CALIBRATION STRATEGY FOR THE MEDUSA CAMERA SYSTEM

K. Nackaerts *, J. Everaerts, R. Choi, B. Delauré, T. Van Achteren, J. Biesemans,

Vito/TAP, Flemish Institute for Technological Research/Remote Sensing Research Unit, Boeretang 200, BE-2400
Belgium - (kris.nackaerts;jurgen.everaerts;bavo.delaure;tanja.vanachteren;jan.biesemans)@vito.be

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ABSTRACT:

The MEDUSA camera system is a high resolution earth observation instrument designed to operate from a long endurance UAV flying at stratospheric altitudes. Due to the technical constraints imposed on the instrument regarding mass, power and dimensions, the MEDUSA instrument shall experience large temperature variations induced by its varying environment in which it is operated. The induced physical changes of the optical system (lenses and opto-mechanics) imply that the parameters of the geometric camera model of the MEDUSA instrument cannot be assumed to be constant. Generating geometric "correct" images under those circumstances requires a calibration procedure which is able to respond to this dynamic behaviour.

This paper presents the calibration strategy for the MEDUSA instrument which is based on a full in-flight self-calibration with block bundle adjustment. A theoretical estimate of the geometrical accuracy of MEDUSA images has been explored. Based on this approach a first sensitivity check to certain temperature variations within the optical system has been addressed. A more detailed study has started making use of a refined image simulator based on the collinearity equations, a camera model and image distortion models. First preliminary results of this approach show the geometric accuracy over the complete image within different temperature windows for a camera model with constant parameters.

1. INTRODUCTION

The PEGASUS (Policy support for European Government by Acquisition of information from Satellite and UAV-borne Sensors) project aims to fill in the gaps that conventional Earth observation cannot provide in terms of spatial and temporal aspects (Everaerts, 2004). It uses a High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV), called Mercator-1, which will ultimately fly at stratospheric altitudes persistently for weeks and even months. To do this, the platform is powered by solar energy during daytime and high capacity batteries during the night. The airplane design is largely driven by mass minimization where the use of lightweight composite material allowed to realize a total mass of about 30 kg. In order to accomplish disaster monitoring and large-scale mapping as its first phase target applications for the Pegasus project, a high resolution camera system, MEDUSA (Monitoring Equipment and Devices for Unmanned Systems at high Altitude), is being developed by a consortium led by VITO (Delauré 2007, Van Achteren 2006, 2007).

The MEDUSA camera system is designed to deliver imagery in the visual spectrum with a spatial resolution of 30 cm from an altitude of 18km and covers a swath of 3 km.

The technical constraints which the MEDUSA instrument is facing, are severe due to the restricted payload capacity of Mercator-1: no more than 2.5 kg total system mass, fitting within a horizontally oriented cylinder of 12 cm diameter and 1 m in length, consuming less than 50 W of electrical power. Apart from those limitations the environmental conditions of the stratosphere are an important factor to be taken into account in the instrument development process. Since the variation of the environmental parameters induce physical changes of the

optical system, the interior parameters (e.g. focal length, principal point coordinates, etc) of the optical system are expected to vary accordingly. Calibration of MEDUSA needs to take the consequences of these constraints into account. In this paper, we discuss the geometric calibration strategy.

2. MEDUSA INSTRUMENT

2.1 Top-level system requirements

The MEDUSA instrument is designed for large scale mapping and disaster monitoring. The top-level system requirements of the MEDUSA camera are summarized in Table 2-1.

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

Table 2-1 MEDUSA system requirements

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* Corresponding author.

