OPTICAL GROUND SUPPORT EQUIPMENT FOR THE SENTINEL-4 SCANNER SUBSYSTEM

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ABSTRACT

RUAG Space is currently developing the scanner subsystem for the Sentinel-4 UVN sounder [1]. The high precision scanner has two rotational degrees of freedom with 14° and 19° of angular range. To measure the repeatable error (e.g. fingerprint) and the pointing performance of the scanner, a measurement system in the micro-radian accuracy range is needed. The combination of the large two axis scanning range in combination with the required measurement accuracy (absolute accuracy ± 10 µrad) is highly challenging. Commercial off-the-shelf solutions either have a too small range or are not precise enough. Therefore, RUAG Space decided to develop a new measurement system. The found solution is based on three commercial off-the-shelf distance measuring laser interferometers and four autocollimators.

Special mathematical calibration- and measurement-algorithms make it possible to quickly calibrate the system before each measurement and to perform the measurements in a very efficient way.

An extensive test program was performed which showed that the performance of the OGSE is in line with the specified values and it has already successfully been used to test the S4 QM scanner.

The developed measurement system is very generic and can be easily adapted for any other two axis large range and high accuracy measurement task.

INTRODUCTION

In the frame of the Sentinel-4 mission, RUAG Space developed a highly accurate mechanical scanner [1]. The scanner is part of a high resolution UVN sounder which is used to measure air pollution for the Copernicus initiative. The scanner has two rotational degrees of freedom with 14° and 19° of angular range, moving the mirror to scan the scene to acquire an image.

In order to achieve the required accuracy, a measurement system with an accuracy in the micro-radian range is needed to:

- assess the repeatable error of the scanner in order to correct it;
- verify the performance of the mechanism.

For that matter, RUAG Space developed an Optical Ground Support Equipment (OGSE). The OGSE uses three laser interferometers to measure three points on the plane defined by the scan mirror. Post-processing those points enable to define the two angles of the scanner. Autocollimators are then used to transfer the angles from the OGSE to the scanner reference.

The OGSE measurement accuracy does not rely on precisely manufactured parts. Its precision is guaranteed through the dimensional stability of the structure, a stable holding of the scanner assembly, and precisely aligned autocollimators and interferometers. Environmental sensors are used to correct the distance measured by the interferometers and thus the measurement stability over time.

A detailed analysis and test program was performed to assess the performance and stability of the OGSE.

DESIGN DESCRIPTION

The S4 UVN Scanner Subsystem OGSE is a measurement setup based on:

- a stable stainless steel structure
- four autocollimators
- three laser interferometers
- a stiff carbon structure (later on referred to as carbon pod) containing the optical references

Mechanical Structure

The structure is built up by two main parts: i) the scanner carrier plate and ii) the autocollimator/ interferometer carrier plate. Four steel bars hold the two carriers together. Structural stiffeners are added to increase the Eigen frequency of the structure. Figure 1 shows a functional schematics of the OGSE setup. Figure 2 and Figure 3 show the OGSE design in CAD.

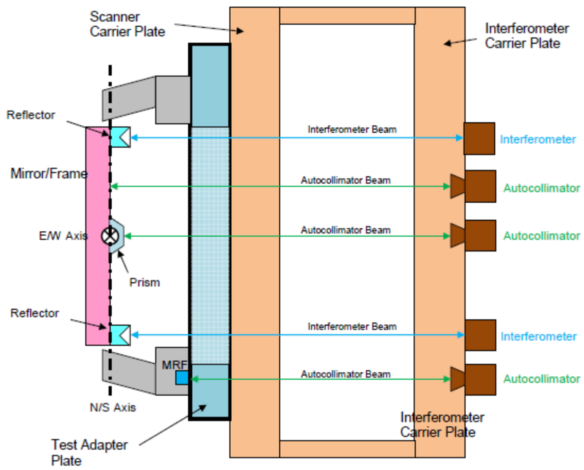

Figure 1 – Functional schematic of OGSE measurement principle. On the left hand side is the scanner which sits on the scanner carrier plate. The scanner carrier plate is connected via four steel bars to the interferometer carrier plate.

