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Experiences with frame CCD arrays and direct georeferencing

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ABSTRACT

The rapid technological developments of the 90's have completely redefined the mapping practice as a whole. In less than a decade, digital techniques have come to outnumber the traditionally analog data acquisition and processing methods. Supported by unprecedented demand for large-volume, accurate spatial data, these new digital techniques emerged as dominant mapping technologies by the end of the decade. Technological change has also recently reached the analog camera-based aerial surveying practice, which supplies about two-thirds of spatial data for mapping and was the last stronghold of analog techniques. Two key components of this emerging technology are the electronic sensor-based digital camera and GPS/INS-based direct platform orientation. In fact, these new platform orientation systems are rapidly becoming a core component of modern airborne mapping and remote sensing systems.
This paper investigates the calibration and performance validation aspects of a GPS/INS/CCD prototype system, including the digital camera calibration and the boresighting misalignment calibration of the positioning component. The calibration performance of the system is evaluated based on data collected during several test flights.

1. INTRODUCTION

The introduction of Mobile Mapping Systems (MMS) heralded the new era of digital mapping techniques in the early 90s (Bossler et al. 1996, El-Sheimy et al. 1995 and Novak et al. 1995). These early land-based surveying systems provided a very cost-effective way of producing current and relatively accurate data for a variety of GIS applications. Based on a completely digital implementation, these systems featured a combination of digital and analog video cameras and GPS/inertial navigation components that provided complete georeferencing of the collected imagery. Recent technological developments have enabled the implementation of airborne MMS systems, in which the overall image resolution, coverage, and positioning requirements are substantially higher.
Electronic imaging systems have been widely used in non-mapping applications for more than two decades. The typical imaging sensor, called Charge-Couple Device (CCD), is usually fabricated on silicon semiconductor technology. CCD's come in linear or area array formats, and their development was primarily driven by the growing demand for customer products such as faxes and scanners (which use the linear format) and video cameras (which utilize the area array format). The negligible demand for larger CCD arrays combined with a low past production yield did not allow for the development of high-resolution CCD's for a long time. By the mid-90's, however, advances in semiconductor technology reached the point that the manufacturing of larger CCD's became feasible. Area sensors with 4K by 4K resolution have been used routinely by now, and sample CCD's are already available in the 8K by 8K resolution range (Bruce 1998 and Pfister et al. 1998).
With the increasing use of various new sensors, including CCD-based digital cameras and multi/hyper-spectral scanners, radiometers, LIDAR, SAR (IFSAR), etc; multisensor data fusion has become a crucial step of any processing of spatial data in mapping. One of the main steps of this data integration process is the georeferencing of data. The use of GPS/INS-based direct platform orientation is mandatory if the new sensors, which work in a continuous scanning mode, are to put in production. This direct platform orientation also offers economic benefits to traditional aerial

surveying. Over the past few years, there has been a steadily growing interest within the airborne survey and remote sensing community over using integrated GPS/INS systems for direct georeferencing (Schwarz et al., 1993; Kerr III, 1994; Schwarz, 1995; Lithopoulos et al., 1996; Skaloud et al., 1996; Abdullah, 1997; Toth, 1997; Mostafa et al, 1998; Toth and Grejner-Brzezinska, 1998). The most pronounced advantage of introducing INS systems into the airborne-GPS surveying is the availability of highly accurate attitude data. Additional benefits are the continuous position and attitude solutions, a further reduction in ground control, a better handling of GPS anomalies such as signal outages, and reduced ambiguity search volume/time for these systems. Implementation of closed-loop inertial system error calibration allows continuous, on-the-fly (OTF) error update that bounds INS errors, leading to increased estimation accuracy. Using a GPS-calibrated, high-to medium-accuracy inertial system for attitude determination can provide accuracy in the range of 10-30 arcsec (Schwarz, and Wei, 1994; Abdullah, 1997; Da, 1997; Grejner-Brzezinska, 1997, Toth and Grejner-Brzezinska, 1998).
The Ohio State University Center for Mapping has developed a prototype of an integrated GPS/INS/CCD system to support the direct platform orientation (DPO) for a fully digital Airborne Integrated Mapping System (AIMS™), designed for large-scale mapping and other precise mapping applications. During the past two years, AIMS™ has been tested over baselines ranging from 20 to 350 km and with flying altitude ranging from 300 to 3 000 m, in order to assess the accuracy of the positioning component and the performance of the 4K by 4K digital camera system. Extended discussion about the system's architecture, integrated Kalman filter design, and GPS/INS error sources and modeling, as well as initial test results were presented in (Da, 1997; Grejner-Brzezinska, 1997; Toth, 1997; Grejner-Brzezinska and Phuyal, 1998). This paper reports recent test results, focusing primarily on the digital camera components and realized georeferencing performance.

2. CCD FRAME ARRAYS

The first CCD's used in mapping were linear arrays. The production of linear CCD arrays is simple, and these sensors offer excellent features, such as defect-free arrays, electronic exposure control and multispectral sensing. From a photogrammetric data processing point of view, however, the use of linear imaging sensors is difficult, since the orientation of every image line requires robust modeling of the data acquisition trajectory. In contrast, area CCD-based systems work with the standard frame camera model, and thus, easily fit current map-production practice. Table 1 lists the existing high-resolution area CCD's.

