

## Oblique Aerial Imagery – A Review

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### ABSTRACT

Oblique airborne photogrammetry is rapidly maturing and entering the workflow of service providers which are trying to complement (or replace) the more traditional pipeline based only on vertical images. Many applications embrace the advantages of airborne slanted viewing geometry which comes close to human perception of scenes while standing on the ground. The paper gives an overview on the properties of oblique airborne images, the most common configurations and applications, the processing pipeline, open research issues as well the on going ISPRS / EuroSDR benchmark.

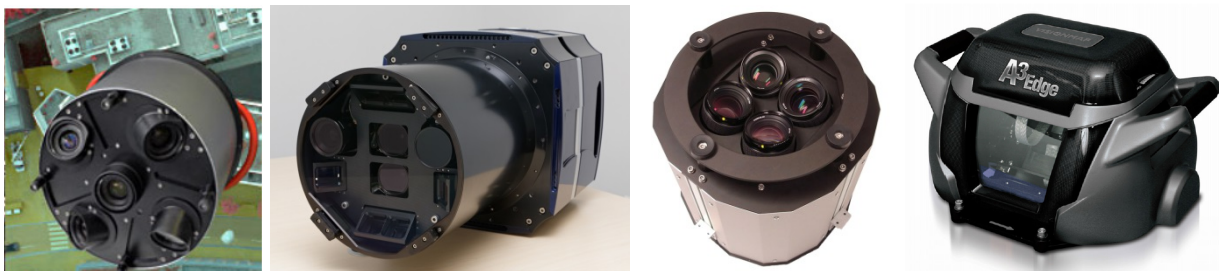


Figure 1: Example of commercial oblique multi-camera system.

### 1. INTRODUCTION

The use of oblique imagery is becoming almost a standard in many civil and mapping applications, thanks to the development of airborne digital multi-camera systems (Fig. 1). Most of the National Mapping and Cartographic Agencies (NMCAs) still rely on the traditional workflow based on vertical photography but changes are slowly taking place also at production level. The indisputable virtue of oblique photography lies in its simplicity of interpretation and understanding and in the fact that they can reveal building façades and footprints. Consequently, it becomes easier for non-expert users to interpret the data as it is more associative of what is seen from the ground. This allows the use of oblique images in very different applications: road land updating (Mishra et al., 2008), building registration and preliminary parcel boundary determination (Lemmens et al., 2008), urban classification and 3D city modelling (Gerke and Xiao, 2013; Nex et al., 2013), identification of unregistered buildings (Fritsch and Rothermel, 2013), mass events' monitoring (Grenzdoerfer et al., 2008), damage assessment (Gerke and Kerle, 2011; Murtiyoso et al., 2014), etc.

To be able to use a block of oblique imagery on a large scale, existing processing workflows must be adapted and commercial tools are currently hurrying up to provide reliable processing chains. Image scale variations (function of image tilt, sensor size, focal length and flying height), large displacements in off-nadir views and variation of radiometry in an image block are some causes of actual difficulties in processing large blocks of aerial oblique images. So far, a combined bundle adjustment including all cameras' parameters, carried out in an automatic fashion, is quite a difficult - if not unsolved - task (Wiedemann and More, 2012; Rupnik et al., 2013).

In this article, after a review of the most common commercial oblique multi-camera systems, the entire photogrammetric pipeline is reviewed with some open research issues stated in the conclusions of the paper.

## 2. CAMERAS AND TECHNOLOGIES

The actual oblique multi-camera systems come under different configurations, varying the sensors number, format, arrangement, mode of acquisition, spectral sensitivity, etc. (Table 1). Review and state-of-the-art of oblique systems are reported in (Karbo and Schroth, 2009; Petrie, 2009; Lemmens, 2014a,b; Rupnik et al., 2015). We can distinguish between:

- *Maltese-cross configuration*: it is the most common and it consists of a single nadir camera and four cameras tilted towards cardinal directions by 40 – 50°. This configuration can host small-, medium- and large-format frame cameras.
- *Fan configuration*: it mainly comes as twin cameras, with the most innovative solution offered by VisionMap (A3 sensor): it is a sweeping frame system which captures up to 64 images per sweep, corresponding to a field of view of 109° (Vilan and Gozes, 2013).
- *Block configuration*: it arranges cameras in a block and, similarly to the fan systems, a sufficient overlap between individual frames allows for rectification and stitching to form a single near-vertical frame of rectilinear shape. A typical example of such configuration was the first generation Z/I DMC cameras, with four medium format cameras on-board, merged in post-processing into a large-format PAN frame. Other examples are Trimble AIC x4 and IGI DigiCam Quattro which are not really oblique multi-camera systems but they can be adapted to become oblique systems.

