MEDUSA – A LIGHTWEIGHT HIGH RESOLUTION CAMERA SYSTEM FOR EARTH OBSERVATION FROM THE MERCATOR-1 UAV

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KEY WORDS: Earth observation, High Resolution, HALE UAV

ABSTRACT:
VITO has initiated the Pegasus program to demonstrate the feasibility of performing earth observation from stratospheric altitudes by means of the HALE UAV Mercator1. 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 local geostationary system, as it is able to remain above a region persistently.
In parallel with the UAV development, the design of a high resolution camera system has been conducted to support the Pegasus program in its mission. Under the PRODEX program of the European Space Agency, a preliminary design study (MEDUSA phase B) has demonstrated the technical feasibility of the camera system development for the Mercator1 UAV, thereby focussing on the main applications of the Pegasus program: crisis monitoring and cartography.
The MEDUSA instrument development is a technological challenge, predominately because of the tight boundary conditions imposed by the UAV platform. Within the mass budget of 2 kg and a power consumption of 50 W, the instrument performance needs to be guaranteed within the extreme environmental conditions of the stratospheric altitudes. Designed to deliver earth observation data in the visible spectrum (400-650 nm), the MEDUSA camera will cover a swath of 3 km. From the operational altitude of 18 km, a ground sampling distance of 30 cm will be realized.
The central part of the camera system is the focal plane assembly consisting of two frame sensors (PAN and RGB). By means of pan-sharpening, colour images at high resolution are produced. The custom designed CMOS sensor has 10000 x 1200 pixels and is read-out in about 30 ms to reduce image degradation due to parasitic light sensitivity. The electronics section of the Focal Plane Assembly contains the functionalities of sensor read-out and a limited amount of on board data processing. The focussing elements of the optical system are purely refractive and its design process is characterised by a constant balance between optical performance, mass and temperature sensitivity. To minimize the frontal area of the camera system, which is mounted in front of the UAV fuselage, the optical axis of the system is placed horizontally. The MEDUSA camera system is equipped with an Inertial Measurement Unit (IMU) and a GPS system for direct georeferencing purposes. To allow a forward overlap of about 70%, JPEG2000 compression of the raw image data is performed. This way the data stream fits within the 20 Mbps direct downlink which is available between the Camera system and the Ground Control Station. With the current antenna design a range of 150 km around the ground control station can be covered. All subsystems of the MEDUSA payload are mounted in a lightweight carbon fibre housing.

Phase C/D (detailed design, production and ground testing) of the MEDUSA development has started on the 27th November 2006. By the end of 2008 the camera will be ready for its first test flights.

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 this 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 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 (GCS), 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 dish antenna to receive the payload data stream, and is able to do so reliably over a distance of up to 150 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) can be produced on demand of the users via a web-interface. For users that require data or information in near real time, simplified processing will be available.

2. THE MEDUSA INSTRUMENT

2.1 Applications

The MEDUSA instrument will be used during the proof of concept phase of the Pegasus program. The mission of the MEDUSA project is:

- to develop a lightweight high resolution instrument for event monitoring and mapping applications, designed to be integrated on the Mercator UAV platform family.

- to develop associated Level1 product generation software.

This paper focuses on the MEDUSA instrument development. The Level1 product generation software is described in more detail in (Biesemans et al., 2006).

In the first phase the MEDUSA instrument will be used for disaster monitoring. For this type of application the near-real time aspect of the data delivery is crucial while the requirements on image quality and positional accuracy are less stringent. In this context a demonstration flight will be performed with the MEDUSA camera system within the FP6-project OSIRIS (OSIRIS, 2007) with the aim of supporting the fire brigade during a forest fire. The UAV sensor will be used to keep an overview of the crisis situation, follow the evolution of the fire frontline and monitor the location where fire fighters are in danger.

During the different flight tests of the MEDUSA instrument the camera system will be further characterized and optimized focusing on high demanding applications with respect to image quality like mapping.

2.2 System requirements and functionalities

The primary goal with the MEDUSA instrument is to acquire high resolution images. As the Mercator-1 will fly at modest speeds (about 70 km/h), a large swath is required, to be able to cover project areas in a reasonable time. In particular for disaster monitoring near-real time data delivery requires a direct downlink of the data. Approximate direct geo-referencing will be performed for disaster monitoring applications. Sub-pixel positional accuracy is realized by

bundle block adjustment. The top-level system requirements are shown in the table below.

