

# MEDUSA – A WIDE SWATH HIGH RESOLUTION DIGITAL CAMERA FOR THE PEGASUS SYSTEM

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### ABSTRACT:

We have advocated the use of a High Altitude Long Endurance Unmanned Aerial Vehicle (HALE-UAV) for remote sensing since 2000. The project, called Pegasus, is now becoming a reality. The platform, an extremely light weight stratospheric aircraft called Mercator-1 has been constructed and is awaiting its maiden flight in the Spring and Summer of 2007. This aircraft is powered by solar energy and high capacity batteries allowing it to fly for weeks and months on end without landing. As such it can be used as a local geostationary system, as it is able to remain above a region persistently. The platform is not bound to an orbit and moves at low speed in a region of the atmosphere where wind speeds are known to be limited.

In parallel with the platform development, the design and construction of a high resolution camera to be carried on it has started as well. This camera will produce imagery (panchromatic and RGB color) at 30 cm resolution over a 3 km wide swath from Mercator-1's operating altitude of 18 km. The MEDUSA phase B project, funded by the PRODEX program of the European Space Agency, was completed in the Autumn of 2006. It produced a preliminary design which demonstrated that all constraints (both environmental and technical) could be met. Based on that, the phase C/D parts of the project were proposed and accepted by ESA/PRODEX. As of November 27, 2006, the final design and construction of the MEDUSA camera has started. The project will run until March 2008.

The challenges in the design and construction that are to be met are considerable. The total system should weigh no more than 2 kg, consume no more than 50 W, operate at -50 to -70 °C, transmit all data to a ground reception station in real time and operate autonomously. A detailed study of MTF and SNR has shown that a refractive optical system is the best choice, although it will be heavier than a reflective design. The CMOS sensor at the heart of the camera is being custom designed, which has allowed us to define an unconventional aspect ratio (10 000 x 1200 pixels). This sensor combines the advantages of line sensors (wide swath) and frame sensors (does not rely on external position and orientation sensors for image reconstruction). Frame rates of up to 30 frames per second can be achieved. This characteristic is not needed to guarantee forward overlap, but it is used to reduce image degradation during readout. The readout electronics interface to a command and data handling unit, which manages the data acquisition of imagery and GPS and IMU systems, analyses the image data to adjust integration time for the next image and performs image compression so that all data can be down linked in a 20 Mbit/s stream, over S-band. All subsystems are mounted in a carbon fiber tube with an 11 cm diameter and 1 m length. Special attention is given to the thermal aspects: at night there is no power available for the camera, so it cools to the ambient temperature of -50 °C; during day time, the ambient temperature is even lower, but the electronics and solar irradiation may give rise to thermal stresses.

The airborne data (image and ancillary data) are received at the ground reception station and then fed into the data processing system. This triggers a cluster of computers to process and archive the data (which may tally up to 1 TB in a single day). In a first step, all data and image metadata required for further processing are collected in HDF5 Level-1B format (product level definitions are adopted from CEOS). When further processing is required, radiometric and atmospheric corrections are applied as well as georeferencing and orthorectification. The processing system is able to produce fully corrected imagery within hours of the data acquisition. However, for applications that require real time data, the chain processing is simplified, resulting in a turn around time of less than half an hour, which is mandatory if this type of remote sensing system is to be used for disaster management as an integral part of a sensor web. This possibility is the subject of a EC Sixth Framework Integrated Project called OSIRIS.

## 1. INTRODUCTION

### 1.1 The Pegasus program

VITO's Pegasus program has several facets: an innovative airborne platform called Mercator-1, a series of Remote Sensing instruments, a ground control station and a central data processing facility. Encompassing all these key elements in an integrating remote sensing system has allowed us to work out a strategy to respond to many of the current and future remote sensing needs.

Mercator-1 is a solar High Altitude Long Endurance Unmanned Aerial Vehicle (HALE UAV), which is designed to fly in the lower stratosphere (between 15 and 18 km altitude). It is powered by solar energy and high capacity batteries allowing it to fly for weeks and months on end without landing. As such it can be used as a local geostationary system, as it is able to remain above a region persistently. The platform is not bound to an orbit and moves at low speed in a region of the atmosphere where wind speeds are known to be limited.

Mercator-1's payload is mounted to its front via a single mechanical and electrical interface. This separates the payload

design from the aircraft, and will eventually lead to a number of interchangeable instrument payloads that can be selected according to the remote sensing mission requirements. An inherent consequence of this modular design is that the data transmission system is a part of the payload. The first of these instruments is a digital camera, which is the subject of this paper. Later on, other payloads such as a LIDAR, a thermal camera or a RADAR instrument may be built. Further plans include a hyperspectral instrument for atmospheric studies (De Maziere *et al.*, 2006).

