Photogrammetric Week '93 Eds. D. Fritsch / D. Hobbie, Wichmann, Karlsruhe, 1993

Integrated sensor systems for digital photogrammetry

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ABSTRACT

New integrated sensor systems are presented, which are designed to overcome remaining problems in daily digital photogrammetric work. The sensor systems may either provide a priori knowledge for automated image processing or they can even inaugurate new data processing techniques and photogrammetric applications. As a special new sensor, the paper will consider the determination of sensor platform attitude parameters with NAVSTAR / Global Positioning System (GPS) multi antenna receivers. An accuracy analysis of airborne kinematic GPS attitude determination is made by a comparison with conventional aerial triangulation results.

1. INTRODUCTION AND MOTIVATION

Recently a strong tendency can be observed to automate most of the daily photogrammetric work. This transition from analytical to digital photogrammetry is characterized and supported by increased computer power and intelligent digital image processing algorithms. Although, first trials to carry out automated aerial triangulations [Tsingas 1991], automatic digital elevation model generation [Hahn/Förstner 1988] and automatic orthophoto production [Düren 1993] have been completed successfully, there are still several problems remaining:

- The amount of data that has to be handled in a photogrammetric block is huge. Typically a color aerial image which is scanned with 10 μm resolution occupies approximately 1.5 GB of data storage. The access to a specific part of the digital aerial image, e.g. in the vicinity of a ground control point, can only be easily accomplished if a priori knowledge about the exterior orientation of the image is available.
- For many digital image processing algorithms it is hard to distinguish between significant and insignificant objects. For example DTM generation algorithms tend to produce DTM's on house roofs or on the tree foliage and not on the earth's surface.
- Digital image processing algorithms need starting values for subsequent iteration steps (e.g. automatic aerial triangulation).
- Automatic object recognition is often not possible, or not reliable enough, just from image based information sources.
- Image based digital photogrammetry is still fairly expensive due to its high hardware and software requirements.
- .....

Most of the mentioned problems can be classified into two categories. Some of them are mainly due to the insufficient knowledge of the observation geometry and the others are characterized by the insufficient knowledge about the surveyed objects (object space). The suitability of aerial images to solve these problems is limited. They provide only indirect information about the observation geometry, as the position and attitude of the camera at the time of exposure can only be reconstructed via ground control points that have to be measured in the images. Although aerial images are an excellent method to reconstruct the earth's surface and to recognize and classify objects on the earth, the information contained in the images may be incomplete and not sufficient. Important features may be covered or shaded by other objects and only a limited spectral bandwidth (visible light or near infrared) is used for the exposure of the film.

From the discussion above it can be seen, that in principle many of the mentioned problems could be solved, if additional information on the observation geometry and the object space would be available. A logical consequence is, that the survey aircraft has to carry an additional sensor package, which has to provide as much of the needed knowledge as possible. In the remainder of this paper several sensors are recommended for the use in photogrammetric applications, however, it has to be clearly stated that the used sensor package is mainly dependent on the type of application and the required photogrammetric end-product.

2. SENSORS IN AN INTEGRATED PHOTOGRAMMETRIC SENSOR SYSTEM

The idea of using additional sensors in photogrammetry is rather old. Already, around 1930 Finnish photogrammetrists tried to measure some parameters of exterior orientation for photomapping with a statoscope and horizon cameras [Lofström 1937]. Since then many different sensors and sensor types (e.g. APR, radio positioning, gyroscopes) have been tested to derive exterior orientation parameters for photogrammetric applications, but the success and acceptance was limited. For object classification an alternative to standard aerial photogrammetry has been found with the development of multi-spectral scanners and the evolution of remote sensing. Both methods have some clear advantages and disadvantages: The geometric accuracy of multi-spectral scanners is worse than the one of aerial cameras. The interpretation of multi-spectral images can be done easier because they may contain more information (soil consistency, water contents, thermal features) than an aerial image with a single spectral band. However, a combination of sensors for a better recording of the object space has not been realized until recently, as the interpretation, classification and reconstruction of the object space was mainly done by specialized and experienced photogrammetric operators manually. But nowadays, if this work is to be done automatically, an integration of these sensors would be desirable.

In recent years a wide variety of sensors and sensor components have been developed, due to the innovations in electronic engineering. Many of these sensors can be used advantageously in integrated photogrammetric sensor systems. As it has been mentioned earlier the sensors may be classified in two major categories, whether they contribute to the information about the object space or the observation geometry. The most significant sensor developments for photogrammetry are summarized in Table 1.

