APPLICATION OF TERRESTRIAL PHOTOGRAMMETRY FOR GLACIER MONITORING IN ALPINE ENVIRONMENTS

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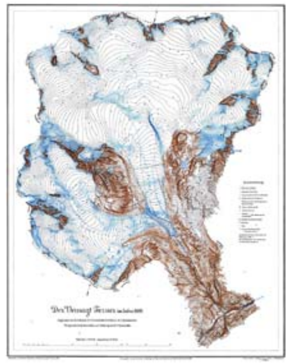
- Terrestrial photogrammetry was the standard method for mapping high mountain terrain in the early days of mountain cartography.

Sebastian Finsterwalder (1862-1951)

Mathematician and geodesist

Map of Vernagtferner
1:10,000 (1889)

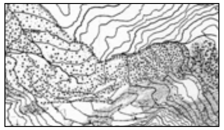
plane-table photogrammetry



Source: Commission for Glaciology of the Bavarian Academy of Sciences and Humanities

Sebastian Finsterwalder was one of the pioneers of photogrammetry; he made substantial contributions to **terrestrial photogrammetry** and to the mathematical fundamentals (Albertz, 2010).

Sebastian Finsterwalder (1862-1951)



Rock glacier north of Krummgampenspitze

Map of Gepatschferner
1:20,000 (1922)

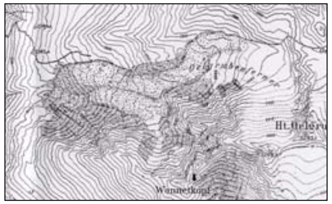
stereo photogrammetry

Der Talschluß des Kaunsertales
in den Oetztaleralpen mit dem
Gepatsch-u. Weißseeferner

Aufgenommen im Jahre 1922
von Dr. Sebastian, Ulrich u. Richard Finsterwalder u. J. Sartorius.
Mit dem Autographen auf Kosten des Konsortiums Luftbild-Stereographik.
ausgearbeitet von
Dipl.-Jng. G. Heß u. J. Sartorius im Maßstab 1:10000 mit 10 m Schichten
Reproduktion im Maßstab 1:20000 mit 20 m Schichten
aus Mitteln des D. u. Oest. Alpenvereins (Ed. Richter-Stiftung).

1:20000

Source: S. Finsterwalder (1928): Begleitworte zur Karte des Gepatschferners. Zeitschrift für Gletscherkunde, 16, p. 20-41.



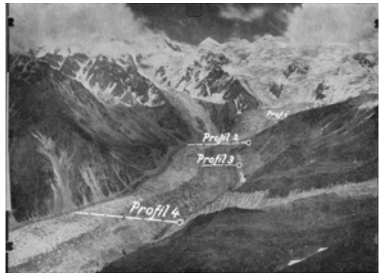
1901: Carl Pulfrich developed the **stereocomparator**.
1909: Eduard Ritter von Orel invented the **stereoautograph**.

Ölgruben rock glacier
Measurement of flow/creep velocity by means of terrestrial photogrammetry,
first survey: 1923, repeat survey: 1924, result: movement max. 50 cm/year (⇨ repeat survey by W. Pillewizer)

Richard Finsterwalder (1899-1963)

Civil engineer and cartographer

TAF (Carl Zeiss Jena)
(Terrestrische Ausrüstung Finsterwalder)
lightweight terrestrial phototheodolite



Rakhiot glacier, Nanga Parbat, 1934

1928: German-Russian Alay-Pamir expedition. Mapping of Fedtschenko glacier. Measurement of glacier velocities.
1934: German Nanga Parbat expedition. He discovered a new form of glacier flow (Block-Schollen movement).
1937: Jostedalsbre, Norway

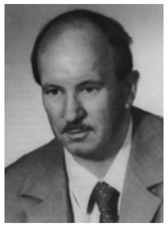
since 1927: “Glacier course”, then “Course for High Mountain Research”

R. Finsterwalder (1930): Grenzen und Möglichkeiten der terrestrischen Photogrammetrie, besonders auf Forschungsreisen. Habilitation treatise

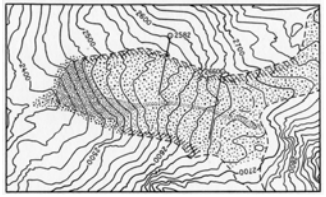
R. Finsterwalder (1931): Geschwindigkeitsmessungen an Gletschern mittels Photogrammetrie. Zeitschrift für Gletscherkunde, Band 19, 251-262.

R. Finsterwalder (1952): Das Ergebnis der photogrammetrischen Gletschermessung seit 1885 in den Ostalpen. Allgemeine Vermessungs-Nachrichten, Heft 3, 66-69.

