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From Off-line to On-line Geocoding: the Evolution of Sensor Orientation

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ABSTRACT

This paper addresses the evolution of sensor orientation and calibration over the past forty years with emphasis on their applications to the acquisition of primary data for further mapping and geoinformation generation. The paper identifies some limitations of the current assumptions and illustrates how to overcome them with an example and several ideas that the author and his colleagues at the Institute of Geomatics have developed and published recently. The current performance of direct and integrated sensor orientation is briefly discussed as well as the evolution of the Global Positioning System and Galileo and their impact.

1. INTRODUCTION: EVOLUTION OF SENSOR CALIBRATION AND ORIENTATION

Current sensor orientation and calibration fundamental concepts, including the concept of self-calibration, were laid down by F. Ackermann (Ackermann, F. et al. (1970)), D.C. Brown (Brown, D.C. (1971)), H.H Schmid (Schmid, H.H. (1974)) and their teams in the late 1960s and early 1970s. Besides the concepts themselves, one remarkable achievement of the early period was the translation of the ideas into software that went into the production lines of almost any photogrammetric production organization worldwide. Not long after the self-calibrating bundle adjustment (SCBA) approach as it is known today matured in the mid 1970s, robust estimators (Krarup, T. et al. (1980), Klein, H., Förstner, W. (1984)) were introduced. In the author's opinion, the relevance of this contribution can hardly be overemphasized and, generally speaking, the relevance of robust strategies is not yet fully recognized. Soon, bundle adjustment was exported to remote sensing (Kratky, V. (1989)) and the Global Positioning System (GPS) was imported to bundle adjustment (Lucas, J.R. (1987), Friess, P. (1991)). Already in 1991, digital aerial triangulation was on the pipe (Tsingas, B. (1991)). The use of inertial/GPS technology for Direct Sensor Orientation (DSO) of frame cameras was already proposed in 1993 (Schwarz, K.P. et al. (1993)). In parallel, inertial/GPS position-velocity-attitude (PVA) determination became the basis for DSO of airborne digital line cameras, hyperspectral cameras, airborne laser scanning (ALS) and airborne Interferometric SAR (InSAR). Between 1995 and 2000, inertial/GPS technology penetrated the large format metric aerial camera segment and became standard photogrammetric equipment (Scherzinger, B. (1997)). Inertial/GPS equipped digital medium- and large-format camera systems became the configuration of choice. The, in principle, higher mechanical stability of digital cameras created high expectations from DSO. However, practical experience has demonstrated (Alamús, R. et al. (2007), Cramer, M. (2007)) that even the high-end large-format digital cameras require SCBA. The same applies to medium-format digital cameras which, in the meantime, have created a market of their own. The last development wave is ALS block adjustment for orientation and calibration (Friess, P. (2006), Kager, H. (2004), Škaloud, J., Lichti, D. (2006)). Here the concept of tie point has been extended to tie plane thus allowing the formation of connected blocks of ALS scenes and therefore of ALS block adjustment.

As a result of this formidable development, the geomatic community has inherited the abstract concept of network modelling and adjustment for the optimal estimation of parameters; be them of the point, orientation, calibration or of whatever other type. The concept is simple though powerful and –in the disciplines of photogrammetry and remote-sensing– applies to both mono- and multi-sensorial systems. From a mathematical point of view it is about solving [large] systems of equations –linear or non-linear, implicit or explicit– and about statistical inference. From a geomatic point of view, it is mainly about modeling of measurements related to signal propagation and to parameter control. Signal propagation modeling, for example, may include emitter/receiver sensor parameters (orientation and calibration) and emitter/receiver ground object parameters (geometric, radiometric, etc.) where, typically, ground objects also serve as tie features between images of the same or different sensor types.

2. ON THE CURRENT CONTEXT AND ROBUST PRODUCTION STRATEGIES

Information Society is built upon information infrastructures, one of which is geoinformation. These infrastructures are developed by private and public organizations that, many times, have to face contradictory situations of a demanding society that is not willing to pay for the cost of what is being demanded. Mapping companies are increasingly facing the situation of governmental contracts bringing less and less money for the same amount of information. Moreover, the tempo of current society is higher than ever before and the time factor is playing a higher role. The situation can be handled either by outsourcing to less expensive organizations elsewhere or by augmenting the productivity through new technology and continued education.

