GLACIER MONITORING SURVEY FLIGHTS BELOW CLOUDS IN ALASKA: OBLIQUE AERIAL PHOTOGRAPHY UTILISING DIGITAL MULTIPLE-IMAGE PHOTOGRAMMETRY TO COPE WITH ADVERSE WEATHER

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ABSTRACT

Contrary to the standard aerial survey methods, oblique aerial photography from relatively low altitudes can often be accomplished when weather conditions preclude traditional vertical aerial stereo-photography. Therefore, a close range digital multiple-image-photogrammetry (convergent or multi-image-photogrammetry with 100% image overlap) method can be used for aerial surveys even when weather would prevent standard survey flights. The combination of a Rollei6008metric survey camera and the *Polarphox* photogrammetric software facilitates the measurement of changes in the ice volume of glacier ablation zones and other geomorphic features of mountain areas. A small single engine airplane with far less operational costs than the normal aerial survey airplane is ideally suited for this. A current project of the University of Göttingen will analyse ice volume changes on several glaciers in south-central Alaska. Recently, most glaciers of the region showed a significant retreat and loss of substance, which is being documented in this project. A modern digital multiple-image-photogrammetry system is used to process the imagery. Similar to stereo-vertical imagery, automated surface measurements are possible. However, photogrammetric analysis of a surface is limited in the same way traditional stereo-photo analysis is limited by a lack of identifiable features on the target. Naturally, fresh unbroken snow surfaces in the accumulation areas of glaciers cannot be measured. This paper tries to point out the advantages and limitations to this new method.

Keywords: Glacier monitoring, oblique aerial photography, digital multiple-image photogrammetry.

INTRODUCTION

Weather conditions are a limiting factor for aerial survey flights, and waiting for favourable weather can cost too much time and money in some circumstances, especially in survey areas which are often cloudy (1,2). In most cases the optical sensors of satellites have the very same problem, since any cloud cover, even if very high based, does affect them. In the case of this study of south-central Alaska's glaciers, located in the coastal mountain ranges under an oceanic climate regime, an innovative aerial survey method that can deal with adverse conditions regarding weather and terrain was applied (3). Conditions in this climate regime often prevent vertical stereo-image survey flights, flown at a high altitude above the ridges and peaks of the terrain because of cloud cover and turbulence. Modern camera mounts have improved the situation with wind and turbulence somewhat (1), but not to an extent that makes a difference in this operational scenario. The glaciers and ablation areas studied here are separate targets with limited surface areas, so they can be surveyed with not too many multiple image clusters (3). Additionally, it is comparatively cheap regarding the equipment requirements and extraordinarily cheap regarding the "platform", a small single engine airplane (1). Thus, a real world alternative system was developed and tested for survey flights with limited financial resources that focus on smaller target areas under cloud cover (3).

The past decades have shown a significant retreat of glaciers and seasonal sea ice boundaries, along with changes to permafrost and vegetation zones, in especially Alaska. Still, there are some glaciers that are advancing. The complex of those observed changes may very well be related to those phenomena known as *global climate change* (4). Many studies have focused on this in recent years, employing a large variety of methods (5). Since the weather and climatic change produces geomorphologic changes and effects, especially in high mountain terrain and the arctic and sub-arctic latitudes, these areas have been getting into focus. Many previously uninhabited high mountain areas all over the world are under use now. In these areas the changes are often observed as an increase in the occurrence of natural hazards. Thus, there is a great motivation to study the geomorphology of those areas, and due to the idiosyncrasies of nature in these areas, there is a need for innovative survey techniques (1,3,6). With a financially feasible, innovative method that fits right into this "niche" of special survey needs, the survey possibilities could be significantly extended with the given (often shrinking) resources. This photogrammetric analysis of convergent oblique aerial photography for documenting glacier volume changes is still in its early stages, the funding for it started in August 2003 and the software designed to measure surfaces automatically is also still under construction and was made available for this study in early 2004. The software, as used in this project, provides réseau cross identification, image rectification, camera calibration, bundle adjustment, manual and automated (least squares matching) surface measurements. It got operational in January 2005. Since the project ends in January 2007, final results with a real error analysis are not yet completed.

