HANDHELD MOBILE MAPPING SYSTEM FOR HELICOPTER-BASED AVALANCHE MONITORING

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Key Words: Photogrammetry, Navigation, Handheld, GPS, IMU, Avalanche mapping.

ABSTRACT

The study of avalanches requires techniques that can provide accurate and sporadic geo-referenced data. When facing difficult accessibility of the terrain and large mapping areas, the aerial photogrammetry offers the best solution to this problem. Nevertheless, in this specific domain, the classical photogrammetry reaches its limits when volumes of snow are the parameters to be determined. The difficulties of installing durable signalization in such areas initiated the development of a system that uses navigation solution to determine the parameters of exterior orientation. It integrates light aerial camera and GPS/INS components to a platform that is free of the helicopter in 6 degrees of freedom. Experimental studies performed in the avalanche test site of "Vallée de la Sionne" allow determining the correct ratio between the system accuracy versus its flexibility. The system should be light and flexible whereas the accuracy of the camera projection centre needs to be determined with an accuracy of 15-20cm and 0.005-0.01° in position and attitude, respectively. The paper presents the design of the system setup on a solid handheld platform, a summary of the results obtained with just GPS integration and a comparison with standard Bundle Block Adjustment.

1 INTRODUCTION

In the specific domain of snow transportation (avalanche, wind), accurate data concerning the snow cover needs to be quickly and sporadically acquired over inaccessible and dangerous areas. Procedures combining Aerial triangulation, DGPS are commonly used to provide DTM and volume measurements. Although those techniques need only a minimum of Ground Control Points (GCP's) (Ackermann, Schade 93), the avalanche and winter environment make the establishment of any signalization a slow and dangerous process (Fig.1). Moreover, it is difficult to maintain permanent and visible signals throughout all the winter, due to frequent avalanches and quickly changing of snow cover. The Swiss Federal Institute for Snow and Avalanche Research (SFISAR), managing several avalanche study sites in the Alps. Among them, the studies conducted in "Vallée de la Sionne" (Issler, 99) require a mapping system that does not need GCP's establishment and that can be mounted on standard mountain's helicopter in a few minutes.

Fig. 1 : Difficulties to setting up the GCP in the avalanche environment

To avoid the use of any GCP's in the photogrammetric process, the six parameters of the exterior orientation has to be measured directly onboard by navigation sensors. The potential of using DGPS and inertial integration for

this purpose has been strongly demonstrated during the eighties (Schwarz et al. 84, Hein et al. 88) and finally found practical and industrial applications in the mapping system during the second half part of the nineties (Abdullah, 97). Its application field has widened to non-photogrammetric system as pushbroom scanner, laser scanner or Synthetic Aperture radar (SAR). Although the utilization of the Laser Scanner or airborne SAR is very attractive for snow mapping, due to the independence in contrast and illumination, their cost, limited setup flexibility and size led to a design of a system that integrates an optical aerial handheld camera and a small lightweight INS/GPS.
In following, the design of the system development will be presented. The emphasis will be on the unique setup of all instruments for such a dedicated task. Finally, results of the test with GPS will be presented.

2 MAPPING REQUIREMENTS

In the Swiss Alps and particularly in the large avalanche test site located in "Vallée de la Sionne", the method of photogrammetry is used to precisely measure the surface of the snow cover before (when possible) and after the avalanche, and to map the boundaries of avalanche events. This allows an estimation of the released mass of snow in the starting and deposition zones. Its periodic mapping revealed following constraints that are not easy to fulfil by the standard procedures:

- An undisturbed cover of fresh snow has very small contrast. Hence, a precise measurement of the snow cover in the release zone before the triggering is difficult. Therefore, a full sunny illumination with optimal incidence angle is necessary to provide sufficient contrast.
- An artificial avalanche release cannot be planned sooner than 3 days in advance. Therefore, the implementation of a mapping procedure must be quick and flexible.
- The pictures of the release zone must be acquired before 9.00 a.m. since the likelihood of a successful triggering quickly decreases after 10 a.m.
- The surveying and placement of GCP's in the release and deposition zones is very difficult, since these points must be placed on exposed rocks that remain clearly visible even after a heavy snowfall and out of reach of the avalanche runoff. Temporary signalization is not conceivable since it is extremely dangerous to access the site during experiments and may result in systematic errors between the events (e.g., unsuitability due snow settlement).