When designing an integrated photogrammetric sensor system, several requirements have to be taken care of. It is clear that the observations of the sensors have to be time synchronized and spatially calibrated (determination of geometric offsets and rotations between the sensors in a known coordinate system). Further it has to be decided what kind of sensors are used for a specific application and how the data of these sensors are algorithmically combined (e.g. mathematical model of integrated data processing).

Typical examples for an integrated sensor system and integrated data processing, which were developed at Stuttgart University, are the combined blockadjustment [Frieß 1990] and the airborne laser profiling system [Lindenberger 1991]. In the combined blockadjustment photogrammetric data and GPS derived positions are processed together in a single adjustment run. The GPS positions are treated as observations for the camera projection centers at the time of exposure. Hence, three of the six exterior orientation parameters are directly observed, which strengthens the block geometry tremendously. Using this technique, it is possible to reduce the amount of required ground control points significantly. Therefore, by integrating GPS positioning with photogrammetric observations, the economic benefit for the photogrammetric user may be extensive. The airborne laser profiling system is a combined sensor system consisting of a pulsed laser range finder, a GPS receiver and an inertial navigation system. The principle of the system is fairly simple: With GPS the position of the laser at the time of a measurement is determined, the INS measures the attitude angles in a

Type of Sensor	*Approx. Year of Development*	*Type of Information*	*Remark*
Multi-spectral Scanner	1960	object space	low geometric accuracy
MOMS	1990	object space	multi-spectral + high geometric accuracy
imaging laser	1990	object space	image + distance information
laser profilers, laser scanners	1980	object space	distance information
GPS Positioning	1980	observation geometry	positions (high accuracy)
GPS Attitude Determination	1990	observation geometry	attitude (medium accuracy)
Inertial Navigation Systems	1980	observation geometry	position + attitude (medium accuracy)

Table 1: Summary of new photogrammetry related sensors.

reference coordinate system and the laser range finder measures the range between the aircraft and the earths surface. With these measurements we have a directed range from a known origin, and therefore the 3D coordinates on the earths surface can be directly computed. The purpose of the system is to derive digital elevation model in areas where conventional photogrammetry fails (dense woods, coastlines,....).

Besides the algorithmically integrated sensors a second set of hardware has been developed that accomplish several tasks simultaneously with one hardware component. For photogrammetrists, the most familiar example is the MOMS-02 high resolution multi-spectral stereo scanner (e.g. Seige/Meissner [1993] and Ackermann [1993]). The particularity of the MOMS-02 scanner is the successful combination of multi-spectral and high resolution stereo image data. This hardware fusion makes it possible to achieve geometrically accurate, multi-spectral data. With such data, geo-scientific mapping and primary data acquisition for geographic information systems can be extremely simplified. An airplane based version of the MOMS-02 sensor is also available (MEOSS), which may be an interesting alternative to the aerial camera in specialized applications. MOMS-02 has been tested on the last German space mission D2, and the results will be of primary interest for the entire photogrammetric community.

The second sensor which may have an important impact on photogrammetric procedures is the imaging laser (Wehr [1991]). The imaging laser is a continuous wave laser which combines distance information with spectral intensity. Hence, it is possible to get not only a gray value matrix of the surveyed surface, but also the distance between the sensor and the objects. The potential of this sensor is extraordinary, provided one could determine the exterior orientation of the imaging laser with sufficient accuracy, the coordinates and the spectral properties of points in the object space could be determined directly. This method which could be called "polar photogrammetry", would simplify the entire photogrammetric data processing techniques and opens the door to real time photogrammetric mapping. However, the development of the imaging laser is still in a preliminary stage and it has to be proven whether the accuracy performance of the laser is sufficient for photogrammetric demands.

2.1 Characteristics of Sensors

Before it has to be decided what types of sensors are integrated on a sensor platform, for a specific photogrammetric application, the sensor characteristics have to be known. A typical sensor setup for a digital mapping project could be as seen in Fig. 1.