Study area

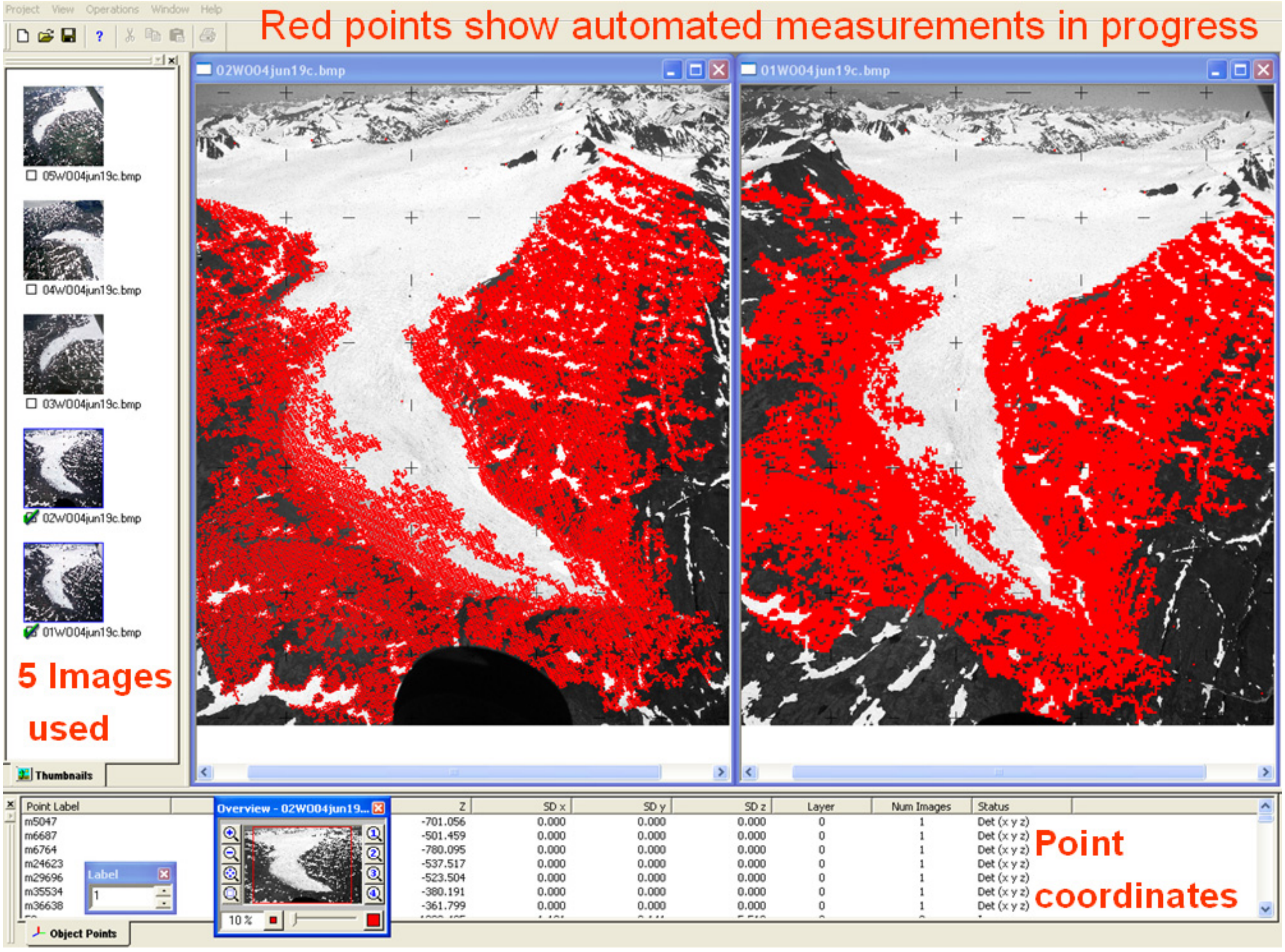
The project investigates the areas under the snow line of several Alaskan glaciers: The USGS benchmark Wolverine Glacier (5), and the Knik (7), Lake George and Colony Glaciers (2). All of them are located in the Chugiak Mountains of south-central Alaska, the last three in the Knik area north-east of Anchorage, while the Wolverine Glacier is located in the eastern Kenai peninsula, which has an even more oceanic climate with extremely high winter precipitation (5).

