VISIONMAP A3 - SUPER WIDE ANGLE MAPPING SYSTEM BASIC PRINCIPLES AND WORKFLOW

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ABSTRACT:

VisionMap was established in 2004 in order to develop a new automatic mapping system. Today the system is fully operational and the paper will discuss the system design, the operational functions, workflow, and the advantages of the system. VisionMap A3 system is a fully automated mapping system. The system is comprised of an airborne digital step-framing double lens metric camera and a ground processing system. During the flight a sequence of frames is exposed in a cross-track direction at a very high speed in order to provide a very wide angular coverage of the ground, thus acquiring both vertical and oblique images. The airborne system consists of dual CCDs with two 300mm lenses, a fast compression and storage unit, and a dual frequency GPS. The scanning mechanism of the camera provides a FOV of up to 104 degrees. The post-processing system consists of a PC server configuration and software that processes the data obtained during the flight into mapping products in an automatic manner. The workflow normally carried out in a typical flight consists of the following: flight planning, aerial survey, copying images and meta-data from the camera storage unit, aerial triangulation block adjustment, digital surface model (DSM) creation, digital terrain model (DTM) creation, orthophoto and mosaic production. All the processes are executed in a fully automated mode. The technology is patent pending.

1. INTRODUCTION

Many words were said and many articles were written about digital aerial camera systems for mapping since 2000 – the de-facto beginning of the new digital aerial camera era. Today there is no question what to use in photogrammetry workflow – digital or analog cameras. We believe that there is wide acceptance that the fully digital photogrammetry workflow, including a digital aerial camera is in many senses preferable to the analog one. CCD detectors have evolved, achieving film comparable output qualities.

Since the year 2000, the development and use of digital photographic systems for photogrammetric mapping has gained momentum. Today, there are many digital aerial photographic systems intended for aerial photogrammetric use. The various systems differ by camera design, photography method, accuracy, work procedures, and the computer software which is provided with the systems.

It is possible to differentiate between digital aerial cameras according to the following characteristic features:

- small, medium or large format cameras,
- frame or push-broom cameras,
- single or multi-lens cameras,
- camera stability and system consistency,
- GPS/IMU integration,
- FMC and a stabilizing platform,
- camera weight and simplicity of installation,
- different types of workflow automation,
- accuracy.

There are advantages and disadvantages almost in every existing camera design. Many of them are optimized for specific photogrammetric tasks, such as corridor mapping or just orthophoto production.

However, some of the abovementioned features are crucial for real photogrammetric mass production:

- full automation: for triangulation, DEM/DSM and orthophoto production,
- large format and accuracy for stereo photogrammetric mapping (which remains a manual process).

We, in VisionMap, have always believed that it is possible to fully automate the processing of mapping products, while maintaining the industry standard accuracies and qualities. VisionMap A3 has achieved this goal, integrating innovative multidisciplinary technology into a mapping product.

VisionMap was established in 2004, aiming to develop a new automatic mapping system. Today the system is fully operational and the paper will discuss the system design, the operational functions, workflow, and the advantages of the system.

VisionMap A3 system is a fully automated mapping system. The system consists of an airborne digital step-framing double lens metric camera and a ground processing system. During the flight a sequence of frames is exposed in a cross-track direction at a very high speed in order to provide a very wide angular coverage of the ground. The airborne system consists of dual CCDs with two 300mm lenses, a fast compression and storage unit, and a dual frequency GPS. In the current configuration, given the aircraft installation, the scanning mechanism of the camera provides a total FOV of up to 104 degrees, but it is limited only by mechanical constraints. The post-processing system consists of PC servers' configuration and software that automates the mapping workflow. The later is comprised of: flight planning, downloading frame images from the camera storage unit, pre processing, preparation and processing tasks, aerial triangulation bundle block adjustment with self-calibration, digital surface model (DSM) creation, digital terrain model (DTM) creation, orthophoto and mosaic production. All the processes are executed in a fully automated manner. A Typical Operational Scenario is: Flight altitude - 12,000 ft, Time of flight - 4 hours, Area mapped - 2,680 square km, Ground Resolution - 12.5 cm, Number of control points – 0, RMS(xy) - 0.23 m, RMS(z) - 0.30 m, RMS(3d) - 0.38 m. Products (automatic outputs) - stereo models, DTM, DSM, color orthophoto.

