DEVELOPMENT OF A HELICOPTER-BASED INTEGRATED SYSTEM FOR AVALANCHE MAPPING AND HAZARD MANAGEMENT

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ABSTRACT

Natural hazard mapping 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 the domain of avalanche studies 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 a navigation solution to determine the parameters of exterior orientation. It integrates light aerial camera, GPS and 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 as light and flexible as possible whereas the accuracy of the camera projection centre should at the 15-20cm level in position and 0.005-0.01° in attitude. The paper presents the analyses of the experimental results using the photogrammetric solution over the avalanche test site and describes the individual components of the system in development.

1. INTRODUCTION

Natural hazard management requires geo-referenced database that can be quickly updated. In a specific domain such avalanche or debris flow, accurate data needs to be acquired only sporadically and over inaccessible areas. Traditionally, large-scale photogrammetry and DGPS assisted aerial triangulation are used in this field to provide DTM, surface and volume measurements. Although this approach reduces the use of GCP (Ground Control Points) to a minimum (Ackernmann and Schade, 1993) the process of their establishment in the avalanche environment is slow and dangerous due to inaccessibility of areas as cliffs, and steep, snow covered slopes (Figure 1). The Swiss Federal Institute for Snow and Avalanche Research of Davos (SFISAR), managing several avalanche study sites among the "Vallée de la Sionne" (Issler, 1999), would like to attain a mapping system, which does not need the GCP establishment and can be mounted on an ordinary rescue helicopter in few minutes. This paper suggests a solution for this particular need and describes the system in development.

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

To circumvent the use of any GCP, the parameters of exterior orientation has to be measured directly by an onboard navigation system. The potential of integrating the DGPS with the existing inertial technology (INS) for this purpose has been strongly promoted in the eighties (Schwarz et al., 1984, Hein et al., 1988). It was not till the second half of the nineties that the airborne mapping industry gave serious consideration to this technology and first results with commercially available systems appeared (Abdulah, 1997; Scherzinger, 1997). The possibility of measuring the instantaneous position, velocity and attitude of the on-board imagery sensor by a DGPS/INS system also widened the application field of non-frame-based imagery including pushbroom or laser scanners and synthetic aperture radar (SAR). Although, the use of the lastly mentioned sensors is attractive for snow mapping due to their independence from contrast and illumination, the constrains placed on system cost, size and flexibility led to an implementation of an optical camera and a small lightweight GPS/INS.

The paper starts with a discussion on the general requirements of the system in development (Section 2). The analysis shows that the avalanche release and deposition areas do not reveal same requirements and serves as a starting point for the system design that is described in Section 3. Section 4 presents a summary of last winter tests with the use of standard photogrammetry.

2. REQUIREMENTS ON SYSTEM PERFORMANCE

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. Even if experimental sites were specifically equipped for avalanche mapping, it would be impossible to proceed as the same in every Alps avalanche area. Last winter, the Swiss Federal Topographic Office has pictured every large avalanche. Although, these images are good as archive but are not directly usable for precise photogrammetric measurements without a large amount of work for post-signalization. The "Vallée de la Sionne" test site is equipped for photogrammetry and its periodic mapping revealed following constraints that are not easy to fulfil by the standard procedures:

1. 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. Moreover, a full sunny illumination is necessary to provide enough contrast whatever the snowy area.
2. An artificial avalanche release cannot be planned sooner than 3 days in advance. Therefore, the implementation of the mapping procedure must be quick and flexible.
3. 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.
4. The surveying of the ground control points (GCP) in the release and deposition areas 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 on site during experiments and it is a source of systematic errors for exterior orientation from one event to another (unstability).

2.1 Accuracy Requirements in the Release Area

To study the avalanche release area, the snow height has to be determined with an accuracy of 15-30cm. If there is good contrast on the imagery, the image coordinates can be measured with an accuracy of 6-8 µm on an image scale between 1:4000 and 1:5500. Although a bad contrast reduces the accuracy of a single height measurement, the experimental studies show that the resulting noise is randomly distributed (Figure 2) and therefore its effect on the parameters estimated over a global area (i.e., the volume) is relatively small. On the other hand, the height of the fracture line is also measured but this parameter is not that sensitive to errors in absolute orientation since it is a relative measurement performed on one image pair. Hence, 2 types of errors affect the mapping accuracy in the release area. In a main part, the systematic errors due to insufficient or bad distribution of GCP's (directly influencing the accuracy of the exterior orientation) and to a lesser part, the lack of contrast (directly influencing the plotting accuracy).

