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Transmitter Beam Bias Verification for Optical Satellite Data Downlinks with Open-Loop Pointing – the 3-OGS-Experiment

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ABSTRACT

Optical free-space data downlinks from LEO satellites benefit considerably from reduced effort on the space segment, when a dedicated pointing mechanism and active tracking of a ground beacon can be avoided. Instead, the attitude of the satellite is dynamically determined from its star cameras and other sensors. Initial calibration for this technique requires recording of the spatial and temporal beam distribution on the Earth's surface. We describe the measurement of the beam intensity on ground by the power detectors of three ground stations in parallel, exemplarily for one specific downlink. From this data we derive the instantaneous center of gravity of the beam spot, and its dynamic movement during the downlink. By comparison with the satellite's own recorded attitude data and its error, the dynamic offset to be corrected on the satellite can be calculated, resulting in optimized pointing-control for future operational open-loop downlinks.

Keywords: optical LEO satellite data downlinks, optical ground station, satellite flash finder, open loop pointing, CPA-less, star camera, dynamic pointing error, beam center-of-gravity triangulation

1. INTRODUCTION

With the immense demand for increasing data throughput in Low-Earth-Orbit (LEO) satellite data downlinks, optical transmission technologies gains importance. It offers much higher data-rates than their RF-counterparts, without requiring frequency coordination. Furthermore, the involved transmitter terminals onboard the satellite are small (few centimeters in transmitter aperture), while also the ground receiver (OGS – Optical Ground Station) is rather small with few decimeters in telescope-aperture diameter [1]. Global standardization is already ongoing for optical space links, currently with emphasis on the direct-to-Earth scenario employing an Optical On/Off-Keying (O3K) modulation format [2]. During the LEO-downlink phase, the transmit beam must be constantly pointed to the OGS, with a precision dependent on the beam-divergence, where this divergence is minimized to allow they highest possible signal intensity at the receiver.

Different approaches are being followed to enable this dynamic downlink pointing: when an optical beacon from ground illuminates the satellite's optical terminal, this signal serves as a reference for the downlink-signal pointing. However, this approach requires a tracking path and -sensor integrated into the terminal, and according control loops which asses the tracking signal's deviation. Then this information needs to be fed into the pointing control of the satellite, or into an -

even more sophisticated – mechanical pointing assembly of the laser terminal itself (Coarse Pointing Assembly and Fine Pointing Assembly, CPA and FPA).

In a simpler approach - only marginally impacting the satellite layout - the laser transmitter collimator is fixed to the satellite's body, and steered open-loop by the satellite's attitude control. This attitude again is controlled by the existing standard sensors such as star-cameras and magnetic field sensors onboard the satellite. Reaction-actuators onboard the satellite allow its rotation according to the overflight trajectory. Any typical LEO satellite can add such optical data downlink technology, as long as attitude precision allows its operation in a laser downlink. What is more, the adoption of the transmitter divergence to the attitude control ability of the satellite will allow an optimized system for each specific satellite mission [3][4].

What remains to be optimized is the knowledge of the satellite's pointing direction: the signal power strength observed by an OGS only allows the estimation of the instantaneous radial error, but does not provide information on the deviation-direction. To enable such, the beam's ground intensity distribution would need to be observed over the whole uncertainty area on ground – which is technically impossible. Instead, by some kind of triangulation with three intensity-measuring receivers (together with the knowledge of the gaussian signal beam shape and -strength), the beam spot's location can be calculated. This method is applied here, where three ground receivers deliver time-tagged received power values at 100 milliseconds each. A fitting algorithm compares the measured intensities with the values estimated from link budget calculations (regarding the tilting of the receiver plane with link elevation), and conveys the real position of the beam's spot center. The deviation from its optimum position can thus be calculated, and in future downlinks this deviation shall be minimized.

