GPS/IMU and LiDAR integration to aerial photogrammetry: Development and practical experiences with Helimap System®

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1. Introduction

The arrival during the 90's of the direct georeferencing technologies (GPS-inertial) and laser altimetry, combined to the emerging high resolution digital imagery, changes drastically the world of aerial photogrammetry. Those techniques widened the application field of airborne mapping: remote area mapping, corridor mapping, fast delivery mapping.

Nevertheless, the commercial "high-tech" products, available on the market, focused essentially on large area mapping and nothing was designed for "local" applications and especially for complex terrain or vertical objects. Generally operated from fixed-wing aircrafts, looking downward mapping systems are not suitable for cliffs or steep slopes for example.

It is now a fact; there is a huge demand for high precision mapping of small surface, where expensive commercial mapping system does not suit either in terms of economical or practical point of view.

Development of Helimap System® started in 1999 in the photogrammetric and geodetic laboratories of EPFL, to address needs for natural hazard mapping (Vallet 2002) in collaboration with the Swiss federal institute For Snow and Avalanche Research of Davos. The requirements were accurate data (<15cm), short notice setup, low cost and high flexibility for complex terrain and steep slopes.

Based at the beginning on handheld analog photogrammetry operated from the side of a helicopter, the system progressively integrated GPS positioning, GPS-INS georeferencing, high resolution CCD camera and finally a laser scanner unit. Thanks to its maneuverability, the system provides high precision (~0.1m) and high density (>2-3 post/m^2) digital terrain/surface model (DTM/DSM) and high resolution orthoimagery (GSD<0.1m) either in "standard" nadir or oblique configuration.

Since 2005, Helimap system® is commercially exploited by UW+R SA in all types of land management project (power lines, cliffs, avalanche, roads, railroads, landslide…), but always focused on small area (<2000ha).

All those practical experiences lead in the past 3 years gave an important feedback and allowed fine tuning of the system either in operational phase or processing phase. Direct georeferencing and LiDAR measurements change drastically the airborne mapping process in positive aspects automation, high resolution but also add complexity and gaps to avoid. Thus, those several flights pinpoint the importance of the calibration step and especially the digital camera calibration stability, the procedure of alignment, and the necessary periodical ground control. The last important issue of our practice is that the imagery should never be neglected! It is the backup for everything.

2. System development

2.1. Concept

The design of the system is based on 6 crucial points:

- Flexibility of flight capability. The helicopter is the only aircraft offering enough flexibility in terms of flight.
- Get a constant mapping accuracy whatever the slope: the accuracy of nadir airborne mapping device (photogrammetry, LiDAR) decreases as the slope angle grows. To prevent this effect, the mapping device is rotated until the slope looks flat. The fact that the system is handhold confers a free motion and orientation to the sensor (fig. 1). It allows using the system either vertically or obliquely during the same flight (fig. 2).

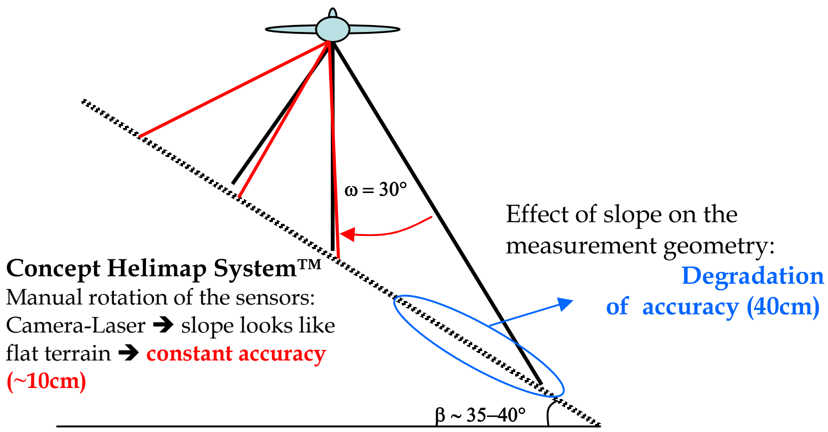


Figure 1: Basic concept of Helimap System®: a handheld operation to fit to the ground