The main characteristics of the system are:

- total automation of all processes (from planning the flight to orthophoto creation),
- synthetic super large format images for stereo photogrammetric mapping,
- high resolution multi-directional vertical and oblique imagery,
- the 300mm focal length enables operation at high altitudes (this is crucial in urban areas in order to support true orthophoto generation and because some countries limit the flight altitude over urban areas);
- high photogrammetric accuracy and process stability,
- a single flight yields both an orthophoto as well as accurately solved oblique and vertical images from multiple directions,
- high efficiency – for a given resolution, throughput in km^2 per hour is substantially better than with other systems that are operated at lower altitudes,
- no preliminary DTM is required,
- no ground control points are needed,
- no IMU is needed.

2. AIRBORNE MODULE KEY CHARACTERISTICS

2.1 Camera Design

A camera module consists of a frame for mounting the camera on the craft, two lenses, and a motor unit.

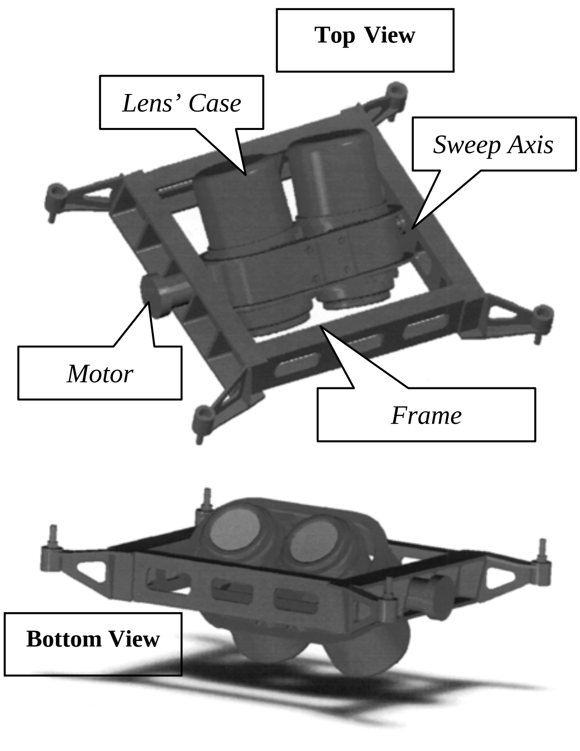

Figure 1. Camera Module Design

The lenses are sweeping simultaneously on the camera axis across a flight line direction. Sweep Motion System consists of the motor and transmission mechanism, encoder and switches, and support structure.

The camera is linked to a specially designed on-board computer, which includes:

- low power Pentium M based computer,
- GPS receiver,
- a power supply unit,
- interface to the camera module,
- removable flash type storage up to 0.5 TB,
- interface to debug console and navigator application.

CCD (dual)	Kodak KAI-11002
Single Frame Size (pix)	4006 x 2666 11 Mpix
Double Frame Size (pix, approx)	7812 x 2666 22 Mpix
Single Frames Overlap in Along-Track Direction (pix)	~ 100
Synthetic Super Large Frame for Stereo. (pix)	**62,517 x 7812 ~ 480 Mpix**
Single Lens FOV (degree)	6.9 x 4.6
Max. Sweep FOV (degree)	104
Number of Double Frames per Max. FOV	27
Sweep Time (sec.)	3-4
Color	RGB
Bit per Channel (bit)	12
Pixel size (µm)	9.0
Optics (lens)	Dual Reflective Lens System
Focal length (mm)	300
Aperture	f/4.5
Forward Motion (FMC)	Mirror based optical compensation and stabilization
Sweep Motion (SMC)	
Vibration (Stabilizer)	
Frame rate (fps)	7
Readout Rate	155 MB/sec
On-Board Compression	Jpeg2000
Data collection capacity	5 hours
Storage Type	Flash Drive
Storage capacity (GB)	500
GPS (Omni Star Supported)	Dual-frequency GPS + L-Band
Total weight (kg)	~ 30
Camera Unit Size (cm)	70 x 70 x 30
Operating temperature (°C)	-30 to + 45

