PHOTOGRAMMETRIC DETERMINATION OF SPATIO-TEMPORAL VELOCITY FIELDS AT GLACIAR SAN RAFAEL IN THE NORTHERN PATAGONIAN ICEFIELD

Hans-Gerd Maas[1], Danilo Schneider[1], Ellen Schwalbe[1], Gino Casassa[2], Anja Wendt[2]

[1] Dresden University of Technology, Germany – hans-gerd.maas@tu-dresden.de
[2] Centro de Estudios Científicos, Valdivia/Chile

Commission V, WG V/6

KEY WORDS: Terrestrial image sequence processing, glaciology, photogrammetric network

ABSTRACT:

The paper describes an approach to determine spatio-temporal velocity fields at *Glaciar San Rafael* in the Northern Patagonian Icefield by terrestrial image sequence analysis. It discusses image acquisition schemes and concentrates on aspects of glacier surface feature tracking, georeferencing and trajectory precision.

Glaciar San Rafael in the *Northern Patagonian Icefield*, with a length of 51 km and an ice area of 722 km^2, is the lowest latitude tidewater outlet glacier in the world and one of the fastest and most productive glaciers in southern South America in terms of iceberg flux. In a joint project of the TU Dresden and CECS, spatio-temporal velocity fields in the region of the glacier front were determined in a campaign in austral spring of 2009. Monoscopic terrestrial image sequences were recorded with an intervallometer mode high resolution digital camera over several days. In these image sequences, a large number of glacier surface points were tracked by subpixel accuracy feature tracking techniques. Scaling and georeferencing of the trajectories obtained from image space tracking was performed via a multi-station GPS-supported photogrammetric network.

The technique allows for tracking hundreds of glacier surface points at a precision in the order of one decimeter and an almost arbitrarily high temporary resolution. The results show velocities of up to 16 meter per day, which is in accordance with former measurements. A significant tidal signal, as theoretically predicted by other authors, could not be observed. As a by-product, a maximum value of 55 meter could be determined for the glacier front height.

1. INTRODUCTION

Glaciar San Rafael at 46°42′ S / 73°50′ W is one of the major outlet glaciers of the *Northern Patagonian Ice Field* in southern Chile. It is the lowest latitude tidewater outlet glacier in the world. The glacier covers an area of about 722 km^2 (Rivera et al., 2007) and calves into the *Laguna San Rafael* at sea level (Fig. 1), which is connected to the Pacific Ocean via a narrow fjord and channel system. Both the glacier and the laguna belong to the 17,420 km² *Laguna San Rafael National Park*, a UNESCO biosphere reserve 120 km south of *Puerto Chacabuco* with elevations up to 4058 m. The area is very wet with a mean annual precipitation of 4,440 mm during the years 1981-85 at the meteorological station of *Laguna San Rafael*. At higher elevations, precipitation increases to up to 7500 mm per year (Escobar et al., 1992). The glacier is moving at a high velocity and currently retreating.

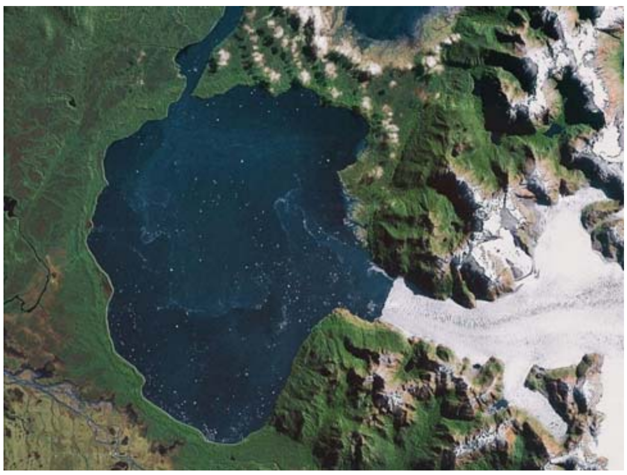

Fig. 1: Glaciar San Rafael and Laguna San Rafael (Google Earth)

Fig. 2: Glaciar San Rafael front seen from the Laguna San Rafael

Since the late 19th century, the glacier front has retreated and advanced rapidly over a total distance of 14 km and is now 60 km^2 smaller than it was 100 years ago (Warren, 1993). A retreat of up to 300 m per year during the 1980s year has been reported, followed by a slight re-advance after 1990 (Aniya et al., 1998). In the past decade, the glacier calving front has been retreating (Rivera et al., 2007; Masiokas et al., 2009) at a steady pace of about 100 linear meters per year, which can also be seen from local markers dating back to 1978.

