

## 10 Years of Direct Georeferencing For Airborne Photogrammetry

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### ABSTRACT

The concept of using GPS-Aided Inertial Navigation systems for Direct Georeferencing of Aerial imagery was first explored in the 1980's and early 1990's by researchers at institutes such as the University of Calgary. New differential GPS processing techniques had shown that the position of a sensor on an aircraft could be computed with unparalleled accuracy, and it was only natural that researchers began looking at using DGPS combined with inertial systems to produce the full exterior orientation solution for photogrammetry. Ten years ago at Photogrammetric Week 1995, Dr. K.P. Schwarz of the University of Calgary presented a paper entitled "Integrated Airborne Navigation Systems for Photogrammetry". A year later Applanix launched their POS DG 510, the first commercial system developed for Direct Georeferencing for Airborne Photogrammetry. This was followed by a flurry of activity in both the private and university sectors at institutes such as the University of Stuttgart IFP to understand the full capabilities of this new technology. Today it is an accepted technique as a replacement or augmentation to Aerial Triangulation, and with the advent of digital cameras and the all-digital workflow, it is quickly becoming a defacto standard.

This paper presents an overview of GPS-Aided Inertial Navigation and its application for Direct Georeferencing. It then looks at some of the challenges that needed to be overcome in the early days of its use, and gives a brief history of its adaptation. Finally, the current state of the art of Direct Georeferencing will be discussed as well what we can expect in the future as the technology evolves. Particular emphasis will be given on new IMU technologies (such as the MEMS technology) and the modernization of GPS (such as the implementation of the new L2C and L5 signals as well as launching the Galileo system and its integration with GPS).

### INTRODUCTION

In the context of airborne photogrammetry, Direct Georeferencing (DG) is defined as the process of assigning the Exterior Orientation of each image frame or scan line directly, without the need to use traditional aerial triangulation techniques. Currently this is achieved by measuring the geographic position and orientation of the airborne imaging sensor directly using Global Positioning System (GPS) and Inertial Navigation System (INS) technology. GPS provides highly accurate measurements of position, while an INS computes a full position and orientation solution. When combined into a single solution, the accurate GPS position measurements are used to control the errors in the INS, effectively helping it or "aiding" it to have a higher accuracy than it could on its own. Such a system is often referred to as a GPS-Aided INS.

Since GPS technology was originally developed for the military, it is natural that the GPS-Aided INS systems first appeared in military applications in the 1980's. However it was quickly recognized by the academic community that having very accurate measurements of position and orientation of an aircraft could have great potential when combined with airborne photogrammetry: it could stream-line and automate the aerotriangulation process, and if the data were accurate enough, replace it completely. The implications were enormous: suddenly remote and inaccessible regions could be accurately mapped, the cost of collecting ground control points could be reduced to collecting a few check-points for quality purposes, ortho-photos and ortho-mosaics could be produced using an existing DEM without need to collect stereo imagery (a big benefit on a film camera due to the costs of film, development, and scanning), flight times could be reduced since there is no longer any need to fly a block with

full forward and side lap to ensure the aerotriangulation is stable (especially important for corridor work), and in the case of a digital camera, map-products could be produced within hours instead of days or even months (In fact real-time photogrammetry is now within our reach and being explored by researchers such as Wu et al (2004)).

The use of GPS-Aided INS (GPS/INS) systems to augment the aerotriangulation process was first suggested in the 1980s by Schwarz et al (1984). The proposal was to use the GPS/INS-derived trajectory parameters as a seed in the aerotriangulation process. The concept of Direct Georeferencing was still not fully developed, and in fact data from the GPS/INS was considered “auxiliary” during the 1980s and early 1990s. However by 1995 the concept was fully realized, and the first Direct Georeferencing article was published in the PHOWO by K.P. Schwarz. Dr. Schwarz directed a team of researchers at the University of Calgary working on different aspects of Direct Georeferencing and developing different systems, such as Skaloud et al (1996) for film cameras, and Mostafa et al (1997) for digital frame cameras. Similar development took place at the Ohio State University for airborne digital mapping (c.f., Toth and Grejner-Brzezinska, 1998). In 1999-2001, the first real evaluation of the direct georeferencing technology in Europe took place at the University of Hannover where thorough tests and un-biased evaluation was carried out to help improve the technology. For details, see Heipke et al (2001).

During the same time period, Applanix Corporation was experimenting using its commercial Position and Orientation System (POS AV) for the purpose of Direct Georeferencing of airborne imaging systems. The first successful demonstration was in 1995 using the Multi-spectral Electro-optical Imaging Sensor (MEIS), a push-broom scanner developed by the Canadian Center for Remote Sensing (CCRS). In early 1996 the first tests of POS AV for Direct Georeferencing of a traditional photogrammetric camera were conducted with Hauts Monts in Quebec City, on a Leica RC30 film camera. These results lead Applanix to offer a commercial product specifically for Direct Georeferencing of film cameras called POS/DG. First results were presented to the photogrammetric community in 1997 by Hutton et al (1997) and Abdullah (1997) as a result of cooperation between Applanix and Earth Data International. Since then, the direct georeferencing concept has penetrated because of its operational and technical advantages.

This paper will begin with a brief overview of GPS-Aided INS systems, and how they are used in Direct Georeferencing. A history of their adoption will then presented, along with highlights of some of the obstacles that needed to be overcome for acceptance. Finally an overview will be given on the current state-of-the art and where the technology is headed for the future.

## GPS-AIDED INERTIAL NAVIGATION: AN OVERVIEW

A GPS-Aided INS used for Direct Georeferencing of aerial imagery is typically comprised of four main components: an Inertial Measurement Unit or IMU, a dual frequency low-noise GPS receiver, a real-time computer system and a post-processing software suite (see Figure 1). The heart of the system however is the Integrated Inertial Navigation software that is implemented both in real-time on the computer system and in postmission using a module of the post-processing software suite. The software implements the sophisticated signal processing algorithms that blend the GPS measurements with the inertial navigation solution, to produce a position and orientation solution that retains the dynamic accuracy of the inertial navigation solution but has the absolute accuracy of the GPS. This is explained in more detail in the following sections.