2.1 Snow Height

The accuracy required on the snow height measurements is 10% of the snow depth and therefore will depend on the thickness of the snow layer. That varies considerably between the deposition and the release zones.
In the release zone, the thickness seldom exceeds 3m and therefore a high accuracy of 15-30cm is needed. Experiments show that the lack of contrast due to fresh snow generates a random noise of 60cm on single point measurement (Vallet et al. 2000). However, although this noise seems critical for a 3D-modelisation of the snow pack, its influence on the final volume is strongly reduced when averaged over larger area. Also, the determination of the height of the fracture line is less sensitive to the errors in absolute orientation because this measurement is relative and involves only one image pair. Hence, two types of errors affect the mapping accuracy in the release area: First and mainly, the systematic errors in parameters of exterior orientation (either bad or insufficient distribution of GCP's or errors in navigation sensors providing these parameters), second, the lack of contrast that directly influences the plotting accuracy.
In the deposition zone, the main parameter of interest is the accumulated snow volume and its distribution. As contrast is usually excellent in this zone, the plotting accuracy is at the level of few centimetres. Therefore, the quality of the exterior orientation is the crucial factor affecting the accuracy of volume measurements in this zone. Since the required accuracy depends on the volume and snow distribution (i.e., absolute snow height), a precise measurements at the level of +/-20-30cm on snow height are required for small avalanches whereas for large avalanches, an accuracy of 50cm is sufficient.

2.2 Exterior orientation requirements

Simulations studies (Vallet, et al. 2000) revealed that an accuracy of 10-20cm for projection centre and 20"-30" for camera attitude allow ground accuracy of 15-30cm.
Considering a DGPS/INS system that provides navigation parameters with an accuracy of 10-20 cm and 20"-30", respectively, the errors in position and attitude have similar effect on the ground coordinates. Such system should be feasible to implement while satisfying the overall requirements of 15-30cm mapping accuracy.

3 SYSTEM DESIGN

The topography of an avalanche area is composed of steep slope in the release zone that decreases toward deposition. To acquire of pictures with constant scale, oblique and vertical photographs are taken. Therefore, the system has to be adjustable at flight to allow capture both type of imagery. For this reason, we propose to keep the camera-INS-GPS frame free from the helicopter. Such setup has an advantage of dampening vibrations with the body instead of employing a complex dampening system (silent block, springs, gyro) on the helicopter.
The choice of a helicopter as the system carrier is justified by its capability to fly close to the ground at low speed. This allows capturing large-scale photographs and provides better flight line navigation flexibility.

3.1. Navigation Component

An embedded GPS receiver and a small, tactical grade strapdown inertial system (LN-200) with fibre-optic gyros are integrated into a loosely coupled real-time aiding loop over the VME (Versa Module Eurocard) bus. The system is capable of performing the real-time code differential aiding and all raw measurements are stored on the hard disk for intense post-mission filtering including carrier-phase differential GPS/INS integration. The GPS receiver provides the L1 and L2 carrier phase data at 10 Hz while the raw inertial measurements are stored at 400 Hz. The high data rate should guarantee that all platform frequencies are recovered without the effect of aliasing. Hence, the camera absolute position and orientation can be found by interpolation between two neighbouring navigation solutions after considering the relative offsets existing among the devices. According to recent studies (Cramer 1999, Skaloud, 1999) such systems should fulfil the accuracy requirement for the parameters of exterior orientation.

3.2. Imagery Component

In order to fulfil the required flexibility while preserving a sufficient image quality, a light handheld Linhof Aerotechnika camera has been selected (Figure 2). This camera stores up to 200 colour, large format photographs (4x5 inch) and has a 90mm wide angle lens. Its total weight reaches 8kg. The Linhof is not a metric camera because the "pseudo" fiducial marks are not clearly defined and that affects the determination of the principal points. Insertion of precise marks has been performed using small diffractive diffusers in the four corners of the picture frame.
Another handheld camera in consideration is the Tomtecs HIEI G4 with 370 colour pictures capacity, 5x5 inch format and 90mm lens. Although it is a metric camera, its weight of 13 kg ranks it as a second choice.

