Integrated system ADS/GPS/INS for direct georeferencing

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Abstract: In last years the direct georeferencing is a modern method to determine ground point position. Direct georeferencing understand is a method to directly register sensor exterior orientation elements by which interesting ground point coordinates become calculated, basing on acquired images without using a number of other control points. The registration of sensor exterior orientation elements in operational flight has been carried out by systems GPS (Global Positioning System) and INS (Internal Navigation System). First ADS (Airborne Digital Sensor) – digital system to capture airborne images, represented on 19-th Congress of ISPRS in Amsterdam, Holland (2000) has appointed a new era of photogrammetric airborne environment. It indicates the beginning of the end of analogue cameras. Integrating three systems ADS, GPS, INS into multi-sensor system for direct georeferencing has more benefits such as reducing cost and time consuming for terrain measurement of Ground Control Point (GCP), as well as independent of bad weather and terrain difficulties.

Keywords: Sensor, linear array, surface or matrix (frame) array, integrating, ADS, GPS, INS, georeferencing.

1. Introduction

First time on the 19-th Congress of International Society of Photogrammetry and Remote Sensing (ISPRS) in Amsterdam, Holland (2000) Airborne Digital Sensor ADS40 (LH System Company) was presented. Since five years ADS has been more and more used in practice. On the world market in 2002 there were only 3 aerial digital cameras sold, but to March, 2005 there were 27. We can also meet other aerial digital cameras as Digital Mapping Camera (DMC) of the Z/I Imaging Company, UtracamD (UD Vexcel corp.), Three Lines Sensor (TLS, Starlabo corp.) etc. Along with technology of Global Positioning System (GPS) and Inertial Navigation System (INS) the Airborne Digital Sensor (ADS camera) becomes really a need for mapping with dominant advantages in the comparison with Conventional Photogrammetry. It allows to determining direct 3D terrain points without a need of Ground Control Points (GCP), with obtained accuracies lower than ±10cm in plan and lower than ±20cm in height. It is very important in practice for reducing cost and time consuming of terrain measurement of Ground Control Points, as well as independent upon prolonging bad weather and terrain difficulty. Compared to film-based photo acquired with analogous camera, digitally acquired image is advantageous because no time is needed for film development and image scanning. Further, digital image processing has been successfully utilized to facilitate automated procedure in interior, relative orientation and the generation of digital elevation models DEM. In photogrammetric processing there are existing trends as follows:

- Substitutions of using analogue camera by airborne digital sensor
- In the competition of high resolution satellite images the airborne digital sensor images need to have a large format and have to be integrated with GPS and INS systems in order to realize direct georeferencing.
- For smaller area projects and reducing financial conditions or risks there is a market for medium to smaller format sensors to be used.

On the world market, to the large format sensor group belong such as ADS40 (LH System, 2000) [1], Starimager (TLS – three line sensor, Starlabo corp., 2003) [8], 3-DAS-1 (Werhli Ass., 2004), Digital Mapping Camera (DMC, Z/I Imaging, 2003) [5], UltracamD (Vexcel corp., 2003) [4], DiMAC (DiMAC System, 2005), etc. To the medium and small format sensor group there are DSS (Applanix corp.), Litemapper (IGI); DAIS-1 (SpaceImaging), Spectra-view (Airborne Data System, Inc.), etc [2].

This paper presents the model integrating three systems ADS, GPS, INS into multi-sensor system for direct determining of 3D terrain points with the current experimental results. Integrated ADS, GPS, and INS system supports fully digital data acquisition needed to directly georeferencing.

2. Actual state of airborne digital sensors

2.1. Construction conceptions of airborne digital sensors

The transition from film to digital images was an historic challenge in photogrammetric processing for over 80 years. After designing more than 15 different aerial film cameras in 20-th century and supporting on the world market over 1200 units, of which the large number still in operational use, LH System at first time publically presented ADS40. Nominal format of film-based image is of 23x23cm. The format size of frame (matrix or surface)) sensor, equivalent to nominal format of film camera contains about 500 millions (23 000 x 23 000) of detector elements (pixels). It is difficult to construct the large matrix format with so many sensitive elements. The format size of 60x60cm (4 inches) is equivalent to matrix (4000x4000) pixels with size of 15μm. Similarly, for film image format of 80x80cm (5 inches) is equivalent to matrix (9000x9000) pixels with size of 8,75μm. Ideally, one individual large format of CCD frame array sensor (or frame sensor) similar to the information contents of existing film formats would be the perfect geometric solution for aerial image acquisition system. Unfortunately, the size of commercially available imaging sensor is limited, causing of electronic technology. Therefore, in order to overcome this limitation the new solution is introduced to producing digital sensors such as DMC, UtracamD, DiMAC and other. The conception of this solution is based on the parallel operation of several compact camera heads directed at the scene under slightly oblique field angles. Fig. 1 represents the solution conception of surface array sensor [5].

