DESIGN PRINCIPLES OF THE LH SYSTEMS ADS40 AIRBORNE DIGITAL SENSOR

Rainer SANDAU[1], Bernhard BRAUNECKER[2], Hans DRIESCHER[3], Andreas ECKARDT[3], Stefan HILBERT[3], Joe HUTTON[4], Werner KIRCHHOFER[1], Erik LITHOPOULOS[4], Ralf REULKE[3], Stefan WICKI[1]
[1]LH Systems GmbH, Switzerland
sandau@lh-systems.com, kirchhofer@lh-systems.com, wicki@lh-systems.com
[2]Leica Geosystems AG, Switzerland
bernhard.braunecker@leica-geosystems.com
[3]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany
Institute of Space Sensor Technology and Planetary Exploration
hans.driescher@dlr.de, andreas.eckardt@dlr.de, ralf.reulke@dlr.de
[4]Applanix Corporation, Canada
jhutton@applanix.com, elithopoulos@applanix.com

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ABSTRACT

Digital imagery from satellites or multispectral and hyperspectral scanners is well accepted. Tremendous challenges are inherent in the development of a digital sensor to acquire imagery suitable for both high precision photogrammetric mapping and image processing for interpretative purposes. The performance of the film aerial camera is almost impossible to reach with current digital technology. Joint development work by LH Systems and Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre, DLR) has led to considerable success using forward-, nadir- and backward-looking linear arrays on the focal plane to provide panchromatic imagery and geometric information, supplemented by further arrays for multispectral data. This has culminated in the ADS40 product.

In the paper, all essential components of the ADS40 are addressed: optics, filters, CCD type and configuration, front-end electronics, computer, flight management and sensor control software, mass memory, and attitude and position measurement system. The imagery from the new sensor will fulfil many market requirements between the highest resolution film imagery (<0.15 m) and high-resolution space imagery (1-10 m). The sensor's unique blend of multispectral information with high quality geometric information will give rise to numerous new applications.

1 INTRODUCTION

LH Systems announced at the end of 1998 after about one year of development that an engineering model of their forthcoming airborne digital sensor had been flown successfully. The development, jointly undertaken with Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre, DLR) in Berlin has been completed now: the ADS40, a genuine alternative to the familiar aerial film camera, is available. Except for producing stereoscopes, LH Systems and its predecessor Leica were never active in image interpretation. Yet this new sensor has multispectral lines on the focal plane: it can generate precise, geometric information about the surface of the earth, but also produces data amenable to remote sensing techniques. It will further soften the demarcation between photogrammetry and remote sensing and accelerate the decline of the photo laboratory, as digital image data can be transferred from the aircraft directly to the workstation.

The debate about airborne versus spaceborne imagery continues. The highest resolution applications, with ground pixel sizes in the one centimetre to one decimetre level, are likely to remain the province of the film camera. Yet there is a huge, pent up demand for top quality, multispectral information in the gap between this and the one metre and coarser resolutions offered by the satellite operators. Both spaceborne and airborne sensors have their advantages and data fusion will flourish as users select the sensors most likely to provide their information in each case and rely on software to use all the data together. The two types of data will be complementary rather than competitive.

2 AIRBORNE DIGITAL SENSORS: REQUIREMENTS

To have any chance of an impact in a market place spoilt for decades by high performance film cameras, an airborne digital sensor must provide: large field of view and swath width; high resolution and accuracy, both geometric and radiometric; linear sensor characteristics; multispectral imagery; stereo. The first requirement, however, seems to rule out area CCD arrays, because most readily available models in mid 1999 are 4kx4k pixels or less, whereas a linear array of 12,000 pixels is readily available, requiring only one third as many flight lines. Considerable research work done in Germany since the 1970s has demonstrated the suitability of three panchromatic lines on the focal plane, with additional multispectral lines near the nadir (Albertz *et al*, 1996; Sandau and Bärwald, 1994; Sandau and Eckardt, 1996). This obviates the need for multiple area arrays to provide a wide field of view and a multispectral capability (figure 1). The left-hand diagram suggests how the focal plane could be populated using the three-line principle: three panchromatic lines give the geometry and stereo, whilst additional lines, their sensitivity controlled by filters, give the multispectral information. In the right hand diagram, multiple area array CCDs and lenses are required to provide the same ground pixel size and multispectral range as the three-line approach. Indeed, the three-line approach makes possible a panchromatic, colour and false colour sensor, consisting of a single optical system and focal plane.

