

# IMAGE PROCESSING WORKFLOW FOR THE PEGASUS HALE UAV PAYLOAD

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## ABSTRACT:

The PEGASUS High-Altitude Long-Endurance (HALE) Unmanned Aerial Vehicle (UAV) system has two major operational modes: (a) large-scale regional photogrammetric and environmental mapping and (b) near real time event monitoring. Given the concept of the HALE UAV camera design (decimetre resolution RGB), a massive data stream of about 0.5 to 1.0 TB/day is expected. The Central Data Processing Centre (CDPC) installed at VITO shall archive the incoming image data into self-descriptive Level1 HDF5 files containing all metadata for further processing. At the CDPC the Level1 data can be further processed towards higher levels upon user request. Typical standard products can be: orthorectified and atmospheric corrected single images (Level2) and orthophoto mosaics (Level3). Upon user request, custom product generation schemes can be integrated in the product generation workflow. This paper presents an overview of the CDPC with respect to the user requirements, product levels, functional flow, hardware system, workflow design, algorithmic components and product distribution issues.

## 1. INTRODUCTION

The PEGASUS (Policy support for European Governments by Acquisition of information from Satellite and UAV borne Sensors) initiative, initiated by VITO (The Flemish Institute for Technological Research) in 2000, is based on very specific user needs, i.e. the need for image data of decimetre resolution for (a) large-scale photogrammetric and environmental mapping applications and (b) for event-monitoring purposes. This inherently requires a better coverage both in the space and time domain than current platforms can deliver.

In response of these user needs, VITO proposes to use a High-Altitude Long-Endurance (HALE) Unmanned Aerial Vehicle (UAV) as innovative platform to conduct remote sensing from. This choice is based on following advantages of HALE UAV systems: (a) longer mission lengths than traditional airborne systems, (b) continuous observation at high update rates of target spots, (c) high resolution imagery combined with regional coverage, (d) flexible trajectories (operates where there are no clouds) and (e) better photogrammetric quality by operating at high altitude since there is less geometric distortions due to smaller view angles.

The first phase of the PEGASUS program is focused on proving the feasibility of the proposed concept by demonstrating and validating the behaviour of all system components, i.e. the HALE UAV platform, the payload, the Ground Control Station and the Central Data Processing Centre (CDPC).

This paper deals with the general design of the CDPC, its processing workflows, algorithmic components and product distribution concepts.

## 2. DESIGN CENTRAL DATA PROCESSING CENTRE

### 2.1 Requirement analysis

All CDPC requirements originate from the following user needs: (1) the need for recurrent availability of decimetre resolution imagery for regional/national mapping (e.g. to update the vector databases of road infrastructure, buildings, etc.) and (2) the need for near real-time availability of high resolution imagery in support of security monitoring and disaster management.

The former user need implies very strict requirements with respect to the positional accuracy. Due to the advances in navigational sensors such as GPS and Inertial Measurement Unit (IMU) other imaging geometries than the classical frame camera systems can be used for photogrammetric applications, such as pushbroom line scanners (e.g. ADS40) and whiskbroom point scanners (often used in hyperspectral imaging, such as AHS160, HYMAP). The perspective geometry of a line scanner is interesting since such images only show perspective in the direction transversal to the direction of flight and the images are orthographic along this direction. However, since every line is a separate image, it will be very difficult to reconstruct an image with a decent positional accuracy upon failure of the GPS/IMU system. Because of this critical dependency on accurate exterior orientation measurements in the case of point or line scanners, a frame type of imaging was chosen for the HALE UAV sensor system.

The latter user need imposes that the sensor system must be equipped with navigational sensors (GPS and IMU) to enable, via direct georeferencing, a smooth and instant integration with the GIS expert systems of the end user. The CDPC shall thus create in near real-time true or false colour imagery, which is orthorectified, and this at a resolution and compression suitable for data transfer for the application at hand.

Because the HALE UAV will operate at elevations between 14 and 18 km, the positional uncertainty after applying direct georeferencing by means of a dGPS corrected GPS time series and a Kalman filtered IMU time series, is still in the order of meters. Since photogrammetry will be one of the major application types of the Pegasus HALE UAV imagery, and because the positional accuracy is then one of the critical factors, a frame sensor will be used for the Pegasus payload. This type of imagery allows for a more straightforward processing in commercial aerotriangulation software.