System	Type	# sensors	Geom. Res. [px]	Pix. size [μm]	Spectral bands	Focal length [mm]
Leica RCD30 Oblique	MC	4+1	10320 x 7752	5.2	RGB, NIR	50 / 80
Vexcel Osprey 2	MC	4+1	11674 x 7514 8900 x 6650	6	RGB, NIR	80 / 120
Dimac Oblique	MC	4+2	(2x) 13000 x 8900 (4x) 7600 x 8900	6	RGB	55 / 210
Pictometry	MC	4+1	2672 x 4008	9	RGB	65 / 80
Midas 5	MC	4+1	5616 x 3744 (Canon EOS-1D) 7360 x 4912 (Nikon D800E)	6.4 4.8	RGB	27/ 90
IGI DigiCAM Penta	MC	4+1	7304 x 5487 8176 x 6132 8959 x 6708 (Hasselblad)	6.8 6 6	RGB, CIR	50 / 80
IGI Quattro DigiCam Oblique	B	4		80 / 300		
Optron/Trimble AIC	B	4	7228 x 5428 (RolleiMetric)	6.8	RBG, CIR	60 / 100
VisionMap A3 Edge	F	2	4864 x 3232 (Kodak)	7.4	RGB, CIR	300

Table 1: Primary commercial oblique multi-camera systems. MC = Maltese Cross; F = Fan; B = Block.

### 3. PHOTOGRAMMETRIC PROCESSING

#### 3.1. Automated tie point extraction

Interior and exterior parameters of aerial images are nowadays normally known a priori, as retrieved with a prior calibration procedure or measured directly with on-board sensors (GNSS/IMU), respectively. Nevertheless, these parameters are generally regarded as approximate if one has metric and automatic applications in mind, therefore an adjustment in a least squares sense is a must. Although precise direct geo-referencing, particularly for oblique images, is still in the future, the current solutions allow at least for approximate measurements, for instance in monoplottting-based applications. Having learnt close-range practices in convergent and unordered terrestrial image blocks, methodologies were adopted and adjusted accordingly. The main obstacle to be overcome is the generation, in a reasonable time, of putative correspondences between overlapping images. Sets (pairs, triplets, etc.) of images which maximize their similarity are normally matched against each other using descriptor/detector operators (e.g. SIFT). Those sets of images are identified with the help of GNSS/IMU information and with a connectivity graph (Rupnik et al., 2014). A connectivity matrix highlights the spatial relationships between the images, speeds up the extraction of image correspondences and reduces the number of possible outliers. The connectivity between images refers to a graph with nodes and edges being representations of images and their relationships, respectively. Two images are linked with an edge if and only if they are spatially compatible. Generally there are three conditions to be fulfilled for an image pair to be regarded as compatible and to use the extracted correspondences in the successive bundle adjustment: (i) their ground footprints coincide by a given percent; (ii) cameras' viewing directions are similar or one of the camera is nadir; (iii) the number of extracted homologous points for the pair is above a given threshold.

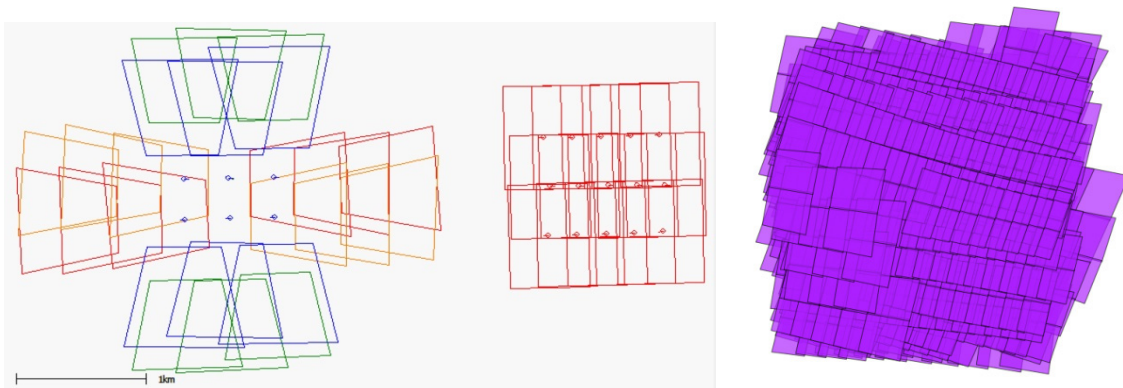


Figure 2: Different block footprints for aerial multi-camera systems: Maltese-cross (left) versus fan (right).