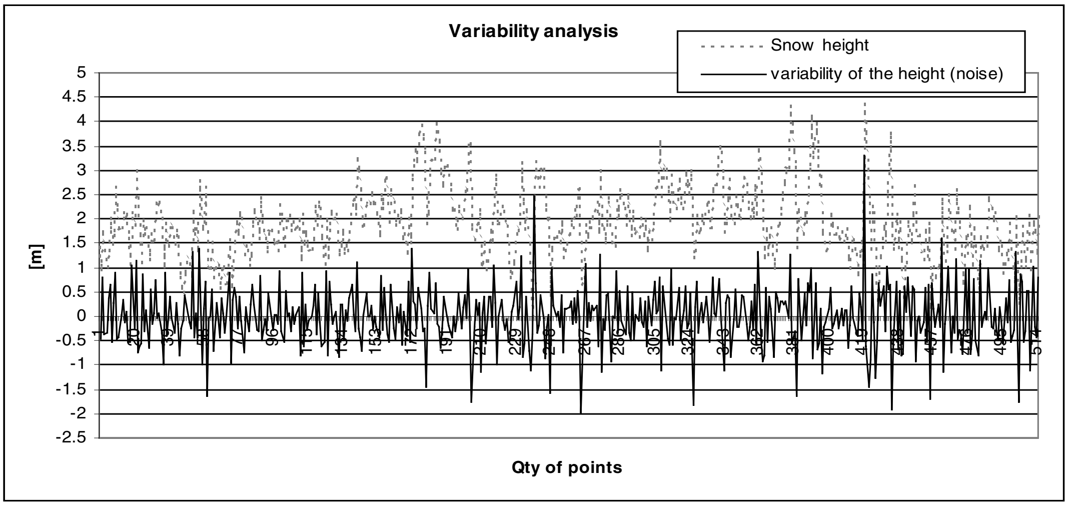

Figure 2: Variability (noise) of single point measurements in the fracture zone the February 10, 1999 avalanche. The noise level is estimated from the differences between neighboring points.

2.2 Accuracy Requirements in the Deposition Area

The main parameter of interest in the deposition area is the accumulated snow volume. As contrast is usually excellent in this zone, the plotting accuracy is at the level of few centimetres. Therefore here again, the quality of the exterior orientation is the crucial factor affecting the accuracy of volume measurements with systematic errors. In this case, the required accuracy depends on the volume and snow distribution (i.e., absolute snow height). For a small avalanche, precise measurements at the level of +/-20-30cm on snow height are required whereas for a large avalanche, accuracy of 50cm is sufficient. The studies in the "Vallée de la Sionne" show that the accuracy required for snow height measurements should be less than 10% of the mean snow depth of the deposition. Table 1 depicts the relation between the volume and the orientation accuracy obtained in different tests performed last winter.

	30.01.99	**10.02.99**	**25.02.99**
Exterior Orientation accuracy (BLUH, HATS)	σGCP: 15cm σPC: 18cm σAngle: 0.015°	σGCP: 30cm σPC: 9cm σAngle: 0.005°	σGCP: 40cm σPC: 20cm σAngle: 0.004°
Mean height	1m	2.20m	4m
Volume [m^3]	~25'000	468'000	876'000

Table 1: Volume/Snow height of deposition versus the accuracy of the exterior orientation.
GCP: Ground Control Point. PC: Projection Centre.

2.3 Requirements on the Parameters of Exterior Orientation

Previous experiences show that the accuracy required for ground measurements is at the level of 15-30cm depending on the treated area. To obtain the requirements on the accuracy of the navigation system that will be providing the parameters of exterior orientation a small simulation has been undertaken. One model from February 25.test was first oriented using all available GCP's. Then, changes on PC coordinates and attitude were simulated to investigate their impact on ground coordinates. Results are presented in Table 2.

	Min/max on GCP's [m]			**RMS on GCP's [m]**		
Variation on orient. parameters	**X**	**Y**	**Z**	**X**	**Y**	**Z**
No variation (Original values)	0 / 0.19	0 / 0.1	0 / .08	0.08	0.06	0.05
2' on Azimuth	0.3 / 1.8	0.01 / 0.5	0 / 0.5	1.15	0.30	0.19
1' on Azimuth	0.15 / 0.75	0 / 0.4	0 / 0.16	0.81	0.22	0.11
30" on Azimuth	0.05 / 0.54	0.05 / 0.3	0 / 0.1	0.34	0.16	0.06
20" on Azimuth	0 / 0.45	0 / 0.18	0 / 0.1	0.21	0.12	0.07
10 cm on X	0 / 0.4	0 / 0.12	0 / 0.07	0.23	0.10	0.04
20 cm on X	0.26 / 0.6	0 / 0.4	0 / 0.13	0.40	0.22	0.06

Table 2: Influence on GCP's coordinates of due to changes in parameters of exterior orientation.