2.2 Environmental conditions

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. Source: the Royal Metrological Institute of Belgium). 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.
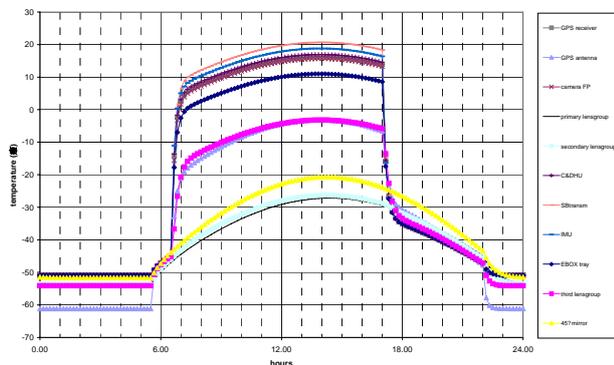

Figure 1: temperature variation of the MEDUSA system during one day (21st June above Belgium) at various positions within the MEDUSA instrument.

The following effects occur:

- Temperature variation during day-time
- Temperature variation depending on day in the operational season
- Thermal gradient along the axis (nose is coldest, back side warmest due to heat dissipation of the electronics)
- Thermal gradient top-down due to the different heat input (sun versus earth)

2.3 MEDUSA Camera System Design

The MEDUSA instrument is plugged onto the front side of the fuselage of the Mercator-1 UAV. To comply with the frontal area constraints of Mercator, the MEDUSA instrument is housed in a horizontally oriented cylindrical volume with a diameter of 12 cm and a length of about 1 m. The MEDUSA instrument, of which more details are described in (Delauré 2007, Van Achteren 2006, 2007), consists of an optics and an electronics compartment Figure 2

Figure 2 shows the layout of the MEDUSA instrument. The former is located at the front of the instrument. It houses the optical system which consists of a folding mirror (to cope with the horizontal orientation of the instrument), a set of lenses and the focal plane assembly containing two CMOS sensors (one panchromatic and one colour) of 10000x1200 pixels each. The focussing elements of the optical system are fixed together in a metal structure (4-lens tube) which is mounted in the Carbon Fibre housing.

The electronics compartment is located at the backside of the instrument. It houses the command and data handling unit (responsible for on-board data processing and housekeeping within the instrument), and a lightweight IMU and dual frequency GPS-system. Via an S-band transmitter and antenna JPEG2000 compressed image data is being transferred at a rate of 20 Mbps to the ground control station. The instrument is designed to generate a forward overlap of 70% taking into account the forward speed and attitude variations of the aircraft. This is realized at a frame rate of 0.7 fps.

Due to the large temperature variations to which the MEDUSA instrument is subjected and the temperature sensitivity of the optical system (focal shift of 20μm/°C), a passive thermal compensation system is implemented. This compensator rod, shown in Figure 2, adjusts the distance between the 4-lens tube and sensor plane, driven by the temperature within the optics compartment. This way the optical system is kept in focus continuously.

Apart from the temperature sensitivity the optical system is also pressure dependent. A focal shift of about 300μm takes place when reducing the pressure from ground-level atmospheric conditions to stratospheric pressure (60 mbar). For this reason a mechanical adjustment needs to be performed on-ground depending on the expected operational in-flight pressure regime.
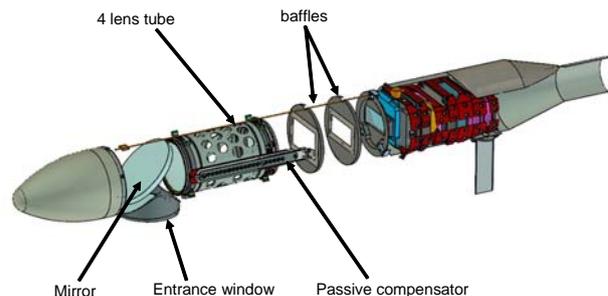

Figure 2: Layout of the Medusa instrument

3. GEOMETRIC CALIBRATION CONSIDERATIONS

Due to the specific design and operational environment of the MEDUSA system, the geometric calibration of the MEDUSA instrument is not straightforward.

Since the MEDUSA instrument faces strong variations of its environment during its operational cycle, the optical system undergoes physical changes. For this reason the camera parameters describing the MEDUSA imaging system cannot be considered to be constant during the operational window. First analyses of the current design indicate the following dependencies:

- Focal length variation (due to change of refractive index and lens surfaces) 20 μm/°C
- Due to the fact that the fixation of the 4-lens tube to the carbon fibre structure is not athermal, the principal point can shift with about 22 μm over a temperature range of 50°C

First simulations show no significant temperature dependence on the radial and tangential lens distortions.

