MONITORING OF GLACIER SURFACES WITH PHOTOGRAMMETRY, A CASE STUDY OF THE TRIGLAV GLACIER

SPREMLJANJE POVRŠJA LEDENIKOV S FOTOGRAMETRIJO, ŠTUDIJA NA PRIMERU TRIGLAVSKEGA LEDENIKA

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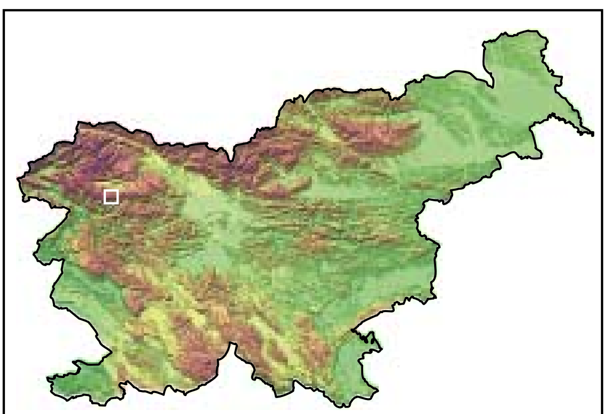
Triglav glacier (1999, photography M. O. Adamič)
Triglavski ledenik (1999, fotografija M. O. Adamič)



Abstract

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Monitoring of Glacier Surfaces with Photogrammetry, a Case Study of the Triglav Glacier

KEY WORDS: photogrammetry, camera calibration, monitoring, orthophoto

The relatively rapid changes of the shape and volume of glaciers that have been recorded in the last few decades can be monitored and recorded in different ways. Photogrammetry, the science of obtaining metrical data about the environment from photographs, is especially appropriate for this task. Modern photogrammetric methods enable solutions for complex tasks such as the reconstruction of the spatial position of a glacier in previous time periods from non-technical (amateur, archive, etc.) photographs. A simpler way is to photograph a glacier with special photogrammetric cameras that have a known and stable construction.

In the case study of Triglav glacier, a photogrammetric team coped with a major professional challenge: how to reconstruct the three-dimensional shape and surface of the glacier from archive photographs. These photographs have been taken regularly almost every month from two fixed standpoints over many years with a simple non-metrical Horizont camera. The solution of this task initially required the calibration of the Horizont camera to establish the geometrical features of the photographs. In addition, a helicopter survey and a terrestrial survey of the glacier using a stereo-technique were done during a major interdisciplinary expedition in September 1999. The archive photographs were linked to the new metrical photographs through selected tie points. Additionally, photographs from the cyclical aerial survey were used. Existing computer programs had to be augmented, and several new programs had to be developed since standard photogrammetric methods were not sufficient to solve the problem

The final aim of this part of the project was the determination of a surface model of the glacier in different time sequences and the computation of the volume differences in different time sequences. Experts from other sciences could use these results for various studies, e. g., estimating correlations between climate changes and the shrinkage of the glacier.

In this paper, the main phases of the photogrammetric work are described. An original solution of the problem is presented in more detail, and partial and expected final results are described. Modern methodology is proposed for the future monitoring of the glacier.

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Spremljanje površja ledenikov s fotogrametrijo, študija na primeru Triglavskega ledenika

KLJUČNE BESEDE: fotogrametrija, kalibracija fotoaparata, monitoring, ortofoto

Relativno hitre spremembe obsega in volumna ledenikov, ki jih strokovnjaki beležijo v zadnjih desetletjih, je možno spremljati na različne načine. Fotogrametrija, ki metrične podatke o prostoru pridobiva iz fotografij, je še posebej primerna za to nalogo. Sodobne fotogrametrične metode omogočajo reševanje zapletenih nalog, kot je rekonstrukcija prostorskega stanja ledenika v starejših časovnih obdobij iz netehničnih (amaterskih, arhivskih ipd.) fotografij, enostavnejša pot pa je fotografiranje ledenika s posebnimi fotogrametričnimi fotoaparati, ki imajo poznano in stabilno konstrukcijo.

Na primeru Triglavskega ledenika se je ekipa fotogrametrov spoprijela z velikim strokovnim izzivom, kako iz arhivskih fotografij, ki so bile posnete v rednih časovnih presledkih in stalnih stojišč v več deset letih s panoramskim fotoaparatom Horizont, rekonstruirati tridimenzionalni obseg in površino ledenika v posameznih časovnih obdobjih. Za rešitev te naloge je bilo potrebno najprej kalibrirati fotoaparat Horizont in na ta način ugotoviti geometrične lastnosti fotografij. Poleg tega je bilo v obsežni interdisciplinarni terenski kampanji v septembru 1999 izvedeno snemanje ledenika iz helikopterja in s tal v običajni stereo-tehniki. Arhivske posnetke smo preko izbranih točk povezali z novimi metričnimi fotografijami in dopolnilno uporabili obstoječe posnetke Cikličnega aerosnemanja. Obstoječe fotogrametrične programe je bilo potrebno dopolniti, ker z uporabo standardnih fotogrametričnih metod problema ne bi mogli rešiti.

Končni cilj tega dela projekta je izdelava ploskovnega modela površine ledenika v različnih časovnih obdobjih in izračun razlike volumna ledenika med temi obdobji. Strokovnjaki drugih strok bodo te rezultate uporabili za različne študije, npr. določitev korelacije med klimatskimi spremembami in krčenjem ledenika.

V članku so opisane vse glavne faze fotogrametričnega dela projekta, podrobneje je opisan izviren pristop k reševanju problema, komentirani so delni rezultati in pričakovani končni rezultati. Predlagana je metodologija sodobnega spremljanja obsega ledenika, ki bi se tekoče izvajal v prihodnje.

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1. Introduction

Triglav glacier is the southeasternmost glacier in the Alps, and therefore the volume changes of this glacier are significant in understanding and explaining possible environmental and climate changes in this region or even globally. Great changes in the glacier's volume have been recorded in recent decades, but unfortunately no three-dimensional surveying had been done previously.

Since 1976, members of the Anton Melik Geographical Institute and meteorologists from the Mount Kredarica weather station have been regularly photographing the Triglav glacier almost every month. The photographs were taken with a simple, non-technical Russian Horizont camera, which has an unusual construction. As the glacier is shrinking obviously, the metrical reconstruction of its shape and surface is significant for any scientific research. Some geodetic field measurements have been done in the past, but the results are only two-dimensional (only the outline of the glacier) and there are not enough measurements in different time periods as well. The idea was to use the non-technical photographs from the Horizont camera in a photogrammetric reconstruction procedure.

Photogrammetry is the science of obtaining metrical data about the environment and depicted objects from photographs. In a conventional photogrammetric survey, two stereo-photographs are usually needed for the spatial reconstruction of any spatial object from the photographs. A stereo effect is achieved when two photographs overlap enough (usually 60%–80%) and the optical axes are not too convergent. The photographs of the Triglav glacier have been always taken from two fixed standpoints, but the optical axes are unfortunately too convergent to get the stereo effect. Thus, a non-conventional method had to be employed.

2. Photogrammetric survey

First of all, we required some metrical data of the region to select useful reference points for the surface reconstruction. For this reason, a major interdisciplinary expedition to the Triglav glacier was organized in September 1999, aiming at various field measurements and research (georadar, surveying, photogrammetry, etc.). This paper describes the photogrammetric survey.

During the expedition, terrestrial and aerial photogrammetric surveys of the glacier were done using a Rolleiflex 6006 metrical camera equipped with a réseau grid. The aerial photographs were taken from a helicopter of the Slovene army flight group. Three photographic strips were taken from three different heights. The helicopter was not specially equipped for aerial survey, and the photographer had to be fastened securely with belts. While shooting, he had to lean well out through the open doors of the helicopter to get the best photographs of the area. Many stereo photographs were taken all together forming a photogrammetric photo-block.