Manufacturer:	Model:	Array Size: [H x V]	Pixel Size: [micron]	Data Rate: [MHz]
Kodak	DCS-460	3,072 x 2,048	9	10
Lockeed Martin	BigShot™	4,096 x 4,096	15	5
Kodak	Megaplus 16.8i	4096 x 4096	9	10
Philips	Icam28	7,168 x 4,096	12	18
Dalsa	CA-260/50	10,080 x 5,040	10	48/64

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Lockeed Martin	F-979F	9,216 x 9,216	8.75	160

Table 1: High-resolution area CCD arrays.

Since 9 by 9 inch format aerial film cameras have been the mapping and reconnaissance workhorses around the world for decades, even new digital camera systems, not only the area CCD-based ones, are still being compared to these analog cameras. Obviously, these CCD’s fall short in size, offering not more than one-fourth the imaging size of an aerial camera. Nevertheless, this difference in size is not too critical for applications such as corridor mapping (where the swath width is small). Furthermore, assuming GPS/INS-provided direct orientation, there is no need for aerial triangulation, and the smaller image size is insignificant to the feature extraction process in a softcopy environment.
Besides having a smaller sensor size, frame CCD arrays have other properties quite different or simply non-existent for analog film. Some of these special features include:

- CCD’s, with over ten million pixels, usually cannot be manufactured without faults, and thus come with a large number of inactive or malfunctioning pixels. The location of these bad pixels can be traced and is available to users enabling the replacement of the bad pixel intensity with some interpolated value.
- The read-out rate, or time it takes to shift out all the pixels from the CCD, can be substantial and is measured in seconds. A high read-out rate can affect the flight plan. Newer designs work with multiple output gates, making this limitation less severe.
- The radiometric sensitivity of CCD’s is around the 100-200 ASA, but can go up even higher.
- In contrast to analog film, CCD’s have a linear characteristic and thus are much more subject to saturation, in which case the charge from the saturated pixel may spill over to neighboring pixels (this phenomenon is called blooming).
- CCD’s, especially cooled ones, can exhibit very good signal-to-noise ratios and can therefore typically produce pixel intensities with 10-12 bit resolution. This is much better than the currently realized 6-7 bit intensity resolution of scanned analog imagery.
- Unfortunately, electronic shutters, while easily incorporated into linear arrays, are not a feasible solution for large CCD’s due to the complexities of manufacturing.

(a) Image overview (b) Image detail

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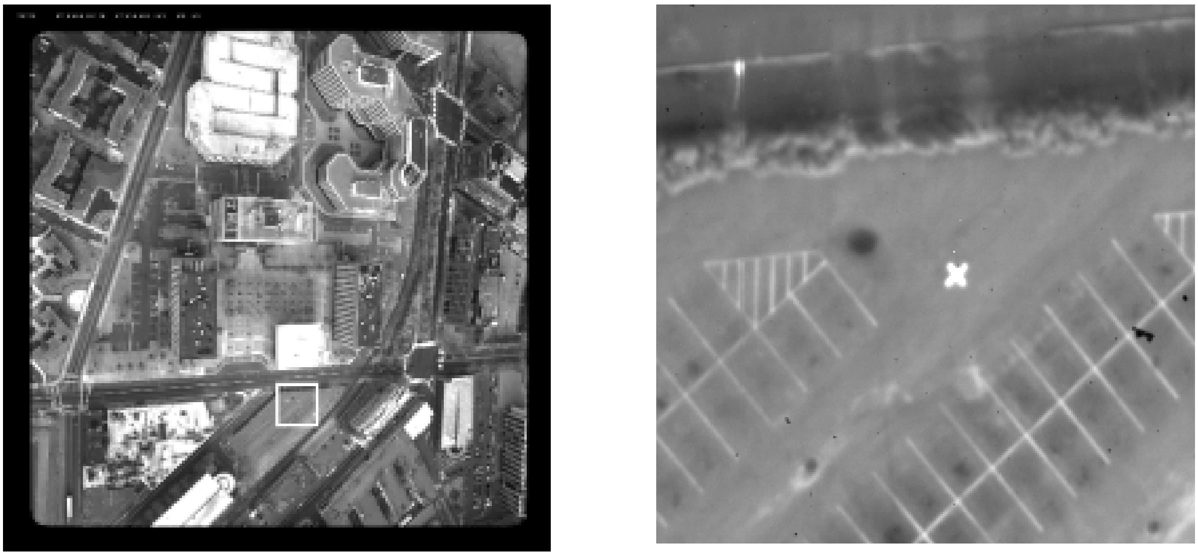

Figure 1: 4K by 4K CCD image taken over the MIT Campus.

