Reliability of Direct Georeferencing - Beyond the Achilles' Heel of Modern Airborne Mapping

JAN SKALOUD, Lausanne

ABSTRACT

Within the past decade, the application of Direct-Georeferencing (DG) via GPS/INS integration has brought a small revolution into the mapping industry by driving down the cost of mapping products and speeding up the production cycle. Although DG can now be considered as a well established industrial method, there remain a number of open questions related to its reliability. This paper gives an overview of the currently adopted approaches and charts other possibilities viable today from which DG could benefit. This work follows as 'a free and non-exhaustive synthese' of recently prepared report to EuroSDR community (Skaloud, 2006) and some additional investigations.

1. BEYOND THE 1ST DECADE

The method of Direct Georeferencing (DG) is not new and already celebrated 10 years of its successful commercial application (Hutton and Mostafa, 2005) and even longer time in academia (Schwarz et al., 1993). After some initial hesitations following its introduction, the application of DG via GPS/INS gradually became an inherent part of modern airborne mapping instrumentation. Implementing DG not only speeds up the mapping process and thus increases the productivity, but also opens the door to new monitoring applications. At the same time, it has enabled the practical introduction of sensors such as lasers, line scanning cameras, and radar systems into civil airborne mapping.

1.1. The method of Direct Georeferencing

Georeferencing can be defined as a process of obtaining knowledge about the origin of some event in space-time. Depending on the sensor type, this origin needs to be defined by the parameters of Exterior Orientation-EO such as time, position, attitude (orientation), and possibly also the velocity of the object of interest. When this information is attained directly by means of measurements from sensors aboard the vehicle, the term direct georeferencing is used. In other words, DG comprises a long process of information flow that involves acquisition, synchronization, processing, integration, and transformation of measurement data from navigation (GPS/INS) and remote sensing instruments such as frame or line scan cameras, lasers or radars. The term of DG is sometimes understood as a one-directional data flow from GPS/INS via the mapping sensor(s) to the mapped object. When there is a common treatment or a feedback between remotely sensed data and navigation parameters, the term of Integrated Sensor Orientation (ISO) is used.

1.2. Motivation

The presence of the DG instrumentation itself does not always guarantee its correct exploitation or the attainment of the needed quality of the EO parameters. The encountered problems related to undetected sensor behavior, varying data quality or consistency may be difficult to eliminate by the technology itself within the framework of its adopted use. In other words, the reliability of DG can be considered as the Achilles' heel of this otherwise revolutionary approach. In practice, the problem of reliability is rationally resolved by the ISO approach that simultaneously mitigates the errors due to GPS/INS, sensor data, calibration, datum or projection. Although proven and robust, the ISO comes with additional expense and – more important – with a considerable latency after the data capture. The goal of this contribution is in charting the current situation in the view of other available approaches or technological solutions which adaptation could help in addressing the reliability aspects of today's DG more rapidly and efficiently. These topics concern both the clients and manufactures, as they are often related to instrument- or method redundancy which influences the cost of a system but also the speed of production.

1.3. Outline

The presented investigations are divided into the following technology fields: GNSS, inertial sensors and estimation methods, integrity and communication, calibration with integrated sensor orientation and problems related to transformation of EO parameters. Each field describes the current situation with respect to DG and discusses additional existing possibilities. These do not claim to be complete or exhaustive; however, they claim to address the essential features, methods and processes, the combination of which could increase the reliability of DG substantially without setting large side penalties.

1.4. Some definitions

Reliability has various interpretations. In the DG context it mainly refers to 1) to the controllability of observations, that is, the ability to detect blunders and to estimate the effects that undetected blunders may have on a solution; 2) the probability of a system to function under stated conditions for a specified period of time. The former is often decomposed into internal and external reliability. Internal reliability relates to the amount of gross error in an observation, not detectable at a certain probability level while the external reliability relates to the effect of non-detectable blunders on the estimated quantities (for example coordinates). The second context can be expressed mathematically as $R(t) = \int_t^\infty f(x)dx$ where *f(x)* represents the Failure Probability Density Function (FPDF) and usually refers to physical signal failures.

By definition, *integrity* is a measure of trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of the system to provide timely warnings to the user when the system should not be used for the intended operation (Ober, 2001). The integrity risk is the probability of an undetected (latent) failure. The systems of highest ambitions are of high reliability (i.e. never break down) and high integrity (i.e. a brake down is immediately detected) but in principle there can be systems of high integrity but low reliability or vice versa.

2. BEYOND THE C/A CODE

According to a conservative estimate there is currently about 50-100 millions of GNSS civilian users that are practically depending on the availability of one system and one signal (Parkinson, 2007). The system is GPS and the one relatively fragile signal is the L1 C/A code, which correct acquisition is still the prerequisite for tracking other signals. This infrastructure dependence is even profound in DG scenario, where (in most cases) the position of the airborne carrier is determined by one dual frequency GPS receiver (and one antenna) on board of a vehicle. The trajectory accuracy is usually improved off-line by carrier-phase differential data using forward/backward processing and ambiguity determination/validation for one or more base stations. In situations like platform stabilization, real-time GPS/INS integration is performed, however, not in the carrier-phase differential mode. This means that the final answer on data accuracy and reliability cannot be obtained with high confidence during the data acquisition phase. Moreover, possible occurrences of local signal distortions affecting both the GNSS code and phase measurements remain difficult to control and become apparent only later in ISO (bundle adjustment, LiDAR strip adjustment). In general, the reliability measures are replaced by "data QC" that is introduced on different levels. It comprises checks on grammatical (physical) and semantic (validity) aspects of the signal, the geometric situation in real time, and processing residuals in post-processing. Overall, the GNSS-derived position is the decisive factor for trajectory accuracy at lower frequencies (<0.1Hz). With all the progress in carrier-phase differential techniques its application usually marks the mission outcome (i.e. success or failure).

