# Problems in Direct-Georeferencing by INS/DGPS in the Airborne Environment

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## Abstract

This paper examines several topics that are important for designing a system for direct-georeferencing by means of INS/DGPS in the airborne environment. The subjects to be discussed are sensor placement, sensor synchronization, system calibration and the initial alignment. Although the nature of some of these problems may be more practical, their significance may equal or exceed the importance of optimal algorithm development. Their successful solution provides considerable challenges at the operational and hardware levels. Rather than providing an exhaustive study of individual subjects, the paper aims to demonstrate their importance as a whole, drawing examples from available data sets and suggesting possible solutions.

## 1 Introduction

To georeference frame-based imagery, the parameters of interior and exterior orientation have to be determined. The interior orientation parameters, i.e. coordinates of the principal point $x_0$, $y_0$, the focal length $f$, and the geometric distortion characteristics of the lens, can be measured in laboratory conditions. These parameters can be considered as more or less constant over a period of time. In contrast, the six parameters of camera exterior orientation ($X_0$, $Y_0$, $Z_0$, ?, n, ?) are changing quickly and their evolvement has to be tracked by a real-time measurement process to achieve georeferencing without the slow and costly establishment of ground control points (Schwarz et al., 1993). In principle, any navigation systems providing position and attitude information with sufficient accuracy can be used for this purpose, provided the following three conditions are met:

- the position and orientation offset between the frames of the navigation and imaging sensors can be determined with sufficient accuracy,
- this offset remains constant or its variations can be modeled,
- the sensors can be synchronized with sufficient accuracy to a common time base.

When the navigation information is provided by an integrated INS/DGPS system, the equation for direct-georefencing takes the form:

$$\boldsymbol{r}_i^m = \boldsymbol{r}_{ins/dgps}^m(t) + \boldsymbol{R}_b^m(t)\,[s_i\,\boldsymbol{R}_c^b\,\boldsymbol{r}_i^c(t) + \boldsymbol{a}^b] \quad (1)$$

where

| | |
|---|---|
| $\boldsymbol{r}^m{}_i$ | is a vector of coordinates to be computed in the mapping frame for a specific point ($i$), |
| $\boldsymbol{r}^m{}_{ins/dgps}(t)$ | is a vector containing the coordinates of the INS center in the mapping frame, determined by the INS/DGPS integration, |
| $\boldsymbol{R}_b{}^m(t)$ | is the attitude matrix from the INS body frame to the mapping frame, determined by the INS/DGPS integration, |
| $s_i$ | is a scale factor between the image and mapping coordinate frames for a specific point ($i$), usually determined by processing the captured imagery in stereo pairs, |

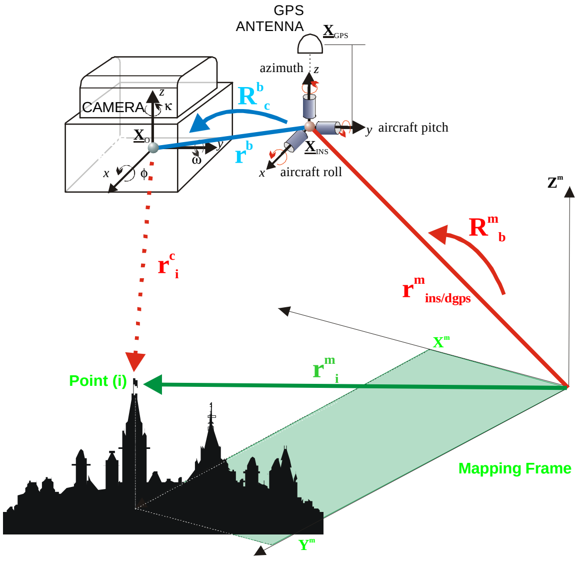

Figure 1. Elements of georeferencing by INS/DGPS.

| | |
|---|---|
| $\boldsymbol{R}^b_c$ | is the rotation matrix (orientation offset) between the camera frame and the INS body frame determined from calibration, |
| $\boldsymbol{r}^c_i(t)$ | is the vector of coordinates (i.e., x, y, -f) observed in the image frame for a specific image (*t*) and point (*i*), |
| $\boldsymbol{a}^b$ | is the vector of the translation offset between the INS and the camera centre in the INS body frame determined by terrestrial measurements as part of the calibration process. |

The relations between the components of Equation (1) are depicted in Figure 1. This formula expresses the fact that the processing chain contributing to the overall performance of an acquisition system is affected by the accuracy of the measured image data, the INS/DGPS position and attitude, the system calibration, the optical properties of the cameras and the effect of image geometry. In other words, when implementing an INS/DGPS the accuracy of the determined parameters of exterior orientation is further affected by:

- sensor placement,
- sensor synchronization,
- initial alignment,
- system calibration.