The Knik Glacier got infamous in the past, because it is responsible for creating one of the largest ice dammed lakes in Alaska (8) and has regularly been triggering dangerous GLOF's (Glacier Lake Outburst Floods) which destroyed the railroad and road connections to Anchorage, Alaska's largest city (7). This happened last in 1966, but a small advance of the Knik Glacier's front could trigger it again (9).

METHODS

Aerial survey pictures of the studied glaciers are taken twice a year, during spring after snowmelt and in the autumn before the first snowfall. At the same time, fieldwork on the ground is done to create GCP's (Ground-Control-Points) in order to be able to set positions, level, altitude and scale to the digital models using the photogrammetric measurements. The GCP's are either recognisable features on rock outcrops or painted markers on rock surfaces or aluminium foil coated rocks set together on tundra surfaces (3). They are identifiable in the imagery and are surveyed with DGPS, tachymeter and triangulation and laser distance measurement equipment. The GCP's used at the Wolverine Glacier are the most accurately surveyed points in the project. They are ideal to evaluate the accuracy of the aerial oblique multiple-image-photogrammetry system that is employed here (Figure 1) (5).

In general terms, the aerial multiple-image-photogrammetry survey of a target object works as follows: Ideally starting out from a high position vertically above the object (if weather/cloud base permits), the light aircraft that is used as the camera platform performs a gradual downward spiral, orbiting the object. All the time pictures are taken of the object with a hand-held medium format Rollei6008metric survey camera out of the open window of the aircraft. A large number of pictures, from any direction, including vertical, if desired, are thus created. This allows for the certain possibility to select the best geometric configuration of images for the multiple-image swathe of the target. The lattice model of photogrammetric measurements gets to be especially accurate due to the higher number of images used for every measurement (10). Depending on the shape of the target, images from all sides are not even always necessary. If the target structure is simple enough, only four pictures from two sides of it may be enough for accurate measurements provided every piece of surface can be seen in at least three pictures (with convergent photogrammetry this is considered the minimum number for measurements) and the angles of the pictures aiming at the target are about 30° apart from each other. Therefore, this method is less affected by weather and low cloud base (3). If any vertical pictures cannot be taken due to weather, the multiple-image-photogrammetry still works (2). The camera is a 6×6 centimetre medium format with a réseau plate that creates a grid on commonly available film (11). The software réseau "transforms" the digitally scanned photograph ensuring that the digital image is restored to the exact proportions it had when the photographic exposure was made. This digital rectifying produces a more precise rendering of features on the image. It is employed where the traditional vacuum-plate flattening of film used in large format survey cameras is impractical. Obviously, the réseau grid cannot be removed from the image (11). The use of modern digital survey cameras would obliterate the whole problem of image rectifying and the undesirable réseau grid in the images, but at this point in time the highest resolution available with a digital survey camera suitable for this special (often very cold weather) application is 21 Megapixels, at a camera price of 65,000 Euros. The slide film camera Rollei6008metric was a more affordable solution providing images of about 80 Megapixel size with the use of the latest scanner technology. It also works reliably at altitude in Alaska and -38°C. The use of a camera with lower resolution would force the use of a quadrupled number of images to obtain the same accuracy, leading to unmanageable increase in manual photogrammetry work.



Point Label	Z	SD x	SD y	SD z	Layer	Num Images	Status
m5047	-701.056	0.000	0.000	0.000	0	1	Det (x y z)
m6687	-501.459	0.000	0.000	0.000	0	1	Det (x y z)
m6764	-780.095	0.000	0.000	0.000	0	1	Det (x y z)
m24623	-537.517	0.000	0.000	0.000	0	1	Det (x y z)
m29696	-523.504	0.000	0.000	0.000	0	1	Det (x y z)
m35534	-380.191	0.000	0.000	0.000	0	1	Det (x y z)
m36638	-361.799	0.000	0.000	0.000	0	1	Det (x y z)

Figure 1: Images of Wolverine Glacier in June 2004, shown in Polarphox *software while automated matching process is underway. If completed all surfaces of the target with identifiable features would be depicted with red measurement points. The fresh snow patches on the areas around the glacier are not covered, since they are only white and featureless.*

In the processing, common natural points (tie points, Gruber points), which can be identified with high accuracy on the target surface, are used for tying the multi-image compositions together (2,3). With the points marked, the multiple-image orientation is the next step. Then the camera positions are known relative to each other. With the knowledge of the position of at least three points on the target surface the system orientation is done, which produces the scale and the level as well as the geographical coordinates to every measurement. Then the camera positions can also be identified with very good approximate positions. Following these work steps, every optically identifiable point visible in three pictures of the multiple image composition can be measured with three-dimensional accuracy (10). The software used in this study is able to automatically generate surfaces from a minimum of three oblique images (photogrammetrically overdetermined) and can measure the position of points with equivalent accuracy compared to a stereophotogrammetry system (see Figure 1) (3).