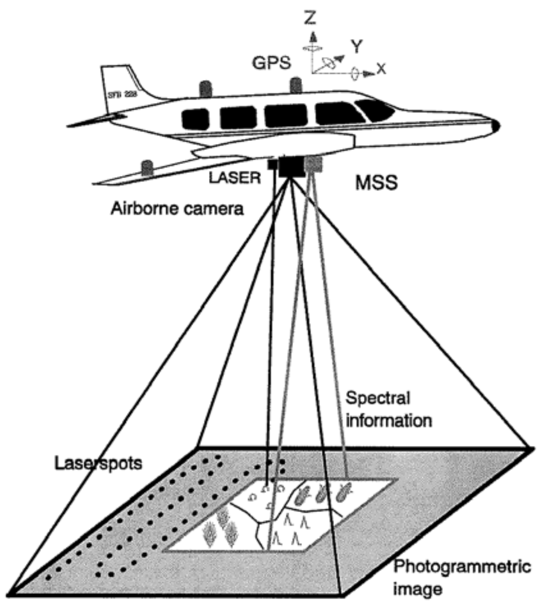

Figure 1: Typical sensor system for digital mapping.

The parameters of exterior orientation of the sensor platform are determined with the NAVSTAR/Global Positioning System. The positions of the moving aircraft can be determined with standard processing procedures to an accuracy of a few centimeters (<10 cm) to a few meters (Frieß [1990]). The determination of attitude parameters with GPS multi antenna receivers is a fairly new technique, which will be discussed in more detail later. Of course position and attitude determination could also be done by an inertial navigation system (INS) or other optical or radio positioning systems (e.g. Hiran, Shoran, Loran-C). Nevertheless, it has to be said, that the accuracy performance and the fairly simple data processing of GPS, makes it an extremely useful tool in photogrammetric applications.
To gain comprehensive information about the object space, three additional sensors may be used, each one giving a certain type of knowledge. The principle and the usage of the aerial camera is well known to the photogrammetrist, so it will not be discussed here. Its highly accurate geometrical representation of the object space is supported by the multi-spectral scanner which simplifies the interpretation of features in the object space. Especially the classification of land use or environmental mapping tasks can be done more easily with multi-spectral data. The purpose of the laser range finder, preferably in a scanning version, is to derive an accurate digital elevation

model for image rectification and for the representation of the third dimension in the map. Further, the laser could also be used for the determination of exterior orientation parameters in combination with the aerial camera (Kilian [1993]).

3. ATTITUDE DETERMINATION WITH THE NAVSTAR/GPS

Meanwhile, positioning with the NAVSTAR / **G**lobal **P**ositioning **S**ystem (GPS), for photogrammetric applications, is widely accepted. Its simple operation, the accuracy features and the economic benefits of GPS positioning are convincing. Besides positioning, new developments to derive attitude from GPS multi antenna receivers gain more and more attention. As the operational conditions and the principles of attitude determination with GPS are fairly new to photogrammetrists, this sensor will be treated here in more detail. Although, the theoretical accuracy expectations of GPS derived attitude is just in the range of 0.05-0.2 decimal degrees, it can be used in several ways for digital photogrammetric applications:

- navigation
- absolute orientation of non-imaging sensors
- absolute orientation of aerial images with low to medium accuracy (e.g. orthophoto generation)
- a priori information for digital image processing algorithms
- absolute orientation of aerial images in a combined sensor system (e.g. GPS positioning, INS, Laser, digital image processing)
- simplified aerial triangulation

As it can be seen from this list, the potential of GPS attitude measurements in photogrammetry is manifold. Therefore, the remainder of this paper is dedicated to a short description of the principle of GPS attitude determination and a practical verification of the accuracy performance under photogrammetric operational conditions. The verification is done by a comparison of GPS derived attitudes with standard aerial triangulation based attitudes.

3.1 Principle of GPS Attitude Determination

Attitude measurements with GPS are based on interferometric phase measurements (see Fig. 2 a). The phase difference $\Delta\Phi$ which can be observed between the 2 antennas results from the different ranges between the satellite to the antennas. As the satellite distance ρ is quite large (> 20 000 km) compared to the baselength B (normally < 10 m) the incoming phase signal can be assumed to be parallel. Therefore, the phase difference is just dependent on the baselength B and the angular position γ of the satellite with respect to the baseline between the two antennas.
The relation between the observed phase difference $\Delta\Phi$ and the angle γ can be formulated as seen in equation 1 (refer to Fig. 2a.):

$$\gamma = \arccos \frac{\Delta\Phi \cdot \lambda}{2\,\pi \cdot B} \tag{1}$$

The baseline B can be measured after the installation of the antennas on the aircraft in a calibration measurement. λ is the wavelength of the GPS carrier phase measurements (e.g. L1=0.192m). It is clear, that equation (1) only holds if the carrier phase cycle ambiguities between the two antennas are determined. For the resolution of the ambiguities several different techniques have been proposed (e.g. Hatch [1990], Counselman/Gourevitch [1981]). The resolution of the ambiguities, in the 4 antenna case for attitude determination, can even be simplified due to the known constraints