In following, the problems related to each of the above mentioned topic will be examined.

## 2 Sensor Placement

The optimal placement of all sensors in an airborne carrier is a non-trivial task. A poor sensor mount is most likely to alter the performance of the whole system and errors of such type may be very difficult to correct for. The requirements on sensor placing are usually motivated by two objectives:

- to minimize the effect of calibration errors on lever-arm corrections
- to avoid any differential movements between sensors.

Addressing the first objective, short distances between sensors reduce the impact of uncertainties in the lever-arm corrections (Schwarz et al., 1993). This especially affects the positioning component of direct-georeferencing. On the other hand, small differential movements mainly alter the attitude performance.

Considering first the lever-arm correction problem, the constraints on placing the sensors in airborne carries are more restrictive as compared to land vehicles. For instance, the mount used in the land vehicle mapping system VISAT (El-Sheimy, 1996) fixes all sensors next to each other on the roof of the van. Such a configuration is not quite possible to be adopted in an aircraft, since the imaging component has to be oriented to look downward while the GPS antenna has

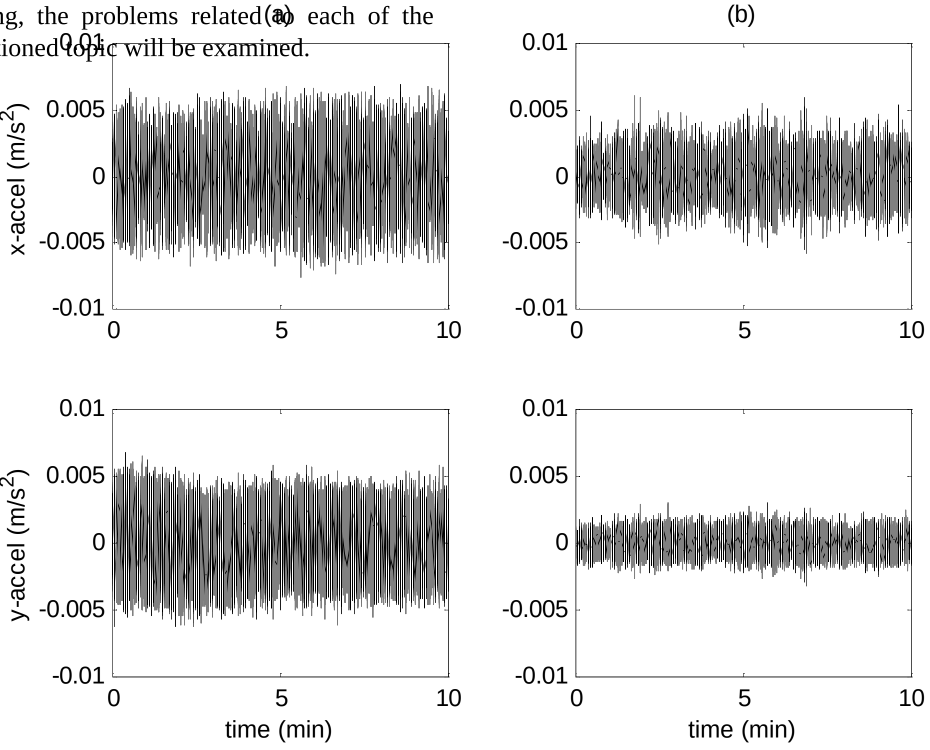

Figure 2. Comparison of the velocity noise in the *x* and *y* channels of the LTN 90-100 (a) without and (b) with vibration dampening using a special mount.