Wolfgang Pillewizer (1911-1999)



Geographer and cartographer



Ölgruben rock glacier: Repeat surveys 1938, 1939 and 1953

Interested in: high mountain cartography, applied photogrammetry, glaciology
Expeditions: Norway, Svalbard, Himalaya-Karakoram, etc.

Rock glacier studies in the Ötztal Alps: *Ölgruben* rock glacier, *Rotschliffkar* rock glacier, *Hochebenkar* rock glaciers

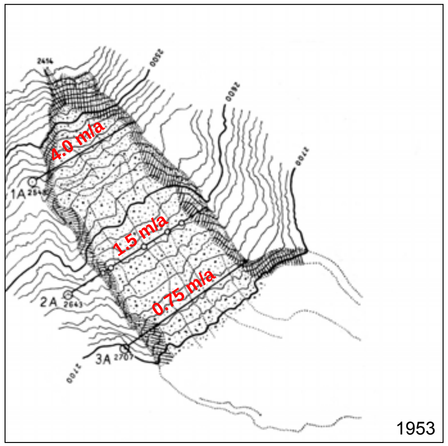
W. Pillewizer (1938): Photogrammetrische Gletscherforschung. Bildmessung und Luftbildwesen, Nr. 2, 1938, 66-73.

W. Pillewizer (1957): Untersuchungen an Blockströmen der Ötztaler Alpen. In: Geomorphologische Abhandlungen. Abh. d. Geogr. Inst. d. Freien Universität Berlin 5, 37-50.

W. Pillewizer (1986): Zwischen Alpen, Arktis und Karakorum – Fünf Jahrzehnte kartographische Arbeit und glaziologische Forschung. Dietrich Reimer Verlag, Berlin, 211 p.

Wolfgang Pillewizer (1911-1999)

1100 m



Äußeres Hochebenkar rock glacier

- Terrestrial photogrammetric survey of 1936.
  1938: photogrammetric velocity profile (3A)
- Terrestrial photogrammetric survey of 1953.
  1953: repeat of photogrammetric velocity profile (3A)
  2 additional velocity profiles (1A) and (2A)
- 1955: repeat of photogrammetric velocity profiles

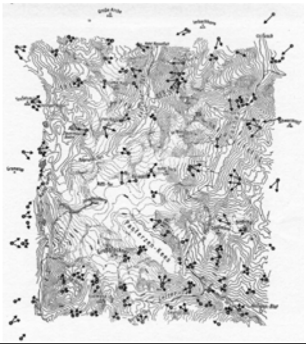
1. Introduction

- Terrestrial photogrammetry was the standard method for mapping high mountain terrain in the early days of mountain cartography.
- It has several drawbacks compared to aerial photogrammetry.

Map of Glockner Mountains
1:25,000 (1928)
by Richard Finsterwalder

stereo photogrammetry

165 baselines
250 photographic plates



- data acquisition is strenuous
- complete coverage is difficult
- problem of surface occlusions
- complete coverage is time-consuming
- mapping is difficult at shallow viewing angles
- inhomogeneous mapping accuracy
- georeferencing of independent stereomodels is troublesome
- no bundle/block adjustment feasible
- etc.

1. Introduction

- Terrestrial photogrammetry was the standard method for mapping high mountain terrain in the early days of mountain cartography.
- It has several drawbacks compared to aerial photogrammetry.
- Terrestrial photogrammetric surveys for mapping small areas in mountain regions were performed from time to time until recently.

1. Introduction

- Terrestrial photogrammetry was the standard method for mapping high mountain terrain in the early days of mountain cartography.
- It has several drawbacks compared to aerial photogrammetry.
- Terrestrial photogrammetric surveys for mapping small areas in mountain regions were performed from time to time until recently.
- Modern low-priced digital consumer cameras and highly automatic digital photogrammetric workflows suggest the rebirth of terrestrial photogrammetry for mapping projects in high mountain environments.

P. Pellikka and W.G. Rees, Eds. (2010): Remote Sensing of Glaciers – Techniques for Topographic, Spatial and Thematic Mapping of Glaciers. CRC Press/Balkema, 330 p.
Several papers on glacier/rock glacier/rock fall/ landslide monitoring using digital terrestrial photographs applying (photogrammetric) computer vision techniques.