Only relative dimensions of depicted objects in the photographs could be reconstructed from the stereo photographs themselves. To get absolute coordinates, enough points with known spatial coordinates must be available. These points, known in photogrammetry as control points, are usually measured with a geodetic or GPS survey.

Before starting the photogrammetric survey, the positions of selected control points on the terrain were marked with a special dye. The target had to be large enough to be visible in the photographs. In our case, the control points were targeted with a circle with an 80-cm radius. The prism for the geodetic survey was placed in the center of the circle during measurements. Although the size of the control points in the field was quite large, they were still difficult to find in the photographs.

The metrical photographs taken with the Rolleiflex camera during the expedition were used to measure the recent shape and surface of the glacier with conventional stereo-photogrammetry. On the other hand, the non-technical archive photographs from the Horizont camera had to be preprocessed, which is described below in more detail.

The construction of the two standpoints for the Horizont camera is not typical for a surveying standpoint because it is not very stable. The iron rod (with) has on top of it a base for the camera, which could be tilted in any direction, what (which) probably happens during winter storms. Due to this fact, it could be supposed that the two standpoints for the camera are positioned within an error circle of 50 cm radius. The locations of the standpoints were geodeticaly measured with usual geodetic methods during the expedition as well.

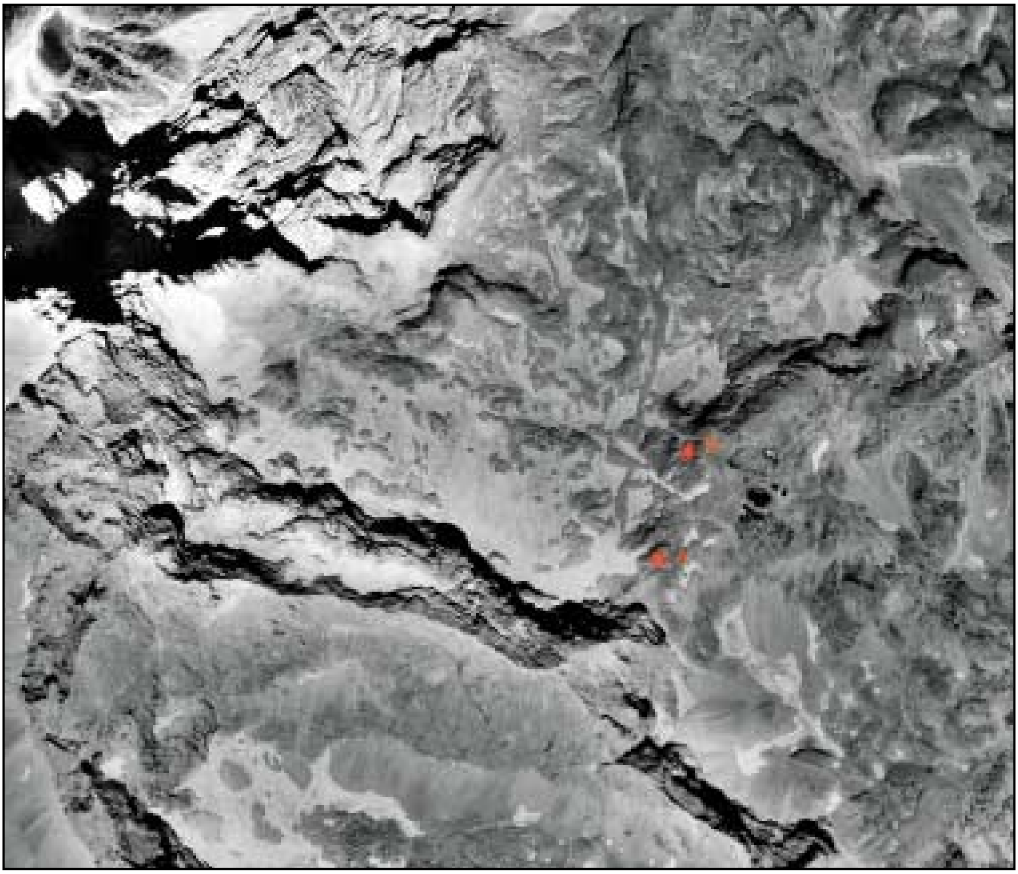

Figure 1: Location of standpoints A and B, marked in the enlargement of an aerial photograph (Source – Archive of Surveying and Mapping Authority of Republic of Slovenia, photo of CAS from 1998).
Slika 1: Poziciji stojišč A in B sta označeni na povečavi letalskega posnetka (Vir: Arhiv Geodetske uprave Republike Slovenije, posnetek CAS iz 1998).

3. Calibration of the Horizont camera

The Horizont camera is a panoramic camera with a view angle of 180°; the theoretical focus of the lens is 28.0 mm. Such a wide angle is achieved not only with a wide-angle lens but also with the special construction of a rotating lens mounted in front of film that is stretched on a cylindrical film carrier. Photogrammetric photographs are normally made in a central projection, and all photogrammetric equa-

Figure 2: Horizont camera (photography Mihala Triglav).
Slika 2: Fotoaparat Horizont (fotografija Mihala Triglav).

tions are based on this fact. Unfortunately, the projection in the Horizont camera was not central but was unknown and had to be determined first. For this reason, a calibration of the camera had to be done as the very first step.

The parameters of a camera's internal orientation comprise three coordinates of a principal point defined in a photo-coordinate system. These are the x and y coordinates of the principal point in the photo plane and a camera constant (focal distance). Additionally, several other parameters such as various lens distortions (radial, tangential, asymmetric, etc.) are determined during the calibration process as well. An image photo-coordinate system in a metric camera is defined using fiducial marks that are recorded in the photograph during exposure. Because the Horizont camera is non-metric, there are no fiducial marks in its photographs and we must define them indirectly.

Various methods can be used for camera calibration (Kraus 1995). Only the method used for calibrating the Horizont camera is described in this paper, i. e. calibration in the test field using points and known geometrical features (German: *Gestalts*). In our case, these geometrical features are horizontal and vertical lines in the test field.

Since there is no laboratory for camera calibration in Slovenia, we used our very good contacts with the Institute of Photogrammetry and Remote Sensing at the Technical University of Vienna. The calibration of the camera was part of diploma work by Mihaela Triglav, and this cooperation was treated as an interchange of students between the universities in Ljubljana and Vienna. The complete calibration process was accomplished under the supervision of Professor Helmut Kager from the University of Vienna.

The test field employs the inner building facades of a courtyard at the Technical University of Vienna. Many photographs of the test field are usually taken, and the camera is rotated slightly between different shots. This type of test field is very suitable for wide-angle lenses.

The test field is targeted with well-defined points whose coordinates are accurately defined by geodetic measurements in a local coordinate system. The targets are retroreflective circles with a radius of 0.5 cm. These control points are placed on horizontal and vertical lines that enable the definition of various types of distortion. During photogrammetric measurements, as many different points as possible on the same horizontal and vertical lines should be measured.

The retroreflective points are visible in photographs only if they are lit using a strong light source from the proper direction so that each point reflects the light in a very narrow angle back to the source. The light sources should therefore be placed close to the camera standpoint.

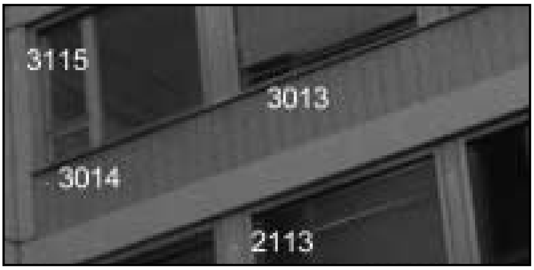

Figure 3: Retroreflective points in the test field at the Technical University of Vienna. Photo from calibration procedure.
Slika 3: Retro-refleksivne točke v testnem polju dunajske tehniške. Fotografija iz postopka kalibracije.

The Horizont camera was placed on a tripod, and a series of photographs were taken with the portrait and landscape positions of the camera. Various exposure times were used in order to get the best possible results.