a) b) c)

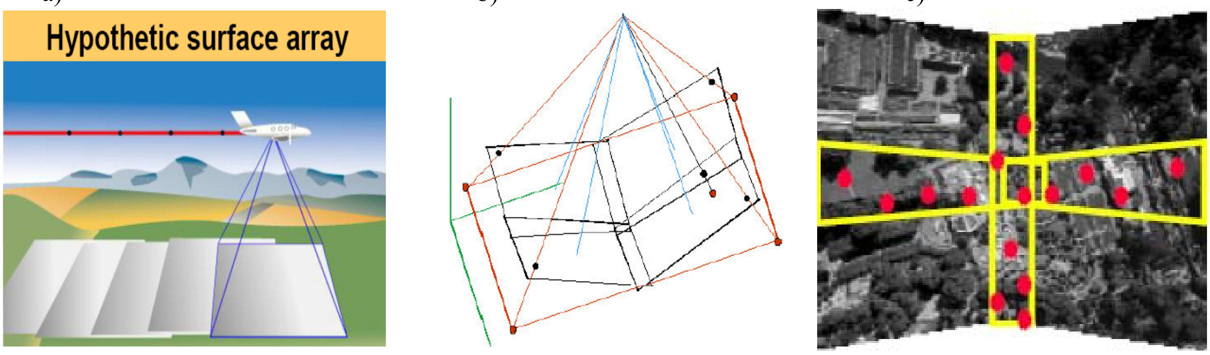


Fig.1. Conception of surface array sensor: a) hypothetic surface array, b) solution conception, c) composite image

Good geometric accuracy of composite image has to fulfill three following conditions:

- All four small (raw) images must be acquired synchronously in time,
- The systematic effect resulting from the different perspective centers must be negligible,
- The relative orientation of the camera heads must be stable.

From investigation of DMC, the first conditions is with a precision of less than 0,01 msec; second condition could be neglected and third condition is also fulfilled, basing on the analyzing of tie point coordinates between borders of four small images with a typical accuracy in the order of 1 to 2 μm (From 1/6 to 1/12 of a pixel having a size of 12 μm). One of the fundamental advantages of surface array sensor is that photogrammetric processing becomes is same as for film images.

a) b) c)

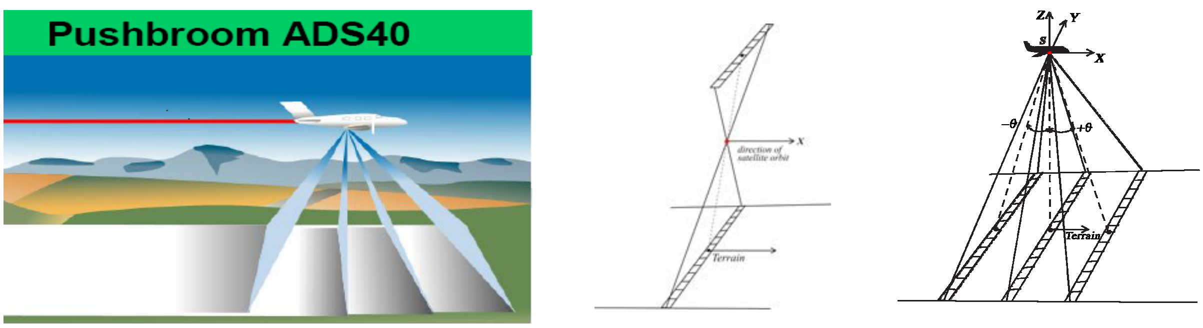
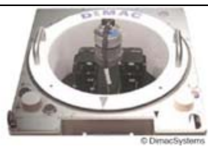


Fig. 2. Conception of linear array scanner: a) perspective overview, b) scan line, c) Three-line scanner Pan.