Comparison of the resulting surface models of different dates in order to quantify the volume and surface changes of the studied glacier termini is the main method of this study. The generated data is to be used for local climate studies, which incorporate all available weather station data and the on-site geodetic field measurements of USGS at the Wolverine Glacier. The monitoring of the Knik Glacier since 1998 with different 8 DEM's of the various seasons is done to study the recent natural hazard potential of this GLOF source (2). With the various multitemporal DEM of the glaciers ablation areas the changes are to be quantified and the trend analysed. With most of these glaciers the trend in their changes can only be measured when the whole terminus surface is taken into account and measured. Especially on the Wolverine glacier, there is no change visible from plain observation, the extent of the terminus does not change in the comparatively short observation period (5). The height of the glacier tongue changes, however, this can only be measured but not directly observed.

Survey Flights

During the many aerial survey flights completed so far the idea of oblique aerial photogrammetry to deal with adverse weather has worked out very reasonably, since low ceilings (cloud base) are the major factor of the weather condition. Those problems are easily addressed by orbiting the target area from lower altitudes, those being far lower altitudes than necessary for any kind of vertical stereo-photogrammetry activity. Experience has shown that weather conditions that allow getting to and orbiting the target area are good enough for taking the pictures, if the light conditions are favourable. The light conditions desirable for mountain flying are usually good enough for photography, too. Of course, light conditions are a limiting factor in any photographic survey activity, so in the way of comparison this is no factor. The only factor that could be argued in this case, is the necessity for quite high shutter speeds with the camera, to achieve a good clear picture, with the minimum of image blur that occurs due to the movement of the aircraft. Since the aircraft in use can fly very slowly (down to 25 knots), this tends to be no significant problem. Due to this fact no IMC (Image Motion Compensation) is necessary and even small targets that require high accuracy can be surveyed from very short distances. Consideration and calculations with the definition of an acceptable image blur can be found in the literature (1) and have to be taken into account especially in this application. Even in the northern latitude of Alaska in the late autumn the amount of light available was always enough for the 100ASA and 64ASA slide film used (2).

Turbulence during the survey flights tends to be a more important factor, especially since turbulence can make otherwise perfect days unusable. This is, of course, especially true in a high mountain environment as an operation area. In this kind of survey flight the factor is not so much the turbulence disabling the aiming of photos, its more about the big impact the turbulence has on the technical aspect of the slow flight part of the survey. It too much compromises safety considerations to try to operate an airplane in a very pronounced slow flight configuration in very close proximity to the terrain (mountains). This factor gets to be a concern before it leads to problems regarding the aiming of the camera from the airplane (2). A lot of emphasis has to be put on the fact that the images can only be used with the multiple-image photogrammetry, if the angles between the images are within the given physical limits; just plain oblique aerial photos of the area cannot be used. Two main reasons exist for the use of oblique imagery, firstly the significant reduction in necessary flight altitude (resulting in flying under the clouds) and secondly, the ideal perspective of the images for measuring objects on steep mountain slopes (resulting in vertical images of a steeply inclined surface).

Since 1998 by far most of the survey flights of this project have been successfully completed in weather conditions that would have prevented any vertical aerial stereo-photo survey.

Field Work

Due to the nature of south-central Alaska this survey/fieldwork schedule poses its own set of problems: In the autumn early snowfalls, that are very difficult to predict, always threaten to cover up the glaciers and the GCP's while waiting for better weather to do the survey flights or the field work. Snowbanks that survived the initial snowmelt in the spring can also be a problem when they cover GCP markers. Since snow deposition and accumulation are greatly varied with wind and terrain influence, their influence is substantial and difficult to predict. The fieldwork on the Knik-, Colony and Lake George areas is more critical, since it is generally done without helicopter, using the "normal Alaskan bushplane", landing on gravel bars along the rivers (Figure 2) and sandbars in the now empty glacier lakes.