Products of photogrammetric quality can thus not be produced in near real-time. Furthermore, the incoming data flow is too large to provide a routine (semi-automatic) aerotriangulation service. Since such services will be carried out in post-processing, this requires a self-descriptive archive file format that contains all information for further processing.

Because virtually all customers of VITO use earth observation derived material for environmental related issues (amongst others: food security, vegetation dynamics, spatial epidemiology, land use and land cover mapping, indirect mapping of potential soil pollution, etc...), the product generation modules must be compliant to very specific user requirements with respect to the models used to convert the raw sensor digital numbers to physical quantities. Given that photogrammetric camera products are more and more used in time series analysis (change detection), attention must be given to the spectral issues. In cloud-prone regions, it can be quite difficult to obtain a regional coverage (both in the space and time domain) of cloud-free imagery. For many applications, to obtain this full coverage, one is often forced to merge data from different sensor types. Radiometric calibration and atmospheric correction algorithms are thus essential topics to deal with in multi-mission and/or multi-temporal analyses. These issues shall be taken care of in the development of the CDPC.

**2.2 Product levels**

The product levels are defined in Table 1. Since the image metadata is as important as the image data, it was chosen to use a self-descriptive file format to enforce that the metadata is physically stored with the image data. Given the facts that (1) HDF\* is a self-descriptive format, (2) HDF is the standard archive format at and Earth Observing System Data Gateway (EOS)\*\*, (3) development of the library is maintained by the National Center for Supercomputing Applications (NCSA), (4) both Windows and Unix platforms are supported, (5) lossless compression can be embedded in the HDF file format and (6) non-standard data types are possible (e.g. 13-bit integer), the HDF format was chosen as standard archive format. Compared with HDF4, the HDF5 library is more scalable, has an improved data model, and is more robust. Consequently, the HDF5 format appears to be the most suitable format for archiving the PEGASUS imagery.

Level 0	Product featuring missing image data and/or image metadata.
Level 1A	Raw user product – Level 1A data products are reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters,

\* <http://hdf.ncsa.uiuc.edu/>

\*\* <http://edcimswww.cr.usgs.gov/pub/imswelcome/>

	e.g., platform ephemeris, external and internal sensor orientation parameters, computed and appended but not applied. A bitmap quick look is added to the archive file.; any and all communications artifacts, e.g. synchronization frames, communications headers, duplicate data are removed.
Level 1B	Raw user product – Level 1B archive files have the same structure as Level 1A files. Platform/sensor exterior orientation is enhanced using GPS base station information. Consequently, the Level 1B file is a completely self-descriptive file, enabling for a full radiometric, atmospheric and geometric correction.
Level 1C	Raw user product – Level 1A/1B data annotated with additional in-situ measurements.
Level 2	User product – Level 2 data products are geometric and atmospheric corrected sensor values of individual scenes. The projection system and projection datum depends on the user request.
Level 3	User product – Level 3 products are variables mapped on uniform space-time grid scales, usually with some completeness and consistency and are the result of combining multiple scenes to cover the user’s region of interest.
Level 4	User product – Level 4 data products are model output or results from analyses of lower level data, e.g. variables derived from multiple measurements. The product is not necessarily a map, but can also be a table or figure.

Table 1. CDPC product levels.

The CDPC is currently able to mass-produce Level1A/1B and Level2 imagery. Level3 and Level4 products (such as orthorectified image composites, true-ortho image composites, surface models, segmented/classified images) are still to be generated by commercial software packages. However, it is foreseen to further automate and integrate the higher level product generation algorithms in the CDPC.

**2.3 Functional analysis – CDPC Workflows**

The incoming imagery originates from a calibrated frame camera system. According the preliminary design of the UAV camera system, an IMU and GPS will be installed on the sensor, which will generate the exterior orientation parameters necessary for direct georeferencing. Within the focal plane of this camera, multiple CMOS frames will be mounted. The sensor preliminary design indicates a panchromatic frame and a RGB frame.

Figure 1 presents a scheme of the concept functional flow of the software system to be installed at the CDPC. From that figure it can be derived that there will be three major workflows: (1) a Level1 product generation workflow (archiving workflow), (2) a dGPS workflow and (3) a Level2/3/4 product generation workflow (processing workflow).