Figure 1a shows a typical picture taken with the 4K by 4K AIMS^{TM} digital camera (Toth 1998). To illustrate the camera resolving power, Figure 1b shows a portion of the same image at full resolution. Since the size of the CCD depends primarily on the wafer size, trends in semiconductor manufacturing can give some foresight about future CCD array developments. In the past, semiconductor production was based on 4” silicon, limiting the sensor size to approximately 60 by 60 mm (4K by 4K at 15 micron pixel size). Today, we are transitioning to a 5” wafer size, which is the technology for the 9K by 9K CCD, 80 by 80 mm sensor area with 8.75 micron pixel size (Bruce 1998). The next level, the use of 6” wafer, is still in the experimental phase but promises to further increase the active sensor area. The 10K by 5K CCD (Pfister et al. 1998) has already been manufactured on the 6” technology.

3. AIRBORNE INTEGRATED MAPPING SYSTEM

AIMS^{TM} is a hardware and software integration of GPS, inertial navigation system, and digital imagery technologies in a mobile platform. The flexible architecture of AIMS^{TM} enables the augmentation of a variety of sensors beyond the high-resolution CCD (Charge-Coupled Device) cameras, including infrared cameras, radar or laser ranging devices, to support various applications. The GPS time is used to synchronize the position information with the measurements from the other sensors. The ultimate goal is to build a real- or near real-time system; however, AIMS^{TM} currently operates in a post-processing mode. Unlike conventional aerial photography, it is anticipated that the system will require no ground control, except for the base station to perform differential GPS positioning. The AIMS^{TM} prototype system built in 1998 is shown in Figure 2.

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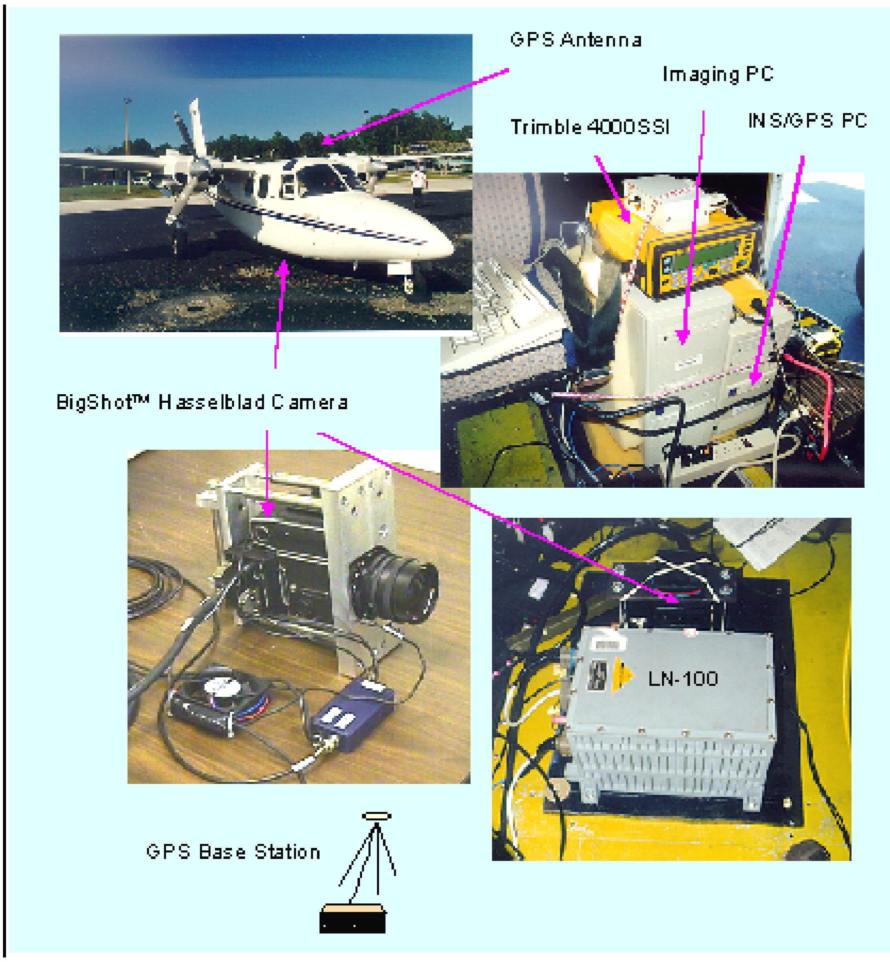

Figure 2: AIMS™ prototype system.

The prototype of the integrated GPS/INS component of AIMS™ comprises two dual-frequency Trimble 4000SSI GPS receivers and a strapdown Litton LN-100 inertial navigation system (0.8 nmi/h CEP, gyro bias – 0.003°/h, accelerometer bias – 25µg). The system collects raw IMU data at 256 Hz, which are subsequently processed together with GPS double-differenced dual-frequency phase observable in the extended Kalman filter mode.