2. Change detection

22.8.2009

20.8.2010

single image acquisition

digital SLR Nikon D300

Digital image processing:

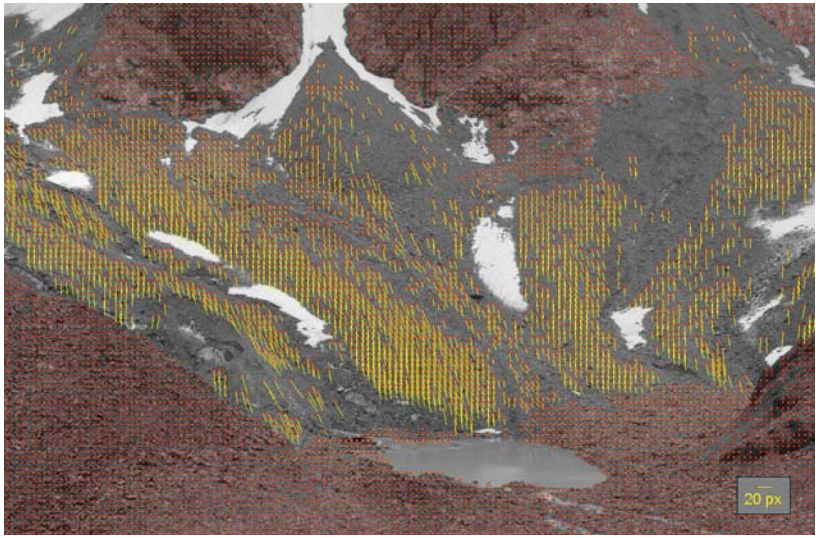
❶ Correct both photographs for chromatic aberration and lens distortion → undistorted photographs

❷ Measurement of homologous points by area-based image matching
(grid/ interest points: Förstner or Harris operator; similarity measure: NCC; back matching strategy)

❸ Compute projective transformation using stable points (RANSAC algorithm may be applied)

❹ Image rectification of the slave image to fit the reference image

❺ Visualization/ animation



Disparity map indicating surface deformation

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Change detection 2009-2010

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Change detection 2008-2009-2010

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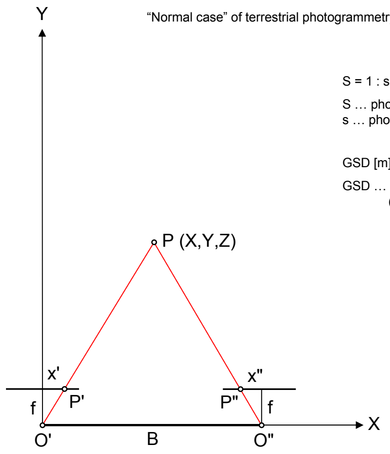
Change detection 1988-2010

3. Photogrammetric mapping and its accuracy

"Normal case" of terrestrial photogrammetry



S = 1 : s = f [mm] : Y [m]

S … photo scale
s … photo scale figure

GSD [m] = pixel size [mm] * s

GSD … ground sampling distance (in vertical wall)

reconstruction

$$X = \frac{Y}{f} \cdot x' \qquad Y = \frac{f \cdot B}{p_x} \qquad Z = \frac{Y}{f} \cdot y' = \frac{Y}{f} \cdot y''$$

horizontal parallax

$$p_x = x' - x''$$

accuracy

$$\sigma_Y = \pm s \cdot \frac{Y}{B} \cdot \sigma_{p_x} = \frac{Y^2}{f \cdot B} \cdot \sigma_{p_x}$$

$$\sigma_X = \pm \sqrt{\left(\frac{x'}{f} \cdot s \cdot \frac{Y}{B} \cdot \sigma_{p_x}\right)^2 + (s \cdot \sigma_x)^2}$$

$$\sigma_Z = \pm \sqrt{\left(\frac{y'}{f} \cdot s \cdot \frac{Y}{B} \cdot \sigma_{p_x}\right)^2 + (s \cdot \sigma_y)^2}$$

accuracy (rules of thumb)

$$\sigma_Y = \pm \frac{Y^2}{f \cdot B} \cdot \sigma_m = s \cdot \frac{Y}{B} \cdot \sigma_m$$

$$\sigma_X = \sigma_Z = \pm s \cdot \sigma_m$$

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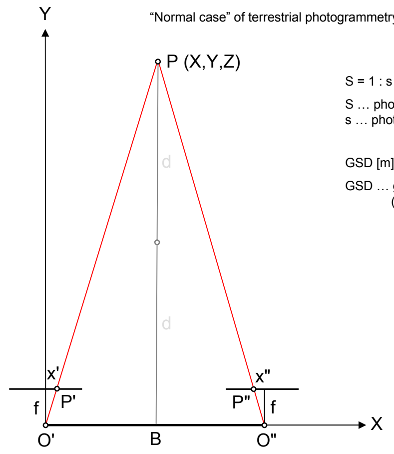
"Normal case" of terrestrial photogrammetry