The “archiving workflow” shall produce in near-real-time self-descriptive Level1 image files from the incoming sensor data streams. These files shall contain all relevant metadata besides the image data, such as: sensor interior orientation, sensor exterior orientation, boresight angles, raw and dGPS corrected IMU time series, sensor spectral response curves, rectified quick-looks. The production of self-descriptive Level1 files allows for (a) near real-time image consultation by the end-user after data acquisition and (b) delivers a start point for Level2/3/4 product generation (i.e. a further value-adding of the raw imagery).

A “dGPS/IMU workflow” corrects the incoming IMU time series for drifts by using base-station GPS time series. This

workflow which takes as input already archived files (Level 1A) and updates by dGPS correction the exterior orientation parameters stored within these archived files. The status of the archived files is then updated from Level 1A to Level 1B.

The “processing workflow” shall be capable of generating user configurable products. Level2/3/4 products will only be generated on-demand and not on a continuous basis (except in the framework of dedicated service contracts).

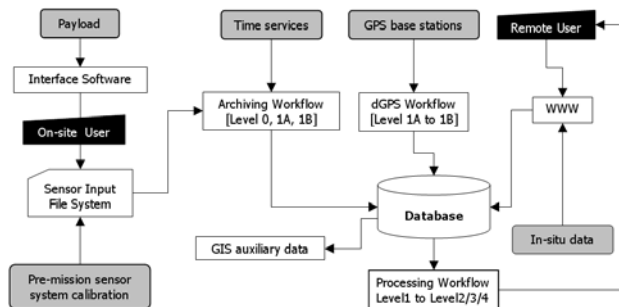


Figure 1. CDPC concept functional flow diagram.

## 2.4 CDPC hardware system

Currently, the CDPC hardware system is a dedicated cluster of 20 dual processor machines (3 GHz Intel XEON). The hard disk arrays are connected via iSCSI interfaces and the partitions are managed through the Linux LVM (Logical Volume Management) software, which allows for on-line (i.e. without having to shutdown the CDPC software system) enlargement of the available storage. The preferable operating system is Linux, however, for some dedicated third party software (e.g. Applanix POSPAC) the Windows operating system is necessary.

## 2.5 CDPC workflow design patterns

Given the volume of the expected data stream, introducing parallelism is inevitable to comply the user requirement of near-real-time product availability. For the CDPC software system, it was decided to combine the task/data decomposition pattern in combination with a master/worker program structure pattern to implement concurrency (Mattson, 2004).

Choosing for third party middleware packages to implement concurrency still requires job construction and job dependency to be programmed. Generally, third party middleware packages include a supervisor unit. The supervisor controls the workstation farm centrally, and has to perform following tasks: (1) load balancing, (2) collect the accept/reject decisions from the workstations, and (3) system monitoring and management. Third party middleware software typically distributes jobs over the workstations that perform the jobs by spreading them evenly according to the computing power of the workstation: job pushing. The supervisor is thus a complex central point. As a result, it is difficult to avoid the supervisor from being a potential bottleneck performance-wise and reliability-wise. Since there is a wealth of third party software, it is a challenging task to pick that software that will fit our future hardware and operating system layout. Furthermore, the middleware must constantly be upgraded to follow the quickly changing hardware/operating system evolutions.

An alternative for a central managed job pushing system is *job pulling*: the workstations can be made to request jobs from a job-queue at the moment they have got the CPU power

available to process another job. Job pulling has the following advantages over job pushing: (a) load balancing, (b) fault tolerance and (c) simplicity.

*Load balancing*: The load on a workstation strongly depends on the characteristics of the images being analyzed. These characteristics only become clear during the image analysis. Job pulling results in a load-balancing scheme that takes the CPU load of each workstation into account. In case of job pushing, this is significantly more complex: the component that sends the job, typically has little information to determine the load of the workstation to which the job is pushed. Mechanisms that make the load information available to the supervisor are complex and will require third party middleware software. Job pulling inherently allows these differences in CPU time to be taken into account. Furthermore, it automatically adapts to the computing power of the workstation.

*Fault tolerance*: Workstations that have crashed are unable to request further jobs. Therefore, the load is automatically balanced over the remaining workstations that are operational. In case of job pushing, the supervisor needs a mechanism to determine whether workstations are operational or not.

*Simplicity*: In case of job pulling, no details of the CPU power of the different workstations, or the types of jobs they are executing need to be known to the supervisor. Nor does the supervisor need to know which workstations it is supervising, and whether they are operational or not.