Figure 1. The Applanix POS AV System

## Inertial Measurement Unit (IMU) and Inertial Navigator

An IMU is comprised of triads of accelerometers and gyros, digitization circuitry and a computer that performs signal conditioning and temperature compensation. The accelerometer and gyro data are compensated for temperature effects (which can cause erroneous measurements) and are output as incremental velocities and angular rates via a serial interface at rates of typically 100 to 1000Hz. The real-time computer then integrates the accelerations and angular rates in a so-called “Strapdown” inertial navigator to produce position, velocity and orientation of the IMU, geographically referenced to the earth. If the IMU is rigidly attached to a remote sensor means the inertial navigator produces position, velocity and orientation of the sensor itself. To ensure maximum accuracy, the IMU’s must be relatively small and lightweight so that they can be mounted as close to the sensor’s reference point (perspective center) as possible. Typical high-quality IMU’s use force rebalance accelerometers and either Fiber Optic Gyros (FOG), Ring Laser Gyros (RLG), Dry Tuned Gyros (DTG), or Quartz Micro-Electro Mechanical Sensors (MEMS) gyros.

The inertial navigator solves Newton’s equations of motion on the rotating earth by integrating acceleration and angular rates sensed by the IMU. In order to do this, the inertial navigator must first be initialized with known position and velocity from the GPS, and aligned with respect to the true vertical and true North. Alignment with respect to the vertical is referred to as *leveling*, while alignment with respect to North is referred to as *heading alignment*. Once aligned the inertial navigator has established a local-level mathematical frame of reference called the navigation frame, whose heading is known with respect to North, and to which the orientation of the IMU is known, as shown in Figure 2.

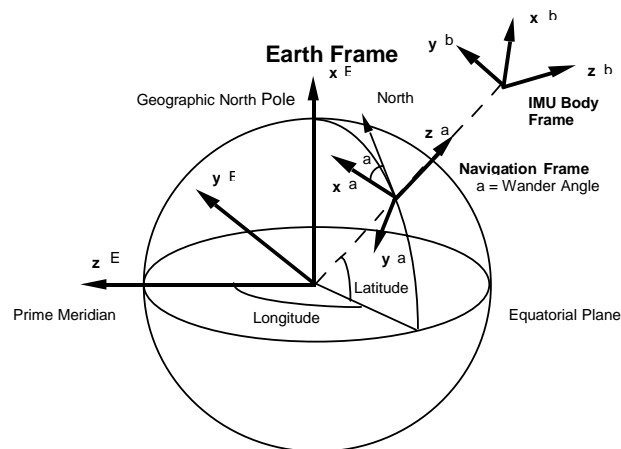


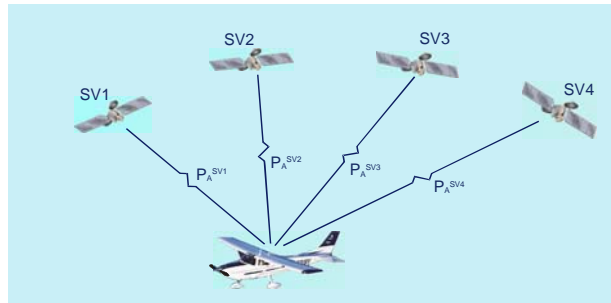
Figure 2. Frames of References Used in Inertial Navigation

In most cases the WGS84 datum is used to model the Earth. After removing the rotation rate of the Earth that (computed as a function of position), the navigator integrates the incremental angles from the IMU to continuously compute the change in orientation of the IMU with respect to the navigation frame. It then uses the orientations to resolve the incremental velocities from the accelerometers into the local-level navigation frame, which it then integrates to compute the position change of the navigation frame over the Earth. Note that this means any error in the orientation will directly contribute to a position error on the Earth. The solution it produces is dynamically very accurate; however, since the inertial navigator uses an integration process, any errors in the accelerometers and gyros will integrate into slowly growing position, velocity and orientation errors.

## Global Positioning System (GPS)

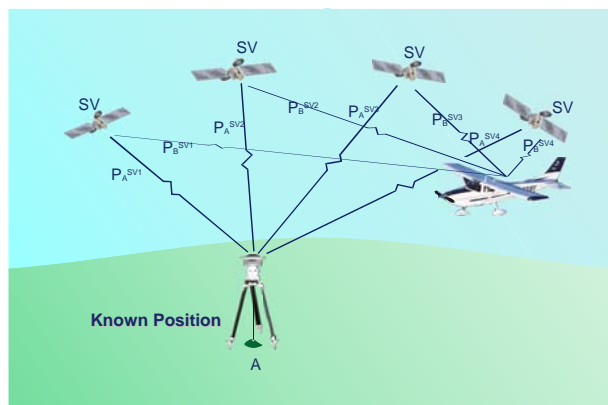
The GPS system is comprised of a constellation of satellites whose positions are known and a remote receiver that uses range measurements to the satellites and triangulation techniques to compute the position of the receiver’s antenna (see Figure 3). The satellites transmit modulated signals centered at 1575.42 MHz, known as the L1 signal, and 1227.6 MHz, known as the L2 signal. Each signal contains a unique code that allows the GPS receiver

to track the signal and compute the approximate range (called pseudoranges) to each satellite. L1 uses the Clear Access or C/A code, and is published for civilian applications. L2 uses the Precise or P Code which is restricted for military use only. The computed pseudoranges comprise the true ranges between the satellites and the GPS antenna of the receiver, plus several errors, the most dominant being the receiver clock bias error. The clock bias is common in all pseudoranges, and contributes 30 centimeters pseudorange error per nanosecond, or as large as 300,000 meter for 1 msec! Hence the receiver clock bias must also be estimated in the triangulation process to compute position, which implies a minimum of 4 satellites must be in view at all times. Once this is estimated, the error in the final computed position is usually at the 4 to 6 m level. The residual error in this so-called “Single-Point Positioning” is caused by signal delays due to the atmosphere (ionospheric and tropospheric delays), residual satellite orbital errors, multipath error and receiver clock noise.