The geometric calibration approach for the MEDUSA instrument needs to be able to cope with this dynamic behaviour.

Second challenge is that the instrument cannot be calibrated at room temperature and atmospheric pressure. Therefore a ground calibration of the MEDUSA instrument would require the operation to be performed in a thermal vacuum chamber. Although this is possible in principle, it is difficult to realize the exact thermal conditions (radial and axial thermal gradients) in this simulated environment.

A third aspect to be taken into account is the presence of the folding mirror. Further investigation is necessary to investigate how possible deformations of the reflecting surface, induced by temperature variations of the mirror material and its interface pieces to the athermal carbon fibre structure, need to be modelled.

4. CALIBRATION STRATEGY

The MEDUSA instrument is designed for large scale mapping and disaster monitoring. Therefore the primary focus of the calibration is on geometric correction of the imagery, which is the topic of this paper. Radiometric calibration of the instrument shall be considered in a second phase.

Ground geometric calibration of imaging platforms remains a most complex operation (Zeitler, 2002). A direct drawback of ground calibration is that the results are only valid for similar operational conditions.

In case of the MEDUSA instrument, this assumption is not valid (see above). For this reason we have opted for a full in-flight geometric calibration approach based on block bundle adjustment. Such a geometric calibration strategy has proved to be successful for other more complex imaging systems such as the ASD40 from Leica (Tempelmann, 2003).

4.1 Geometric Ground calibration

During the performance test of the optical system in a thermal vacuum chamber a rough determination of the focal length and principal point will be performed. This will be used as starting value for the in-flight calibration method.

4.2 Geometric In-flight calibration

The in-flight calibration is prepared by a two-phase sensitivity analysis for various aspects of the instrument based on expected ranges of environmental parameters.
In a first phase, the generalized photogrammetric accuracy of the instrument is explored for the "normal case" (Kraus, 2007). This provides a first insight into the significance of different parameters on the potential photogrammetric accuracy of the MEDUSA instrument.

According to the normal case equations:

$$\sigma_X = \sigma_Y = m_b \cdot \sigma_x$$

$$\sigma_Z = m_b \cdot \sigma_x \cdot \frac{Z}{B}$$

with

$$m_b = \frac{Z}{FocalLength}$$

Z = elevation
σ_x = accuracy of tie point identification in the image
B = distance between observations

For the expected accuracy at which tie points can be identified (σ_x) a value of 1/3 of the pixel size is taken as a first estimation. In best case scenario's, this accuracy can reach ¼ of a pixel or better.

The distance between observations can be estimated based on the image characteristics and planned along track image overlap:

$$B = W \cdot (1 - R)$$

with

$$W = Z \cdot \frac{Pixels \cdot Pixelsize}{FocalLength}$$

R = overlap

When we assume the Medusa instrument will operate between 15000 and 21000 meters above ground, the expected overall planar accuracy can be estimated to be within the decimetre range (Figure 3).

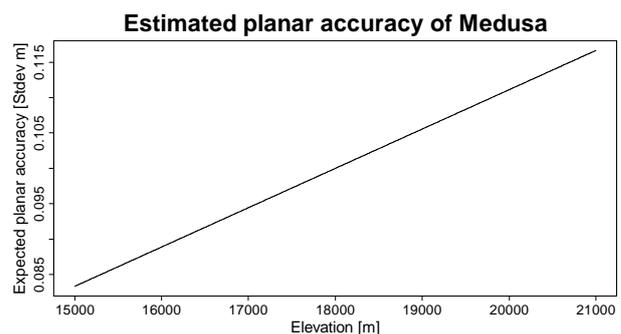**Estimated planar accuracy of Medusa**

Figure 3: Planar accuracy of Medusa versus altitude

The overall vertical accuracy is expected to be approximately 1.5 meter, when using 60% side overlap (Figure 4).