Fig. 2: Both Tomtecs and Linhof handheld light aerial

Furthermore, some type of digital camera is considered to arrive with a fully digital mapping system. Even if the chip's format is still to small, tests are performed to compare the noise level with an analogue camera.

3.3. Synchronization

The GPS and INS data are synchronized over the VME bus at the level of 1 µs in the GPS time frame. The event of camera exposure is also brought in as a pulse to the VME bus and the accuracy of the time stamping driven by an interrupt is at the level of few µs.

For the Linhof camera, the triggering of the shutter was planned to be performed by a switch but several tests revealed that the delay between the switch pulse and the real shutter aperture was changing with temperature at a level of 6-7ms for a range 20°C → 0°C.

Since the temperature of the camera changes during the flight, a shutter aperture with electro-optical solution was implemented. Four photodiodes detect the shutter aperture and send trough integrated circuit a TTL signal to Event input of the GPS receiver. The event is recorded at the falling front edge of a 10ms wide pulse. Overall, this method allows synchronization to be better than 2 ms, which corresponds to the aperture speed at 1/500 sec. The Tomtecs camera is synchronized by a Mid Exposure Pulse signal fed by PPS and NMEA signals.

3.4. Helicopter Mount

Placing a sensor in an airborne carrier is a non-trivial task. A poor sensor mount is most likely to alter the performance of the whole system and errors of such type may be very difficult to correct for (Skaloud, 1999). In this case, the requirements on sensor placing are motivated by following objectives:

- to minimize the effect of calibration errors on lever-arm corrections,
- to avoid any differential movements between sensors,
- to minimize noisy vibrations of the helicopter.
- to enable manual orientation of the camera towards the mountain face and to capture oblique as well as vertical imagery.

Addressing the first objective, short distances between the sensors reduce the impact of uncertainties in the lever-arm corrections. This especially affects the positioning component of direct-georeferencing.

For this reason the IMU is mounted directly over the top of the camera through a common platform which carries also the GPS antenna (Figure 3-4). Stiffness and lightness of the antenna mast is assured by a carbon pipe of 21mm.

On the other hand, small differential movements mainly alter the attitude performance. This undesirable effect should be prevented by the rigidity of the steel-aluminium-carbon holder connecting all system components. The first version of the camera holder implements no vibration dampers and these are dampened through the body of a person handholding this lightweight system during the picture session (Fig 5).

Fig. 3 : Tomtecs camera mounted with GPS antenna. The INS is mounted under the camera. During the picture session, the block camera-antenna is only hold by the operator.

During the transition flight the systems is stiffly mounted outside the helicopter on a steel frame (Fig. 3). At the beginning of the picture session, the INS-GPS-camera block is removed from the steel frame through the side door and becomes totally handheld by the operator.

Fig. 5: The camera is held and the vibrations are dampened by the body of the operator.

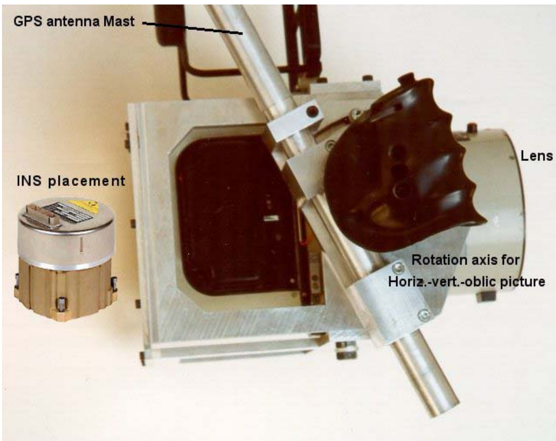

Fig. 4: Detailed views of the camera frame with the INS position and possible rotations for the GPS