Figure 2: vertical (nadir) and oblique operation of the system

- Be able to make remote mapping over inaccessible or dangerous area, by suppressing the constraints of Ground control points (GCP's). This is achieved by integrating direct georeferencing techniques (GPS-INS).
- Be operational on a very short notice independently of the carrier. Most commercial system requires complex installation in the aircraft. By preventing any fixed mount to the helicopter, the system can be deployed within an hour on any type of helicopter.
- Get a single calibration system. Classical system considers their sensors separately during the installation (GPS, Camera-INS, Lidar-INS). Each time the system is installed/uninstalled, offsets between sensors must be controlled. By building a single rigid block integrating all sensors, the system needs to be calibrated only one time.
- Provide results quickly on any type of surface: thanks to LiDAR measurements, the time consuming step of stereo plotting is replaced by the automated generated point cloud. The

poor contrast surfaces like snow or sand or poor stereoscopic vision area like forests are treated like other surface with the same accuracy.

2.2. Components

To address the previous requirements, the system incorporates a modular design with off-the-shelf sensors and modern communication to facilitate replacements or upgrade.
The 4 following sensors:

- CCD camera with 22 mega pixels chip and 35mm lens with FOV of 57°
- Riegl 2D airborne scanner with a measurement rate of 10'000 post/sec, a max operating range of 300-400m and a FOV of 60° compatible with the camera. The wave length of 900 nm ensures favorable reflection even on snow surfaces. Only water and pure ice reflects poorly.
- GPS/GLONASS antenna, linked to carrier phase receiver
- Tactical grade IMU with 500Hz measurement rate

composed the system and are assembled with a carbon-aluminum frame (fig. 3).
This compact block provides complete rigidity between sensors and lightweight (12 kg) permitting its handheld operation. The installation time is minimal (~30 minutes) and does not require modification of the helicopter. No re-calibration is needed while the components are not disassembled.
Data acquisition module (DAM) is composed of custom hardware interfaces, power supply unit, GPS receiver and PC that ensures instrument command, data synchronization and storage. The system is linked to the DAM via sets of strong shielded cables and MIL connectors. Pilot navigation is also ensured by the DAM.

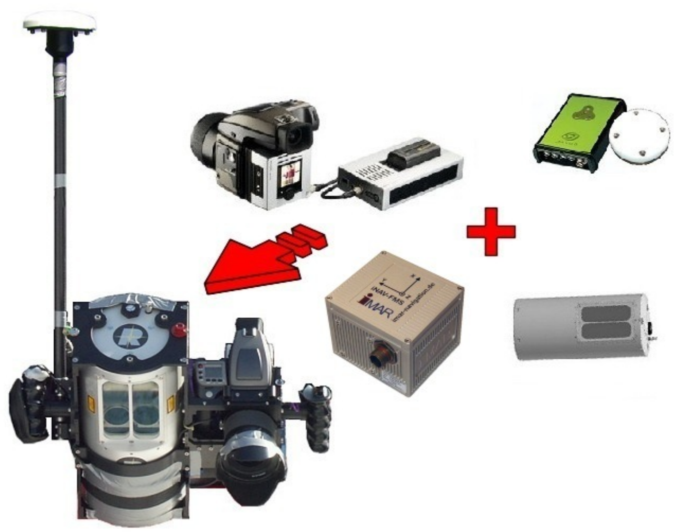


Figure 3: Helimap System® with components

2.3. Data flow

The figure 4 illustrates the coarse data flow from the sensors to the final products (DTM/DSM, orthoimage). GPS trajectory is firstly computed and then integrated to IMU measurements to provide position and orientation for camera shots and laser measurements. Laser data are manually separated in flight lines and then processed trough LiEO to generate point clouds. A laser filtering software allows the separation of the DTM/DSM.