A tight GPS/INS integration scheme, based on a single Kalman filter that optimally estimates position, velocity, and attitude errors, as well as errors in the inertial and GPS measurements, is implemented in AIMS™. Tight integration supports cycle-slip fixing in the GPS data, and allows robust OTF ambiguity resolution, providing bridging during GPS losses of lock. A closed-loop INS error calibration allows continuous, OTF error update that bounds INS errors, leading to increased estimation accuracy. The state unknowns are errors in position, velocity, and orientation, three biases and three scale factors for the accelerometers, three gyro drifts, deflections of the vertical, and the gravity anomaly. In addition, GPS ionospheric delay is estimated for every satellite in the solution. Optionally, the lever arm errors can be included in the state vector. For more details on the system's architecture and tightly integrated Kalman filter design the reader is referred to (Da, 1997; Grejner-Brzezinska, 1997; Toth, 1997; Toth and Grejner-Brzezinska , 1998; Grejner-Brzezinska et al., 1998).

The AIMS™ imaging component in the current configuration consists of a digital camera based on a 4,096 by 4,096 CCD with 60 by 60 mm imaging area (15-micron pixel size), manufactured by

Lockheed Martin Fairchild Semiconductors. The imaging sensor is integrated into a camera-back (BigShot™) of a regular Hasselblad 553 ELX camera body, and the camera is installed on a rigid mount together with the INS. The current 6-sec image acquisition cycling rate is limited mainly by the CCD read-out rate. This slow acquisition time does not always allow to achieve the required 60 % forward overlap for fast moving airborne platforms. For such missions, a special flight pattern can be applied, where the flight lines are flown several times, and the required overlap is obtained by combining images from the repeated passes. For slower moving platforms, such as helicopters this is not a problem, Figure 3 shows the installation of the camera system on a recent helicopter flight. Since the BigShot™ camera-back interface has no support for time-tagging the actual lens opening, an external signal-conditioning circuit was designed and built, tapping into the lens shutter signal and providing a TTL-compatible output for the timing system, such as the GPS external event marker or timer board input.

(a) Helicopter (b) Camera and INS mounting

Figure 3: Helicopter mounting of the 4K by 4K AIMS™ digital camera and the LN-100 system.

4. CAMERA CALIBRATION EXPERIENCES

Calibration is a refined form of measurement conducted to assign numbers to represent relationships among particular properties of a measurement system. The necessary accuracy of this procedure depends on requirements of the measurement system. If camera calibration results are to be used for photogrammetry, the calibration procedure should produce highly accurate numerical values representing spatial relationships of the measurement system. These include numerical estimates of camera interior orientation represented by focal length, location of the principal point, and coefficients of appropriate models representing lens distortion. The calibration procedure should include environmental influences if full spatial accuracy capability of the system is to be realized. Traditionally, photogrammetric cameras have been periodically laboratory-calibrated. Since CCD-based cameras are not professional metric devices, their calibration raises some issues, such as the long-term stability of the parameters and the way in which the calibration should be or can be performed (collimators built for calibrating large format aerial cameras cannot properly handle the small sensor size). This naturally leads to self-calibration techniques and to the use of various test

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fields, including in-flight scenarios. Self-calibration techniques are well understood and widely used (Robson et al. 1998).

The 4K by 4K AIMS™ prototype digital camera has been repeatedly calibrated before and after test flights. These calibrations were performed in a laboratory environment using a rather large number of target points. Images were taken from various positions with different camera orientations. Figure 4 shows a recently used 3D laboratory calibration field, where images were taken from six positions.