The autocollimators are connected to this main structure with rotational stages. Like this, they can be aligned to their respective optical target in all three orientations. For the interferometers, stages with 2 translational and two rotational degrees of freedom is used. This is because the interferometers need to be aligned in rotational as well as translational orientation.

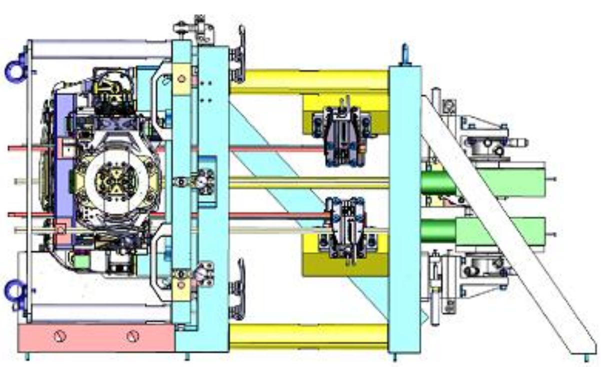

Figure 2 – OGSE from the side: Left: Scanner on test adapter plate, Middle: Connecting steel bars and interferometers, Right: Autocollimators

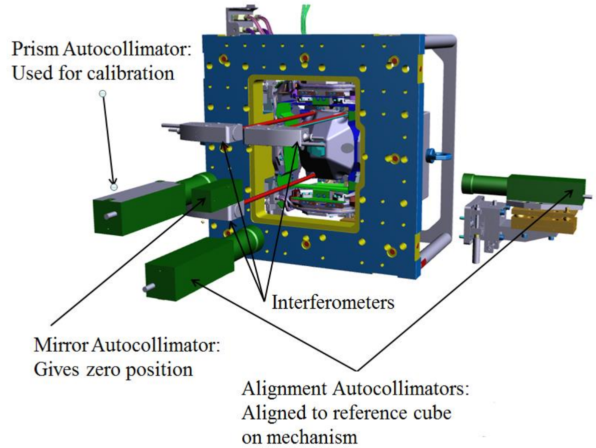

Figure 3 – OGSE design overview with all optical elements

Optical Elements

To measure the angle of the mirror of the S4 mechanism, three laser interferometers are used. They point at three retro-reflectors mounted on a carbon pod (see Figure 4) which is mounted on top of the scanner mirror during testing. A fourth retro-reflector is available to make the pod symmetric and hence usable in two different orientations. In the middle of the carbon pod sits the prism which is used to calibrate the OGSE.

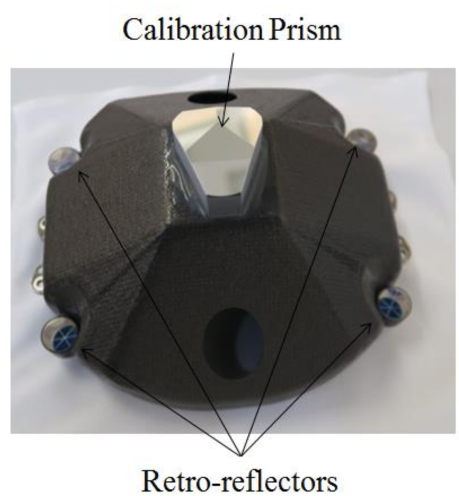

Figure 4 – Carbon pod with optical references (four retro-reflectors and the calibration prism)

Due to the use of small retroreflectors and a lightweight pod design, the impact of these elements on the dynamic behavior of the scanner is kept to a minimum in order not to upset the dynamic control stability of the close-loop system.