Table 1. Camera technical characteristics

2.2 Optics Design

As seen in Table 1, a folded reflective optical system is used for the lenses. The lens is an optical assembly with a total focal length of 300 mm. The long focal length yields comparatively high ground resolution when flying at high altitudes, enabling efficient photography of large areas in high resolution. In addition, mirror based folding optical system considerably reduces the complete dimensions of the optic assembly.

Finally, in order to support operation in a wide range of ambient temperatures, from -30 °C to +45 °C, the optics are a-thermal (designed and manufactured to ensure minimal sensitivity to temperature changes).

2.3 Angular and Movement Stabilization

There are three different movements which affect the image quality – forward motion, sweep motion, and general vibrations of the aircraft. A unique mirror based optical compensation and stabilization method for all potential movements was developed. The traditional stabilization methods are based on using the stabilization platform for the entire camera system stabilization. In digital cameras, three methods are generally used to compensate forward motion: changing the read out time to minimize the forward motion effect, mechanical FMC for the CCD, or Time Delayed Integration (TDI).
The design implemented by VisionMap is based on using acceleration sensors, GPS data (for aircraft velocity calculation), and the motor encoders for calculation and control of the required motion compensation. Both linear and angular compensations are done by tilting the mirror mounted on the folding optics. Since the total weight and size of the mirror are small, motion compensation is performed efficiently.

2.4 On-Board Image Processing

The imagery grabbing and processing is based on real-time lossless JPEG2000 compression. Since writing raw images at the systems' bit rate exceeds the standard capabilities of a common SATA bus, on-board compression is crucial in order to enable usage of standard I/O interfaces to storage devices. The compression is done with custom made compression cards, designed to provide high performance lossless J2K compression on board, while using less than 10% of the on-board CPU resources.

3. FLIGHT OPERATIONAL ASPECTS

3.1 Image Capture Principles

The camera is mounted on the plane so that the sweep axis is along the fuselage (which is the flight direction). The two lenses of the camera sweep simultaneously across the flight direction from one side to the opposite side. The maximum sweep angle is 104 degrees. During the sweeping motion, each CCD captures ~27 frames (54 frames for two CCDs). After completing the first sweep, the lenses return to the start position and are ready for the next sweep. The sweep back time is 0.5 sec. Each CCD captures 7 frames per second (1 frame in 0.142 sec.). Therefore, a single sweep is completed in approximately 3.6 sec. The time between sweeps depends generally on the aircraft speed, flight altitude, and the required overlap between two consecutive sweeps. Some technical parameters of the flights at different altitudes are presented in Table 2.
The sweeping motion of the camera during image capture and exposure is smooth and not incremental. This is enabled by the Sweep Motion Compensation (SMC) which is carried out by the compensation mechanism described in section 2.3.
There are overlaps between the frames. Two adjacent Single Frames along the flight form one Double Frame (Fig. 2). The overlap between them is about 2% (~100 pix). The overlap between two adjacent double frames across the flight direction is about 15%. The overlap between two consecutive sweeps along the flight direction is typically 56%, but it may be different according to the defined specifications of the aerial survey. The overlap between two consecutive flight lines is generally 50% to enable stereo photogrammetric mapping. All overlaps are defined during flight planning, and may be changed during the flight. There is some shift between two adjacent double frames along the flight direction. With typical aircraft speed of about 72 m/sec (140 knots), the shift between adjacent frames along the flight direction results in about 9.6 m. The total shift between the first and the last frame in one sweep results in approximately 260 m.

