

## The New Vision Map A3 Airborne Camera System

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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 frame metric camera and a ground processing system. During the flight, sequences of frames are 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 rotating mechanism of the camera provides a FOV of up to 104 degrees. The post-processing system consists of a PC server configuration and VisionMap software that processes the data obtained during the flight into mapping products in an automatic manner. The typical workflow 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 with radiometric correction. All the processes are executed in a fully automated mode.

### 1. INTRODUCTION

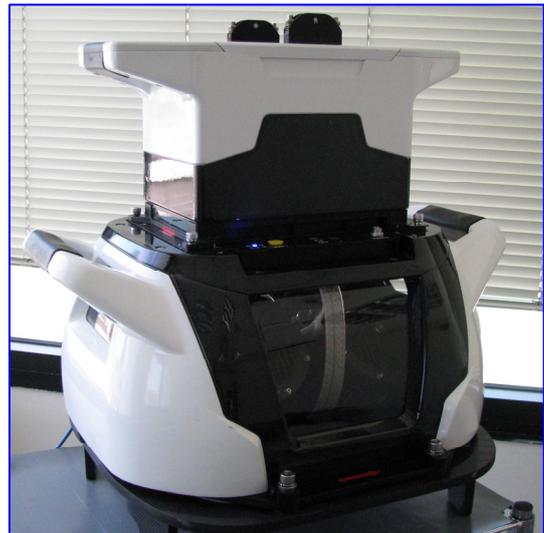
Many words were said and many articles were written about digital aerial camera systems for mapping since 2000 – the de-facto beginning of the new digital aerial camera era. Today there is no question whether to use analog or digital cameras for the photogrammetry. We believe that there is wide acceptance 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, aerial survey productivity, accuracy, workflow, computer software and computational productivity.

In our opinion, the following features are required in order to achieve photogrammetric mass production:

- aerial survey automation and high productivity,
- fully automated workflow: from triangulation through DEM/DSM to orthophoto production,
- high computation and processing productivity,
- large format and high accuracy frames for stereo compilation (which remains a manual process).

Vision Map's philosophy is that it is possible to fully automate the photogrammetric workflow, while, on the one hand, the industry standard accuracies and qualities are maintained, and on the other hand high aerial survey and calculation productivity is achieved. VisionMap A3 has achieved this goal, integrating innovative multidisciplinary technology into a photogrammetric workflow. An



emphasis was put into generating highly efficient, productive aerial survey and mapping system. The design was motivated by the need to reduce flying and processing cost.

VisionMap A3 is a fully automated aerial survey and mapping system. The system consists of an airborne digital rotating double lens frame metric camera and a ground processing system. During the flight, sequences of frames are 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 and given the aircraft installation, the scanning mechanism of the camera provides a total FOV of more than 100 degrees. The 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,
- preprocessing, 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 with radiometric correction,
- super large frame (SLF) creation.

All the processes are executed in a fully automated manner.

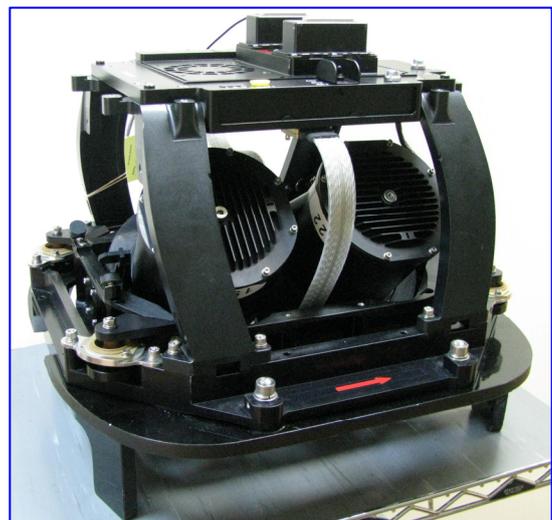
The main characteristics of the system are:

- high productivity both in aerial survey and in processing: for a given resolution, throughput in  $\text{km}^2$  per hour is substantially better than with other systems that are operated at lower altitudes,
- total automation of all processes (from flight planning to orthophoto creation),
- super large format (SLF) images for stereo compilation,
- high resolution multi-directional accurately solved vertical and oblique imagery. All images participate in the block adjustment and receive equally accurate exterior orientation parameters, that enable their immediate automatic utilization in the urban monitoring GIS systems.
- high photogrammetric accuracy and processing stability,
- fully integrated automatic orthophoto production workflow,
- operation in large range of flying altitudes (high altitudes yielding high resolution is crucial for urban areas and TMAs because of flight altitude limitations)
- no preliminary DTM is required,
- no ground control points are needed,
- no IMU is needed.

