HELIMAP: Rapid Large Scale Mapping Using Handheld LiDAR/CCD/GPS/INS Sensors on Helicopters

Jan Skaloud, *EPFL*, Julien Vallet, *UW+R, Switzerland*
Kristian Keller, *DNSC, Denmark*
Gregory Veyssiere, *EPFL*, Otto Kölbl, *EPFL, Switzerland*

BIOGRAPHY

Jan Skaloud is a senior scientist and lecturer at Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland. He holds a Ph.D. and M.Sc. in Geomatics Engineering from the University of Calgary and conducts research in GPS/INS/Sensor integration, mobile mapping and kinematics geodesy.

Julien Vallet graduated from EPFL with M.Sc. and Ph.D. in 1998 and 2002, respectively. He is currently responsible for directing airborne operation at UW+R SA.

Kristian Keller is a M.Sc. in geodesy and scientist at the Danish National Space Centre (DNSC). He has over ten year experience with airborne laser scanning and airborne gravimetric surveys.

Grégory Veyssière is a visiting research fellow at EPFL working towards diploma engineering thesis at INSA Strasbourg, France.

Otto Kölbl is a professor at EPFL. He directs laboratory of photogrammetry and has a long research record in this field.

ABSTRACT

The HELIMAP is a portable mapping system for quick helicopter deployment. It integrates high accuracy navigation sensors (GPS/INS) with Airborne Laser Scanner (ALS) and high-resolution digital (CCD) camera. The system is operated from the side of a helicopter and its unconventional design offers several conceptual advantages in comparison with other systems: quick installation (minutes), no need of recalibration after installation, possibility to map vertical or horizontal features with an optimal geometry and maintaining optimal flying parameters for camera and laser sensors at the same time. The products are high-resolution (<1m^2) / high precision (~0.1m) DSM/DTM and ortho-rectified image (<0.05m/pixel).

The paper presents the system hardware and software components, system calibration and a road map from acquisition to mapping product. Solved and open problems related to confrontation of GPS/INS with the challenging environment of helicopter navigation are exposed. The system mapping accuracy is evaluated for different scenarios using integrated or direct sensor orientation. Finally, the paper focuses on evaluating the laser surface determination accuracy under different scenarios and over different terrain.

INTRODUCTION

History

The development of the HELIMAP system started back in 1999 as a response to the country needs in natural hazards mapping and management. The emphasis was placed on high resolution and accuracy (10-15cm), low cost and system portability (i.e. independence of a carrier). The sensor choice was a high-quality portable analogical camera [1] that was later replaced with high-resolution digital camera [2]. Originally adopted approach to GPS/INS integration was a commercial solution that was later replaced with an internal development on hardware

Figure 1: System in nadiral configuration.

and software level [3], [4]. Parallel development focused on methods for rigorous system calibration [5]. More recently, the system has been extended for a medium-range ALS (LiDAR) and started to attract attention [6]. New imagery and LiDAR sensors were implemented during winter 2004/2005 (Figure 1). Currently, the HELIMAP integrates the latest in sensor technology and in sensor orientation and calibration. The system operates in missions related to natural hazard management and corridor mapping while serving the academia as a unique research tool. When needed, its data are exploited by universities, mapping-agencies, administration, and rescue services as the system can be quickly and easily put from stand-by into operation mode.

Concept

The system concept adapts a modular design with off-the-shelf sensors and modern communication to facilitate upgrades or part replacements. Its setup proposes combination of hardware the cost of which is lower than €100K in total (LiDAR, CCD, IMU, and GPS) and does not require a dedicated carrier for its utilization. Its structure and the 'hand-held' or 'hook-on' mounting (Figure 1) is unique world-wide and represents number of advantages. The main characteristics are the following:

- Lightweight carbon-aluminum structure combining GPS/INS/ALS with high resolution digital camera to a common sensor block of 40x40x25 cm / 12kg. The block can be handheld or easily suspended on the side of a helicopter.

- Perfect setup for large-scale/small-area airborne surveying: Natural hazards mapping, corridor-mapping (power lines, railroads, highways, etc.), open pit mines, gravel pits (periodic determination of extracted volume), forestry (oblique ALS-mapping allows to gather more information about the canopy).

- Very little installation time (<30min) allowing fast deployment on a short notice. Thanks to the sensor-head structure, no re-calibration of spatial offsets or boresight is needed after the installation.