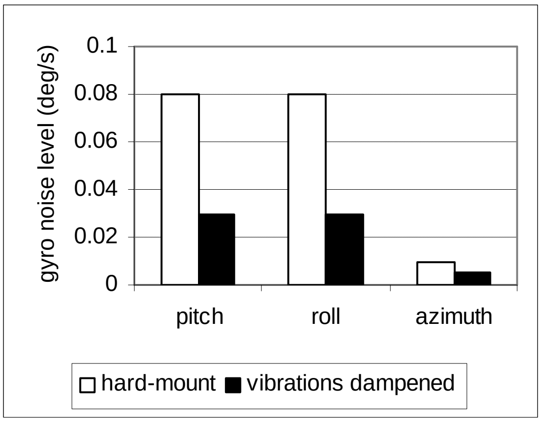

Figure 3. Comparison of the gyro noise level in the LTN-90-100 with and without vibration dampeners.

to be mounted on top of the fuselage. Hence, a somewhat larger distance between these two devices will always exists and can be minimized only by placing them underneath each other. An optimal place for an inertial system would then be somewhere between these two devices, but most likely directly on the top of the camera for the reasons discussed in the following.

Of the problems of lever arm corrections and differential movements between the sensors, the latter is the more difficult to overcome. Rigidly mounting the camera and the inertial system to a solid and common structure solves this problem only partially, because the sensors in either of these devices may not be rigidly connected to their chassis in order to dampen vibrations (i.e., to prevent the blur of the imagery in an aerial camera). However, the dampening responses are the most likely ones to differ between devices, thus causing inevitable attitude errors in a vibrating environment such as an aircraft. The seriousness of this problem has been realized in the first commercially available product for direct georeferencing offered by Applanix$^{TM}$ (Reid et al., 1998) in which it was solved by mounting a small, tactical-grade IMU directly to the body of the camera. Although this solution seems to give satisfactory results, using the same approach to accommodate heavier navigation-grade inertial systems would most likely exceed the permissible load of the camera holder.

Another possible solution is to design a solid structure, isolate it from vibrations and mount both devices to its frame. This approach has been taken by Mostafa et al. (1998) when designing a holder for a digital camera and a navigation-grade strapdown INS. Since data sets were collected with and without a vibration dampener while using the same INS and the same type of an aircraft, the effect of vibration on the inertial output can be quantified. Figure 2 depicts the velocity noise from the *x* and *y* accelerometers during a 10 minute cruising period. As can be seen from this figure, the noise level is about 1.5 to 2 times smaller when the vibration dampener is used. Using the noise estimation approach which analyze the inertial signal above the motion bandwidth (Skaloud et al, 1999) , the level of the noise in the gyro output was estimated in both cases. The results are plotted in Figure 3. Again, the noise level is approximately twice as small when vibration dampeners are used.

## 3 Sensor Synchronization

The requirements for time synchronization between the INS, the GPS and the imagery data streams increase with accuracy requirements and vehicle dynamics. If not handled properly, they will be a serious source of errors because they directly affect the determination of the vehicle trajectory in thus all

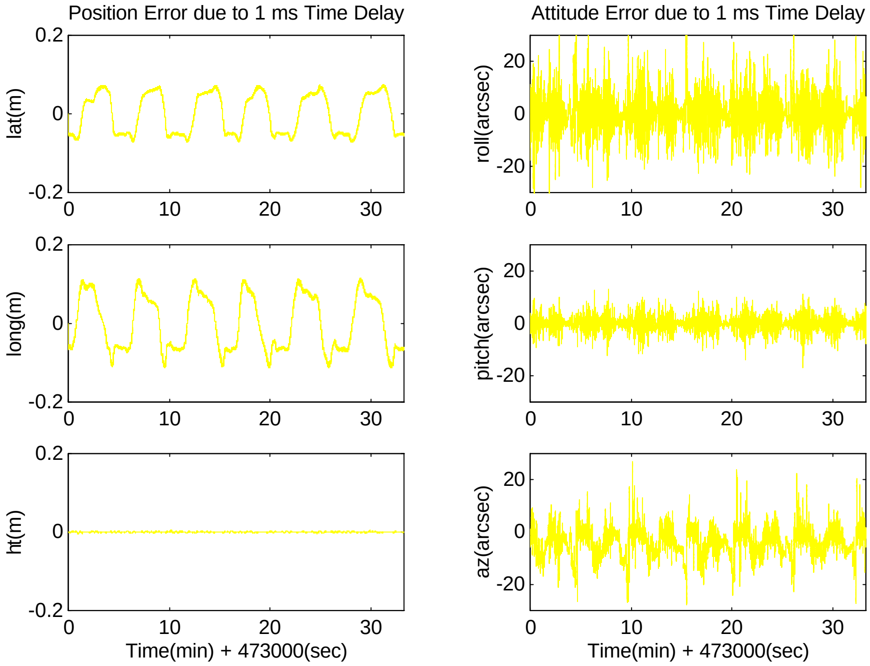

Figure 4. Error in navigation parameters due to synchronization error of 1 ms during a flight.