Current geoinformation technology generates large digital data sets that many times have to be processed under higher time pressure or by less prepared staff than before. On the other hand, current geomatic measurement techniques are extremely precise. Under such circumstances, robustness has become an issue and new generation geomatic strategies for geoinformation production should emphasize it.

The concept of a robust strategy is illustrated next. If the nominal or classical operational procedures are followed and the data are not flawed the robust strategy will deliver acceptable –within specifications– results. Under these ideal circumstances, a classical strategy will likely deliver better results. However, if nominal procedures are not exactly followed and some data are wrong, the robust procedure will still deliver acceptable results –i.e., results that are worse than those obtained under ideal conditions but still within specifications– whereas classical procedures will fail. A robust strategy should, as well, self-diagnostic failure situations.

In the paragraph above, strategy means the set of operational procedures, models and estimation techniques used. One example of robust strategy was the Ackermann-Friess approach to GPS aerial triangulation where mission asks for, in principle, redundant control, where the aerial control functional model includes an, also in principle, unnecessary shift parameter and where, on top, a robust least-squares estimator may be used. Robust strategies should not be confused with robust estimators although a robust strategy is likely to include robust estimation techniques.

The geomatic community cannot become mainstream if their software tools fail just because a final user did not read –usually the case– and did not faithfully apply the user’s manual.

3. CURRENT ENABLING TECHNOLOGIES AND THEIR PERFORMANCE

The main current enabling technologies for sensor orientation are; GPS satellite positioning-navigation-timing (PNT); inertial position-velocity-attitude (PVA) determination, geodetic and topographic surveying, mono- and multi-sensorial image correspondence or registration, and network modeling and adjustment. There are other technologies and instruments used for orientation like barometric altimetry, odometers, star trackers, etc. However, as they are either less relevant or less accessible they will not be discussed here.

Performance of GPS positioning, both static and kinematic is well known and has been analyzed and reported many times. It depends on the quality of the GPS receiver, the satellite distribution, the distance to reference station(s) and/or the fidelity of ionospheric delay modeling, the environment (geometric multipath and radioelectric signal interference) and, last but not least, the processing algorithm and software.

Similarly, performance of inertial/GPS position-attitude (PA) determination is well understood [for some] and less understood [for most]. It depends on the performance of GPS positioning, of the inertial measurement unit (IMU) quality, of trajectory geometry and dynamics and on the processing software.

Consensus figures for inertial/GPS trajectory determination accuracy with dual frequency geodetic-grade receivers and navigation-grade IMUs range within 0.05-0.10 m for the horizontal components and within 0.07-0.15 for the vertical component. Attitude accuracy is 0.005 deg for the roll, pitch angles and 0.008 deg for heading. However, time dependent error processes cannot be well described by just a global standard deviation (σ) or root mean square (RMS) value. A closer analysis, not only for inertial but also for GPS solutions, reveals strong short term correlations and short term higher precision values (Friess, P., Tuell, G. (2006)).

The usual stochastic modeling of GPS and inertial/GPS derived aerial control in DSO and ISO assumes, however, independent, identically distributed errors in position (P) or position-attitude. However, this is neither the case for GPS nor for inertial/GPS. As a result, the accuracy properties of GPS and, particularly, of inertial/GPS P and PA control are not fully exploited. A strategy to overcome these problems is presented in section 6.

Recent analyses on integrated sensor orientation (ISO) (Ip et al., 2006) corroborate previous findings (Heipke, C. et al. (2002)). DSO figures are typically 2 to 4 times worse than those of ISO. However, a direct comparison of ISO and DSO performance in terms of accuracy does not make as much sense as in DSO, because systematic errors from external sources may contaminate the results. The results of the recent EuroSDR experimental research project “Digital Camera Calibration” (Cramer, M. (2007)) can be regarded as ISO performance tests for the new generation digital cameras. They are summarized in table 1.