## 2. AIRBORNE MODULE

### 2.1. Camera Design

The camera module consists of a frame for mounting the camera on the aircraft, two lenses, and a motor unit. The lenses sweep cross-track simultaneously. The Sweep Motion System consists of the motor and transmission mechanism, encoder and switches, and support structure. The camera is linked to a custom made on-board computer.



|  |  |
|--|--|
| CCD (dual)   | Kodak KAI-11002  |
| Single Frame Size (pix)  | 4006 x 2666; 11 Mpix                                   |
| Max. Sweep FOV (degree)  | ~100   |
| Sweep Time (sec.)  | 3-4  |
| Color  | RGB  |
| Bit per Channel (bit)  | 12 pre LUT, 8 post LUT                                 |
| Pixel size ( $\mu\text{m}$ )   | 9.0  |
| Optics (lens)  | Dual Reflective Lens System                            |
| Focal length (mm)  | 300  |
| Aperture   | f/4.5  |
| Forward Motion (FMC)<br>Sweep Motion (SMC)<br>Vibration (Stabilizer) | Mirror based optical<br>compensation and stabilization |
| Frame rate (fps)   | 7.4  |
| Readout rate   | 155 MB/sec   |
| Compression  | Jpeg2000   |
| Data collection capacity (hours)                                     | 5  |
| Storage Type   | Flash Drive  |
| Storage capacity (GB)  | 400  |
| GPS (Omni Star Supported)  | Dual-frequency GPS<br>+ L-Band                         |
| Camera Unit Size (cm)  | 50 x 50 x 40   |

Table 1: Camera technical characteristics.

## 2.2. Optics Design

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, a mirror based folding optical system considerably reduces the complete dimensions of the optic assembly.

## 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 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

Imagery grabbing and processing is based on real-time lossless JPEG2000 compression. Since writing raw images at the system's bit rate exceeds the standard capabilities of common SATA hardware, 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 real-time lossless JPEG2000 compression onboard. It is possible to view and analyze captured images on the fly and to modify aerial survey parameters accordingly.

### 3. GROUND PROCESSING SYSTEM

The ground processing system is tightly coupled with the camera. The main features of the ground processing system were influenced by the following requirements:

- The camera acquires thousands of square kilometers of high resolution imagery in one day. The ground processing system should be capable of processing such areas into mapping products within few days.
- The ground processing system should be fully automatic in order to maintain the superior imagery acquisition efficiency of the camera.
- The processing should rely on well known photogrammetric methods, in order to ensure accuracies. As a result of the camera design, bundle adjustment with significant number of frames should be possible.
- QA should not be a bottleneck in the processing workflow and should commensurate to the large amount of imagery data.
- Self calibration is required in order to provide accurate mapping products.

As a result, the design of the ground processing system provided the following:

- Scalable parallel computing processing. The scalability allows the user to utilize more computers in order to obtain better performance. Experiments carried out with a typical hardware configuration showed that 1000 sq. km in 12 cm GSD are processed, forming a bundle adjustment, SLF stereo pairs for mapping and an orthophoto within approximately two days.
- The system is automatic. After a pre-process stage, in which the user specifies the required outputs and the output parameters, all the photogrammetric processes (matching, block adjustment, DSM, DTM and orthophoto) are executed automatically. The exterior orientation of the block is based on the GPS coordinates of the projection centers of every image. For most projects, the accuracy that is achieved without ground control points ("direct georeferencing") is sufficient. However, there are tools that enable adding ground control points to the solution.
- The entire processing is purely photogrammetric. In order to ensure accuracy and robustness, all images, vertical and oblique, participate simultaneously in the bundle adjustment with self calibration. Robustness is provided by maximizing the number of tie-points: a typical bundle adjustment of 1000 sq. km contains millions of tie points.
- As the system is fully automatic, a comprehensive set of QA reports is provided to the user. This set includes textual, visual and geographical reports, allowing the user to concentrate the QA effort only in areas requiring attention, thus providing shorter QA phases.