The GPS-INS derived exterior orientation of the images, computed with CamEO, is imported in the photogrammetric software. Then two options are offered, computing orthoimage with Direct georeferencing parameters and laser DTM, or processing an automated aerial triangulation (AT) to improve accuracy and remove residual parallaxes. The AT step is necessary if stereoscopic measurement are done.

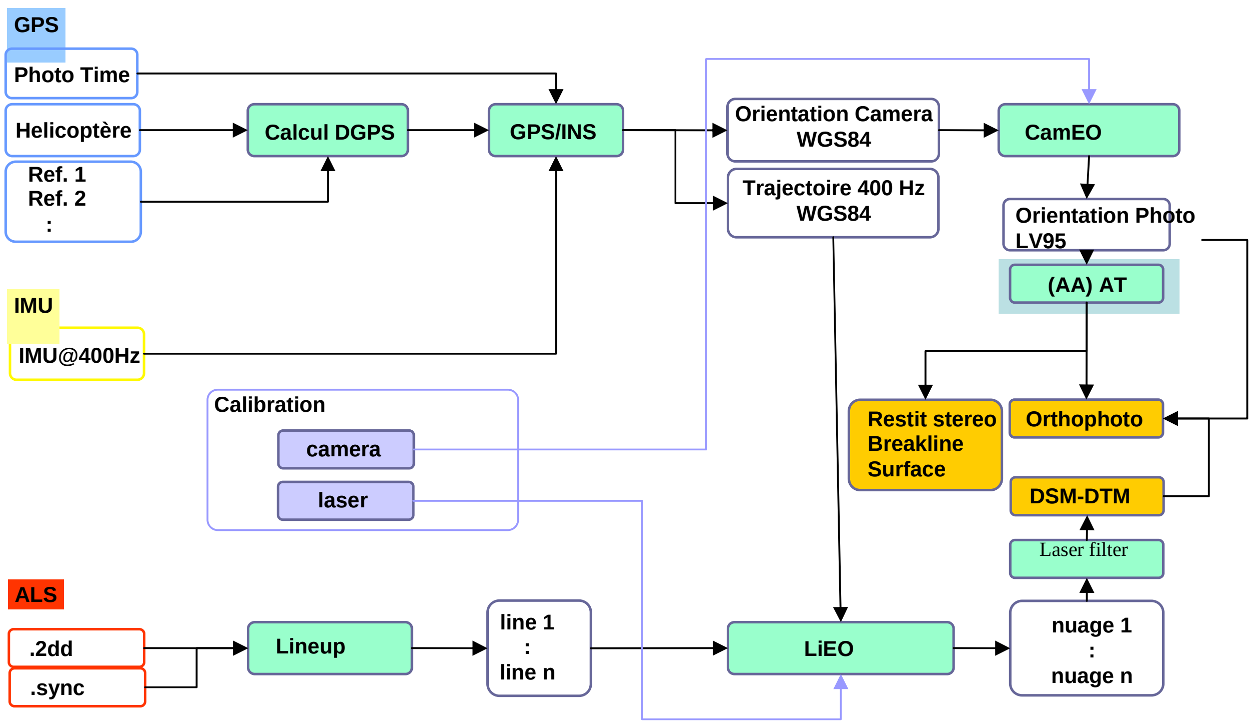


Figure 4 : Direct georeferencing data flow for the orthoimage and DTM/DSM production

3. System calibration

System calibration is divided in two major steps, lever arm and boresight. The lever arm represents the spatial offsets (vector) between sensors origin (GPS-IMU, GPS-CAM, ALS-IMU). Its determination is achieved with sub-centimeter level by tacheometric measurement.

The boresight characterizes the misalignment of the respective reference frame between IMU and CCD/LiDAR, due to the mechanical imperfections of the mounting. The determination of the both boresights is performed on flight with different procedures.