2.1. Aviation technologies

There are several technologies and methods put forward by aviation from which DG could benefit. Let mention at least few of them. In terms of physical reliability and integrity, there is a great difference between aviation-certified GPS receivers and the consumer (even high-end geodetic) GPS receivers (Studeny and Clark, 2004). Apart from the resistance to harsh environment, electromagnetic interference, clearly defined low-dB tracking scenarios and time to first-fix, the avionic receivers use standardized methods for Fault Detection and Exclusion (FDE). The whole process is also known as Receiver Autonomous Integrity Monitoring (RAIM). It requires a minimum of 5 satellites and uses the probability density function and minimum bias or worst bias with fixed or variable threshold (Kuusniemi et al., 2004). It is based on the Bayesian approach of mixing probability density functions (nominal & failure case) and weighted by their probabilities of occurrence (Ober, 2000). RAIM can provide alarm during the flight but it is useful only if the operator has access in real time to this information and the possibility to act in order to correct the problem; for example by collecting new data or by changing the trajectory. RAIM is not a standard option in GNSS receivers (Ochieng et al., 2002) but is often available on high-end receivers. Nevertheless, it is not clear to which extent it is used in the acquisition phase of the DG process.

The Satellite-Based Augmentation Systems (SBASs) is another technology available for civilian users, which potential is most likely not fully exploited in the DG. SBAS currently comprise WAAS covering good part of North America, EGNOS covering Europe and parts of its surroundings, and MSAS covering part of Asia and Pacific including the Japanese territory. The signal of these systems is interoperable and they offer satellite signal integrity monitoring in flight (Ober, 2001) as well as estimates on 'normal' deviations in GNSS signals (such as atmospheric delays, satellite clock-, and ephemeris errors). In other words, such a system 'flags' obviously erroneous measurements and computes quality metrics for the others that are broadcast along with the corrections. It is important to note that the decision what to do with this information is left upon the user receiver. Again, the receiver behavior using SBAS-input is regulated only in case of avionic equipment (Administration, 2002). The positioning accuracy using the suchlike augmented GPS signal is reported to be 1 to 2 meters vertically and around 1 meter horizontally for EGNOS (Toran-Marti and Ventura-Traveset, 2004), and slightly worse for WAAS (Yousuf and Skone, 2005) under optimal conditions. Although this accuracy is better than standalone GPS it is still insufficient for most DG applications. Nevertheless, the concept of monitoring the integrity and quality of the code-measurements can well contribute to the DG acquisition phase. Most likely, this has not yet been fully exploited for various reasons.

2.2. GNSS modernization

The modernization of the GPS signal comes in different phases. First, L2C (C/A code on L2) is being introduced on the IIR-M block of satellite. Although one SV has been in orbit since

September 2005, the nominal 24 satellites providing this signal are not scheduled before 2014 (Parkinson, 2007). The main advantages of this enhancement are an improved interference resistance and tracking capability (~3dB higher). Some L2C-ready receivers are already available on the market. The impact on trajectory accuracy and thus DG performance is not expected to be significant before the introduction of the 3rd civil carrier frequency (L5) on the Block IIF and Block IIIA satellites. This will take at least additional 10 to 15 years to materialize (Parkinson, 2007).

The GLONASS constellation is currently enjoying a new boom that is scheduled to continue until reaching a complete constellation of 26 SV in 2012. Its impact on DG applications has been limited up to now but may gain importance once more SVs become available. Since end of December 2005, the first experimental Galileo satellite has been transmitting its signal in space. Its full constellation is scheduled note before 2012; however, the 'five years goal' has been shifted already several times in the past. Hence, the improved reliability through redundancy of systems, satellites and signals is not expected to happen any earlier before 5-7 years from now.

2.3. The network is the receiver

The double differencing (DD) of GPS carrier-phase (CP) and code data is the most common technique in trajectory estimation that allows achieving cm- to dm- level positioning accuracy under 'normal' conditions. For this end, the best estimate of the DD carrier-phase ambiguity needs to be computed. The expected performance of ambiguity resolution is measured by its success rate given by the probability distribution of the integers. In theory, instantaneous success rate of ~99.90% can be obtained in 'optimal tracking conditions with 6 satellites over short baseline. However, local disturbances such as multipath, radio interference or ionospheric disturbances can quickly jeopardize this theoretical value. Another limit affecting the ambiguity fixing/reliability is the baseline length between the base station and the rover. This limit can be effectively mitigated via a network of reference stations.

The network differential GPS techniques fall into one of three categories: (1) measurement domain, (2) position domain, and (3) state-space domain. Category (1) algorithms provide the user with corrections from a reference station or a weighted average of corrections from a network of reference stations. In approach (2), the user derives independent positions using corrections from separate reference stations. A weighted average of these solutions is then computed. The disadvantage of algorithms of group (1) and (2) is a degradation of accuracy with distance from the network centre. Moreover, (2) is not very well suited for ambiguity resolution although it is probably the most common approach used in DG applications (in post-processing). Its alternative is the true multi-baseline processing that is more common in studies of geodynamic phenomena. In this approach, all baselines are computed together, taking into account the inter-baseline correlations which arise from observing a GPS network simultaneously (Craymer and Beck, 1992). The approach (3) tries to estimate the real physical parameters as satellite clocks and orbits, reference station tropospheric- and clocks errors. However, its success depends not only on correct modeling but also on parameter observability and correlation. The adopted RTCM 3.0 standard foresees transmitting the reference measurements rather than the corrections or parameters to the user, who is finally left with the option to decide how to exploit them (Brown et al., 2005). Hence, some previously investigated concepts of the trajectory reliability within the GPS network may become more practical to apply (Talaya, 2000).