Manual control allows fulfilling the last requirements on orientation towards the mountain face around the omega angle. To capture either oblique or vertical picture, the camera can rotate around the Phi axis in relation to the GPS mast, which remains more or less vertical. This angle cannot be adjusted during the flight to keep the offset parameters constant. Its adjustment is preformed prior to the flight according to type of photographs to be captured.
Safety cables limit the vertical motion of the antenna below the rotor and secure the system in case of emergency. The frame has been designed as light as possible for handholding in collaboration with a helicopter company. A second GPS antenna is placed on the tail of the helicopter to aid the inertial system with the GPS-derived azimuth.
The helicopter Alouette III (Fig. 3) has been chosen because of its sliding door and the absence of skis, that gives free view angle from ground to sky. Moreover, this type of helicopter is designed for mount-aineering flight (e.g. powerful turbine, light weight, maneuverability). Data acquisition is centralized in the cockpit of the helicopter. The required time to mount the whole system is about 20 minutes.

3.5. System Calibration

The calibration of all sensors used in the integrated system is an essential step prior to a survey mission. System calibration can be divided into two parts: calibration of individual sensors and calibration between sensors. The calibration of the individual sensors may include the calibration for camera interior orientation, INS calibration for constant drifts, biases or scale factors, GPS antenna multipath calibration, etc. An extensive literature exists on each of these topics. Calibration between sensors involves determining the relative orientation difference between the camera and the inertial system as well as the constant synchronization offset inherently present due to data transmission and internal hardware delays. For that purpose, it is essential to use a well-determined block with images of strong geometry to derive the parameters of exterior orientation by means of a bundle-adjustment with an accuracy of 10-15 cm in position and 20 arc seconds (~ 0.005°) in attitude. For this purpose a permanent calibration test field is going to be established near the airport so the calibration can be performed routinely before and after each mission. The targets will be permanent ground marks and building corners that stay clear throughout the winter.
Shift offsets between GPS antenna, IMU center and projection center are directly measured with a theodolite with an accuracy of 5 mm.

3.6 Costs

Another aspect of the design was to minimize the cost. Although navigation sensors are quite expensive (INS above all), the global cost of this system is inferior to 80'000 US$. In comparison with other potential system as Laser scanner (1 Mio US$) or standard aerial camera, this system is relatively cheap. With the use of GPS only the cost could be reduce for half.

4 TEST OF GPS EXTERIOR ORIENTATION AT "VALLÉE DE LA SIONNE"

Photogrammetric avalanche mapping is a difficult task but four years of experiences at the "Vallée de la Sionne" have demonstrated the feasibility of the method (Vallet, 2000). The placement of GCP's being the crucial problem, we investigate in ways to perform the exterior orientation with a minimum of GCP's.
As IMU was not ready to install, we decided to make a test with only one GPS antenna and the Tomtecs camera.. Indeed, it is possible to determine the entire exterior orientation parameters using two strips with a large side overlap with only GPS data. The second strip serves to determine the omega angle (roll) which can not be fixed with one single line.

4.1 Experimental procedure

We use for this test the GPS receivers Leica SR500 with 10Hz data rate sampling. Reference station is situated near the test field. The base line is about 1.5 km and the height difference is about 1000m (Fig. 6).
We flew over the avalanche site according four lines:

- 2 strips in the release area forming a block with a side overlap of 70%. The scale is about 1:4000 for the first line and 1:4500 for the second line. In order to respect the winter condition, we took oblique pictures. The ground is partly covered of snow (May) but allow tie point measurements with a good distribution. The area is signalized with 21 aluminum plates determined by terrestrial measurements (theodolite) with an accuracy of 10 cm. Those points are impossible to determine by GPS survey because they are located in cliffs.
- 2 strips in the deposition area. The scale is about 1:6000. The fact that the helicopter deviated from the planned line involves a poor geometry block. The presence of shadow in this area obliged to decrease the speed aperture of the shutter to 1/125 sec instead of 1/500 sec. It results in some blur pictures. For those reasons, those strips have not been used. The deposition area is signalized with 20 aluminum plates measured by GPS.