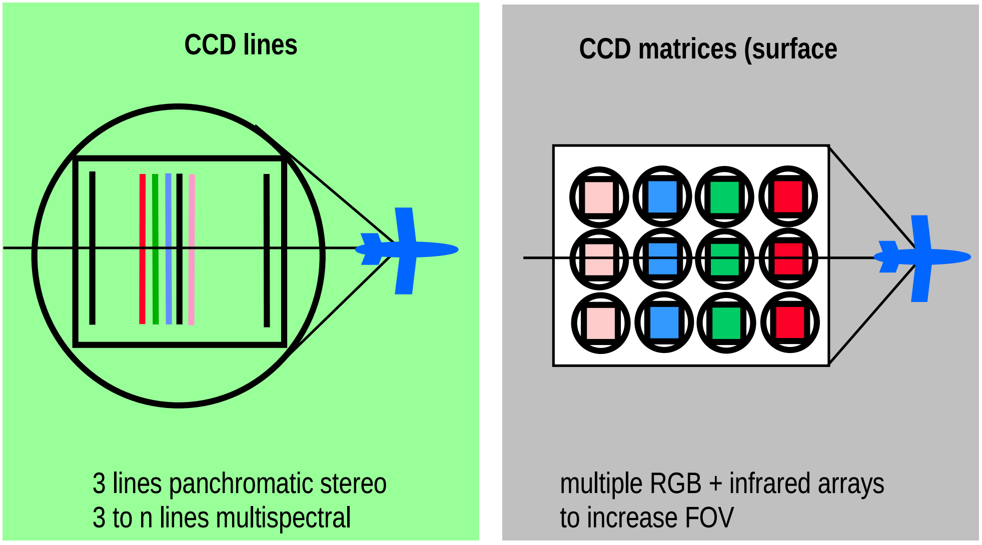

Figure 1. The alternatives: linear and area CCD arrays

3 THREE-LINE SENSOR APPROACH

The three-line concept results in views forward from the aircraft, vertically down and looking backward (figure 2). The imagery from each scan line provides information about the objects on the ground from different viewing angles assembled into strips. With three lines there are three possible pairings for stereoscopic analysis – strips 1 and 2, 2 and 3, and 1 and 3. The angles are given in table 1. The gaps between the 3 CCD lines in the focal plane can be filled with further CCD lines to be used for multispectral imaging.

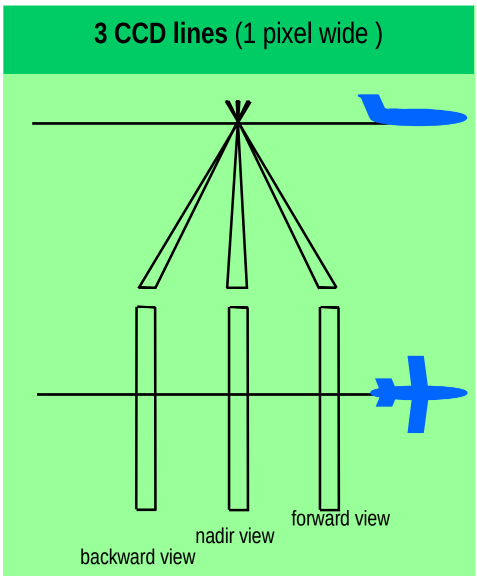

Figure 2. Basic geometric characteristics of three-line digital sensor

4 OPTICS AND FILTERS

The innovative optics of the ADS40 are designed for high-resolution photogrammetric and remote sensing applications. The lens is similar in its external dimensions, weight, resolution and light efficiency to the lens of LH-Systems' RC30 film camera. However, both optical designs are completely different owing to the different recording modes. While the minimisation of distortion is of prime interest in the case of the film lens, the most demanding requirement for the digital lens is *telecentricity* at the image side. This specification is in general useful for any digital camera, but absolutely critical for the ADS40 owing to the requirement for the request for multispectral, narrow band recording.