2.4. “Real” is better than “virtual”

Only a few GPS receivers offer RTK solutions that work with several bases simultaneously, i.e., the user can set up a mini-network without implementing servers and other network-specialized tools. In one particular case, the firmware of the receiver allows three modes. The first mode selects the best (nearest) base and works with it. The second default mode works with all (up to three) bases independently and provides a weighted solution. The third mode works with all three baselines simultaneously inside the triangle provided the rover belongs to it (firmware-based instant Virtual Reference Station - VRS). In much wider scale, the VRS approach is frequently adapted by many European states that are covered by permanent networks in total of their territories. These networks have most applications in terrestrial or maritime domains. The provided correction rates of up to 1Hz are sufficient for the expected flight dynamics when using GPS/INS integration. Their main product are the real time and post-mission corrections, mostly provided as ‘nearest’ or ‘VRS’ modes (Vollath et al., 2002). Unfortunately, neither of these modes is well suited for trajectories that stretch over larger areas as the base needs to be frequently re-selected to prevent too long baseline lengths. Although some networks propose area-correction parameters (FKP), their derivation uses proprietary (and thus non-transparent) methods where reliability measures cannot be added without difficulties. Hence, the ground reference station measurements are usually applied off-line using the previously mentioned approach (2). The situation for DG applications can, however, improve when all reference data become available to the rover as proposed in the master-auxiliary messages concept (Brown et al., 2005). The major challenge will then remain in establishing a robust and fast communication link between the network and the carrier.

2.5. Summary

Table 1 summarizes the available GNSS methods with respect to the reliability measures and their ‘estimated’ usage in DG. The robustness of GNSS positioning as a method will improve with the increasing number of satellites and signals made available, however, the technologies available today could be better explored.

Segment/Error	Mitigation in RT	Mitigation post mission	Situation in DG
SV functionality	SBAS	DGPS analyses	Rarely done in RT
Rover functionality	RAIM	Too late	RT–usually only geometry
Base functionality	RT-Network	Network	Sometimes, no RT
Atmospheric Delays	SBAS	PPP, DGPS, CP-DGPS	via CP-DGPS, rarely in RT
Diff. Troposphere	Sensors at carrier + base(s)		Parameters not observed
Multipath/Interference	Receiver and antenna hw/sw design		Follows the evolution
Long Base	Multi-base processing, Master-Auxiliary		Not optimal, no RT
Ambiguity	RTK	CP-DGPS	Separated per base, no RT

Table 1: Reliability techniques in GNSS (RT= Real Time)

3. BEYOND “THE” KALMAN FILTER

Although the use of inertial technology in life-critical navigation and guidance applications requires the employment of several (redundant) inertial measurement units (IMU), DG exploits (almost exclusively) only one sensor. Should the unit start malfunctioning, the technology providers rely on detecting obvious failures within the hardware (in real-time) and the detection of eventual performance degradation via the integration with GPS data and its post-mission analysis. The conventional GPS/INS integration tools usually cannot identify sensor degradation from incorrect stochastic/model assumptions without the interpretation of an experienced user. In other words, the models and estimation methods used in DG are generally well optimized for expected sensor behavior but not for the marginal cases.

3.1. Physical redundancy

A redundant IMU (internally, in terms of sensors) is composed of more than three accelerometers and three gyroscopes. One approach is to combine the inertial observations in the observation space to generate a 'synthetic' non-redundant IMU; a second approach is to modify the inertial mechanization equations to account for observational redundancy. The latter may have some economical benefits as it does not require 'doubling' of all sensors. On the other hand, doubling or tripling all critical components is most likely the simplest, but not necessary the most economic way for fault detection and isolation. Although the concept of sensor redundancy is a common way for increasing the system reliability in avionics (Da and Lin, 1995; Yang and Farrell, 2003), this method is relatively novel in DG (Colomina et al., 2004) and also not available in commercial systems.

3.2. Analytical redundancy

The traditional GPS/INS integration cannot be considered as a good replacement of sensor redundancy and Fault Detection and Exclusion (FDE) for the following reason: the integration is usually performed within a Kalman Filter (KF) that is often engineered to trust the inertial senor more than the GPS in case of unpredicted disagreement. In other words, the KF is configured to reject GPS measurements outside the predicted interval of confidence that is built upon the models. As these models are tuned for the expected stochastic behavior of the sensors, they are not prepared to react correctly under unexpected conditions. The idea behind the analytical redundancy is in simultaneous evaluation of multiple models and assumptions. In case of KF, this concept can be described as sets of more than one KF organized into successive integration. A sensor or a subsystem is associated with a sub-KF, the output of which is re-integrated in the overall KF. In such federated design, each sub-KF is accompanied with an index that expresses the trust given to its results (by an internal controlling mechanism). In principle, fault detection can be achieved by comparing the outputs of the different sub-KF (Broatch and Henley, 1991; Wei and Schwarz, 1990). If there is only one IMU, a bank of KFs can be dedicated to run on different stochastic assumptions and models (Da and Lin, 1995). Although it can be very computational-intensive, the filter banks can provide the FDE via the analyses of innovation or estimate history even for tightly-coupled GPS/INS integration (Nikiforov, 2002). The available DG systems, though, are usually limited to conventional GPS/INS integration (tightly or loosely coupled) and do not offer specialized fault-detection algorithms.

More recently, the theory of Artificial Neural Networks (ANN) has been applied to the navigation-system modeling and fault detection. The ANN concept is based on a training process by which a set of coefficients are determined, usually without a physical meaning. The disadvantage of this concept in GPS/INS integration is that different motion scenarios require different training procedures and any abrupt change in motion may trigger an alarm that can erroneously be considered as a fault (Napolitano et al., 1998). Again, this technique is not known to be used in DG applications.