Table 1: Top level system requirements of the MEDUSA instrument.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground resolution</td>
<td>30 cm (@ 18 km)</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>400 – 650 nm (RGB)</td>
</tr>
<tr>
<td>Swath width</td>
<td>3000 m (10 000 pixels)</td>
</tr>
<tr>
<td>SNR</td>
<td>100 @ 8:00 am equinox</td>
</tr>
<tr>
<td>Sensor type</td>
<td>Frame</td>
</tr>
<tr>
<td>Shutter</td>
<td>Electronic</td>
</tr>
<tr>
<td>Forward overlap</td>
<td>60%</td>
</tr>
<tr>
<td>RF downlink range</td>
<td>150 km from the ground station</td>
</tr>
</tbody>
</table>

2.3 Boundary conditions

It is a technological challenge to bring an airplane-ship with an endurance of days to months up to stratospheric altitudes of 15-20 km. The Mercator1 UAV is able to realize this goal by means of a carefully optimized design with an extreme focus on mass reduction and power efficiency. It has a total mass of not more then 35 kg for a wingspan of 16m. As a consequence the restrictions on the instrument are stringent transforming the instrument development into a challenging process as well. The payload mass is about 2 kg. The available electric power is limited to 50 W during day time. The volume of the instrument is limited to a cylinder of 12 cm in diameter and a length of 1m, being positioned in horizontal direction along the UAV fuselage to keep the frontal area limited for aerodynamic reasons.

The lower stratosphere’s environment is characterized by low air pressure (down to 60 mBar) and low relative humidity. The ambient temperature is low and varies around -55°C with a 3 sigma deviation going up to 15°C (based on averaged temperature–data acquired above Belgium over a 20 year period). Apart from the fluctuating air temperature, the temperature within the instrument is dominated by its two main heat sources: sun (external) and electronic power dissipation (internal). As the MEDUSA camera system is not screened by the air plane it experiences a strong temperature variation induced by the relative orientation of the sun with respect to the instrument. This is shown in Figure 1. After a sharp rise in temperature at start-up in the morning the electronics modules of the instrument, produce a constant heat input.

Figure 1: temperature within different subsystems of the MEDUSA instrument during 24h (21st June)
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. Nevertheless it should be noted that due to the high altitude small angular deviations still correspond to significant shifts: 0.01° corresponds to about 3m or 10 ground pixels shift from an altitude of 18km.

3. MEDUSA SYSTEM DESIGN

As the design of the UAV is fully focused to complete its primary goal, a long endurance flight at stratospheric altitudes, there is no room for any regulating function with respect to the MEDUSA instrument: temperature, electric power, health status check of the payload and its subsystems. Therefore the instrument needs to be designed in such a way that it is able to guarantee its performance within the fluctuating environment it is facing. Furthermore the instrument needs to react autonomously on the evolving circumstances.

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. The design of the optical system is a balance between the SNR requirement and the MTF. Where the acquired light intensity needs to be maximized to reach a sufficiently good SNR, this needs to be combined with a sufficiently short integration time to reduce the motion blurring of the images. It has been proven that a single color sensor could not fulfill the identified requirements. To solve this issue a two sensor configuration has been selected: one pan-chromatic sensor generating the high resolution image at sufficient SNR and one RGB sensor generating the color information in a lower spatial resolution mode.

3.1 MEDUSA subsystems

The MEDUSA camera system consists of a number of subunits as indicated in Figure 2:

- CMOS sensor configuration
- Focal-plane assembly
- Command and data handling unit
- Optical system
- GPS-system
- Inertial Measurement Unit (IMU)
- S-band antenna and transmitter

Figure 3: Preliminary design of the MEDUSA instrument.

3.2 CMOS Sensor configuration

The MEDUSA instrument will be equipped with two CMOS sensors, one with panchromatic and one with RGB filtering (Bayer pattern). The sensor will have 10000 x 1200 pixels. Each pixel has a size of 5.5 µm and is electronically shuttered in a snapshot mode. The pixel design is optimized to reduce the parasitic light sensitivity, i.e. sensitivity to light of the storage element in the pixel compared to the photodiode sensitivity. Due to the motion of the UAV this could result in a smeared background. To further reduce the effect of photon collection while the shutter is closed, the read-out time of each sensor is kept as short as possible (of the order of 30 ms).

Both sensors are positioned on one silicone substrate in a single ceramic package. This excludes the need of an alignment mechanism to position both sensors in one plane. The panchromatic sensor is centered around the optical axis to minimize the image distortion at the edge of the field. By doing this the principal point of the sensor is located at the sensitive area of the sensor. The layout of the CMOS sensor configuration is shown in Figure 4.