The CCD-IMU misalignment is extracted from a GPS aided AT with a set of GCP's. Misalignment angles are computed with an accuracy of 0.008°. During this flight the interior orientation parameters of the camera are determined (AT-GPS bloc adjustment). However, focal length and principal point (PP) of actual medium format CCD camera are not so stable. By using regularly few control points on production flights, it is possible to check the stability. As it depends on temperature and submitted level of vibration endured by the camera, a variation of ~30µm for focal length and ~15µm for PP has been observed over one year.

The LiDAR-IMU boresight requires a special flying pattern over selected features. The popular empirical technique uses cross sections to determine the offset between two flight lines (same line but opposite direction). This technique provides satisfactory results for the boresight estimate in the roll direction while the pitch and heading is badly estimated. Then a new approach was designed (Skaloud and Lichti, 2006) by expressing the boresight within the direct-georeferencing equation of each laser point and constraining a group of points to lie on common plane surface (using roof). This approach gave adjustment of the flight lines within the internal accuracy of the laser distance measurements (0.03m).

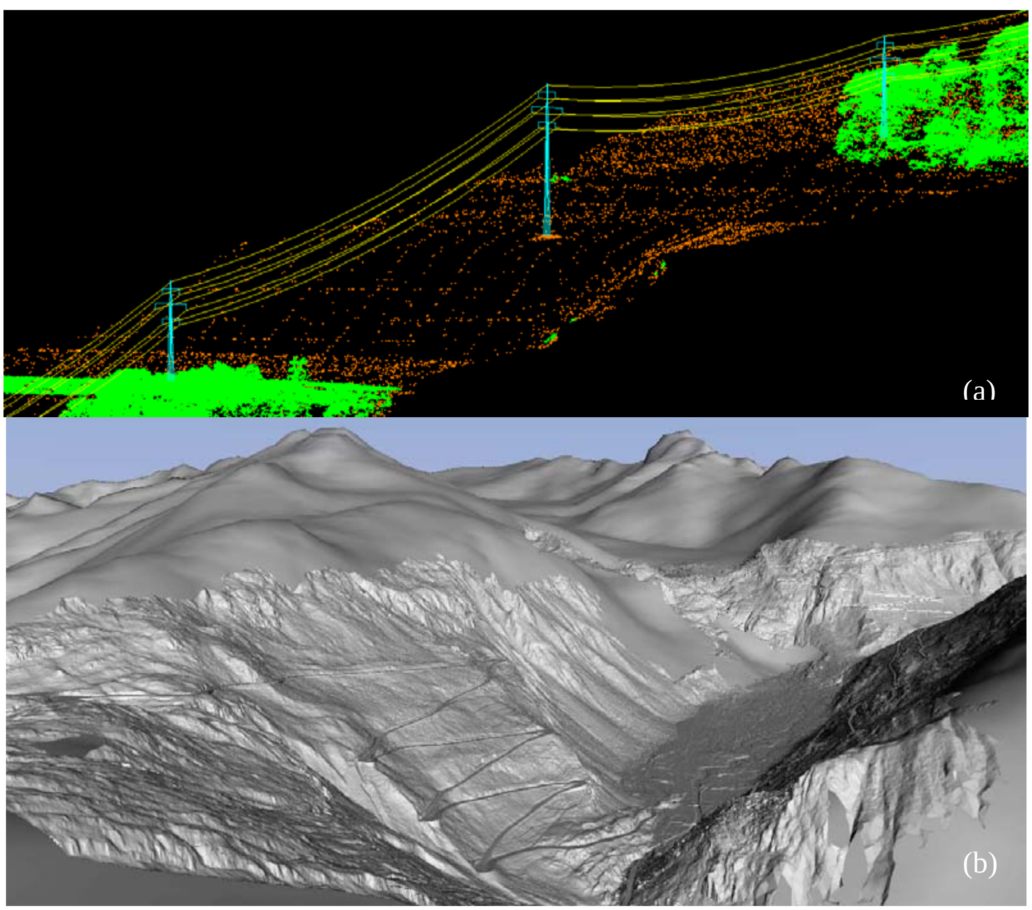
4. Practical experiences

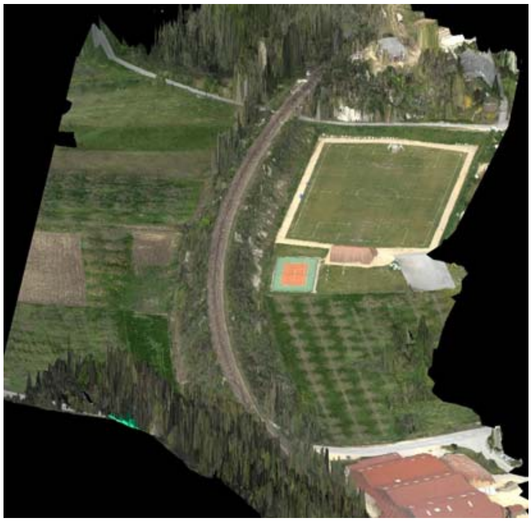
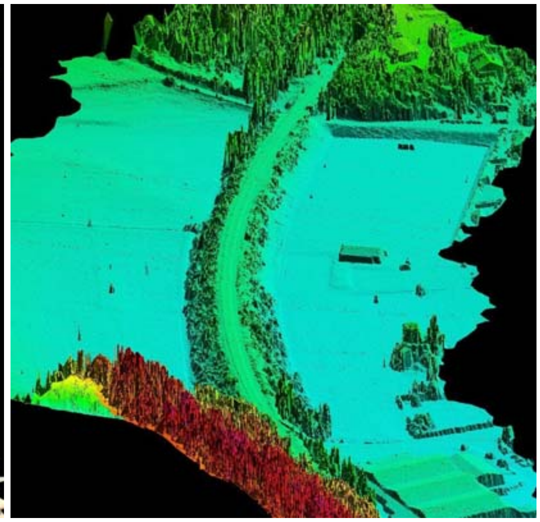
Helimap system® entered in production since the end of 2004. During 3 years, more than 60 flights were realized giving enough feedback to make the system evolving.

4.1. Application Field

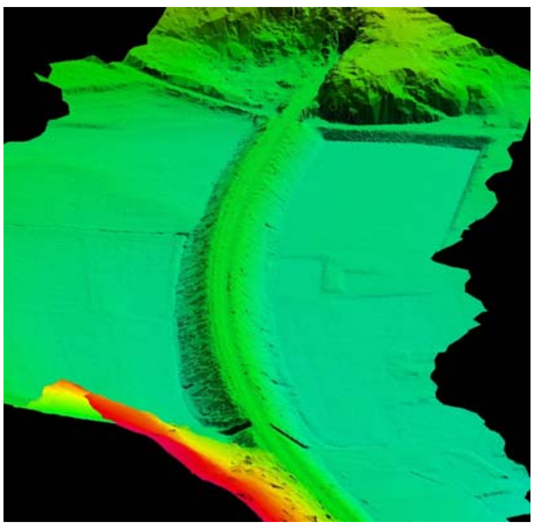
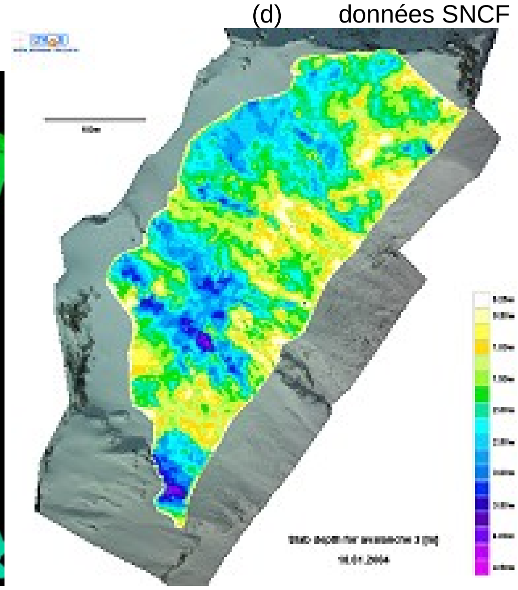
Helimap System® was designed for small area mapping (between 10 and 2000 ha) or medium corridor (<100km). The good synergy between the camera and the LiDAR properties offers suitable complementary information.
Along the 60 missions, we cover the following application fields (fig. 5)