Second conception of ADS is based on the optic-electronic scanner. Sensor in this scanner is linear array of sensitive detector elements CCD placed in focus surface of lens [1, 8]. Image processing is realized simultaneously in flight direction. From point of view of measurement necessities there are three-line scanners which take simultaneously three “forward”, “nadir” and “backward” images of same terrain. At the result, from a flight three stereo models can be acquired. There are available in practice linear array sensor (pushbroom) of 12 000 sensitive elements (pixels), with possibility of increasing twice this number. Belonged to be second conception are ADS40 (LH System, 2000), Starimager (TLS – three line sensor, Starlabo corp., 2003), 3-DAS-1 (Werhli Ass., 2004), etc. The Fig. 2 represents the principle of second conception. In the table 1 there are some ADS of large formats presented in the world market.

Tab. 1. Presentation of some sensors in world market

Nr	Sensor	Chosen characteristis	Presentation
1	**DMC** • Z/I Imaging (2003)	Module panchromatic: • f=120mm; Pixel size: 6µm; • Surface: 13000x8000pixels. • Angle of view: 74°x44° • Resolution radiomatric : 12 Bite	
2	**UtracamD** • Vexcel Corp. (2003.)	• f=101,400mm; • Surface: 11500x7500 pixels. • Pixel size: 9µm • Ratio S/N: 9bite	
3	**DiMAC** • DiMAC Sys. (2005)	-	
4	**ADS40** • Leica Geosystem (2000)	• f=65.5mm; Resolution:150pair line/mm • Panchromatic loine: 2*12 000 pixels. • RGB, IR : 12 000 pixel. • Pixel size: 6,5µm; GSD:16cm • Angle of view: 16° , 26°, 42°. • Ratio S/N.: 12bites; • Radiometric Resolution: 8b.	
5	**STARIMAGER** • Starlabo Corp. (2004)	• f=60mm; • 14 400 piixels/linii • Piksel: 5µm • Angle of view: 17°, 23°, 40°. • Ratio S/N: 9bites.	
6	**3.DAS-1** • Wehrli Ass. (2004)	• f=35mm; 60mm; 100mm. • Line: 600pixels - 12 µm; 800pixels - 9µm; 14 400pixels - 5 µm; • Angle of view: 16°, 26°, 42°. • Ratio S/N: 12bites;	

2.2. Airborne digital sensors on the world market

Four sensors such as ADS40, DMC, and UtracamD in large format and DSS in medium format are certainly the most relevant for standard photogrammetric use currently. Less than one year after the official market introduction at the Amsterdam 2000 ISPS Congress first ADS40 phased-in market in spring 2001. From that time there were 26 units sold. For DMC up to now 22 systems are sold, about 16 of them successfully installed and used in practice. Table 2 presents current number of sensors distributed on the world market [2].

Table 2. The distribution of sensors on the world market

Sensor	**America** [unit]	**Europe** [unit]	**Asia** [unit]	∑ [unit]	**Forecasting in 2010**
1. ADS40	14	7	6	27	80 units
2. DMC	7	5	10	22	
3. UltracamD	-	-	-	19	Medium.:12-15 units./year
				68	
4. DSS				33	

3. Geometric model of integrated system ADS/GPS/INS

3.1. Mathematical principle of direct georeferencing by ADS/GPS/INS

Main idea of direct georeferencing is quite sample. For each image captured with ADS the exterior orientation elements (X_o, Y_o, Z_o; φ, ω, χ) of the perspective center at the scanning moment t must be determined. System GPS/INS can provide these information with quality which depends on the navigation accuracy (X_{INS}, Y_{INS}, Z_{INS}; pitch, roll, yaw (azimuth)) and on accuracy of calibration parameters relating sensor (camera) and INS body frame. The position and attitude performance of an integrated GPS/INS is complex process depending on variety of parameters, quality and the type of sensors, sensor placement configuration, their operational aspect and solving algorithm.