#### 3.2. Image triangulation (bundle adjustment)

Outliers in the image observations could lead to inaccurate results. Moreover the complex network's geometry of oblique image blocks and the non-linearity of collinearity model enforce the need of good initial approximations for all unknown parameters. The bundle adjustment with a multi-camera system must handle different cameras with different interior (IO) and exterior orientation (EO) parameters. The camera parameters can be retrieved without constraints - i.e. each image is oriented using an independent EO for each acquisition - or with additional constraints - i.e. equations describing the relative rotations and displacement between cameras are added to the mathematical model, lowering the number of unknowns and stabilizing the bundle solution (Rupnik et al., 2013). One prerequisite, however, to make this an efficient constraint is a synchronous camera triggering, which cannot always be guaranteed, especially in semi-professional systems.

Additionally, the IO of each camera can be assumed known from a lab calibration or simultaneously computed in the bundle solution with a self-calibration. The large observation redundancy in oblique images (Fig. 3) is helping in selecting the best correspondences and to achieve high accuracy in 3D reconstructions.

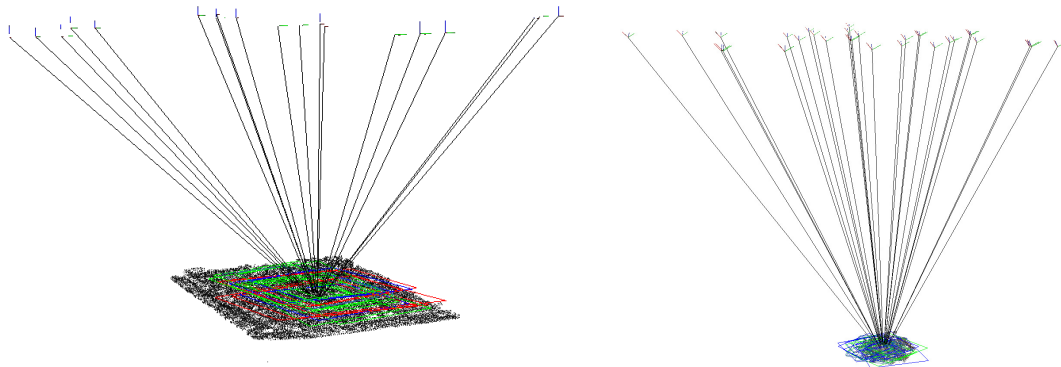


Figure 3: Example of observation redundancy for a Maltese-cross (left) and fun (right) oblique camera system.

### 3.3. Dense image matching

Oblique images provide information for a deeper and more complete description of urban areas, allowing to extract denser point clouds and more information in the ‘smart city’ domain, with façades and buildings typically completely reconstructed (Fig. 4). Mismatches or wrong reconstructions can still be present as: (i) objects (building, roads, etc.) are captured with different scales, (ii) the number of occluded areas normally increase due to the different looking directions, (iii) the depth and image GSD vary much more compared to vertical images, leading to relatively large disparity search spaces, (iv) the smaller intersection angles and baseline between images make the point cloud generation more sensitive to noise. To overcome some of these issues, higher overlap flights are highly suggested - although they lead, beside some higher costs, to larger datasets and higher number of point clouds to be further processed and visualized.



Figure 4: Example of dense point clouds from oblique datasets. Shaded view produced with MicMac from a MIDAS dataset (left) and colour cloud obtained using SURE on a PentaCam IGI dataset (right).

### 3.4. 3D city models

Many municipalities maintain (or are starting to produce) 3D city models. Oblique images can be employed in many ways in this context. First of all, façade information are retrievable from oblique airborne images and can be used to augment existing geometric models (e.g. coming from LiDAR

sensors), at least for texturing. Oblique imagery can also be used for further interpretation and inspections, e.g. to derive the number of floors or building usage (e.g. commercial, housing, or mixed). For more detailed modelling, e.g. in LOD3 according to the cityGML standard (architectural models), details along the façade and on lateral parts on the roof can be extracted. This is feasible in software which uses a dense matching point cloud as input, or – for higher accuracy and detail – uses the images directly, such as ImageModeler (Autodesk) or Tridicon (3DCon). In Figure 5 an example is given, showing a 3D model derived from oblique images over Enschede, The Netherlands.