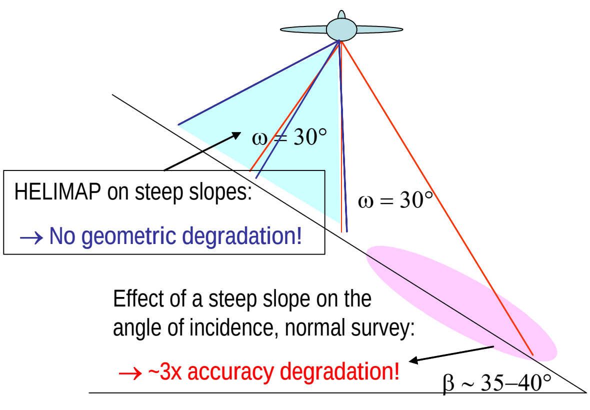

Figure 2: Steep slopes looks flat with HELIMAP as the system is kept perpendicularly to the terrain.

- Oblique and nadir surveying can be performed with the same configuration and the same accuracy. As shown in Figure 2, the usual accuracy degradation due to the week angle of incidence on steep surfaces is eliminated by turning the sensor's head towards the slope. This is achieved either manually (hand-held installation) or during the setup (suspended installation).

- The LiDAR and the digital camera have very similar field of view of 60° and 56°, respectively, and the flying parameters (height and speed) can be kept optimal simultaneously for both devices in most missions.

SENSOR HEAD

The sensor head consists of navigation and remote-sensing devices, all rigidly joined by a carbon-aluminum structure (Figure 3a). Besides the sensors, the frame contains also the points of anchorage for safety cables and suspension as well as handles for manual steering. A button of camera manual trigger is connected to one handle together with a switch for accepting automatic trigger from a PC based on LiDAR and navigation data. The operator can always override the camera automatic trigger using this button.

LiDAR

The ALS is short-range 2D scanner LMS-Q240-60 [7]. The scanning angle is 60 degrees with maximum range of 450m at 80% reflectance. Its rotating-mirror mechanism provides linear, unidirectional and parallel scan lines with a programmable rate up to 80 scans/s. The rate is chosen as a function of desired point density and flight parameters. Contrary to most today's airborne scanners, this instrument adapts a shorter laser wave length of 900nm that assures favorable reflection also on snow covered surfaces.

Camera

The digital camera is a Hasselblad H1 with focal length of 35mm or 80mm. The choice of the lens was based on its low distortion, a comparison of MTF curves and field tests [8]. Attached to the lens is the digital back Imacon Xpress 132C. The hosted CCD chip has 5448x4080 pixels (22Mpix) with 9µm pixel size. The maximum image rate is less than two seconds. The shutter aperture generates a pulse that is interfaced via X-sync bus of the H1 camera to GPS event marker input.

GPS/INS

The sensor head also incorporates the LN200/A1 tactical grade IMU and GPS-L1L2/GLONAS airborne antenna. The antenna is mounted on a carbon mast that can change orientation with respect to LiDAR/camera plane from 15 to 90 degrees according to mapping requirements.