The simulation is performed in terrestrial mode (Azimuth, Nadir, Kappa) due to high obliquity of the images. In this way, X axis is corresponds to Z axis in aerial mode. That means that errors of exterior orientation have bigger impact on altimetry than on planimetry. 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 requirements of 15-30cm mapping accuracy.

2.4 Available Systems

From the mapping systems currently available, two types were considered:
- Light aerial photogrammetry, coupled with small GPS/INS sensors.
- The aerial Laser altimeter-GPS/INS integrated system.

Both systems possess advantages and limitations that are summarised in Table 3. The method of laser scanning (Optech ALTM 1020) was tested last fall on fresh snow surface and slopes of different steepness. Although, the obtained results meet the accuracy needs of nivology, the system has not been chosen due to its limitations on quick implementation, flexibility and cost. Should these limitations diminish in the near future, its application will become very attractive.

	Photogrammetry GPS/INS	Laser Scanning GPS/INS
Advantages	+ Flexible, quick to implement + Accuracy on ground of 15-30cm for standard photogrammetry (GCP's, contrast). + No field access required. + GCP independent with GPS/INS. + Low cost for small area.	+ Independent from contrast and illumination. + Inner accuracy on fresh snow of 10-15cm. + No field access required. + GCP independent. + Small post treatment.
Limitations	- Lack of contrast on fresh snow. - Difficulties to maintain a permanent signalization on field (without GPS/INS). - Necessity of a sunny weather (contrast). - Important post treatment (plotting).	- Weak flexibility, slow to implement in an emergency situation - High system cost for small area.
Costs	➢ Direct: ~ 150'000 CHF. ➢ Indirect: 1 operator for plotting.	➢ Direct: ~1'500'000 CHF. ➢ Indirect: 1 technician.

Table 3: Comparison between photogrammetry and Laser scanning concerning Snow surface mapping.

3. PARTICULARITIES OF THE SYSTEM IN DEVELOPMENT

The experience from tests performed over the last four years served as a starting point on the system choice. The crucial factors considered were the best system flexibility for a given ground accuracy of 15-30cm. This pointed to GPS/INS assisted photogrammetry, using a light handheld aerial camera. It comprises of a light handheld camera with fast signal acquisition, a high data rate GPS receiver and a small light weight strapdown inertial measurement unit (IMU), all integrated on a common platform. The details of each component are presented in the following. 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.

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 military 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 3). This camera stores up to 200 colour, large format photographs (4x5 inch) and has a 90mm wide angle lens. Its total weight reaches 8kg. Another handheld camera in consideration is the Tomtecs HIEI SEII-α with 370 colour pictures capacity, 5x5 inch format and 90mm lens.

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 analogue camera.

Fig. 3: Both Tomtecs and Linhof handheld light aerial camera

3.3 Synchronisation

The GPS and INS data are synchronised over the VME bus at the level of 1 μs in the GPS time frame. The event of camera exposure is also brought to the VME bus by a RC circuit and the accuracy of time stamping is at 0.1 ms level. The triggering of the shutter is sensed by four photodiodes that have been additionally placed into corners of the camera.. The signal is brought to the event input of the GPS by an integrated RC circuit. Overall, this method allows synchronisation better than 2-3ms, which corresponds to the aperture speed at 1/500 sec.

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 minimise the effect of calibration errors on lever-arm corrections,
- to avoid any differential movements between sensors,
- 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 sensors reduce the impact of uncertainties in the lever-arm corrections. This especially affects the positioning component of direct-geo-referencing. 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 4 - 5).

On the other hand small differential movements mainly alter the attitude performance. This undesirable effect should be prevented by the rigidity of the steel-aluminum-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 (Figure 6).

Fig.4: Global view of the system mounted on the helicopter Alouette III.