3.3. Outside the limits

There is no such thing as a perfect instrument and, despite its undoubted power; the integration cannot completely eliminate all possible errors. In other words, the data integration handled by a

Kalman filter/smoother cancels only the non-overlapping part of the sensor's error budget, i.e. the observable errors. Thus the 'band width' of the error cancellation may overlap only partially with the motion of interest as a function of instrument type and precision and the dynamics of an aircraft. For that reason, de-noising inertial data prior to mechanization has proven in some cases to be indispensable for attitude determination and effective procedures have been developed for that purpose (Skaloud et al., 1999). Another significant portion of the residual orientation errors is most likely to be affected by the quality of the in-flight alignment. Usually, the filter/smoother keeps on refining the attitude of the inertial platform all along the flight. The strength of this process is in its ability to decorrelate the misalignment errors from other error sources and is enhanced when sufficient dynamics are encountered (strong correlation among the desired parameters lowers the trust or the reliability in the estimated performance measures). Its weakness remains in the susceptibility to be influenced by the changes of the accelerometer errors and non-modeled part of the gravity field. Both influences appear as wrongly sensed accelerations that are 'eliminated' by (numerically) re-adjusting the previously aligned platform. Dropping the coupling with the accelerometers is possible once the platform is aligned and high accuracy gyros are available (i.e. 0.002-0.01 deg/h). As the high frequency part of the anomalous gravity field is likely to remain unmodeled, this concept may be appealing for certain types of applications when operating over a 'rough, unknown' gravity field or when flying along survey lines at constant velocity.

3.4. Summary

In general, the failures and malfunctioning in a GPS/INS solution can be detected and corrected for, or eliminated, by adopting either sensor or analytical redundancy. Although centralised KF have proven to provide better estimates, their fault detection capabilities are inferior to the decentralised and federated architectures. However, the centralized KF can be used for fault detection in a setup where a bank of filters of different stochastic assumptions is run in parallel and redundant sensors are provided. In principle, sensor redundancy is a necessity, i.e., without it only 'massive errors' or 'stop-of-operation' can be quickly detected. Although life-critical applications require triple redundancy as the minimum for the detection of failures and malfunctions, this may seem bit of luxury in DG domain. On the other hand, the evolution of inexpensive MEMS sensors may quickly remove such economical constrains. It also depends on whether it is sufficient to identify a faulty operation within a particular application, or whether exclusion and measurement replacement needs to be provided. In both cases, the currently available DG systems have little to offer as the (additional) sensor redundancy is practically non-existing and the analytical redundancy with FDE not adopted.

4. TOWARDS EARLY ALARMS

As formerly defined, integrity asks for the alarm in real-time or with a predefined latency. The bulk of DG applications require the fusion of data collected on the carrier and on the ground (e.g. by CP-DGPS). The prerequisite of integrity-factor calculation on all levels is therefore the establishment of reliable (intra-system) communication links between all important components. This approach is generally applied in avionics by expensive and redundant infrastructure while it is almost non-existing in DG. As the demand on trajectory accuracy in DG applications is usually higher, the approaches pursued in avionics can only be regarded as complementary. On the other hand, the time latency is less critical in DG and therefore the publicly available methods of mobile communication represent an interesting solution.

4.1. Integrating integrity concepts

In the current state of GNSS it is only the integrity of C/A code measurements that can be estimated efficiently. The aviation uses SBAS, GBAS (Ground-Based Augmentation System) and ABAS (Aircraft-Based Augmentation System) in the computation of the integrity level. Theses techniques include or can be complemented with RAIM and GPS/INS integration. Unfortunately, the applications of DG require a higher level of accuracy than provided by code measurements. Nevertheless, some conceptual approaches or existing integrity algorithms can most likely be applied to carrier-phase data and to GPS/INS integration. For instance, the integrity concept exploiting CP-DGPS technology has been proposed for the CAT-III landing with the help of ground beacons – pseudolites (pseudo-satellites) (Pervan et al., 1995). The application-based limits when broadcasting integrity messages were identified as multipath and radio interference (Braasch, 1996; Yang et al., 2004). The concept of pseudolites is also better suited for locally-limited applications and thus not for DG in general.

The integrity verification of phase measurements in real time requires redundancy in the computation of the positioning solution. Ideally, a second (redundant and independent) solution is computed. An approach could be based on the new civil signals of GPS and Galileo and the TCAR- (Triple- (or Three-) Carrier-Phase Ambiguity Resolution) (Forssell et al., 1997; Hatch et al., 2000) or FAMCAR techniques (Factorized Multi-Carrier Ambiguity Resolution) (Vollath, 2004). Thus, over-determination could be provided by a multi-carrier solution and a "traditional" CP-DGPS solution with the possible help of GPS/INS integration.

4.2. Another radio

Communication links are required for the real-time transmission of GPS corrections or measurements and integrity information. The transmission of this information ranges from (geostationary) satellites to terrestrial wireless data transmission techniques. For CP-DGPS, radio, cellular terrestrial, satellite, and wireless transmission are compared in Table 2 based on the availability of the communication network, the provided bandwidth, the range, and the cost of the communication link. The integrity requirement in avionics asks for a priority communication link, which is perhaps not necessary in DG. Furthermore, the communication link must not interfere with the GNSS signals (this issue is critical for satellite communication (Burrell, 2003)).