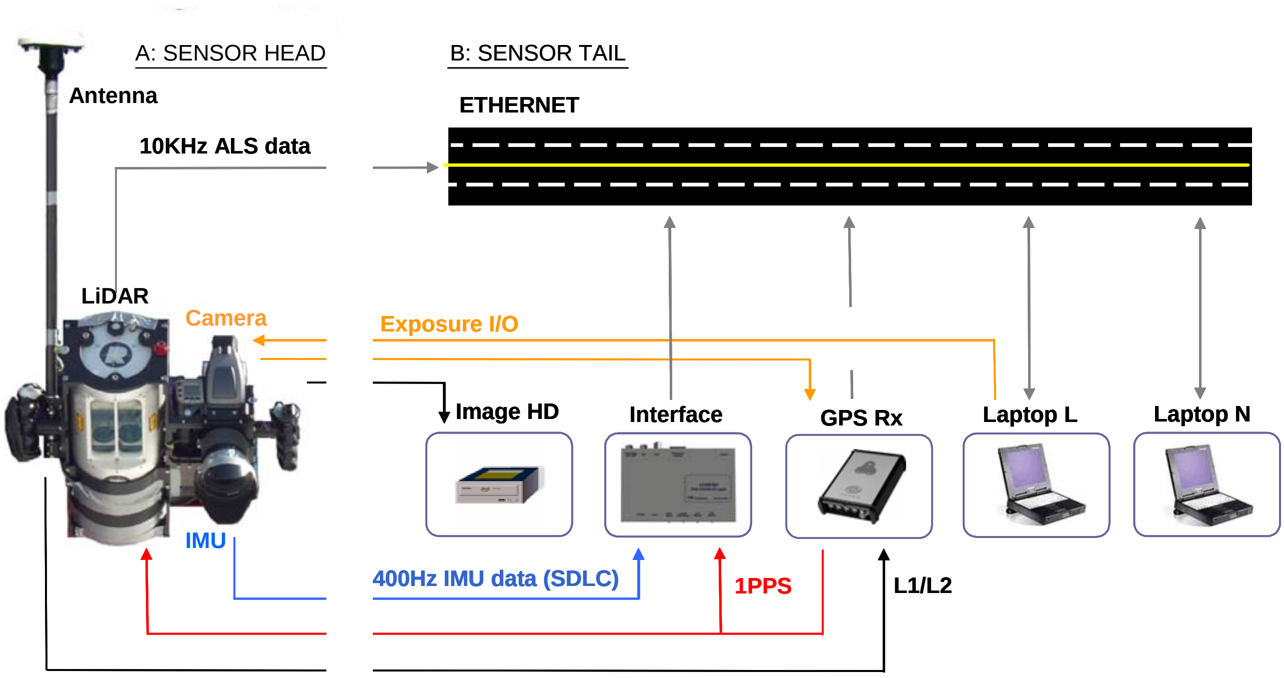

Figure 3: a) Image of compact sensor head, held or suspended outside helicopter. b) Schematic organization of ‘sensor tail’ responsible of data acquisition, synchronization, navigation and instrument command.

SENSOR TAIL

The sensor head is connected via cables to sensor ‘tail’, an infrastructure that assures instrument alimentation, command, data synchronization and data storage. As shown in Figure 3b, the system communication spine is the Ethernet that assures fast data exchange between the devices. The GPS, the LiDAR and the computers implements Ethernet naturally, the IMU is connected to this backbone via a specially designed interface [4] that also synchronizes the incoming inertial data in GPS time frame. The laptop ‘N’ in Figure 3b is charged with GPS/INS data acquisition, interpretation and flight management. The laptop ‘L’ gathers the voluminous LiDAR data and pilots the camera shutter in function of flying speed, height above terrain and a chosen overlap. The camera events are time-stamped by the bi-frequency GPS receiver and back communicated to the flight management program. Images are stored on an external image bank that allows taking up to 850 pictures at full resolution. With the Ethernet as a backbone the interfaces between the individual elements are standardized and the system adapts an open and modular design with replaceable off-the-shelf components. Finally, an uninterrupted power supply originally designed for the IMU and its interface [4] was extended to supply power to the whole system. It ensures seamless switching between helicopter and 24VDC battery power and conforms with instruments requirements.

DATA FLOW

A coarse data flow from the sensors to digital surface / terrain model (DSM/DTM) and ortho-rectified image is depicted in Figure 4. The carrier-phase differential GPS positioning is integrated with inertial data in a loosely-coupled configuration. The setup allows for use of different software packages and foresees real-time version with thorough RT quality control in the future. The laser range, amplitude and encoder measurements are first interactively separated into individual flight-lines. These data and the 400Hz GPS/INS trajectory estimate are combined together with calibration information in the LiEO package to generate laser point-clouds in desired coordinate system. This output is further handled by TerraScan™ or other laser point clouds processing package for final surface and/or terrain model determination. This last step may be guided (or potentially integrated) by the image data.