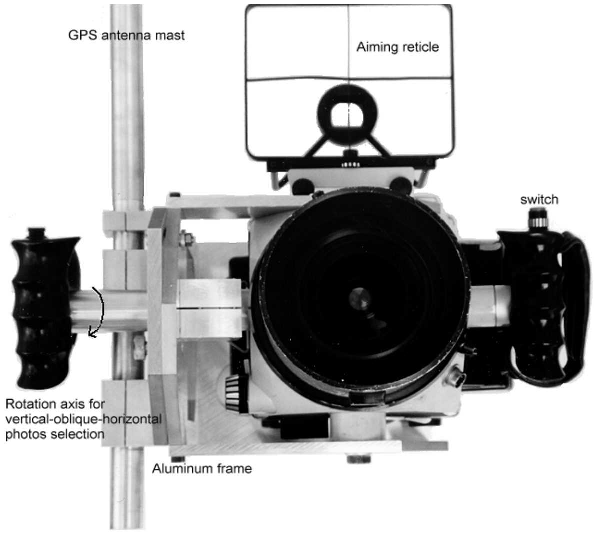

Fig. 5: Detailed view of the camera frame. The aluminum mast will be replaced by carbon mast to decrease inertia.

Fig. 6: The camera is held and the vibrations are dampened by the body of the operator.

During the transition flight the systems is stiffly mounted outside the helicopter on a steel frame. At the beginning of the picture session, the INS-GPS-camera block is removed from the steel frame through the side door, is totally handheld by the operator and become free of motion. This allows fulfilling the last requirements on manual 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 so as to keep offset parameters constant. Safety cables limit the vertical motion of the mast (for the rotor) and hold back 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 obtain the approximate azimuth during the calibration period.

The helicopter Alouette III 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 mountaineering flight (powerful turbine, light weight, manoeuvrability).
Data acquisition is centralised 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 synchronisation 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.

4. PRELIMINARY TESTS

This section summarises the measurements performed in the test site of "Vallée de la Sionne" during the last winter. Three important avalanches were studied and the snow volumes and profiles of fracture lines were measured by standard photogrammetric procedures without the GPS/INS assistance (Vallet, Gruber, 2000).

4.1 Mapping accuracy

The experimental study performed in the in the "Vallée de la Sionne" during last winter shows the mapping accuracy achieved in each measurements session. In this test site, the release and the deposition areas are signalised with 50 GCP's. That allows indirect computation of these parameters and estimation of their accuracy. Table 4 shows the mapping accuracy, related to GCP's, for different test scenarios. These values reflect directly the systematic influence due to errors in exterior orientation. These results reveal the well-known fact that the accuracy of the exterior orientation is mainly affected by the distribution and the quality of the GCP's.

Area time Date	Plotters/ Adjustment	Image type Scale	Nbr. GCP Distribution / quality	RMS GCP's [cm]	
				XY	Z
Deposition Before 30.01.99	Analytical Aviosoft-ORI	Oblique 1 :5500	12 +/+	**12**	**18**
Deposition After 30.01.99	Analytical Aviosoft-ORI	Oblique 1 :5500	10 +/+	**15**	**12**
Fracture After 30.01.99	Analytical Aviosoft-ORI	Horizontal 1 :8000	10 -/0	**50**	**40**
Fracture Before 10.02.99	Analytical BLUH	Oblique 1 :4500	10xy 9z 0/0	**15**	**13**
Fracture After 10.02.99	Analytical BLUH	Oblique 1 :5000	6xy 5z -/0	**25**	**27**
Lower Deposition After 10.02.99	Digital HATS	Little oblique 1 :5500	11 +/+	**35**	**22**
Upper Deposition After 10.02.99	Analytical Aviosoft-ORI	Oblique 1 :6000	6 0/+	**15**	**12**
Fracture After 25.02.99	Analytical BLUH	Oblique 1 :4500	19 +/+	**10**	**19**
Deposition After 25.02.99	Digital HATS	Vertical 1 :10000	11xy 12z 0/0	**40**	**35**

Table 4: Overview of the quality of the photogrammetric measurements before and after the avalanche triggering during the 99 winter sessions. For February 10th and 25th deposition, control points have been destroyed and replaced by temporary signals. One can notice that the accuracy decreases significantly.

4.2 Volume Results

In the avalanche of February 25th, an accuracy of 50cm was sufficient because the average snow height was about 5m. The usually good contrast in the deposition zone prevented the restitution errors from becoming significant.

In the events of February 10th and 25th the avalanche has destroyed many GCP's and temporary signals had to be installed. This kept the accuracy of exterior orientation at the 30 to 50cm level, which meets the study requirements. Results of snow distribution between February 25th and 10th are shown in the Figure 7 and snow volumes are presented in Table 5.