A third element of the program is the Ground Control Station (GSC), and its crew, who are responsible for flight planning and control, for data reception and forwarding to the processing centre. The GCS uses a parabolic disk antenna to receive the payload data stream, and is able to do so reliably over a distance of up to 180 km (this distance can be increased by using a larger dish at a well situated location).

Finally, the data is forwarded to the central data processing facility for archiving and processing, via high capacity data lines or satellite uplink. The considerable data volumes that will ensue from the instrument (up to 1 TB per day) make automation a priority: data need to be archived along with their metadata and data from other sources (ground GPS observations, spectral measurements, meteorological observations, ...). Further processing (e.g. radiometric, atmospheric, geometric corrections, georeferencing, orthoprojection, mosaicking and higher level products) are produced on demand of the users via a web-interface. For users that require data or information in near real time, simplified processing is available.

## 2. THE MEDUSA INSTRUMENT

### 2.1 System requirements

A digital camera was selected to prove the Pegasus concept. As the Mercator-1 will fly at modest speeds (about 70 km/h), a large swath was one of the requirements, to be able to cover project areas in a reasonable time. The top-level system requirements are shown in the table below.

Ground resolution	30 cm (@ 18 km) or less
Wavelength range	400 – 650 nm (RGB)
Swath width	3000 m ( $\geq 10\,000$ pixels)
SNR	100 @ 8:00 am equinox
Sensor type	Frame
Shutter	Electronic
Forward overlap	60%
RF downlink range	150 km from the ground station

Table 1. MEDUSA system requirements

### 2.2 Restrictions

The Mercator-1 aircraft, powered by solar energy alone, is extremely low in mass (not more than 35 kg), of which about 2 kg can be used by the instrument payload. During day time, 50 W will be available for the payload. The payload is housed in a tube of 1 m length and 12 cm diameter.

The instrument is composed of these major components: optics; image sensor and front-end electronics; GPS and IMU; command&data handling unit and a data downlink system.

The lower stratosphere's environment is characterized by low air pressure (100 mBar) and relative humidity. The ambient temperature is low, but has a diurnal variation between -50 and

-70 °C; inside the instrument, temperature gradients are expected between the electronics compartment and the optical part. Modeling the temperature dynamics (within the atmosphere but with virtually no convection) has proven to be difficult, but it could span a range of 70° C during day time.

Typical wind speed profiles show a minimum at altitudes between 15 and 18 km. Turbulence is expected to be limited, but this will have to be confirmed during flight trials. It should be noted that the MEDUSA instrument has a long focal length, so any change in attitude results in considerable image motion. This effect has been included in the MTF modeling at the basis of the instrument design.

### 2.3 System design

The camera design philosophy, including trade-offs with respect to ground sampling distance, focal length, MTF and SNR has been documented in Van Achteren *et al.*, 2006. Figure 1 shows the layout of the different components within the payload volume.

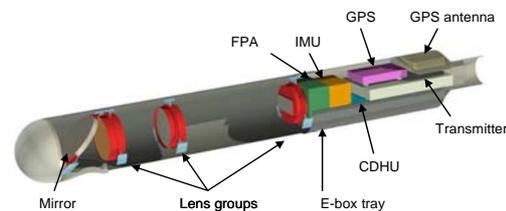


Figure 1. The MEDUSA subsystem layout.

**2.3.1 Image Sensor:** From the start, it was decided to not use a mechanical shutter; these have a limited number of cycles even at room temperature. Hence, an image sensor with electronic shutter was required.

Our attention was drawn to the New Metric Camera that was used in the GeoPIE project (EC 5<sup>th</sup> framework program, IST-1999-57456; Mayr *et al.*, 2004). This camera produces frames of 10000x1600 pixels, by “arranging multiple sensors in 1 folded focal plane”. Although it doesn’t reach the 12 000 pixel wide swath that is generated by the Leica Geosystems ADS-40 camera, which uses line sensors, this concept was preferred due to the stronger geometry of overlapping frame images. Still, arranging multiple (small) sensors in a focal plane is a difficult mechanical process, and there were some concerns about the stability of the focal plane.

After discussions with a local image sensor producer, it was decided to have a custom made sensor made (saving mass as no folding mechanism for the focal plane is required). As a result, a 10000 x 1200 CMOS chip will be produced. In fact, the image sensor package will contain 2 of these image sensors, one with and one without an Bayer RGB pattern. Since both are on the same silicon substrate, alignment is guaranteed by design.