1.1 Challenges of satellite's pointing control

One service steering a satellite is the attitude and orbit control subsystem (ACS). During routine operations, the ACS is responsible for several tasks (performed as ACS modes), like pointing solar panels to the sun, inertial pointing for observe celestial objects like the moon, pointing to nadir during data acquisition or ground station contacts and finally pointing a laser on a target on ground or elsewhere. All modes can come with additional commandable offset parameters, e.g. a constant offset from the roll axis supports off-NADIR earth observations, or constant offsets respect building offsets of components. Depending on the complexity of the ACS onboard soft- and hardware, further parameters are possible like a constant rotation along some selected satellite axis.

The commanded attitude mode is achieved by actuators, like reaction wheels or thrusters. While sun and inertial pointing are rather stable activities, where the ACS just needs to compensate for small error after the corresponding mode is achieved, other like Nadir-pointing need a constant interaction of the ACS software with the given actuators and sensors to constantly keep the deviations from a target small. Pointing towards a selected target on Earth has an even higher dynamic. The rate of change is small in the beginning of a visible pass over the target. During the pass the dynamic is highest in moment of highest elevation. From the satellite's perspective this is a moving target, passing by in a certain distance. To achieve the required level of accuracy, software should be performant enough to come up with steering controls for the actuators in time and all hardware components involved should have optimal conditions.

Laser communication with on/off keying modulation – as employed here - is not affected by rotation around the beam axis. This gives one additional degree of freedom, that can be used to hit the target while avoiding blinding of the star sensors by the Sun or the Earth.

2. ELEMENTS OF THE EXPERIMENT

2.1 The FLP-Satellite and its laser data transmitter OSIRISv1

The small satellite "Flying Laptop" (FLP), launched in July 2017, was developed and built by graduate and undergraduate students at the Institute of Space Systems of the University of Stuttgart with support from space industry and research institutions. The mission was planned with a two-year lifetime but was extended twice as the satellite proved to be working fine. The satellite has a mass of 110 kg and is currently in its fifth year of operation. Besides the "Optical Space InfraRed downlInk System" first version (OSIRISv1), its mission goals include Earth observation with its multispectral camera system and AIS receiver as well as providing an educational show case during the curriculum of aerospace engineering in Stuttgart. Flying Laptop has a three-axis stabilized attitude control system. The attitude determination uses two star cameras from the Technical University of Denmark (DTU) and four fibre-optic gyroscopes [5]. During operation of OSIRISv1, the satellite points towards the ground station without feedback from the instrument. OSIRISv1 has two body mounted collimators which are facing Flying Laptop's z-axis with a small deviation from the normal axis of that face. This deviation was calibrated in relation to the Star Cameras with data from previous overflights over DLR's Optical Ground Station Oberpfaffenhofen (OGSOP). During 3OGSE, the collimator with 1mrad FWHM divergence and 1W transmit power was used. The setup of OSIRISv1 on Flying Laptop is shown in figure 2 [6][7].

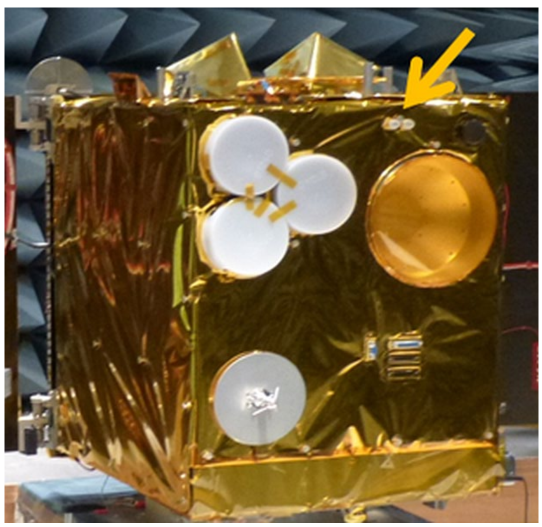

Figure 1. Photograph of Flying Laptop Satellite and the two transmitter collimators of OSIRISv1 (beneath arrow).