the parameters of exterior orientation. Considering Equation (1) for direct georeferencing, errors in the synchronization directly affect the determination of the vehicle trajectory in the translation vector $\boldsymbol{r}^{m}_{ins/gps}(t)$ as well as the rotation matrix $\boldsymbol{R}_b^{\,m}(t)$. Since the severity of this error source increases with the platform speed and dynamics, its mitigation is important especially when using airborne carriers. A practical demonstration of this fact is given in Figure 4 where the effect of a 1 ms (milisecond) delay is projected on aircraft position and orientation, respectively. As can be seen from the figure, the 1 ms synchronization error jeopardizes both position and attitude parameters during the survey mission. The along-track position error can be easily obtained by multiplying the delay by aircraft velocity (i.e., a 1 ms delay causes a 10 cm along track position error for the aircraft velocity of 360 km/h). Its influence on height determination is rather negligible once cruising altitude is reached. Although the orientation dynamics lack a simple pattern, the impact of a delay on the attitude parameters can again be quantified by multiplying the delay by the rotation rate. Hence, considering a 10 deg/s rotation rate, a 1 ms delay causes an orientation error of 36".

The effect of imperfect synchronization seems to be less critical for airborne gravity surveys by strapdown INS/DGPS. Typical accelerations are about ±1000 mGal/s (1 mGal = $10^{-5}$ m/s$^2$) with extreme values of about ± 3000 mGal/s (Glennie, 1999). That means that a time delay of 1 ms between the INS and GPS data streams causes a 1 mGal error which in most cases is below the system noise level.

El-Sheimy (1996) analyzed the synchronization errors when using a decentralized hardware configuration consisting of an INS, a GPS receiver, digital cameras and a data logging computer. The error sources can be divided into three main categories as described in Table 1. In general, airborne applications require a centralized synchronization approach via a multi I/O timing board to keep the registration delay under the 1 ms level. When such hardware is implemented, the quality of the synchronization is then mainly affected by the delays due to transmission and processing before measurements are registered. The difficulties are more profound in the airborne application and has been for instance encountered in the design of the Airborne Integrated Mapping System (Grejner-Brzezinska et. al, 1998)

Addressing first only inertial systems, a constant value of the system delay (i.e., time difference between a measurement occurrence and actual measurement output) is usually provided by the manufacturer. Such a number accounts for all internal processing delays due to A/D conversion, filtering, data transmission etc., and its value can be rather large (e.g. 50-60 ms for a navigation grade INS). Also given as a constant, it may vary in time if some form of adaptive filtering is implemented. The transmission delay needs to be calibrated.

The GPS data stream presents less of a problem, because these measurements are already time-tagged internally by the receiver clocks. Synchronization errors in camera exposure epochs can vary greatly. Even if the registration of the shutter pulse is performed internally by the GPS receiver, the transmission delay will always be present. Moreover, the event marked as an exposure may correspond to different stages of shutter opening or closing. This problem may be quite significant especially for cameras of older design where the shutter marker has been installed subsequently. Nevertheless, as long as the delay in registering camera exposure remains a constant it may be estimated within the calibration procedure as will be described later.

Table 1. Time synchronization error sources.

| General Error Source | Specific Error Source | Possible Mitigation |
|---|---|---|
| Internal hardware delay | A/D conversion | Specified by the manufacture |
| | Internal DSP processing | A constant delay may be calibrated |
| | Transmission to communication ports | |
| Data transmission delay | Communication board/protocol | A constant delay may be calibrated |
| Registration delay | Computer clock reading | Low level coding with real time clock |
| | Computer IRQ priorities | Multi I/O timing board |

## 4 Initial Alignment

The alignment process determines the initial body-to-local-level orientation matrix $\boldsymbol{R}_b^{\,l}$ of an inertial system. It precedes the survey mission and is generally done in two stages: coarse and fine alignment. Considering a stationary environment, the coarse alignment estimates the attitude parameters approximately using the raw sensor output and the assumption that nothing but Earth rotation and gravity are sensed. This information is then refined in the fine alignment using a Kalman filter with ‘misalignment states’ and zero velocity as updates. This procedure usually takes 10-15 minutes for a navigation grade strapdown INS to achieve about 1'-3' accuracy in azimuth and 30"-60" accuracy in roll and pitch (Liu, 1992). In an integrated system, the alignment uncertainties are further refined during the kinematic periods using GPS position and velocities as external measurements. Among other factors, the level of improvement during these periods mainly depends on the level of platform dynamics.