## 4. FLIGHT OPERATIONAL ASPECTS

### 4.1. 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. During the sweeping motion, each CCD captures up to 29 frames (58 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 0.3 sec. Each CCD captures 7.4 frames per second (1 frame in 0.135 sec.). Therefore, a single sweep is completed in approximately 4 sec. The time between sweeps depends generally on the aircraft speed, flight altitude, and the required overlap between two consecutive sweeps.

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 earlier.

There are overlaps between the frames. Two adjacent Single Frames along the flight form one Double Frame (Fig. 3). The overlap between them is about 2% (~100 pix). The overlap between two adjacent double frames across the flight direction is about 30%. The overlap between two consecutive sweeps along the flight direction (forward overlap) is typically 30-60%. The overlap between two consecutive flight lines (side overlap) is generally 50-60% or more to enable stereo photogrammetric mapping and to ensure high photogrammetric accuracy. All overlaps are defined during flight planning, and may be changed during the flight.

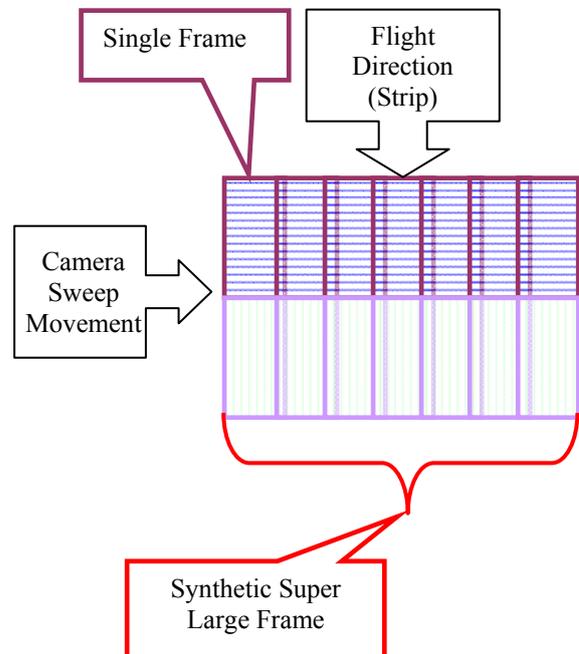


Fig. 3: Flights with the VisionMap A3 Camera.

### 4.2. Oblique Images

One sweep provides 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 possibility to obtain accurately solved oblique images simultaneously with regular verticals is a unique and highly important feature of the A3 system enabling immediate utilization of all accurately georeferenced images in GIS systems.

### 4.3. Synthetic Super Large Frame for Stereo Photogrammetric Mapping

Synthetic Super Large Frame is composed of all single frames of one sweep (Fig. 3). The size of the Super Large Frame (SLF) is 7812 pixels along the flight and 62,517 pixels across the flight direction at maximal number of frames. The ordinary forward overlap between two consecutive SLFs in one strip is of about 30-60%. The side overlap between two SLFs in adjacent flight lines is 50-60% or more. 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) and higher velocities, as V/H increases, the system decreases the angular coverage and the number of single frames in one sweep in order to maintain the forward overlap.

| <b>Altitude above ground (m)</b> | <b>1,700</b> | <b>5,000</b> | <b>10,000</b> |
|----------------------------------|--------------|--------------|---------------|
| Typical velocity (knot)          | 120          | 250          | 360           |
| GSD at nadir (cm)                | 5            | 15           | 30            |
| GSD at oblique (cm)              | 5.3          | 18.1         | 43.0          |
| Forward Overlap (%)              | 40           | 55           | 60            |
| Side Overlap (%)                 | 60           | 62           | 62            |
| FOV (deg)                        | 39           | 68           | 92            |
| SLF' Height (m, along flight)    | 394          | 1,180        | 2,361         |
| SLF' Width (m, across flight)    | 1,319        | 7,411        | 22,240        |
| <b>SLF' Area (sq. km)</b>        | <b>0.53</b>  | <b>9.65</b>  | <b>63.78</b>  |

Table 2: SLF technical characteristics.