Given all upper considerations, following decisions were made: (a) third party middleware shall not be used to schedule the jobs, and (b) a job pulling strategy will be implemented conform the master/worker pattern using Java. The latter encompasses:

- The production of a very lightweight platform independent Java “worker” (i.e. they contain no intelligence, they simply look for jobs and launch the C++ programs on the client to do the processing).
- The production of a platform independent Java “master” which decomposes the problem at hand in parts that can be executed concurrently (according the task/data decomposition pattern) and determines the dependency of all these smaller parts.
- The production of a lightweight platform independent Java “management tool” which can communicate with all running workers and the master on a subnet over a socket. This software module is intended to present the workflow operator, a quick overview of the workflow status.

## 3. CDPC ALGORITHMIC COMPONENTS

### 3.1 dGPS correction

The dGPS processing workflow takes as input already archived files (Level 1A) and updates the raw exterior orientation parameters stored within these archive files. After the dGPS correction the archive files are labelled as Level 1B. The workflow is designed conform the master/worker pattern and is permanently scanning the database for level 1A files and GPS base station files. When relevant data sets are found, the raw IMU time series is corrected towards a so called “Smoothed Best Estimated Trajectory” (SBET) file.

The algorithmic core of the dGPS workflow is constituted by the Applanix POSPAC software package.

For missions in Flanders, the workflow is organized to automatically retrieve data from the FLEPOS GPS base station network (Figure 2). For missions in remote areas, the mobile GCS will be configured as a GPS reference station.

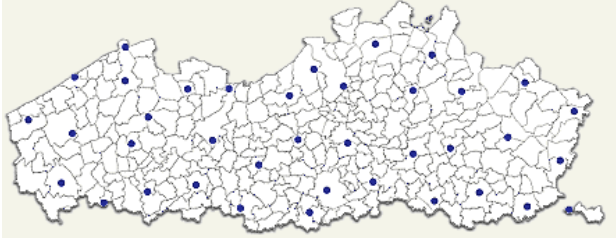


Figure 2. FLEPOS GPS base stations ([www.flepos.be](http://www.flepos.be)). The mean distance between the base stations is 17 km.

### 3.2 Direct georeferencing

Direct georeferencing (DG) is the direct measurement of the position (by means of a GPS) and orientation parameters (by means of an IMU) of a sensor (Abdullah, 2004) and it is a technique increasingly used in airborne mapping applications because of its economical advantages (Honkavaara, 2004). For the validation of the DG methodology, ADS40 (pushbroom line scanner), CASI2 (pushbroom line scanner), CASI550 (pushbroom line scanner), AHS160 (whiskbroom point scanner), HYMAP (whiskbroom point scanner) and DSS (frame CCD camera) images were used.

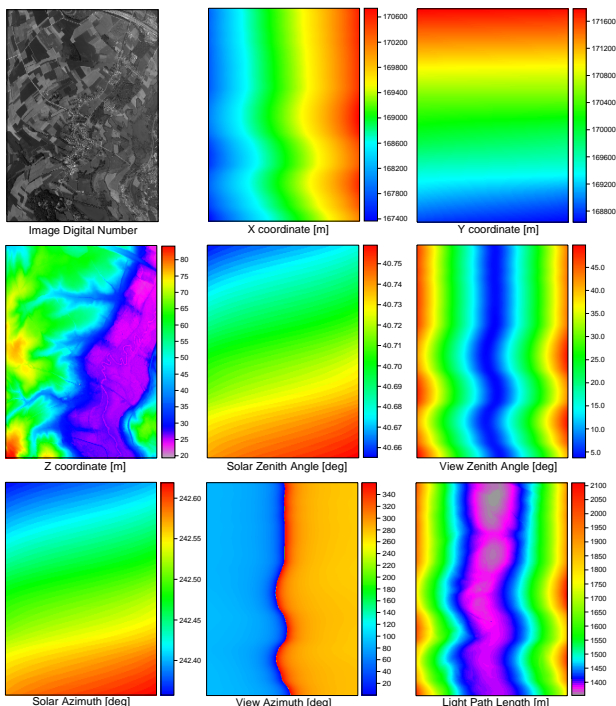


Figure 3. Output of the CDPC direct georeferencing module.

Figure 3 presents a graphical overview of the output of the DG orthorectification module integrated in the CDPC. The output grid features 8 information layers, containing all pixel dependent position and viewing geometry parameters of importance for the atmospheric correction of the observed

radiance. All these data layers are stored in the Level2 HDF5 product file.