From an operational point of view, the 10-15 minute period of static alignment is quite impractical. Moreover, if executed with the aircraft engines running[1], its accuracy deteriorates due to vibrations. Furthermore, inertial systems of poorer accuracy (i.e., tactical-grade INS) cannot be aligned in static mode, because the level of sensor noise in these systems completely masks the needed signal coming from Earth rotation. All of these arguments speak for a dynamic alignment which can be executed quickly, and which guarantees a sufficient accuracy level prior to the georeferencing process. The following discussion will show that dynamic alignment is feasible if aircraft maneuvers are executed in such a way that accelerations in all channels result.

To illustrate the motivation for introducing aircraft maneuvers for obtaining better alignment accuracy, the equation for velocity errors in the local-level frame will be discussed in detail. It is of the form

$$\begin{aligned} d\dot{v}_e &= f_z g_n - f_n g_z + b_e \\ d\dot{v}_n &= -f_z g_e + f_e g_z + b_n \\ d\dot{v}_z &= f_n g_e - f_e g_n + b_z \end{aligned} \qquad (2)$$

where the subscripts *e*, *n*, *z* denote east, north and up components, *f* is the specific force measurement, $g$ is the misalignment error and *b* is the accelerometer bias. Equation (2) indicates that the velocity error in a particular channel is generated by misalignment errors coupled with specific force measurements in the other two channels. Since $f_z$ is always large, due to gravity, the velocity errors due to $g_e$ and $g_n$ can be observed continuously. In contrast, $f_e$ and $f_n$ have nonzero values only when the aircraft is accelerating in the horizontal plane. Thus, the accuracy of determining $g_z$ and the separation of errors in the different channels mainly depends on the extent of horizontal maneuvers. Overall, if aircraft maneuvers provoke sufficient horizontal acceleration, the misalignment uncertainties become quickly observable through the velocity errors and can be estimated by a filter using DGPS velocity updates. An example of this effect will be shown in the following.

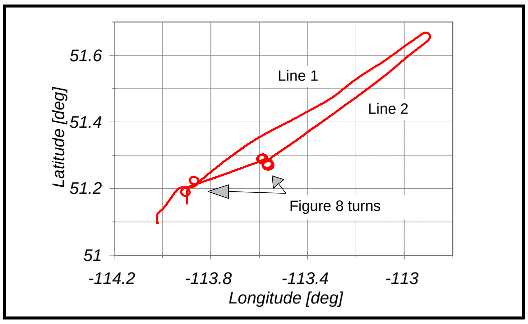

Figure 5. Test flight trajectory with maneuvers to provoke horizontal acceleration of the aircraft.

Figure 5 depicts a flight trajectory with heading maneuvers indicated by the arrows. On board the aircraft were two INS/DGPS systems: a navigation-grade LTN-90-100, loosely integrated with a geodetic GPS receiver, and a tactical-grade IMU, C-MIGITS II, tightly integrated with a C/A code GPS receiver. The performance of the latter was to be tested while the navigation-grade INS/DGPS system served as a reference (for a detailed analysis and test description, see Skaloud et al., 1997). The flight started with the static alignment of the LTN-90-100 whose attitude was then transferred to the C-MIGITS II[2]. After take-off, a first figure-eight pattern was flown to improve the ‘transfer’ alignment of the C-MIGITS II, since a small orientation difference exists between both systems due to uncertainties in their housing. Two flight lines were then flown. After that, the C-MIGITS II was re-initialized and a dynamic alignment was performed while executing two figure-eight maneuvers to provide horizontal aircraft acceleration. Figure 6 depicts the C-MIGITS II attitude errors before and after the dynamic alignment using the LTN-90-100 as the reference. Comparing the statistics before and after the in-flight alignment, it is apparent that the attitude performance is considerably improved with respect to the transfer alignment. This is especially obvious for the azimuth where according to Equation (2) the largest improvement should be expected. This also suggests that repeating the in-

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[1] Since the power for an inertial system is usually drawn directly from the aircraft, its engines have to be started prior to the initialization of the inertial system.