Figure 2: Despite the terrain and weather, up to this point the fieldwork has been successful and all planned GCP's have been installed and surveyed. In this project with very limited resources, all field work is done by the project scientist/first author, who also acts as the sole aerial survey pilot.

The fieldwork using the bushplanes with short field takeoff and landing (STOL) abilities is naturally highly influenced by weather and the conditions at the landing areas, which can be too soft to land (or take off again) when it rained in the area recently. This effect led to a significant problem during one landing in the dry lakebed of Upper Lake George in the past, when the aircraft could not be stopped at the landing and ended up damaged in the creek at the end of the usable area. The very cold rivers in the area are generally too deep and too swift to be crossed, they usually carry drifting glacier ice debris, too. This set of problems prompted the use of a private floatplane on the surface of Lake George, which is the moraine dammed lake of the calving front of the Colony Glacier. With the many icebergs and ice debris in the very silty waters of the lake, this method is considered too dangerous to be repeated. The set of problems like this clearly shows why almost all commercial survey activities rely completely on helicopters, and thus avoid most of the time-consuming adverse situations. With the given funding, and the objectives at hand, this was not an option.

RESULTS AND DISCUSSION

Preliminary results of the Photogrammetric Processing

Successful automated surface measurements with the multiple-image-photogrammetry software *Polarphox* were so far conducted for five different surveys (multitemporal) of the Wolverine Glacier, one of the Colony Glacier and one for a rock glacier. In general, the measurements worked satisfactorily, covering the whole ablation area of the targeted glaciers. The results were found to depend distinctively on the quality of the scans being used and on the selection of the right patch size for the matching process, depending on the natural size and scale depiction of the surface features to be measured on the glacier surface. Naturally, areas with insufficient surface features, like fresh snowdrifts on the glacier terminus, cannot be measured. But the findings show the measurements to extend to the outermost perimeter of recognizable features, which is very satisfactory (Figure 4). Cloud shadows going over the glacier in high winds still pose a problem, similar dark shadows of mountains on the ice. Most of those problems can be countered by the use of enough pictures to get the ideal perspectives and by selecting the right time of the day. Very few glaciers are so smooth on their surface below the firnline that points are difficult to measure (2). The higher the rate of debris coverage is, the easier the measurements are, because the debris provides identifiable features. This makes the Wolverine Glacier the most difficult target, since it has no medial or upper moraine or debris coverage whatsoever, and its surfaces of the terminus are characterised by the runoff of surface water due to its steepness. This creates line features in contrast point features which are easier to measure and are more prominent on the other glaciers.