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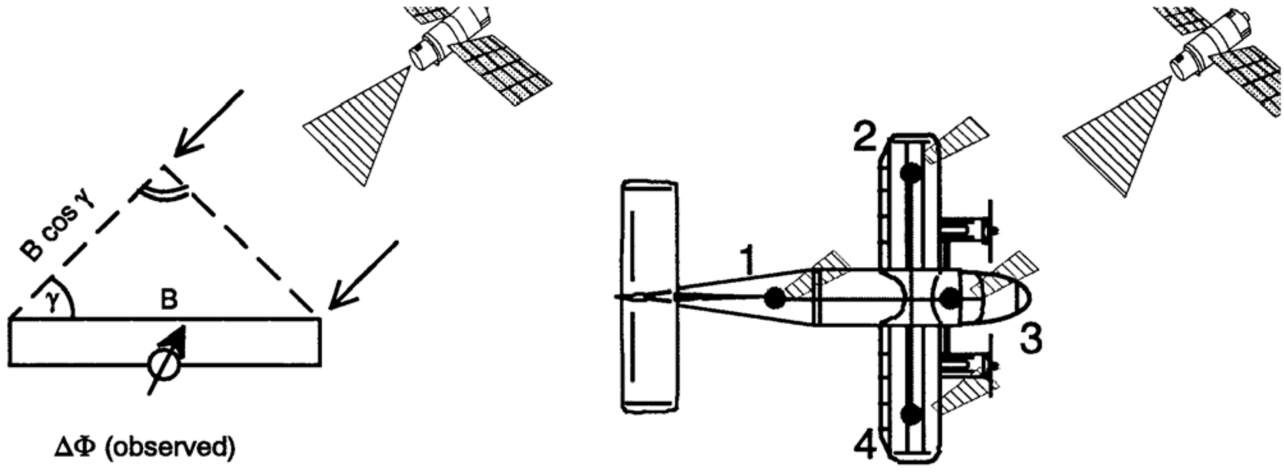

Figure 2: Measurement principle of interferometric attitude determination (a.) and typical antenna setup on the survey aircraft (b.).

between the antennas. A typical antenna setup for a survey aircraft can be seen in figure 2b. The attitude angles of the aircraft are directly defined in the aircraft fixed body frame. The heading and pitch of the aircraft can be determined from the antenna baseline 1-3 and the roll from the baseline 2-4. From these angles the attitude of the interferometer can be determined in a reference coordinate system, with a set of well defined coordinate transformations (e.g. Hartl/Wehr [1986])

3.2 Accuracy Analysis of GPS Attitude Determination

In order to assess the accuracy of GPS attitude determination under photogrammetric conditions a testflight was carried out in December 1992. This test was done in cooperation with the University of Calgary/Canada and a survey aircraft of Rheinbraun AG was used. Entirely 69 aerial images were taken over a well controlled photogrammetric testfield in an open pit mine close to Cologne. About one hour of data was recorded with a four antenna ASHTECH 3DF receiver on the aircraft and an ASHTECH LX-12 receiver on a reference station close to the testfield. Both receivers recorded every second the phase and the pseudorange observations on the L1 frequency. The entire photogrammetric block consisted of 4 strips, which have been processed in a conventional photogrammetric way (see figure 3).
The attitude parameters which have been determined in the aerial triangulation serve as reference values for a comparison with the GPS derived values. The aerial triangulation attitudes may be taken as error free, as the expected accuracy of these angles is in the range of 3-10 mgon, which is about 10 times better as the expected accuracy from GPS (100-300 mgon). The location of the antennas on the aircraft body have been pre-surveyed by conventional terrestrial survey methods, to derive the baseline lengths between the antenna pairs and to relate the antenna array to the coordinate system defined by the fiducial marks of the aerial camera.
The GPS data processing was done with a software package, which was developed at the Institute for Photogrammetry (University of Stuttgart). Continuous recording of the GPS phase observations is not required, as the double difference carrier phase cycle ambiguities between the antenna array were estimated for each photogrammetric strip independently. For the ambiguity resolution a modified version of the Hatch [1990] algorithm was used, which is described in more detail in Schade [1992]. Additionally the range constraints between the antenna pairs were used for the