Several authors have published results of glacier movement velocity measurements. Naruse (1987) performed theodolite triangulation measurements and determined glacier surface velocities of 17 meters per day at the calving front, dropping to 13 meters per day 500 m behind the front. Rignot et al. (1996) present one-dimensional interferometric velocities from NASA's Spaceborne Imaging SAR data obtained during the 1994 Space Shuttle mission. While the precision of these measurements is very high (5 mm per day), interferometric SAR data processing failed in the fast and rugged snowfree region near the calving front. Therefore the velocity field measurements were complemented by (less accurate) feature-tracking results near the calving front. They determined velocities of 2.6 meter per day near the equilibrium-line altitude, increasing to reach 17.5 meter per day at the calving front.

Warren et al. (1995) derived an average thickness of the glacier tongue at the terminus of 200 m from bathymetry data in the lagoon and ice cliff heights. Thomas (2007) predicts a tide-induced variation of the ice-front velocity of 2 cm per hour.

The main goal of the research work presented here was the determination spatio-temporal velocity fields near the calving front with high spatial and temporal resolution. For this purpose, a camera was installed at the northern hillside of the glacier to take image sequences similarly to the implementation shown by Maas et al. (2008). The camera system will be briefly shown in section 2. Glacier surface features were tracked by subpixel accuracy least-squares-matching (section 3). The image space trajectories were scaled to the glacier surface via the results of a GPS-supported multi-station photogrammetric network (section 4). Results are shown in section 5.

2. CAMERA SETUP

Monoscopic terrestrial image sequences were recorded with an intervallometer mode (also referred to as time-lapse mode) high resolution digital camera over several days. The camera was a Nikon D300 with a 4288 x 2848 pixel CMOS sensor, equipped with a 28mm lens which yields an opening angle of 46°. The camera was programmed to take images in 15 minute intervals. The camera was installed on a tribrach which was fixly screwed to the rock. In the ideal case, the camera should be oriented perpendicularly to the glacier motion direction. Due to restrictions posed by the local topography, this perpendicularity could not perfectly be achieved when aspiring maximum glacier coverage of the camera field of view. This deviation from perpendicularity (26.5°) has to be regarded when deriving actual glacier motion velocities from image space measurements. Some fiducials in the image foreground were used to allow for a compensation of possible camera movements, which cannot be completely avoided due to the plastic body of the camera. The image sequences were recorded in March/April 2009.

Basically, determining 3D glacier surface feature trajectories would require a stereoscopic camera setup. In our implementation, a monoscopic setup was preferred over a stereoscopic setup for several reasons: The main reason for avoiding stereo was the extremely rugged glacier surface (**Fig. 3**), which made it very difficult to determine homologous points in stereo views, either interactively or automatically by applying image matching techniques. A stereo baseline would have to be in the order of 500 to 1000 meter to obtain a good stereo ray intersection warranting a good precision in all three coordinate components of the glacier surface feature trajectories. At this baselength, it was in most cases impossible to detect homologous points in the images. Moreover, local topographic constraints hampered stereo setups with reasonable intersection geometry. Therefore we decided to go with a monoscopic setup and to determine 2D glacier surface feature trajectories in a plane perpendicular to the camera viewing direction, corrected by projection effects caused by the non-perpendicular viewing direction. This 2D approach is also justified by the fact that there will usually be no significant across track components in the glacier motion field. The monoscopic setup necessitates the determination of a scale factor for each image space trajectory, which is outlined in section 4.

3. GLACIER SURFACE FEATURE TRACKING

Fig. 3 shows one image out of an image sequence. In these image sequences, a large number of glacier surface points can be tracked by subpixel accuracy feature tracking techniques. We used least-squares-matching (LSM) to establish correspondences between surface patches in consecutive images. LSM applies 2 to 6 parameters of an affine transformation between two image patches to minimize the sum of the squares of greyvalue differences. It will usually converge to the correct solution in a few iterations. The analysis of the LSM covariance matrix allows deriving an estimate on the translation vector precision. Under good circumstances, LSM may deliver a precision of $^1/_{50}$ pixel or even better. With the rugged glacier surface and varying illumination conditions, though, the precision will often be significantly worse than this.

Fig. 3: Glacier surface image section for feature tracking

To be able to correct the image space trajectories for possible camera movement effects, some fiducials in the image foreground were tracked using the same technique. Camera movements of up to 0.7 pixel were detected and applied to correct the trajectories.

4. TRAJECTORY GEOREFERENCING

The monoscopic image space trajectories have to be scaled to the glacier surface in order to determine glacier velocities. The glacier surface shows large height differences and a temporary changing elevation model, and the camera images represent a rather oblique view onto the glacier surface. As a consequence, there are strong variations in the image scale, introduced by both projective and perspective effects. This necessitates the determination of an individual scale factor for each tracked glacier point in order to translate its trajectory from image space to the glacier surface.

