A lightweight and wide swath UAV camera for high resolution surveillance missions

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ABSTRACT

Designed to execute mapping and surveillance missions for crisis monitoring on a solar powered High Altitude Long endurance UAV 18 km high up in the stratosphere, the MEDUSA high resolution camera is able to acquire frame images with a ground sampling distance of 30 cm and swath of 3 km. Since mass is a dominant driver for the UAV performance the MEDUSA payload was severely mass optimised to fit within the physical boundaries of 2.6 kg, 12 cm diameter and 1 m length. An inertial navigation system and data transmission equipment is included. Due to the innovative dual sensor on single chip concept the MEDUSA payload hosts two independent frame camera’s of each 10000x1200 pixels (one panchromatic and one colour sensitive). The MEDUSA stratospheric camera has completed its system level test campaign in autumn 2012 and is ready for its maiden flight.

Using the main building blocks of this stratospheric camera a modified version is being developed which is adapted to more conventional UAV’s flying at lower altitude. The current design is targeting a ground resolution of 10 cm and swath of 1 km with each single image. First test flights have been conducted with an engineering model version of the camera generating representative image data. Also the functionality is being expanded by adding hyperspectral sensitivity to high spatial resolution image acquisition within the same compact camera system.

Keywords: UAV, multispectral, high resolution

1. INTRODUCTION

Traditionally earth observation is being conducted from airborne and satellite platforms, each having specific advantages regarding performance parameters such as spatial resolution, ground coverage, availability and flexibility. Depending on the application one platform is better suited than the other. Various technological developments over the last decade have lead to an new type of platform which bridges the gap between manned aircraft and satellites: a local geostationary system operated in the stratosphere. Various platform concepts, mostly airship or aircraft, are being developed aiming at persistent availability for not only earth observation but also for telecommunications [1,2]. Besides the research which is performed on the platform side, an additional challenge lies in the development of instruments which are adapted to the new specifications, environmental and operational conditions of those innovative platforms.

Within the Pegasus program [3] initiated by VITO, the Flemish Institute for Technological research, a lightweight high resolution camera MEDUSA was developed to fly on a solar-powered high altitude long endurance (HALE) unmanned aerial vehicle (UAV) at stratospheric altitudes around 18 km. This aircraft is powered by solar energy and high capacity batteries allowing it to fly for weeks or even months without landing. As such it can be used as 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. The longest unmanned flight ever was realized by QinetiQ in 2010 keeping this type of platform in the air for 14 days [4].
2. INSTRUMENT DESCRIPTION

2.1 Applications and system requirements

In order to accomplish disaster monitoring and large-scale mapping a high resolution camera system, MEDUSA (Monitoring Equipment and Devices for Unmanned Systems at high Altitude), has been developed by an industrial consortium led by VITO [5,6]. The top-level instrument requirements extracted from the target applications are summarized in Table 2-1.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Ground resolution</td>
<td>30 cm (@ 18 km) or less</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>400 – 650 nm (RGB)</td>
</tr>
<tr>
<td>Swath width</td>
<td>3000 m (&gt;= 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>

Table 2-1 MEDUSA system requirements

2.2 Constraints

The MEDUSA payload will operate under very strict and challenging physical and environmental constraints. As the UAV platform is extremely low-weight (35 kg), the total allowed weight for the payload is also strict: 2 to 3 kg depending on the required mission length. The pressure at operational altitude is around 60 mbar. The total power consumption is limited to 50 W during the day. No power is available at night, and all mechanical and electronics components have to survive severe thermal cycles with temperatures in worst cases down to -70°C and up to 60°C. Thermal gradients and temperature evolutions are also experienced over the day, mainly due to the change in sun elevation and the direction of flight. The volume of the payload is restricted to a more or less cylindrical tube of 1 meter length and an outer diameter of 12cm.