**Figure 3. Single Point GPS Positioning**

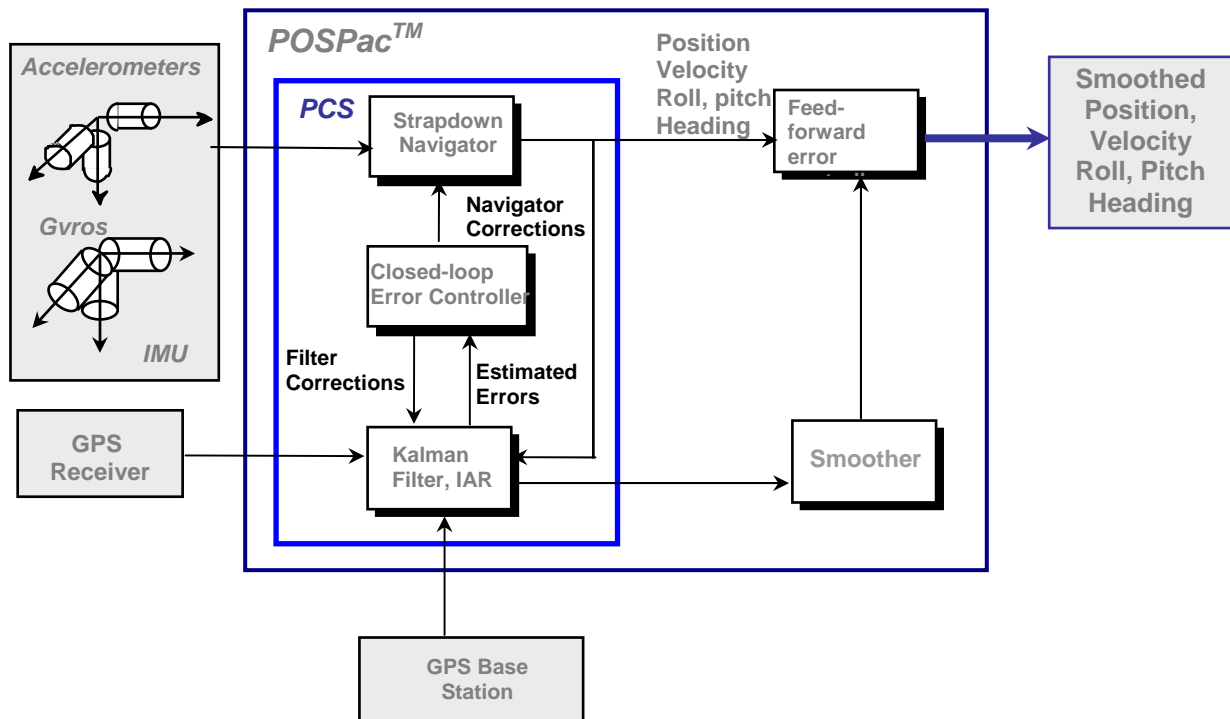
Another method to computing the range to each satellite is to use the phase of the L1 carrier signal. This can be determined very accurately, and as long as the integer number of wavelengths (approximately 19 cm) to each satellite can be determined, decimeter accuracy can be obtained. Carrier phase differential GPS is an advanced technique that combines the phase data from two receivers (one on the airplane and one stationary on the ground) so as to eliminate the residual errors in the phase measurements and estimate the correct ambiguities (see Figure 4). Redundant phase observations from 5 or more satellites provide the information to resolve the ambiguities, thus translating each satellite's estimated phase cycles into precise range measurement. A high precision satellite-to-receiver range measurements allow the computation of the baseline (interstation) vector between the receivers and hence the position of the remote receiver to decimeter or better accuracy. The challenge using this technique for airborne positioning is that the residual ionospheric delay in the phase differences does not fully cancel out, but rather grows the further the aircraft is away from the base station. A dual frequency receiver uses the difference between the L1 and L2 phase to try and estimate the delay, but even this technique can be limited when the distance to the base station is over about 25 km. Hence when practical a multiple number of reference stations is employed to ensure the base-line separation is maintained below this level.



**Figure 4: Differential GPS Positioning**

## GPS-Aided Inertial Navigation

The GPS-Aided Inertial Navigation software implemented in real-time and in post-mission typically uses an architecture as shown in Figure 5:



**Figure 5. Closed-Loop GPS-Aided Inertial Navigation**

The Kalman Filter implements a linearized and discretized set of differential equations that model the inertial navigator errors and the IMU sensor errors that drive them. Differences between the position from the inertial navigator and the position from the GPS are processed in the Kalman filter (typically at 1 Hz), to estimate the slowly growing position error in the inertial navigator. Since this error is a function of both errors in the orientation and errors in the inertial sensors, (as modeled by the differential equations in the Kalman filter), observing the inertial position errors means the orientation errors and IMU sensor errors can also be implicitly estimated.

The closed-loop error control algorithm is used to apply resets to the inertial navigator using the Kalman filter-estimated parameters. Estimates of the inertial sensor errors are also applied to the IMU-measured raw incremental angles and velocities before they are integrated, which has the same effect as calibrating the sensors. The resultant integrated inertial navigation solution has its position and velocity directly regulated to the absolute accuracy of the GPS position and velocity, and its orientation accuracy indirectly improved by the calibration of the inertial sensor errors. This is the solution that is computed and output by the computer in real-time.

The Smoother is a module that computes the optimal estimates of the inertial navigator and IMU sensor errors, by processing the data backwards in time and then combining it with the estimates from the forward in time Kalman filter. The resultant error estimates are based upon all available information from the past and future, and hence are more accurate. The Smoother is implemented only in the post-mission software.

With proper mission planning, careful flight operations to minimize satellite loss of lock, and multiple base station deployment to ensure the maximum baseline separation between the remote and base receivers are within 10 - 50 km, position accuracies in the range of 5 to 30 cm RMS are achievable using post-processed carrier phase Differential GPS. Most of the position error is due to residual propagation delays caused by the ionosphere, which are low frequency in nature and cannot be removed by blending with the inertial data. This means the absolute accuracy of the post-processed smoothed navigation position from will also typically be 5 to 30 cm RMS.

The orientation accuracy of the smoothed GPS-Aided INS solution is described best in terms of *absolute accuracy* and *relative accuracy*. The *absolute accuracy* is the total RMS error including mean, while the *relative accuracy* describes the high frequency sample-to-sample error. It is convenient to do this since in most cases the orientation error is comprised of a slow varying signal with almost no noise, and in some applications it is the accuracy of the change in orientation that is most important (such as that in a digital line scanner). The relative accuracy of the roll, pitch and heading is a function of the gyro noise and residual gyro bias after smoothing.