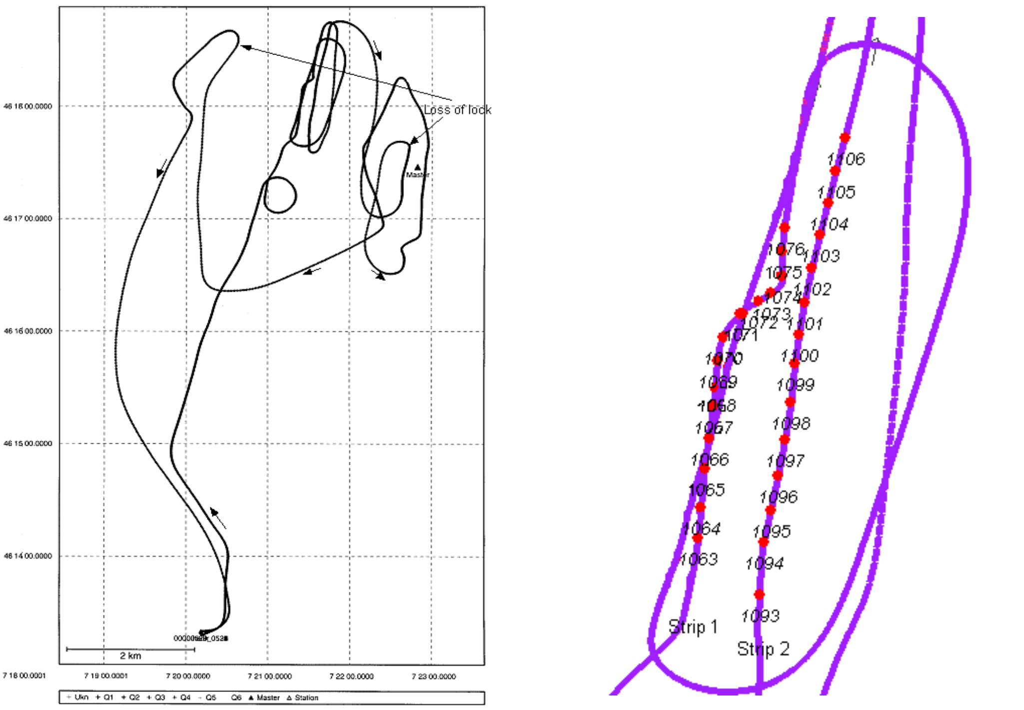

Fig. 6 : Map of the flight. Entire Flight (left) and Detail for the release area with the camera position(right).

During the transition flight, from the airport to the interest area, the camera was mounted on the helicopter frame. Astonishingly, the feared vibrations was not so important. It is probably due the weight of the system (15kg) giving some inertia. At each picture session, the set camera-GPS antenna was removed from the frame and all the vibrations were damped by the operator. Due to the high weight of the Tomtecs G4 camera, the system was re-mounted on the helicopter frame between each line. We expect to avoid this with the lighter Linhof camera.

The main purpose is to see which precision on the GCP's residuals we can obtain with the measurements of the camera position by GPS with as less control points as possible. In this way, we have the block in the release area which meets the requirements (2 strips, 70% side overlap) for GPS adjustment without control points.

Pictures have been scanned with the DSW200 scanner, with a pixel size of 10 microns. 130 tie points and 21 GCP's have been manually measured on the block of 15 images with Socet Set of LH systems. The offset ***e'*** between the GPS antenna and the projection center was determined with theodolite measurements and with an accuracy of 5 mm.

4.2 Results

We have used the software GRAFNAV for the GPS computation and BINGO-F for all the block adjustments. Time marks are printed on the picture (Tomtecs, 2001). All the angles are given in the PHI, OMEGA, KAPPA sequence.

4.2.1 GPS results:

Six satellites were available during all the flight. We detect two loss of lock. One just before the third line in a quick turn, probably due to the inclination of the helicopter and another one before returning (turn) (fig. 6). We did not encounter any problem of reception through the propeller. We used only L1 to compute the position until the first loss of lock. Ambiguities were fixed until this point and the positions of the antenna for each picture in the strips 1 and 2 has been determined with an accuracy of 5-7cm.

4.2.2 Triangulation results

In order to have a point of comparison, we have computed first a standard aerial triangulation (AT) with all the GCP's and tie points (tab. 1). As we had not the real calibration sheet of the camera HIEI-G4, we computed also a self-calibration parameters to determine the focal length ***c'*** and the position of principal point of symmetry (***x', y'***). Those computed values have been used after for all adjustment.
We have made several kinds of computation with the GPS data:

- GPS data and 3 GCP's
- GPS data and 3 GCP's with SHIFT and DRIFT parameters
- GPS data and 3 GCP's with SHIFT parameter
- GPS data without any GCP's
- GPS data with 1 GCP
- GPS data and all GCP's

All the results figure in the following tables 1 and 2.