### 3.3 Atmospheric correction

The objective of any atmospheric correction is the extraction of physical earth surface parameters such as reflectance, emissivity and temperature (Richter, 2004). The solar radiation on the top of the atmosphere is known, the at-sensor radiance is measured and the atmospheric influence on radiances is traced back by a radiative transfer code (RTC) and finally the surface radiance of each pixel on the earth surface is calculated. Within the CDPC, the MODT RAN4 RTC model (Berk et al., 1999) is integrated. With respect to the physical and technical details of the procedure, reference can be made to De Haan and Kokke (1996), Berk et al. (1999) and The (2000). The latter references contain an elaborated description how an RTC can be used to calculate correction coefficients to determine the at-surface reflected and emitted radiation for land and the sub-surface reflected radiation for water.

The integrated atmospheric correction technology is equivalent with the ATCOR4 theory (Richter, 2004) and is internally identified by the term WATCOR4. WATCOR4 contains an extension of the ATCOR4 model, which generates better atmospheric correction results over salt and fresh water bodies. Full reference can be made to The (2000) for the technical details concerning this atmospheric correction model.

After the geometric correction, the orientation of every pixel relative to the sun and the sensor position is known (see figure 3). Based on these orientation parameters and the optional in-situ measured atmospheric parameters, MODTRAN4 can be configured and executed, resulting in the necessary information to apply the correction. If spectral measurements are available of clearly identifiable targets, atmospheric corrected imagery can be iteratively created by the CDPC operators. In such iterative process, MODTRAN4 parameters describing the atmospheric composition (e.g. visibility, water vapor content and aerosol type) are altered to better describe the atmosphere, and this is done until the calculated target reflectance is in good accordance with the measured reflectance.

The geometry is pixel-dependent. In principle the atmospheric correction should be performed for each pixel independently, but this is not practically possible with respect to the necessary amount of computing time. As a workaround one often uses look up tables (LUT): these are produced by running the RTC for a discrete set of samples in the geometry space and saved to disk. Later in the atmospheric correction the LUT is combined with an interpolation technique. LUT values depend on the atmospheric state and are sensor-dependent due to the specific spectral bands. Hence, the LUT approach is non-generic. Therefore, the atmospheric correction in the CDPC is equipped with a direct interpolation method: for each image and each spectral band, a number of samples is taken from the relevant geometry space, for these samples a number of RTCs are executed just before the atmospheric correction, which is performed by interpolating the RTC results in the geometry space.

Hence, the CDPC does not use the traditional approach of a LUT, but performs the atmospheric correction “on the fly”: during the image processing MODTRAN4 configuration files are created, the needed parameters are determined by the given image geometry and possible in-situ measurements, the

MODTRAN4 runs are performed and finally the MODTRAN4 output is used to calculate the atmospheric correction using the approach of The (2000).

To enable a correct correction in the water absorption bands, the methodology of Rodger and Lynch (2001) is integrated. In the absence of in-situ observations, this algorithm determines the columnar water vapor concentration. This information is then used in the subsequent atmospheric correction.

Figure 4 presents an example of the at-sensor radiance and at-surface reflectance output by the CDPC and ATCOR4 for a pixel located in a forested area of an AHS160 image and processed with the same MODTRAN4 RTC configuration parameter values. Although the CDPC atmospheric correction algorithms are based on ATCOR4 methodology, it differs from ATCOR4 in the way the MODTRAN4 RTC is used. ATCOR4 uses a LUT, while the CDPC atmospheric correction component configures and runs MODTRAN4 ‘on-the-fly’. Consequently, the CDPC atmospheric correction module can generate image specific geometry parameters, which might result in slightly different results.

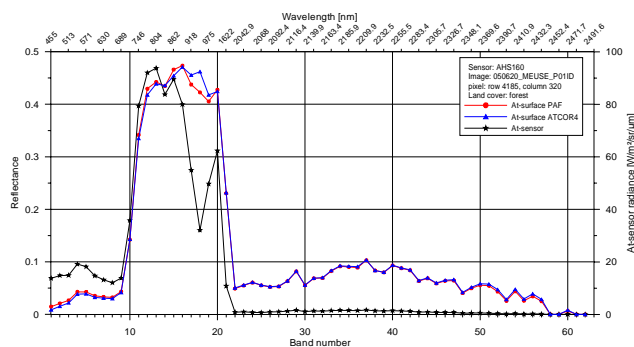


Figure 4. At-sensor radiance and at-surface reflectance output by the PAF and ATCOR4 for a pixel located in a forested area of an AHS160 image (AHS160 hyperspectral imagery acquired during the “2005 group shoot” funded by the “Belgian Science Policy” BELSPO).