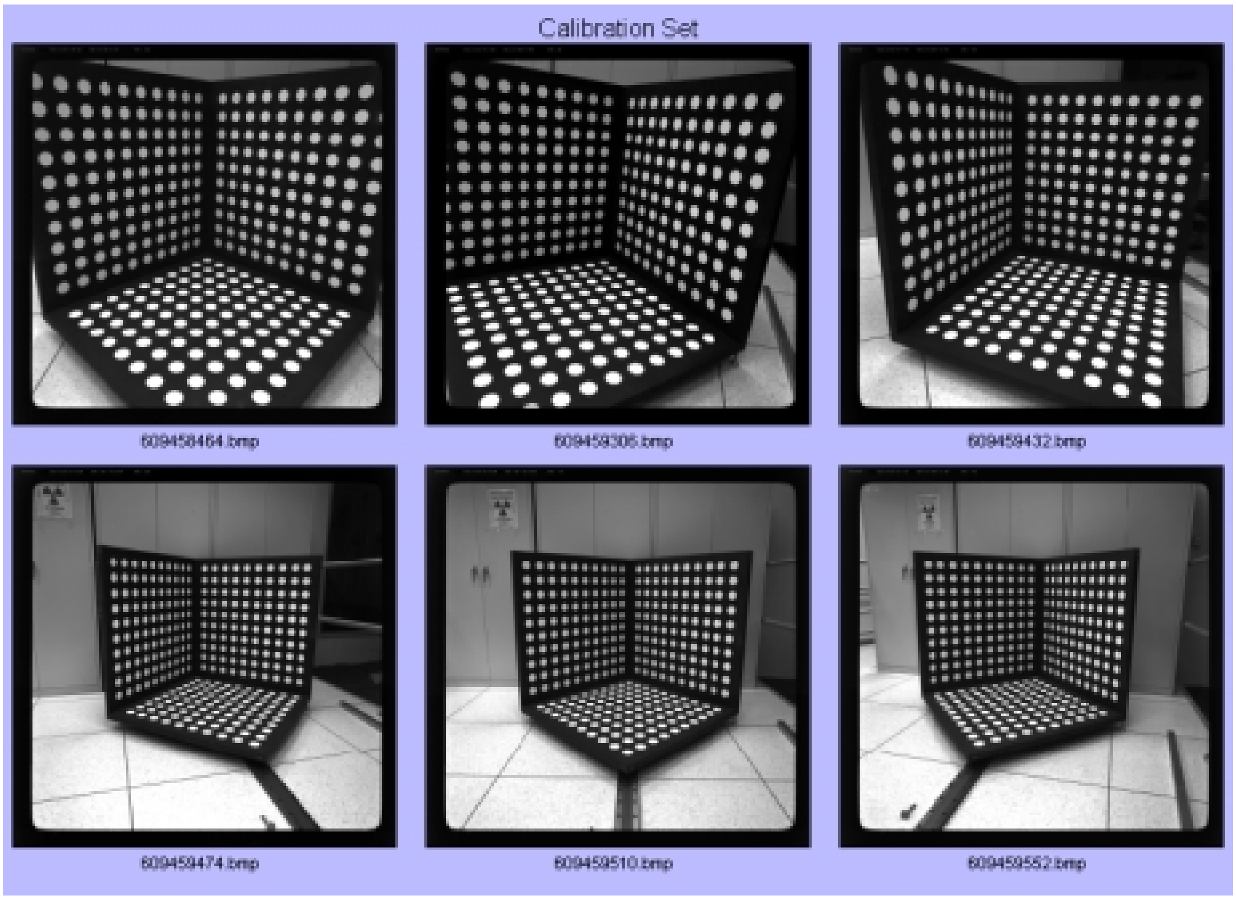

Figure 4: Recently used laboratory calibration test field, courtesy of NASA JPL.

When a 2D calibration range was used, multiple images were taken from each position with the camera rotated around its optical axis by 90 degrees. Image measurements were obtained in a softcopy environment and subsequently processed with the OSU Bundle-Adjustment with Self-Calibration (BSC) software. Estimates of the focal length, principal point, and lens distortions were then computed according to the USGS camera calibration model (Light 1992). Figure 5a shows the radial symmetric distortion components of the 50 mm lens-equipped AIMS™ digital camera. Clearly, this camera exhibits quite significant distortions (on the order of 450 microns or 30 pixels) towards the edges of images. Such distortions are typical to a camera/lens that is not specifically designed for photogrammetric applications. The distortions also explain why only limited in-flight calibrations were feasible – none of the project areas had adequate control point distribution for complete self-calibration.

(a) Radial symmetric distortion surface (b) Radial symmetric distortion difference

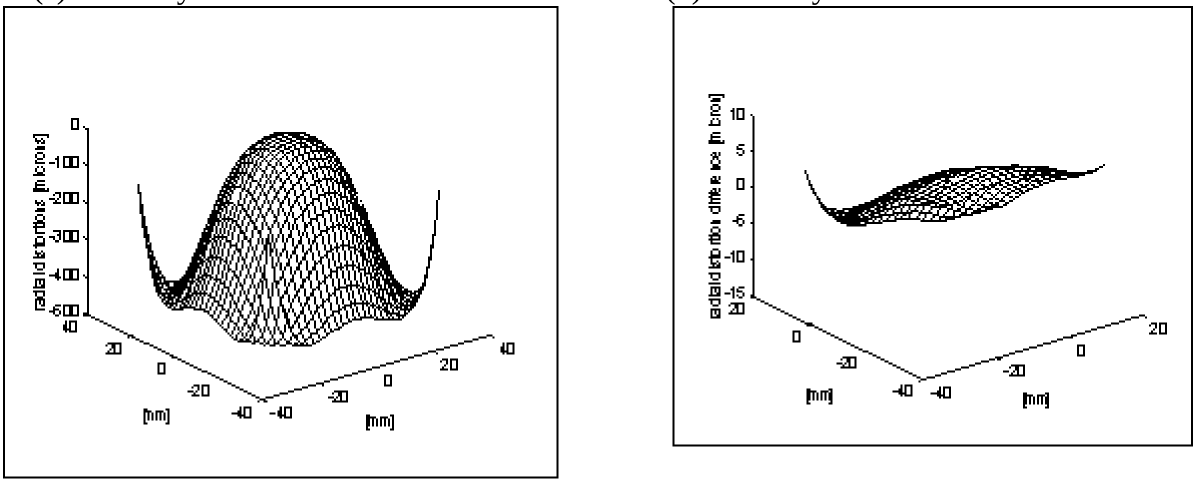

Figure 5: Typical radial symmetric calibration patterns, Carl Zeiss Distagon 4/50 lens.