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 of about 15°C from this mean value (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 airplane against external influences it experiences a strong temperature variation induced by the relative orientation of the sun with respect to the instrument.

2.3 System design

The MEDUSA high resolution camera system contains the following subunits:

- A refractive optical system composed of 5 lenses and a folding mirror to accommodate the horizontal orientation of the MEDUSA camera system
- Focal Plane assembly (FPA): with two wide-swath sensors of each 10000x1200 pixels on a single chip: one panchromatic and one with colour sensitivity realized by Bayer filter. Those can be combined via pan-sharpening to generate a colour image product with high resolution.
- Command & Data Handling Unit (C&DHU)
- GPS L1/L2 antenna and receiver,
- Inertial Measurement Unit (IMU),
- S-band (2 GHz) antenna and transmitter.

The presence of the GPS receiver and the IMU allows direct geo-referencing of the camera images. The on-board data processing provides sensor-related image corrections, brightness control and JPEG2000 compression. Processing and archiving will be conducted on-ground where data will be received by the ground station and forwarded to a Central Data Processing Centre (CDPC) at VITO, Belgium [7].

The MEDUSA camera subsystems are installed in a light-weight carbon fiber support frame which serves at the same time as housing. The support frame is mounted horizontally on the front of the Mercator 1 HALE UAV. It consists of three separable dismountable units: the front fairing, an optical tube and an electronics tube in the back. Figure 1 illustrates the relative positioning of the subunits within the payload structure. Figure 3 shows a picture of the integrated MEDUSA flight model camera system.

![MEDUSA flight model camera system](image)

**Figure 1.** Schematic view of the inside of the MEDUSA payload.

### 2.4 MEDUSA CMOS sensor

To cover the required swath of 3 km, a custom designed CMOS sensor has been developed by Cypress Semiconductor Cooperation Belgium (now ON-Semi) for the MEDUSA camera system. The sensor is a single CMOS chip which consists of two sensitive areas each having 10000x1200 pixels. One area serves as panchromatic sensor, the other as color sensitive sensor (by means of color filters in a Bayer pattern). Both sensors are read-out independently. Due to the fact that the sensors are located on a single die, they are geometrically aligned by design. The MEDUSA sensor is equipped with micro-lenses to increase the light intensity on the sensitive area of the pixel. A picture of the MEDUSA sensor encapsulated in its ceramic package with the field flattener lens is shown in Figure 2.
Figure 2. MEDUSA wide swath CMOS sensor with and without field flattener lens.

Figure 3. integrated MEDUSA flight model camera
3. SYSTEM LEVEL TEST CAMPAIGN

In order to verify the functionality and performance of the MEDUSA FM camera an extended test campaign was executed both in stand-alone mode and while integrated on the HALE UAV platform. The most challenging tests were however the environmental tests (temperature, pressure, structural,...).

In order to verify the performance of the MEDUSA camera system at representative environmental conditions a test campaign was conducted within a thermal vacuum chamber facility at ESA/ESTEC. Apart from a functional verification at different temperatures within the operational temperature range the proper operation of the thermal compensation mechanism to keep the optical system in focus during temperature variations within the payload. Also the pressure correction to bridge the gap between atmospheric pressure and the pressure in the startosphere was verified.

The optical performance test at low pressure and temperature was executed with the same procedure as described in [8]. Tests are conducted in a thermal vacuum chamber to verify the theoretical dependencies of focus position versus pressure and temperature that are respectively 0.314 mm/bar at 20°C and 11µm/°C at 60mbar. A high quality 25mm thick optical window closes the climatic chamber. An external test telescope built from simple Melles Griot Achromatic lens 01LAO767 is used to project a 10 lp/mm Ronchi ruling frequency onto the FPA through this window. The electronic processing of the images grabbed on the FPA permits to retrieve on line the modulation of the Ronchi as imaged by the FPA. The Ronchi ruling is mounted on a micrometer translation stage. Since the lateral magnification from the test telescope to the FPA is 0.314, the longitudinal magnification is 0.1. A through focus modulation by moving axially the Ronchi ruling then permits to be extremely sensitive in detecting the focus position in the MEDUSA payload.
Figure 4. thermal vacuum chamber facility at ESA/ESTEC. On the left side of the thermal vacuum chamber the test telescope is installed on a tri-pod.