	ADS		DMC		UCD	
	E/N	h	E/N	h	E/N	h
RMS @ check-points in ppm (of flying height)	25	55	25	65	25	50

Table 1. Performance of ISO for the Leica Geosystems ADS40, the Intergraph/ZI DMC and the Microsoft Imaging UCD after (Cramer, M. (2007)). [E/N: horizontal coordinates, h: height]

Matching techniques to solve correspondence problems and to identify ground control largely differ from sensor to sensor technology and depend on object texture. In optical measurement techniques a precision of 0.2 pix is becoming standard. In ALS the precision of plane matching in ALS block adjustment has not yet been investigated. In (Oller, G. et al. (2005)) a 0.7 pix accuracy in optical/SAR matching is reported. Progress is to be expected in the heterogeneous correspondence problem as the state-of-the-art is far from mature. Moreover, new satellite missions as the COSMO SkyMed (4 SAR) and Pleiades (2 Optical) or TerraSAR-X high resolution SAR data that could be combined with optical images will require this technology.

4. PROGRESS IN POSITIONING AND NAVIGATION TECHNOLOGIES

Predicting future trends is always a risky business, likely useless and ridiculous prone. However, there are a number of realities in other areas of geomatics and navigation that will certainly impact calibration and orientation, be it in their quality or on their procedures or in their cost.

The future Galileo satellite PNT system will be Europe's contribution to a Global Navigation Satellite System (GNSS) or system of systems. Galileo and a modernized GPS will, in less than a decade –officially much less–, duplicate the number of current available satellites and provide more precise, accurate and robust signals. Satellite clock stability and orbit determination will improve. Global and regional differential services, private and public, will become better known and more used.

Receiver technology in general and signal processing in particular is evolving fast. One remarkable development, yet not mature, is that of software defined radio GNSS receivers. A definite advantage of software receivers is their flexibility in accommodating new algorithms including tighter inertial/GNSS integration levels like "tightly coupled" or "deeply coupled" architectures (Gebre-Egziabher, D. (2007)). In the tight/deep inertial/GNSS coupling modes the inertial estimates of a vehicle's velocity are fed back to the GNSS receiver. With this information, the Doppler effect produced by the relative satellite-receiver velocity can be predicted and the receiver frequency, phase and delay lock loops (FLL, PLL and DLL) can narrow their bandwidths. This results in a higher signal-to-noise ratio –which translates into observables precision– and improved resistance against signal outages either due to vehicle dynamics, interference or jamming. In (Silva, P.F. et al. (2007)) the performance of close and tight inertial/Galileo integration was compared and for the L1 BOC(1,1) signals improvement factors of 2 (0.6 m to 0.3 m for the code) and 3 (0.8 mm to 0.3 mm for the phase) were demonstrated.

The development in satellite navigation technology, at the system and at the user terminal level, will net the geomatic community with precision, accuracy and robustness levels at least two times better that today's ones and with higher flexibility in mission planning and execution. A foreseeable by-product of this will be a shift from off-line to on-line procedures.

Inertial sensing technology does not seem to evolve significantly in terms of performance. Rather, the effort is put on price and size reduction.

5. SUCCESSFUL PARADIGMS, INERTIAL THINKING AND MISUNDERSTANDINGS

In all respects, geodetic network adjustment, GPS PNT, inertial/GPS PVA and their application into all the flavours of sensor orientation, from self-calibrating bundle adjustment to direct procedures, have been a success story. This, together with a rather stable type of product demand has not been exactly conducive to creativity. On the contrary, over time, it has developed some inertial thinking and some wrong assumptions that the context did not make apparent. Related to this, there is a number of misunderstandings (MU) and obsolete procedures that have gone undetected and that hamper the performance of geomatic processes. They are listed and briefly discussed below.

MU 1 on the stochastic properties of inertial/GPS: Inertial/GPS derived PA estimates are introduced in the orientation processes as independent, identically distributed random variables whose error characteristics are modeled according to the so-called “absolute accuracy specifications (RMS)” whereas, in reality, inertial and inertial/GPS PA estimates are samples of a same stochastic process at different time epochs. As a result, the high short term precision of inertial/GPS estimates is not used and their correlations neglected. In principle, the current approach is justified by computational convenience. However, computationally convenient does not necessarily mean statistically meaningful. (See Martínez et al. (2007) for more details on an alternative formulation and a related example in section 6.)