In addition to the interferometers, four autocollimators are used to:

- Calibrate the OGSE
- Find the zero position of the scanner
- Align the OGSE to the scanner reference frame defined by reference cubes on the scanner

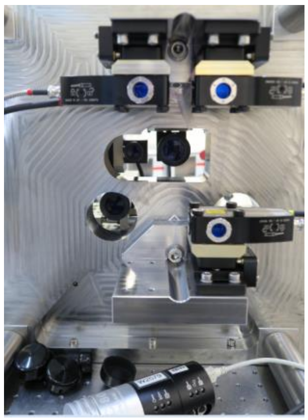

Figure 5 – Close up view of optical elements (three interferometer in the front and three autocollimators at the back

Environmental Sensors

In order to improve the stability of the OGSE, environmental sensors are used. They measure:

- Air temperature
- Humidity
- Pressure

The data of these sensors is used to compensate for wavelength changes of the laser of the interferometers.

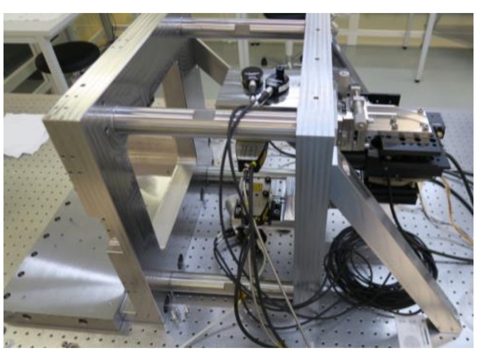

Figure 6 – Overview of OGSE structure with no scanner mounted. Left: Position where scanner will be placed, Middle: Interferometers and environmental compensation sensors, Right: three of the four autocollimators.

MEASUREMENT METHOD

Computing the scanner angles using the OGSE is a two-step process. First, the OGSE needs to be calibrated. In this process, the distances between the interferometers is computed. Once this step is completed, the angles can be calculated using the interferometer distance measurements.

Calibration

Before an angle can be computed, the OGSE needs to be calibrated. This is done by moving the scanner such that, one after the other, surfaces of the calibration prism on the carbon pod are aligned to the prism autocollimator. The calibration algorithm takes the interferometer measurements of these four alignment positions along with the knowledge of the prism angles to compute the distances between the interferometers. This principle is shown in *Figure 8***Error! Reference source not found.**.

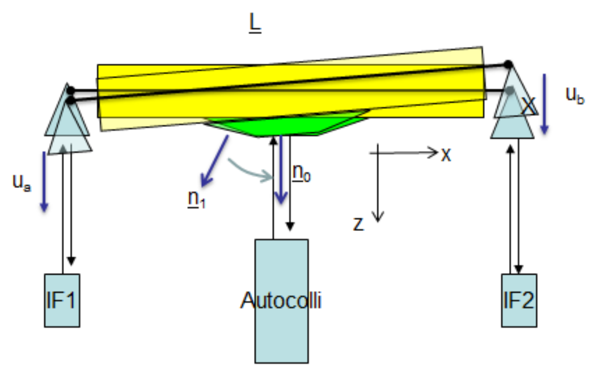

Figure 7 – Schematics of OGSE calibration: Autocollimator is used to align the four surface of the prism to a known position. Using the interferometer distances at these four positions, the distances between the interferometers can be computed.

Angular Computation

The angular computation of the optical metrology system is based on three laser interferometers that perform simultaneous distance measurements. The measurement of these three points combined with the knowledge of the distance between the interferometers (obtained by calibration) define the plane given by the scanner mirror and hence the two scanner angles.

The interferometers measure the distance from a reference plane to the retro-reflectors on the mirror. This defines one degree of freedom of the points in space. The second two degrees of freedom, which are the distances between the interferometers, are given by the calibration. A schematic of this measurement principle is shown in Figure 8.