To analyze the long-term stability of the calibration parameters, the results of four separate calibration sessions are presented in Table 2. While the distortion parameters and the focal length do not change significantly, a noticeable shift can be observed in the principal point location. This is a natural consequence of the design of the 4K by 4K AIMS™ prototype digital camera. The camera back containing the CCD chip is detachable from the camera body and hence does not provide a firm connection. Thus any time the CCD is removed and re-attached to the camera body, a significant change in the principal point location should be expected, and the camera should be recalibrated. As illustrated in Figure 5b, the radial symmetric distortion remains practically constant between calibrations.

Parameter	**Calibration 1**		**Calibration 2**		**Calibration 3**		**Calibration 4**	
	Value	**Sigma**	**Value**	**Sigma**	**Value**	**Sigma**	**Value**	**Sigma**
C [mm]	51.568	0.008	51.762	0.008	51.688	0.008	51.570	0.007
Xp [mm]	0.314	0.010	0.669	0.005	-0.075	0.004	0.296	0.004
Yp [mm]	0.112	0.013	0.227	0.005	0.376	0.005	0.073	0.005
Rad1 [K1]	-2.77E-05	9.35E-07	-2.71E-05	3.40E-07	-2.76E-05	2.80E-07	-2.68E-05	4.14E-07
Rad2 [K2]	1.44E-08	5.77E-10	1.38E-08	2.50E-10	1.36E-08	9.30E-09	1.35E-08	3.07E-10

Table 2: Camera calibration results, Carl Zeiss Distagon 4/50 lens.

5. OVERALL SYSTEM PERFORMANCE

The performance of the AIMS™ system has regularly been tested during the development of the prototype. Laboratory, land-based and airborne tests included both validations of the individual components and of the complete system. The overall accuracy of the multi-sensor system is a function of the processing sequence involving individual components and of the coupling between these components. These individual terms include continuity of the lock to the GPS signal, quality of the GPS position update and INS attitude/positioning, camera calibration, time synchronization,

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lever arm and boresight calibration, common mount rigidity, resolution of the imaging component and vehicle dynamics. All these components contribute to the total accumulated error, which is a function of the sensor quality, the reliability and stability of system calibration, and the Kalman filter design, which determines the effectiveness of the data processing and error estimation procedures. Figure 6 depicts the concept of the airborne multi-sensor system, its calibration components, and the interaction among the sensors.

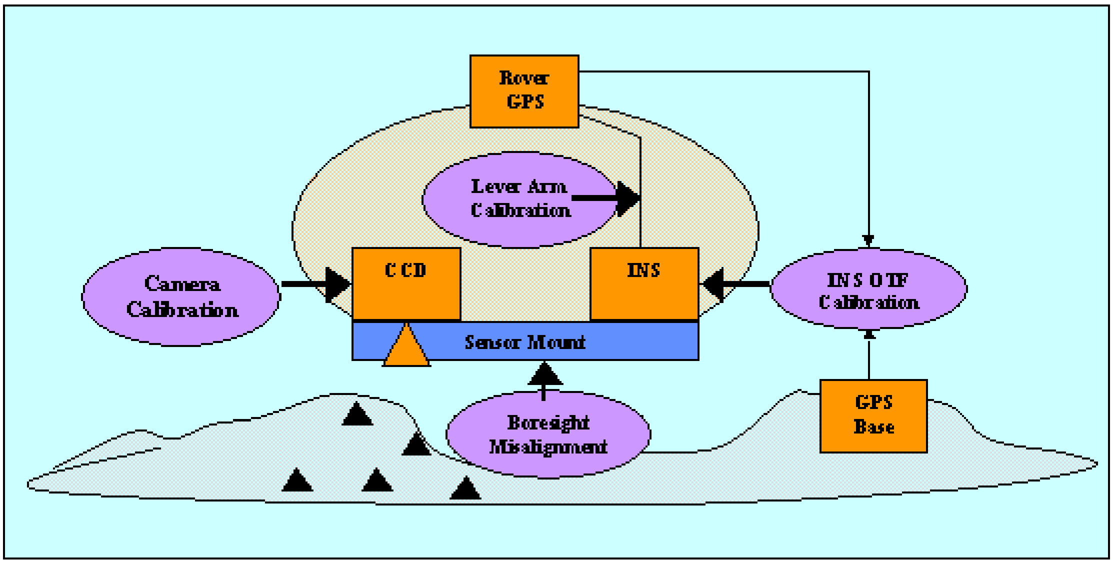

Figure 6: The multi-sensor calibration concept.

The four main components of airborne multi-sensor system calibration are:

- The calibration of the camera, which is the proper modeling of the camera projection system, is a standard and well-understood process and is usually performed in a laboratory. Therefore, only environmental factors (the difference between the laboratory and flight conditions) are of concern.
- The lever arm, defined as the GPS antenna phase center location in the INS frame, describes the geometrical relationship between the GPS and INS sensors, and can be either directly measured or recovered during the Kalman filter processing.
- The boresight transformation represents the geometrical relationship between the GPS/INS and camera frames. The two components of boresighting are the offset vector between the INS center and the camera perspective center and the rotation matrix from the INS body frame to the camera optical axis. The boresighting computation is relatively straightforward, provided that two positioning/orientation solutions, one from GPS/INS and one from photogrammetry, are available for a data set. The critical component of boresighting is the rotation component, since an angular inaccuracy, unlike an offset, is amplified by flying height and has a significant impact on the photogrammetric data production. Thus, the calibration parameters should be estimated with the highest achievable accuracy and should stay constant for subsequent missions. In other words, no flex or rotation can occur between the INS and camera devices; the whole sensor mount should be sufficiently rigid.

