecht Meydenbauer (1834-1921) for architectural applications. Sebastian Finsterwalder, then only 27 years old, conducted a first glacier mapping project at Vernagtferner in the Ötztal Alps, Austria, applying the technique of plane table photogrammetry in addition to a conventional geodetic survey. The ease of use of the photogrammetric principle was enormously increased by the stereocomparator invented by Carl Pulfrich (1901) and the stereoautograph designed by Eduard Ritter von Orel (1907). Both instruments were built by the company Carl Zeiss. In 1922 Sebastian Finsterwalder led another topographic mapping project in the Ötztal Alps focusing on two glaciers, i.e. Gepatschferner and Weißseeferner, using stereophotogrammetry (Finsterwalder, 1928). During this work he discovered two rock glaciers in the mapping area, i.e. Ölgruben rock glacier and the rock glacier north of Krummgampenspitze, well aware of previous rock glacier studies (Chaix, 1923) that had been conducted in the Swiss Alps. In 1923 and 1924 Sebastian Finsterwalder carried out two dedicated terrestrial photogrammetric surveys to measure a velocity profile across Ölgruben rock glacier. He obtained maximum flow velocities of up to 50 cm/year and was a little disappointed because he had expected larger values (Finsterwalder, 1928; Pillewizer 1957). Further repeat surveys at Ölgruben rock glacier using the same photogrammetric principle were undertaken by Wolfgang Pillewizer in 1938, 1939, and 1953 (Pillewizer, 1957; see Figure 2). Flow velocity measurements at Ölgruben rock glacier are still ongoing, employing modern satellite-based positioning techniques (Hausmann et al., 2007). One of Finsterwalder's co-workers in the previously mentioned mapping project in the Ötztal Alps was his son Richard.

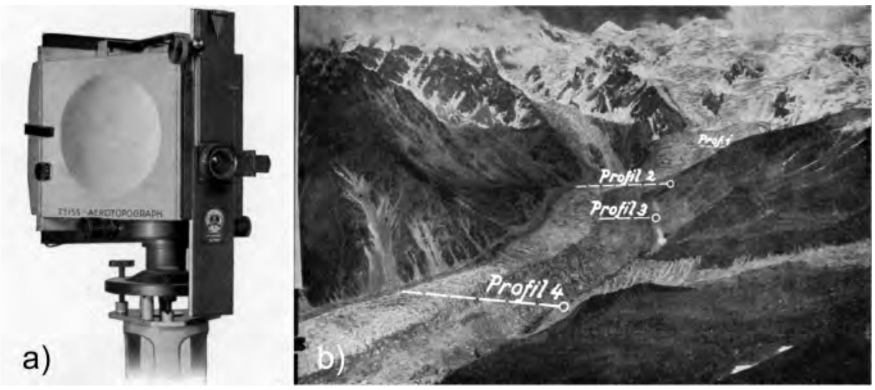

Figure 3: a) TAF (*Terrestrische Ausrüstung Finsterwalder*) is a lightweight terrestrial phototheodolite designed by Sebastian and Richard Finsterwalder and built by Carl Zeiss Jena. This instrument was optimized especially for the use in high mountain environments. Source of photograph: Rube, 1938. b) Terrestrial photograph of Rakhiot glacier, Pakistan, showing the position of the four motion profiles measured by R. Finsterwalder in 1934. Photograph taken by R. Finsterwalder. Source of reproduction: Pillewizer, 1938.

2.2 Richard Finsterwalder (1899-1963)

Richard Finsterwalder (Figure 1b; Brunner and Welsch, 1999) followed

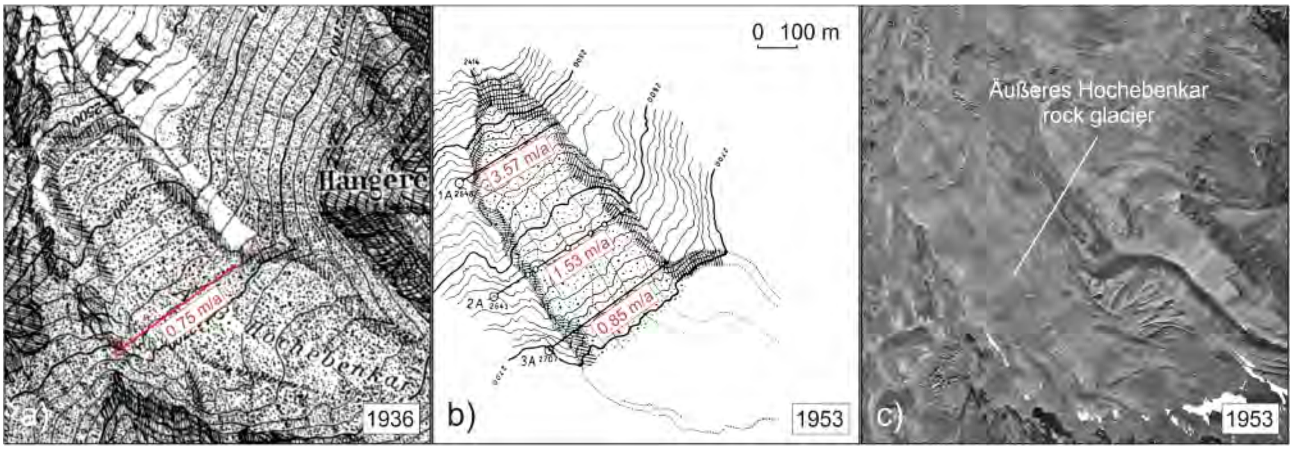

Figure 4: a) Clip of the map "Ötztaler Alpen – Gurgl" 1:25,000 of the Austrian Alpine Club published in 1949. It shows the Äußeres Hochebenkar rock glacier and its surroundings. The topographic content was compiled by means of terrestrial photogrammetry in 1936. Superimposed in red color: profile 3A (established by Wolfgang Pillewizer in 1938) and its maximum mean annual flow velocity for the time period 1938-1953 as obtained from terrestrial photogrammetric measurements. b) This map (photogrammetric manuscript) shows a repeat survey compiled by Pillewizer in 1953, and in red color the maximum mean annual flow velocities obtained for the time period 1953-1955 applying also the photogrammetric technique of motion parallax measurement. c) Digital orthophoto of Äußeres Hochebenkar rock glacier (aerial flight of 1953) compiled by the author. Aerial photograph: © Austrian Federal Office of Metrology and Surveying, Vienna. All three maps shown are georeferenced and display the same area.

in his father's footsteps and he finally also became professor at Technische Hochschule Munich, Germany, lecturing on photogrammetry, topography, and cartography. Finsterwalder's glaciological research was recognized by his election as President of the Commission on Snow and Ice of the International Union of Geodesy and Geophysics in 1957. Finsterwalder improved his father's terrestrial phototheodolite. The new instrument (see Figure 3a) was named TAF ("Terrestrische Ausrüstung Finsterwalder") and manufactured by Carl Zeiss Jena. It was lightweight and optimized for topographical and glaciological surveys in high mountains. Richard Finsterwalder actively participated in several expeditions, e.g. the German-Russian Alay-Pamir expedition in 1928, the German Nanga Parbat expedition in 1934, and the expedition to the Jostedalsbreen glacier in Norway in 1937. During the expedition of 1928 he not only mapped Fedchenko glacier by means of terrestrial photogrammetry but also measured its velocity using the same technique. In 1930 he submitted his habilitation thesis entitled "Grenzen und Möglichkeiten der terrestrischen Photogrammetrie, insbesonders auf Forschungsreisen" (Finsterwalder, 1930). In Finsterwalder (1931) he published his technique of measuring glacier flow velocities by means of terrestrial photogrammetry. Another achievement was the measurement of the flow velocity of Rakhiot glacier during the Nanga Parbat expedition (see Figure 3b). In 1937 the third pioneer, Wolfgang Pillewizer, came into play. He became assistant to Richard Finsterwalder, who was professor at Technische Hochschule Hannover at that time. Pillewizer also took part in the Jostedalsbreen expedition where he was in charge of geodetic and terrestrial photogrammetric work.