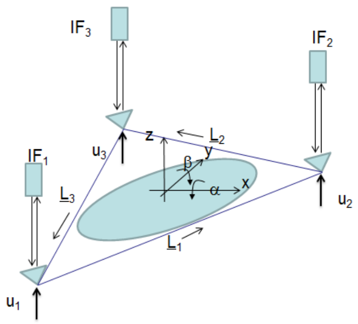

Figure 8 – Schematic of the OGSE working principle: Three interferometers point at retro-reflectors on the mirror. Using the distances from the interferometers to the retro-reflectors and the distances between the interferometers, the two angles of the plane can be computed. The distances between the interferometers can be computed using the calibration prism.

The prism autocollimator and the mirror autocollimator are aligned to the cube autocollimators, which are again aligned to the reference cubes of the scanner defining the scanner reference frame. Like this, the OGSE is aligned to the scanner reference frame.

PERFORMANCE VERIFICATION

In order to show that the performance of the OGSE is in line with the requirements, an extensive verification test program was performed. This program can be divided into three steps.

First a set of functional tests was performed. In this step:

- the algorithm used to compute the scanner angles is verified using simulation data;
- interferometer measurements are used to compute real angles;
- the range of the OGSE is verified by moving the mirror in the scanner range.

In the second step, the stability of the OGSE is verified. For the stability investigation, first individual building block are tested. For further tests more building bocks are investigated together until the stability of the whole OGSE is measured.

The last and third step consists of taking the results from the two previous steps and using a geometrical model, assessing the overall performance of the OGSE. For the performance assessment, possible error sources are analyzed and their effect on the accuracy investigated. For some error sources manufacturer specified value are used. For more complex error sources, measurements are needed.

Functional Verification

To compute the angle of the scan mirror using the interferometer measurements, an algorithm based on geometry is used. A numerical algorithm was developed to derive the scanner angles based on a set of non-linear equations. The verification of the algorithm was performed using a CAD simulation of the system. The test data generated by the simulation consists of the distances from a reference plane to the retroreflectors for the:

- calibration positions
- the mirror zero position
- a random position which is used to check the algorithm.

This test data is generated first for the ideal case and then also for the imperfect case, where the prism is rotated with respect to the mirror.

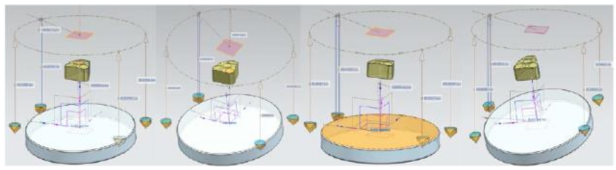

Figure 9 – Images from the CAD simulation to generate test data to verify the OGSE algorithm

The next step of the functional verification is to use the OGSE with real interferometer data. A main success criteria of this test is also that the OGSE covers the full angular measurement range.

Stability Verification

When working with accuracies in the order of magnitude required for the OGSE, even smallest environmental effects can cause large deviations on the measured angle. An important property of the OGSE is therefore to have a good stability over time. In addition to that, if deviations occur, the OGSE needs to be easy to reset.

The first stability test consists of verifying the environmental compensation. For this, one interferometer points at a static retro-reflector. Both elements are mounted on a temperature stable Invar jig. This setup is shown in Figure 10.

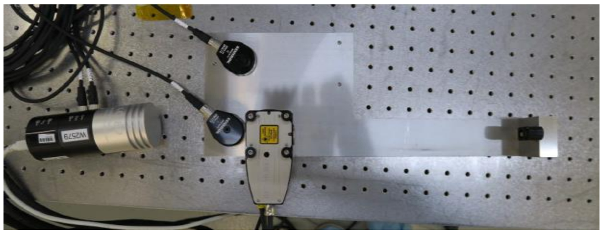

Figure 10 –Test setup for environmental compensation verification: Interferometer and retro-reflector are statically mounted on temperature stable jig. Environmental data and interferometer data is recorded for 24 hours

For 24 hours, the interferometer distance, as well as the environmental data, are monitored. The laser wavelength is then compensated using the Edlén equations [2]. Both the compensated and uncompensated distance measurements are plotted in Figure 11. It can be seen that the compensation works and that the signal is much more stable than the uncompensated measurement.