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- The INS OTF calibration, a continuous IMU error calibration done by GPS, is probably the most critical determinant of the multi-sensor system performance. The INS can provide a self-contained and independent method for three-dimensional positioning with excellent short-term accuracy. The INS accuracy, however, degrades over time due to unbounded positioning errors caused by the uncompensated gyro and accelerometer errors. Integration of GPS with INS bounds the positioning errors of the inertial system, leading ultimately to continuous INS calibration. The effective error level depends on systematic and random sources affecting the GPS measurements, as amplified by satellite geometry. Using precise GPS observables, the GPS/INS integration filter can estimate the error states affecting INS measurements that are subsequently used to calibrate the INS system. The INS works with higher data update rates (in AIMS™, it is 256 Hz) and the GPS calibration update happens whenever GPS data is available, usually at a normal GPS data rate (in AIMS™, it is1 Hz).

The performance assessment of any high-precision navigation system is difficult and requires an independent reference system with accuracy characteristics at least an order better than that of the navigation system being tested. Unfortunately, there are no such systems in the AIMS™ target accuracy range that are available to us. Since the Kalman filter system estimates the error terms of the position and attitude data, a first measure of the quality of the georeferencing component is easily available. Early test flight results confirmed that internal accuracy of 4-7 cm in position and 5-10 arcsec in attitude could be easily achieved (Grejner-Brzezinska et al, 1998). Yet the question remained of what could be realized from this remarkable potential. Using photogrammetric techniques, position and attitude data can be independently determined and then compared to the GPS/INS data. Two problems, however, arise from this approach. First, the actual geometrical fit, or difference between the aerial triangulated photo center and the actual position of the camera, was not really addressed in the past (early airborne-GPS experiences revealed a shift in the vertical coordinates that was primarily due to the environmental dependency of the camera calibration). Second, the 4K by 4K AIMS™ digital camera had a rather modest angular resolving power (in a coarse comparison, it has about one third that of a regular large format aerial camera), limiting the photogrammetric performance.

Exterior orientation	Image point measurement RMS	Perspective center RMS	Control point RMS
X_0	7μ	0.12 m	0.02 m
Y_0	7μ	0.14 m	0.02 m
Z_0	N/A	0.04 m	0.02 m
ω_0	N/A	1.5 arcmin	N/A
φ_0	N/A	1.3 arcmin	N/A
κ_0	N/A	0.3 arcmin	N/A

Table 3: Aerial triangulation results.

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The aerial triangulation results of a typical AIMS™ test flight are shown in Table 3. A block of 18 images was triangulated by the bundle adjustment method. The photo scale was 1 : 6 000; the 50 mm lens-equipped camera was flown at an altitude of 300 m. Control points with accuracy estimated at the 2 cm level were available from a static GPS survey. The image measurements were taken manually using the Autometric SoftPlotter digital workstation (configured with the appropriate camera calibration parameters determined during the camera calibration stage, as described in section 3). The accuracy of the image coordinate measurement was at the level of 7μ (half a pixel). Compared to the high internal accuracy estimates of the positioning components, these aerial triangulation results are modest and consequently represent a lower bound for the overall system performance. In fact, these results failed to come close to the 1 arcmin angular resolution of the camera. Even though the control points were surveyed at cm-level accuracy on the ground, due to their poor signalization, their image measuring accuracy was not close to the otherwise sub-pixel image measurement performance. Based on six centrally located images containing the majority of the control points, the boresight estimation was performed by comparing AT and GPS/INS positioning and attitude estimates. The resulting boresight standard deviations were 0.29, 0.17 and 0.15 m for the linear displacements and 3.7, 2.7 and 1.7 arcmin for the rotation angles, respectively. These accuracy measures were not as good as expected. Possible reasons for this besides the modest photogrammertic processing accuracy are the mechanical flex of the camera body/mount and the image time tagging anomalies. In summary, the manual measurements of checkpoints from the GPS/INS georeferenced stereo imagery resulted in about 20 cm accuracy (about two pixels). This represents a good overall performance of the AIMS™ system, even though high accuracy of the georeferencing system has not yet been realized.

The camera calibration, the lever arm and the boresight misalignment represent the static components of multi-sensor system calibration. The INS OTF, however, is a dynamic process and depends on the continuous availability of quality GPS data. The extended loss of GPS lock can be a major problem for an otherwise well-calibrated system, since it will switch the georeferencing system to free navigation mode. Figure 7 shows the effect when the INS calibration was intentionally turned off; the difference was computed with respect to the GPS/INS solution for both test flights.