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accuracy (rules of thumb)

$$\sigma_Y = \pm \frac{Y^2}{f \cdot B} \cdot \sigma_m = s \cdot \frac{Y}{B} \cdot \sigma_m$$

$$\sigma_X = \sigma_Z = \pm s \cdot \sigma_m$$

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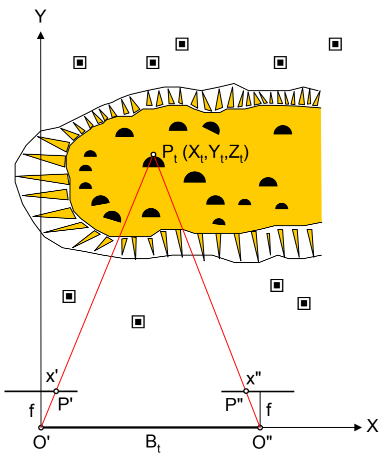
Measurement of 3D deformation vectors



▣ … stable point
◓ … moving point

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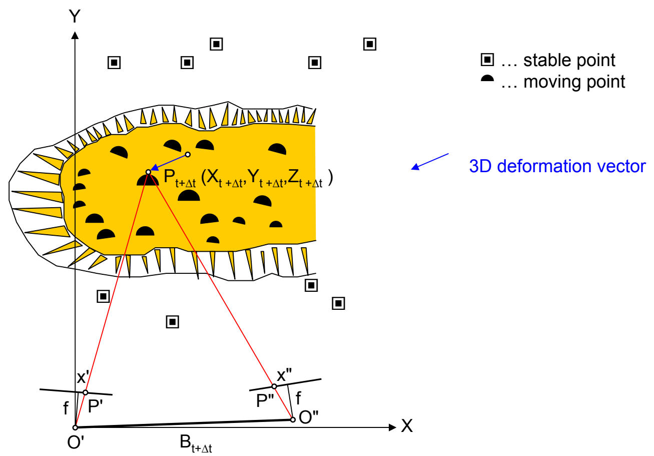
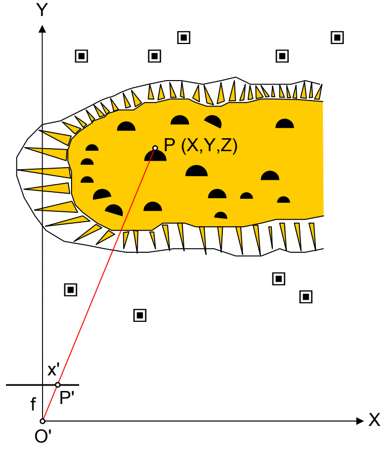
Measurement of 3D deformation vectors