MU 2 on the re-parameterization of inertial/GPS attitude: Inertial/GPS derived A estimates are usually parameterized in the heading-pitch-roll sequence and their associated rotation matrix brings an instrumental frame forward-right-down aligned into a terrestrial local frame north-east-down aligned. Re-parameterization of attitude information is usually performed in intermediate, error-prone steps to fit the omega-phi-kappa convention. However, this is not necessary if the attitude control models (observation equations) are appropriately formulated.

MU 3 on the information provided by inertial/GPS: It is again well known for some but less known for most, that inertial/GPS provides PVA control information and not just PA control. Velocity control can be used to perform time calibration of mono- and multi-sensorial systems in both ISO and DSO. A further advantage is that time inconsistencies between the various instrumental time reference frames –the various instrument clocks– can be de-correlated from spatial errors. Another advantage is that velocity control can be used to perform temporal self-calibration in low-cost hardware systems where the required electronics for accurate time synchronization may be just too expensive. This misunderstanding is related to the next one. (More details on the problem and its solution to be found in Blázquez, M. , Colomina, I. (2008).)

MU 4 on the 3D nature of sensor system orientation and calibration: Sensor orientation and calibration is a 4D problem, not a 3D problem. In a sensor system it is often the case that every instrument has its own oscillator which defines its own instrumental time reference frame. Oscillator frequency stability can be affected by a number of factors, from oscillator quality itself to temperature changes. This is, for example, the case in IMU instruments. Orientation and calibration procedures and even mission design should not overlook this fact. (More details to be found in Blázquez, M., Colomina, I. (2008).)

MU 5 on the inertial/GPS and the Kalman-filter solution approach: It is [wrongly] believed that the derivation of GPS P and inertial/GPS PVA trajectories requires the use of the “predictor – Kalman filter” approach. This is only true for real-time applications whereas network adjustment based solutions can be used to take advantage of additional tie information like cross-over points. There are two keys to the use of network adjustment techniques for inertial/GPS trajectory estimation: the interpretation of inertial mechanization equations as stochastic differential equations and their discretization as stochastic difference equations; and the extension of the current [static] network adjustment concept to dynamic network adjustment with time dependent parameters (stochastic processes). (See Colomina , I., Blázquez, M. (2005), Sansò, F. (2006) and Términs, A., Colomina, I. (2004) for more details.)

MU 6 on what ISO is: It is generally believed that ISO is aerial triangulation plus inertial/GPS PVA aerial control. In fact, ISO refers to the use of whatever observational data is available and/or required to estimate parameters of interest. For instance, ISO can be used in corridor mapping applications with the following configuration:

- inertial/GPS PVA aerial control (the dominant large control data set),
- geodetic surveying ground control (a small data set) and
- photogrammetric image observations for the ground control points (a small data set).

With the above observational configuration ISO can be performed even with self-calibration of the camera focal length. Of course, here the full benefits of self-calibration will be lost but there will be no risks as for the geodetic reference frame of the solution. This misunderstanding is related to the next one.

MU 7 on the limitations of ISO for rapid-response and real-time applications: It is generally believed that ISO cannot be used for rapid-response and real-time applications because the measurement of image coordinates takes too long (sic). However, if an observational configuration like the one described in the paragraph above is carefully processed by:

- interpreting the sensor orientation and calibration parameters as time dependent parameters,
- and using a “sequential least-squares” or “predictor – Kalman filter approach”;

then, it is possible to provide rapid-response and real-time solutions while enjoying the benefits of limited self-calibration and safe geodetic reference frame fixing.

MU 8 on the role of boresight calibration: The determination of the orientation matrix between the IMU reference frame and the sensor reference frame is a must in DSO. However, ISO can be performed without IMU-to-sensor orientation matrix if inertial/GPS attitude control is used in a relative mode (Martínez et al. (2007)). This is possible because the relative attitude between the sensor absolute attitudes at times, say T_1 and T_2, is the same as the relative attitude between the IMU at times T_1 and T_2. A similar rationale can be applied to position control thus leading to a formulation without shift parameters but still enjoying the same systematic error absorbing properties. If the relative control approach is combined with the remarks of MU 2, a robust model is obtained as users need to make no assumptions on the IMU-to-sensor validity periods, shift parameter assignments and cannot make mistakes while transforming between different attitude parameterizations. Plus, trajectory “jumps” due to changing GPS satellite configurations can be easily detected and removed while the rest of relative position control can be still used.