Figure 5. MEDUSA camera system installed in the thermal vacuum chamber facility at ESA/ESTEC.
Figure 6 shows the result of the through focus measurements executed in the thermal vacuum chamber over a range from -70°C to -9°C. A stabilization period of 2 hours was respected bring the system into thermal equilibrium. The graph shows very good correspondence between two extreme temperatures -9°C and -70°C confirming that the thermal compensation mechanism is working.

![Graph showing through focus measurement results](image)

**Figure 6.** Through focus measurement results (modulation measured on the MEDUSA camera versus the position of the target at the OGSE telescope) at several temperature for a stabilization time of 2 hours minimum.

4. MEDUSA ENGINEERING MODEL

In order to conduct MEDUSA test flights at an early stage in the development to demonstrate the functionality of the camera system an engineering model of the MEDUSA camera has been built consisting of the same electronical subsystems as the MEDUSA FM but with a COTS optical system with a focal length of 80 mm in stead of the lightweight custom designed MEDUSA lens system. All subsystems are integrated in a ruggedized mechanical structure.

In autumn 2012 the MEDUSA engineering model was embarked on a manned balloon and flown in a 1.5 h mission at an altitude of around 1.5 km. The camera was operated at a frame rate of 1 fps and acquired both panchromatic and colour images at a ground sampling distance of 10 cm and a swath of 1 km. Figure 7 shows a typical dual image of the MEDUSA camera system. Figure 8 shows a composite of panchromatic images of a limited set of images.
Figure 7. A typical combined PAN+RGB image acquired during a single acquisition with the MEDUSA engineering model camera in flight: colour image (top), panchromatic image (bottom).

Figure 8. Image composite produced from panchromatic images of the MEDUSA engineering model acquired in a fraction of the balloon flight line from an altitude of 1.5 km (GSD 10 cm – swath 1 km).
Due to form factor of the MEDUSA CMOS sensor (10000x1200 pixels) the MEDUSA imager is very well suited for hyperspectral imaging. A 10000 pixels wide camera can be realized with 1200 lines to separate the incoming light in different bands. Due to the presence of the 2 sensors on single chip which can be independently controlled it is possible to acquire both hyperspectral images and broad band frame images (colour or panchromatic) from one single camera. VITO has integrated a breadboard version of this type of camera with a linear variable filter with a FWHM of around 17 nm. First imaging tests have been conducted at ground level.
6. CONCLUSION AND OUTLOOK

The MEDUSA high resolution camera system has passed its system level test campaign successfully since autumn 2012. The functionality and performance of the flight model camera was demonstrated both at room temperature and within representative temperature and pressure environment. The MEDUSA camera system is now ready for its maiden flight.

Besides the light weight HALE UAV camera an engineering model camera was integrated by VITO making use of the same building blocks as the FM camera apart from the COTS optical system and the mechanical structure. First flight trials have been executed with an engineering model of the MEDUSA camera system during which high resolution image data has been acquired from an altitude of 1.5 km. In a next phase a modified version of the MEDUSA camera will be developed which is compatible with and optimized for use on a medium altitude fixed wing UAV system.

Apart from the standard MEDUSA CMOS sensor configuration (PAN + RGB) a hyperspectral version of the camera has been realized by installing a linear variable filter in front of the panchromatic MEDUSA CMOS sensor. This way the camera can acquire both broadband colour images and a hyperspectral image data. First imaging tests have been executed in a laboratory environment. In a next phase the camera concept will also be demonstrated in flight.

7. ACKNOWLEDGEMENT

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