▣ … stable point
◓ … moving point

Quality control (robustness) by redundancy



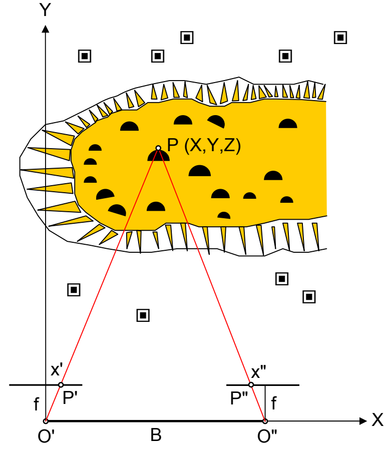
■ … stable point
◓ … moving point

single photograph

3 unknows (X,Y,Z)
2 image coordinates

r = m-u = -1

Quality control (robustness) by redundancy



■ … stable point
◓ … moving point

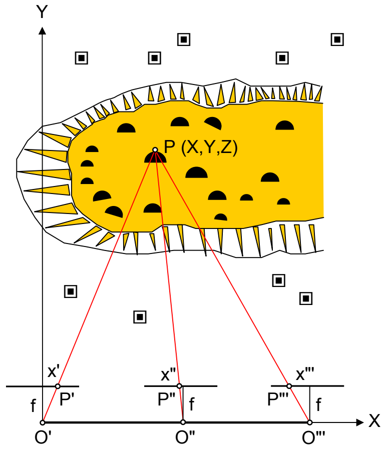
stereopair

3 unknows (X,Y,Z)
4 image coordinates

r = m-u = 1

essential matrix

Quality control (robustness) by redundancy



■ … stable point
◓ … moving point

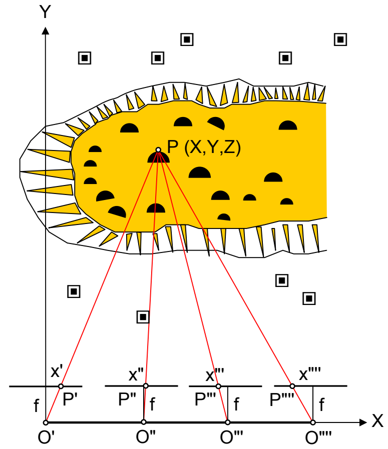
stereo triplet

3 unknows (X,Y,Z)
6 image coordinates

r = m-u = 3

trifocal tensor

Quality control (robustness) by redundancy



■ … stable point
◓ … moving point

stereo quadruplet

3 unknows (X,Y,Z)
8 image coordinates

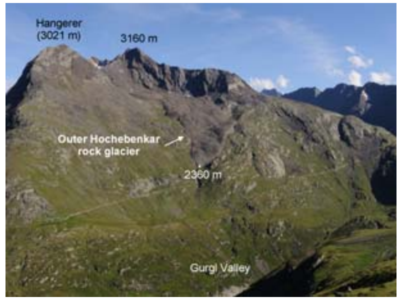
r = m-u = 5

multi-ray photogrammetry

4. An example on rock glacier monitoring

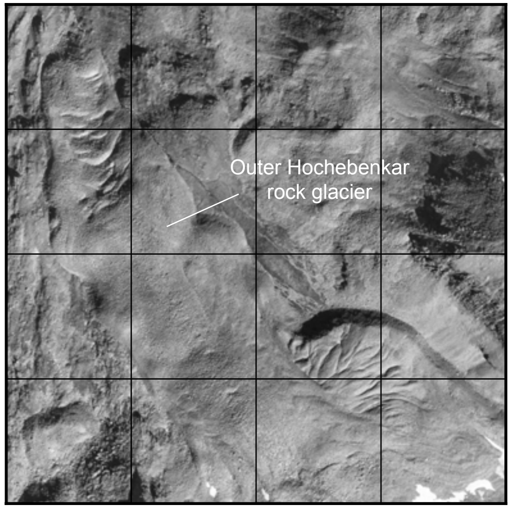
Panorama
Obergurgl - Hohe Mut - Rotmoostal - Hangerer - Äußeres Hochebenkar - Gurgler Ferner

Terrestrial photogrammetric survey
of the Outer Hochebenkar rock glacier
by Viktor Kaufmann and Walter Krämer (TU Graz),
10 August, 2008.



250 m

250 m



Horizontal flow/creep 1997-2003

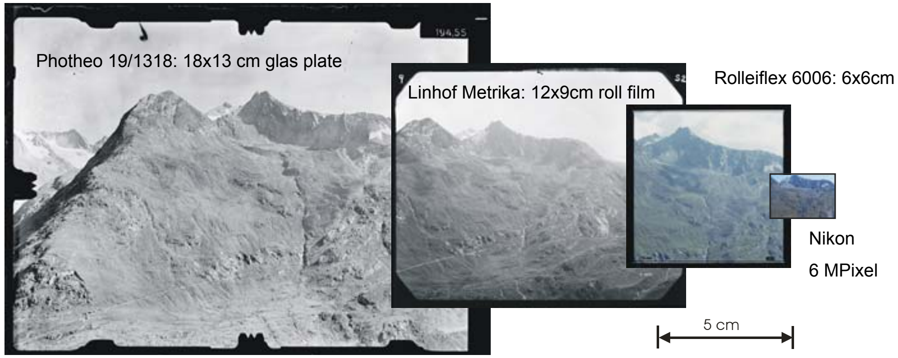
Computer animation

Terrestrial photogrammetric surveys 1986-1999-2003-(2008)-(2010)

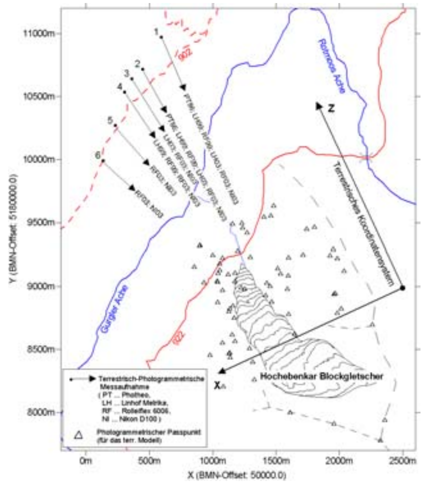
23.9.1986

Photheo 19/1318 (built 1961)	Linhof Metrika	Rolleiflex 6006	Nikon D100 (digital)
190mm-lens	150mm-lens	150mm-lens	50mm-lens

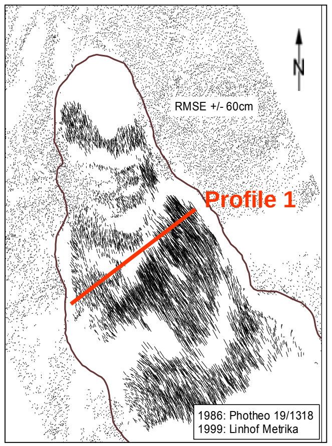
Terrestrial photogrammetric surveys 1986-1999-2003