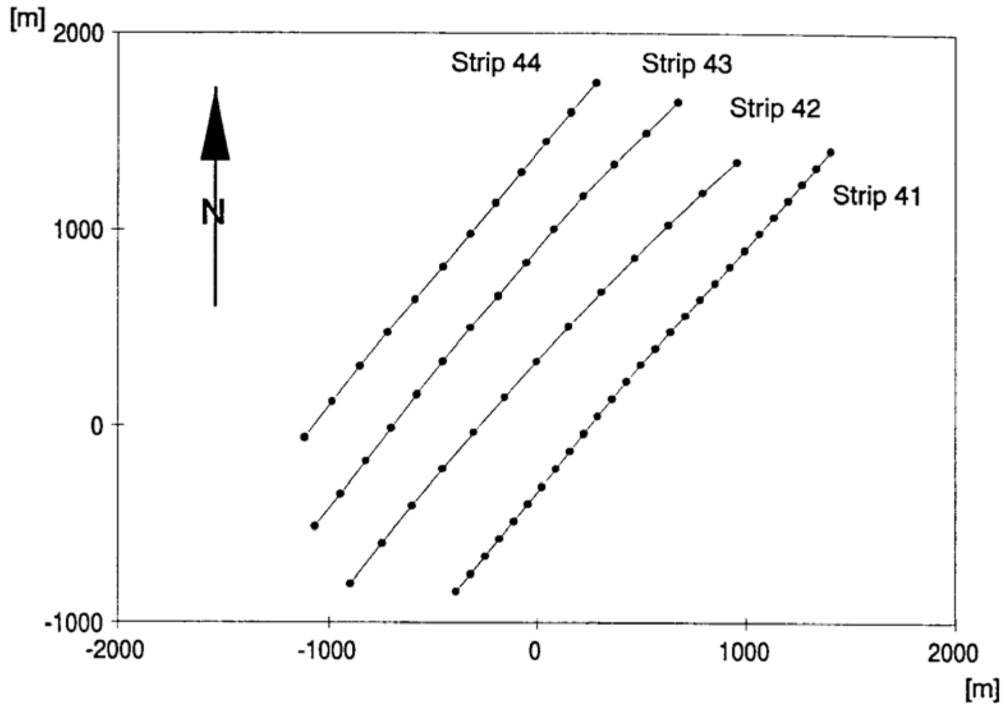

Figure 3: Perspective centers of the attitude-testblock near Cologne.

ambiguity resolution. In this context it has to be clearly stated that the terrestrial measured ranges may not be considered as error free. During the flight external forces act on the aircrafts body and wings, resulting in structural deformations of the survey aircraft. Rather, the aircraft has to be treated as a semi rigid platform and the ranges between the antennas are only known to certain limits. The size and the existence of these effects has been recorded and published in Cohen/Parkinson [1992].

For the computation of the attitude angles the least squares algorithm of Lu et al. [1993] was used, because the information from all four antennas is incorporated in an adjustment process to derive the best fitting attitude angles of the aircraft. For post-analysis only the strips 41, 43 and 44 have been selected, due to insufficient satellite constellations strip 42 has been omitted in the data processing. Figure 4 a-c show the aircrafts heading, pitch and roll for the examined time span.

For the comparison of the GPS derived attitudes and the aerial triangulation attitudes, the GPS angles were interpolated onto the times of exposure of the aerial camera. For this interpolation a simple linear polynom was used, as the flight dynamics in the photogrammetric strips is assumed to be small. Figure 5a shows the differences between the two used methods in all three attitude components. The constant offsets of the three curves, are due to the misalignment of the coordinate systems defined by the antenna baseline 1-3 and the fiducial marks of the aerial camera. These empirical biases can be computed as mean values of the three curves in figure 5a. The misalignment angles could also be determined from the terrestrial calibration measurements prior to the flight. Table 2 summarizes the bias values as determined from GPS and from the terrestrial measurements.