The typical post-processed *absolute* accuracy for each Applanix POS AV model is given in Table 1, for a typical survey mission profile. The post-processed relative orientation accuracy for each POS AV model is given in Table 2. The difference in performance is a function of the type of IMU and error model used in each system.

**Table 1. Post-processed POS AV Absolute Accuracy**

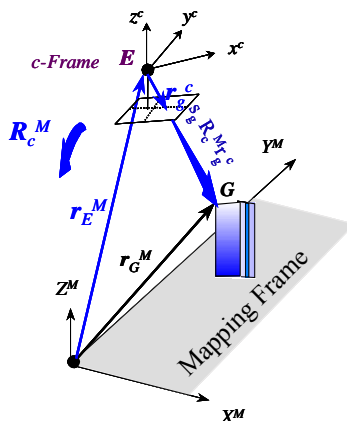
| <i>Parameter Accuracy (RMS)</i> | <i>POS AV 310</i> | <i>POS AV 410</i> | <i>POS AV 510</i> | <i>POS AV 610</i> |
|---------------------------------|-------------------|-------------------|-------------------|-------------------|
| <i>Position (m)</i>             | 0.05 -0.30        | 0.05 -0.30        | 0.05 -0.30        | 0.05 -0.30        |
| <i>Velocity (m/s)</i>           | 0.010             | 0.005             | 0.005             | 0.005             |
| <i>Roll &amp; Pitch (deg)</i>   | 0.013             | 0.008             | 0.005             | 0.0025            |
| <i>Heading (deg)</i>            | 0.035             | 0.015             | 0.008             | 0.0050            |

**Table 2, Post-processed POS AV Relative Orientation Accuracy**

| <i>Parameter Accuracy</i>              | <i>POS AV 310</i> | <i>POS AV 410</i> | <i>POS AV 510</i> | <i>POS AV 610</i> |
|--|-------------------|-------------------|-------------------|-------------------|
| <i>Random Noise (deg/sqrt(hr))</i>     | 0.15              | 0.07              | < 0.02            | 0.005             |
| <i>Residual Bias (deg/hr), 1 sigma</i> | 0.5               | 0.5               | 0.1 - 0.5         | 0.05              |

## DIRECT GEOREFERENCING

Direct Georeferencing using GPS-Aided INS implies the direct measurement of the Exterior Orientation (EO) of each single image frame or scan line at the moment of data acquisition. In principal, this allows immediate map production using the photogrammetric unit (either a stereopair of images, or a single image+DEM). Ultimately, this approach totally bypasses the aerotriangulation step with no ground control point requirement, except for quality control. This of course also assumes that the camera Interior Orientation is well calibrated and stable. Figure 6 shows the georeferencing concept.



**Figure 6. Image Georeferencing**

In order to accurately compute the ground coordinates of a point using Direct Georeferencing, a number of requirements need to be met:

1. The IMU needs to be rigidly attached directly to the camera to ensure there is not flexure between the camera perspective center and the sensing center of the IMU
2. The physical misalignments of IMU with respect to the Camera need to be calibrated
3. The lever-arm offsets from the camera perspective center to the IMU and to the GPS antenna need to be calibrated
4. The exact time of image exposure needs to be recorded by the GPS-Aided INS so that the navigation parameters at that time can be computed
5. The position and orientation from the GPS-Aided INS navigation data need to be transformed to the EO used by most photogrammetric plotters. This usually involves a transformation from the geographic frame to a local level user frame, which means the appropriate transformation parameters must be known or computed.
6. The camera interior geometry (principal point, lens distortion, focal length) must be well calibrated and stable.

This section discusses these requirements in more detail.

### **IMU Mounting and Boresighting**

The ease at which an IMU can be added to an airborne imaging sensor is dependent upon the size and weight of the IMU, but most importantly, whether or not the sensor has been designed with this purpose in mind. Ideally the IMU should be mounted as physically close to the perspective center as possible, enclosed by some cover for protection, yet still easily accessible. Legacy systems such as film cameras have no provision for this, while all new digital cameras such as the DSS, DMC, ADS40 and UltraCam are designed to hold an embedded IMU. For most film cameras, the only choice is to mount the IMU externally.

Once the IMU has been installed properly, the physical misalignments of the IMU with respect to the camera frame must be calibrated. These angles are often referred to as the IMU boresight angles, and theoretically describe the misalignment angles between the IMU and the digital camera frames of reference as shown in Figure 7.

A key assumption is that the boresight angles remain constant as long as the IMU remains rigidly mounted to the camera. The most convenient and accurate means of determining the boresight is to solve for it implicitly in a classic bundle adjustment by introducing the three- $\Theta_x$ ,  $\Theta_y$ , and  $\Theta_z$  angles as observable quantities in the adjustment process (Mostafa 2001). This method does not require ground control except for quality assurance.

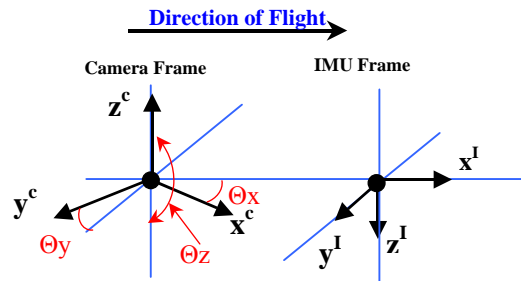


Figure 7: Boresight Angle Definition

### Lever Arm Calibration Requirement

A lever arm is a relative position vector of one sensor with respect to another. In a camera installation, the sensor reference point is the camera perspective center, and there are two lever arms that must be measured. The IMU lever arm is the relative position of the inertial center of the IMU with respect to the sensor reference point, and the GPS lever arm is the relative position vector of the phase center of the GPS antenna with respect to the sensor reference point. These two vectors allow the GPS-Aided INS system to translate the navigation center from the IMU to the camera perspective centre. As with the boresight angles, these lever arms must be measured to an accuracy better than the positioning accuracy of the GPS-Aided INS, in order for it not to contribute to the overall positioning error budget. If the camera is mounted on a stabilized mount, the GPS lever arm will change as a function of the mount motion, and the gimbal encoder data must be used to compute a dynamic lever arm for maximum accuracy.