	Radio	GSM	GPRS/UMTS	SatCom	802.x
Proprietary	+	+/-	-	+/-	-
Data rate	+	-	+	-	+
Availability	+	-	-	+	+/-
Range	+/-	+	+	+	-
Multi-channel	-	-	+	-	+
Cost	+	-	-	-	+/-

Table 2: Comparison of communication links

Radio transmission is used for the traditional RTK applications. Its inconvenience for DG applications is the low range due to the low transmission power (regulated by legal requirements). GSM connection is limited by its data rate of only 9.6 kbps that corresponds approximately to 5 Hz of dual-frequency measurements from one reference station (Skaloud et al., 2004). The network setup or the arrival of new civil GNSS signals further increases the demand on data throughput. The availability of GSM (as well as GPRS and especially UMTS) decreases in rural regions of European countries and these technologies are not 'generally' available in many countries. The problems related to cell registration and hand-over are known to occur for fast moving carriers, such as aircrafts. GPRS has higher data bandwidth as compared to GSM. Unfortunately, the unexpectedly reduced and varying data throughput have proved to be an important inconvenience for kinematic CP-DGPS applications (Lehmann, 2005). The newly implemented UMTS technology can handle even higher data transfer rates; however, the transmission is usually handled by 'bursts' of packets and therefore has varying latency. The principle advantage of satellite communication based on Low Earth Orbiting- (LEO) satellites (the availability of GEOs is highly reduced in mountainous regions) is their availability. Some systems are limited to 9.6 kbps (for Globalstar), while the broadband service providers (e.g. skybridge, teledesic) offer somewhat higher data rates. The 802.x wireless communications techniques are of very short range with the exception of a directive array.

4.3. Summary

A complete integrity concept for DG would need to face a challenging communication problem when operating over large areas or remote regions. Although the use of dedicated infrastructure would be technically feasible, it is more realistic to foresee sub-optimal or hybrid systems that make a better use of the available technologies such as SBAS, nation-wide GPS networks, and existing modern communication systems. In smaller projects, the use of radio transmission seems (still) to be the most appropriate communication means for passing GNSS data or corrections and – perhaps in the future – integrity messages.

5. TOWARDS BETTER CALIBRATION

In the context of reliability, the Integrated Sensor Orientation (ISO) currently represents the security net for the DG. The net casting can be wider or narrower according to the sensor-type, accuracy requirements, and performance of navigation data. Moreover, the use of ISO is inevitable for the system calibration. Performing in-flight calibration is necessary to calibrate the aerial sensor (e.g. parameters of camera interior orientation, LiDAR range-finder offset, etc.) as well as some parameters related to the system installation (e.g. boresight). The concepts of state-space estimation (KF in GPS/INS) and bundle adjustments (AT) have the ability to accommodate and estimate additional calibration parameters. However, doing so may cause severe correlation among the variables and hamper the reliability of the whole process. Hence, independent methods and parameter separation is recommended whenever feasible. While the methods of integrated adjustments have room for improvements, this space is much larger for LiDAR or SAR than for the frame- or line-based sensors.

5.1. Calibration of aerial sensor

The calibration procedures for digital cameras were recently very well documented by the EuroSDR-initiated activity (Cramer, 2004). The situation remains less clear for LiDAR (Katzenbeisser, 2003) and almost proprietary in case of airborne SAR. The nature of DG stretches the requirements not only on the calibration accuracy but also on the separation (de-correlation) between the parameters. Moreover, the evolution of the parameters susceptible to environmental conditions (e.g. focal length changes due to temperature and pressure) needs to be modeled. ISO is less demanding in such explicit determination as it allows absorbing individual uncertainties (and their combination) thanks to the redundancy. Unfortunately, the DG is less tolerant in this respect and the need for introduction of temperature dependent camera model is getting recognized by some manufactures of modern digital sensors (Gruber, 2006).

5.2. Calibration of installation parameters

The calibration of the installation parameters can be divided into spatial (lever-arm) and orientation components (boresight). The use of GPS/INS or ISO for lever-arm calibration is not indispensable but often pursued. Although lever-arm effects can be correctly modeled within the KF (GPS to IMU) and/or within the bundle adjustment (GPS or IMU to aerial sensor) even the good observation conditions cannot match the accuracy of determination by independent geodetic means. Even worse, the lever-arm parameters are often strongly correlated with other systematic errors, e.g., of the inertial or the GPS observations (Skaloud and Schaer, 2003). Nevertheless, the software-driven approach of adding additional parameters represents often the most economic and convenient way for the user that is unaware of the related dangers. Finally, non-compensated variation of the lever-arm between GPS and the IMU due to platform stabilization is a frequent error committed in the practice.

In contrary to the lever-arm, the calibration of the boresight requires performing an ISO for attaining sufficient accuracy. The situation for frame-cameras is relatively well understood, although some conceptual approaches are better than the others and possibilities for improvements exists (Skaloud and Schaer, 2003). Conceptually, the situation is not very different for line-based scanners when ‘pushbroom’ image blocks are formed and adjusted (Tempelmann and Hinsken, 2005). On the other hand, the correct recovery of the LiDAR-IMU misalignment is considerably more complicated. The adopted approaches while functional, are recognized as being sub-optimal since they are labor-intensive (i.e., they require manual procedures), non-rigorous, or they provide no statistical quality assurance measures. The more rigorous class of calibration procedures or strip adjustments uses the modeling of systematic errors directly in the measurement domain (Filin, 2003; Filin and Vosselman, 2004), yielding practical and adequate results with good de-correlation between all parameters (Skaloud and Lichti, 2006). Although proven to work for LiDARs of different types (Skaloud and Schaer, 2007), the wider adaptation of such methods is yet to come.

6. BETTER HANDLING OF TRANSFORMATIONS AND DISTORTIONS

The traditional equations of photogrammetry are usually formulated within Cartesian frames. National mapping coordinates, however, are not Cartesian and the conventional approach addresses this fact via application of corrections due to earth curvature and map length distortion. Further, national maps are often based on geodetic datum that differs from the reference frame in which the GPS/INS solutions are obtained. There are, in principal, several different ways to solve these difficulties. Nevertheless, when DG is applied with the aim of performing the restitution directly in national coordinates the parameters of EO needs to be transferred there too. This usually implies enchaining several transformations for both the position and orientation while also considering the height reference system based on physical parameters.