The parameters of camera exterior orientation (EO) are calculated by the CamEO based on the same GPS/INS trajectory and appropriate calibration information. If rapid or less accurate products are needed, camera direct-georeferencing (DG) is used together with the laser-determined DTM for ortho-photo production. In the integrated sensor orientation scenario, (‘Assisted-Automated’) Aero-Triangulation (AA) AT is introduced as an additional step for improved robustness and accuracy. The inclusion of GPS/INS derived EO can substantially ease the process of automated tight-points generation and this approach usually works well in a

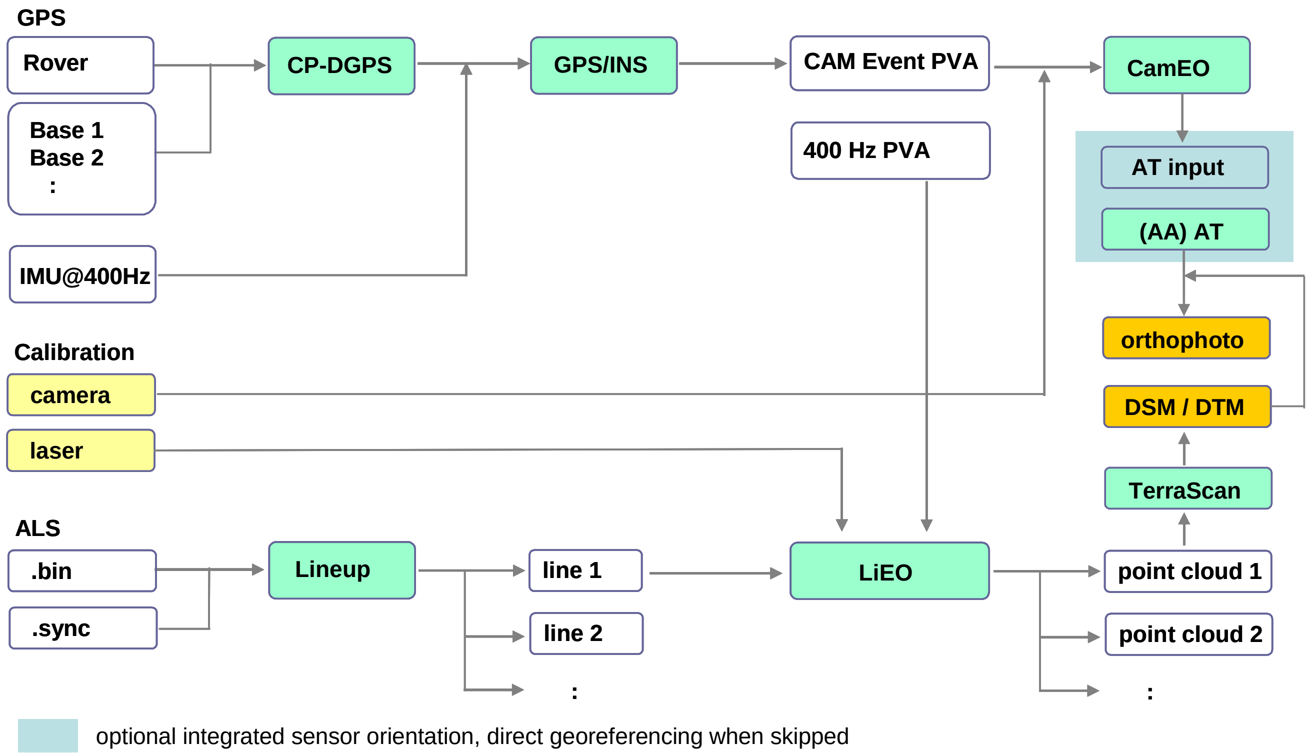

Figure 4: Direct georeferencing data flow for the orthophoto and DTM/DSM production.

terrain of a favorable texture (generally, outside the forest).

SYSTEM CALIBRATION

The system calibration is divided into the following steps:

Lever arm
Lever arm is the spatial offsets between the sensors origins for all possible GPS antenna positions (15° to 90° in 15° steps). This is determined with sub-centimeter accuracy and once for all in the laboratory by tachometric means.

Boresight
Boresight describes the angular misalignment between the IMU and the CCD/LiDAR due to the mounting. The boresight with respect to the camera is determined using a thorough approach introduced in [5], and with an accuracy better than 0.005°. The boresight determination with respect to LiDAR requires special flying pattern over a selected terrain or feature(s). After that, there are numerous 'ad-hoc' approaches adopted by the ALS industry with varying level of exactness. We have first tested a method based on matching the DTM between different flight lines [9] that is implemented within the TerraMatch™ package. Most likely due to complicated terrain nature, this approach had only a limited success. Finally, a widely used 'try-and-error' approach based on matching selected terrain profiles has yielded satisfactory results. A rigorous approach for ALS boresight is most likely yet to come.