## 5. GENERAL WORKFLOW

### 5.1. 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 and/or operator navigation and 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 Flush-memory storage. After the landing, the storage unit 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 flight data QC and preliminary data processing.
2. A processing sub-system, which includes:
  - 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, as well as computer resources management.
  - The automated photogrammetric application, used for image matching, block adjustment, DSM/DTM generation, orthophoto and orthomosaic production and radiometric corrections. The status and progress of all processes are reported to the management module.

Significant advantages of the system are multi tasking and scalability. Multi-core processors are used to process multiple tasks and projects 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 images.

## 5.2. 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:

- Accurately solved single vertical and oblique images. The solution for each image is the result of the photogrammetric bundle block adjustment with self-calibration.
- SLF – Super Large Frame. The synthetic image covers a large area and is useful for stereo photogrammetric mapping.
- DSM – Digital Surface Model. The DSM is calculated in high resolution and may be provided at 30-50 cm density.
- DTM – Digital Terrain Model. The DTM is generated from the DSM for orthophoto production.
- Orthophoto – global and local radiometric correction is applied to all frames. The mosaicing process is fully automated and is based on the topographic data (DTM) and radiometric analysis of the area.

## 6. TESTING AND EVALUATION

### 6.1. Visionmap's Test Field

A test field for the experimental and evaluation purposes was established in an area which spreads from Netania to Hedera cities (Fig. 4). The area is about 22 by 12 km. 27 well defined control points were measured in the test field. The control points are situated in the urban and rural area and cover the area evenly. All control points were measured by GPS with an accuracy of  $\pm 5$  cm. The test field is a slightly hilly area with altitudes from 0 to 70 m. There are urban areas with middle and high buildings in the south and north part of the test field. Vegetation - garden types. And additional large set of control points includes well defined points from large scale photogrammetric mapping. The accuracy of these photogrammetric points is about 20 cm.

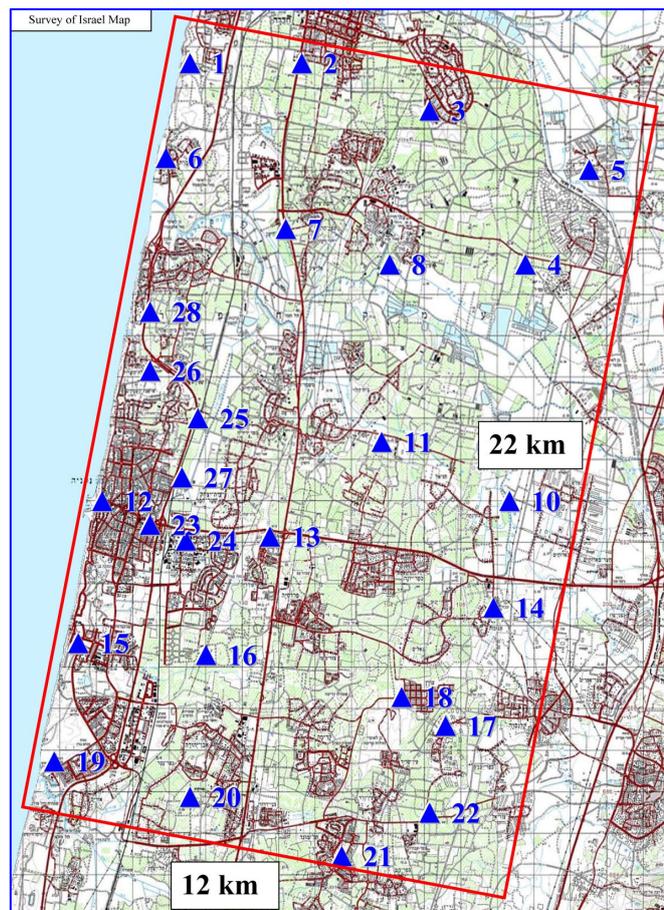


Fig. 4: Visionmap Test-Field.

## 6.2. 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 practical and experimental projects (over 50,000 sq. km). Table 3 presents some adjustment results which have been achieved at the Visionmap test field.

| Test Field | Altitude (feet) | Area (sq. km) | GSD (cm) | Strips | GCP/ChP | RMSx (m) | RMSy (m) | RMSz (m) |
|------------|-----------------|---------------|----------|--------|---------|----------|----------|----------|
| Netania    | 12,000          | 195           | 11       | 8      | 0/22    | 0.30     | 0.27     | 0.26     |
| Netania    | 12,000          | 195           | 11       | 8      | 11/11   | 0.19     | 0.11     | 0.23     |
| Netania    | 28,000          | 247           | 26       | 7      | 0/27    | 0.54     | 0.44     | 0.47     |
| Netania    | 28,000          | 247           | 26       | 7      | 11/14   | 0.21     | 0.35     | 0.44     |

Table 3: Aerial triangulation accuracy.