The non-Cartesian character of national (often conformal) projections is causing distortions when DG is performed without special modifications of the bundle adjustment software (Ressl, 2002). Until recently, the problem alleviation by modified transformation of GPS/INS-derived EO was not addressed correctly (Legat, 2006). The following citation from the commercial software designed for DG resume such handling impeccably: “*In aerial photography, it has been demonstrated that it is very common to find a Z-bias between the ground control points coordinates and the airborne-GPS derived elevation due to mapping projections.*” Unfortunately, it is the absence of the geometrical correction in this particular software that is at charge, the effect of which will be demonstrated in the following example.

The example is taken from a flight above high mountains, where the orientations of the flight lines follow the direction of the principle valleys and mountain ranges. The absolute flying height thus varied considerably from 1700 to 4000 m, while the relative height above the terrain is only 1000 m. The employed digital camera had a focal length of 55 mm and was part of a popular system used for medium scale mapping (Mostafa, 2003). To avoid other influences the datum was kept to that of WGS84 and the map projection was UTM. The mean longitude of this flight was very close (by 0.2°) to that of the central meridian. Figure 1 depicts the EO differences in position calculated with and without application of the geometric correction, where the latter corresponds to that of the commercial solution. The magnitude of the vertical discrepancies varies from 0.50 m to 0.85 m. As shown in (Skaloud and Legat, 2007), the residual discrepancies on the ground across the image footprint did not exceeded *0.015 m* if the geometrical corrections of EO were applied, on the other hand, reached up to *0.800 m* when they were omitted (as in the industrial solution).

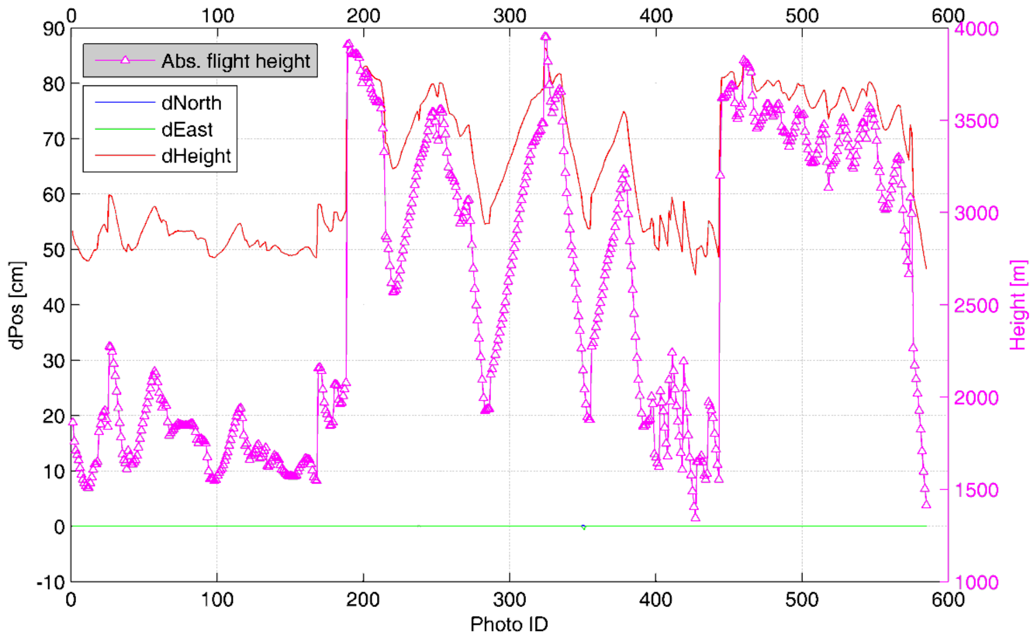

Figure 1: Positioning differences between the EO in UTM projection derived by DG with (Skaloud and Legat, 2006) and without geometrical correction (ordinate axis on the left-hand side and solid lines) that are directly correlated to the absolute flying height (ordinate axis on the right-hand side and 'points').

6.1. Summary

The concept of ISO is very powerful in the reliability control and needed for system calibration. The main problems of this approach are: (1) the additional work that cannot be fully automated and therefore delays the delivery; and (2) the fact that it comes as a last step and therefore almost too late (from an economical point of view) if the decision to re-fly needs to be taken. The procedures for system calibration can be still improved and the best available methods are not always followed. The latter applies also to the use of DG in map projections and local coordinate systems.

7. CONCLUDING REMARKS

As the GPS/INS technology starts to represent the sole means of sensor orientation (DG) in many projects, the factors concerning its reliability are gaining importance. The reliability is closely related to sensor or analytical redundancy and system complexity and thus the overall system cost. However, the higher 'upfront' expenses for more reliable systems could be saved later when dropping current (and sometimes less reliable) methods of quality control, consistency checks, or the laborious process of integrated sensor orientation. This is even more evident if integrity concepts (related to reliability checks in real-time) can be introduced.

The chain of data flow in DG is long and the method is only as strong as its weakest link (in the absence of ISO). In the context of reliability, this continues to be the carrier-phase differential GPS, nevertheless, there are a number of possible technologies existing today, the combination of which may well alleviate the problem. Similarly, there are many possibilities for improvements within the GPS/INS integration itself, both on the hardware- and software level. Furthermore, some rigorous approaches to calibration are still far from common practice and the stability of the aerial sensor with respect to its environment remains a challenge for DG without integrated sensor orientation. Finally, the user know-how and experience play very important role in the correct exploitation of the DG technology (Legat et al., 2006).

8. ACKNOWLEDGEMENT

The author would like sincerely thank the doctoral students at EPLF-TOPO, namely Fadi-Atef Bayoud, Valérie Renaudin and Adrian Waegli for their important contributions in the literature review and problem synthesis. Part of this work stems from joint investigations and perfect synthesis of Dr. Klaus Legat during his academic stay at EPFL-TOPO in Lausanne.