Interior orientation
The focal length and the principal point of the camera is calibrated in-flight by the AT approach and with the use of GPS/INS data. As shown later on, no systematic errors were found in LiDAR. Hence, the factory calibration in ranges corresponds to the specified noise level of 0.03m.

OPERATIONAL CHALLENGES

The operating environment of a helicopter represents a challenging environment for GPS/INS integration when searching the sub-decimeter and sub-arc-minute positioning and attitude accuracy, respectively. On the one side, the benign helicopter dynamic has a direct influence on the alignment accuracy of the inertial system. On the other side, the vibration level induced by the rotor may be sufficiently intrusive to limit INS short-term orientation precision. Both factors may limit the overall system performance when employing a tactical grade IMU with 1°/h gyro drift rates.

To improve the INS alignment accuracy, GPS-derived azimuth aiding has been adopted [1] by placing a second antenna on helicopter tail. Nevertheless, this approach was found less practical in some missions and was therefore replaced with periodically repeated flight patterns that take short time to execute.

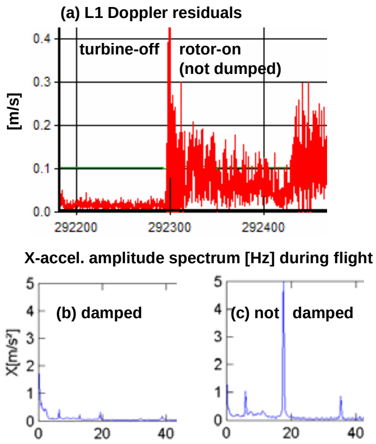

Figure 5: Effect of vibrations on GPS and IMU sensors.

The difficulties of rotor-induced vibrations are twofold. First, they jerk the laser beam and limit IMU pointing accuracy. Second, they may excite unwanted harmonics on the carbon-rigid mass holding the GPS antenna. The amplitude of this vibration can be sufficiently strong to hamper the GPS-velocity (used for aiding the inertial system) or in extreme, to cause satellite loss of lock (Figure 5a). Fortunately, the vibration level may be efficiently mitigated by a designed suspension for the sensor head as shown in Figure 5b,c on the IMU data. Similar level of dampening is achieved when the sensor block is hand-held by the operator.

DIRECT VS. INTEGRATED SENSOR ORIENTATION

The dilemma of choosing direct georeferencing (DG) or integrated sensor orientation depends on many factors. The rapidity of the former and the robustness of the latter have already been mentioned. Other selection criteria for a specific remote-sensing task are discussed for instance in [10]. A non-trivial and often underestimated decisive factor is the choice of a mapping frame and projection in which ortho-photos are delivered. The non-Cartesian character of national-wide projections is causing theoretical and practical distortions within the AT bundle adjustment using GPS/INS observations [11]. A detailed discussion on this subject is, unfortunately, beyond the scope of this paper. In summary there are three main-stream solutions when using AT/GPS/INS:

1. Set of tight-points (homologous points) is determined first in a Cartesian coordinates (e.g. tangent-plane projection) and then transformed to the national frame and map projection. Subsequently, the AT is re-run using the new set of coordinates for these points and thus with respect to the national system. The drawback is the introduced distortion to the bundle of image rays, see [11] for details.

2. Cartesian, typically, tangent-plane projection is used to reconstruct the complete scene and the ortho-image. Subsequently, the model is rigorously transformed to the EFEC-frame (Earth-Fixed-Earth-Centered) and then datum transformation and a projection is applied. This is a rigorous approach but requires relatively laborious 3D ortho-image transformation and re-sampling.

3. The EOs observed by GPS/INS are modified for the chosen frame and projection prior to the AT input. The AT software can then be run only once and the ortho-images are generated directly in the desired system of coordinates. This approach is fast but not rigorous for the same reason as the first one. Further approximations are usually taken in the transformation of the camera observed attitude.

The generation of the laser point cloud and the subsequent derivation of a DSM/DTM do not escape the datum-projection problematic. Here, either of the approaches two and three is applicable, although the point-to-point transformation of the DTM usually does not require additional re-sampling. Height corrections due to geoid apply in all cases.

The following evaluation presents the system absolute accuracy at discrete points determined on the images. A test field with 25 GCPs was repeatedly used for this purpose. The scale of the taken images within few strips varied from 1:9000 to 1:11000 and the accuracy of GCPs (used also as check-points) was ~0.02m. As some GCPs were not specially signalized, the measurement of their image coordinates may introduce additional error of 4-8μm (i.e. 3-8cm in the object space).