### Timing

In order to compute the correct position and orientation of the images, the exact time of the mid exposure must be recorded in the same time frame as the GPS-Aided INS. Any time mismatches between the two will directly contribute to position and orientation errors as a function of the velocity and angular rate. Accuracy must be at least 1 msec or better. The timing is usually achieved by having the camera create a Mid-Exposure Pulse (MEP) and send it to the GPS-Aided INS where it is latched in hardware and assigned with the correct GPS time. If the time at the beginning or end of the exposure is recorded instead of the middle of the exposure, it is necessary to compensate this for the shutter speed.

### Computation of Exterior Orientation

With respect to photogrammetry, the Exterior Orientation of an image is defined as the translation  $(X, Y, Z)$  and rotation  $(\phi, \omega, \kappa)$  of the image with respect to an object space. In most cases the object space is assumed to be a local level mapping frame comprised of a user specific datum and projection. In contrast, the position outputs from a GPS-Aided INS are with respect to the Earth-Centered Earth fixed Geographic frame (lat, lon, alt), and the orientations (roll, pitch and heading) are with respect to the instantaneous tangent to the WGS84 ellipsoid (see Figure X). Hence they usually need to be transformed before they can be employed in the photogrammetric process.

Transformation of position is relatively straightforward using standard projection and datum definitions. The orientation angles  $\phi$ ,  $\omega$ , and  $\kappa$  are computed from the roll, pitch and heading angles  $\Phi$ ,  $\Theta$ , and  $\Psi$  as follows: (Škaloud et al 1996).

$$\mathbf{C}_i^m(\phi, \omega, \kappa) = \mathbf{C}_E^m \mathbf{C}_g^E(\text{lat}, \text{lon}) \mathbf{C}_b^g(\Phi, \Theta, \Psi) \mathbf{C}_i^b \quad (1)$$

Here  $C_i^b$  is the boresight rotation matrix between the IMU body frame  $b$  and the Image frame  $i$ ,  $C_b^g$  is the rotation matrix from the IMU body frame to the local-level geographic frame  $g$  defined by the measured roll, pitch, and heading,  $C_g^E$  is the rotation matrix from the local-level geographic frame to the Earth-centered Earth fixed frame  $E$  defined by the measured latitude and longitude, and  $C_g^L$  is the rotation matrix from the Earth-centered Earth fixed frame to the local level mapping frame and projection defined by the user.

### Camera Interior Orientation

The camera model or interior orientation (IO) describes the physical internal geometry of the image plane with respect to the projection center. This information is required to project the image ray to an object point on the ground. Typical parameters that need to be calibrated include focal length, principal point offset and lens distortions.

Unlike aerotriangulation, which can absorb instabilities or slight errors in the IO calibration by warping the EO to fit the Ground Control Points, Direct Georeferencing requires the IO calibration to be accurate and stable. Any errors or changes during the flight will directly produce errors on the ground independent of how accurate the EO might be.

### Digital Orthophoto Production Data Flow

A typical Orthophoto production project includes calibration, navigation data processing and image data processing. The calibration consists of imaging sensor calibration (e.g., a digital camera), boresight calibration, and lever arm calibration. The Earth-Fixed Earth-Centered (ECEF) position and orientation angles derived by the GPS-Aided INS, are compensated for the boresight and lever arm calibration parameters. The trajectory parameters are then interpolated at the recorded camera events and transformed into the required local mapping frame (M-frame) using the post-mission software. If the boresight and lever arm calibration parameters are not available, the post-mission software solves for them using the navigation and image data. This yields the exterior orientation (EO) parameters of each single image frame or scan line coordinatized in the local mapping frame ( $X$ ,  $Y$ ,  $Z$ ,  $\omega$ ,  $\phi$ , and  $\kappa$ ). In a Softcopy, image data and exterior orientation data are processed either in single image mode or in stereo mode to produce ortho mosaics using either available DEMs or produced DEMs from stereo imagery, respectively.

## HISTORICAL OVERVIEW

### Academic Developments

Some of the very first tests of Direct Georeferencing on a film camera were done in July 1995 by the University of Calgary using a Litton LTN-90 INS mounted on a Zeiss RMK film camera (Skaloud, et al 1996). Data from the INS and from an external GPS receiver were collected separately, then post-processed using the University of Calgary KINGSPAD software. Although the results were not as accurate as the theory predicted, they did fundamentally prove the feasibility of Direct Georeferencing.

The following year in 1996, tests were flown by the University of Calgary of an all-digital prototype that used two Kodak DC420 C digital cameras (Mostafa et al, 1997). One camera was mounted in the nadir direction and the second camera was mounted in the oblique direction (see Figure 9). The Direct Georeferencing solution was generated using KINGSPAD and data logged from a Honeywell INS and an external GPS receiver. Over 100 ground-control points were used to study the accuracy of the Direct Georeferencing solution and the stability of the camera calibration.



**Figure 9: University of Calgary Digital Camera System**

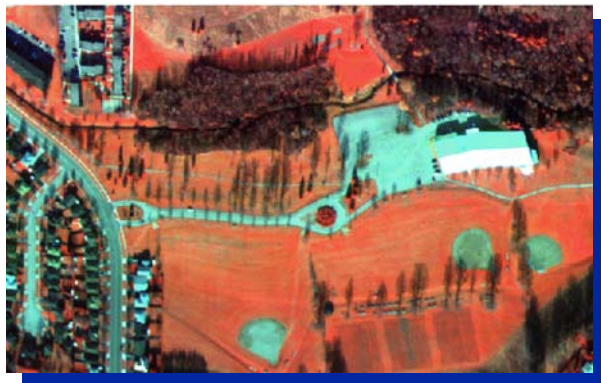
A similar system called the AIMS or Airborne Integrated Mapping System, was developed in 1998 at the Ohio State University (Toth et al, 1998). In this system a single BigShot Hasselblad 4Kx4K digital camera was integrated with an LN100 INS and a GPS receiver, and data were processed using Ohio State's proprietary software.