For providing mathematical relationship between the ground point in local system L and multi-sensor positions ADS/GPS/INS the Fig. 3 is represented. As shown in Fig. 3 the coordinates of ground point P in local system L, determined with direct geofererencing from image having perspective center O in moment t can be described by the formula:

$$\mathbf{R}_{P,L} = \mathbf{R}_{O,L}(t) + k.\mathbf{A}_{c,L}.\mathbf{r}_c(t) \quad (1)$$

with
$$\mathbf{A}_{c,L} = \mathbf{A}_{INS,L}(t).\mathbf{A}_{c,INS} \quad (2)$$

where: $\mathbf{R}_{P,L} = [X \;\; Y \;\; Z]^T$ – georeferenced 3D vector of an arbitrary object P in local system L,

$\mathbf{R}_{O,L}(t) = [X_o(t) \;\; Y_o(t) \;\; Z_o(t)]^T$ – 3D position vector of the perspective center at the scanning moment t,

$\mathbf{r}_c(t) = [(x_c(t)- x_o) \;\; (x_c(t)- y_o)/k_y \;\; -f]^T$ – 3D coordinates vector of the image point p in the image (c-frame) scanned in the moment t; $x_c(t)$, $x_c(t)$ – the image coordinates of the point p corresponding to object point P; x_o,y_o – principle point offset from the CCD format center; f – calibrated focal length of the lens; k_y – a factor accounting for the non-squareness of the CCD pixels,

k - scale factor,

$\mathbf{A}_{c,L}$ – image orientation matrix which rotates image (camera frame or c-frame) into system O_LXYX, utilizing three rotation angles φ, ω, χ.

$\mathbf{A}_{INS,L}(t)$ – INS-derived rotation matrix rotating the INS body-frame into the O_LXYX system. $\mathbf{A}_{INS,L}(t)$ contains the attitude angles (roll, pitch, yaw), obtained from the GPS/INS integration scheme shown in Fig. 3,

$\mathbf{A}_{c,INS}$ – Relative transformation matrix which rotes the INS-body frame into the c-frame.

It is better for integrating when GPS antenna is laid on the same Z (nadir) axis and Inertial Measurement Unit (IMU) is mounted inside camera head. For ADS40 as same as DMC the IMU is mounted inside the camera head. Unlike existing frame camera 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 sometime arise when the IMU is mounted externally.

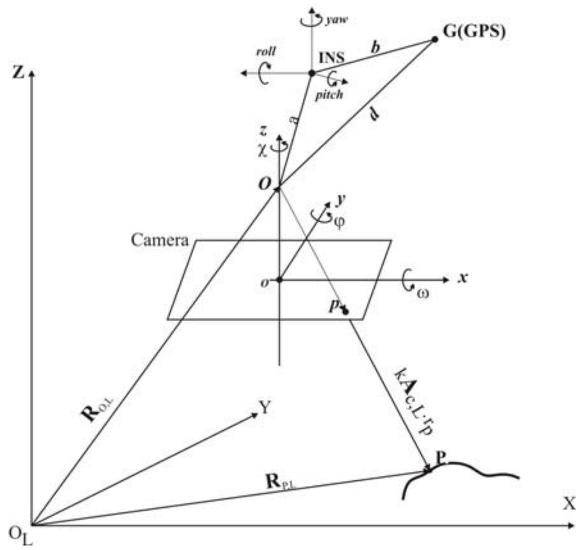


Fig. 3. Direct georeferencing Model of multi-system GPS/INS/ADS

a) b)

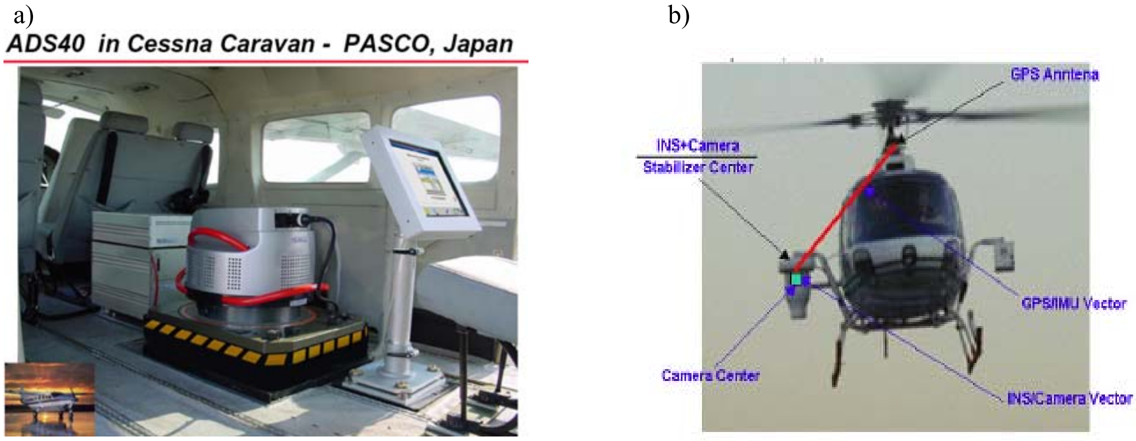


Fig. 4. Installation of multi-system in platform: a) ADS40 in airplane, b) Starimager in helicopter

As indicated in Fig. 3 the INS, the GPS antenna and ADS cannot occupy the same spot in 3D. The INS-derived attitude angles (roll, pitch, and yaw) are in the coordinate system of the INS body frame and they should be related to the image orientation angles φ, ω, χ for use Eq. (1). Therefore, before testing the system in flight, the GPS/INS/ADS offsets were determined.