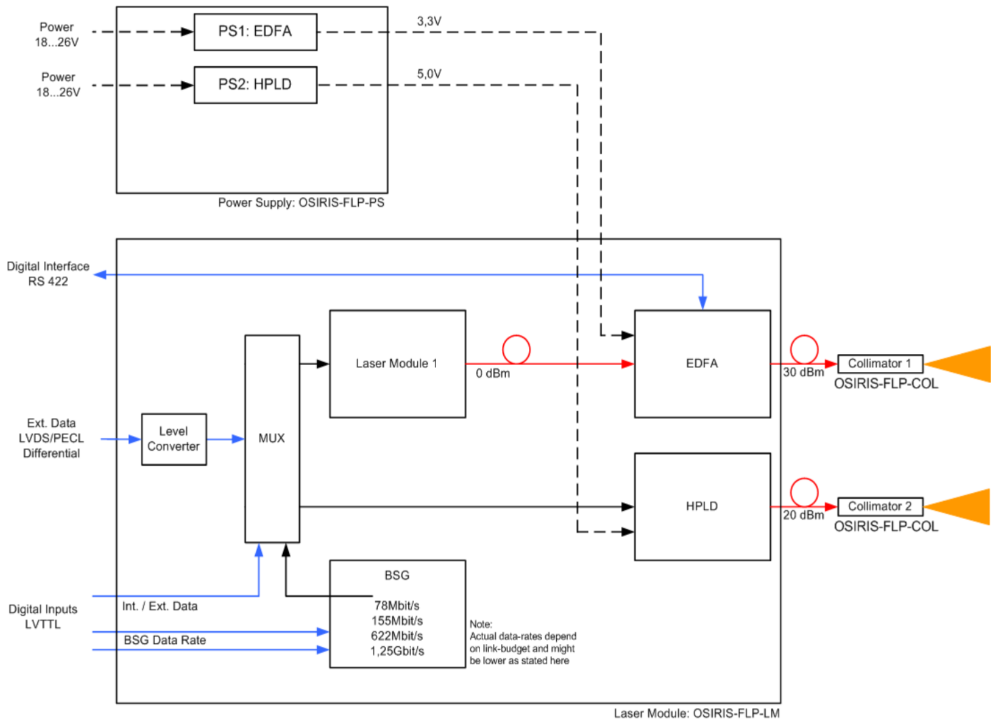

Figure 2. OSIRISv1 setup, as located onboard FLP.

2.2 Satellite orbit, specific downlink contact, and OGSs topography

The FLP satellite was launched on 14th July 2017 to attain a Sun-synchronous orbit at altitude 586x604 km and inclination 97.5º.

In the evening of the 20th October 2021 between 20:24:37 and 20:34:50 UTC (*22:xx local time*) the laser signal from OSIRISv1 onboard FLP was observed by three Optical Ground Stations located at the DLR-site Oberpfaffenhofen. Figure 3 shows azimuth, elevation, and distance, over time, to GSOC-OGS, but we assume these data equal for all three receivers since they were located very close together.