2.3 Wolfgang Pillewizer (1911-1999)

The Austrian Wolfgang Pillewizer (Figure 1c; for his autobiography see Pillewizer, 1986) studied geography and natural sciences at the University of Graz, where he habilitated in 1940. In 1958 he was appointed Director of the Institute for Cartography at Technische Hochschule Dresden. From 1971 to 1981 he was Head of the Institute of Cartography and Reproduction Technology at Technische Hochschule Vienna. Pillewizer, disciple of Richard Finsterwalder, was also interested in high mountain cartography, applied photogrammetry, and glaciology (Pillewizer, 1938) and participated in several expeditions. In 1936 Wolfgang Pillewizer was an assistant to Hans Biersack, who was in charge of terrestrial photogrammetric surveys in the Ötztal Alps for map production for the German and Austrian Alpine Club. Two years later and based on the work of Sebastian Finsterwalder (Finsterwalder, 1928), Pillewizer installed terrestrial photogrammetric motion profiles at Ölgruben rock glacier (as already mentioned), at Rotschliffkar rock glacier (with no further repeat surveys), and at Äußeres Hochebenkar rock glacier (see profile 3A in Figure 4). Äußeres Hochebenkar rock glacier had already been stereoscopically mapped during the 1936 survey. The motion profile 3A at Äußeres Hochebenkar rock glacier was repeated by Pillewizer after the Second World War in 1953. At the same time he extended this single motion profile by two more profiles (profiles 1A and 2A of Figure 4) used by Leopold Vietoris (1891-2002), who had started his own geodetic measurements in 1951, and accomplished a repeat stereophotogrammetric survey of the whole rock glacier for reasons of comparison. In 1955, he repeated his photogrammetric motion profiles at Äußeres Hochebenkar. Detailed results of motion analysis were published in Pillewizer (1957). For reasons of comparison see also Vietoris (1972), Schneider & Schneider (2001), and Kaufmann and Ladstädter (2002a). In this publication, a summary of the motion analyses 1938-1953 (profile 3A) and 1953-1955 (profiles 1A, 2A, and 3A) is shown graphically (see Figure 4). Pillewizer estimated the velocity at the rock glacier front at 4 m/year, attributing the increase in velocity to a topographic slope change.

3. Principles of terrestrial photogrammetry

The geometric principles of terrestrial (close-range) photogrammetry can be looked up in primers on photogrammetry, such as Kraus (2007), Luhmann et al. (2006), or McGlone et al. (2004). Figure 5 shows the classical geometric setup ("normal case") of terrestrial photogrammetry. The left drawing shows the ground plan of a standard (normal case) terrestrial photogrammetric setup. Stereo images are taken from two observation points separated by base length B. Camera axes are parallel to each other and orthogonal to the base. Viewing direction is horizontal. The XY-plane is parallel to the ground, the Z-axis is projective. Three-dimensional object reconstruction can be carried out by spatial intersection of homologous rays (red lines) defined by its homologous image points. Image coordinates need to be measured. The difference in x-coordinates defines the image or horizontal parallax. The y-parallax has to be zero by definition. The computed object distance Y depends linearly from f and B, and reciprocally from the horizontal parallax measured (upper right box). The precision of the derived object coordinates X, Y, and Z depends on image scale, imaging geometry (base-to-distance ratio) and measuring accuracy of the image coordinates. The lower right box contains formulas (rules of thumb) for the practitioner for computing precision (accuracy) estimates. Remark: The precision of point P' (at double object distance) in Y-direction is 4-times worse than for P.

The normal case of stereo image configuration has long been a prerequisite for practical work in order to facilitate numerical calculations, stereomodel setup, analog or even analytical stereoplotting, and to minimize expensive and time-consuming measurement of ground control points. Today's digital photogrammetry, however, resolves many of the previous limitations of classical terrestrial photogrammetry. Modern digital photogrammetric workstations support multi-view geometries with arbitrary viewing directions. The "stereo normal case" still plays a decisive role in photogrammetry/computer vision, because normalized images are needed for proper stereo viewing using stereo displays and for speed-up of image matching along epipolar lines. The rules of thumb given in Figure 5 provide a good clue of precision/accuracy which can be obtained in stereo mapping. The formulas given describe a typical characteristic of terrestrial photogrammetry, i.e. inhomogeneity of precision/accuracy in the stereomodel. The main obstacle lies in the geometric fact that the precision in viewing direction is proportional to the square of the object distance. Adequate project planning is therefore needed to account for allowed error limits.

The progress in data acquisition (photography) applied to terrestrial photogrammetry from analog metric cameras using voluminous glass plates to semi-metric cameras using roll film to inexpensive, but non-metric, digital consumer cameras fostered "democratization of terrestrial photogrammetry". Powerful computer software, e.g. Photomodeler (Photomodeler, 2011), enables the layman to carry out terrestrial photogrammetric projects.