- Corridor mapping : railroad mapping, power lines management and control in mountains area, highway mapping and high accuracy profile determination (accuracy of 2-3cm), coast mapping
- Forestry : inventory, settlements, damage
- Natural hazards: avalanche monitoring, snowmelt study, landslide, rockfall… (fig. 5)
- Glaciology : mass balance of small glacier
- Gravel pit and open mines for volumetric control
- Land management and site rehabilitation (urbanism, construction)
- Cliff mapping for geology studies



(c) données SNCF (d) données SNCF

(e) données SNCF (f) données SLF

Figure 5: Power lines mapping (a). By flying at 100m above ground, it is possible to detect wires, pylons and obstacles. Steep slopes mapping (Grimsel-Furka road) for 3D road model (b). Orthophoto draped on DSM (c)/DSM (d) / DTM (Laser filtering) of railways (SNCF) (e) / Snow volume measurement of a slab avalanche (vallée de la Sionne, VS) (f).

4.2. Output data quality

The basic data issued for Helimap system® are high density digital terrain/surface models (density of 1-20 pts/m^2), high resolution orthoimages (GSD of 3 to 10 cm) and accuracy stereo plotting (breaklines, features) to complete the DTM/DSM laser model. Then all derived output data can be extracted from it (volume, object classification…).
The output data quality check is an important task when using DG based system. For several flights, GCP's were measured to estimate the accuracy of the system. All operation modes (photogrammetry, LiDAR, oblique, nadir) were evaluated to finally give the performance of the system. The operating height was ~300m, i.e. 1:9'000 scale imagery.
Another specific test was recently done to estimate the potential of reaching 1-2cm accuracy level with airborne solution (flight height of 40-60m)
It can be characterized according 3 aspects:

- Imagery: the gain brought by the digital images related to analog film, 4x less noise, 3x sharper. This fact permits to reduce the image scale by a factor 2 without any loss of image details (Vallet et al. 2004).
- Photogrammetric mapping accuracy: the 3 different ways of orientation were explored, the standard AT with GCP's, the AT-GPS without use of GCP's and the AT with DG (no GCP's). Figure 7 depicts the RMS of residuals on ground Check points. We can notice that the mapping accuracy without GCP's is better when using AT-GPS approach. So what would be the advantage of DG-AT? The main constraint of AT-GPS is that it requires at least 2 flight lines overlapping otherwise the roll is very unstable. Then, this technique is not usable for corridor. The second advantage of DG-AT is the quasi full automation of the tie points transfer (only forest areas remain problematic and requires manual editing), while it is not the case with AT-GPS, especially if working with oblique images. The use of DG without AT is also possible but the experiences shows that residual parallaxes make impossible accurate stereo measurements and create disjuncture within the mosaic (5-20cm). Then for precise purpose, AT is strongly recommended.
  The test conducted for high accuracy purpose (centimeter level) reveals the high potential of the method. By flying at 50m above roads it was possible to achieved stereo plotting with maximum residuals better than 0.02m while the RMS of GCP's residuals is ~0.004 m (fig. 6). The price to pay to achieve this precision level is GCP's measurements with a sub-centimeter accuracy. The DG is only used to automate the AT process.