[2] The high noise level of the C-MIGITS II IMU prevents a static alignment.

flight alignment regularly after flying at constant speed and azimuth for longer periods of time results in better attitude accuracy. The overall orientation performance achieved in this test corresponds to the attitude quality delivered by a tactical-grade inertial system with quartz rate sensors.

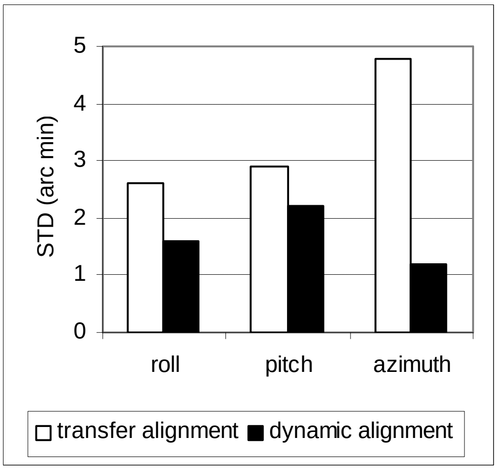

Figure 6. Comparison of alignment accuracies.

It should be noted, however, that although the INS/DGPS integration never stops refining the initial alignment, the accuracy of this process is limited by other factors apart from the dynamics. Two such limitations are directly apparent from Equation (2). First, the estimation process depends on the accuracy of the GPS velocity. Hence, for applications with high accuracy requirements the determination of GPS velocity needs to be handled with special care (for a comparison on filtering methods for high precision GPS velocity determination, see for instance Bruton et al., 1999). Second, the tilt error is coupled with the accelerometer bias. In other words, the quality of the accelerometers indirectly affects the attitude accuracy, and therefore, their quality should correspond to the quality of the gyroscopes. An additional limiting factor comes from the uncertainties in the anomalous gravity field which appears as a disturbing signal in the accelerometer output. Although such an error source could be negligible at some geographical locations, a rough gravity field may cause substantial attitude errors (Figure 7) and limit the accuracy of the georeferencing process in such an environment.

## 5 System Calibration

The calibration of all sensors used in the integrated system is an essential step prior to a survey mission. System calibration can be divided into two parts: calibration of individual sensors and calibration between sensors. The calibration of the individual sensors may include the calibration for parameters of interior orientation, INS calibration for constant drifts, biases or scale factors, GPS antenna multipath calibration, etc. An extensive literature exists on each of these topics. Calibration between sensors involves determining the relative location and orientation between the camera and the navigation sensors as well as the constant synchronization offset due to data transmission and internal hardware delays. Some practical issues concerning this subject will be discussed in the following.

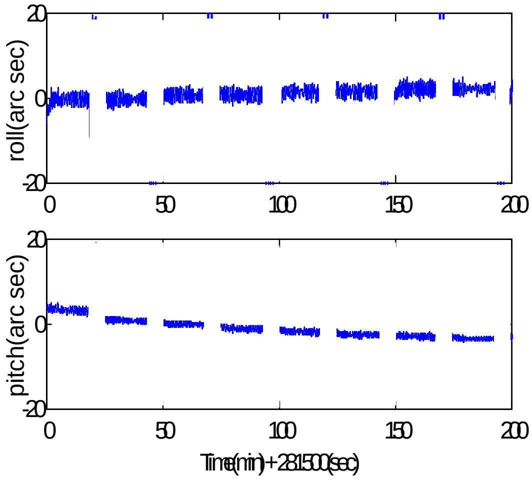

Figure 7. Attitude errors induced by anomalous gravity field in Rocky Mountains.
Aircraft turns eliminated (Glennie, 1999).