Electronic shuttering has a disadvantage: parasitic light sensitivity (PLS), meaning that some light is still integrated, even when the pixels are shuttered. PLS will affect pixels more depending on the time between exposure and readout. If, during this time, the camera is moving, it will produce a smeared

background. To minimize the effects of PLS, the readout time of the image frame was reduced to 33 ms (so the camera is capable to output images at 30 fps!). Also, a PLS compensation is foreseen in the data processing chain, based on inter-line grey value comparison and image motion information from the GPS and IMU sensors. The former can be implemented within the Command&Data Handling Unit, the latter will be a part of the data processing in the ground segment, as it requires accurate (post-processed) navigation and orientation data.

The properties of the CMOS image chip are also well suited for other applications than remote sensing. The wide swath and high frame rate are attractive for industrial product inspection as well. By design, the image sensor and its electronics can be integrated with other, possibly even off-the-shelf, optics.

**2.3.2 Optics:** As shown in Figure 1, a refractive solution was chosen, because it performs better at larger field of views, has a better MTF (the diffraction limit depends on the physical aperture, which is partly obscured by secondary mirror(s) in a reflective system) and a better SNR (collecting more light than a partly obscured reflective system). Clearly, chromatic aberrations need more attention, and lenses are typically heavier than mirrors.

A major point of attention is the thermal cycling that is expected during the operational phase: the refractive index of the lens materials changes with temperature, the relative positions of the lens groups need to be controlled, and the whole imaging system will be subject to mechanical stress.

**2.3.3 GPS and IMU:** These subsystems are integrated for obvious reasons. They will allow for approximate georeferencing in near real time data processing, and support automatic tie point extraction for high accuracy bundle block adjustment.

Thermal cycling may cause the IMU to exhibit time-dependent drifts; adding heaters near critical components should compensate for this. However, we will model this behavior after stratospheric flights and acquiring image series with stable geometric configurations above well known ground control, so that we can generate a reference with bundle block adjustment.

**2.3.4 Command&Data Handling Unit:** the C&DHU is the heart of the instrument. It triggers other subsystems, collects their data and adjusts settings as required (e.g. integration time of the image sensor, which is based on a histogram analysis of the previous image). Furthermore, it performs data compression on the images using JPEG-2000 (on a dedicated chip) and it formats the data stream that is sent to the transmission equipment.

The C&DHU is programmable, so its functionality can be adapted to the needs that appear during flight trials. The MEDUSA camera is designed to operate for months in a totally autonomous way, but if it malfunctions or does not produce data as expected, Mercator-1 can be brought to land and the payload can be modified.

**2.3.5 Data transmission:** All image and ancillary data is down linked via an S-band transmitter to the ground reception station in real time. Data rates of up to 20 Mbit/s are achievable, but only to a dish antenna that is within about 150 km of the aircraft. Uplink to geostationary satellite would of course be an important asset, but the required power to achieve this with a non-directional antenna is simply not available.

## 2.4 Camera calibration

**2.4.1 Geometry:** A laboratory calibration of the MEDUSA camera will be difficult to perform because the environmental conditions at which the it will be working need to be recreated during the laboratory calibration (low air pressure and temperature). Furthermore, the camera's hyperfocal distance (Kraus, 2000) is considerable: objects closer than about 2.8 km are not in focus in the image plane.

At present we are considering possible work-arounds to these challenges, such as astronomical methods, e.g. imaging the sun or moon while it transits the image plane (Ethrog, 2006).

A more practical alternative is to use self-calibration supported by bundle block adjustment to determine the camera parameters and the boresight to the IMU. This is done on images acquired during flight, so it will represent the camera's operational properties best.

**2.4.2 Radiometry:** the imaging sensor will be fully characterized (relative sensitivity of the individual pixels to known illumination intensity and frequency).

The complete system will behave differently, however (e.g. the refraction index of the lenses is temperature dependent), so an system radiometric calibration will be performed in the lab.

This calibration cannot be done reliably during operational flights, even with reference targets, because of the atmospheric effects that affect the images of these targets (in both radiometric and spectral way).

## 3. THE MEDUSA GROUND SEGMENT

### 3.1 Components

The MEDUSA ground segment has two components: the Ground Control Station (GCS) which controls the aircraft and receives the data generated by the MEDUSA instrument and the Central Data Processing Centre (CDPC), which is responsible for archiving and processing of the data.

**3.1.1 Ground control Station:** The GCS is designed as a transportable system which is self-sufficient when required. It connects to the CDPC via high capacity communication infrastructure (land lines or via satellite uplink). It provides the control team with a all necessary control and monitoring systems to manage the aircraft. During ascent and descent of Mercator-1, there will be direct interaction with the aircraft; in the nominal survey mission phase, the aircraft executes the flight plan that is uploaded into its memory.

The GCS receives the payload data, verifies its integrity and forwards it to the CDPC. When the forwarding is not possible, the data are buffered for later transmission.