The position of the camera during shooting must not be known, we do not need to measure geodetic position of standpoint before the shooting and that does not consume any additional time, so the work in a test field went relatively quickly. Four different photographs were taken from each standpoint to get the overdetermined the position of a point which is measured more than once is over overdetermined measurements specifically needed for better definition at the edges of the photographs where large distortions could be expected. After the development of the films, the best photographs were chosen in which the most retroreflective control points were visible. The selected photographs were measured using the Sun Solaris BC3 analytical photogrammetric instrument. The measurements were done with the MCP mono-comparator program.

The program requires certain initial data, e. g., the type of photographs, initial rotation angles, etc. Indirect fiducial marks (photograph corners) are then measured. As the photograph corners are not well defined, they are measured indirectly with two points at the edge of the photograph near the corners. The corner coordinates are then computed as the intersection of the two lines. The retroreflective control points were measured with the smallest floating mark of the analytical instrument (10 µm). The theoretical accuracy of measurements on the BC3 comparator is 5 µm.

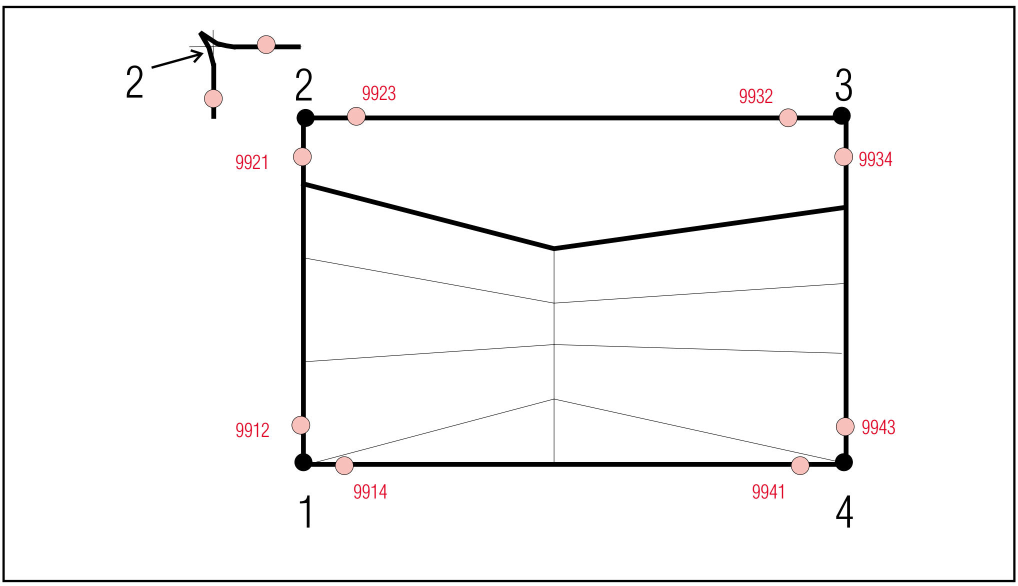

Figure 4: Indirectly measured corners. Identification numbers of the points are used during the measurements.
Slika 4: Posredno merjenje vogalov. Identifikacijske številke točk so bile uporabljene med meritvami.

After introducing a photo-coordinate system in this manner, calibration points were measured in all the photographs, all together around 300 points in each photo. It is very important to give the proper identification number to each point during the measurements of all the photographs. However, gross errors could be detected during the calibration computations because the wrong points had the largest residuals. These points were deactivated during further adjustment procedures.

Calibration points are placed on vertical and horizontal lines. Only well defined points in the lines were measured, and the points on the vertical lines were particularly important since vertical distortion was our prime concern. Not all the identical points could be found in the all photographs, but the sample was large enough to establish the model.

It was already mentioned that the Horizont camera does not have a perspective projection. Therefore, a special geometric projection model that suits the physical features of the camera had to be developed. The Institute of Photogrammetry and Remote Sensing of the Technical University of Vienna developed the ORIENT photogrammetric computer program, a sophisticated program whose development began in the 1970's that is able to solve practically all known problems in analytical photogrammetry. The »father« of the program is Professor Helmut Kager, and many upgrades have been already implemented.

To solve the problem of calibrating the Horizont camera, Prof. Kager developed a new model and implemented it using ORIENT. The model is a combination of a perspective model and a laser scanner model.

The film in the camera is stretched on a cylindrical surface and not on the normal plane plate, and the shutter moves during exposure across the entire film area. The exposure is controlled by the aperture width, and the shutter rotates together with the camera lens.

From Figure 5, it is evident that the image photo-coordinate system in the Horizont camera is dependent on time. Prof. Kager decided to use a mathematical coordinate system. For each vertical line in the photo, a local coordinate system must be defined in which vertical distortion is represented on the y-axis. There is no distortion on the x-axis because the local line has the dimension on the x-axis equal to zero. The principal point, which represents the projection of the projection center on the film in the local coordi-

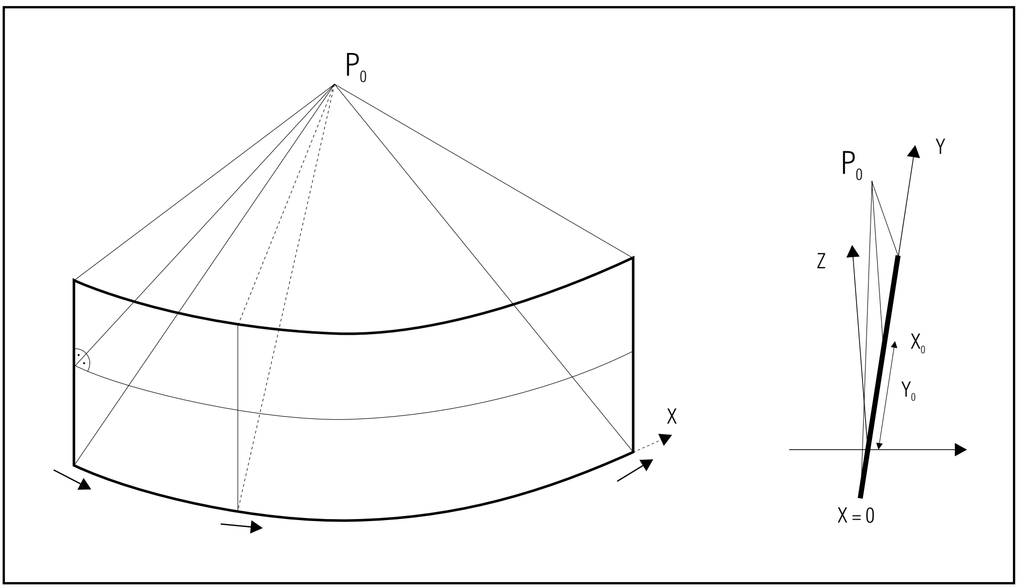

Figure 5: Photo-coordinate system in the Horizont camera.
Slika 5: Slikovni koordinatni sistem fotoaparata Horizont.

Figure 6: Original photograph of a test field. It is obvious that the model is not perspective since the lines in the buildings are not depicted as lines but as curves. Photo from calibration procedure.
Slika 6: Originalni posnetek testnega polja. Očitno je, da model ni perspektiven, ker linije niso upodobljene kot ravne linije temveč kot krivulje. Fotografija iz postopka kalibracije.

Figure 7: Resampled photograph of a test field. The lines from the test field are depicted as lines in the photograph as well; thus we have a central perspective photo.
Slika 7: Prevzorčen posnetek testnega polja. Linije iz testnega polja so sedaj upodobljene kot linije, torej imamo posnetek v centralni projekciji.

nate system, could have a small displacement from the vertical line in this moment. Thus, the coordinates of the principal point are x0 and y0, where x0 is theoretically equal to zero.