4. Measurement of 3D displacement vectors

Geometric change detection of a rock glacier or any other

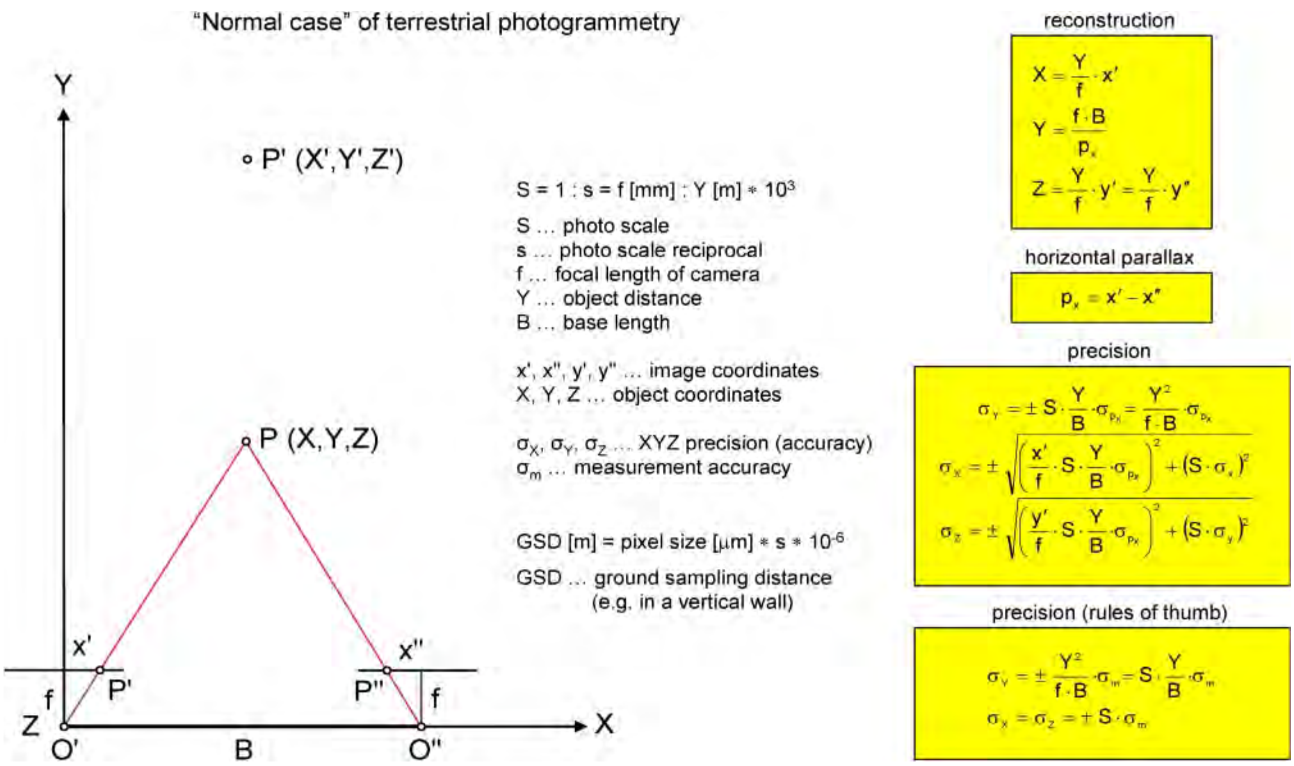

Figure 5: "Normal case" of terrestrial photogrammetry.

landform of interest, such as a glacier or a landslide, using terrestrial photogrammetry requires repeat photography (multiple data takes) at different epochs. In this paper we will consider conventional deformation analysis only (Welsch and Heunecke, 2001). This means that the moving rock glacier and its supposedly stable neighborhood need to be dissolved into discrete points in such a way that both the movement and the deformation of the rock glacier can be determined properly. Deformation implies the change in shape and/or size of the body. Since we are interested in geometry only, the simple congruence model of deformation analysis can be applied by comparing the object points of two epochs. The so-called null or initial epoch is taken as a reference. The measuring task is to photogrammetrically track homologous points in space and time. As a result a vector field of all displacement vectors for all object points is obtained. If the time intervals of the different epochs are known, kinematic parameters, such as velocity and acceleration, can be computed. It is also possible to carry out a geometric strain analysis in order to separate rigid body motion from deformation (Debella-Gilo and Kääb, 2012). Stable, non-moving object points in the vicinity of the rock glacier define the coordinate reference frame over time. Figure 6 outlines the general concept of the measurement of 3D displacement vectors by means of photogrammetry. The terrestrial case can be transferred to the airborne one and vice versa. (Kääb, 2005; Kaufmann and Ladstädter, 2003).

The drawings of Figure 6 are in ground plan. A tongue of a rock glacier is moving from right to left. The viewing direction of the cameras shown is horizontal and almost perpendicular to the main moving direction of the rock glacier. Stereomodels of both image pairs must be built and registered to one another using stable points. Some of the stable points should have known coordinates derived, for example, from a geodetic survey (total station, Global Navigation Satellite Systems/ GNSS) or an airborne survey. Minimum geometric information is needed to define at least scale and leveling of the stereomodels. In order to compute 3D displacement vectors of the moving rock glacier distinct points of the rock glacier surface have to be tracked in space and time. This is best accomplished by means of digital image matching techniques. In practice, photographs can be taken with hand-held cameras, and therefore, viewing directions will differ from the classical "normal case", which is no disadvantage at all. In most practical cases the viewing directions will be slightly convergent. Remark: The practical example of Section 6 refers to photographs which have been taken approximately in frontal view of the rock glaciers. As pointed out earlier the stereomodel set-up has implications on the obtainable precision/accuracy. The configuration shown in this figure is best for obtaining flow velocities, for example.

5. Quality control by redundancy

The photogrammetric principle does not allow the 3D reconstruction of an object point from one single photograph/image since the so-called redundancy is -1 as indicated in Figure 7a. Additional information, e.g., the distance from the observation point to the object point or the Z-coordinate of the object point, is needed to compute its 3D position or any kinematic parameter, such as velocity, from time-series. The latter procedure is known as monoplotting and uses a DEM which is intersected by the projection rays for 3D reconstruction/ mapping. This method has been applied, for example, to landslide monitoring by Travelletti et al. (2012). The stereo case (Figure 7b), however, allows reliable 3D reconstruction of the object. Since four image coordinates are measured and three unknowns have to be solved, the redundancy is 1. A radical control of the reconstructed object point is only feasible with three images (see Figure 7c). The geometric condition of intersection is inherent to the trifocal tensor, whereas the fundamental matrix connects two images (McGlone et al., 2004). In general, an erroneous image point measurement can be detected using the disposition of Figure 7c. Since it is impossible to identify the image containing the erroneous measurement, the respective object point must be rejected. Consequently, full control of proper space intersection is facilitated by using image quadruplets. The importance of multi-view geometry in photogrammetry has been discussed recently (Haala, 2011). Redundancy is not only beneficial to object point precision/accuracy but, most of all, to quality and robust-

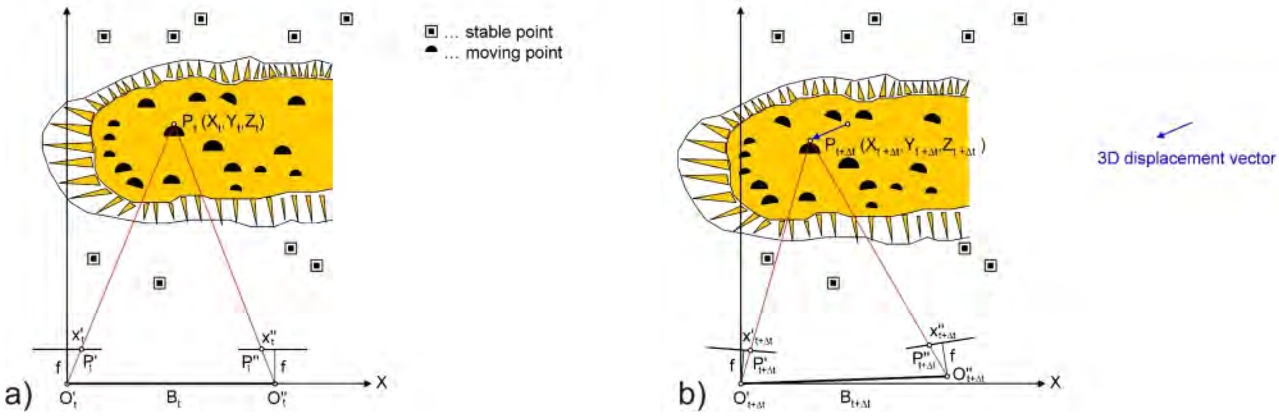

Figure 6: Measurement of 3D displacement vectors using photogrammetric stereopairs of two epochs t and t+?t.

ness/reliability of 3D reconstruction.