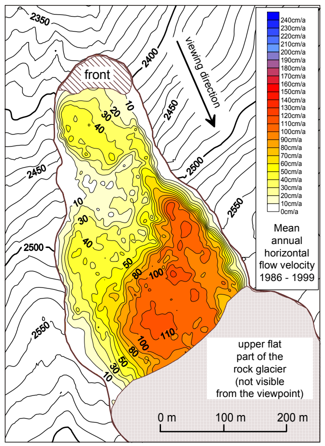
Imaging geometry 1986-1999-2003



Photogrammetric mapping 1986-1999-2003



Gauss-Krüger coordinate system



Ladstädter & Kaufmann (2005)

Mean annual horizontal flow velocity 1986-1999

Computer animation

Flow/creep 1986-1999-2003

Discussion and outlook

- Terrestrial photogrammetry for glacier/rock glacier monitoring only has a promising future if the evaluation of the digital photographs can be fully automated.
- Prototype software is already available.
- Results shown (by other authors) are very promising.
- Project proposal: Environmental monitoring in Alpine regions by means of digital consumer cameras

For further information, please contact:

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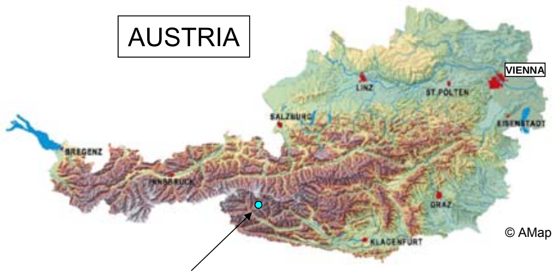
http://www.geoimaging.tugraz.at/viktor.kaufmann/

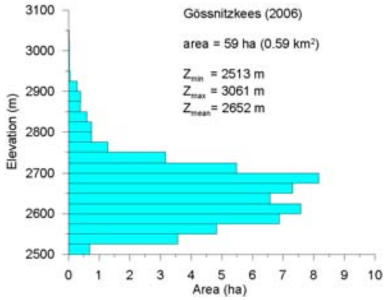
5. An example on glacier monitoring

Study area



Schober group with Gössnitzkees glacier

Gössnitzkees glacier



- A distinct accumulation area for snow and firn is missing.
- Avalanches from couloirs of the headwalls nourish the glacier with snow, ice and rocks.
- Gössnitzkees is to a great extent covered by a thin layer of debris.

Gössnitzkees glacier

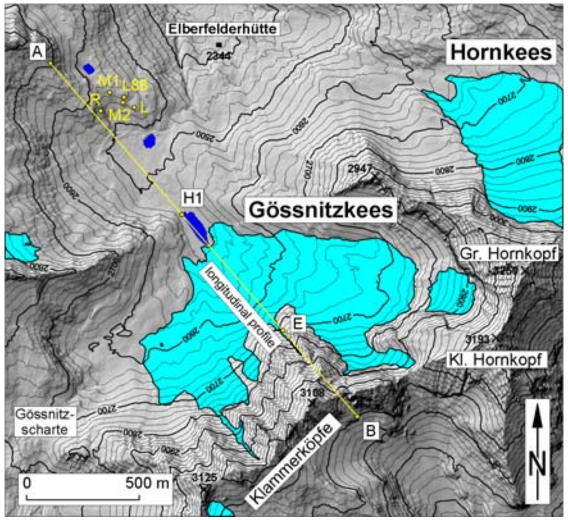
- Two glacier inventories (1969 and 1998) have been compiled for the Austrian Alps.
- The glaciers history (1850-2006) of Gössnitzkees has already been investigated in depth based on old maps, field evidence, and multi-temporal aerial photographs.
- Measurements of glacier length change are carried out annually by volunteers of the Austrian Alpine Club (OeAV) at about 100 Austrian glaciers.
- The volunteers' glacier reports often comprise terrestrial photographs of the glaciers taken from the same positions each year.

1982

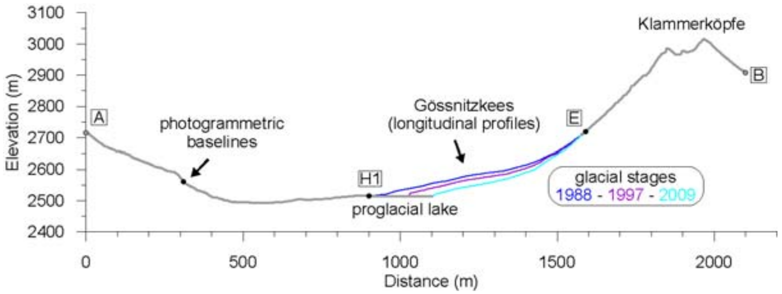
Terrestrial photogrammetric surveys 1988-2009

- The successful application of terrestrial photogrammetry in mountain regions is to a great extent controlled by topography.
- An opposite slope is needed for frontal view of the area of interest.
- Mapping accuracy primarily depends on the baseline-to-distance ratio, image scale, and measuring accuracy of image coordinates.
- Multi-image geometry of convergent photography can be handled by modern digital photogrammetric workstations.
- The first terrestrial photogrammetric survey of Gössnitzkees, conducted in 1988, was done in the classical normal-case geometry using a Zeiss TAL phototheodolite.