The indirect (AT), integrated sensor orientation and DG approaches to photogrammetric mapping are compared in Table 1 in terms of constrains and empirically estimated accuracy. The RMS values for the DG are slightly higher than those for the indirect or integrated approach, but still remain at decimeter level. Therefore, the price to pay when adopting DG is not necessary in reduced accuracy but rather in lower robustness and quality control. On the other hand, adopting DG will increase the delivery speed and thus the productivity.

Method	Constrains		RMS at GCPs [cm] application field		
	GCP	Block	σ_0 [μ]	X,Y	Z
AT	•	•	2	4	4
AT-GPS		•	2	9	10
AT-GPS-INS			2	9	10
DG			7	10	14

Table 1: Mapping accuracy vs. different approaches.

SURFACE DETERMINATION

The quality of surface determination depends on the accuracy of the laser measurements, the point density and the precision of the orientation of the laser platform. For the terrain modeling one has also to take into consideration the terrain obstruction; furthermore the derivation of a digital terrain model requires the thinning out of the point cloud and the derivation of break lines. Various tests have been run and meanwhile also a number of projects have been realized. For data processing we used the DTM software Terra Scan which is specially conceived for the processing of laser measurements and offers a vide variety of filtering and modeling processes and tools for the evaluation of the resulting data. As additional control data were injected into photogrammetric workstations and control data were determined by GPS measurements and photogrammetric measurements.

In order to show here the quality of a laser-derived DTM we refer to a test flight over a hockey ring, which was snow covered at the time of the survey flight. Several overlapping and crossing lines were flown over the terrain with different characters with a very high-point density of up to 5 points/m^2 (cf. Fig 6).

A / A purely qualitative precision analysis is obtained by the derivation of a shaded relief and the terrain presentation by contour lines with an interval of up to 10cm. Furthermore the obtained 3D scenes were rendered (cf. Fig. 7a).

B/ Data post processing is a very important part as the laser points are in general very dense, whereas the user of a DTM wants a minimum of mass points and the determination of break lines. Depending on the terrain roughness the optimum point density can be estimated according to various formulas (cf.[12]). Applied to the points density of a DTM derived from laser measurements we obtained the relation shown in Figure 7. One remarks that the DTM accuracy remains constant for point densities between 0.3m and 1 point per 5m^2 m. However depending on the soil cover the initial laser sampling rate must be much higher; in order to remain on the safe side about 5-10 times higher then the final point density.

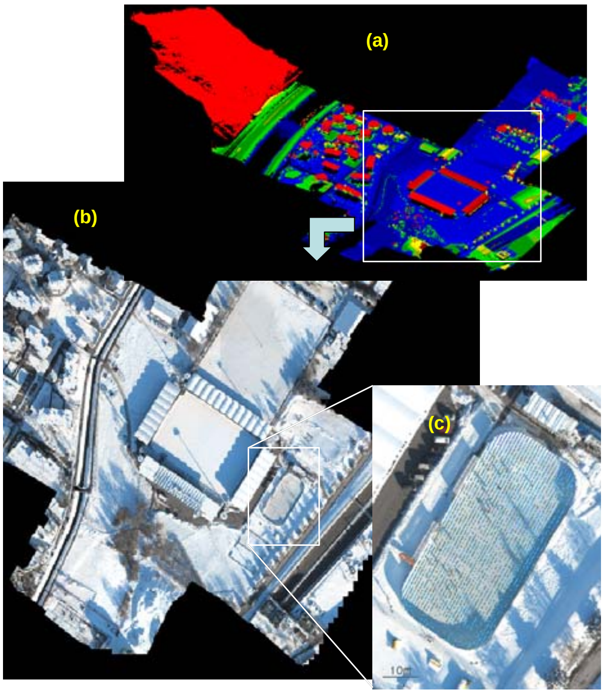

Figure 6: Two strips over snow-covered stadium: (a)-color coded laser point cloud, (b)-orthophoto, (c)-zoom on the hockey ring with overlaid laser points on the ice.