6. Practical example

In the recent past, terrestrial photogrammetry has been successfully applied to several projects in mountainous environments, such as glacier studies (Kajuutti et al., 2011; Triglav-Èekada, 2011; Kaufmann and Ladstädter, 2008), landslide monitoring (Travelletti et al., 2012), monitoring of steep slopes and rock walls (Barazzetti et al., 2011), and also monitoring of rock glaciers (Mat?as et al., 2009). In this paper we want to present another example of successful application of terrestrial photogrammetry to rock glacier monitoring.

6.1 Äusseres Hochebenkar rock glacier

Äußeres (Engl. “Outer”) Hochebenkar rock glacier (46°50' N, 11°01' E) is an impressive tongue-shaped rock glacier located in the Ötztal Alps, Austria (see Figure 8). The lower end of the rock glacier (2360 m) can be easily reached from the village of Obergurgl (1910 m), Ötztal valley, following an access footpath. The rock glacier has been the subject of research for many decades. Detailed permafrost mapping was conducted for the first time by Haeberli and Patzelt (1982). Recent studies (Abermann et al., 2012) have focused on field mapping of the bedrock and sediments and geomorphic features, grain-size analysis of the debris cover, thermal regime of the ground, hydrology, georadar, and flow velocity measurements. Investigations on the kinematics of Äußeres Hochebenkar first started in 1938 with the initial work of Wolfgang Pillewizer as already outlined in Section 2.3. In the course of time different measurement techniques have been applied, such as terrestrial photogrammetry (Pillewizer, 1957; Ladstädter and Kaufmann, 2004 and 2005), aerial photogrammetry (Kaufmann and Ladstädter, 2002a, 2002b, and 2003), differential synthetic aperture radar (SAR) interferometry (Rott and Siegel, 1999; Nagler et al., 2002), tacheometry (Vietoris, 1972; Schneider and Schneider, 2001), and, most recently, differential satellite-based positioning. A remarkably long record of flow velocity measurements, covering a time span of more than 70 years, is thus available for Äußeres Hochebenkar rock glacier.

The kinematics of Äußeres Hochebenkar rock glacier is characterized by the fact that its mean annual flow velocity more or less increases from the rock glacier’s rooting zone towards

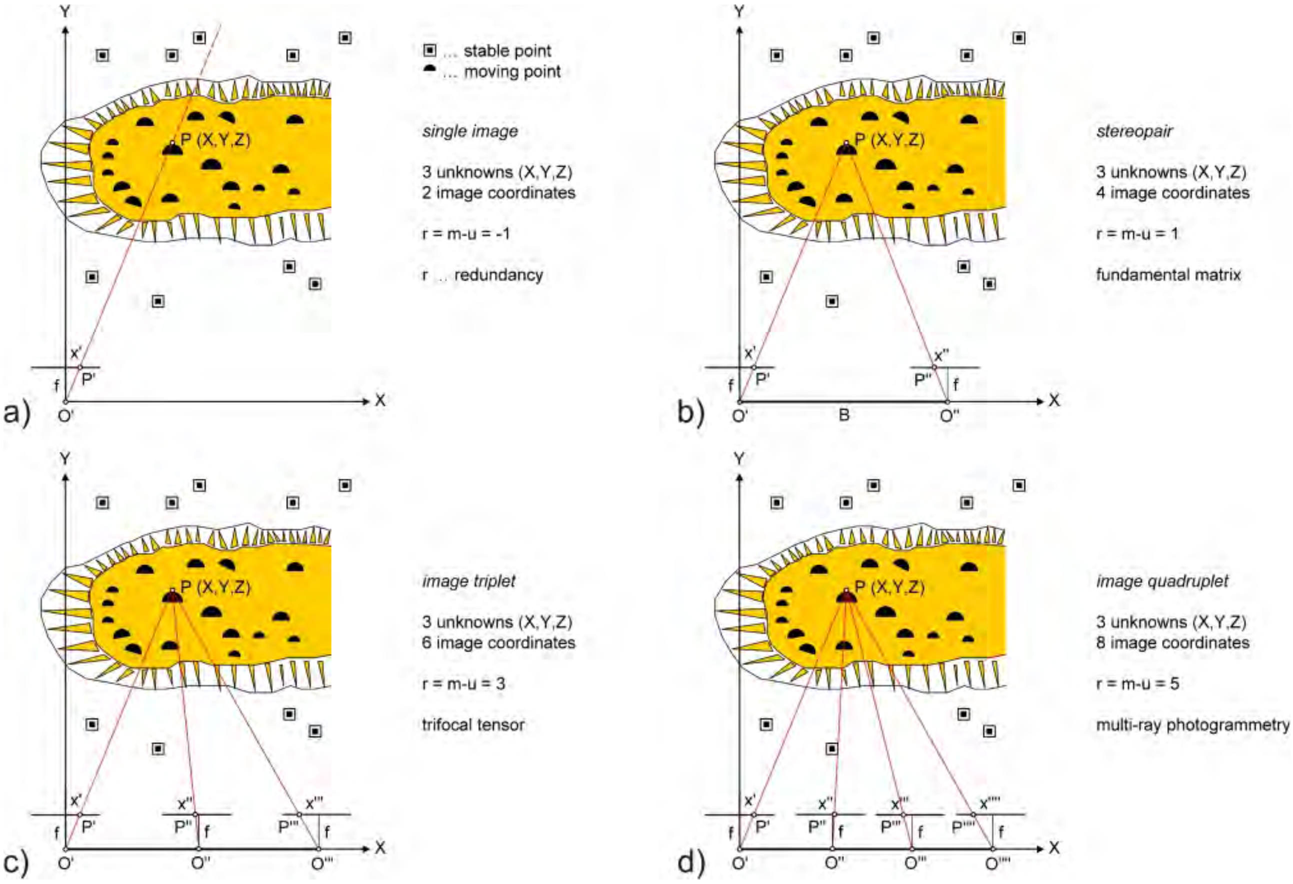

Figure 7: Drawings a) to d) illustrate possibilities of 3D object reconstruction from images/photographs. a) 1 image: An infinite number of possible object points exist for each image point. In general, the reconstruction of a 3D object from a single image is not possible. The successful reconstruction needs either a second image of the same object taken from a different place (see Figure 7b) or additional geometrical information about the location of the point, for example, the object distance or the height Z. b) 2 images: This geometry is the basis of classical stereophotogrammetry. The calculated redundancy of 1 reflects the so-called coplanarity condition (fundamental matrix). Measurement errors in horizontal parallax p_x cannot be detected. c) 3 images: Two independent stereomodels can be generated with three images. These two models are congruent if homologous rays intersect in space. The trifocal tensor describes this relationship. Discrepancies detected indicate erroneous image coordinate measurements. d) 4 images: Higher redundancy increases the reliability of the reconstructed object point. The robustness of 3D reconstruction can be greatly improved.

its lower end (frontal slope). The longitudinal acceleration of movement of Äußeres Hochebenkar rock glacier can most likely be attributed to the special topographic situation, i.e., the rock glacier starts from a low inclined cirque floor and is moving into ever steeper terrain. The highest mean annual flow velocities are associated with a break in terrain. Active landsliding of the permafrost body is observed below this characteristic morphologic line. The absolute value of flow velocity is subject to inter-annual changes. On-going research seeks to explain this phenomenon (Kellerer-Pirklbauer and Kaufmann, this volume).