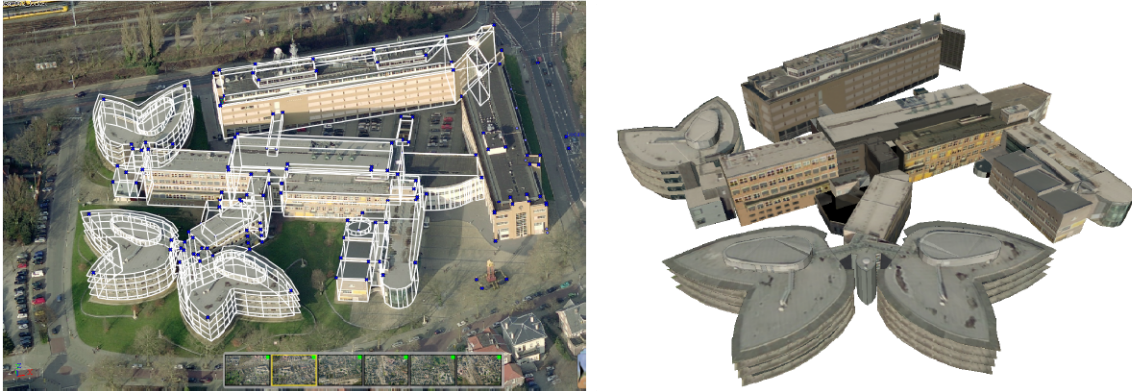


Figure 5: 3D building modelling in Autodesk ImageModeler. Image © Blom.

### 3.5. Monoplotting

In applications where only approximate measures are required, monoplotting in oblique images might be an adequate tool. Using only one image and a pre-existing terrain model, distances in horizontal and vertical direction can be computed and CAD-like models can be produced. In particular, the fact that façades are visible in airborne oblique images makes them attractive for height measurements. The principle is sketched in Fig. 6 (left): the terrain point  $T$  of an observed point  $T'$  in the image is computed by intersecting the viewing ray (defined by the projection centre and  $T'$ ) and the terrain model. The vertical distance  $dh$  above  $T$  is computed by scaling the observed  $dr'$  with the scale at  $T$ .

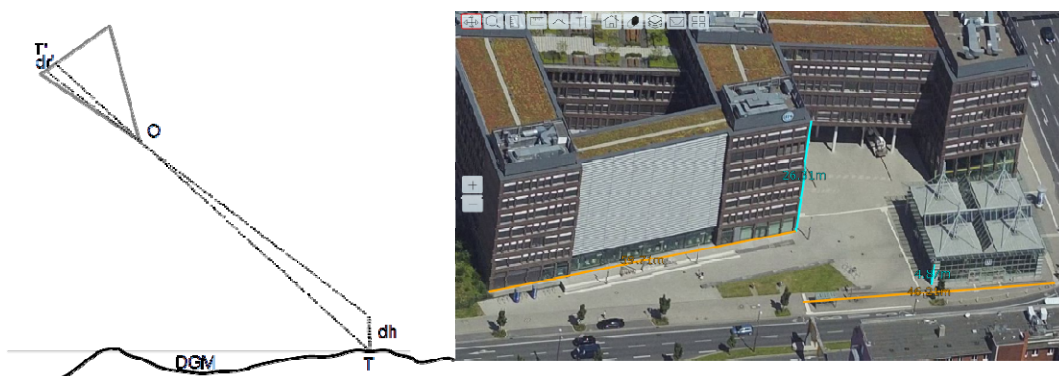


Figure 6: Monoplotting principle (left). Screenshot from the Idansoft Oblivision viewer – image © Aerowest: horizontal (orange) and vertical (light blue) distances extracted with the tool (right).

Fig. 6 (right) shows an example from the online Oblivision viewer by Idansoft (<http://www.idansoft.com>) which allows to easily extract horizontal and vertical measures of man-

made objects. Similar tools are available, for example, from Orbitgt (<http://www.orbitgt.com>) or Overit (<http://www.overit.it/en>).