This task was accomplished by establishing a GPS-supported multi-station photogrammetric network. A total of 5 images were taken from locations along the northern hillside (**Fig. 4**). As the glacier surface and the southern hillside were inaccessible, no control points for georeferencing (or at least scaling) the network could be established. Instead, the coordinates of the 5 camera projection centers were determined by GPS. With a non-linear arrangement of the 5 projection centers (**Fig. 4**), this basically allows for a full geo-referencing of the photogrammetric network, though at a poor error propagation especially in the vertical coordinate direction. Therefore, additionally some visible points along the waterline of the fjord (representing sea level) were measured to support the georeferencing.

Fig. 4: Multi-station photogrammetric network configuration

Summing up, the bundle adjustment of the photogrammetric network was based on the following information:

- Image coordinates of glacier surface points (those points which were tracked in the image sequences), used as tie points.
- Further tie points on the southern hillside.
- Water level points introduced as height control points.
- GPS measurements of the camera projection centers.
- Camera pre-calibration parameters.

An automatic determination of homologous points in glacier surface images from different views turned out to be impossible as a consequence of the extremely rugged surface pattern. Therefore the tie point coordinates were measured in Photomodeler for convenience. The further processing in Photomodeler was constrained by the limited datum definition options in the program. Moreover, the bundle adjustment in Photomodeler turned out to deliver rather instable results. Therefore the measurements were imported to our own bundle adjustment software package (Schneider and Maas, 2007). The standard deviation of unit weight produced by the bundle adjustment was 1.3 pixel, which corresponds to the expectations considering the manual tie point measurements and the interpretation difficulties. Due to the network configuration, the glacier surface point standard deviation depends on the distance of the points from the camera base, increasing approximately with the square of the distance. On average, a standard deviation of 3.3 / 4.3 / 0.4 meter was obtained for the X/Y/Z coordinates of the glacier surface points, with the camera viewing direction approximately in the Y-direction. The better value in the Z-direction can be explained by the water level height control points. As the results of the bundle adjustment are only used for scaling the image space trajectories, the obtained accuracy is more than sufficient.

Scaling information for each glacier surface point can be derived from its 3D coordinates and the camera parameters. These scale factors can then be used to translate the glacier surface point trajectories from image space to the glacier surface. Errors from the bundle adjustment will propagate as a linear scale factor into the trajectories. From the results of the bundle adjustment, an average scale error of 0.4 % can be estimated.

5. RESULTS

Some glacier surface point trajectories obtained from the data processing chain as outlined in the previous sections are shown in **Fig. 5**. The maximum movement of points close to the glacier front was 16 meter per day, dropping to 6-7 meter per day some 800 meter behind the glacier front.

One camera pixel corresponds to 20 cm on the glacier surface at a distance of 1000 meter. The least squares tracking procedure yielded translation parameter standard deviations between 0.004 pixel and 0.08 pixel with an rms of 0.015 pixel. Due to the fact that least squares matching is using signals with stochastic properties on both sides of the observation equation, these results can usually be considered too optimistic. Nevertheless, the pure image tracking contribution to the individual trajectory link is in the centimeter-range. The error accumulates with the square-root of the number of trajectory links (with a typical trajectory length of 51 frames). In addition, as outlined in section 4, the trajectory georeferencing scale error has to be considered. The scale error depends on the distance of the glacier surface point to the camera and the number or rays in the photogrammetric network (2 to 5) and is between 0.3% and 1.6% of the trajectory length. Summing up, a well trackable glacier surface point situated in the middle of the glacier close to the glacier front will have a trajectory length standard deviation in the order of 10-20 cm, corresponding to about 1% of the trajectory length.

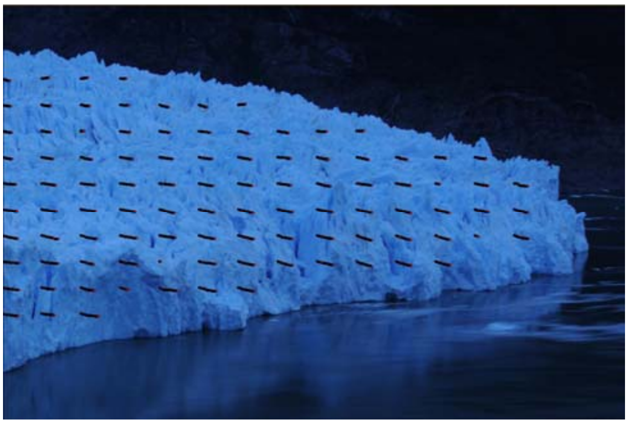

Fig. 5: Glacier surface point tracking results

Thomas (2007) predicted a tide-induced variation of the ice-front velocity of 2 cm per hour, which is about 3% of the average velocity. In a data capture and processing scheme which was similar to the one shown in this paper, Maas et al. (2008) were able to show clearly significant tide effects in the vertical component of glacier surface points of *Jacobshavn Isbræ* Glacier in West Greenland. The accuracy as estimated above should be large enough to unveil these tide-induced motion effects. Nevertheless, in the results of our *Glaciar San Rafael* image sequence processing, no significant tide-induced effects, neither in movement velocity nor in the vertical component of the glacier tongue motion, could be detected.