6.2 Terrestrial photogrammetric surveys

In 1986, Robert Kostka (Elsner, 2011) and Viktor Kaufmann, accompanied by Gernot Patzelt, carried out a terrestrial photogrammetric survey of Äußeres Hochebenkar rock glacier using a Zeiss Photheo 19/1318 phototheodolite. A stereopair of coated glass plates was successfully exposed. The terrestrial stereomodel obtained was compared with a stereomodel based on aerial photographs of 1977 in order to get quantitative information about the activity of the rock glacier (for more information see Kaufmann, 1996). Repeat surveys were successfully conducted in 1999, 2003, and 2008 using different camera systems (large-/medium-/small-format, analog/ digital, metric/ semi-metric/non-metric) as shown in Figures 9 and 10. In 1986, photographs were only taken from two observation points (Figure 13, standpoints 1 and 2), whereas the subsequent surveys included additional observation points (Figure 13, standpoints 3 to 6) permitting the setup of multiple stereomodels and/or stringent bundle blocks of multi-view geometry. Additional terrestrial photogrammetric surveys conducted in 1995 and 2010 have not yet been considered for photogrammetric evaluation. All image data is archived at the Institute of Remote Sensing and Photogrammetry, Graz University of Technology.

6.3 Image pre-processing

The digital photogrammetric processing chain consists of (1) appropriate pre-processing of the terrestrial image data and (2) photogrammetric evaluation. Depending on the image data available, the following pre-processing steps need to be carried out: analog-to-digital conversion (Zeiss Photheo 19/ 1318, Rolleimetric 6006), elimination of color fringes due to chromatic aberration (all digital cameras), elimination of lens distortion (all cameras, if applicable), correction for film unflatness and film distortion (Rolleimetric 6006), masking of réseau crosses for better visual perception and successful digital image matching (Linhof Metrika 45, Rolleimetric 6006). Technical details are given in Ladstädter and Kaufmann (2004 and 2005). A prerequisite, of course, is the knowledge of the elements of inner orientation of the camera systems used. The idea of the concept is to generate and finally work with "perfect" central-perspective images with the principal point located in the image center and without any image distortion.

Pre-processed (rectified) image data have proved to be very useful from a practical point of view. However, this pre-processing step is not mandatory.

State-of-the-art camera calibration using either a planar calibration target or a 3D test field was carried out at the author's institute (Fauna et al., 2008). For a general overview of digital camera calibration techniques see Remondino and Fraser (2006).

6.4 Detection and visualization of rock glacier movement

In this subsection we introduce a simple method for image-

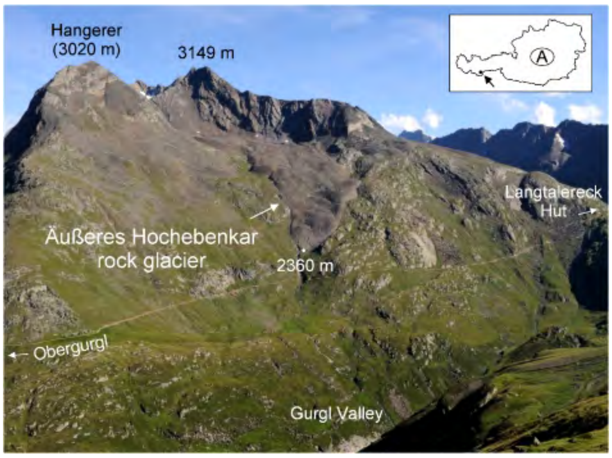

Figure 8: Terrestrial view of Äußeres Hochebenkar rock glacier as seen from the counter slope (cp. with Figure 13). Viewing direction is southeast. The tongue of the rock glacier ends 70 m above an access path which connects the village of Obergurgl (1910 m) with Langtalereck Hut (2430 m). The lower end of the rock glacier tongue is morphologically characterized by active landsliding. Photograph was taken on 10 August, 2008 by the author.

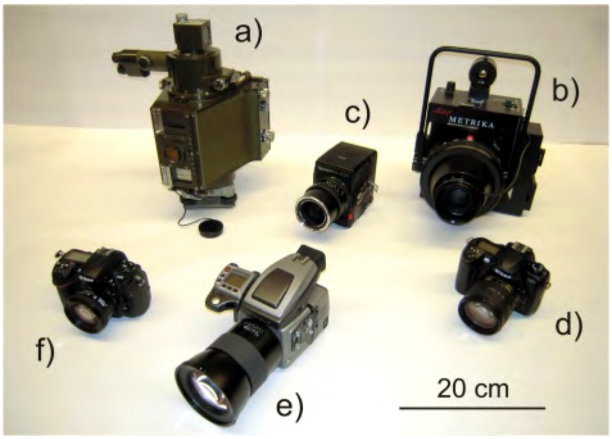

Figure 9: The following camera systems have been used in terrestrial photogrammetric surveys of Äußeres Hochebenkar rock glacier: a) 1986, Zeiss Photheo 19/1318, phototheodolite, metric camera, f=190 mm, coated glass plates. b) 1999 and 2003, Linhof Metrika 45, metric camera, réseau glass plate, f=150 mm, roll film. c) Rolleiflex 6006, semi-metric camera, réseau glass plate, f=150 mm, roll film. d) 2003, Nikon D100, digital consumer camera, non-metric, f=50 mm, CCD sensor. e) 2008, Hasselblad H3D-39, digital semi-professional camera, medium-format, f=80 mm, CCD sensor. f) 2008, Nikon D300, digital consumer camera, non-metric, f=50 mm, CMOS sensor. All cameras are property of the Institute of Remote Sensing and Photogrammetry, Graz University of Technology.

based detection of rock glacier movement using multi-temporal terrestrial photographs. A prerequisite for this method is that all repeat images must be taken from the same observation point. Referring to the practical example of Äußeres Hochebenkar rock glacier, this prerequisite was fulfilled for all image acquisitions at observation point 1. Since this point is permanently marked with a metal sign, it was relatively easy to position the camera systems next to each other within an error box better than half a meter (virtually). Theoretically, the nodal points of the cameras must coincide in space (remark: this prerequisite must also be fulfilled when stitching multiple overlapping photographs for a panorama). In order to detect 2D motion parallaxes all multi-temporal images need to be co-registered precisely, preferably to a reference image of good quality. Image registration was accomplished using in-house developed software based on Matlab. Homologous points were measured digitally applying area-based image matching. The normalized cross-correlation coefficient was selected as a similarity measure. The consistency check was based on back-matching. Stable reference points outside the rock glacier area were selected manually for computing the 8 parameters of a