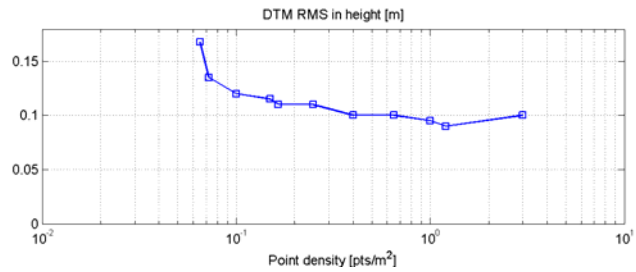

Figure 7: Vertical DTM accuracy as a function of grid spacing (=sampling density).

C/ The most thorough control is achieved by control points; ideal are field measurements (GPS points) due to the high accuracy. However these points should be representative and model also problematic areas. In order to avoid that the points lie only in a commodity position we mainly worked with dense profiles, derived from photogrammetric measurements.

Surface	Accuracy-RMS [m]	
	relative	absolute
Road	0.03	0.06
Snow	0.06	0.10
Prairie	0.05	0.09
Vegetation	0.09	0.14

Table 2: DTM profile accuracy on different surfaces.

Table 2 shows the synthesis of several tens of profiles restituted over different surfaces. The absolute precision varies from 6 to 14cm depending on the soil character: the higher the vegetation the higher the incertitude in the laser last-echo return with respect to the real terrain. The relative precision (noise) within individual strips varies from 3cm on road to 9 cm in dense vegetation. However, it is important to keep in mind that the accuracy of the control data is also in the order of 3cm.

SUMMARY

This paper presented the design of a portable system baptized HELIMAP. Its concept of integrating LiDAR with a digital camera and GPS/INS sensors represents a new 'light-weight' class of instruments that can well serve part of the large-scale airborne mapping industry. Quick mounting and dismounting, no recalibration after installation and flexibility in geometry are some of its characteristics. Other advantages include modularity and lower acquisition costs (by airborne standards) of its individual components. The system has been recently upgraded and the new sensors were exposed to numerous missions in natural hazards and corridor mapping flown during the last few months. This experience served as a base for accuracy and performance analysis from which we judge the DSM/DTM accuracy determined by the system at $\leq$0.1m and 200m flying height. This conforms to the requirements on orthophoto generation which has at this height a pixel size of 5cm for the 35mm focal length.

REFERENCES

[1] J. Skaloud and J. Vallet, "High Accuracy Handheld Mapping System for Fast Helicopter Deployment," presented at Joint International Symposium on Geospatial Theory, Processing and Applications, ISPRS Comm. IV, Ottawa, Canada, 2002.

[2] J. Vallet and J. Skaloud, "Development and Experiences with A Fully-Digital Handheld Mapping System Operated From A Helicopter," presented at The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Istanbul, 2004.

[3] J. Skaloud and P. Viret, "GPS/INS Integration: From Modern Methods of Data Acquisition to New Applications," *European Journal of Navigation*, pp. 60-64, 2004.

[4] VNR, "LN-200 IMU Data Interface/Logger," VNR Electronic SA, www.vnrsa.ch, 2003.

[5] J. Skaloud and P. Schaer, "Towards A More Rigorous Boresight Calibration," presented at ISPRS International Workshop on Theory Technology and Realities of Inertial/GPS/Sensor Orientation, Castelldefels, Spain, 2003.

[6] P. Gordon, "The ISPRS 2004 Technical Exhibition - Istanbul: Dominating Airborne Imaging Sensors," *GeoInformatics*, vol. 7, pp. 30-37, 2004.

[7] Riegl, "LMS-Q240, www.riegl.co.at," 2004.

[8] O. Kolbl, "Transfer Function in Image Data Collection," in *50th Photogrammetric Week*. Stuttgart, Germany, 2005.

[9] H. Burman, "Calibration and Orientation of Airborne Image and Laser Scanner Data Using GPS and INS," in *Geodesy and Photogrammetry*. Stockholm: Royal Institute of Technology, 2000, pp. 107.

[10] I. Colomina, *GPS, INS And Aerial Triangulation: What Is The Best Way for The Operational Determination of Photogrammetric Image Orientation*, vol. 32. Munchen, 1999.

[11] C. Ressl, "The Impact of Conformal Map Projections on Direct Georeferencing," presented at Photogrammetric Computer Vision, Vienna, 2002.

[12] A. Flotron and O. Kolbl, "Precision terrain models for civil engineering," Official publication Nr. 38 of OEEPE December 2000.