The calibration for relative location and orientation between sensors has been previously described for digital cameras and land-vehicle applications by El-Sheimy (1996), for frame-based imagery in the airborne environment by Skaloud et al. (1994), and for pushbroom scanners by Cosandier et al. (1994). Although each of these cases differ in details, the main concept remains the same. Considering Equation (1) of direct georeferencing, the translation offset ($\boldsymbol{a}^b$) between sensors is measured by conventional survey methods and the orientation offset ($\boldsymbol{R}_c^b$) is determined by comparing $\boldsymbol{R}_b^m$ and $\boldsymbol{R}_c^m$ where the latter is computed from photogrammetric triangulation using overlapping imagery and ground control points. Since the parameters $\boldsymbol{a}^b$ and $\boldsymbol{R}_c^b$ are directly used in this equation, they need to be determined with an accuracy at least matching the total requirements of exterior orientation. The determination of the vector $\boldsymbol{a}^b$ presents less of a problem, since an accuracy of a few centimeters is usually sufficient and can be achieved by using a total station for instance. In contrast, determination of $\boldsymbol{R}_c^b$ is a tedious process, because it requires the determination of $\boldsymbol{R}_c^m$ with the same accuracy as $\boldsymbol{R}_b^{\,m}$ in order to fully exploit the quality of the navigation sensors. It should be noted that, especially for digital cameras, this may become the limiting factor for the overall accuracy when transforming INS/DGPS attitude to the camera-frame. The following discussion gives some suggestions on how to improve the accuracy of $\boldsymbol{R}_c^{\,b}$ using INS/DGPS and a given photogrammetric block with ground control points.

1. The formula for obtaining $\boldsymbol{R}_c^{\,b}$ should have the form:

$$\boldsymbol{R}_{\boldsymbol{c}}^{\boldsymbol{b}}(t_i) \text{ ' } \left[\boldsymbol{R}_{\boldsymbol{l}}^{\boldsymbol{c}}(t_i)\,\boldsymbol{R}_{\boldsymbol{b}}^{\boldsymbol{l}}(t_i)\right]^T \qquad (3)$$

   where $t_i$ corresponds to the exposure epoch of an image contained in the block. Assuming a constant misorientation, an average value of this matrix can be used for the transformation of the attitude data. Since the parameters of exterior orientation are better estimated in the middle of the block, only those images should be used to determine the values. It should be noted that expressing the differential rotation matrix in the body frame (as in Equation 3) rather than in the local-level frame, assures its independence from the aircraft attitude. Should it be otherwise, the differential rotation matrix would appear to be time-varying in the local-level axes, as a function of aircraft orientation.

2. Although the photogrammetric model is flexible with regard to the choice of a coordinate system, the chosen map projection has to represent a system of curvilinear geographic coordinates and also has to be conformal to assure compatibility with the INS/DGPS attitude. A Transverse Mercator (TM) projection with a choice of the central meridian in the middle of the flight area fulfills this condition and also minimizes the azimuthal correction due to meridian convergence. However, the azimuthal correction has to be applied in order to transfer $\boldsymbol{R}_c^{\,m}$ to $\boldsymbol{R}_c^{\,l}$. When the sequence of rotations is reversed in the bundle adjustment (i.e., *?-f-?*), the azimuthal correction can be directly subtracted from *?* (i.e., the rotation about the z-axis).

3. If GPS ambiguities can be fixed, the INS/DGPS derived position of the camera perspective center should be used in the bundle adjustment. Fixing the camera perspective center in space provides de-correlation between the parameters of exterior orientation which subsequently results in a better estimate of $\boldsymbol{R}_c^{\,l}$ and thus $\boldsymbol{R}_c^{\,b}$. Moreover, it also allows to refine the calibration of the camera focal-length at the same time.

4. Since the accuracy of $\boldsymbol{R}_b^{\,l}$ also directly affects the determination of $\boldsymbol{R}_c^{\,b}$ in Equation (3), the inertial system should be well aligned prior to acquiring the first strip of images of the photogrammetry block (see the previous section) .

Considering all the points mentioned above, an example of determining the orientation differences for pitch and azimuth is depicted in Figure 8, when using a navigation-grade inertial system and a camera orientation estimated by a highly over-determined photogrammetric block of seven flight-lines as described in Skaloud et al. (1996). As can be seen from the first plot in Figure 8, the agreement in pitch