In the calibration procedure, the vertical distortion and the non-perspective model of the photograph are determined so that each photograph is divided into a regular grid of 1 mm^2 squares. This means that each photograph is split into 100 columns and 52 rows, and for each intersection point a value without distortion is computed. Tomaž Gvozdanovič wrote a computer program based on the described model for the rectification of the raster image from the Horizont camera. First, undistorted values were computed for the 5200 points in the image, and all the other points were then interpolated. The Cyl2per transformation program needs five minutes to transform a black and white digital photograph size of 10 MB and resolution of 14 µm to an image without the errors of distortions. The final resolution of the image was then resampled to 10 µm.

Figure 8: Original photograph of the Triglav glacier (source: Archive of Geographical institute).
Slika 8: Originalni posnetek Triglavskega ledenika (vir: arhiv Geografskega inštituta).

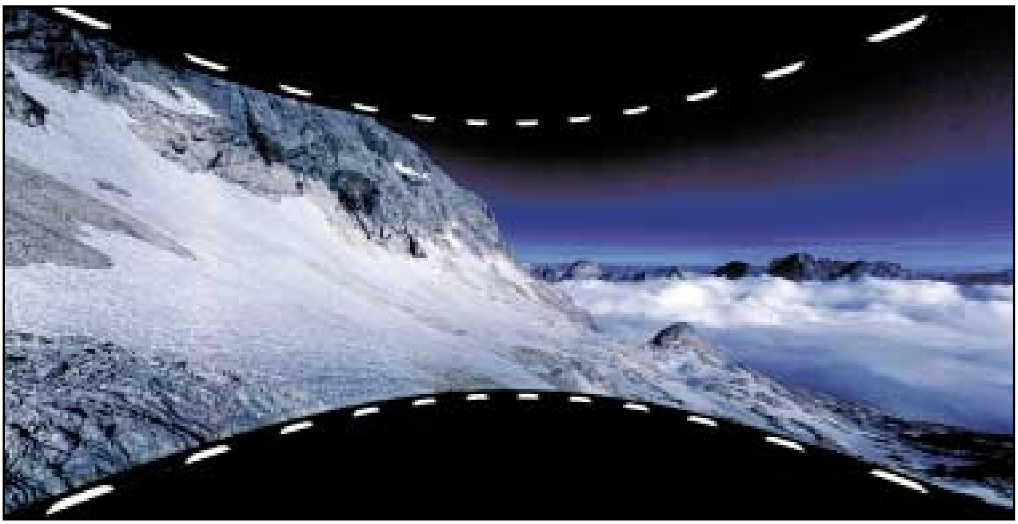

Figure 9: Resampled (transformed into central perspective) photograph of the Triglav glacier.
Slika 9: Prevzorčen posnetek (transformiran v centralno projekcijo) Triglavskega ledenika.

4. Linking of metrical and non-metrical photographs

The orientation procedure must be done in order to get the results in spatial coordinates (in a local or reference coordinate system). The internal orientation of non-metrical photographs was defined using the calibration procedure, while the external orientation is computed on the basis of the known spatial coordinates of the control points and their measured photo points. The spatial coordinates of the control points were computed from surveying measurements in a local coordinate system. The control points must be identified in the photographs (Figures 10, 11, 12, and 13). Field sketches of the control points helped us identify the small targets shown in the photographs. On the basis of the computed external orientation, we first started the stereo compilation of metric Rolleiflex photographs of the recent shape and surface of the glacier.

Figure 10: Identification of control and tie points in different photographs. The upper two photographs are terrestrial, the photographs below are aerial. Red points are control points; green points are tie points (source: Photogrammetric survey during the expedition in September 1999).
Slika 10: Identifikacija oslonilnih in veznih točk na različnih posnetkih. Zgornji dve fotografiji sta terestrični, posnetki spodaj so letalski. Rdeče točke so oslonilne točke, zelene točke so vezne točke (vir: Fotogrametrična izmera med odpravo v septembru 1999).

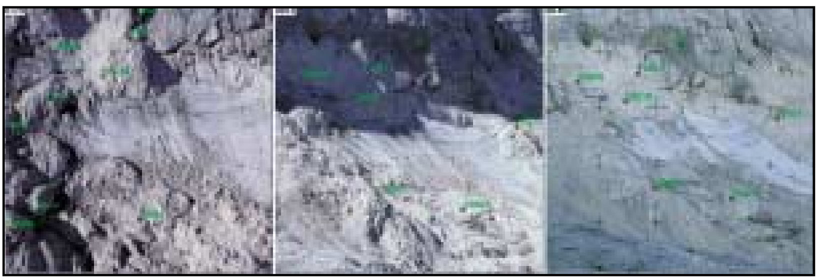

Figure 11: Identification numbers of control points in enlarged photographs.
Slika 11: Identifikacijske številke oslonilnih točk na povečavah.

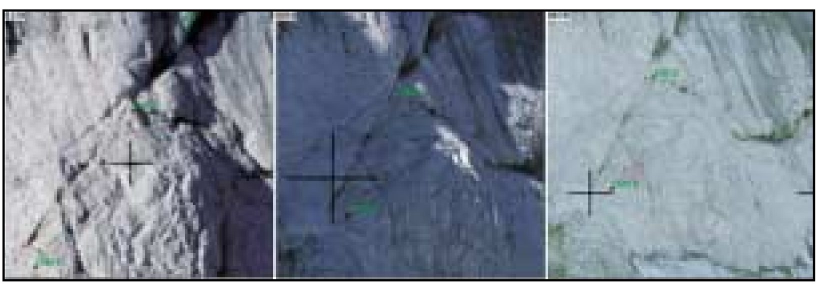

Figure 12: Interpretation of control points is dependent on the quality of the photographs. Brightness and shadows are different, and interpretation of the same points is therefore difficult (source: Photogrammetric survey durign the expedition in September 1999).
Slika 12: Interpretacija oslonilnih točk je odvisna od kvalitete posnetkov. Različna je svetlost posnetkov, različne so sence na posnetkih, kar otežuje interpretacijo istih točk (vir: Fotogrametrična izmera med ekspedicijo v septembru 1999).

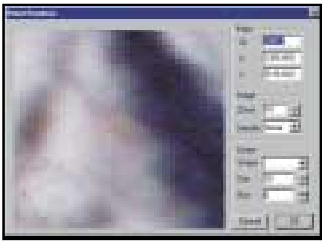

Figure 13: Ten times enlargement of a photograph for precise measurement of a control point, which has the size of only a few pixels in a digital image.
Slika 13: Desetkratna povečava posnetka za natančne meritve oslonilne točke, ki ima velikost le nekaj pikslov na digitalni sliki.

After transforming non-metrical Horizont photographs into a perspective model, these photographs were linked with metric ones on the basis of several well-defined tie points. Tie points are identical points on Rolleiflex and Horizont photographs, and we know their spatial coordinates. It was not an easy task to find good tie points due to the varying brightness of photographs, types of photographs (black and white, colour), different dates of photographs, etc. (Figure 14). Different brightness and shadows in the photographs affect the visibility of details. It was not possible to identify tie points in some Horizont photographs (Figure 16), so these photographs could not be included in the reconstruction procedure.

Figure 14: Difficult interpretation of tie points due to varying quality of photographs.
Slika 14: Otežkočena interpretacija veznih točk zaradi različne kakovosti posnetkov.

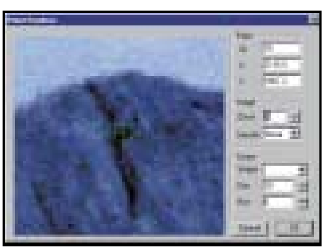

Figure 15: Six times enlargement of a photograph for precise measurement of tie point number 16.
Slika 15: Šestkratna povečava posnetka za natančne meritve vezne točke številka 16.