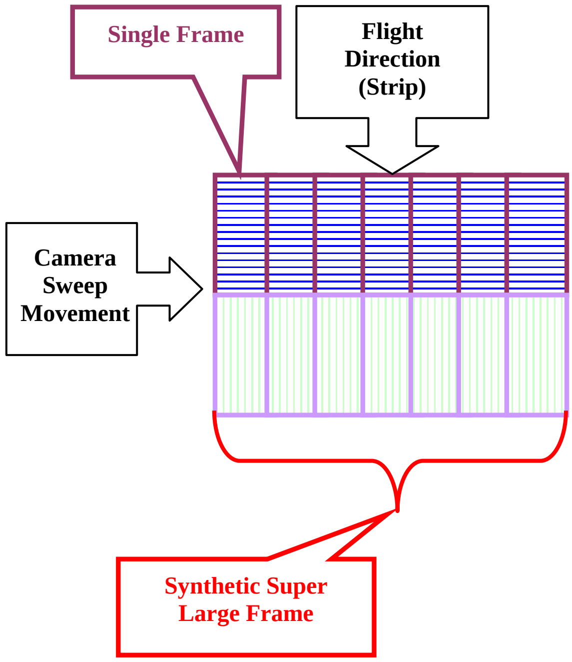

Figure 2. Flights with the VisionMap A3 Camera

3.2 Oblique Images.

As previously said, the Sweep FOV of the camera is 104 degrees. It provides orthogonal coverage of the nadir area and oblique coverage of the remainder of the sweep image. As all images participate in all stages of the analytical computations, after performing matching and block adjustment, we have accurate solutions for all images including the oblique images. The resolution for oblique images acquired from different flight altitudes is presented in Table 2.
In our opinion, the possibility to obtain accurately solved oblique images simultaneously with regular verticals is a unique and highly important feature of the A3 system.

3.3 Synthetic Super Large Frame for Stereo Photogrammetric Mapping

Synthetic Super Large Frame is composed of all double frames of one sweep (Figure 2). The size of the Super Large Frame (SLF) is 7812 pixels along the flight and 62,517 pixels across the flight direction. The ordinary overlap between two consecutive SLFs in one strip is 56%. The overlap between two SLFs in adjacent flight lines is 50%. The SLFs may be used for stereo interpretation and stereo photogrammetry map production.
The angular coverage of the SLFs is constrained by the mechanical characteristics of the platform aperture. However, in lower altitudes (lower than 9000 feet), as V/H increases, the

system decreases the angular coverage in order to maintain the inter-sweep overlap.

Map Scale	250	1,250	2,500	5,000
Photo Scale	5,000	10,000	14,000	25,000
Flight Altitude (m)	1,500	3,000	4,200	7,500
Flight Altitude (ft)	4,921	9,842	13,779	24,606
SLF' Short Side (m)	354	709	992	1,772
SLF' Long Side (m) (Swath)	1,435	7,679	10,751	19,198
SLF' Area (sq.km)	0.5	5.4	10.7	34.0
Stereo Area between Sweeps, 56%,(sq.km)	0.3 *	3.0	6.0	19.1
Stereo Area between Strips, 50%,(sq.km)	0.7	2,7	5,3	17.0
Base Ratio Between Sweeps (B/Z)	1:7.6	1:7.6	1:7.6	1:7.6
Base Ratio Between Strips (B/Z)	1:0.8	1:0.8	1:0.8	1:0.8
Nadir GSD (m)	0.05	0.10	0.14	0.25
Oblique GSD (m)	0.08	0.16	0.23	0.41

(*) – Swath for 5,000 photoscale is decreased to 1,435 m for stereo area between sweeps.