Geometric setup



Geometric setup



- Since 1996, a longitudinal profile of Gössnitzkees has been measured annually by means of a total station.
- Ground control points (GCPs) for absolute orientation of the photogrammetric model (2003) were provided in 2003.

Camera systems used

Year	Camera	Type	Sensor
1988	TAL	metric	photographic glass plate
1997	Rolleimetric 6006	semi-metric	film-based
2003 & 2004	Rolleimetric 6006	Semi-metric	film-based
	Nikon D100	non-metric	CCD
2005	Nikon D100	non-metric	CCD
2006	Hasselblad H2D-39	non-metric	CCD
	Nikon D100	non-metric	CCD
2007	Nikon D80	non-metric	CCD
2008	Nikon D300	non-metric	CCD
2009	Nikon D300	non-metric	CCD

Camera systems used


Zeiss TAL phototheodolite


Rolleiflex 6006 réseau camera

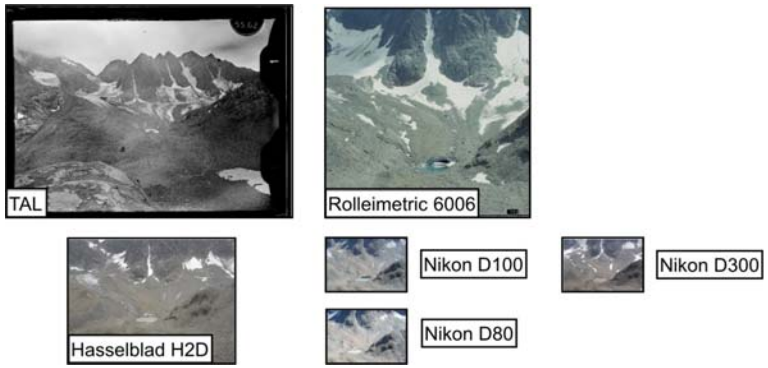

Nikon D100 digital camera


Nikon D80 digital camera


Hasselblad H2D-39 digital camera


Nikon D300 digital camera

Image data used



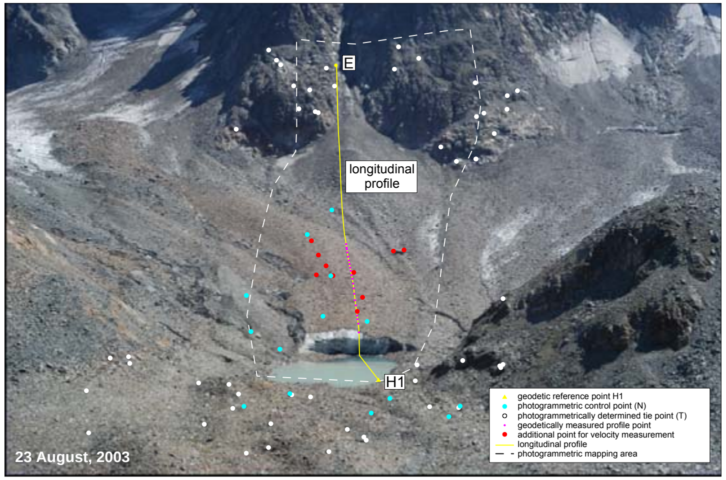
Examples of terrestrial photographs
(all in relative scale)

Photogrammetric evaluation

Before starting with the actual digital photogrammetric evaluation, various pre-processing steps had to be carried out depending on the type of camera used:

- Scanning of the analog photographic data (UltraScan 5000 of Vexcel Imaging Austria)
- Camera calibration of all four digital cameras (planar target of PhotoModeler & 3D test field of Vexcel Imaging Graz)
- Correction for the effect of chromatic aberration (DISTCORR, Nikon Capture, Hasselblad FlexColor)
- Correction of film unflatness and film distortion of the Rollei data
- Computation of distortion-free images with the principal point located in the image center (not mandatory)