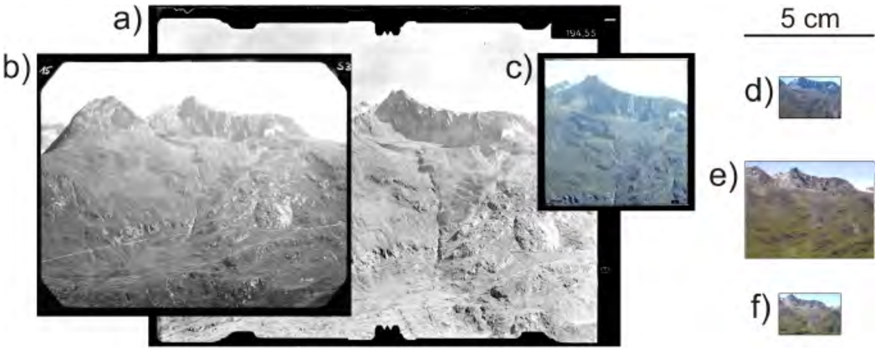

Figure 10: The photographs shown refer to the camera systems listed in Figure 9. Analog photographs were digitized with a resolution of 10 µm using the UltraScan5000 of Vexcel Imaging Graz. The physical image sizes are different: a) 18 cm x 13 cm, 18000 x 13000 pixel, b) 12 cm x 9 cm, 12000 x 9000 pixel, c) 6 cm x 6 cm, 6000 x 6000 pixel, d) 3008 x 2000 pixel, pixel size 7.8 µm, e) 7216 x 5412 pixel, pixel size 6.8 µm, f) 4288 x 2848 pixel, pixel size 5.5 µm.

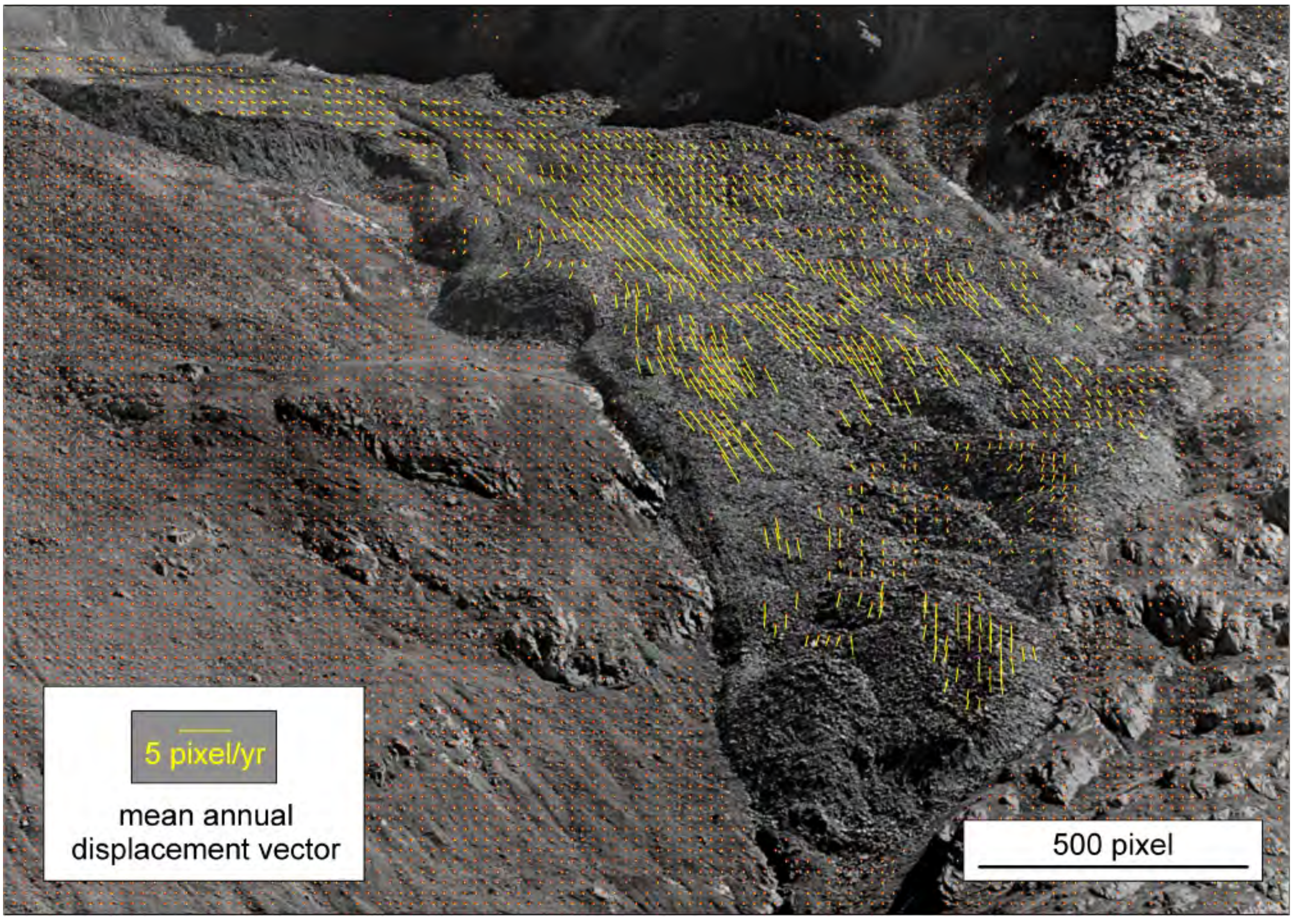

Figure 11: This figure shows the 2D vector field (in yellow) of mean annual displacement of surface points of Äußeres Hochebenkar rock glacier for the time period 1986-1999. The reference geometry is based on the Nikon D300 digital image of 2008. The measurement accuracy is ±0.1 pixel/yr. Maximum displacements amount to 3.2 pixel/yr in the image plane. The pixel size in nature is 21.1 cm (horizontally and vertically) for the lower end of the rock glacier, 24.6 cm for the central part of the rock glacier, and 33.3 cm for the rooting zone and head walls. The respective ground sampling distances (GSD) are much larger and depend on the inclination of the slope (cp. numerical values given in Ladstädter and Kaufmann, 2004).

2D homography (for the mathematical background see any text book on photogrammetry). The quality of image registration can be assessed by computing the root mean square error in x and y direction. Sub-pixel fit can be expected with the proposed method. (Remark: the whole process of image registration can be fully automated using SIFT (Lowe, 1999) for course image registration and RANSAC (Fischler and Bolles, 1981) for robust parameter estimation as already exemplified in student works at the author's institute.) Disparities larger than the 2-fold or 3-fold of the computed error level of image registration indicate significant motion parallaxes. If the time span between two epochs is known the disparities/displacements can be converted to velocities. The metric is still on pixels. As outlined earlier, this 2D geometric information can be back-projected into 3D space applying monoplotting (as shown in Travelletti et al., 2012) or other simplifying geometric assumptions. Change detection is most easily accomplished using human vision. Time-series of co-registered images can be stacked together to form animated GIFs.

The example shown in this paper refers to the following time-series: 1986 (Zeiss Photheo 19/1318), 1999 (Linhof Metrika 45), 2003 (Rolleiflex 6006), and 2008 (Nikon D300). Figure 11 depicts the apparent movement of the Äußeres Hochebenkar rock glacier in the Nikon D300 image plane, which served as a geometric reference for image registration. No displacement vectors could be computed in areas with low texture, dark shadows, and excessive surface change.