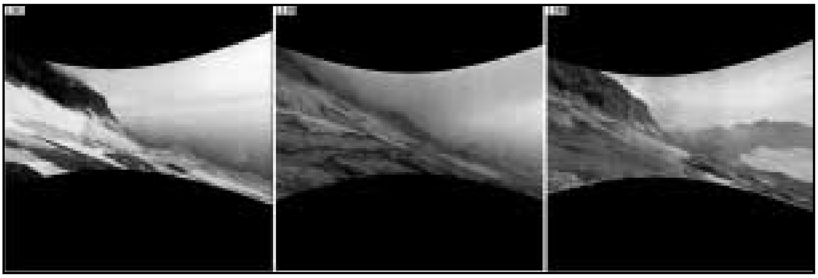

Figure 16: Horizont photographs in which no tie points could be identified (source: Archive of Geographical institute).
Slika 16: Horizontovi posnetki na katerih ni bilo možno identificirati veznih točk (vir: Arhiv Geografskega inštituta).

Tie points should be homogeneously distributed over the entire area (Figures 17 and 18) to ensure greater accuracy of the results.

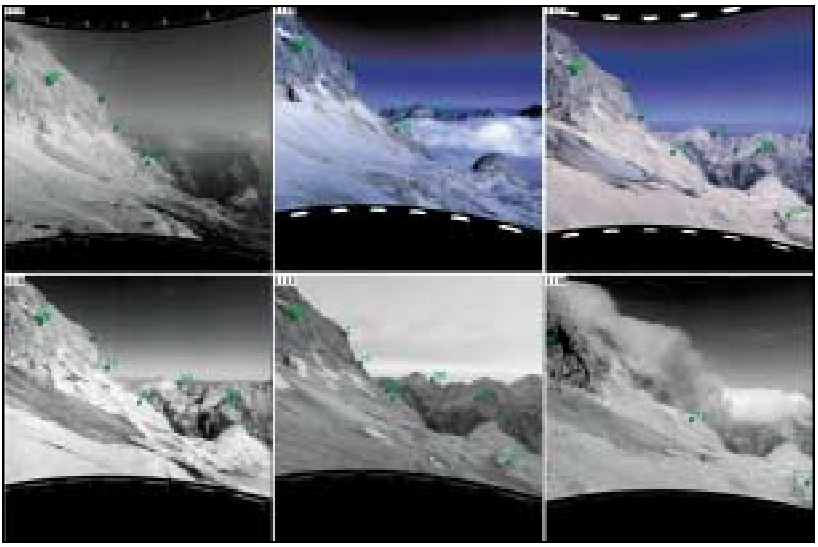

Figure 17: Disposition of tie points on photographs from standpoint A (source: Archive of Geographical institute).
Slika 17: Dispozicija veznih točk na posnetkih iz stojišča A (vir: Arhiv Geografskega inštituta).

Figure 18: Disposition of tie points on photographs from standpoint B (source: Archive of Geographical institute).
Slika 18: Dispozicija veznih točk na posnetkih iz stojišča B (vir: Arhiv Geografskega inštituta).

The Horizont photographs were then pre-oriented to the oriented model of Rolleiflex metric photographs. Thus, a better relative accuracy of measurements on Horizont photographs is assured. We discovered that tie points in the direction from Kredarica to Glava were very poorly defined and were therefore deactivated in the further procedure. The best tie points were defined in the mountain peaks in the background since these points have the greatest parallax.

5. Digital elevation model

A digital elevation model of the surroundings of the glacier was needed in order to resample the Horizont images. The digital elevation model (DEM) measured from the Rolleiflex photographs do not cover enough area around the glacier, since many tie points are positioned over a larger area. After considering several possible solutions, we decided to measure the digital elevation model from the photographs from the cyclical aerial surveys (CAS) that have been carried out in Slovenia since the beginning of the 1970's in a three years cycle. The photographs are 1 : 17,500 scale. We found several good photographs from the years 1993, 1994, and 1998 in the archives as well as some special aerial surveys taken after the earthquake in the Soča region in 1998.

From two stereo-pairs taken in 1994 and 1998, we measured a digital elevation model with a grid cell of 10 m. The shape of the glacier was measured from these photographs as well.

6. Orientation of Horizont photographs

We already observed that the Horizont photographs from the two standpoints do not form a stereo-pair for stereo-measurements. Thus, a non-conventional method must be used. First we use the measured DEM from the CAS photographs as a reference and resample each Horizont photograph on this DEM to pro-

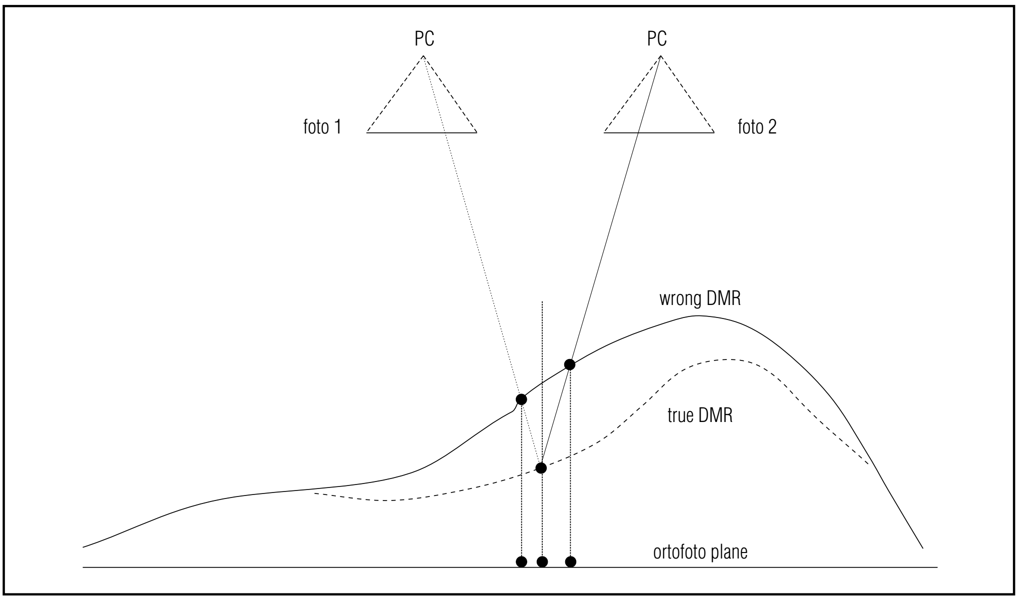

Figure 19: Geometrical model for computing height differences from orthophotographs on the basis of the »incorrect« DEM in the area of the glacier.
Slika 19: Geometrični model izračuna razlik višin na osnovi »napačnega« DMV na območju ledenika iz ortofotografij.