Figure 4: CMOS sensor configuration within the MEDUSA instrument.
The properties of the CMOS image chip are also well suited for other applications than remote sensing. For example, the wide swath and high frame rate are attractive for industrial product inspection. By design, the image sensor and its electronics can be integrated with other, possibly even off-the-shelf, optics.

3.3 Focal Plane Assembly-Command and Data handling Unit

In the order to minimize mass volume and power consumption the electronic camera head of the CMOS sensor combines the following functionalities:

- Sensor read-out
- (limited) on-board data processing
- FPN-PRNU correction
- Housekeeping of the payload subsystems

The forward overlap of the MEDUSA camera system has been defined in order to allow block bundle adjustment. Taking into account 70% overlap, a nominal UAV ground speed of 25 m/s and two standard deviations for the motion blur statistics, the minimum required frame rate is 0.7 frames/second for both the panchromatic and color sensor. This corresponds to a total data rate of 170 Mbits/second. To fit within the available bandwidth of the downlink the data is compressed via JPEG2000 and combined with GPS and IMU data into a data stream of 20 Mbps. Data compression is also possible via downsampling of the color image. This is acceptable since the pan-sharpening technique (Zhang, Y., 2004) only needs a low resolution color image.

At present, the MEDUSA instrument will be running autonomously without interaction from the ground control station. All commands and control are sent from the Command and Data handling unit. This implies that the camera needs to regulate itself to optimize image quality (brightness control, compression adaptation,…). In the future, camera parameter settings will be accessible from the ground control station via the uplink of the Mercator1 UAV.

Onboard data processing is kept to a minimum. Permanent data storage is not planned.

3.4 Optical system

The optical system is the most critical and demanding subsystem of the MEDUSA instrument due to the stringent mass restriction and the variation of the environmental conditions over the acquisition period. Apart from the 45° deflection mirror (shown in Figure 3) the optical system is purely refractive consisting of 5 lenses. The first four lenses are grouped into a rigidly connected assembly, the last lens acts as field flattener and is fixed directly on the ceramic package of the CMOS sensor. The total length of the optical system along the horizontal axis is less then 53 cm. The design of the optical system has been optimized in order to reduce the mass and the temperature sensitivity of the optical performance. The design parameters of the optical system are listed in Table 2.

Table 2: Design parameters of the optical system of the MEDUSA instrument.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>330 mm</td>
</tr>
<tr>
<td>Clear aperture</td>
<td>80 mm</td>
</tr>
<tr>
<td>FOV across direction</td>
<td>9.5°</td>
</tr>
<tr>
<td>FOV along direction</td>
<td>2.48°</td>
</tr>
<tr>
<td>Type</td>
<td>Refractive</td>
</tr>
</tbody>
</table>

For a spot size of two pixels the depth of focus of the optical system is about 90 µm. To guarantee the optical performance of the instrument the CMOS sensor needs to stay positioned within this distance. The four dominating parameters which need to be controlled are:

- Sensor flatness
- Alignment of the sensor with respect to the focal plane of the optical system
- Temperature of the lenses
- Pressure within the instrument volume.

The first two parameters can be controlled by manufacturing and design and will not be discussed in more detail. The temperature is the dominating effect.

As indicated in Figure 1, during a single day the optical system is expected to experience temperature variations of more than 20°C. Due to temperature dependence of the index of refraction and deformations of the lens surface, the focus of the optical system shifts with about 11µm/°C. To bypass this thermal defocusing effect a passive compensation mechanism is introduced to adapt the distance between the lens system and the sensor to keep the system in focus.

As the optical system has a certain length, the different lenses are not on the same temperature during normal operation of the instrument. Therefore an axial thermal gradient is introduced within the optical system. The magnitude of this axial gradient is directly proportional to the focal shift of the optical system, has an effect on the position of the focal plane along the optical axis. Therefore the axial position of the CMOS sensor needs to be corrected by an off-set.

Apart from the temperature dependence, the focus point of the optical system shifts over a distance of about 300µm going from a 1 Bar atmospheric environment down to the stratospheric low pressure regime. Here it should be noted that the altitude control of the Mercator1 is driven by a pressure measurement. This way the MEDUSA instrument will always operate in a more or less constant pressure regime. Calibration of the instrument to the operating pressure of the UAV is required.

In the opto-mechanical design special attention has been paid to the lens mounts and its material. This is imposed by

- the centering requirements on the individual lenses to guarantee the optical performance
- the thermal stresses which are to be kept within acceptable limits over a temperature range from -70°C to +60°C and taking into account CTE mismatch between the different materials.