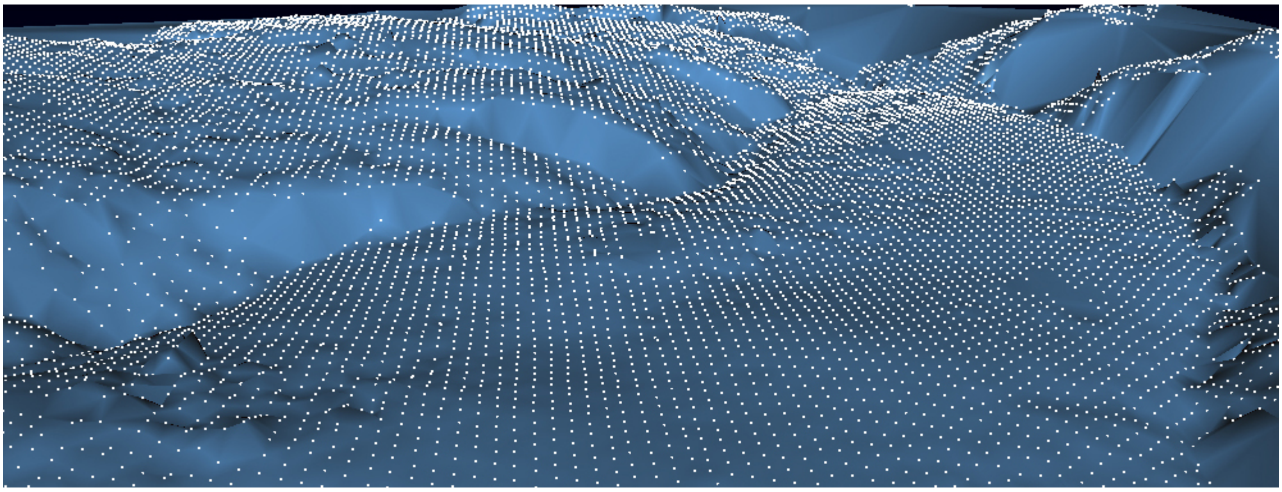


Figure 3: Uncorrected DEM of the Wolverine Glacier surface, with point measurements shown. The Réseau-crosses reappear on the glacier surface, because they have to be masked out on the images for the automated grey-scale-differences matching process. Apart from that, the depiction of the surface itself is very realistic.

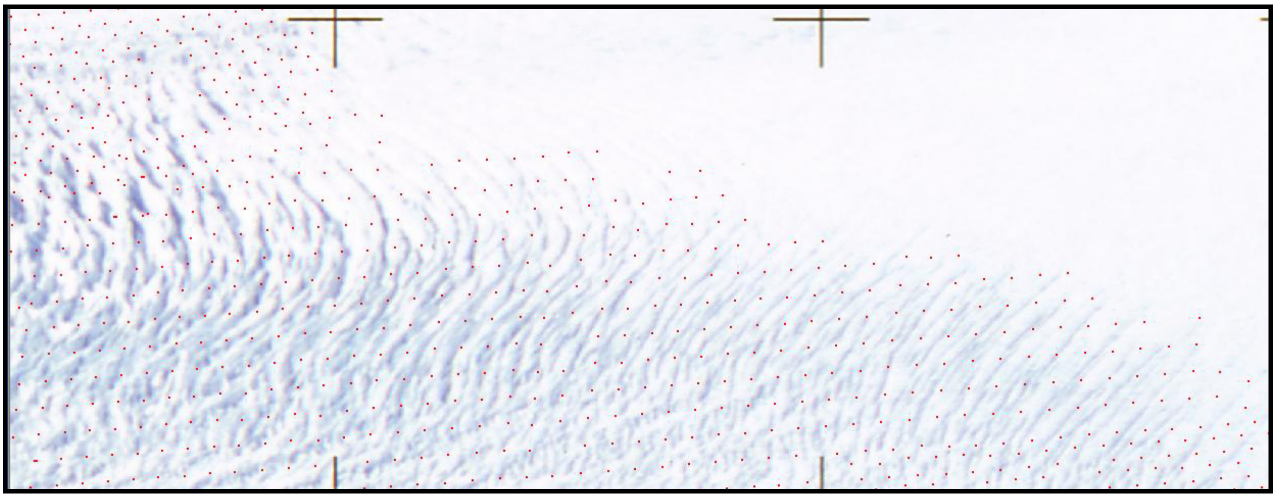


Figure 4: A fraction of the surface of Wolverine Glacier in the Polarphox *photogrammetry software, after automated surface point measurements. The extent of the red measurement points shows the satisfactory use of available surface features and the inherent problem with fresh snow cover.*

A Comparison with lidar and InSAR

Due to the nature of this study, a brief comparison with other methods in use in this field of remote sensing and glacier and snow surface measurements appears appropriate.

In the past years, this field of work has seen the introduction of several new survey techniques, and this method should be put in context with them, especially from the financial and practical standpoint. The use of the SAR and InSAR satellite data in this field of work, with the high mountain environment, seems to be related to a lot of inherent problems. Radar penetration into a snow surface is difficult to quantify, because it depends on moisture content and results in the imaging of a measured surface below the real snow surface. With both these methods large areas can be densely sampled with very high relative accuracy at relatively low cost, after high initial costs of the equipment. Changes in snow-moisture content, melting, fresh snowfall and snow creep can all lead to loss of interferometric coherence, while steep terrain produces radar shadow, image distortion and layover, resulting in lost data. This is also limiting the availability of useful ground control points. Therefore, the control of the survey often consists entirely on DGPS/INS. Airborne (aircraft based) SAR and InSAR can work without the terrain radar shadow, if the flightpath can be set up accordingly. This is a major advantage, but the availability and cost of the airborne SAR is very high.