Tab. 1 : Sigma and RMS values on the exterior orientation parameters for each type of computation

Adjustment type	Sigma [µm]	RMS X,Y [m]	RMS Z [m]	RMS Φ [g]	RMS Ω [g]	RMS K [g]
AT	7.44	0.09	0.08	0.014	0.01	0.0085
GPS-3GCP	8.62	0.03	0.03	0.009	0.006	0.007
GPS-3GCP shift	8.17	0.10	0.12	0.023	0.007	0.010
GPS-3GCP Shift/drift	7.87	0.14	0.15	0.029	0.0111	0.014
GPS	7.98	0.03	0.02	0.011	0.0067	0.008
GPS-all GCP	8.17	0.03	0.02	0.006	0.005	0.006
GPS-1GCP	8.10	0.03	0.02	0.009	0.006	0.007

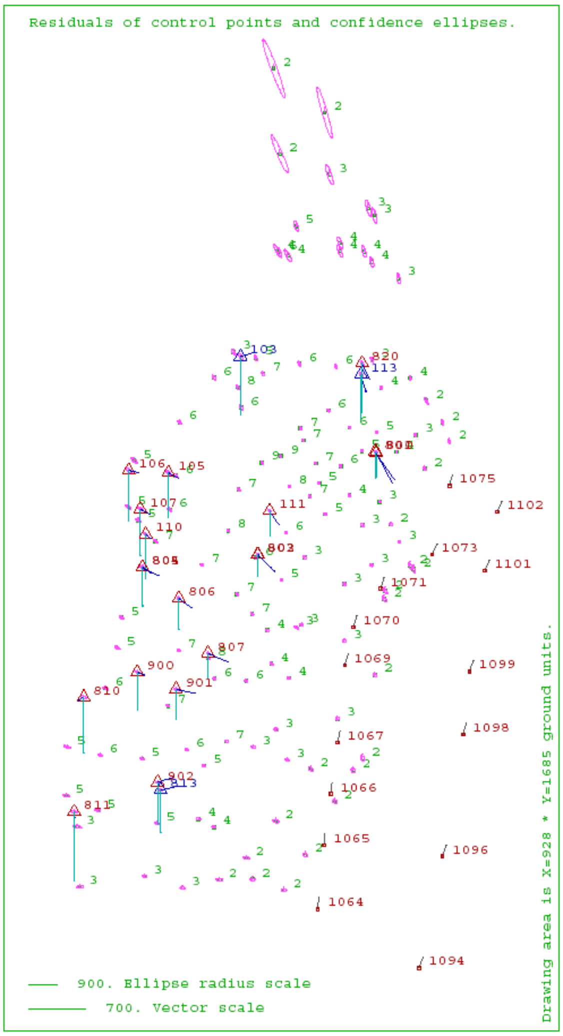

Fig. 7: Residuals on the GCP's for the adjustment with GPS data only.
The systematic error in Z appears clearly.

Tab. 3 : *Self-computed* / a posteriori s determined with Helmert 3D transformation on the GCP's shift.

Adjustment type	Shift X [m]	Shift Y [m]	Shift Z [m]
GPS-3GCP shift	*0.05*	*0.01*	*-0.53*
GPS	0.10	0.22	-0.46
GPS-1GCP	0.10	0.21	-0.45

Tab.2 : RMS values of the residuals on Control points for each type of computations.