Several spectral bands between 400 nm (blue) and 900 nm (infrared) are specified with very steep spectral edges (see table 1 near the end of the paper), leading to band pass filters with complicated interference structures. The filters, which must be placed near to the CCD-pixels for constructional reasons, should not change the spectral response across the wide angular field of view. Therefore, each filter stripe and consequently each adjacent pixel line have to be illuminated by light of normal angular incidence, i.e. striking the line at right angles, which is accomplished by a telecentric lens. The loss of angular symmetry between object and image side, however, leads to a length of 420 mm (figure 3). Such a design characteristic is difficult to avoid, however, when demanding specifications are set for the spatial resolution across the field of view in both directions, along and across track. The resolution values must be kept constant over a wide range of temperature and flight altitude, i.e. pressure range. The same insensitivity must also hold for the registration error, i.e. the allowable change of the mapping geometry, which describes the change of the ground viewing angle of each pixel.

Thus, all the requirements - wide angular field of view, broad spectral range, high resolution, telecentricity and environmental stability - finally lead to a lens layout of at least the same complexity as the film lenses of the RC30. The ADS40 uses eight parallel sensor lines: three panchromatic lines (forward, nadir, backward) and five spectral lines (red, green, blue, new infrared 1 and optional near infrared 2). The three colour lines, each equipped with 12000 pixels, are optically superimposed during the flight using special arrangement of dichroitic mirrors. The near infrared channels are slightly offset with respect to the panchromatic nadir CCD lines.

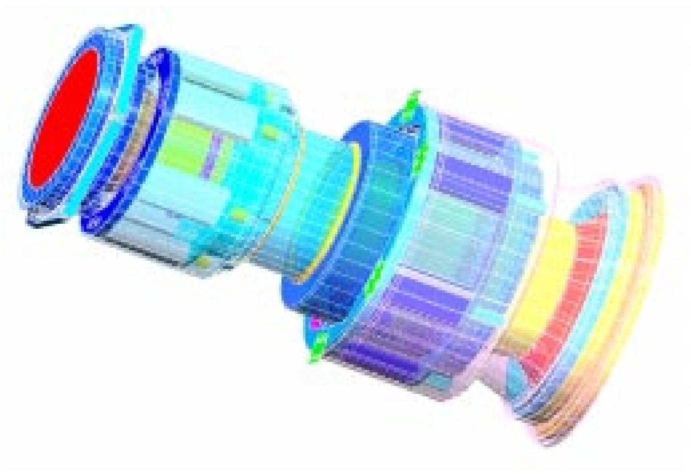

Figure 3. View of the lens of the ADS40

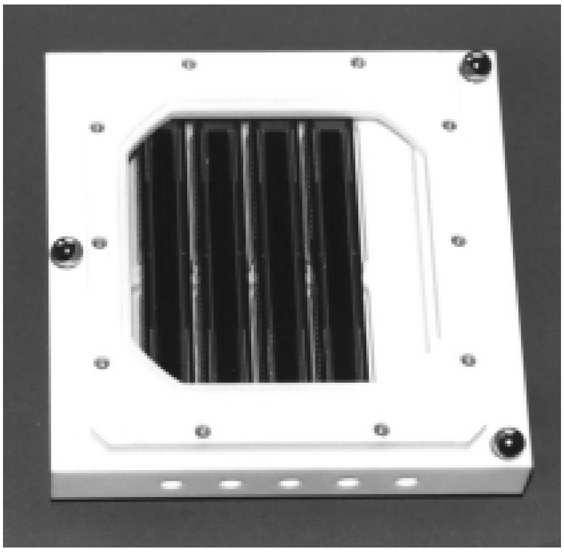

Figure 4. The focal plane module of the ADS40

5 CCD AND FOCAL PLANE MODULE

The focal plane (figure 4) consists of four CCD housings: two of them contain single lines and two contain triple line configurations. Both types are specifically developed for the ADS40 . Each CCD line consists of two linear arrays, each with 12000 pixels but staggered by a 0.5 pixel shift. The panchromatic lines make use of this staggered arrangement thus halving the achievable ground sample distance. The colour lines (RGB, NIR1, NIR2) use 12000 pixel linear arrays.