Spatio-temporal change in the kinematics of Äußeres Hochebenkar rock glacier can be deduced from Figure 12. The isotachs computed show lines of equal displacement/apparent velocity in the Nikon D300 image geometry. Animated GIFs based on these example data can be downloaded from the Internet (Kaufmann, 2011).

In cases where the photographic observation points have different locations rigorous 3D modeling of the temporally changing scene is necessary for fusing multi-temporal image data, see next subsection.

6.5 Measurement of 3D displacement vectors

Kaufmann and Ladstädter (2002a, 2002b, and 2003) have developed a concept of automatic measurement of 3D displacement/flow vectors in digital multi-temporal aerial photographs for rock glacier studies. The basic principle of the concept is that point tracking is not done in the original image space but in object space using quasi-orthophotos. Quasi-orthophotos are generated using approximate DEMs. A prerequisite is the proper exterior orientation of all image frames.

The applicability of the outlined 3D measurement technique to the terrestrial case was investigated by Ladstädter and Kaufmann (2004 and 2005) for the example of Äußeres Hochebenkar rock glacier based on image data of the epochs 1986, 1999, and 2003. All photographs were pre-processed following the procedure described in Subsection 6.3. The absolute orientation of all terrestrial stereomodels was accomplished using ground control points derived from aerial photographs (see Figure 13). In a further step, all 21 image frames were pre-rectified using a preliminary DEM of the project area. The vertical projection plane selected for deriving the quasi-orthophotos was orthogonal to the main viewing direction (see also

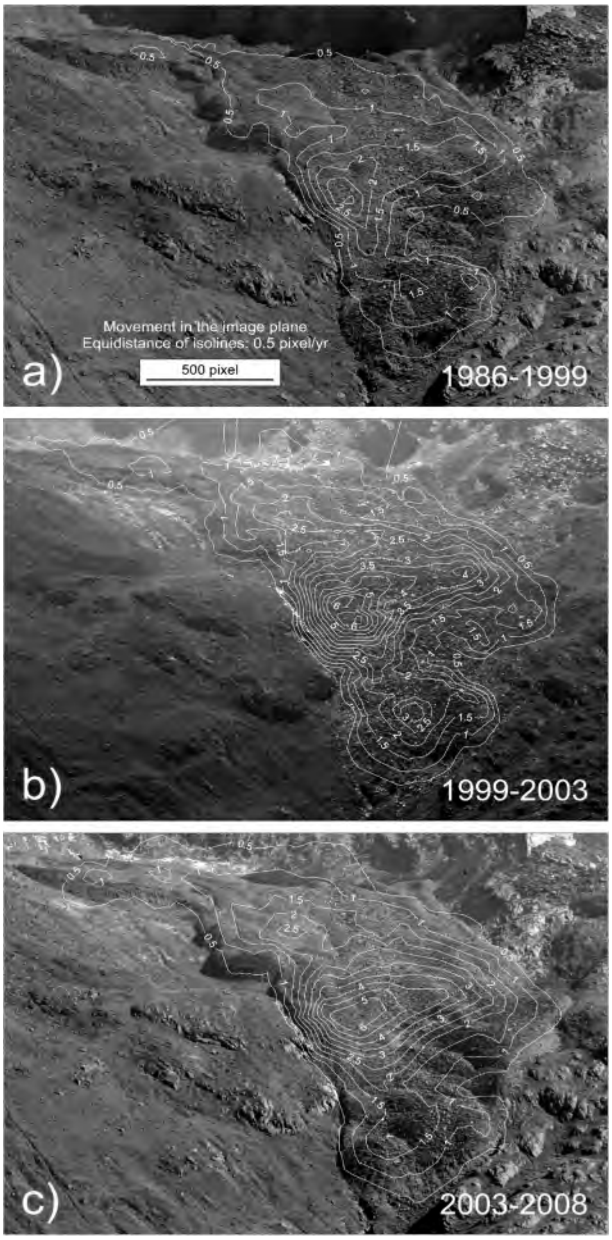

Figure 12: The spatio-temporal change of Äußeres Hochebenkar rock glacier projected onto the Nikon D300 image plane is visualized graphically using isolines of constant displacements/velocities for the time intervals a) 1986-1999, b) 1999-2003, and c) 2003-2008. Isolines are given in units pixel/yr. Accuracies obtained are a) ±0.10 pixel/yr, b) ±0.22 pixel/yr, and c) ±0.14 pixel/yr. Maximum displacements amount to a) 3.2 pixel/yr, b) 6.8 pixel/yr, and c) 5.6 pixel/yr. From the results obtained we can conclude that the mean surface movement/deformation of the rock glacier for the time period 1999-2003 was approximately double that for the period 1986-1999. During the last observation period 2003-2008 a small decrease in activity was observed. The largest image displacements were always measured at the same place at the orographic right side of the rock glacier, close to the break in surface topography. These findings agree with 3D results derived elsewhere (see Subsection 6.5).