Adjustment type	RMS X [m]	RMS Y [m]	RMS Z [m]
AT	0.08	0.07	0.20
GPS-3GCP	0.08	0.08	0.26
GPS-3GCP shift	0.07	0.13	0.20
GPS-3GCP Sft/dft	0.09	0.15	0.24
GPS	0.16	0.15	0.49
GPS-all GCP	0.05	0.12	0.19
GPS-1GCP	0.09	0.11	0.31

The different RMS of the table 1 shows that the block is stable because the RMS on the angles are small (~30 arc second). There is no floating solution. The same kinds of adjustment have been performed on a single line (except without GCP's) but the Phi angle show an instability (RMS PHI= 0.1 g).
The table 2 shows that it is possible to obtain an accuracy of 30cm on the ground control point with only one determined control point. The graphical analysis of the residuals shows a systematic error (fig. 7).
For the computation without any GCP's, we determine the residual shift with a Helmert transformation on the control points and the final residuals on the control points. The computed shift is similar to the shift self computed with GCP's. Except for the standard triangulation (AT), this shift of 10 cm in planimetry and 40-50 cm in altimetry appears in each adjustment (tab.3).

The origin of this residual systematic error on the GCP's (or Check points) is hard to find. We have tried to modify both the focal length ***c'*** and the principal point coordinates but while the sigma increases, the shift does not change.
The other source could come from the fact that the GCP's have been determined by tacheometric survey. A shift between both way of measurements could explain it. But for now, it is impossible to say exactly where this shift comes from.
Once the effect of this shift is removed, either by self-computation or by Helmert, the residuals on the control points do not exceed 10 cm in planimetry and 15cm in altimetry.
If we used the 1 GCP' in the adjustment, the residuals are the same after the Helmert (8cm X,Y and 12cm Z).