The ATCOR4 LUT has a limited number of dimensions (generally 7 dimensions): sensor elevation, relative azimuth, solar zenith, view zenith, water vapor, visibility and aerosol type. Since MODTRAN4 has about 176 tunable parameters, the major advantage of running MODTRAN4 ‘on-the-fly’ is that in principle all 176 parameters can be customized. Consequently, all MODTRAN4 functionality becomes available for the research expert operating the CDPC.

#### 4. PRODUCT DISTRIBUTION

Level 1A/1B products will be made by default, however, given the massive incoming data stream, Level 2, 3 and 4 products will be created upon user-demand and are thus not produced on a continuous basis.

For the time being, the main mechanism for product distribution will be (a) the WWW interface towards the image database allowing for querying the product catalogue and (b) FTP for product downloading.

It might be possible that for some higher level products the portal towards the product database will be hosted by the

official governmental distribution centres in Flanders. Via ‘web services’ the CDPC database can then be queried.

Currently, it is also being evaluated how the CDPC can be plugged in a Sensor Web (Botts et al, 2006). UAV borne sensors can form important information sources during monitoring or disaster management applications. If these sensors can be plugged into a Sensor Web, the life of the end-user can be eased since he/she has not to query every sensor system separately but can query the sensor web for relevant information, allowing for simultaneous querying of all available sensor systems in his region of interest. This configuration will be evaluated and demonstrated by VITO in a forest fire monitoring application within the framework of the FP6 (European Commission, Sixth Framework Programme) project OSIRIS “Open architecture for Smart and Interoperable networks in Risk management based on In-situ Sensors”.

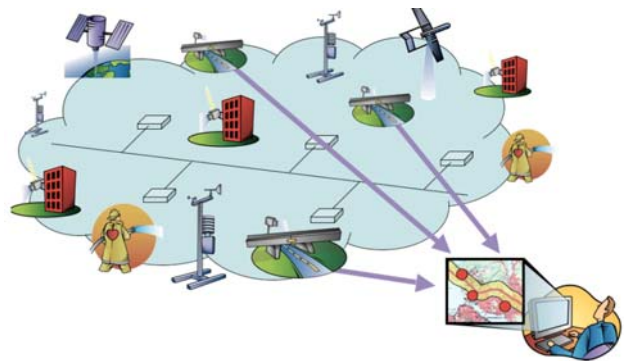


Figure 5. Conceptual diagram of a Sensor Web configuration (from Botts et al, 2006)

#### 5. CONCLUSIONS, THE FUTURE OF RS

The CDPC can handle all currently available digital aerial sensors such as hyperspectral pushbrooms or whiskbrooms and photogrammetric frame cameras. The CDPC is heavily dependent on the DG method for its georeferencing. If good quality LIDAR DEMs or DSMs are available and the image resolution is in the order of meters, pixel or sub-pixel accuracy can be obtained with dGPS corrected IMU time series.

However, if the resolution of the imagery is in the order of decimetres, DG is currently not enough. Block bundle adjustment, automatic tie-point generation algorithms and surface model generation method are needed to generate products of photogrammetric quality that can be used in high precision mapping applications. It is theoretically possible to fully automate these procedures, however the quality of the end product heavily depends on the mission planning, i.e. the overlap of the frames.

If, for reasons of automated photogrammetric processing, the mission planning was organized so that very high overlap was realized (e.g. more than 85%), special algorithms can generate super-resolution composites, allowing for even better object positioning.

With the constant improvement of the IMU technology and GPS technology (here GPS is used to indicate all GNSSs such as NAVSTAR GPS, Galileo, Glonass) and since LIDAR surface models become more and more available, it is expected that DG will generate centimetre accuracy. Furthermore, with

the introduction of digital camera systems and since mass data storage becomes cheaper, photogrammetric missions featuring a very high degree of image overlap will become standard procedure. It can be concluded that fully automated workflows for photogrammetric product generation (i.e. true-ortho images) and product validation can be realized within the forthcoming decade (Grubera et al., 2004).

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