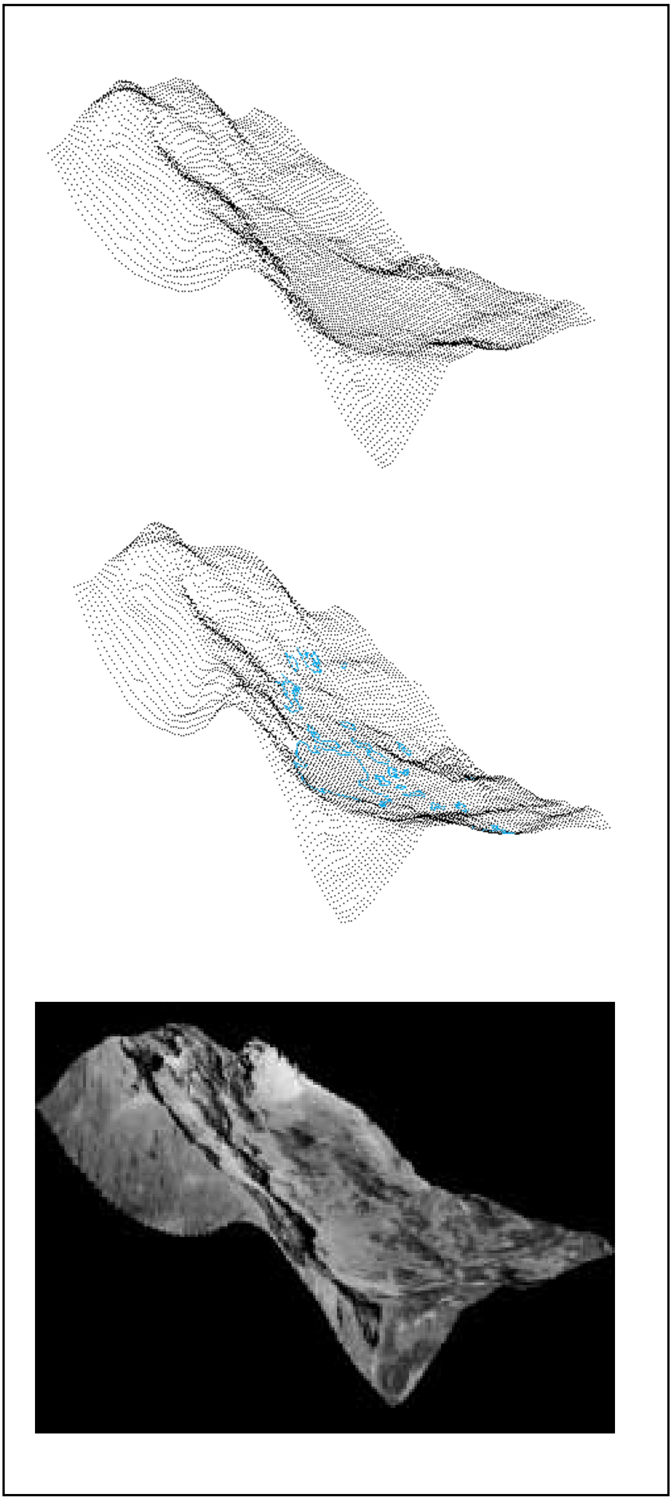

Figure 20: Doted digital elevation model DEM of Triglav glacier made from data of CAS 9. 8. 1998. On the second picture of DEM is added ice-barrier of glacier from the date 9. 8. 1992 CAS. On the third picture is DEM covered with the identical part of CAS with arial photography of glacier on the same day.
Slika 20: Točkovni digitalni model višin DMVnarejen iz podatkov CAS snemanja dne 9. 8. 1998. Druga slika prikazuje DMV z obrobo ledenika izmerjeno na CAS stereoparu iz dne 9. 8. 1992. Tretja slika predstavlja DMV prevlečen z letalskim posnetkom območja, ki ga prikazuje.

duce a pseudo-orthophotograph of the area. Resampling is done on the basis of defined control points from the CAS photographs (measured in a spatial coordinate system) and the same points in the Horizont photographs. We produced similar orthophotographs for each pair of photographs from the two standpoints. Of course, the DEM in the area of the glacier is incorrect; since it has changed over time, we get incorrect values in the glacier area. However, from the differences we can compute the parallax and from the known parallax we can then finally compute the heights of the glacier surface points (Figure 19).

This theoretical consideration seems feasible, and we are now developing a computer program for this final step. At the moment, we can not report on the final results, i. e., digital surface models of the glacier in different time periods, but we have overcome all the theoretical and practical problems so far and we expect to have the final results soon.

From the differences in the surfaces in different time periods, differences in volume can be computed. Experts from other sciences will use these results for their studies, e. g., the estimation of correlations between climate changes and the shrinkage of the glacier. The methodology has been tested on some selected photographs, and it will be subsequently applied to other pairs of Horizont photographs.

7. Proposed methodology for monitoring the glacier surface in future

Obviously, it is easy to measure the shape and surface of the glacier using metrical photographs. The control points that were targeted during the expedition can be used in later aerial surveys as well. Aerial surveys from a helicopter are a good solution, and it is only an organizational decision to make regular surveys every year. In this way, we could quickly obtain very accurate and up-to-date results that could be used in further investigations of the glacier's status. On the other hand, reconstruction of metrical data from archival non-metrical photographs is difficult and time-consuming; however, modern technology makes it at least possible to get information from the past.

8. Acknowledgement

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10. Summary in Slovene – Povzetek

Spremljanje površja ledenikov s fotogrametrijo, študija na primeru Triglavskega ledenika

Mihaela Triglav, Mojca Kosmatin Fras, Tomaž Gvozdanovič

1. Uvod

Triglavski ledenik je najbolj jugovzhodni ledenik v Alpah, zato so njegove spremembe pomembne za razumevanje in razlago možnih okoljskih in klimatskih sprememb v regiji in celo v svetovnem merilu. V zadnjih desetletjih so bile zaznane velike spremembe volumna tega ledenika vendar žal ni bilo izvedenih tridimenzionalnih meritev, na osnovi katerih bi te spremembe lahko natančneje opredelili.

Sodelavci Geografskega Inštituta Antona Melika in meteorologi na Kredarici od leta 1976 redno fotografirajo Triglavski ledenik skoraj vsak mesec. Fotografije so narejene z enostavnim, amaterskih ruskim fotoaparatom Horizont, ki je neobičajno zgrajen. Ker se ledenik očitno krči, je metrična rekonstrukcija njegovega obsega in površine signifikantna za vse znanstvene raziskave na to temo. V preteklosti je bilo narejenih nekaj geodetskih meritev, vendar so rezultati le dvodimenzionalni (samo njegov zunanji obod), meritve tudi niso bile izvedene dovolj pogosto. Možna rešitev problema je v ideji, da se uporabi arhivske posnetke Horizont v postopku fotogrametrične rekonstrukcije.

Fotogrametrija je znanost o pridobivanju metričnih podatkov o okolju in objektih iz fotografij. V konvencionalnih fotogrametričnih postopkih se za prostorsko rekonstrukcijo upodobljenih objektov običajno uporabljajo stereofotografije. Stereoefekt je dosežen, ko se dve fotografiji zadostno prekrivata (običajno 60 %–80 %), optični osi pa ne smeta biti preveč konvergentni. Fotografije Triglavskega ledenika so bile vedno posnete iz dveh znanih stojišč, vendar sta optični osi žal preveč konvergentni, da bi lahko dosegli stereoefekt. Zato smo morali uporabiti nekonvencionalno metodo.

2. Fotogrametrična izmera

Najprej smo potrebovali nekatere metrične podatke na bližnjem območju ledenika, zato da smo dobili referenčno osnovo za rekonstrukcijo površine. Iz tega razloga je bila septembra 1999 organizirana interdisciplinarna odprava na Triglavski ledenik, ki je imela za cilj terenske meritve in raziskave (georadarske meritve, geodetske in fotogrametrične meritve idr.). V članku se omejimo le na fotogrametrične meritve.

Med to odpravo je bila izvedena terestrična in zračna izmera ledenika z uporabo metričnega fotoaparata Rolleiflex 6006, ki je opremljen z r***seau mrežo. Letalski posnetki so bili narejeni iz helikopterja letalske enote slovenske vojske. Posneti so bili fotogrametrični pasovi iz različnih višin. Ker helikopter ni bil posebej opremljen za snemanje, je moral biti snemalec dobro pritrjen z varovalnimi pasovi. Med snemanjem se je snemalec moral precej nagniti čez odprta vrata helikopterja, da je lahko naredil kar najboljše posnetke območja. Narejenih je bilo precej stereoparov, ki skupaj tvorijo fotogrametrični blok.

Iz samih fotogrametričnih stereoposnetkov lahko rekonstruiramo le relativne dimenzije upodobljenih objektov. Za pridobitev absolutnih koordinat moramo poznati dovolj veliko število točk z znanimi prostorskimi koordinatami. Te točke, ki jih v fotogrametriji imenujemo oslonilne točke, običajno izmerimo z geodetskimi ali GPS meritvami.

Preden smo začeli s fotogrametričnim snemanjem smo na terenu signalizirali izbrana mesta oslonilnih točk s posebno barvo. Signali točk so morali biti dovolj veliki, da so kasneje vidni na posnetkih. V našem primeru so bile točke signaliizirane s krogom premera 80 cm. Pri geodetskih meritvah smo prizmo postavili v center kroga. Čeprav je bila velikost oslonilnih točk na terenu precej velika, smo jih kljub temu težko našli na posnetkih.