All CCDs have to be placed with a height tolerance of a few micrometres only. To achieve a dynamic range of 12-bit with a radiometric resolution of 8-bit, a temperature stabilisation system has been introduced. Furthermore, the focal plane is equipped with a ventilation and air drying system to avoid condensation of water vapour on the cover glass of the CCD packages and focal plane deformations.

6 CCD SIGNAL PROCESSING

The focal plane electronics contain the CCD lines with only a minimum of electronics necessary to operate the CCDs. The subsequent CCD signal processing is concentrated in separated sub-units. Each 24k CCD achieved by two staggered 12k CCDs is processed like two independent 12k CCDs. Each of the 12k pairs can independently be used for different colours, and, of course, the usage of only one 12k line is also possible. This modular concept of the ADS40 allows, theoretically, product variants that use from one 12k CCD up to 3x24k (pan) + 6x12k (colour) CCDs. This requires a high flexibility of signal processing implemented on complex electronic printed circuit boards. Each board includes all the necessary functions for complete analogue signal processing (ASP) of a CCD: input clamping, correlated double sampling, analogue and digital offset correction, 14-bit analogue to digital conversion providing a signal dynamic range of at least 12-bit, dark signal non-uniformity (DSNU) correction and photo response non-uniformity (PRNU) correction.

7 DIGITAL COMPUTER AND MASS MEMORY

The camera computer system consists of several components:

- camera computer as data processing platform and camera control unit
- mass memory systems as storage device for image and other mission data
- electronics of the position and orientation system
- operator and pilot interface as user control elements
- IO-Box as interface unit to other sensors and devices.

7.1 Camera Computer

The main component of the camera computer (figure 5) is the high-speed image data channel, designed to compress the image data provided by the camera head in real-time. The compression supports a sustained input data rate of up to 40MB/s and features two standard compression modes: lossless and JPEG. The back end of the data channel is built by means of a recording interface which multiplexes and spools data from different sources and formats the stream to be stored on the mass memory system in an optimal manner. The peak performance of the recording interface reaches up to several hundred MB/s and supports a flexible data management while storing data on to the mass memory system. In addition to the image data channel, the camera computer contains the hardware platform for the flight and sensor control software and features various interfaces for data exchange and communication.

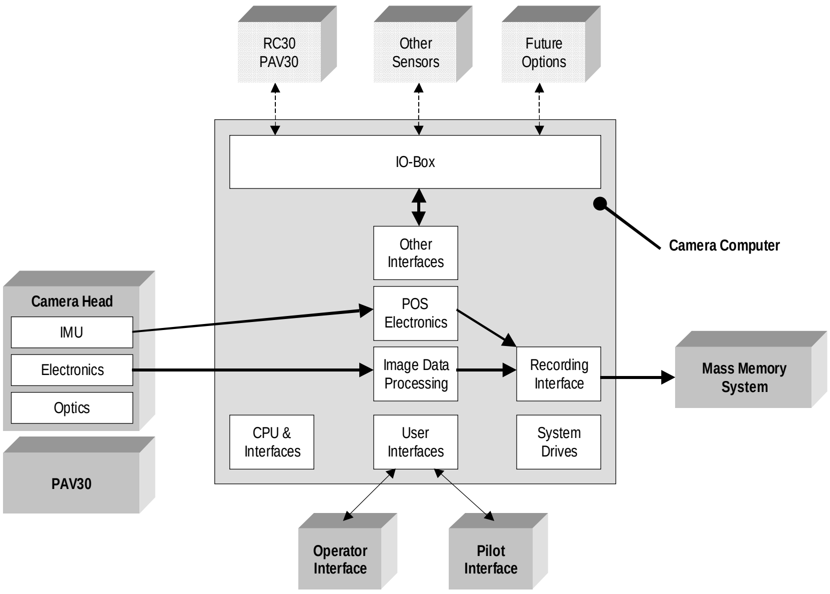

Figure 5. Components and connections of the camera computer

7.2 Mass Memory System

The mass memory system stores all mission data, such as image, orientation and housekeeping data, collected during a survey flight. It is based on a rugged disk array and meets the extended environmental conditions required for airborne applications. The device allows fight missions with up to four hours' recording time and supports a sustained data rate of 40-50 MB/s. In order to achieve optimal performance parameters during read and write operations a proprietary file system has been implemented. Nevertheless, transparent data access is supported by different utilities.