In the framework of the OSIRIS (Open architecture for Smart and Interoperable networks in Risk management based on In-situ Sensors) project (OSIRIS, 2007), a data processing capability will be added to the GCS, so that it will be able to provide decision makers in the field with near real-time information during natural crisis situations.

**3.1.2 Central Data Processing Centre:** The CDPC is situated at VITO, in Belgium. It is a scalable cluster of processor machines connected to a large storage array of disks (Biesemans *et al.*, 2006). It receives all data from the GCS, requests additional (e.g. GPS base station) data and archives the Level-1 data in HDF-5 format. Subsequent processing is triggered by requests via a web-interface.

In the framework of the OSIRIS project, the Pegasus sensor system will be integrated in a sensor web via the CDPC.

### 3.2 Generic data processing chain

Figure 2 shows the concept of the processing system. It is inspired by the automated processing systems that are used for satellite remote sensing. The HDF-5 files are self descriptive, so that image data and meta-data are kept together. All algorithms are designed in a generic way, so it is possible to process data from different sensors with the same software. This concept has been validated using image data coming from Vexcel UltraCam and Applanix DSS cameras, CASI and AHS hyperspectral imaging systems and even PAL video streams.

Once the functional validation was complete, the processing system was stress tested as well: images were input into the system at regular intervals for days on end. This allowed us to detect and solve cluster processing related problems (Biesemans *et al.*, 2007).

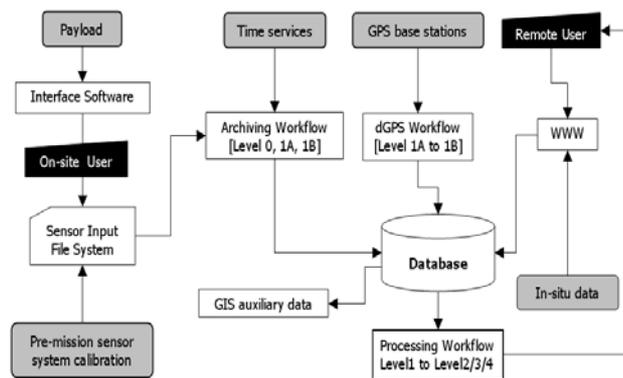


Figure 2. CDPC concept functional flow diagram.

### 3.3 MEDUSA specific processing

Apart from the use of generic processing (e.g. atmospheric correction, georeferencing, orthorectification), using data from the MEDUSA instrument within the Pegasus program requires specific processing, depending on the application.

**3.3.1 Real-time applications:** in crisis situations (e.g. flooding, forest fires, industrial accidents), the delay between image acquisition and product delivery should be minimized. Even without georeferencing, the images need to be mosaicked, so that larger areas can be shown in a comprehensive way. The people that are responsible for crisis management have good knowledge of the area, so they provide ad-hoc georeferencing. This is an issue for any remote sensing instrument that is used in these circumstances, so it applies to traditional aircraft and low-altitude UAV systems as well.

This problem is now being addressed in a research project “Reliable Image Management Systems in support of urban services and disaster management (RIMS)”.

**3.3.2 Image Resolution Improvement:** achieving 30 cm ground resolution from a distance of 18 km is a big challenge. Improving on that on the instrument side requires (a) a longer focal length (b) a larger physical aperture and (c) shorter integration times. Within the constraints of the current payload, this cannot be done. However, the images generated by the MEDUSA camera are suitable for superresolution techniques: the field of view is small, images can be acquired in quick succession under constant lighting conditions, and the same area can be imaged repeatedly if required. VITO is addressing these issues in the SUPERRES research project.

Once again, the use of the resulting methods is not limited to MEDUSA on Pegasus. Low cost survey systems (e.g. UAV helicopters using video cameras) will benefit from superresolution techniques as well.

**3.3.3 Future work:** the MEDUSA instrument on Mercator-1 will open new possibilities for remote sensing, by offering high spatial resolution alongside the potential for high temporal resolution, at reasonable cost.

This will open up new research opportunities in many traditional remote sensing applications (e.g. in agriculture, it will be possible to monitor crop growth with unprecedented update rates) and probably create new remote sensing applications. Already, the Pegasus system is being integrated in a sensor network for crisis management.

## 4. CONCLUSIONS

Designing and building a wide-swath digital camera for use on a stratospheric unmanned aircraft is challenging. The physical limitations for such a system installed on a very lightweight aircraft such as Mercator-1 have forced us to evaluate the impact of user requirements to the system design.

Based on the expected data volume that will be produced by the camera once it is operational, we have designed and implemented a processing system for archiving and data processing. This system has already been shown to reliably process digital imagery as well as imaging spectroscopy input.

The image sensor and its electronics may also have other uses outside the remote sensing field.

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