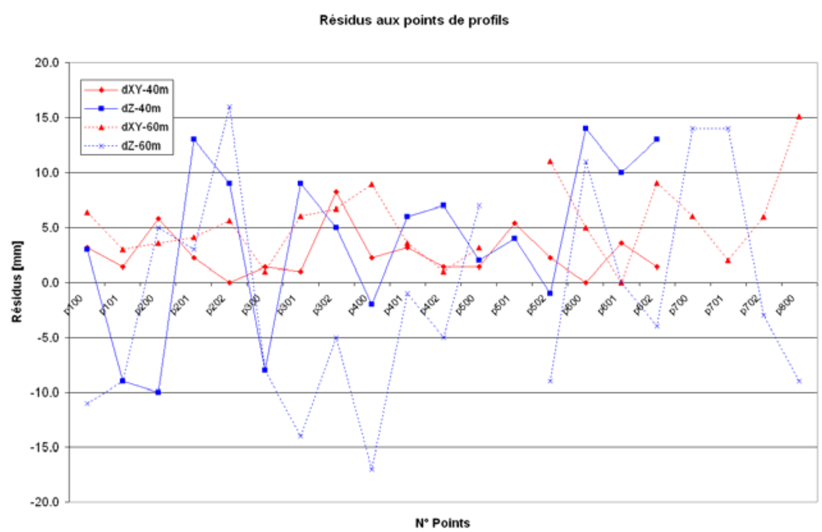


Figure 6: Stereo plotting residuals on road profiles

- LiDAR mapping accuracy : The accuracy of the LiDAR was estimated according two 3 level, the inner accuracy that characterized the noise inside the point cloud, the relative accuracy that is the discrepancies between several overlapping flight lines and finally the absolute accuracy, estimated by GCP's (Škaloud et al. 2005). The figure 7 illustrates the results for relative and absolute accuracy according to the type of surface. The noise has been measured on flat roads at different flight height and appears to be identical (~0.03m) (fig. 8).

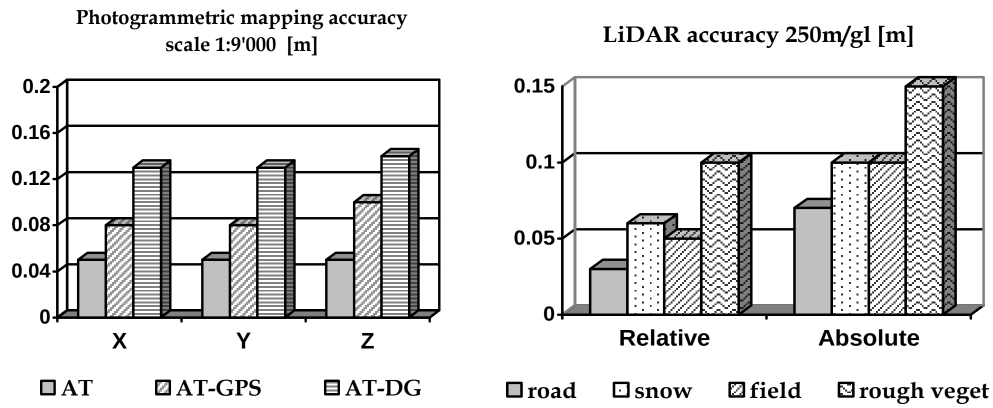


Figure 7: Mapping accuracy level for a flight height of 250-300m

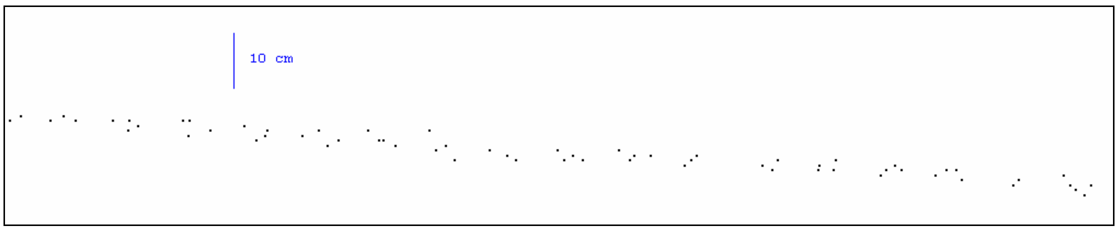


Figure 8 : Residual noise on a flat road

Due to the inner noise of the laser measurements, it is impossible to achieve an absolute precision better than 3 cm (if we assume that the trajectory is error free…). By flying at 50m height above roads, we confirm this idea: Without shift adjustment on GCP's, there is no way to get the altimetry better than 6cm. By adjusting the point cloud and using a smoothing filter (decrease point density by computing key points), it is possible to reach the noise level (tab. 1).