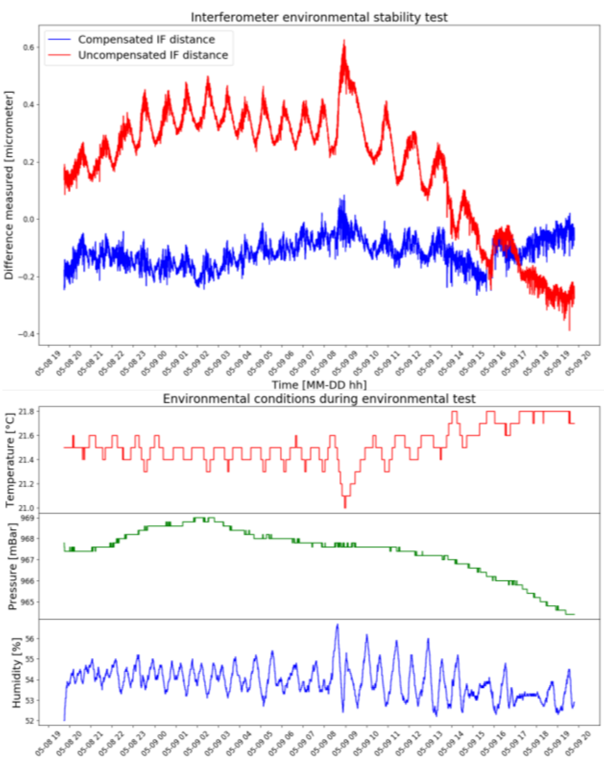

Figure 11 - Environnemental Compensation Test Conditions. Top: Compensated and uncompensated distance measurements. Bottom: Environmental sensors data.

The second stability test is the verification of the structural stability. The goal of this test is to assess the stability of the interferometer measurement including the OGSE structure. For this, the carbon pod is mounted on a stable steel bar where usually the scanner would be placed. The test setup is shown in Figure 12. The three interferometer distances, as well as the environmental sensors, are then monitored for 24 hours. From the interferometer measurements, the resulting angles are then computed. The results can be seen in Figure 13. The maximum deviation seen after 24 h is 15 µrad. To compensate this effect, several temperature sensors would have to be placed on the structure along with a detailed model for thermal expansion. This is not needed since we can align the mirror to the mirror autocollimator in order to reset the OGSE.

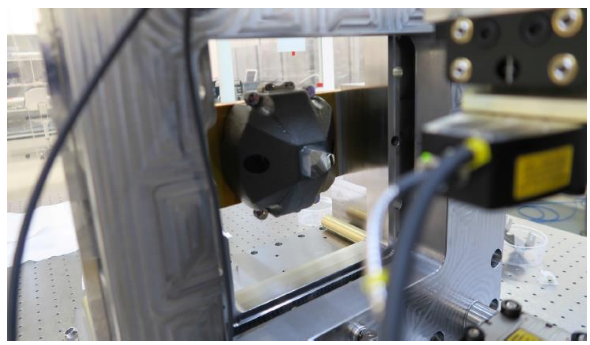

Figure 12 – Test setup for OGSE structure stability: The carbon pod is mounted on a stable steel bar. The interferometer distances as well as the environmental sensors are monitored for 24 h.

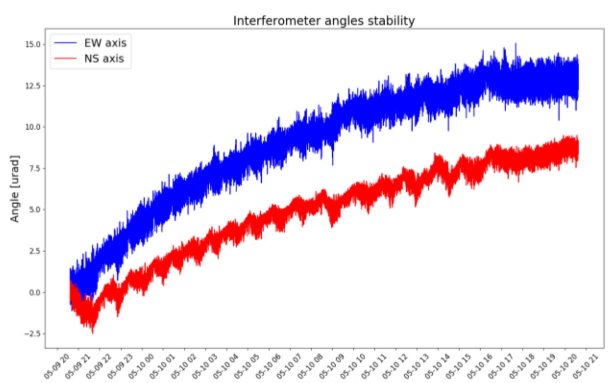

Figure 13 – OGSE structure stability test results after environmental compensation. The remaining deviation can be explained by small structural movements due to local temperature changes. The deviation can easily be reset by aligning the mirror to the mirror autocollimator.