Photogrammetric orientation

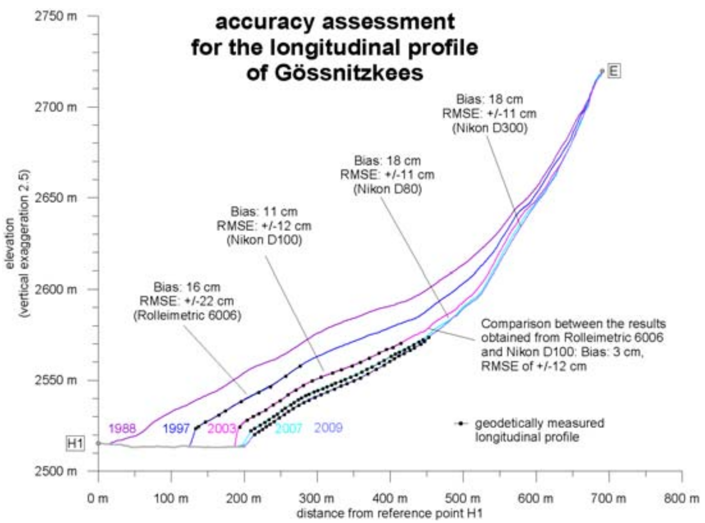


Photogrammetric mapping

- Interactive digital stereocompilation
- 3-dimensional data collection was restricted to the mapping area shown before.
- Regular grid of surface points with a GSD of 5m
- Linear features: terminus position, glacier boundaries, drainage lines, ridge lines.
- Digital elevation models with a grid-spacing of 2.5 m were derived.
- The multi-temporal shorelines of the proglacial lake could not be traced completely due to difficulties in proper 3 D vision.
- Large parallax differences in the near range of the stereomodel

Accuracy assessment

- The accuracy of the DEMs obtained was assessed empirically by (1) comparison with the annual geodetic measurements (1997, 2003-2009) and
(2) by comparison of the DEMs of the same epoch derived from different camera systems.



Documentation of glacier change

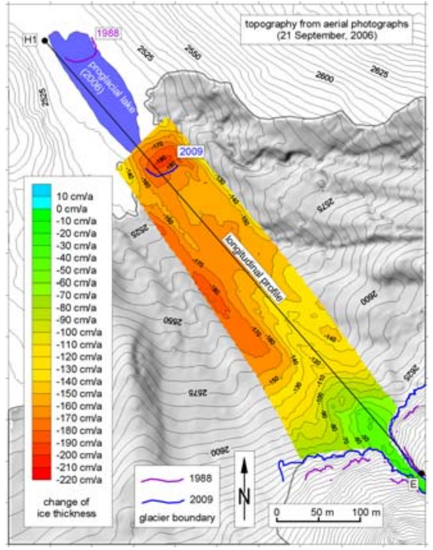
- The change in ice thickness is calculated by subtracting DEMs of different epochs (glacial stages).
- Obvious glacier retreat can also be quantified numerically by calculating the positional change of the glacier terminus and glacier boundaries at the bergschrund.

Change in ice thickness and glacier length change

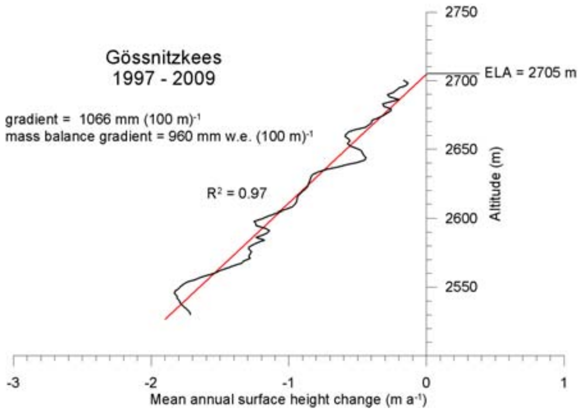
Time period	Mean change in ice thickness^{+}	Glacier length change^{++}
1988-1997	-1.51 m/year	-87.6 m (= -9.7 m/year)
1997-2003 [a]	-2.03 m/year	-60.2 m (= -10.0 m/year)
2003-2007 [b]	-1.52 m/year	-15.9 m (= -4.0 m/year)
2007-2008 [c]	-1.35 m/year	-2.4 m/year
2008-2009 [d]	-1.58 m/year	-2.8 m/year
1988-2009	-1.60 m/year	-167.7 m (= -8.0 m/year)

[a] stereo models of Rolleimetric 6006
[b] stereo models of Nikon D100 and Nikon D80
[c] stereo models of Nikon D80 and Nikon D300
[d] stereo models of Nikon D300
$^{+}$only for the elevation interval 2530-2560 m
$^{++}$measured along the direction of the longitudinal profile

Change in ice thickness of Gössnitzkees for the time period 1988-2009



Estimation of equilibrium line altitude (ELA) for Gössnitzkees (longitudinal profile) for the time period 1997-2009



Discussion

- Mean surface height change of Gössnitzkees can be determined with an accuracy better than ±20 cm/year with all the digital camera systems investigated.
- Assuming a mean annual surface height change (lowering) of about 2 m, a relative measurement error not worse than ±10% can be expected.
- Prerequisites are a good camera calibration and stable ground control points in the proximity of the glacier.
- Surface height measurements of a single epoch will most likely be affected by a systematic offset.

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