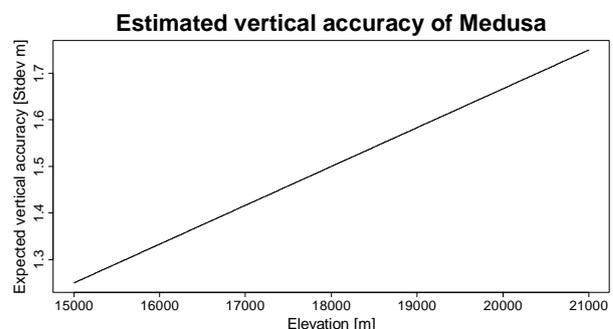**Estimated vertical accuracy of Medusa**

Figure 4: Vertical accuracy of Medusa versus altitude.

By comparing the expected vertical accuracy as extracted out of along track (Figure 5) versus across track (Figure 6) overlapping imagery, it is highly advisable not to use along track overlap for the extraction of elevation data. The vertical

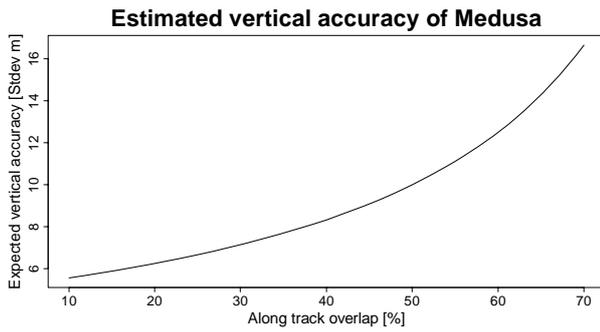accuracy is ten times lower when only along track overlap is used.

Estimated vertical accuracy of Medusa

Figure 5: Effect of along track overlap
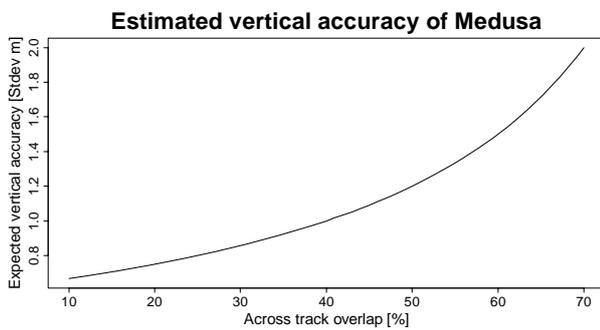
Estimated vertical accuracy of Medusa

Figure 6: Effect of across track overlap on generalized vertical accuracy

Because of the distinct rectangular shape of the sensor, the image base is much smaller along track compared to across track. The extreme altitude at which the Medusa operates amplifies this.

The same "normal case" approach also allows us to get a first impression on the effect of system temperature on the geometric performance of the instrument. Simulation studies have indicated that the focal length changes with 20 μm per °C, we can simulate the effect on the overall planar accuracy, assuming a flying height of 18000 meter (Figure 7):
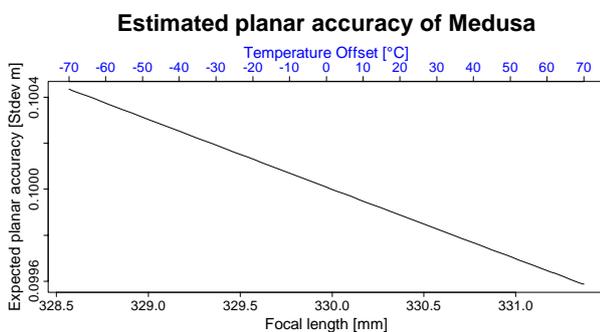
Estimated planar accuracy of Medusa

Figure 7: Effect of temperature on generalized planar accuracy

Figure 7 indicates clearly that the variable focal length, caused by temperature differences, has a limited effect on the generalized photogrammetric performance of the Medusa instrument.