### **Commercial Developments**

Although the concept of Direct Georeferencing and its feasibility had been thoroughly explored by the academic community, developing a commercial product offering presented its own unique challenges. The research showed that it worked; but could it be implemented in a production environment?

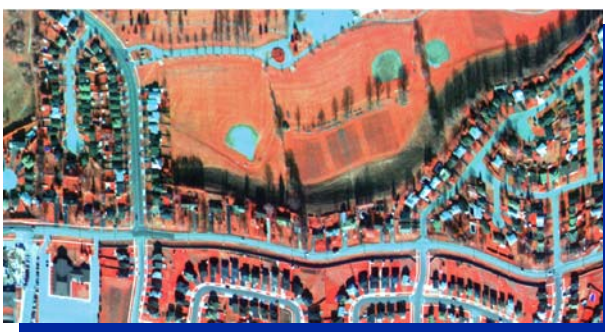
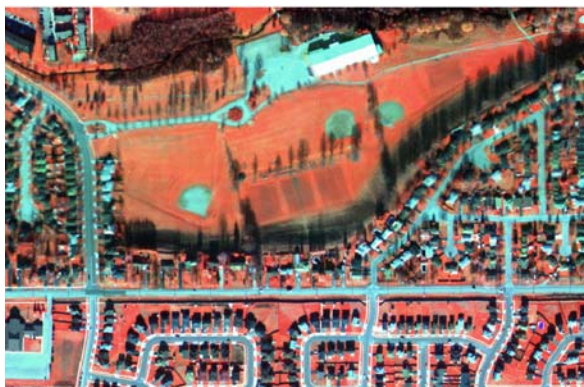
The first airborne Direct Georeferencing tests conducted by Applanix were in 1995 using the Multi-spectral Electro-optical Imaging Sensor (MEIS), a push-broom scanner developed by the Canadian Center for Remote Sensing (CCRS). The MEIS was developed in the late 1980's, and was originally designed to be georeferenced using an un-aided INS and aerotriangulation to control the position drift. Adding a POS AV unit was very straight forward, and the aerotriangulation step was simply by-passed. The photogrammetric processing was done using a software package called GEOCOR, which was also developed in house by CCRS. GEOCOR used the position and orientation from the POS to georectify each scan line and produce the final ortho mosaic (see Figure 10). Compared to the compact sensors of today, the MEIS was something of a mammoth; it took up almost the entire cabin space of a Twin Otter. However it proved the feasibility of Direct Georeferencing push-broom scanners, the same principles that are in use today with systems such as the ADS40.

## Uncorrected Imagery



### MEIS Imagery

- altitude = 1.5 km
- resolution = 0.7 mrad (1 m)



### Ortho Image:

- geocorrected & geocoded
- no ground control

**Figure 10: Directly Georeferenced MEIS Imagery**

The successful results of the MEIS test directly lead to the first commercial POS AV installation in 1996 on a CASI multi-spectral scanner owned by Aquater of Italy. Included with the system was the GEOCOR software, which resulted in a seamless end-to end workflow. The primary application of the system was mapping pipe-line corridors for environmental damage.

In the beginning of 1996, Applanix started experimenting with Direct Georeferencing on traditional film cameras. The early tests were done in conjunction with Hauts Monts of Quebec City, Canada, who supplied the aircraft, an RC30 film camera, and the final photogrammetric processing. These tests were followed by an extensive research program with EarthData, USA, to outfit their RC30 cameras and thoroughly investigate the capabilities of using Direct Georeferencing in a production environment. This led to the first European adaptors, notably EuroSense, in 1997.

The first challenge at hand was to figure out how to mount the IMU. The RC30 has an interesting, modular design, using two separate film canisters which allow the film to be changed quickly and easily in flight. However, it also means that there is very little available surface for mounting an IMU. Furthermore, how do you convince someone to let you drill holes into their \$300,000 piece of equipment? Needless to say with a little ingenuity a solution was found that involved removing one of the handles and adding a special mount to existing holes (see Figure 11)



**Figure 11: IMU Mounted in Handle of RC30 Camera**

Boresighting of the IMU's was done by comparing the GPS-Aided INS derived EO solution to the EO derived by aerotriangulation for a sub-block of imagery. Subsequent analysis showed that GPS-Assisted AT was required to decorrelate the positions from the orientations in the AT results, in order to produce angles that "properly" matched the GPS/INS angles (in a traditional AT solution, the position and orientation are solved to produce the smallest tie/pass-point residuals, and do not necessarily represent the same physical angles as the INS measures).

The next big challenge was to transform the position and orientation into Exterior Orientation for input into the existing analytical and softcopy plotters. Coming mostly from an Aerospace background, those involved assumed that this would be a trivial step. After all, wasn't it all described in the Manual Photogrammetry? As it turned out legacy issues with the existing photogrammetric workflows became a significant barrier to Direct Georeferencing being accepted by the industry. It was very soon discovered that:

- Many plotters could not accept EO directly, but rather expected an adjusted set of tie and pass-points
- The definition of the sequence of rotations for the EO was not standardized
- Many of the transformations between the WGS84 datum and the local level mapping frame were poorly defined
- Some local mapping frames expected a different datum for their heights than for the horizontal coordinates
- Some plotters applied a vertical scale factor to account for earth curvature, others did not (and did not document this)

Most of these issues existed for one very simple reason: aerotriangulation had ensured the plotters produced results consistent with their measured ground control points.

Fortunately, at the same time that Direct Georeferencing was being developed commercially, there was also a paradigm shift away from analytical plotters to soft-copy photogrammetry, driven mostly by the availability of powerful and relatively low-cost computers. The soft-copy developers quickly realized the need to add or streamline support for Direct Georeferencing, and companies such as Z/I, Leica, BAE and Inpho were among the first to do so.

The appearance of commercial Direct Georeferencing systems helped to push researchers at academic institutes such as the University of Stuttgart IFP (Cramer, 1999) and the Cartographic Institute of Catalonia (Collomina, 1999), to understand the full potential of the new technology. However it was a definitive study conducted by The European Organization for Experimental Photogrammetric Research (OEEPE) that really proved to the community what its strengths are (Heipke et al, 2001). The study involved a multi-site test to investigate that accuracy of Direct Georeferencing on film cameras by comparing it to aerotriangulation, with the ultimate goal of easing the transition of the new technology to the users. The results were very well received, and resulted in the development of improved workflow software and procedures for using the systems in a production environment.