Table 2. Flight technical characteristics

3.4 Preliminary Accuracy Analysis

In traditional photogrammetry (Kraus, 1993), the accuracy of photogrammetry is defined by the base ratio, the ratio between photographic base and flying altitude, and the photo scale. As the base ratio is larger, the potential photogrammetric accuracy is higher. In Table 2 one can find important relations for photogrammetric production. As shown, the base ratio between consequently taken SLFs in two sweeps with 56% overlap is 1:7.6. The base ratio between two SLFs taken from adjacent strips is 1:0.8. The first one is in the range of the traditional base ratio for narrow lenses (f=60 cm) and the second - in the range of super wide lenses (f= 9 cm) with 56% overlap.

For expected accuracy analysis of digital images in VisionMap A3 camera the next scheme of images are taken into consideration:

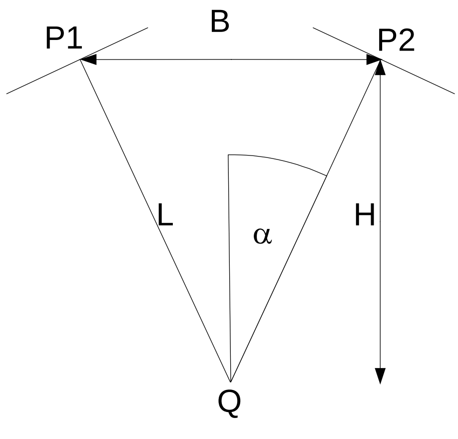

Figure 3. A scheme for accuracy analysis

Here: P1, P2 – images, H – altitude, B – photographic base, L – distance from image to ground point, α – angle between vertical direction and line L.

The following formulas were used for expected accuracy calculation:

$$\Delta x = \frac{l}{\sqrt{2}\, f \cos\alpha}$$

$$\Delta y = \frac{l}{\sqrt{2}\, f}$$

$$\Delta z = \frac{l}{\sqrt{2}\, f \sin\alpha}$$

Here, f – focal lens divided by matching accuracy.

The matching accuracy in digital photogrammetry is about 0.3 of the pixel size (Fritsch, 1995). In our case, with CCD resolution of 9μm, the matching accuracy is 3μm. The value of angle α generally depends on the base-ratio.

For the base-ratio 1:7.6, that is relevant to stereo measurements from Sweep Based Stereo Area, the angle α is 3.8 degrees. For the base-ratio 1:0.8, for the Strip Based Stereo Area, the angle α is 32.6 degrees.

Resulting accuracies for different mapping scales are presented in Table 3.

Map Scale	Photo Scale	σx	σy	σxy	σz
Base-ratio 1:7.6 between Sweeps					
250	5,000	0.01	0.01	0.02	0.16
1,250	10,000	0.02	0.02	0.03	0.32
2,500	14,000	0.03	0.03	0.04	0.45
5,000	25,000	0.05	0.05	0.08	0.81
Base-ratio 1:0.8 between Strips					
250	5,000	0.01	0.01	0.02	0.02
1,250	10,000	0.03	0.03	0.04	0.05
2,500	14,000	0.04	0.04	0.05	0.07
5,000	25,000	0.07	0.06	0.10	0.12

Table 3. Expected accuracy for different base-ratio

The following table shows a comparison between the obtained calculated accuracy and the accuracy requirements from ASPRS standard (FGDC-STD-007.3-1998) for photogrammetric works.

Map Scale	Photo Scale	σxy (m) Class 1	σxy (m) Class 2	σxy (m) Class 3
250	5,000	0.063	0.125	0.188
1,250	10,000	0.31	0.63	0.94
2,500	14,000	0.63	1.25	1.90
5,000	25,000	1.25	2.50	3.75

Table 4. ASPRS Planimetric Accuracy Requirements

As can be seen from these tables, the expected planimetric accuracy for both types of Stereo Area (Sweep and Strip), matches all the criterions of the ASPRS accuracy requirements. The abovementioned accuracy is calculated with respect to the flight altitude. The estimated accuracy figures are presented in the following table.