In all cases GCP = 0 means that the block adjustment was executed without control points. No cross strips were used.

## 7. AERIAL SURVEY PRODUCTIVITY

One of the most important features of the A3 system is its very high aerial survey productivity. In comparison with other analog and digital large frame cameras, the A3 productivity is larger in 2-5 times. The next table shows aerial survey productivity calculations for different GSDs and typical aerial survey flight plans:

| <b>GSD at nadir (cm)</b>                        | <b>5</b>   | <b>15</b>    | <b>30</b>    |
|---|------------|--------------|--------------|
| Altitude above ground (m)                       | 1,700      | 5,000        | 10,000       |
| Typical aircraft velocity (knot)                | 120        | 250          | 360          |
| Allowable orthophoto angle ( $2\alpha$ , °)     | 20         | 35           | 50           |
| Forward Overlap (%)                             | 40         | 55           | 60           |
| Side Overlap (%)                                | 60         | 62           | 62           |
| Orthophoto side overlap (%)                     | 10         | 10           | 10           |
| <b>Aerial survey productivity (sq. km/hour)</b> | <b>157</b> | <b>1,313</b> | <b>5,595</b> |

Table 4: Calculated aerial survey productivity.

In Table 4, the allowable orthophoto angle ( $2\alpha$ ) means a maximal allowable FOV for orthophoto generation. Generally, the angle's value depends on the required mapping accuracy, DEM accuracy and a character of the relief. The orthophoto side overlap means the overlap between orthophoto strips (which are defined by allowable orthophoto angle) from consecutive parallel flight lines. This area generally serves to eliminate gaps between strips and for orthophoto cut lines creation.

Table 5 shows practical results from several projects flown recently with A3 camera.

| <b>Project</b>                                      | <b>V1</b>  | <b>V2</b>    | <b>V2</b>    | <b>O1</b>  | <b>O2</b>    | <b>O3</b>  | <b>O4</b>  |
|---|------------|--------------|--------------|------------|--------------|------------|------------|
| <b>GSD (cm)</b>                                     | <b>11</b>  | <b>26</b>    | <b>26</b>    | <b>14</b>  | <b>14</b>    | <b>14</b>  | <b>14</b>  |
| Flight Altitude, (average, m)                       | 3,600      | 8,500        | 8,500        | 4,400      | 4,400        | 4,400      | 4,400      |
| Aircraft velocity (average, knot)                   | 184        | 221          | 221          | 190        | 180          | 181        | 172        |
| Aerial survey area (sq.km)                          | 195        | 247          | 247          | 700        | 900          | 2,100      | 3,100      |
| Number of strips                                    | 8          | 7            | 4            | 8          | 6            | 15         | 22         |
| Side overlap (average, %)                           | 57         | 84           | 66           | 70         | 70           | 70         | 70         |
| Gross flying time (hour)                            | 0.67       | 0.50         | 0.28         | 1.02       | 0.95         | 2.68       | 4.35       |
| Net flying time (aerial survey, hour)               | 0.27       | 0.20         | 0.11         | 0.72       | 0.82         | 2.15       | 3.28       |
| Gross aerial survey productivity (sq.km/hour)       | 291        | 494          | 882          | 686        | 947          | 783        | 712        |
| <b>Net aerial survey productivity (sq.km/hour)</b>  | <b>722</b> | <b>1,235</b> | <b>2,245</b> | <b>972</b> | <b>1,097</b> | <b>977</b> | <b>945</b> |
| Theoretical published net productivity (sq.km/hour) | 701        | 1,228        | 2,552        | 970        | 939          | 944        | 887        |

Table 5: Practical aerial survey productivity.

The projects V1-V3 were pilot projects executed by Visionmap. The projects O1-O4 were flown by Ofek Aerial Photography Ltd., as part of a country wide orthophoto production project.