As a by-product, the photogrammetric network also allows to determine the glacier front height. Here, heights of up to 55 meter could be measured.

6. CONCLUSION

Monoscopic terrestrial high resolution image sequence processing may be a powerful tool to determine spatio-temporal velocity fields on fast moving glaciers. With subpixel precision image analysis and proper georeferencing by a GPS-supported multi-station photogrammetric network, a high glacier surface point trajectory precision can be obtained. For *Glaciar San Rafael* in the Northern Patagonian Icefield, velocities up to 16 meter per day in the region of the calving front were determined in a measurement campaign in March/April 2009. While the temporal resolution and accuracy of the method is high enough to resolve small tide-induced variations in the trajectories, no such effects could be detected at Glaciar San Rafael.

ACKNOWLEDGEMENT:

The research work presented in this paper is the result of a joint project of the CECS in Valdivia, Chile, and TU Dresden, Germany. It was partly funded by the Chilean *Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT)* and the *International Bureau* of the German *Federal Ministry of Education and Research (BMBF)*. The permit of *Conaf (Corporación Nacional Forestal)* Chile and the support of their local rangers are also greatly acknowledged. Last not least we would also to thank Eliana Chong and Stephanie Joyce, who supported us in a rainy field campaign at *Glaciar San Rafael*.

The joint research project was initiated by Dr. Jens Wendt. Jens Wendt died in a plane crash one week after our measurements at *Glaciar San Rafael* when returning from a laserscanner survey flight to the Nevados de Chillan. This paper is devoted to his commemoration.

7. REFERENCES

- Aniya, M., Naruse, R., Casassa, G., Rivera, A. 1999: Variations of Patagonian glaciers, South America, utilizing RADARSAT images. Proceedings of the International Symposium on RADARSAT Application Development and Research Opportunity (ADRO), Montreal, Canada, 13-15 October 1998
- Escobar, F., Vidal, F., Garin, C., Naruse, R., 1992: Water balance in the Patagonia Icefield. Glaciological researches in Patagonia, Japanese Society of Snow and Ice, Data Center for Glacier Research (Eds. Naruse, R., Aniya, M.), pp. 109-119
- Maas, H.-G., Schwalbe, E., Dietrich, R., Bässler, M., Ewert, H., 2008: Determination of spatio-temporal velocity fields on glaciers in West-Greenland by terrestrial image sequence analysis. IAPRS Vol. XXXVII, Part B8, pp. 1419-1424
- Masiokas, M., Rivera, A., Espizua, L., Villalba, R., Delgada, S., Aravena, J., 2009: Glacier fluctuations in extratropical South America during the past 1000 years. Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 281, pp. 242–268
- Naruse, R., 1987: Characteristics of Velocity Distribution in Patagonian Glaciers. Geophysical BulIetin of Hokkaido

University, Sapporo, No. 49, pp. 211-219

- Rignot, E., Forster, R., Isacks, B., 1996: Interferometric radar observations of Glaciar San Rafael, Chile. Journal of Glaciology, Volume 42 (No. 141), pp. 279-291
- Rivera, A., Benham, T., Casassa, G., Bamber, J., Dowdeswell, J., 2007: Ice elevation and areal changes of glaciers from the Northern Patagonia Icefield, Chile. Global and Planetary Change (2006)
- Schneider, D., Maas, H.-G., 2007: Integrated Bundle Adjustment of Terrestrial Laser Scanner Data and Image Data with Variance Component Estimation. The Photogrammetric Journal of Finland, Volume 20/2007, pp. 5 - 15
- Thomas, R., 2007: Tide-induced perturbations of glacier velocities. Global and Planetary Change, Volume 59, pp. 217-224
- Warren, C., 1993: Rapid recent fluctuations of the calving San Rafael Glacier, Chilean Patagonia: Climatic or non-climatic? Geografiska Annaler 75A (3), pp. 111-125
- Warren, C., Glasser, N., Harrison, S., Winchester, V., Kerr, A., Rivera, A., 1995: Characteristics of tide-water calving at Glaciar San Rafael, Chile. J. Glaciol. 41, pp. 273-289