#### **4. THE ISPRS / EUROSDR BENCHMARK**

In the research community a common way to evaluate new platforms, data and algorithm is to prepare and share benchmarks. The success and visibility of some benchmark activities - like the Middlebury test on dense image matching (<http://vision.middlebury.edu/stereo>), the ISPRS WGIII/4 test on urban object detection and 3D building reconstruction (Rottensteiner et al., 2013), the KITTI suite for mobile robotics and autonomous driving research (Geiger et al., 2013) or the image matching benchmark promoted by EuroSDR (Haala, 2014) – show that the provision of common datasets, in combination with a scientific task, allow researchers to objectively compare their own methods with those of others and to identify common problems and open challenges. Inspired by these concepts, within an ISPRS Scientific Initiative and in collaboration with EuroSDR, a benchmark was proposed with the aims of creating and managing a new image dataset for the research community, consisting of different typologies of images over the same (built-up) area. The aims of the benchmark are (i) to provide data on different areas, focusing on different terrain and building style and epochs and (ii) to assess the accuracy and reliability of the current methods in the calibration/orientation as well as integration of those data for dense point cloud generation and feature extraction.

##### **4.1. Data sets and deliverables**

The project (Nex et al., 2015) deals with the acquisitions and processing of different datasets (on two test areas) consisting of: airborne oblique images, covering all 4 cardinal and the nadir directions and acquired with an IGI PentaCam camera (flown by Aerowest); nadir and oblique UAV images, acquired with a multi-rotor DJI S800; convergent and redundant terrestrial images (of some selected buildings); ground truth data in form of Airborne Laser Scanning (ALS) and Terrestrial Laser Scanning (TLS) point clouds as well as topographic and GNSS-based points. Since the data will be open, other research topics, like investigation into radiometry of multi-view images (BRDF) or semantic analysis is expected and appreciated as well. The evaluation of the orientation results are performed using primarily check points (CKs). The dense point clouds delivered by participants will be compared to ground truth data (plane fitting, cross-sections, etc.) following the methodology described by Cavegn et al. (2014). A dedicated webpage has been implemented on the ISPRS website ([http://www2.isprs.org/commissions/comm1/icwg15b/benchmark\\_main.html](http://www2.isprs.org/commissions/comm1/icwg15b/benchmark_main.html)). Any participant can download the available data after a registration procedure.

#### **5. THE EUROSDR QUESTIONNAIRE**

In order to better understand the current practice and possible needs of users with oblique multi-camera systems, in 2014 EuroSDR initiated a survey on the current status of oblique airborne imagery (Gerke and Remondino, 2014). The questionnaire went online in spring 2014 for about 6 months. The questionnaire differentiated between users of oblique imagery and vendors of systems (hardware and software) or services. Almost 150 persons participated in the survey, 11 of them from the group of vendors. The majority of participants (45%) was from academia, followed by National Mapping Agencies NMAs (21%). In most of the questions, both groups, users and vendors, agree largely with their answers. The potential usage beyond simple visualization or texturing of city models, is for instance in building mapping. This might be attributed to the fact

that the majority of users comes from academia and NMCAs. Dense image matching is another of the applications seen most relevant as facades are mostly visible and therefore complete buildings could be matched and reconstructed in 3D. The users were also asked which general tasks can be done better if oblique airborne images got used. Given the multiple selections, the majority of participants (71%) ticked “easier identification of objects”, a result which fits quite well with the general property of those images i.e. an easy recognition and identification of buildings and other elevated objects. Only 40% of the answers expect an increase in automation, which seems quite pessimistic, whereas around 60% expect an increase in reliability.

## 6. CONCLUSIONS

The paper presented an overview of current aerial multi-camera systems, including the processing pipeline for delivering 3D metric information e.g. for mapping purposes. Oblique imagery is nowadays a powerful source of geodata with various applications and potential, particularly over urban areas. As reported, oblique imagery allow:

- an easier (or improved) object identification and readability of geographical information;
- the generation of denser 3D point clouds, also on vertical elements, with higher reliability with respect to traditional vertical acquisitions;
- the measurement of heights, lengths and areas of features directly from the single images;
- the quick generation of true-orthophotos;
- an extension of traditional 2D GIS data.

Additional costs of oblique flights, especially additional flight lines, might be compensated by these additional outcomes and benefits.

We can hereafter summarize the current open research issues related to multi-camera systems and oblique imagery:

- scale and radiometric changes (BRDF);
- correct and fast identification of homologues points, also across viewing directions;
- processing time;
- redundancy / overlap exploitation;
- fusion of point clouds coming from different viewing directions (and with different accuracy);
- automation in interpretation, especially for complex architectures.

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