An a-thermal fixation of the optical system to the Carbon fiber housing was not possible to realize within the restrictions of mass and volume. Therefore the optical system will shift to a lower vertical position with decreasing temperature inducing a
shift of the principal point on the sensor. By precisely monitoring the temperature of the optics mount this shift can be corrected.

3.5 GPS-IMU

For direct georeferencing purposes the MEDUSA instrument is equipped with a lightweight L1/L2 GPS receiver with corresponding lightweight antenna and an Inertial Measurement Unit. Both GPS and IMU data are transferred to the Command and Data Handling Unit and then transmitted via the downlink to the ground control station. In the central data processing center dGPS correction is performed on the position data and the position and attitude data are post-processed via Kalman-filtering.

GPS and IMU will allow for approximate georeferencing in near real time data processing. This will be of direct use for the disaster monitoring applications. GPS and IMU data will support automatic tie point extraction for high accuracy bundle block adjustment, this for applications where more precise georeferencing is required.

3.6 Data communication

The three data blocks of camera, GPS and IMU are combined into one stream of 20 Mbps. After convolutional coding the data is OQPSK modulated and transferred via a lightweight omni-directional antenna to the dish antenna of the Ground Control Station. All data will be transferred over a range of 150 km with a Bit Error Rate of not more then 10^{-7}.

3.7 System design

All payload subsystems are mounted within a carbon fiber housing. The internal structure of the instrument has been subdivided in an optics and an electronics compartment, which can be separated for reasons of alignment, module access and maintenance.

To monitor the dynamics of the temperature along the optical system throughout the operational acquisition window, a number of temperature sensors are being distributed over the payload structure. They will be used during the commissioning phase of the instrument in order to link the optical performance to the temperature distribution.

Due to the low pressure within the MEDUSA instrument no convection through the air takes place. Therefore special care should be taken to make sure that the dissipated heat in the PCB can be transferred via conduction to the carbon housing of the instrument. A heating system is installed in order to bring all electronic subunits within their specified operational temperature range before start-up.

4. MEDUSA GROUND TESTING AND CALIBRATION

4.1 Testing

Within the MEDUSA phase C/D project ground testing of the MEDUSA instrument will be performed in the laboratory. Low pressure and temperature will be simulated in a thermo-vacuum chamber. In a first step the thermal compensation mechanism and the pressure dependent calibration of the focal plane will be verified with a test sensor. In a second step the complete optical performance of the MEDUSA camera system will be characterized.

4.2 Geometric calibration

At present the geometric calibration method and procedure is being worked out in more detail. However, similar to the development of the complete MEDUSA instrument, the geometric calibration will be a challenge as it needs to be performed under the operational conditions of the camera.

Since both PAN and RGB sensor are located on the same silicon substrate and illuminated by the same optical system, the MEDUSA instrument can be categorized in class I of (Cramer, 2004) as a 2D matrix with a single camera head. This keeps its calibration procedure much simpler in comparison to other multi-sensor digital camera systems like the Intergraph DMC (Hefele, 2006) or the Vexcel UltraCam.

As outlined in this paper a number of the camera parameters are known from the design to vary during the daily acquisition cycle and this because of the fluctuating temperature:

- Focal length
- Principal point position

This needs to be taken into account when accurate imagery is to be provided.

Since the operational environmental conditions cannot be reproduced perfectly within the laboratory, the ground test will be used to characterize the performance and the identify trends in the behavior relative to the temperature, axial thermal gradient and pressure.

Apart from that, self-calibration supported by bundle block adjustment is performed 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 at best.

5. CONCLUSION AND OUTLOOK

Designing and building a wide-swath digital camera for use on a lightweight stratospheric unmanned aircraft is feasible but challenging. The MEDUSA instrument is designed to guarantee the optical performance within the varying environmental conditions during the operational acquisition window. This is realized by introducing the necessary compensation mechanisms in the design.

Currently the detailed design of the MEDUSA instrument is being finalized. Hardware manufacturing and assembly will be started in autumn 2007. The instrument will be fully ground tested by the end of 2008 such that the first test flights with the MEDUSA camera system can be conducted as of Spring 2009.

ACKNOWLEDGEMENTS

The MEDUSA project is funded by the European Space Agency under the PRODEX program.

OSIRIS is an Integrated Project (IST-2005-2.5.12-033475) funded by the European Commission in the 6th framework program.
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