## DIRECT GEOREFERENCING TODAY AND ITS FUTURE

Ten years on, Direct Georeferencing is now a proven and common tool used by the aerial photogrammetric industry. The systems are compact, easier to use, and have established workflows through the photogrammetric software. This section provides a brief overview of the current state-of-the-art and future trends.

### Inertial Technology

Most of the GPS-Aided INS systems in use for Direct Georeferencing employ IMU's incorporating Fibre Optic Gyro (FOG) or Dry Tuned Gyro (DTG) technology. DTG's are mechanically machined and use a resonant mechanism in the rotor to virtually eliminate friction. FOG's use a winding of fibre optic (typically 150 to 1000 m) through which light is passed in opposing directions. When the gyro is rotated, the difference in path length causes an interference pattern that is correlated with angular rate. A new generation of IMU's has also appeared that uses high-end Quartz MEMS gyros. A Quartz MEMS gyro uses a piece of quartz micro-machined into a "tuning fork" configuration that senses angular rate through centripetal acceleration.

Accelerometer technology is quite mature, and most incorporate a proof mass with a single degree of freedom that is displaced during acceleration, with a rebalance mechanism to null the displacement. Typically they are made from quartz or silicon, and often are micro-machined.

So where is IMU technology headed? Due to their simple design, quartz MEMS gyros can be mass produced at a much lower cost than FOG's or DTG's. Lower accuracy versions of the gyros are currently being used in the automobile industry for traction control system. As demand increases, costs are being driven down accordingly through improved manufacturing efficiencies. This will in turn reduce costs for the higher accuracy gyros required for Direct Georeferencing since they are built using the same manufacturing process.

In addition to quartz MEMS gyros, silicon MEMS gyros are also starting to exhibit a performance good enough for Direct Georeferencing. These gyros use sensing elements machined out of silicon, and are very inexpensive to mass-produce, even less so than quartz gyros.

Hence we can fully expect there will be a transition away from DTG and FOG based IMU's to less expensive MEMS based IMU's over the next few years.

### GPS and Galileo

The current state-of-the-art for airborne positioning is to log data from a L1/L2 survey grade GPS receiver and multiple-based station receivers, and generate a post-processed integer carrier phase DGPS solution at the 10 cm level accuracy. Most countries now have permanent GPS reference networks that can be used free of charge, so a single base station deployed at the airport is usually all that is required. However for those areas that do not, it can be very expensive or sometimes impossible to set up the base stations needed to achieve high accuracy.

What can we expect going forward? GPS is in the process of being modernized. Satellites are being launched starting at the end of 2005 that will include the new L2C Civil Code. This is a code on the L2 carrier signal that will be un-encrypted for civilian use, making it much easier to acquire and track the L2 frequency. This should in turn greatly improve the robustness of the ionospheric delay, implying faster, more robust ambiguity resolution. Full constellation of 18 satellites is expected by 2005 (Hotem, 2004). In addition to the L2C, a third carrier, L5, will be introduced in satellites launched starting about 2009 (Hotem, 2004). The L5 is a carrier signal, located at 1176.45 MHz in the Aeronautical Radio Navigation Service range, which will have much higher power for improved tracking at lower elevations, protected for safety-of-life applications. Additionally, it will not cause any interference to existing systems. Having three carriers also means an improved Ionosphere estimation, leading to faster ambiguity resolution and higher accuracy over longer base lines.

Finally, the European satellite based positioning service, Galileo, is expected to be launched starting in 2008 (Hotem, 2004). When combined with the GPS modernization, plus the existing GLONAS system maintained by the Russians, the net result could be up to 60 satellites in view with up to 4 difference carriers. This would allow

instant ambiguity resolution and greatly improved positioning performance through a drastic reduction in PDOP (the degradation in precision due to satellite geometry).

### Precise Single Point Positioning and Satellite Based Augmentation Services

Differential GPS relies on simultaneous observations with a base station or multiple base stations to cancel out common errors phase measurements due to orbital errors, satellite clock errors, and atmospheric errors, to a level that will allow correct ambiguity resolution. In order to do this in real-time, the base station data need to be transmitted to the remote receiver with little or no delay. Needless to say this is not practical in an airborne environment, which is why the data are usually logged and post-processed. Furthermore, what if a base station can simply not be placed close enough to the area to be mapped to ensure the desired accuracy? A relatively new approach to GPS positioning is showing great potential to solve both these problems.

The International GPS Service (IGS) and JPL both make available precise orbit, clock and atmosphere corrections that can be used to increase the accuracy of GPS positioning without the need to use base stations. The corrections are computed from a network of ground stations around the world, and are available at different levels of accuracy depending upon the speed of availability. The IGS is a voluntary organization and its corrections are free, and are distributed via the web. The JPL corrections are available for a license fee, and are normally incorporated into commercial correction services.

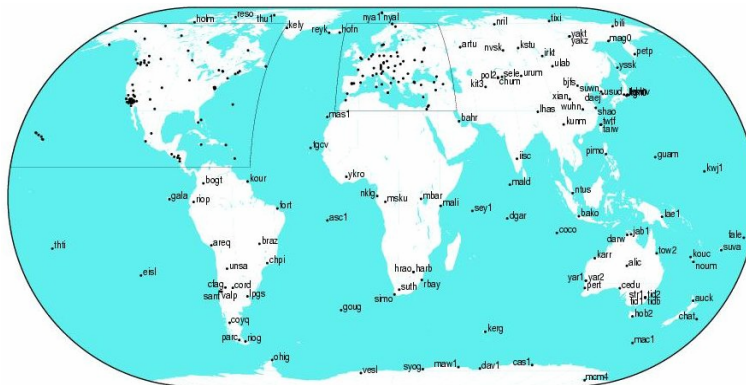


Figure 12: The IGS World-wide Network

The corrections to the orbits, clocks and atmosphere are accurate enough to allow a floated carrier phase solution (resolve the ambiguities in the carrier to a floated number of cycles instead of an integer number of cycles) to be computed after about 30 minutes of convergence time. This is impressive since no base stations are required.