3.2. Determination of ADS/GPS/INS offsets

In order to perform direct georeferencing the vector $\mathbf{R}_{O,L}(t)$ and rotation matrix $\mathbf{A}_{c,INS}$ appeared in Eq. (1), (2) must be determined. For determining it the ADS/GPS translation and ADS/INS rotation offsets have to be calculated in calibration process. Fig. 4 shows that the positions and rotations from GPS/INS do not refer to the perspective center of the imaging sensor directly. In the Fig. 5 the ADS/GPS translation offset **d** is defined as the vector from camera perspective center (O) to GPS antenna (G) in the local system L. Let $\mathbf{r}_G$ be offset vector in the image system, we have following formula:

$$\mathbf{r}_G = (\mathbf{R}_M)^T.\mathbf{d} \qquad (3)$$

where $\mathbf{R}_M$ – rotation matrix of the image plane (c-frame) which rotes image plane with respective to local system L. The ADS/GPS translation offset **d** can be determined using conventional terrestrial surveying methods after installation of the sensors in the airplane used to imaging flight. This offset can be included in the aerotriangulation as control information. The offset vector $\mathbf{r}_G$ is transformed into the local ground coordinate system by Eq. (1).

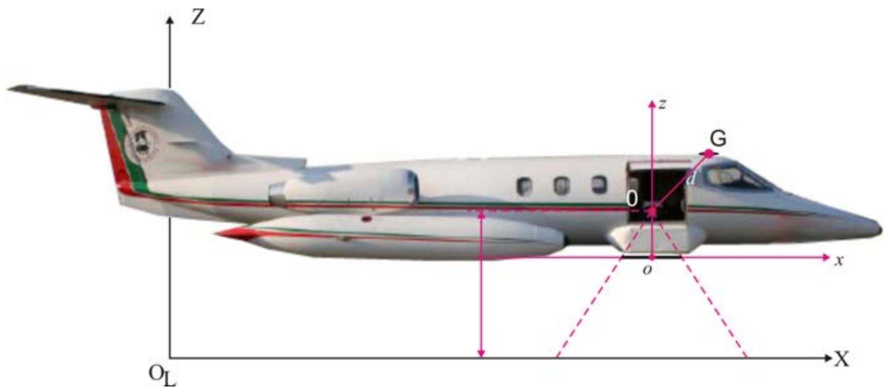


Fig. 5. Calibration of ADS/GPS translation offset vector in the image coordinate system

The rotation offset between the INS sensor axes and ADS coordinate system cannot be determined via conventional survey methods. Therefore, these rotation offsets (or misalignment angles) between the INS and ADS have to be computed with triangulation using a small number of tie and control points similar to conventional aerial film-image. It is better for determining ADS/INS rotation offsets $\mathbf{A}_{c,INS}$ the terrain elevation variation of 7% to 10% on which aerotriangulation is carried out improved the recovery of the φ, ω angles as compared to using flat terrain. The Digital Photogrammetric Workstation (DPW) used to measurement of image coordinates of control points is required with accuracy of 0,1 pixel. Basing on the Eq. (1) the rotation matrix $\mathbf{A}_{c,L}$ is calculated via space backward intersection, including also GPS data. Then, rotation offset $\mathbf{A}_{c,INS}$ of ADS/INS will be computed from Eq. (2).

3.3. Geometric accuracy of direct georeferencing with integrated ADS/GPS/INS system

The object positioning accuracy from direct georeferencing with integrated ADS/GPS/INS system is in influence of different sources of errors. There are three main sources of errors which strongly affect the overall integrated system accuracy [6]:

- The precision of same produced individual system of ADS, GPS, INS, DPW.
- The precision of calibration of integrated system.
- The accuracy of imaging process and photogrammetric processing.