9. REFERENCES

Administration, D.o.T.F.A., 2002. Airborne navigation sensors using the Global Positioning System (GPS) augmented by the Wide Area Augmentation System (WAAS). In: A.C.S. FAA (Editor), Washington, DC, pp. 8. http://topo.epfl.ch/documents/EuroSDR/faa02.pdf

Braasch, M.S., 1996. Multipath effects. In: A.I.o.A.a. Astronautics (Editor), The Global Positioning System - Therory and Application

Broatch, S.A. and Henley, A.J., 1991. An integrated navigation system manager using federated Kalman filtering. IEEE. http://topo.epfl.ch/documents/EuroSDR/broatch91.pdf

Brown, N., Keenan, R., Richter, B. and Toryer, L., 2005. Advances in ambiguity resolution for RTK applications using the new RTCM V3.0 master-auxiliary messages, GNSS 2005. The Intstitute of Navigation, Long-Beach, CA, pp. 73-80. http://topo.epfl.ch/documents/EuroSDR/brown05.pdf

Burrell, J., 2003. Disruptive effects of electromagnetic interference on communication and electronic systems. http://topo.epfl.ch/documents/EuroSDR/burrell03.pdf

Colomina, I. et al., 2004. Redundant IMUs for Precise trajectory determination. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 34, Part B(Commision 1): 7. http://topo.epfl.ch/documents/EuroSDR/colomina04.pdf

Cramer, M., 2004. The EuroSDR network on digital camera calibration, Phase 1, Stuttgart. http://topo.epfl.ch/documents/EuroSDR/cramer04.pdf

Craymer, M.R. and Beck, N., 1992. Session versus baseline GPS processing, ION GPS, New Mexico. http://topo.epfl.ch/documents/EuroSDR/craymer92.pdf

Da, R. and Lin, C.F., 1995. Sensor failure detection with a bank of Kalman filters. Proceedings of the American Control Conference, WP4-3:50. http://topo.epfl.ch/documents/EuroSDR/da95.pdf

Filin, S., 2003. Recovery of systematic biases in laser altimetry data using natural surfaces. Photogrammetric Engineering and Remote Sensing, 69(11): 1235-1242. http://topo.epfl.ch/documents/EuroSDR/filin03.pdf

Filin, S. and Vosselman, G., 2004. Adjustment of airborne laser altimetry strips, ISPRS Congress. International Archives of Photogrammetry and Remote Sensing, Istanbul, Turkey, pp. 285-289. http://topo.epfl.ch/documents/EuroSDR/filin04.pdf

Forssell, B., Martin-Neira, M. and Harris, R.A., 1997. Carrier phase ambiguity resolution in GNSS-2, 10th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation GPS ION'97, Kansas City. http://topo.epfl.ch/documents/EuroSDR/forsell97.pdf

Gruber, M., 2006. Geometric performance of the digital large format aerial camera UltraCam-D, Conference of the American Society for Photogrammetry and Remote Sensing (ASPRS), Reno, Nevada, USA

Hatch, R.R., Jung, J., Enge, P. and Pervan, B.S., 2000. Civilian GPS: the benefits of three frequencies. GPS Solution, 3: 1-9. http://topo.epfl.ch/documents/EuroSDR/hatch00.pdf

Hutton, J. and Mostafa, M., 2005. 10 years of direct georeferencing for airborne photogrammetry. GIS Business (GeoBit), 11: 33-41

Katzenbeisser, R., 2003. About the calibration of lidar sensors, ISPRS Workshop 3-D Reconstruction from Airborne Laser-Scanner and InSAR data, Dresden. http://topo.epfl.ch/documents/EuroSDR/katzenbeisser03.pdf

Kuusniemi, H., Lachapelle, G. and Takala, J.H., 2004. Position and velocity reliability testing in degraded GPS signal environments. GPS Solutions, Volume 8(4). http://topo.epfl.ch/documents/EuroSDR/kuusniemi04.pdf

Legat, K., 2006. Approximate direct georeferencing in national coordinates. ISPRS Journal of Photogrammetry Engineering and Remote Sensing, 60: 239-255

Legat, K., Skaloud, J. and Schmidt, R., 2006. Reliability of Direct Georeferencing Phase 2: A Case Study on Practical Problems and Solutions., Checking and Improving of Digital Terrain Models / Reliability of Direct Georeferencing. EuroSDR Official Publication 51. http://topo.epfl.ch/documents/EuroSDR/EuroSDR_ReliabilityDG_Phase2.pdf

Lehmann, M., 2005. Réalisation d'un serveur de corrections GPS accessible par GPRS, EPFL, Lausanne. http://topo.epfl.ch/documents/EuroSDR/lehmann05.pdf

Mostafa, M., 2003. Design and performance of the DSS. In: D. Fritsch (Editor), Photogrammetric Week, Stuttgart

Napolitano, M.R., Windon, D.A., Casanova, J.L., Innocenti, M. and Silvestri, G., 1998. Kalman filters and Neural-Network schemes for sensor validation in flight control systems. IEEE Transactions on Control Systems Technology (5).
http://topo.epfl.ch/documents/EuroSDR/napolitano98.pdf

Nikiforov, I., 2002. Integrity monitoring for multi-sensor integrated navigation systems, ION GPS 2002. The Institute of Navigation, Portland, OR, pp. 579-590.
http://topo.epfl.ch/documents/EuroSDR/nikiforov02.pdf

Ober, P.B., 2000. Integrity according to Bayes. In: D.U.o. Technology (Editor), IEEE.
http://topo.epfl.ch/documents/EuroSDR/ober00.pdf