Base-ratio		Sweep 1:7.6	Strip 1:0.8
Flight Altitude	Photo Scale	σz	σz
1,500	5,000	0.16	0.02
3,000	10,000	0.32	0.05
4,200	14,000	0.45	0.07
7,500	25,000	0.81	0.12

Table 5. Expected Z accuracy for different base-ratio

Table 6 presents the ASPRS elevation accuracy requirements. The Strip Based Stereo Area provides Class 1 accuracies in all altitudes. The Sweep Based Stereo Area matches the requirements of Classes 2 and 3. But, naturally, it is possible to obtain images from lower flight altitude and thus to reach the Class 1 requirements. In all cases, using the Strip Based Stereo Area for stereo photogrammetric mapping is significantly advantageous, as resolution and coverage are not compromised, yet the accuracy meets Class 1 requirements.

Contour Interval (m)	0.50	1.00	2.00	2.50	4.00
Class 1 Altitude (m)	1,000	2,000	4,000	5,000	8,000
Class 2 Altitude (m)	1,100	2,200	4,400	5,500	8,800
Class 3 Altitude (m)	1,250	2,500	5,000	6,250	10,000
Class 1, σz (m)	0.08	0.17	0.33	0.38	0.67
Class 2, σz (m)	0.16	0.33	0.67	0.75	1.33
Class 3, σz (m)	0.25	0.50	1.00	1.25	2.00

Table 6. ASPRS Elevation Accuracy requirements

4. GENERAL WORKFLOW

4.1 Workflow Supported by the System

The workflow supported by the system consists of aerial and ground segments operation. The aerial segment includes the following components:

- VisionMap A3 camera and dual frequency GPS,
- A pilot flight management system,
- A camera computer system for managing aerial survey processes. This computer manages the activity of the camera, carries out on-board testes, changes camera settings, and executes automatic exposures. The system reports to the operator or to the pilot about errors or faults in task execution and makes it possible to repair the faults on the fly. The system enables viewing of the collected images during the flight.
- Data collection system with removable FD storage.

After the landing, the FD storage with GPS data, meta-data and images are taken to the processing system.
The ground segment consists of two sub-systems:

1. A pre-flight application for aerial flights planning and an immediately post-flight application for preliminary data processing.
2. A processing sub-system includes:
   a. A WEB-based process management application to manage and monitor the processing workflow and to enable parallel processing and prioritization of multiple tasks and projects.
   b. The automated photogrammetric application, used for image matching, block adjustment, DSM/DTM generation, orthophoto and ortho mosaic production.

Significant advantages of the system are multi tasking and scalability. Multi-core processors are used to process multiple projects and tasks in parallel. The user may define new groups of computer resources. Utilization of additional computers may be done instantaneously.
This workflow and the system design provide a highly efficient workflow that is able to process very large areas that consist of hundreds of thousands of image frames.

4.2 Processing Workflow

After the landing, the images and meta-data are transferred to the processing station for the next stage:

1. The project is formed according to the properties defined in the flight plan,
2. GPS data preprocessing is carried out, using standard DGPS or PPP methods,
3. The area of interest is specified. The system can also retrieve previous flights in order to cover the area of interest.
4. Preliminary (coarse) matching for flight lines is carried out. QA is done to confirm that raw material for the area of interest is available and adequate.
5. Accurate block adjustment is carried out. In this stage, if it is necessary, Ground Control Points (GCP) may be used. The QA may be done versus existing blocks or with extra control points. Accuracy report is compiled.
6. DSM and DTM are calculated (optional).
7. Super Large Frames are calculated and exported (optional). Each SLF is solved and provided after radiometric correction.
8. Orthophoto is calculated. The process includes a rectification, mosaicing, and radiometric correction. All the processes are executed automatically. A final image is provided in TIFF format.
9. The products are stored in the internal storage system.