If the misalignment bias is removed the empirical standard deviation of the GPS determined attitudes is in the range of 0.2-0.3 decimal degrees (see Fig. 5b). These results agree quite well with the theoretical expectations of airborne, kinematic GPS attitude determination. With more sophisticated data processing techniques and an improved satellite geometry, slightly better results can be expected. A more detailed description of the testflight can be found in Schade et al [1993].

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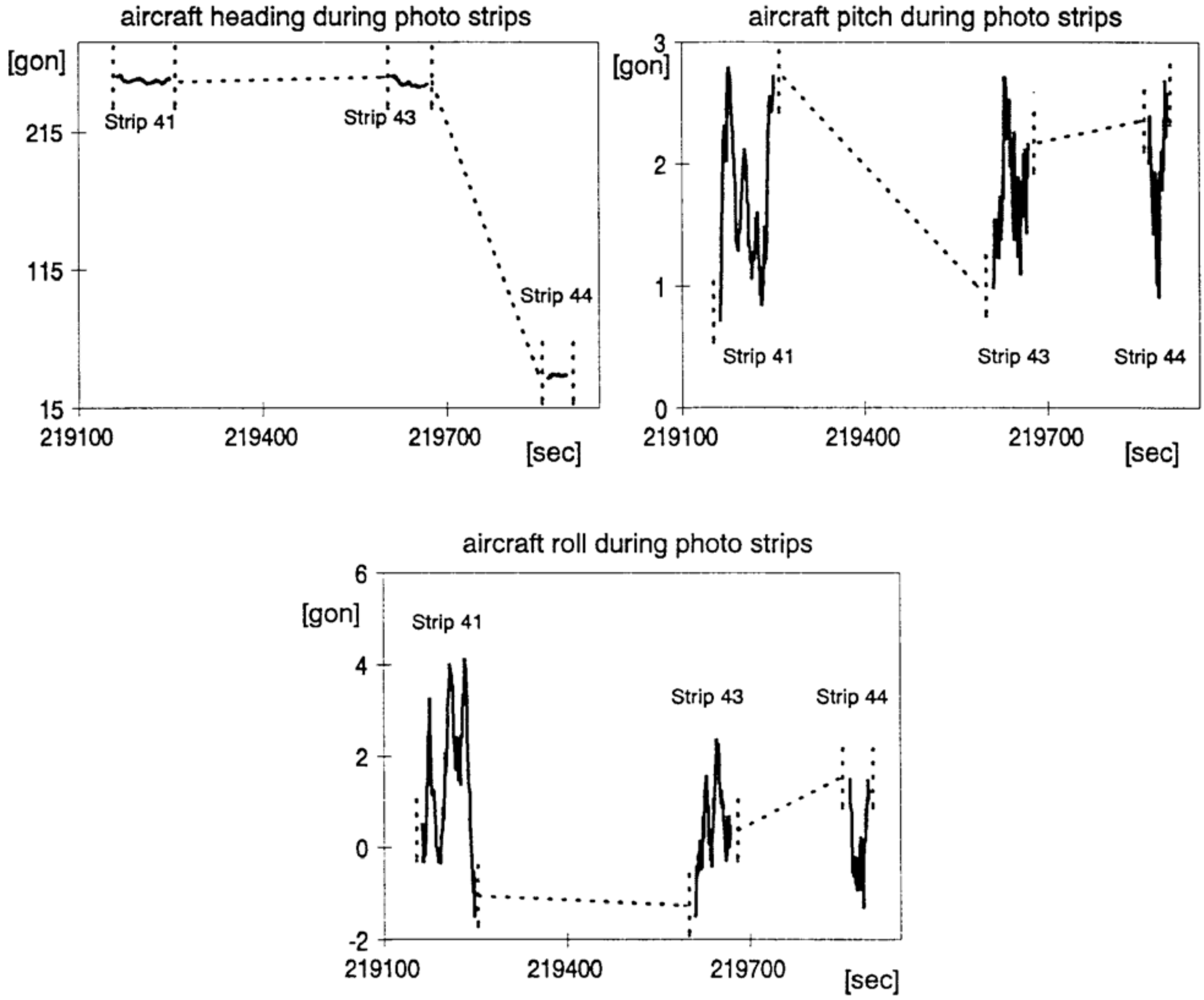

Figure 4: Heading, pitch and roll angles of the aircraft during the photo strips.