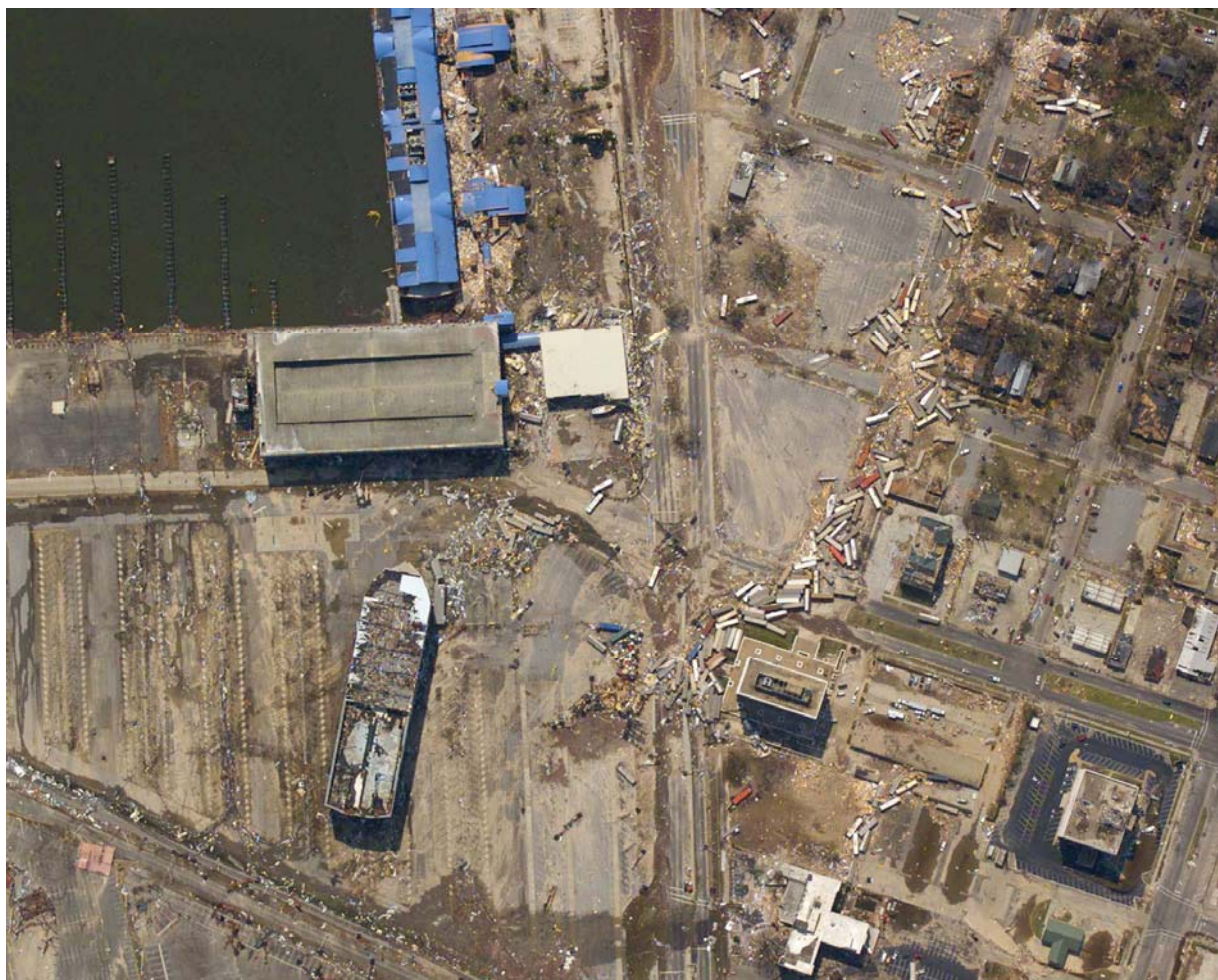
Two commercial companies are offering real-time solutions based upon the JPL corrections broadcast from satellites. The first is NavCom with their StarFire system, and the second is Omnistar with their XP system. Typical airborne accuracy is at the 30 cm level horizontal, and about 60 cm vertical (Mostafa, 2004). Any loss of lock of will cause a degradation in the accuracy since the ambiguities will need to be re-established which takes time. However this level of accuracy is more than adequate for many Direct Georeferencing applications.

As an alternative to the real-time correction services, a software package called Precise Point Positioning (PPP) from the University of Calgary uses the IGS corrections in post-mission. This has the advantage of being able to run both forward and reverse in time to improve the robustness and accuracy of the overall solution. Although still quite experimental, preliminary results are showing this to be an excellent option for areas where base stations are not available or possible.

### Rapid Response Mapping and Real-time Photogrammetry

Direct Georeferencing with digital cameras also means that map products can now be produced in real-time or in near real-time, which is ideal for quickly mapping and monitoring disaster situations. The real-time position and orientation are either used to ortho rectify the digital imagery in the air for radio transmission to the ground, or are processed with the images immediately upon landing (Wu, 2004). Examples include the Applanix Digital Sensor

System (DSS) which is a complete mapping system including a POS AV, a medium format Digital Camera and a flight management system. Small and compact, it is easy to install and fly in almost any aircraft. Since the images are relatively small in size compared to a large format digital camera, they are much easier to handle on standard computer equipment and for transmitting across the web. An example of this is the mapping of the coastline done by NOAA immediately after a hurricane strike. Figure 13 is a section of a georeferenced DSS image showing the extreme damage caused by hurricane Katrina in the USA. The image was taken by NOAA on August 30<sup>th</sup>, 2005, the day after Katrina made landfall, and posted on the web on August 31<sup>st</sup>.



**Figure 13: Section from DSS Image Showing Hurricane Katrina Damage, courtesy of NOAA**

## SUMMARY

A proper history of the development of Direct Georeferencing for aerial photogrammetry would require input from many different people from all parts of the world, and would probably take up a whole text book itself. This paper really only scratches the surface of an enormous amount of work that has been done on this subject both academically and in the private sector.

A well proven technology after 10 years of development, we can see that a stream of new innovations will continue to evolve Direct Georeferencing into higher levels of performance and operational efficiencies.

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