Metrične posnetke narejene s fotoaparatom Rolleiflex smo uporabili za meritve trenutnega oboda in površine ledenika z uporabo običajne stereofotogrametrije. Arhivski, netehnični postnetki narejeni s fotoaparatom Horizont pa morajo biti na drugi strani predhodno obdelani, kar je opisano spodaj.

Konstrukcija obeh stojišč za snemanje s fotoaparatom Horizont ni najbolj stabilna in torej ni tipična geodetska točka. Železna cev s podstavkom za fotoaparat se lahko nagiba v vseh smereh, kar se tudi najbrž dogaja pozimi med nevihtami. Kljub temu pa lahko predpostavimo, da je natančnost pozicije stojišča zagotovljena v polmeru 50 cm okoli cevi. Prostorski poziciji obeh stojišč sta bili izmerjeni v okviru odprave.

3. Kalibracija fotoaparata Horizont

Fotoaparat Horizont je panoramski fotoaparat s snemalnim kotom 180°, teoretična gorišča razdalja objektiva je 28,0 mm. Takšen kot ni dosežen samo s širokokotnim objektivom, temveč je uporabljena posebna konstrukcija z vrtečega se objektiva, ki se nahaja pred filmom napetim na cilindrični nosilec. Fotogrametrični posnetki so običajno narejeni v centralni projekciji in vse fotogrametrične enačbe temeljijo na tem dejstvu. Na žalo6st pa projekcija, ki jo ustvari fotoaparat Horizont, ni centralna, temveč je neznana in jo moramo najprej definirati. Prvi korak je bila zato kalibracija fotoaparata.

Parametri notranje orientacije fotoaparata so tri koordinate glavne točke v slikovnem koordinatnem sistemu. To sta x in y koordinata glavne točke v slikovni ravnini in konstanta kamere (gorišča razdalja). V procesu kalibracije dodatno definiramo še nekatere druge parametre kot npr. različne parametre distrozije (radialna, tangencialna, asimetrična, …). Slikovni koordinatni sistem metričnega fotoaparata je definiran z robnimi markicami, ki se upodobijo na posnetku med ekspozicijo. Ker fotoaparat Horizont ni metričen, tudi nima robnih markic, zato jih moramo definirati posredno.

Kalibracijo fotoaparata lahko izvedemo z različnimi metodami (Kraus, 1995). V članku je opisana le metoda, ki smo jo uporabili za kalibracijo fotoaparata Horizont, to je kalibracija v testnem polju z uporabo točk in znanih geometričnih entitet (nem. Gestalts). V našem primeru so bile to vodoravne in navpične linije v testnem polju.

Ker v Sloveniji nimamo laboratorija za kalibracijo fotoaparatov, smo uporabili dobre povezave z dunajsko tehniško univerzo, Inštitutom za fotogrametrijo in daljinsko zaznavanje. Kalibracija fotoaparata bo predstavljala del diplomskega dela Mihaele Triglav in to sodelovanje je bilo obravnavano kot študentska izmenjava med ljubljansko in dunajsko univerzo. Celoten proces kalibracije je bil izveden pod vodstvom Prof. Helmuta Kagerja iz dunajske univerze.

Testno polje se dejansko nahaja na fasadah v atriju poslopja tehniške univerze. Običajno se posname več posnetkov, pri čemer se fotoaparat lahko zasuka med različnimi posnetki. Takšne vrste testno polje je še posebej primerno za kalibracijo širokokotnih objektivov.

Testno polje je signalizirano z dobro definiranimi točkami, ki imajo zelo natančno izmerjene koordinate z geodetskimi meritvami v lokalnem koordinatnem sistemu. Signali so retro-refleksivni krogi s polmerom 0,5 cm. Oslonilne točke so nameščene v vodoravnih in vertikalnih linijah, s čemer je omogočena določitev različnih vrst distrozij. Med fotogrametričnim meritvami je potrebno zajeti kar največ točk na isti vodoravni oz. navpični liniji.

Retro-refleksivne točke so vidne na posnetku le v primeru, če so v trenutku ekspozicije osvetljene z močno svetlobo, ki je usmerjena v pravo smer. Točke reflektirajo svetlobo v zelo ozkem kotu nazaj proti izvoru svetlobe. Reflektorji morajo biti zato nameščeni blizu stojišča fotoaparata.

Fotoaparat Horizont je bil nameščen na stativu in izdelane so bile serije posnetkov z fotoaparatom v portretnem in krajinskem položaju. Z namenom, da se doseže čim boljši rezultat, so bili uporabljeni različni časi ekspozicije.

Ni potrebno, da je pozicija kamere v času snemanja poznana, zato se fotografiranje v testnem polju razmeroma hitro izvede. Iz vsakega stojišča so bili narejeni štirje posnetki, zato da so meritve nadštevilčne in da so s tem bolje definirani robovi posnetkov, kjer so pričakovane distorzije največje. Ko so bili filmi razviti, smo izbrali tiste najboljše posnetke, na katerih je bilo vidnih največ retro-fleksivnih oslonilnih točk. Izbrani posnetki so bili izmerjeni na analitičnem fotogrametričnem inštrumentu Sun Solaris BC3. Meritve so bile izvedene v MCP mono-komparatorskem programu.

V programu moramo na začetku vnesti nekatere začetne vrednosti, npr. vrsto posnetkov, začetne vrednosti rotacijskih kotov, itd. Nato posredno izmerimo robne marke (vogali posnetka). Ker vogali posnetkov niso dobro definirani, jih posredno izmerimo z dvema točkama na robu blizu vogala. Koordinate vogala so nato izračunane kot presek dveh linij. Retro-refleksivne oslonilne točke so bile izmerjene z najmanjšo plavajočo markico na anlitičnem inštrumentu (10 µm). Teoretična natančnost meritev na komparatorju BC je sicer 5 µm.

Potem, ko smo na opisan način uvedli slikovne koordinate, smo izmerili kalibracijske točke na vseh posnetkih, skupaj 300 točk na posnetek. Zelo pomembno je, da vsaki točki priredimo pravo identifikacijsko številko na vseh posnetkih. Grobe napake lahko sicer odkrijemo med izravnavo, ker imajo napačne točke največja odstopanja. Takšne odkrite točke izločimo iz nadaljnjega procesa izravnave.

Kalibracijske točke so nanizane na navpičnih in vodoravnih linijah. Izmerimo samo tiste točke, ki so dobro definirane. Pri tem so še posebej pomembne navpične linije, saj nas odprava vertikalne distorzije najbolj zanima. Na posnetkih nismo mogli najti vseh identičnih točk, vendar je bil vzorec dovolj velik, da smo lahko ustvarili model.

Omenili smo že, da fotoaparat Horizont ne ustvari perspektivne projekcije. Zato je bilo potrebno razviti poseben geometrijski model projekcije, ki se ujema s fizikalnimi lastnostmi fotoaparata. Dunajski inštitut od 70-ih let razvija programski paket ORIENT. To je zmogljiv program, ki lahko reši praktično vse znane probleme iz analitične fotogrametrije. »Oče« tega programa je Prof. Helmut Kager in do sedaj je bilo narejenih že več nadgradenj tega programa.

Da smo lahko rešili problem kalibracije, je Prof. Kager razvil nov model in ga implementiral v ORIENT. Ta model je kombinacija perspektivnega model in modela laserskega skenerja.

Film v kameri je napet na cilindrično površino in ne na ravno površino, kot je to običajno v fotoaparatih. Zaslonka se med ekspozicijo premika preko filma. Ekspozicija se uravnava z velikostjo odprtine. Zaslonka se vrti skupaj z objektivom fotoaparata.

Iz slike 5 je razvidno, da je slikovni koordinatni sistem fotoaparata Horizont odvisen od časa. Definiran je bil matematični koordinatni sistem. Za vsako navpično linijo mora biti definiran lokalni koordinatni sistem v katerem je vertikalna distorzija predstavljena z y-osjo. V smeri osi x ni distorzije, ker ima lokalna linija dimenzijo v x smeri enako 0. Glavna točka, ki predstavlja projekcijo projekcijskega centra na filmu v lokalnem koordinatnem sistemu, je lahko rahlo premaknjena iz vertikalne linije v tem trenutku. Torej so koordinate glavne točke x0 in y0, pri čemer je x0 teoretično enak 0.