The error components related with particular source can be depicted as follows:

- Belonging to first source there are sensor geometry and radiometry, the accuracy level of GPS, INS and DPW used to measure.
- Belonging to second source there are accuracies (errors) of interior sensor calibration, GPS/INS/ADS position offsets, INS/ADS rotation offsets.
- Belonging to third source there are errors of GPS-derived position, INS-derived orientation, stability of sensor geometry, image measurement error in DPW.

For two styles of sensor construction based on CCD linear array and CCD surface (matrix or frame) array concept, currently obtained geometric accuracies of direct georeferencing are given in table 3 and 4. Table 3 represents the geometric accuracies of ADS40 – linear array sensor, acquired in summer 2004 by Leica and IFP, University Stuttgart [2]. The test was realized from image block (4 long and 2 cross strips) with 1500m flying height. The GPS/INS trajectory information was obtained from LN200 IMU. Compared to theoretic accuracy of ±7cm and ±9cm for horizontal and vertical, respectively, it is obvious from table 3 that for direct georeferencing (zero GCP) the horizontal positioning RMSE is close to required theoretical value, but vertical component is less than factor 2 worse.

Direct georeferencing from film-images [3] was done with RMSE object coordinates for East, North and Vertical position of ±8,8cm, ±11,9cm and ±17,8cm, respectively. These accuracies are same as presented in Tab. 3 for digital images.

Table 3. Geometric accuracy of direct georeferencing from ADS40

Nr **GCP/**ChP	Accuracy	East [m]	North [m]	Vertical [m]
12/190	RMS	0.052	0.054	0.077
	Mean	0.000	0.022	0.045
	Std Dev.	0.052	0.050	0.063
	Max Dev.	0.133	0.188	0.242
4/198	RMS	0.055	0.054	0.106
	Mean	-0.008	-0.008	0.083
	Std Dev.	0.055	0.053	0.065
	Max Dev.	0.145	0.191	0.295
0/202	RMS	**0.110**	**0.086**	**0.158**
	Mean	0.094	0.064	0.142
	Std Dev.	0.057	0.056	0.068
	Max Dev.	0.242	0.256	0.351

The detail analysis of UtracamD – CCD surface array sensor done by IESSG, University of Nottingham, University Park, UK is shown in Tab. 4 [7]. The block contains of 2 strips per 9 images taken at 1500m flying height. The IMU/GPS is produced by Applanix POS 510 with positioning accuracy of ±0.05m to ±0.30m and roll & pitch rotation of ±0.005^{o}.

Table 4. Geometric accuracy of direct georeferencing from UtracamD

Strip/**GCP**	RMSE of image coor.[μm]		RMSE of GCP [m]			RMSE of ChP [m]		
	x	y	X	Y	Z	X	Y	Z
2/**12**	2.75	3.00	0.150	0.114	0.044	0.124	0.107	0.388
2/**4**	2.01	2.31	0.107	0.110	0.045	0.125	0.109	0.357
2/**0**	2.01	1.89				**0.121**	**0.112**	**0.276**

Basing on the Tab. 4 it is considered that RMSE of image coordinates is in theoretical value (±3 μm). Geometrical accuracy of direct georeferencing is not compared to required theoretical value. Only one way to explain is that fitting process into geodetic network is not very good, causing of bad identification of Ground Control Points. It is obvious that RMSE of Check Points in horizontal position has values similar to RMSE of Ground Control Points.

Next, investigation of direct georeferencing (*Kremer J., Gruber M.,* 2004) [4] also indicated that horizontal RMSE of ±14cm and vertical component of position in a range of ±23cm can be observed.

Other accuracy analysis of different sensor can be found in [2]

4. Conclusion

The potential of integrated system ADS/GPS/INS is delivering full digital data information for photogrammetric processing. The accuracy of direct georeferencing can be available to ±10cm and ±20cm for horizontal and vertical position, respectively. In order to develop better accuracy of direct georeferencing the calibrating process must be done exactly for determining position and rotation offsets between GPS, ADS and INS, ADS.

Integrated system ADS/GPS/INS support in short time date information necessary to mapping process and other thematic purposes. By such way direct georeferencing with multi-sensor ADS/GPS/INS can be competitive with high resolution satellite images.

Other advantages of multi-sensor ADS/GPS/INS for direct georeferencing are very practical in application for mountain terrain where the geodetic measurements of Ground Control Points are in very difficult conditions, sometime unavailable.

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