A status and progress of all processes are reported to the management module.

4.3 Final Products

The processing system is designed to provide high performance processing of the imagery obtained during the flight. The products of the processing system are:

1. Accurately solved single images (vertical and oblique) of the area of interest. The solution for each image is the result of the photogrammetric bundle block adjustment with self-calibration.
2. SLF - Super Large Frame. The synthetic image covers a large area and is useful for stereo photogrammetric mapping.
3. DSM – Digital Surface Model. The DSM is calculated in high resolution and may be provided at 30-50 cm density.
4. DTM – Digital Terrain Model. The DTM is generated from DSM for orthophoto production.

5. Orthophoto with the resolution up to the source frame resolution. Global and local radiometric correction is applied to all frames. The mosaicing process is fully automated and is based on the topographic data (DSM) and radiometric analysis of the area.

5. AERIAL TRIANGULATION ACCURACY

After Matching, block adjustment is carried out. In order to achieve high accuracy, all images and coordinates of projection centers, obtained by GPS, take part in the simultaneous bundle block adjustment with self-calibration. No INS is required.
As a huge number of single frames are obtained, with significant overlaps between them, a huge amount of common bundles are yielded. This leads to very high redundancy and robustness of the solved system and, therefore, to high final accuracy and to solution stability.
The system was tested in many projects (over 30,000 sq.km). Below are typical results of one of them (altitude – 12,000 ft, area – 2,680 sq.km, number of single images -6,700, ground resolution – 12.5 cm, **without Ground Control Points**):

Check Points	**Dx**	**Dy**	**Dz**	**Lxy**	**Lxyz**
P1	-0.20	0.02	-0.06	0.20	0.21
P2	0.10	-0.04	0.11	0.11	0.15
P3	-0.19	0.07	-0.09	0.20	0.22
P4	-0.17	-0.09	-0.16	0.19	0.25
P5	0.43	0.04	0.74	0.43	0.85
P6	-0.13	-0.24	-0.44	0.27	0.52
P7	-0.03	-0.03	-0.20	0.04	0.21
P8	-0.14	0.05	-0.17	0.14	0.22
P9	-0.12	-0.15	-0.30	0.20	0.35
P10	0.07	-0.28	-0.21	0.29	0.35
P11	-0.14	-0.11	-0.13	0.18	0.22
AVG:	**-0.05**	**-0.07**	**-0.08**	**0.20**	**0.32**
RMS:	**0.18**	**0.13**	**0.30**	**0.23**	**0.38**

Table 7. Automatic Block Solution Accuracy

6. CONCLUSIONS

This paper presented the operation and workflow of A3. The main advantages of the system, as presented, are:

- Total automation of all processes,
- Oblique and vertical multi-directional images,
- Super Large Images,
- Operation in high altitudes,
- No ground control needed,
- Designed to handle urban areas with high-resolution,
- Inherently (almost) true orthophoto,
- Light weight and simple air craft installation,
- Industry standards accuracies

In practical terms, the utilization of A3 provides the following advantages:

1. Lower data production cost
   - Full automation, even in urban areas,
   - Very high area coverage rate reduces drastically the flight/operation cost,
   - No need to buy DTM for rectification purposes.
2. Lower cost of operation
   - Coverage rate reduces sensitivity to weather conditions,
   - Less planes/cameras cover more area,
   - High flight altitude provides more flexibility to fly over urban areas.
3. Integrated DTM/DSM capability – supports automatic ortho-rectification.
4. Integrated mosaicing capability – automatic optimal cut-line selection in dense urban areas.
5. Integrated geo-registered oblique imagery provides extra value.
6. Super Large Frames for stereo models enable efficient and accurate stereo mapping.
7. All in one – from autonomous imagery, through automatic solution, toward accurate orthophoto and map production.

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