Preliminary research performed at the Institute of Geomatics with moderately sized blocks, do not exhibit any significant *Bierbauch effect* due to the more unfavourable error propagation properties of relative control (see section 6). Similarly, the precision simulation analysis and the empirical accuracy analysis with check points show no significant degradation.

MU 9 on IMU boxes: If the inertial/GPS inertial mechanization equations are interpreted in terms of stochastic difference equations as discussed in MU 5 and the relative redundancy of the network *d/n* is computed (where *d* stands for the degrees of freedom and *n* is the number of equations) is 0.05. The geometric interpretation of this in terms of the usual least-squares orthogonal projectors and redundancy numbers shows that –assuming absence of outliers in the inertial observations data stream– the calibration of IMU systematic errors is contextual. Contextual calibration refers to the situation where an instrument –the IMU– seems to be calibrated –but in fact it is only partially calibrated– because the trajectory exhibits no pathologies and the residuals at the filter steps are small… as long as the trajectory dynamics or geometry do not change. Apparently, there are only two recipes against this: calibration manoeuvres or accurate instruments. However, in the low-end applications' technology (as for small unmanned vehicle platforms) the use of dual IMU configurations begins to receive some attention and in high-end applications, the use of Skewed Redundant IMUs has been proposed by several authors and is currently under research.

MU 10 on the restriction of ISO to optical measurements: For many years and from many people, it was believed that ISO would not make sense for ALS data. Fortunately, this is no longer the case and although the orientation of an ALSU requires inertial/GPS PA control it has become now clear that ALSU calibration and orientation can be performed under the ISO and network adjustment paradigm. (See Friess, P. (2006), Kager, H. (2004) and Škaloud, J., Lichti, D. (2006) for details.)

MU 11 on coordinate reference frame handling: There is considerable confusion on the transfer of orientation parameters between different coordinate reference frames. Particularly preoccupying is the situation with the transfer of orientation parameters from computational coordinate systems (usually global or local 3D Cartesian systems) to mapping coordinate systems. The situation has been so far approached by chaining approximate corrections to image coordinates and to orientation parameters. Within the realm of approximate corrections, there are a number of different "reasonable" tactics to do the transfer. As a result, confusion is granted unless a description of the correction sequence is described and the application software is prepared for that particular tactic. In the opinion of the author, the safest procedure is to apply no corrections and leave to each application software component the responsibility and the freedom to handle the situation. This applies to photogrammetry, to ALS and to the rest of remotely sensed data. (It is out of the scope of this paper to further discuss the handling of mapping coordinate reference frames in the various application areas that exploit orientation information. However, a general principle is that with current computer technology things should be solved where they belong; i.e., instrument calibration, atmospheric refraction, etc. belong to the image space but issues related to coordinate systems, etc. belong to the object space.)

6. AN ILLUSTRATIVE EXAMPLE

In order to illustrate some of the issues discussed above, one block of the Pavia data set (Franzini, M. (2006)) was processed under the absolute (classical) and the relative inertial/GPS aerial control paradigm as suggested in section 5 and related to MU 1, 2 and 8 (Martínez et al. (2007)). The block consists of 131 Wild RC30 images distributed in 7 regular plus 4 cross strips, and 477 points. The cross strips are located at the ends of the block in two groups of almost coincident strips. Approximate focal length is 150 mm, approximate image scale is 1:8000 and approximate image overlap is 60% x 60%. From 32 ground surveyed points, 24 points are used as check points and 8 as control points (4 pairs at the block corners). The standard Ebner 12-parameter set was used for the image self-calibration model. Standard deviations for control information are given in table 2.

ground control points (cm)	sE, sN = 8 sh = 10	
image coordinates (µm)	sx, sy = 6	
GPS abs. air control (cm)	sE, sN = 7 sh = 11	
INS/GPS abs. air control (cm, deg)	sE, sN = 7 sh = 11	sPi, sRo = .005 sHe = .008
GPS rel. air control (cm)	sE, sN = 4 sh = 8	
INS/GPS rel. air control (cm, deg)	sE, sN = 4 sh = 8	sPi, sRo = .0027 sHe = .0027