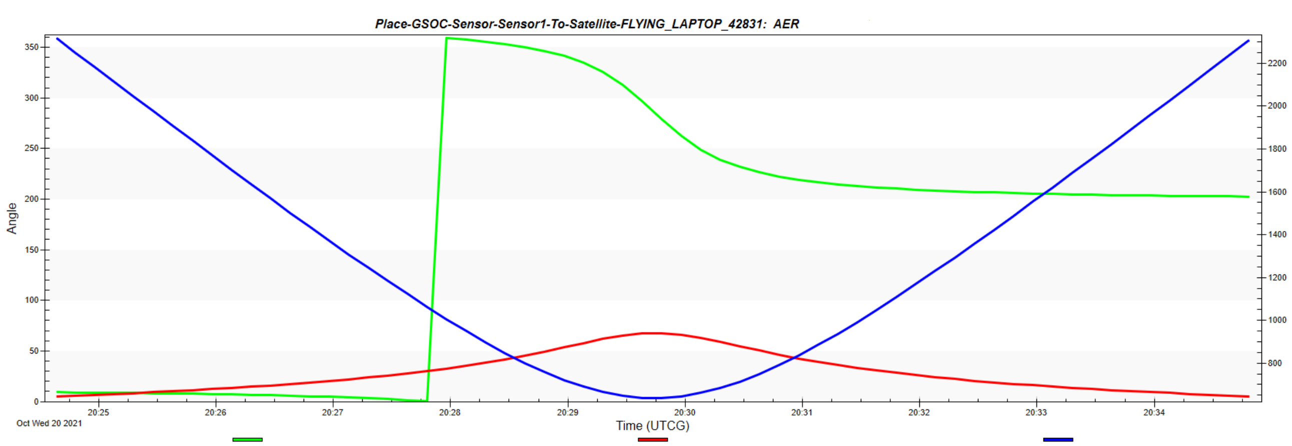

Figure 3. Az-El-Dist Plot of the specific downlink.

The ground terminals were arranged in a close-to right-triangle. The downlink signal was switched on (and partly observed on ground) from 5° elevation to maximum of 67.7° and back to 5° elevation.

Several OGS' are available for experiments at German Aerospace Center, site Oberpfaffenhofen [8]. For the 3OGSE described here, we employed one OGS on the roof top of the German Space Operations Center (GSOC-OGS), another on the roof of the Institute for Communications and Navigation (IKN-TOGS), and a newly developed "Satellite Flash Finder" (SFF) – see figure 4 [7][8][9].

Figure 4. Aerial view of the receiver-site, indicating the locations of the three OGS. North is at top. The red area shows the ideal FWHM beam intensity at ~25° link elevation, centered on the GSOC-OGS. The three OGS-locations approx. resemble a rectangular triangle, with leg distances of: GSOC-SFF ~172m and SFF-IKN ~290m.
[Satellite picture by Google Maps, © GeoContent, Maxar Technologies]

Before "open-loop-pointing" satellite downlinks can be employed on a regular and reliable basis, the orientation-bias of the laser transmitter direction versus a reference axis of the star sensor must be identified and ground-pointing must be calibrated accordingly. Depending on the mounting concept and the rigidness of the satellite structure, the initial error can reach high values (up to nearly one degree), making estimation of this bias possibly a long-term and high effort exercise.

2.3 The Satellite Flash Finder "SFF" as an additional OGS for intensity measurement

To ensure that the communication links are performed without any major alignment errors, the Satellite Flash Finder (SFF) was developed, which speeds up and simplifies the calibration phase of satellites using appropriate hardware. Automated regular operation for satellite-path observation, and identification of correct pointing timing was the main development goal. The SFF consists of a pan/tilt unit, a daylight- and an infrared camera, and according control software.

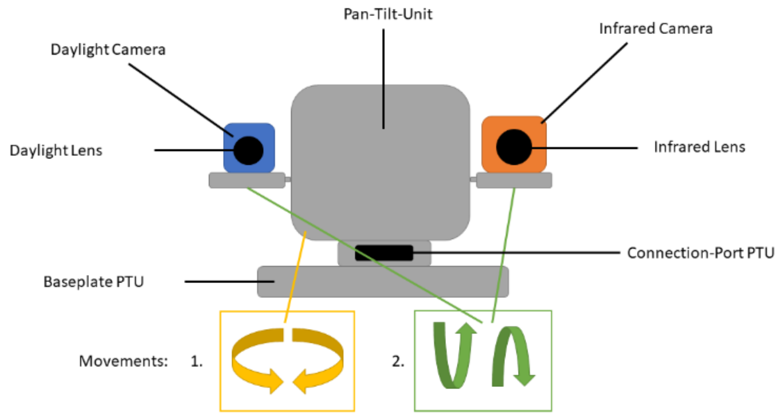

Figure 5. Functional diagram of the Satellite Flash Finder.