(a) Horizontal error growth (b) Horizontal and vertical error growth

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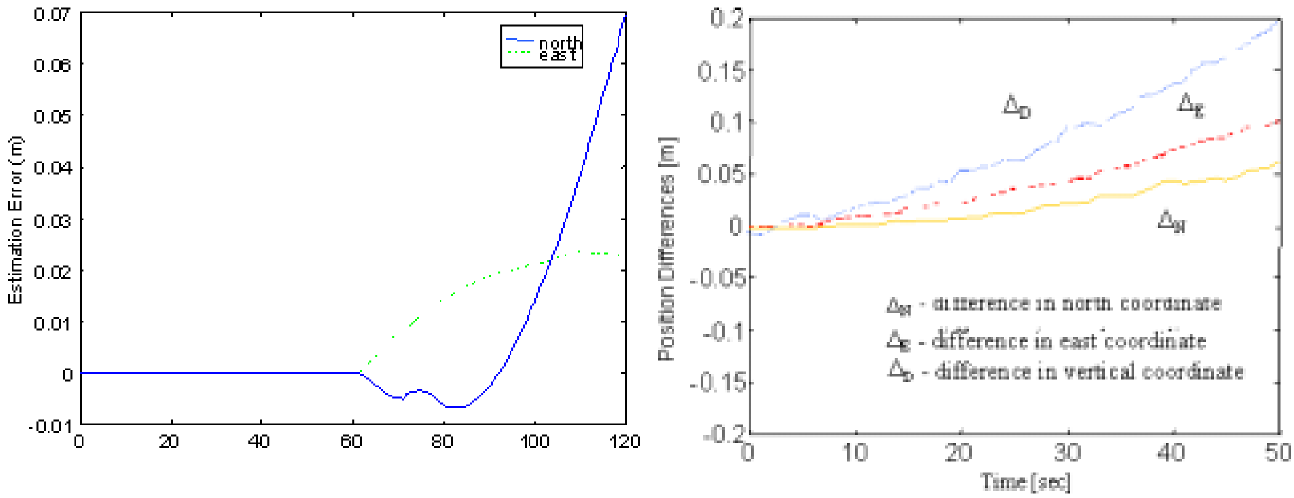

Figure 7: Error growth during GPS signal outage.

A test flight conducted over the MIT Campus in Boston encountered several unexpected and excessive losses of GPS lock. As Figure 1 illustrates, this was a low-altitude flight and in the proximity of downtown. The large number of various electromagnetic devices on the rooftops of tall buildings, which emitted electromagnetic signals and heavily polluted the electromagnetic spectrum, caused interference in the GPS receiver. During these flights, the loss (sometimes extended) of GPS lock was frequent during workdays. Table 4 shows four randomly chosen gaps in GPS data. These data nicely illustrate that the performance of the INS depends on the duration and the quality of the INS calibration before the loss of GPS lock.

	Units	Gap 1	Gap 2	Gap 3	Gap 4
Total error	East [m]	0.19	0.12	19.0	131.0
	North [m]	0.40	0.06	33.4	209.2
	Height [m]	0.58	0.18	7.2	162.4
Gap duration	[sec]	84	140	320	1200
INS calibration	[sec]	236	723	860	1050

Table 4: Positioning error growth during GPS signal outage.

6. CONCLUSIONS

Both the hardware and software components of the AIMS™ system prototype have shown consistent performance in a large number of test flights. The 4K by 4K AIMS™ digital camera has delivered a large number of superior quality images in a variety of flying conditions. The accuracy of the positioning system has also been confirmed repeatedly, both by internal estimation and by external validation using photgrammetric technique (although the current 4K by 4K digital camera lacks the sufficient angular resolving power to realize the accuracy range defined by the original AIMS™ objectives).

Images captured by the 4K by 4K AIMS™ digital camera have been processed routinely in a softcopy environment, including self-calibration, aerial triangulation, automatic DEM extraction and interactive feature extraction tasks. All these experiences demonstrate that area CCD's can be effectively used for airborne surveying to produce highly accurate spatial data. While current area CCD's remain limited in sensor size, they can definitely offer a conceivable alternative both to analog aerial cameras and digital line cameras. However, a major drawback of area CCD's is their inability to perform multispectral imaging (which can be achieved only at the price of reducing CCD's geometrical resolution capabilities).

The experiences with the GPS/INS-based AIMS™ positioning component have confirmed that already commercially available positioning sensors could meet the accuracy requirements of airborne surveying. However, the use of direct orientation in aerial surveying, whether employing a traditional large-format aerial camera or an emerging digital camera, may compromise the accuracy of the acquired spatial data. By eliminating the aerial triangulation and bundle block adjustment, direct orientation removes the built-in support that would automatically compensate for systematic errors in the system. Any error in both the interior and exterior orientation will translate into positional error in the features extracted from the images. In the past, discrepancies between the aerial triangulation-derived exterior orientation parameters and the actual physical location of the camera was never optimized (as the aerial triangulation results were primarily concerned with the geometry of the ground control points). Because of its potential to cause systematic errors, the use of direct orientation is casting more attention on the individual calibration of the sensors, as well as on the overall system calibration and continual quality control.

7. ACKNOWLEDGEMENTS

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