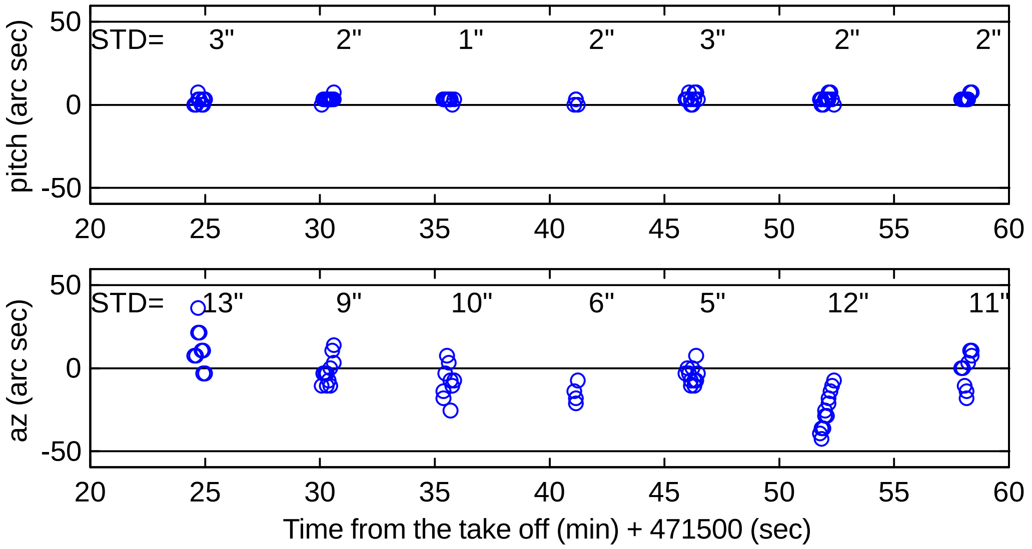

Figure 8. Variations in INS/DGPS - camera orientation in pitch and azimuth.

is free from biases and the standard deviations of 1-3 arc seconds are actually at the limit of $\boldsymbol{R}_c^m$ determination by this mean. The azimuth differences have random character within the individual flight lines with mean standard deviations of about 10 arc seconds. However, although a drift is not apparent during the whole test period, the mean of these differences tends to vary between the flight lines with values up to ±20 arc seconds. The agreement along the roll axis is not shown due to the camera holder stability problem encountered along this axis. Should the roll be determined with the accuracy of the pitch (i.e., 2-3 arc seconds) it could be concluded that the quality of the attitude component in this particular test is sufficient to achieve mapping accuracy of 10-15 cm.

The method of calibrating $\boldsymbol{R}_c^b$ as described above can also be used to estimate a constant synchronization error between the navigation data and the camera exposure. The matrix $\boldsymbol{R}_b^l(t)$ is substituted into Equation (3) as $\boldsymbol{R}_b^l(t+?)$, where *?* is varied in small steps up ±100 ms. Then, the standard deviations of the $\boldsymbol{R}_c^b$ orientation angles are evaluated for each *?* and the maximal correlation shift is computed. An example of this is plotted in Figure 9, where the relative synchronization error between the imagery and navigation data streams is found to be 85 ms.

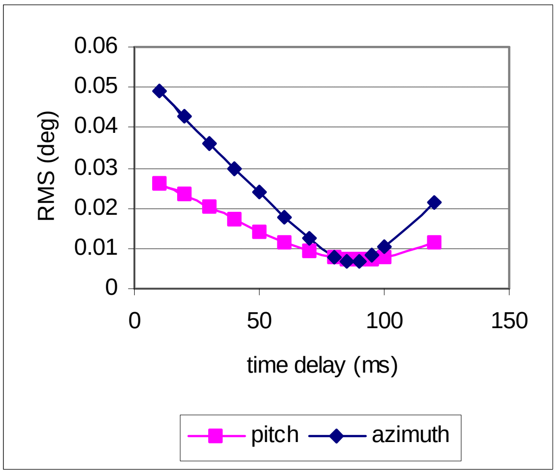

Figure 9. Estimation of the relative synchronization error by means of differences between $\boldsymbol{R}_b^l(t)$ (INS/GPS) and $\boldsymbol{R}_c^l$ (photogrammetry).

## Conclusions

Increasing demand for up-to-date information in spatially referenced Geographic Information Systems (GIS) requires the development of fast, reliable and accurate acquisition systems. The method of INS/DGPS has the potential to fulfill this requirements. However, apart from the selection of sensors and data processing methods, there is number of equally imported subjects to be considered when designing an airborne survey system. In other words, the decision made and methods used with respect to sensor placement, synchronization, initial alignment and system calibration are as important as optimal data processing and filtering algorithms. Inadequate decisions on these aspects can seriously affect overall system accuracy.

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