V postopku kalibracije sta bila definirana vertikalna distorzija in neperspektivni model posnetka na tak način, da je bil vsak posnetek razdeljen na pravilno mrežo velikosti 1 mm^2. To pomeni, da je bil vsak posnetek razdeljen na 100 stolpcev in 52 vrstic in za vsako točko preseka je bila izračunana vrednost brez distorzije. Tomaž Gvozdanovič je napisal računalniški program za razpačenje rastrske (digitalne) slike, ki je temeljil na opisanem modelu. Najprej se za 5200 točk izračunajo slikovne nespačene vrednosti za vseh teh 5200 točk, ostale točke pa se nato interpolira. Program za transformacijo se imenuje Cyl2per in je potreboval 5 minut za izvedbo transformacije črno-bele slike velikosti 10 MB, ki ustreza resoluciji digitalne slike 14 μm. Končna resolucija digitalne slike je prevzorčena na 10 μm.

4. Povezava metričnih in ne-metričnih fotografij

Rezultate v prostorskem koordinatnem sistemu (lokalnem ali referenčnem) dobimo s postopki orientacije posnetkov. Notranja orientacija ne-metričnih posnetkov je bila določena s postopkom kalibracije, medtem ko je zunanja orientacija izračunana na osnovi znanih prostorskih koordinat oslonilnih točk in njihovih merjenih slikovnih koordinat. Prostorske koordinate oslonilnih točk so bile izračunane iz terenskih meritev v lokalnem koordinatnem sistemu. Oslonilne točke je bilo potrebno identificirati na posnetkih (Slike 10, 11, 12 in 13). Terenske topografije oslonilnih točk so nam pomagale, da smo lahko identificirali te točke na posnetkih. Na osnovi izračunane zunanje orientacije smo najprej začeli s stereo-izvrednotenjem oboda in površine ledenika iz Rolleiflex metričnih fotografij.

Potem, ko smo Horizontove posnetke transformirali v perspektivni model, smo te posnetke povezali z metričnimi posnetki na osnovi dobro definiranih veznih točk. Vezne točke so iste točke na obeh vrstah posnetkov in za njih praviloma ne poznamo njihovih prostorskih koordinat. Zaradi različne svetlosti posnetkov, različnih vrst posnetkov (črno-beli, barvni), različnih datumov posnetkov, itd. (slika 14) ni bilo lahko najti dobrih veznih točk. Različna osvetlitev in sence vplivajo na vidnost podrobnosti. Na nekaterih Horizontovih posnetkih ni bilo možno definirati veznih točk (slike 16), zato teh posnetkov ne moremo vključiti v postopek rekonstrukcije.

Vezne točke morajo biti homogeno razporejene po celotnem območju (sliki 17 in 18). To zagotavlja večjo natančnost rezultatov.

Horizontove posnetke smo nato priorientirali k modelu metičnih Rolleiflexovih posnetkov. Na ta način smo zagotovili boljšo relativno natančnost meritev na Horizontovih posnetkih. Ugotovili smo, da so vezne točke v smeri od Kredarice proti Glavi slabše definirane, zato smo jih izločili iz nadaljnjega postopka. Najboljše vezne točke so bili vrhovi gora, ki so v ozadju in imajo tudi največjo paralakso.

5. Digitalni model višin

Digitalni model višin (DMV) okolice ledenika smo potrebovali za prevzorčenje Horizontovih posnetkov. DMV, ki je bil izmerjen iz Rolleiflexovih posnetkov, ni pokrival dovolj velike površine okoli ledenika, na kateri so bile razporejene številne vezne točke. Ko smo preučili različne možne rešitve, smo se odločili, da izmerimo digitalni model višin iz posnetkov cikličnega aerosnemanja (CAS), ki se v Sloveniji izvaja od začetka sedemdesetih let v triletnih ciklih. Posnetki so v merilu 1 : 17.500. V arhivu Geodetske uprave RS smo našli nekaj dobrih posnetkov iz let 1993, 1994, 1998 in nekaj posnetkov posebnega snemanja po potresu v Posočju v letu 1998.

Iz dveh stereoparov iz let 1994 in 1998 smo izmerili digitalni model višin z velikostjo celice 10 m. Iz posnetkov smo izmerili tudi obris ledenika.

6. Orientacija Horizontovih posnetkov

Omenili smo že, da Horizontovi posnetki iz dveh stojišč ne oblikujejo stereopare za stereomeritve. Zato je potrebno uporabiti drugačno metodo. Najprej smo kot referenco uporabili izmerjen DMV iz posnetkov CAS in nato vsak Horizontov posnetek prevzorčili na ta DMV, to je, izdelali smo psevdoortofoto območja. Prevzorčenje je izvedeno na osnovi definiranih oslonilnih točk na posnetkih CAS (merjenih v prostorskem koordinatnem sistemu) in istih točk na Horizontovih posnetkih. Za vsak par posnetkov smo izdelali ortofotografije iz obeh stojišč. Seveda je DMV na območju ledenika napačen, saj vemo, da se je skozi čas spreminjal, torej dobimo napačne vrednosti na območju ledenika. Iz razlik lahko izračunamo paralakso, iz le-te pa lahko končno izračunamo višine točk na ledeniku (slika 19, 20).

Te teoretične predpostavke so realna podlaga za izvedbo in sedaj smo v fazi razvijanja računalniškega programa. Ne moremo še poročati o dokončnih rezultatih, to je digitalnem modelu površine ledenika v različnih časovnih obdobjih, vendar smo dosedaj uspeli prebroditi vse teoretične in praktične probleme in končne rezultate pričakujemo v kratkem.

Iz razlik površin v različnih časovnih obdobjih lahko izračunamo razlike volumna. Strokovnjaki drugih strok bodo te rezultate lahko uporabili v svojih študijah, npr. pri določitvi korelacije med klimatskimi spremembami in krčenjem ledenika. Metodologijo smo dosedaj testirali na izbranih posnetkih in jo bomo kasneje uporabili na drugih parih Horizontovih posnetkov.

7. Predlagana metodologija za sledenje površine ledenika v prihodnje

Jasno je, da je iz metričnih posnetkov možno relativno enostavno izmeriti obod in površino ledenika. Oslonilne točke, ki smo jih signalizirali med ekspedicijo, se lahko uporabljajo pri naslednjih fotogrametričnih snemanjih. Snemanje iz helikopterja je dobra rešitev, saj ga lahko ob ustrezni organizaciji snemanja izvajamo redno vsako leto. Na ta način lahko hitro dobimo zelo natančne in aktualne rezultate, ki se lahko uporabijo pri nadaljnjih raziskavah stanja ledenika. Po drugi strani pa je metrična rekonstrukcija iz arhivskih, ne-metričnih posnetkov težka in zamudna, vendar moderna tehnologija sploh omogoča, da dobimo metrične informacije iz preteklosti ledenika.

8. Zahvala

Avtorji se iskreno zahvaljujemo Inštitutu za fotogrametrijo in daljinsko zaznavanje dunajske tehniške univerze, še posebej Prof. Karlu Krausu, vodji inštituta, ki je sodelovanje podprl, Prof. Helmutu Kagerju za kalibracijo kamere in ideje, gospodu Tschanerlu za pomoč pri kalibraciji. Hvala tudi kolegom iz Geodetskega inštituta Slovenije, ki so sodelovali v odpravi, posebej Stanetu Tršanu in Miranu Janežiču za terenske meritve in številne sugestije, kot tudi direktorju IGF Romanu Renerju in direktorju DFG Consultinga Zmagu Frasu za njuno podporo projekta. Ne nazadnje, hvala kolegom in Geografskega Inštituta Antona Melika, da so nam dali izziv.

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