The main task of the SFF is to record the optical satellite signal over the entire pass. This is done by creating a pointing model with the daylight camera, tracking the satellite orbit with the pan/tilt unit and recording of the optical satellite signal with the infrared camera with a rather wide field-of-view. Based on the recordings, it is possible to make precise statements about the alignment and intensity of the optical signal.

Since the SFF is light and compact, it was used as another ground station for the 3OGS-experiment. On the evening of the experiment, FLIR's pan/tilt unit (PTU 5) was used to track the satellite. The pointing model was created by the daylight camera (DMK33GX265) developed by "The Imaging Source" with an attached Fujinon lens (HF35XA-5M), giving a field of view of 12 degrees. The optical satellite signal was recorded by the infrared camera (Goldeye G-008 TEC1) developed by Allied Vision with an attached Kowa lens (LM100JC1MS), resulting in a field of view of 4 degrees. The SFF was controlled using custom software developed in-house.

Figure 6. Photograph of the Satellite Flash Finder with an infrared- and a daylight-camera.

2.4 Optical ground station and power sensor at GSOC – "GSOC-OGS"

This optical ground station consists of a 30cm Cassegrain telescope (TS 12"-f/8-Ritchey-Chrétien-Astrograph, TS-Optics), and an optical SOFA-unit mounted at its focus (Small Optical ground station Focal Assembly) [10]. The entire setup is installed on an ALT-ALT mount (NTM600, Astelco Systems). The SOFA includes a daylight camera (DMK33GX265, The Image Source)), an IR camera (Bobcat320, Xenics), a power meter (OE-200-S, FEMTO) and an optical detector for data reception (APD-RFE100new), developed in-house. The daylight camera is required to create the precise pointing model. The IR camera performs the closed-loop tracking of the satellite, and the optical power meter (controlled via a remote connection) was used for the power measurements analyzed here, providing a FoV of 1.03mrad. The amplified output signal is acquired by a DAC, time-tagged, and stored for further processing [11]. Figure 6 shows the schematic structure.

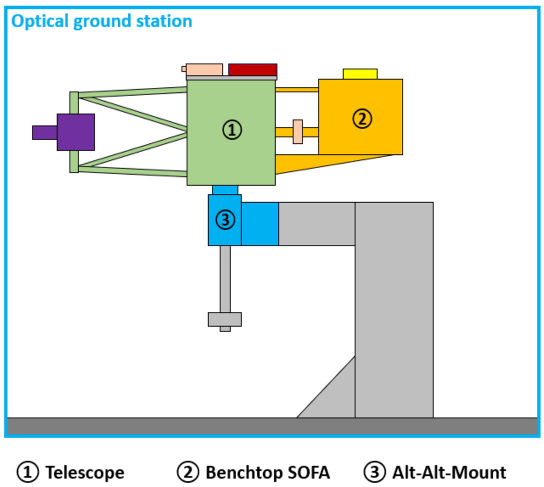

Figure 7. Schematic structure of the 30cm optical ground located at GSOC.

2.5 Station on IKN-rooftop - "IKN-TOGS"

DLR's Transportable Optical Ground Station (TOGS) is currently located on the rooftop of the Institute of Communications and Navigation (IKN) at Oberpfaffenhofen [8]. With its 60 cm Ritchey-Chrétien Telescope it provides the ability of open loop pointing as well as closed-loop tracking of an infrared optical signal. TOGS has been used for FLP satellite tracking within this experiment. For characterization of the received optical signal, it has been equipped with an additional power sensor, that is based on the development in [12] mounted next to the primary mirror of the telescope. The sensor consists of a two-inch diameter telescope, holding an optical filter (1550 nm center wavelength, 50 nm bandwidth) as well as a 200 mm focal length lens. A Variable Gain Photoreceiver Module (Femto OE-200-IN2) with its 0.3 mm diameter InGaAs-PIN detector is attached at the focal point of the lens. The amplified output signal is acquired by a DAC, time-tagged and stored for further processing. The power-sensor thus acquires infrared signals from within a Field of View of 1.5 mrad onto a 50 mm aperture. It has been co-aligned to the TOGS' pointing by use of a 1550 nm test-source, located at a distance of 6.6 km. Measurements had been taken previously in lab for proper sensitivity calibration.