When we compare this temperature related effect with variations in overlap, it becomes clear that the temperature effect on focal length is negligible (Figure 8):

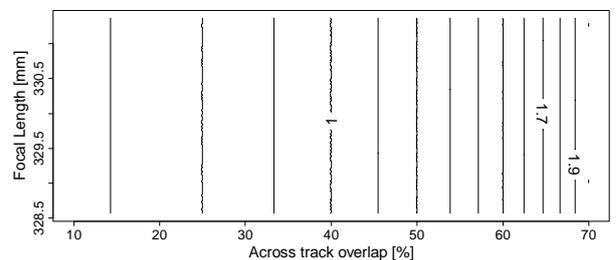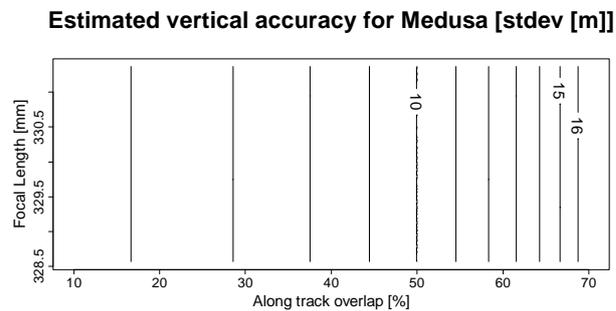**Estimated vertical accuracy for Medusa [stdev [m]]**

Figure 8: Effect of changes in focal length versus along and across track overlap. The vertical lines visible in the plot correspond to isolines of equal generalized vertical photogrammetric accuracy [stdev[m]]

The highest gradient in generalized vertical photogrammetric accuracy is visible along the "% overlap" axis. Relative to this, changes in focal length due to expected temperature differences has no influence.

In a second phase, sensitivity analysis is performed more in detail based on collinearity equations, a camera model and image distortion models. A refined (image) simulator is developed that allows us to simulate each characteristic of the Medusa instrument in detail and estimate the effect on measurement precision and accuracy. Figure 9 illustrates the concept.

These simulations allow us to get a thorough understanding of the type of image distortions we can expect. Moreover, it allows us to estimate the effect on the geometric performance of the Medusa instrument if we cannot correct for the distortions.

Figure 10 illustrates preliminary results of this approach: In case changes in focal length would not be taken into account when extracting object (real world) coordinates out of imagery using direct georeferencing, measurement errors of up to 6 meters can be expected at the outer regions of the imagery. No additional error is simulated in the exterior orientation (theoretical GPS/IMU values) for these direct georeferencing simulations.
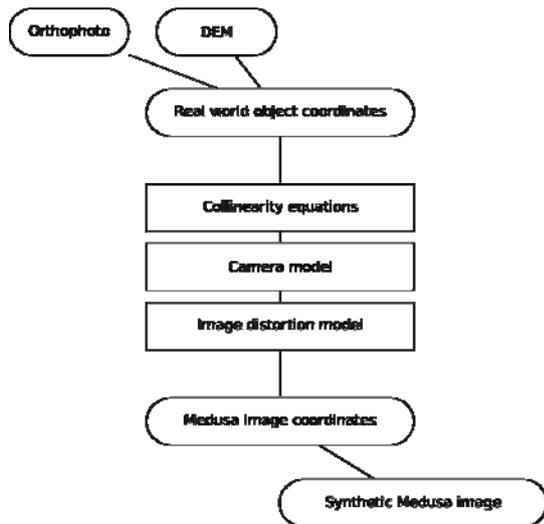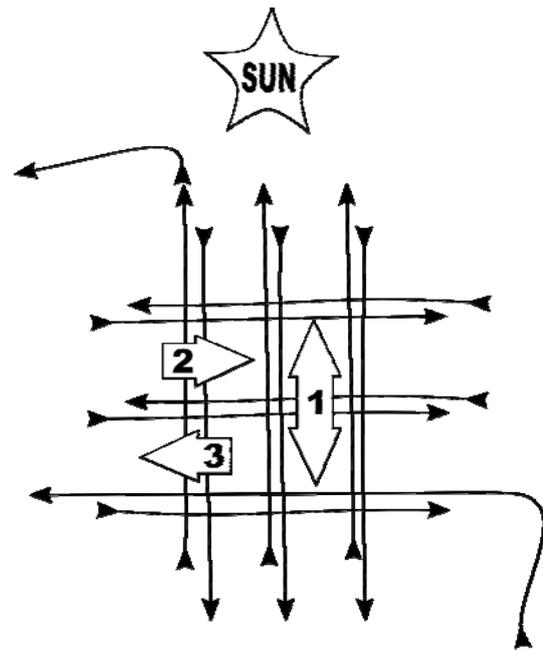
Figure 9: Medusa simulator concept