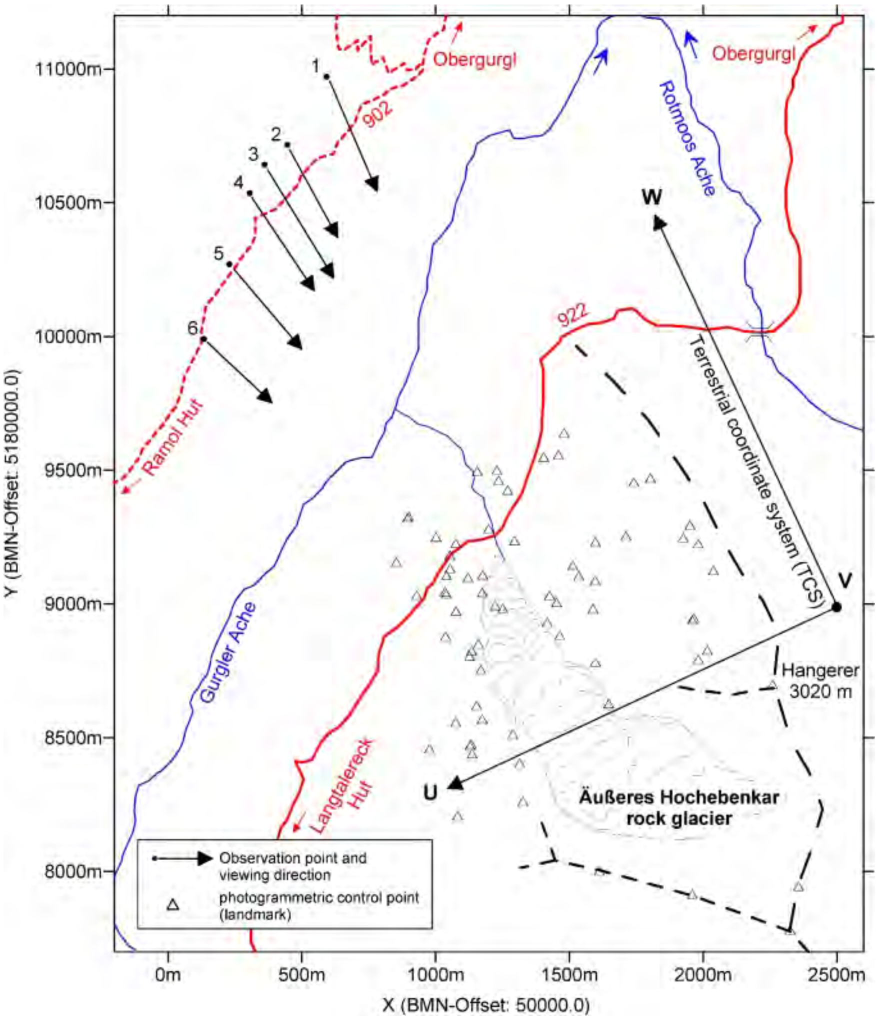

FIGURE 13: Map of the terrestrial photogrammetric survey of Äußeres Hochebenkar rock glacier. The rock glacier originates from a cirque and creeps downslope in northwesterly direction forming a characteristic tongue which ends not too far above hiking trail 922, which connects Obergurgl with Langtalereck Hut. Photographs were taken from the counter slope at positions 1 to 6, which are located close to hiking trail 902, route Obergurgl to Ramol Hut. Viewing directions are indicated. Photogrammetric control points are plotted as triangles. The local terrestrial coordinate system is outlined.

Figure 13). The benefit of this procedure is obvious: the warped photographs are geometrically very similar to one another, thus greatly facilitating automatic image matching using the in-house developed ADVM (Automatic Displacement Vector Measurement) software. Digital elevation models for each epoch and 3D displacement vectors describing the surface deformation could be derived from the object points obtained. Figure 14a presents the horizontal displacement vectors derived for the time interval 1986-1999. Figure 14b depicts the mean annual horizontal flow velocity.

7. Conclusions and outlook

In this paper we have reviewed the historical and technical development of terrestrial photogrammetry applied to high mountain cartography with special emphasis on monitoring of rock glaciers. The question of the future of terrestrial photogrammetry in high mountain mapping was already raised by Richard Finsterwalder some 70 years ago (Finsterwalder, 1938). Finsterwalder's answer was quite pessimistic because of the obvious drawbacks of terrestrial photogrammetry and the superiority of aerial photogrammetry. However, Finsterwalder was confident that the development of terrestrial photogrammetry would continue and that terrestrial photogrammetry could be a good choice for specific applications in alpine environments.

In the meantime, digital photography (cheap consumer cameras with high resolution) and computer technology (digital photogrammetry, computer vision) have opened completely new possibilities in image-based object reconstruction both for experts and lay people, leading to a democratization of photogrammetry. Based on literature study and own experience, the author expects a rebirth of photogrammetry for high mountain applications and especially for rock glacier monitoring, because of the following arguments:

- Digital consumer cameras can replace expensive metric cameras to a high degree. The former are cheap, stable, lightweight, easy to operate and provide the necessary high image resolution. Hand-held photography is possible.
- Data acquisition is fast. Acquisition time can be selected freely according to user needs. A photograph/image provides area-wide information.
- Data acquisition is cheap and additional photographs can be obtained at no extra cost.
- Digital consumer cameras are already or will be equipped with additional sensors, such as GPS, inclinometer, gyro compass, etc., for obtaining camera pose (exterior orientation) at the time of exposure.
- Computer software is going to provide fully automated image triangulation and subsequent 3D surface reconstruction (Irschara et al., 2010).
- Dedicated software will allow the complete automatic analysis (change detection) of repeat terrestrial photographs. Prototype software is already available.

The main inherent drawback of terrestrial photogrammetry is that the observation point is necessarily earth/ground-bound. This means that it will not always be possible to find a sufficiently good frontal view of the object. Synergy can be expected from using small unmanned aerial vehicles (UAVs). Finally, terrestrial photogrammetry will be cost-efficient in local studies only, such as monitoring of single glaciers or rock glaciers.

Acknowledgments

The author dedicates this paper to his colleague and predecessor in office Robert Kostka, who not only introduced the author to high mountain cartography but also to terrestrial photogrammetry applied to cultural heritage and also to glacier and rock glacier studies. Richard Ladstädter, now with Microsoft Photogrammetry Graz, is thanked very much for his "photogrammetric enthusiasm" during several years of joint work at the institute. The author had the good fortune to meet Wolfgang Pillewizer personally in 1995 and to receive from him some interesting private documents about his own rock glacier research at Äußeres Hochebenkar. In 1997, the author also had the privilege of corresponding with Leopold Vietoris, who was at that time already 106 years old and still interested in ongoing research at Äußeres Hochebenkar rock glacier. The author is grateful for his sound advice. Critical comments of Hermann Häusler and Wilfried Haeberli which helped to improve an earlier version of the manuscript are highly appreciated.

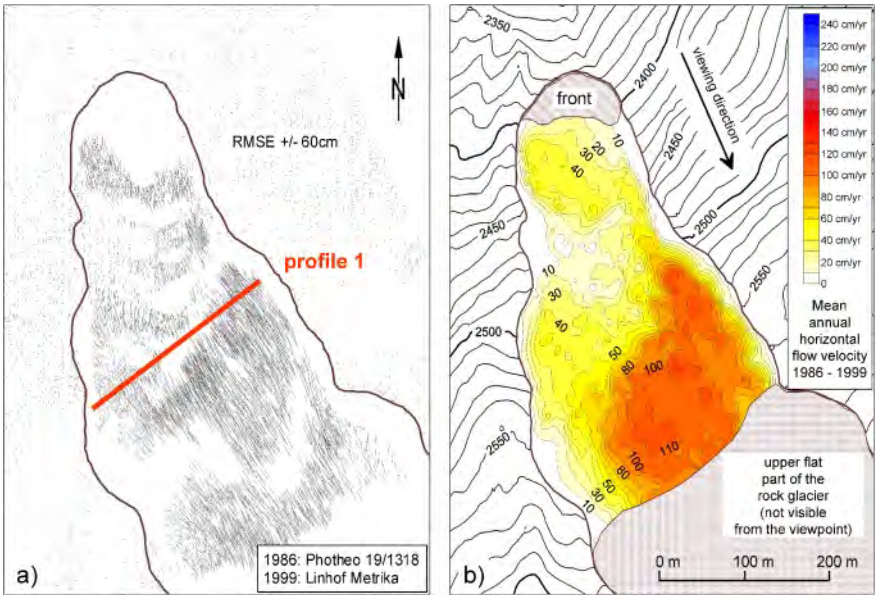

Figure 14: a) Horizontal displacement vectors at Äußeres Hochebenkar rock glacier derived from terrestrial photographs 1986 (Zeiss Photheo 19/1318) and 1999 (Linhof Metrika 45). A root mean square error of ±60 cm in horizontal vector length was achieved, resulting in an accuracy of ±4.6 cm/yr. Results obtained in profile 1 (which is actually profile 1A of Figure 4b) are in good accordance with the geodetic measurements (Schneider and Schneider, 2001). Areas with low texture, dark shadows, and also excessive surface change, as well as areas which are occluded in the original photographs do not show any displacement vectors. b) Mean annual horizontal flow velocity derived from the results presented in a). A relatively inactive zone can be identified on the orographic left side of the rock glacier. The result obtained for the time period 1999-2003 (not shown in this paper) reveals a more than 200% increase in flow velocities.

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Received: 30 January 2012
Accepted: 1 August 2012

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