	Point number	Max resid. [m]	Average [m]	Std deviation [m]	RMS [m]
40m	524'355	0.094	0.034	0.030	0.045
40m smooth 1cm	219'693	0.104	0.035	0.030	0.045
40m smooth 5cm	31'509	0.099	0.038	0.027	0.047
60m	652'821	0.106	0.056	0.025	0.061
60m smooth 1cm	311'343	0.106	0.056	0.025	0.062
60m smooth 5cm	34'657	0.111	0.057	0.027	0.063
Altimetry adjustment					
40m smooth 1cm	219'693	0.064	0.005	0.030	0.030
60m smooth 1cm	311'343	0.051	0.006	0.025	0.025

Table 1 : Altimetry residuals of laser point cloud on GCP's. Smoothing filter have been applied to estimate the noise removal potential

4.3. Practical recommendations

60 helicopter flights brought lots of experiences and teach us a lot of useful practical recommendations to follow.

The calibration step is one of the crucial points because the final mapping accuracy will depend on it. The lever arm is the less sensitive because it propagates the error only in translation. The boresight is more critical because errors propagate with distance to ground. Once the calibration is performed, the experience shows that the IMU-LiDAR boresight is quite stable (depends only of the rigidity of the assembly) while the camera-IMU boresight might be strongly affected by the inner orientation stability. Thus, it is extremely important to regularly check the inner orientation parameters of the camera. Usually medium size CCD camera is composed of a body separated from the digital back. While the back keeps its removal function (for cleaning CCD), it will be hard to guaranty a perfect stability of the PP. The focus must be set on the immobilization of the package back-body-lens. The temperature and vibration also affects the focal length and PP. To prevent from making errors in image processing, there is a way to have inner control to detect problems: comparing laser measurements with stereoscopic view of the image. If only a systematic shift in altimetry is observed, it is possible to correct only the focal length without GCP's to fit both together but it is rarely the case. Usually, PP and focal can move and then only few GCP's and aerial triangulation can recover a correct inner orientation. In 30 flights, we noticed that the calibration of the camera changed by period (temperatures, sensors maintenance, shocks) in a range of 30μm for focal and 15μm for PP.

Regularly, we measures 5-10 GCP's on a part of the area and check the calibration there. It is extremely recommended for high accuracy purpose.

The second important aspect is the GPS quality. As the entire computed GPS-IMU trajectory depends on the GPS processing, it is crucial to plan the flight in favorable satellites visibility especially in mountain areas or when flying at low height. Thus, it is relevant to compute satellite visibility by taking into account terrain obstructions.

The final tip concerns the redundancy of the acquired data. Integrating photogrammetry and LiDAR provides redundancy. It would be pity not to use it. As systems become more and more complex, the reliability of all sensors can not been guarantied at 100%, even with expensive commercial system. Then it is interesting to think in terms of "back-up" data. The imagery is the best back-up while it is possible to reconstruct everything from it.

5. Outlooks

Helimap system® is not a frozen system. Practical experiences lead to evolution of it. The system is currently operational and provides accurate results within the 10-15 cm accuracy level with the unique capability to map flat or vertical areas with the same resolution and precision. Its fast setup allows deploying it within hours. Respecting certain rules ensures reliability in the quality of the data.

The current development focused on more ergonomic pilot navigation software and on a more compact and integrated data acquisition module. Future investigation will lie on the use in other aircrafts (motorized parasail for example) or for terrestrial kinematics applications (boat, truck).

Acknowlegment

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