Performance Verification

The last step of the verification consists of taking the results from the stability tests along with the error estimation of the individual components and feeding it into a geometrical model. The geometrical model can take these error estimations and convert them into an angular error over the range of measurement.

The results of the combination of all error sources can be seen in *Table 1*. The results are well within the needed accuracy to measure the performance of the S4 scanner.

Absolute Accuracy	± 10 urad
Relative Accuracy	1 urad
Angular Resolution	0.0056urad
Speed Capability	3.33 rad/s
OGSE Range	14° NS and 19° EW simultaneously

Table 1 – Results of performance verification

RESULTS FROM S4 QM TESTING

The OGSE was first used for the Sentinel 4 QM mechanism with good results. As described above, the OGSE is used to measure the fingerprint as well as the performance of the mechanism.

Figure 14 shows the measurement of the fingerprint of the EW axis. The top view shows the overview of the whole range of motion of the EW axis, which looks like there was a lot of noise present. But in the bottom view, which shows a close up of the fingerprint, we see that the "noise" is actually the harmonic fingerprint of the encoder. The encoder fingerprint was in line with the expectations gained on previous component level tests.

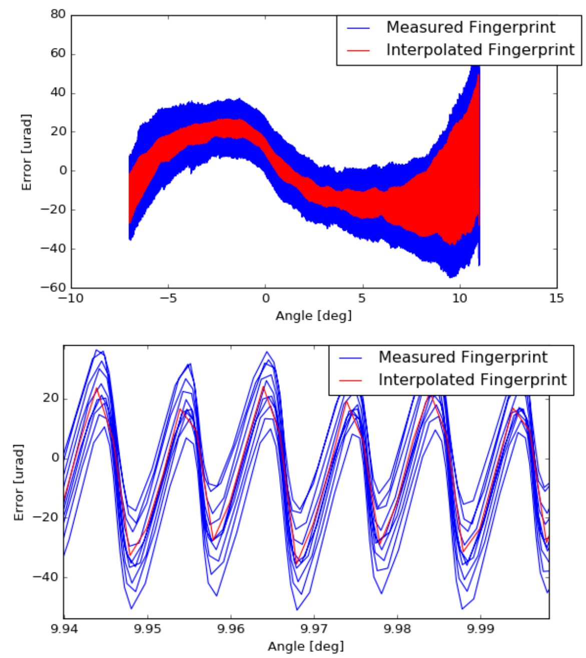

Figure 14 – EW axis fingerprint measured by the OGSE after multiple scans (blue) and interpolated fingerprint correction (red). Top: Overview over the whole range of the EW axis. Bottom: Close-up view reveals the harmonic error of the encoder.

SUMMARY AND CONCLUSION

For the Sentinel 4 mission, RUAG Space has developed a high precision two axis scanner. In order to measure the fingerprint of this scanner and to verify the performance of the scanner, an optical measurement system was developed (OGSE). The system is based on three interferometers which measure three points on the mirror plane and hence define the two scanner angles. Four autocollimators are used to calibrate the OGSE and align the measurement system to the scanner coordinate system. The calibration approach adopted by RUAG for the OGSE avoids the need to have highly precise manufactured parts and exact direct measurements of the sensor targets, which would be nearly impossible for the high accuracy required over a large scanning range.

A detailed test program was performed to verify the performance and stability of the OGSE. The results of the verification were in line with the specified values and the OGSE has successfully been used on the S4 QM mechanism.

The developed measurement system is very generic and can be easily adapted for any other two axis large range and high accuracy measurement task.

REFERENCES

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[2] Edlén, B. (1966). The refractive index of air. *Metrologia 2, 71-80*