Table 2. Observations' standard deviations

Following the ideas presented in section 2, the results presented here are not the result of any iterative tuning process: the observations' standard deviations were set from prior quality estimates and no outlier detection procedure other than standard regression diagnostics was used. The functional models for the absolute GPS and inertial/GPS aerial control are the usual ones with shift parameters per strip. The relative control models can be found in (Martínez et al. (2007)) and it is noted that in the relative control mode there are no boresight calibration unknowns as well as no shift parameters. It is also noted that in the attitude control formulation, both in the absolute and relative models, a Gauss-Helmert implicit formulation had to be used and that in both cases the original attitude parameterization (heading, pitch and roll) was kept. Therefore, the original inertial/GPS derived control had to undergo no transformation.

	GPS ABS			GPS REL			INS/GPS ABS			INS/GPS REL		
	E	N	h	E	N	h	E	N	h	E	N	h
RMS @ 24 check-points												
in cm	3.8	2.7	3.0	3.2	2.7	3.0	3.5	2.7	2.6	3.3	2.6	2.7
in µm (at image scale)	4.7	3.4	3.8	4.0	3.4	3.8	4.4	3.4	3.2	4.1	3.2	3.4
in ppm (of flying height)	39	22	25	27	22	25	29	22	22	27	22	22

Table 3. Comparative analysis of GPS and inertial/GPS absolute and relative aerial control. [E/N: horizontal coordinates, h: height]

Table 3 summarizes the results for the four configurations reported here: GPS absolute (GPS ABS), GPS relative (GPS REL), inertial/GPS absolute (INS/GPS ABS) and inertial/GPS relative (INS/GPS REL). As can be seen, there are no significant differences between the two control modes.

(At the Institute of Geomatics, the Pavia block is also being used to address MU 6 and 7. For this purpose, single strips are being analyzed with minimal ground control and just photogrammetric observations for the ground control points. The results are encouraging but too preliminary to be reported here in detail.)

7. NEW TRENDS AND CHALLENGES

Sensor orientation and calibration has not yet been applied –or at least, neither generally nor fully applied– to some recent earth observation systems and to some exiting sensors. Additional research is required for small satellites, their orbits and their sensors. Airborne InSAR still does not benefit from ISO. The coming new, high resolution space sensors will be integrated with airborne sensors including ALS. Hidden proprietary sensor models deserve further attention and more sophisticated mathematical tools. Accurate calibration of medium-format cameras for mapping is becoming a hot topic. Integration of ALS with medium- and large-format frame cameras is in its infancy, terrestrial static and mobile multisensorial systems keep on evolving. Last not least, the rigorous radiometric calibration of the classical sensors has been largely overlooked so far. However, the availability of information in digital form calls for this development and the vision of radiometric calibration block adjustment has been already formulated.

8. CONCLUSION, PERSPECTIVES AND HOMEWORK

After forty years of service, sensor orientation and calibration continues to be a fundamental and necessary step in the geoinformation production line, between primary data acquisition and information generation. Sensor orientation and calibration has reinvented itself many times over the past decades; importing enabling technologies such as GPS, inertial navigation and image processing. It has been at the forefront of photogrammetric evolution and has influenced sister disciplines.

Network modeling and adjustment continues to be an essential part of sensor orientation and calibration as proven by its extension to almost all geomatic sensors. Self-calibrating bundle adjustment, its generalization and evolution continue to be a necessary tool. It has lost part of its frame camera “market” but it has opened new ones as new sensors have entered the geomatic arena. (It seems that there is no sensor that can escape the self-calibrating network modeling and adjustment approach.)

Sensor orientation and calibration can be performed off-line, on-line and in-between. It can be achieved with (indirect or integrated) or without (direct) matching-measurements on the imaging sensor data. In the paper, in addition to the traditional ISO and DSO procedures, recently developed new orientation modes have been presented.

Sensor technology and its orientation and calibration enablers keep on evolving. The immediate future is full of opportunities and challenges. This means some homework for the geomatic community which, in the author’s opinion, is related to modeling –of sensors and of their enablers–, to education of users and to hardware design with emphasis on stability.

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