The initial expense of about 50 000 USD for the complete multiple-image-photogrammetry system compares with much higher initial costs for a lidar (12). The expense and the low availability of airborne laser scanning (lidar: light detection and ranging) systems, combined with the operational technical (platform) problems to employ them, often prevents a widespread use. Also, the systems seem to be extremely intolerant of the usual aircraft landing forces, since they have to be reset and serviced after most landings, which is expensive and time-consuming. With lidar the content of moisture in the air seems to be a very limiting factor, since even moisture content below the visible level, or any haze, will prevent gathering of data (12). Also, with laser technology, wet ice, which is a widespread phenomenon on coastal glaciers, tends to create a heavy backscatter and rough signal. But, specific limitations apply to any photogrammetric topographic mapping of snow-covered glaciers within steep mountain terrain (3,13,14).

Compared to the two techniques discussed above, modern airborne photogrammetry (both stereo- and convergent/multi-image) is a cheap, flexible and easily controlled option, especially with the recent software and DGPS developments. Modern convergent photogrammetry is a very competitive method, especially due to the operational flexibility it gives the researcher in the field while acquiring the pictures. There was no such flexibility before the digital photogrammetric tools had been developed. Today, photogrammetry can work and automatically measure points despite unknown camera positions and convergent oblique aerial photos, without straight flightlines, using near 100% image overlap and ideal convergence angles. This technological change makes the use of small (or medium) format survey cameras for mapping of limited sized areas a competitive option, a method impossible until recently (1,3,10).

The inherent problem of photogrammetry cannot be countered, of course if there are no surface features because of fresh, white snow, no measurements are possible. Especially with glaciers as the target of the study, this factor is very significant. Hence, it seems a combination approach of lidar data for the dry and snowy areas above firnline, combined with photogrammetry at the wet terminus of the glacier, would yield the ideal results. In the area around the equilibrium line of the glacier where both systems start to encounter their difficulties, the combination of the data would allow for both cross-evaluation of the methods and denser measurements. If good lidar data is available (technically and financially), it is an impressive method with comparatively less post-processing than necessary in case of aerial multiple-image-photogrammetry, which can require many time-consuming manual measurements. Government subsidising is often the only reason for financially competitive lidar data sets. If this is not the case, aerial multiple-image photogrammetry can be the affordable solution to gain data about a given natural surface.

CONCLUSIONS

Multiple-image photogrammetric analysis of digitised analogue hand-held oblique aerial photography exposed from relatively low-flying light aircraft reduces many of the traditional restrictions imposed by vertical aerial photography. For example, the aircraft is not required to achieve a specific altitude as defined by scale, lens focal length, and ground coverage. Instead, the aircraft is free to orbit the target area and can also closely approach important targets to increase accuracy, depending on requirements. This method significantly reduces the weather requirements for the survey flight. The recent results clearly show the possibility of an aerial application of digital multiple-image photogrammetry *with* automated surface measurements, which are based on matching algorithm and grey-scale differences in a search patch. With the use of a medium format camera for aerial surveys, the highest available scan quality with low image noise is necessary. Consumer product type scanners have proven unsatisfactory. The general reasoning for use of oblique imagery for detailed evaluations in high mountain terrain (2,3,6) appears as a valid method, especially with its possible use despite adverse weather. The remaining question is, whether the automated surface measurements can produce an accurate surface model *over the full extent of the whole target area* under these special conditions. For many earth science studies in remote or unsurveyed areas this approach should open up new possibilities of making use of otherwise unattractive aerial surveys. The low cost and enhanced adverse weather ability should be significant enough to get access to data that would not be attainable otherwise. Adding positioning data from a differential global positioning receiver and mounting an inertial navigation system to the survey camera may eliminate the need for establishing ground control points in the target area in the near future. The aerial use of Convergent-Multi-Image Photogrammetry can be a cheap and flexible option, too, but certainly so only if the area to be surveyed is comparatively small. As soon as a high number of image bundles is necessary, the workload and the cost of the needed manual photogrammetry work outgrows its usefulness. A smaller glacier, a volcano, a mountain or an open pit mine are suitable targets for the aerial use of convergent photogrammetry, but with large acreage targets like counties, cities, states or whole mountain ranges all other methods are more reasonable approaches.

ACKNOWLEDGEMENTS

We want to express our special thanks to numerous private individuals in Alaska, who helped with the fieldwork; and to USGS for their assistance; furthermore, to the Deutsche Forschungsgemeinschaft for funding this project.

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