Effect of changing focal length due to temp. diff. on direct georeferencing
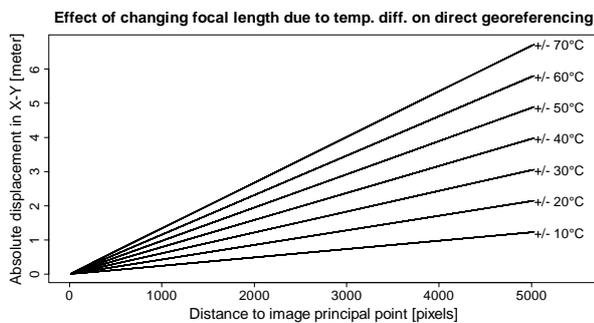
Figure 10: Effect of changing focal length on direct georeferencing.

This indicates that a thorough self-calibration approach is necessary when metrically correct products need to be derived from the Medusa instrument.

The in-flight calibration will be based on self-calibration by means of block bundle adjustment. The DGAP block bundle adjustment software (http://www.ifp.uni-stuttgart.de/ publications/software/openbundle/index.en.html) will be used for this. A predefined flight pattern will be flown over a fixed study area with sub centimetre accurately measured GCPs. Figure 11 illustrates a minimally required flight pattern resulting in maximally overlapping imagery with flight over the same area in opposite directions.

Because of the expected temperature effects, a specific flight pattern, oriented relative to the sun's positions is needed. The data will be processed in three independent blocks, illustrated as numbered arrows in Figure 11. During the flights within block one, the temperature gradient within the instrument will remain relatively constant. For flights in block two and three, temperature gradients will change direction. The proposed flight pattern will allow to examine if the foreseen temperature gradients will have a significant effect on the optical characteristics of the system.

Figure 11: Minimal required flight pattern for Medusa instrument calibration

Parameters that will be estimated by block bundle adjustment are:

- Physical models
  - Exterior orientation (6 parameters)
  - Interior orientation
    - Principal point offset (2 parameters)
    - Focal length offset (1 parameter)
  - Radial-symmetric distortions (3 parameters)
  - Radial-asymmetric and tangential distortions (2 parameters)
  - Affinity and shear in the image plane (2 parameters)
- Mathematical models
  - Ebner (12 parameters)
  - Grün (44 parameters)

Because of the correlations that may exist between some parameters (e.g. Platform altitude versus focal length offset), the adjustment will be run piecewise.

For modern geometric frame cameras, it can be expected that the parameters of the mathematical models are not significant: these parameters are not correlated with the interior and exterior orientation of the imaging system and are used to correct distortions in the plane caused by for example deformations of analog film products. However, usage of an optical mirror in the Medusa instrument might introduce similar deformations and will therefore be examined with care.

5. CONCLUSION AND OUTLOOK

A specific calibration strategy is proposed for the Medusa instrument. Because of the technical constraints of the instrument and its specific operation environment, in-flight calibration was selected. On the one hand, the instrument comprises an optical mirror, which could introduce planar

image distortions uncommon in modern metric frame cameras. On the other hand, temperature is expected to have an impact on various optical characteristics of the Medusa instrument.

A thorough sensitivity analysis will be conducted at first. Block bundle adjustment, in combination with a specific flight pattern will be used to determine the significance of thermal effects on the geometric performance and the system's internal and external calibration model.

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