4.2.3 Comparison between GPS adjustments and Aerial Triangulation (AT)

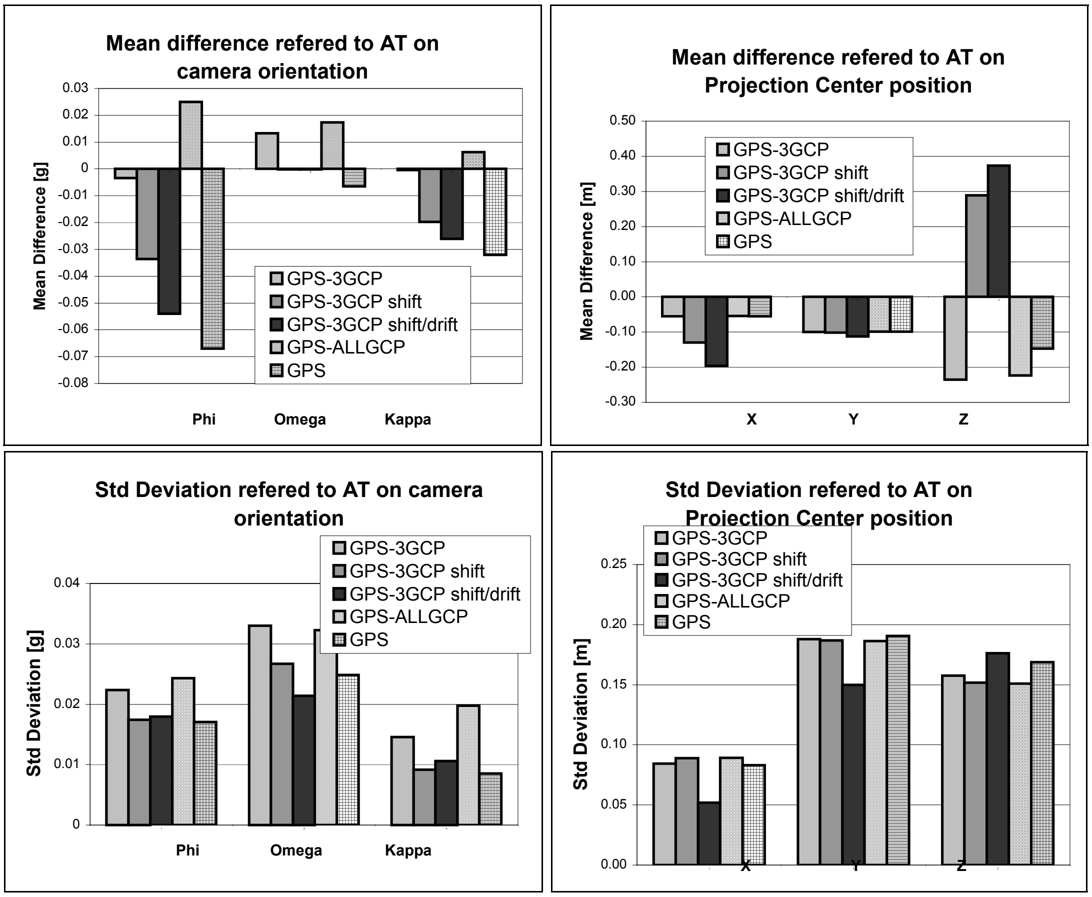

Fig. 8: Comparison of the exterior orientation parameters between the different types of GPS adjustment and the AT. First line of graphics shows the systematic deviation regard to AT whereas the second line shows the standard deviation of the orientation parameters for each type of adjustment regard to AT.

The comparison between the use of external data (GPS) to determine the orientation parameters and a standard Aerial triangulation confirms the presence of a systematic error (Fig. 8).

If the residuals on the GCP's do not vary a lot in relation to the sort of adjustment, the differences on the orientation parameters change significantly and systematically. For example, we can see that Phi systematically changes of –0.05 gon for the GPS adjustments. This systematic deviation of the angles is balanced by the computed shift (either self computed or Helmert). This phenomenon is easily understandable: the value of Phi is near 60 gons. A variation of 0.05 gon at 450m gives involves a shift in Z of 35 cm and 10 cm in X,Y (the slope is more or less perpendicular to the optical axis).

For the position, the systematic error is less significant with values about 10-15cm. We reach, on one hand, the limits of the accuracy of the GPS in Kinematic mode, and on other hand, the accuracy of the control points.

If we compare the coordinates of the tie points between each kind of adjustment with AT, the systematic component does not exceed 13 cm in X,Y and 20 cm in altimetry (shift effect removed). Standard deviation is about 10 cm in X,Y and 15 cm in Z. Without the removal of the shift, systematic component reach 35 cm in Z with no GCP's and 28 cm with one control point.

5 CONCLUSION

The goal of this test was to answer to the question: what is the minimum of necessary GCP's with GPS data to get exterior orientation parameters providing an accuracy of 20-30cm on ground measurements with a light handheld system?

Those results showed that with GPS, it is possible to obtain an accuracy of 15cm without GCP's. The use of 3 GCP's does not increase significantly the accuracy but gives a control. Even if there is a shift on the GCP's residuals, we have to keep in mind that the final aim is to measure volume by differentiation between two flights. It means that if the shift stays constant between two flight, its effect on the volume measurement will be insignificant. Obviously, it is crucial to control if the shift is constant. In this way, we recommend to use one or two ground control points. If possible, the control points should be measured by GPS in order to remove the eventual shift between two coordinates systems.

We can also infer that with 2 strips, it is possible to perform stable exterior orientation with GPS data without any GCP's whereas it is well known that on one single strip the roll angle can not be determined.

Another crucial aspect of this test is that the reception of GPS signal is not affected by the propeller. Neither loss of lock nor cycle slip were detected because of the propeller obstruction. Nevertheless, the GPS constrains the way of piloting the helicopter. The pilot has to care to make flat turns with the helicopter, otherwise satellites can be lost.
Moreover, the variation of the refraction coefficient around the propeller due to a variation of the air density is unknown. Its on the propagation of the carrier phase is also unknown.

Finally, from a practical point of view, the handheld system meets our expectations. It is enough flexible to take both vertical or oblique photographs and the feared vibrations during the transition flight were largely lower than we thought. It is a positive aspect for the future IMU integration. These latest integration is yet to be tested over the upcoming weeks and first results hope to be presented at the time of the workshop.
We have now an operational handheld system that meets the needs of the avalanche volume mapping. Indeed, the minimal number of ground control points can be reduced to two. This will allow us to determine snow volumes in the runoff area, where it was previously impossible.

AKCNOWLEDGMENT

We thank Dr. W. Ammann, Dr. U. Gruber and F. Dufour of the Swiss Federal Institute for Snow and Avalanche Research of Davos for their active participation in this research project.

The Helicopter company Air Glacier in Sion is thanked for providing their expertise during the design and testing stages of the system.

Tomtecs AG. in Japan is also thanked for lending us their HEIE G4 Camera for all of our tests and developments.

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