Type of Rotation	*Bias determined from GPS in [gon]*	*Bias determined from terrestrial measurements in [gon]*
Heading	1.712	1.432
Pitch	1.449	1.289
Roll	0.401	0.723

Table 2: Misalignment biases determined from GPS and terrestrial measurements.

4. CONCLUSIONS AND SUMMARY

Integrated sensor systems are getting more and more important in digital photogrammetric applications. Additional sensor data is used to overcome deficiencies of digital image processing algorithms. Various sensors have been presented, which are suitable to support the aerial camera in digital mapping applications. As one of these potential sensors, special attention has been paid to

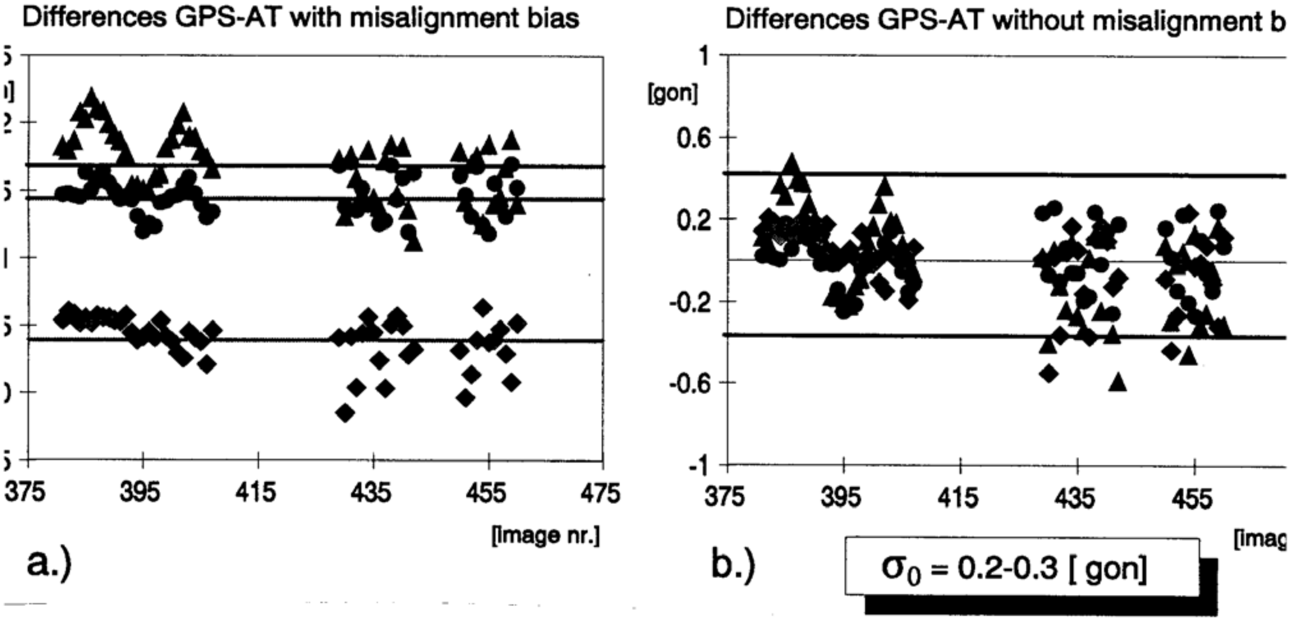

Figure 5: Differences between photogrammetric and GPS attitudes with a.) and without b.) misalignment bias.

airborne kinematic attitude determination with GPS multi antenna receivers. An empirical test, under photogrammetric conditions, has shown an accuracy level for the attitude angles in the range of 0.2-0.3 decimal degrees. These accuracies agree very well with the theoretical expectations for airborne kinematic attitude determination with GPS, although the test was carried out under sub-optimal conditions. The achieved results have to be verified in further tests. For these tests, more sophisticated data processing techniques, to derive the attitudes, should be used.
Additional research has to be done in the mathematical modelling of the different sensor data for photogrammetric applications. The data fusion should be done on an early stage in an integrated data processing system (e.g. Kalman Filter). The image processing algorithms and techniques have to be modified to incorporate the a priori knowledge derived from additional sensors.
In conclusion it is the authors opinion, that it will be necessary to integrate sensors and sensor information for a fast, successful and reliable completion of digital photogrammetric tasks. Further it is believed that GPS attitude may play an important role in integrated digital photogrammetric systems.

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