The attitude and positioning of the ADS40 is important as it partially determines the performance of the overall system. This is being provided by an Applanix Position and Orientation System (POS) developed specifically to meet the ADS40 requirements. The inertial measurement unit (IMU) of the POS is located in the camera head and senses the motions of the focal plate. The electronics are located in the camera computer system and are, owing to their high level of integration, transparent to the user. The data generated by the POS are stored as part of the mission data on to the mass memory system and can be retrieved for post-processing after the flight without any overhead. For flight guidance and navigation purposes the real-time data of the POS is provided to the navigation module.

7.4 Operator and Pilot Interface

During flight missions a single, easy to use operator interface is important to handle complex projects. This becomes more important as the complexity and performance of the imaging system increase. The ADS40 is a new milestone along the road of digital sensor systems and features therefore a touch-screen, high-resolution terminal as the next generation of user interface. Similarly, the pilot interface is independent from the operator interface and fulfils the requirements to be installed in the cockpit of an aircraft.

7.5 IO-Box

The IO-Box supports a flexible interface to external devices. It is based on a modular concept and allows the ADS40 to be extended in the near future to a multi-sensor control system. For this reason it will be possible to operate the ADS40 together with other high-performance systems such as an RC30 or a PAV30, or almost any other sensor system, for example spectrometer or laser scanner.

8 FLIGHT AND SENSOR CONTROL MANAGEMENT SYSTEM (FCMS)

The best, most powerful, most advanced hardware for an airborne digital sensor is of no use without a heart that controls, coordinates and monitors the individual subsystems and provides a graphical user interface to allow easy use of the sensor system.

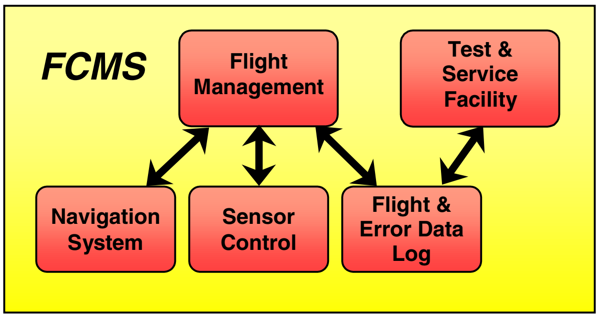

Figure 6. Components of the FCMS

Survey flights are still a challenging task for pilots and operators of an airborne imaging system. The main objective is to perform the survey flight with the least possible flight time and the best possible results during the imaging sequences. This is a complex situation where the Flight and Sensor Control Management System (FCMS) gives top assistance to both the operator and the pilot. The FCMS can logically be divided into five separate parts each of them providing individual functionality within the sensor system and to the operator (figure 6).

8.1 Flight Management

The flight management module is the core of FCMS and coordinates the navigation system, the sensor control and the flight and error data log. Using a graphical touch display the operator interacts with the flight management system. The design of the graphical user interface is aimed at easy operation with highly recognisable screen representations. Therefore the general layout is graphical, menus are selected via a button bar with icons and texts are kept to a minimum in order to allow unproblematic internationalisation. A two-stage help system, including the user manual, helps the operator become familiar with the system and to find the way back when lost.

8.2 Navigation System

Focussed on providing the best guidance throughout the survey mission, the navigation system is designed to reduce flight time and optimise work sharing between pilot and operator. The pilot can concentrate fully on navigating and steering the aircraft while the operator takes care of the sensor system and image acquisition. Based on flight plans from LH Systems' ASCOT product for film cameras and supported by the high accuracy attitude and position measurement system, the navigation system performs the following tasks:

- Guidance to the mission area
- Approach to pre-planned imaging lines
- High-precision guidance on the imaging lines.

Orientation is being improved by the implementation of moving map displays, based on standard pixel maps. Displacements from the planned flight line are displayed and corrective actions suggested to the pilot (figure 7). The displayed flight path is calculated using an abstract model of the aircraft characteristics and the dependent parameters such as aircraft speed over ground and wind drift.

Independent of the operator's display the pilot can select his own display configuration and representation of the screen. No longer do both the pilot and the operator have the same display. Acting as a client the pilot can indeed control the complete sensor system from his interface in the case of operation by a one-person crew.