Figure 8. The 60 cm Ritchey-Chrétien-Cassegrain Telescope of DLR-TOGS, with the black 2" Power-Sensor mounted on top next to the primary mirror.

3. OPTICAL INTENSITIES MEASURED AT OGS' AND TRIANGULATION OF THE SPOT'S CENTER OF GRAVITY MOVEMENTS

3.1 Link budget of the OSIRIS-downlink

The expected received signal intensity can be estimated by a link budget calculation. Necessary boundary parameters are aperture-area, telescope-internal losses, and signal splitting between different sensor branches inside the receiver. The Tx signal power from the satellite, the beam divergence, distance, and atmospheric attenuation define the axial intensity on ground. This theoretical axial value is the on-axis optimum when beam pointing is directly onto the OGS [13].

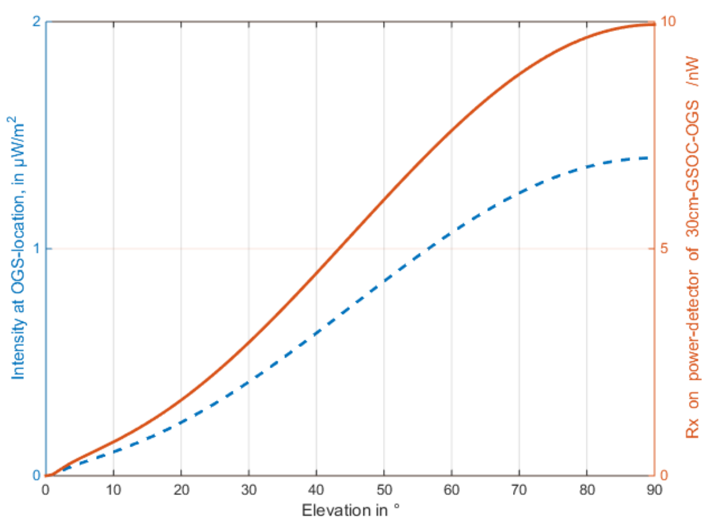

Figure 9. Calculated axial Intensity at OGSs-distance (dashed line, left axis) and optical power onto the power detector of the GSOC-OGS (solid line, right axis)

Figure 10 shows the data basis for the offset-estimation, the three intensity vectors observed during the optical downlink. GSOC-OGS shows deterministic outages due to data-unloading of the measurement device. Intensity-data was back-calculated from the three received power vectors, regarding telescope-areas, telescope-internal attenuations, and detector sensitivities.