Ober, P.B., 2001. SBAS integrity concept. Eurocontrol.
http://topo.epfl.ch/documents/EuroSDR/ober01.pdf

Ochieng, W.Y. et al., 2002. An assessment of the RAIM performance of a combined galileo/GPS navigation system using the marginally detectable errors (MDE) algorithm. GPS Solutions, 5(3). http://topo.epfl.ch/documents/EuroSDR/ochieng02.pdf

Parkinson, B., 2007. Navigation systems status - planery session, ENC-GNNS, Geneva, Switzerland

Pervan, B.S. et al., 1995. High integrity GPS-based precision landing using beacon pseudolites, ISPA, Braunschweig, Germany, pp. 7. http://topo.epfl.ch/documents/EuroSDR/pervan95.pdf

Ressl, C., 2002. The impact of conformal map projections on direct georeferencing, Photogrammetric Computer Vision. Symposium, Vienna.
http://topo.epfl.ch/documents/EuroSDR/ressl02.pdf

Schwarz, K.P., Chapman, M.A., Cannon, M.E. and Gong, P., 1993. An integrated INS/GPS approach to the georeferencing of remotely sensed data. Photogrammetric Engineering and Remote Sensing, 59(11): 1167-1674

Skaloud, J., 2006. Reliability of Direct Georeferencing Phase 1: An Overview of the Current Approaches and Possibilities, Checking and Improving of Digital Terrain Models / Reliability of Direct Georeferencing. EuroSDR Official Publication 51.
http://topo.epfl.ch/documents/EuroSDR/EuroSDR_ReliabilityDG_Phase1.pdf

Skaloud, J., Bruton, A.M. and Schwarz, K.P., 1999. Detection and filtering of short-term (1/f) noise in inertial sensors. NAVIGATION, Journal of The Institute of Navigation, 46(2): 97-107. http://topo.epfl.ch/documents/EuroSDR/skaloud99.pdf

Skaloud, J., Gontran, H. and Merminod, B., 2004. GSM-distributed RTK for precise analysis of speed skiing, 8th European Navigation Conference GNSS 2004, Rotterdam.
http://topo.epfl.ch/documents/EuroSDR/skaloud04.pdf

Skaloud, J. and Legat, K., 2006. CAMEO - Camera Exterior Orientation by Direct Georeferencing. Swiss Federal Institute of Technology Lausanne (EPFL).
http://topo.epfl.ch/research/techtransfer/

Skaloud, J. and Legat, K., 2007. Theory and reality of direct georeferencing in national coordinates. EPFL internal report submitted to publication.

Skaloud, J. and Lichti, D., 2006. Rigorous approach to bore-sight self calibration in airborne laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing, 61: 47-59

Skaloud, J. and Schaer, P., 2003. Towards a more rigorous boresight calibration, ISPRS International Workshop on Theory Technology and Realities of Inertial/GPS/Sensor Orientation, Castelldefels, Spain. http://topo.epfl.ch/documents/EuroSDR/skaloud03.pdf

Skaloud, J. and Schaer, P., 2007. Towards automated LiDAR boresight self-calibration, The 5th International Symposium on Mobile Mapping Technology, Padova, Italy

Studeny, J. and Clark, B., 2004. The aviation GNSS receiver. ION Newsletter, 14(3): 4-5. http://topo.epfl.ch/documents/EuroSDR/studeny04.pdf

Talaya, J., 2000. Robust GPS kinematic positioning for direct georeferencing. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 33, Part B2: 546-551. http://topo.epfl.ch/documents/EuroSDR/talaya00.pdf

Tempelmann, U. and Hinsken, L., 2005. Triangulation of ADS40 pushbroom image blocks - Not much different from classical frame blocks? SGPBF Annual Meeting, Lausanne, Switzerland. http://topo.epfl.ch/documents/EuroSDR/tempelmann05.pdf

Toran-Marti, F. and Ventura-Traveset, J., 2004. The ESA EGNOS project: The first step of the European contribution to the Global Navigation Satellite System (GNSS). GNSS-1 Project Office. http://topo.epfl.ch/documents/EuroSDR/toranmarti04.pdf

Vollath, U., 2004. The Factorized Multi-Carrier Ambiguity Resolution (FAMCAR) Approach for Efficient Carrier-Phase Ambiguity Estimation. In: T.T. GmbH (Editor), ION GPS 2004. http://topo.epfl.ch/documents/EuroSDR/vollath04.pdf

Vollath, U., Landau, H., Chen, X., Doucet, K. and Pagels, C., 2002. Network RTK Versus Single Base RTK - Understanding the Error Characteristics, ION GPS, Portland, OR. http://topo.epfl.ch/documents/EuroSDR/vollath02.pdf

Wei, M. and Schwarz, K.P., 1990. Testing a decentralized filter for GPS/INS integration. Proceesdings of the IEEE PLANS - Position, Lcation and Navigation Symposium: March 1990. http://topo.epfl.ch/documents/EuroSDR/wei90.pdf

Yang, Y. and Farrell, J.A., 2003. Magnetometer and differential carrier phase GPS-aided INS for advanced vehicle control. IEEE Transactions on Robotics and Automation, 19(2). http://topo.epfl.ch/documents/EuroSDR/yang03.pdf

Yang, Y., Hatch, R.R. and Sharpe, R.T., 2004. GPS multipath mitigation in measurement domain and its applications for high accuracy navigation, ION GNSS 2004, Long Beach, California. http://topo.epfl.ch/documents/EuroSDR/yang04.pdf

Yousuf, R. and Skone, S., 2005. WAAS Performance evaluation under Increased ionospheric activity. In: T.I.o. Navigation (Editor), GNNS 05. The Institute of Navigation, Long-Beach, CA, pp. 2316-2327. http://topo.epfl.ch/documents/EuroSDR/yousuf05.pdf