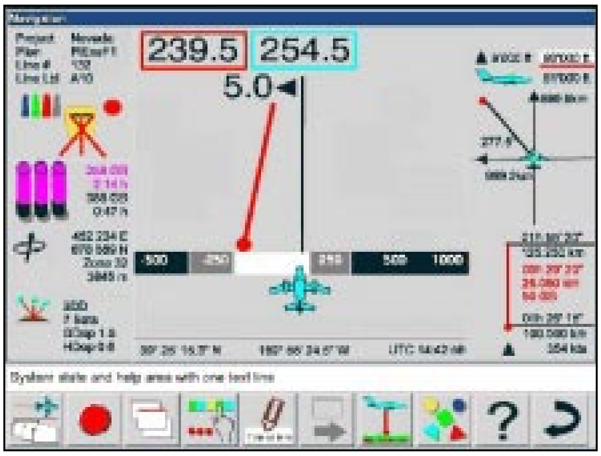

Figure 7. Navigation systems example screen

8.3 Sensor Control

The sensor control module interfaces the specialised image data acquisition hardware. Parameters either set by the operator or defined by the flight plan are transferred to the hardware and status information read back. Through modelling the hardware and related aspects, the ADS40 is encapsulated and represented in abstract form to the flight management system.

8.4 Flight and Error Data Log

During the flight a wide range of different data is stored in order to allow precise evaluation. The flight track together with start and stop locations of imaging sequences together with the individual sensor parameter settings can be retrieved after the flight. Additional entries in the log provide exact servicing and error analysis functionality, a feature that eases and optimises the maintenance of the ADS40.

8.5 Test and Service Facility

The test and service facility is mainly used by trained service personnel or specially trained operators. It assists the servicing process and deeply analyses the complete sensor system with all its subsystems. As a result turnaround times and maintenance intervals can be improved and optimised, allowing the service technician to locate and replace faulty parts directly or update internal software with the latest releases.

9 ATTITUDE AND POSITION MEASUREMENT SYSTEM

In order to reconstruct high-resolution images from line scanner data, the orientation data of each line has to be determined. This can be done by using observations from image matching techniques only, as provided in modern aerotriangulation packages. But computational effort for this indirect method is so large that direct observations from attitude and position sensors are seen as the means of reducing processing time: the indirect method is time consuming, whereas the direct method is capital intensive. The decision was made to find an optimal trade-off by including direct measurements from GPS and IMU sensors of only a certain accuracy into the triangulation. Attitude and position measurements, therefore, are provided by an integrated GPS/inertial Position and Orientation System (POS) that has been designed specifically by Applanix Corporation to meet the unique requirements of the ADS40. The advantages are:

- data processing time to rectify line scanner data is reduced significantly
- price/performance ratio of medium priced IMU sensors is likely to improve over time.

The tight integration (figure 8) with the focal plane of a digital line sensor has great potential for further reduction of ground processing.

The system comprises four main components: an inertial measurement unit (IMU), a POS computer system, a high performance L1/L2 GPS receiver and a post-processing software package for optimal carrier-phase DGPS/inertial processing.

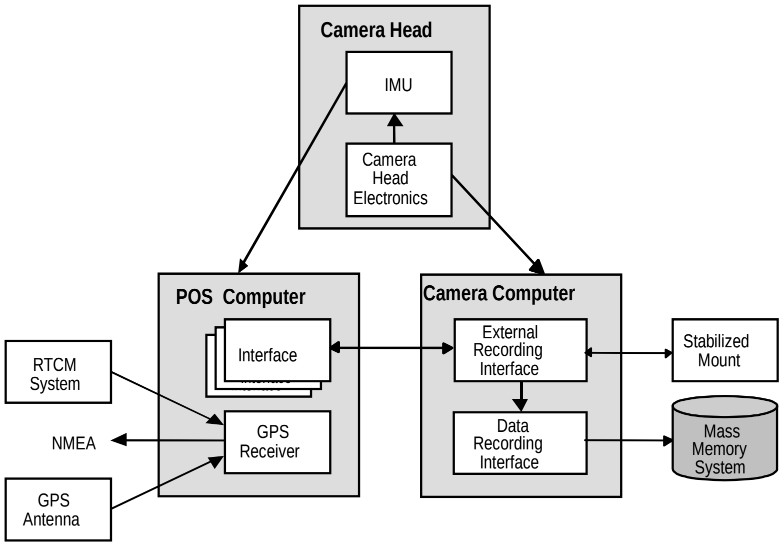

Figure 8. Main components of tight integration of IMU/GPS and a three line sensor camera