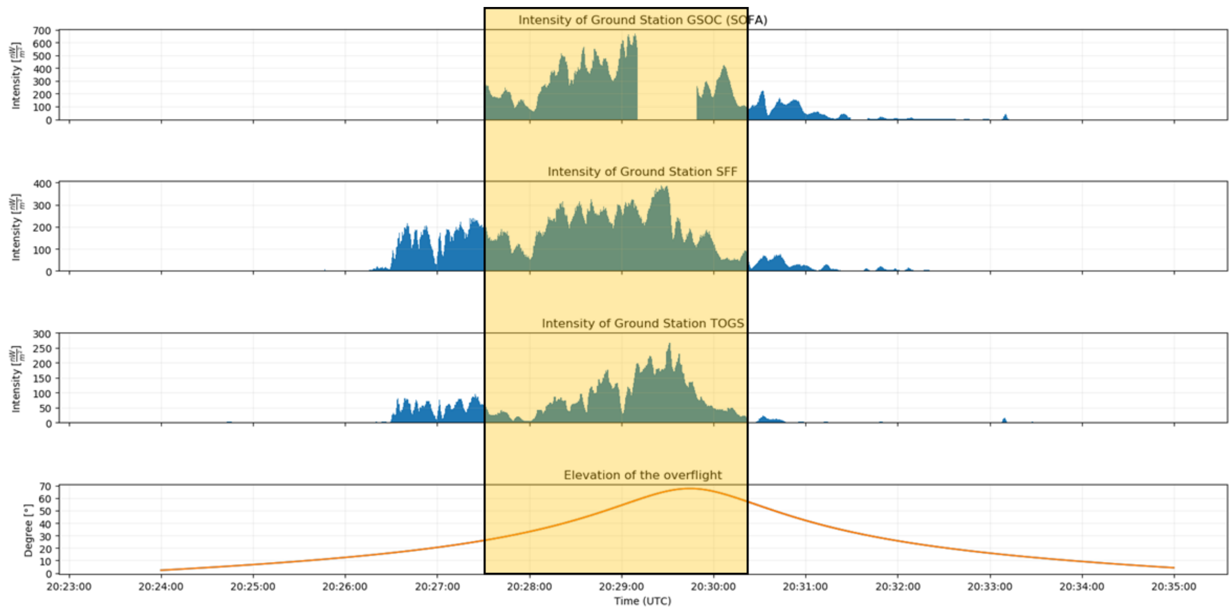

Figure 10. Intensities onto the three OGS' vs time, back-calculated from the measured received optical power. Time-window evaluated for 3OGSE is marked. Lowest plot shows the elevation over time.

3.2 Algorithm deriving the run of pointing-deviation

To determine the center-of-gravity (CoG) migration of the optical signal, all recorded data from the 3OGS were used. Each ground station recorded the FLP optical signal differently. All data were converted to intensity values in the uniform format nW/m^2. In addition, the data were time synchronized at 100 ms intervals.

On the evening of the flyover, the optical ground station at GSOC was chosen as the target for pointing the FLP and so it was taken as the reference point for all further calculations to determine the CoG of the optical signal. Using the beam divergence θ, the distance z and the transmitted power P at a given time, the theoretical Gaussian intensity distribution - in the plane perpendicular to the beam axis - can be calculated as:

$$I(X,Y,z) = P \cdot \frac{2}{\pi \cdot \omega_0{}^2(z)} \cdot e^{-2 \cdot \left(\frac{\left(\frac{X}{x_0}\right)^2 + \left(\frac{Y}{y_0}\right)^2}{\omega_0{}^2(z)} \right)}$$

$$with: \omega_0(z) = \frac{1}{2} \cdot z \cdot \theta_{e^{-2}}$$

The next figure shows the theoretical Gaussian intensity distribution for the overflight point at 20:27:30.200 UTC with an azimuth of 2.317 degrees and an elevation of 26.084 degrees in the plane perpendicular to the optical beam centered on the GSOC ground station. The locations of the other ground stations TOGS and SFF are mostly not in the perpendicular plane and so it is necessary to project them in. Thus, depending on the overflight coordinates, other distances of the ground stations to each other are obtained.

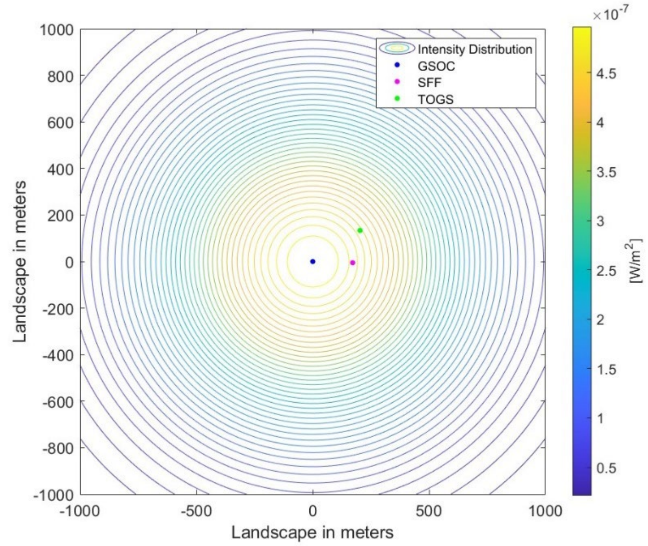

Figure 11. Theoretical Gaussian intensity distribution of FLP's optical signal at 20:27:30 UTC (25° elevation, 1203km link distance), in the perpendicular plane to the laser beam.