It has to be mentioned that technically, A3's FMC mechanism supports any practical aircraft speed, even in low altitudes. In addition, the system provides flexibility to balance the swath width with the speed of flight and altitude. However, above certain altitudes, there is no practical speed limitation (because the system is able to maintain the maximum swath at any speed).

From the point of view of productivity, this enables users to use high speed aircrafts at high altitudes to achieve extremely high aerial survey productivity.

For example, for a country wide orthophoto project with 30 cm GSD: an A3 camera installed on a Learjet aircraft with cruise speed of 460 knot and a ceiling of 13,700 m, each hour of flight will yield 7,100 sq. km of imagery for orthophoto.

## 8. PROCESSING PRODUCTIVITY

A3 is one of the first end to end mapping systems. Great effort had been invested in tight integration of the camera to the processing system, in order to provide users an efficient end to end workflow. Therefore, a discussion of the processing efficiency of the system is required.

However, accurate productivity comparison between different processing systems is difficult because of two reasons: – different systems use different combinations of processing software and hardware, – there are very few publications on this subject.

During the execution of the abovementioned projects, all processes were timed and recorded. The processing includes the following sub-processes: GPS processing, matching, block adjustment, orthophoto generation, mosaicing and radiometric corrections. All the processes were carried out in a fully automatic mode without any user intervention. Additionally, for the productivity and accuracy examination in dependence of the side overlap, block V2 was processed twice: – for all 7 strips with 82% side overlap, – and for just 4 strips ( 1,3,5,7 strips) with 67% side overlap. Both blocks cover the same area.

The standard HP cluster that is supplied as part of the A3 system consists of 5 blades with 8 CPU cores in each blade. However, all the processing projects that are detailed in table 6 utilized only 21 CPU cores in 3 blades. The time results are shown in next table:

| Project   | V1        | V2        | V2        | O1        | O3        |
|---|-----------|-----------|-----------|-----------|-----------|
| Orthophoto resolution (cm)                            | <b>12</b> | <b>30</b> | <b>30</b> | <b>15</b> | <b>15</b> |
| Flight Altitude (average, m)                          | 3600      | 8500      | 8500      | 4400      | 4400      |
| Orthophoto area (sq.km)                               | 195       | 247       | 247       | 700       | 2100      |
| Number of strips                                      | 8         | 7         | 4         | 8         | 15        |
| Side overlap (average, %)                             | 57        | 84        | 66        | 70        | 70        |
| Maximal allowable orthophoto angle (deg)              | 35°       | 22°       | 44°       | 39°       | 39°       |
| Independent processing time (hour)                    | 9h 15m    | 7h 55m    | 4h 01m    | 31h 15m   | 133h      |
| Simultaneous processing time (hour)                   | 11h 31m   |           | -         | -         | -         |
| Independent processing productivity (sq.km/24 hours)  | 506       | 749       | 1482      | 538       | 379       |
| Simultaneous processing productivity (sq.km/24 hours) | 1133      |           | -         | -         | -         |

Table 6: Practical processing productivity.

The average processing productivity for 12-15 cm GSD orthophoto production is about 500 sq. km per day. For 30 cm GSD – it is about 1,500 sq. km per day. The processing productivity depends on the computer system resources and the block parameters.

## 9. CONCLUSION

This paper presents the operation, workflow and practical evaluation of Visionmap's A3 aerial survey and mapping system. The main advantages of the system are:

- Very high aerial survey and processing productivity,
- Oblique and vertical images in one flight by one camera,
- Fully automatic orthophoto production (including all computational processes),
- Super Large Frames for stereo compilation,
- Large range of flying altitudes,
- No ground control and no IMU needed,
- Light weight and simple air craft installation.

The utilization of A3 provides the following practical advantages:

1. Aerial survey cost reduction:
  - Pre-flight preparation time is reduced;
  - Total flight time is reduced;
  - Maximal utilization of flight hours with good weather;
  - Very effective high resolution aerial survey in urban area and TMA zones;
  - Reduction in number of planes, cameras and project execution time;
  - Overall simplification of aerial survey logistics.
2. Photogrammetric processing cost reduction:
  - Fully automatic triangulation, DTM, orthophoto and mosaic;
  - Very high processing productivity;
  - One program processing workflow;
  - Computer system scalability;
  - Parallel execution of multiple projects;

- Generally – no need for control points;
- Effective stereo-compilation with SLFs.

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