High rate incremental velocity and angle data from the IMU are integrated in a strapdown navigator to produce a full six degrees of freedom navigation solution of the camera (position, velocity and orientation). Position and velocity information from the GPS receiver are then used to observe and correct the low-frequency errors in the navigation solution. The net result is a high-rate, high-bandwidth position and orientation solution that has the dynamic fidelity of a pure inertial based solution and the absolute accuracy of GPS.

The IMU is mounted inside the camera head. Unlike existing frame cameras, the ADS40 has been designed for the IMU to be mounted directly on its focal plane. This eliminates the problem of relative motion between the camera and the IMU that can sometimes arise when the IMU is mounted externally.

The POS computer system and the GPS receiver are embedded in the camera computer system. Data from the IMU are transmitted to the POS computer via a fibre optic link. Other inputs include RTCM 104 differential GPS corrections and gimbal encoder input from the stabilised platform.

The ADS40 POS system generates both a real-time and post-processed position and orientation solution. The real-time solution is used for input to the flight management system and for control of the stabilised mount. By providing both position and orientation, POS has the ability to control automatically the stabilised platform yaw to remove crab and drift. The post-processed solution is generated using Applanix’s POSPac software, which processes carrier phase GPS measurements and raw IMU data in an optimum Kalman filter/smoother to produce the smoothed best estimate of trajectory (SBET) navigation solution. The SBET navigation solution is then applied to the image data to build up a sequence of rectified line images for each flight line. The rectified images are then triangulated using the SBET and automatic tie point matching/bundle adjustment techniques to produce a georeferenced photogrammetric block.

10 SUMMARY AND CONCLUSIONS

LH Systems has chosen the three-line scanner approach for photogrammetric imaging. The very short development time for the ADS40 of less than three years was possible owing to the transfer of knowledge from DLR’s space sensor development program within a joint development project. To achieve a high ground resolution with large swath width, the staggered array principle is applied, resulting in the equivalent of up to 24000 pixels. Additional spectral imaging lines (RGB, NIR1 and optional NIR2) with 12000 pixel arrays are used for multispectral imaging. The spectral channels are chosen to allow remote sensing applications also. Both photogrammetric and multispectral imaging occur simultaneously during a single flight. The ADS40 is optimised for image acquisition with a dynamic range up to 12-bit and a radiometric resolution of ≥8-bit (including the effects of the Poisson distribution of the incoming light). The compressed data are stored in an on-board mass memory with a storage capacity up to over a half a terabyte. The imaging process (sensor control and flight guidance) is controlled by an appropriate ADS40 software system implemented in the digital computer system connected to the camera head system via optical fibre links.

Focal length	62.5 mm
Pixel size (pitch)	6.5 µm
Panchromatic line (staggered)	2 * 12000 pixel
RGB and NIR line	12000 pixels
FoV (across track)	46°
Stereo angle forward to nadir	26°
Stereo angle forward to backward	42°
Stereo angle nadir to backward	16°
Red	608-662 nm
Green	533-587 nm
Blue	428-492 nm
NIR 1	703-757 nm
NIR 2	833-887 nm
Dynamic range	12-bit
Radiometric resolution	8-bit
Ground sample distance (3000 m altitude)	16 cm
Swath width (3000 m Altitude)	3.75 km
Read out frequency per line	200-800 Hz
In flight storage capacity	200-500 GB

Table 1. ADS camera characteristics

The effects on the push-broom type sensor caused by the flight dynamics of the aircraft are rectified using the high precision information from the position and attitude measurement system provided by Applanix. Table 1 summarises the main characteristics of the ADS40. The processing of the data retrieved from the mass memory system can be done using SOCET SET®. Furthermore, standard data output formats are provided to allow the data processing with other platforms also; the necessary sensor model is provided by LH Systems.

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