	30.01.99	10.02.99	25.02.99
Volume	~20'000	467'700	876'500
Erosion	-	-	18'200

Tab. 5. Relative Volume of an event /previous one in [m^3].

In the release area, the fracture line was always measured with an accuracy of 15cm for each event. The volume on the February 10th was measured with an accuracy of 30cm due to an existence of systematic orientation error between blocks caused by an insufficient distribution of GCP's. For a total of 98'000 m^3, distribution is presented in the Figure 8.

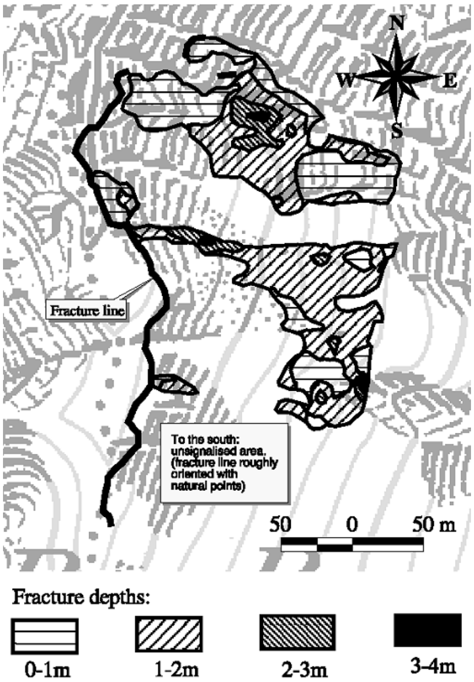

Figure 8: Measured fracture depths in the signalized part of the release area of the February 10th avalanche.

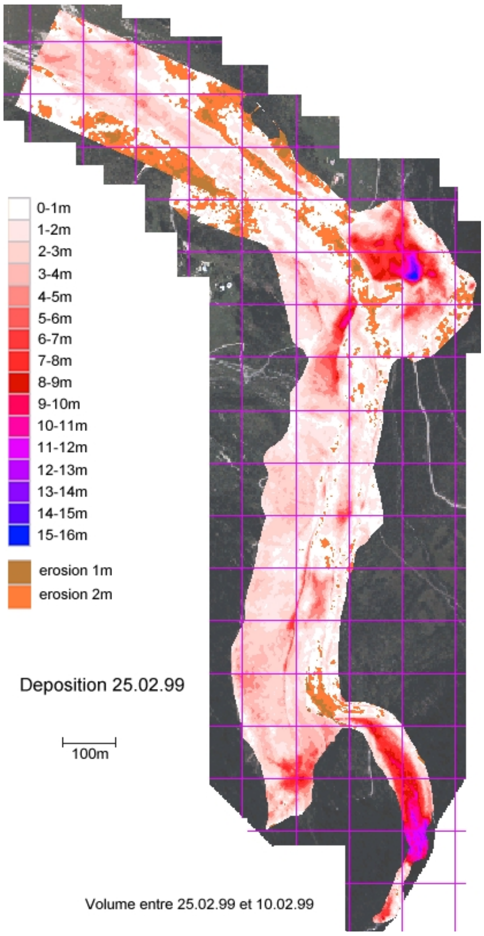

Figure 7: Volume distribution for the avalanche of 25.02.99.

Since not all navigation components have been prepared yet, a large field test campaign is scheduled for the next summer session, following the photogrammetry tests conducted during the avalanche cycle in the year 2000. The experimental avalanche test filed is signalised with 50 control points. It serves for initial system evaluation as well as for system calibration and will be used also later to control the stability of the system.

5 CONCLUSION

Experiments performed during the last two years in "Vallée de la Sionne" avalanche test site showed that helicopter based photogrammetry is able to provide snow volume measurements with an accuracy of 20-30cm when good conditions for accurate exterior orientation and contrast are fulfilled. Standard photogrammetry reaches its limit because in the natural hazard conditions (snow, wind, avalanches, landslide, etc.) the needed GCP's cannot be permanently defined. To circumvent those problems, the integration with a navigation system is under way. The main criteria are the flexibility and accuracy of the system (15-20cm for PC and 20 arc seconds for attitude). The combination of a light aerial Linhof camera with a GPS/INS promises to satisfy the needs in terms of applicability, flexibility and accuracy. The latest parameter is yet to be tested over the upcoming months.

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