However, the figure shows the case if the optical beam would have illuminated the GSOC-OGS perfectly. At that time the GSOC ground station measured an intensity value of 269.85 nW/m^2, which is a significant deviation compared to the maximum Gaussian intensity value of about 500 nW/m^2. To determine the CoG of the optical signal, the center of the theoretical Gaussian is shifted meter by meter. For each step, the differences between the theoretical and measured intensities are calculated for all ground stations. The squared sum of the differences gives an indication of how good the pointing of the optical beam was at that step/position. The next figure shows the squared sum of the intensity differences over the whole analyzed area:

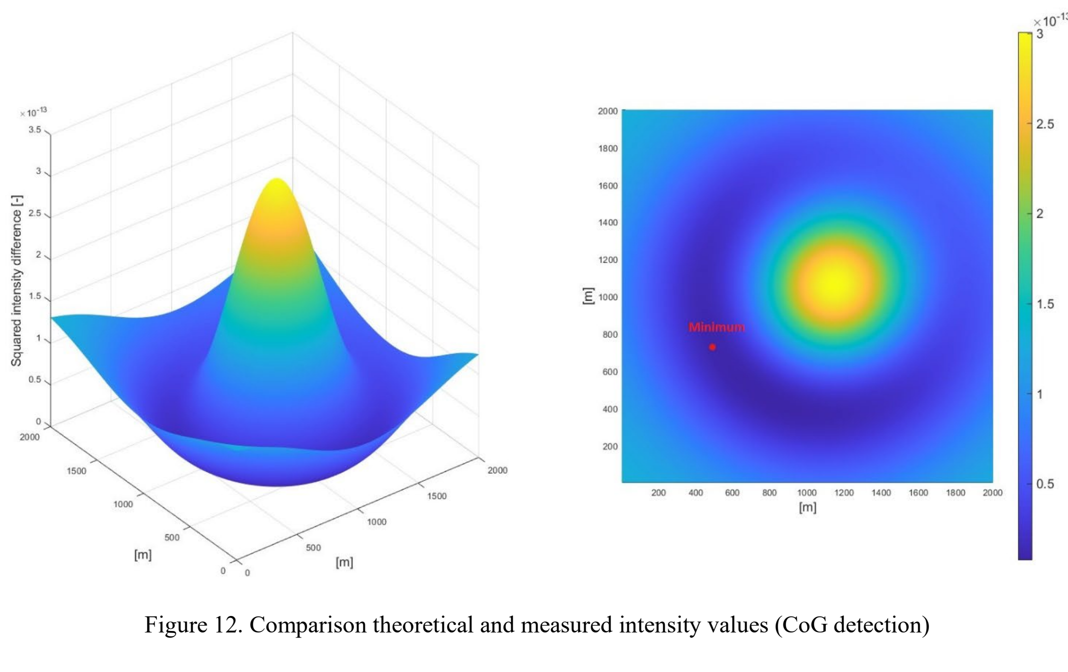

Figure 12. Comparison theoretical and measured intensity values (CoG detection)

Based on the evaluated data, an absolute minimum can be determined, which represents the center of gravity of the beam for an overflight point. The strongly pronounced maximum, on the other hand, indicates the point where the difference was the highest.

3.3 Practical estimation of CoG offset from individual optical power measurements

In the preceding chapter, the CoG of the optical beam at one overflight point was determined. Now, using the recorded intensities between 20:27:30 to 20:30:20, the complete centroid migration of the signal spot in the plane individually centered on the GSOC (axis of rotation) is calculated and shown in the next figure:

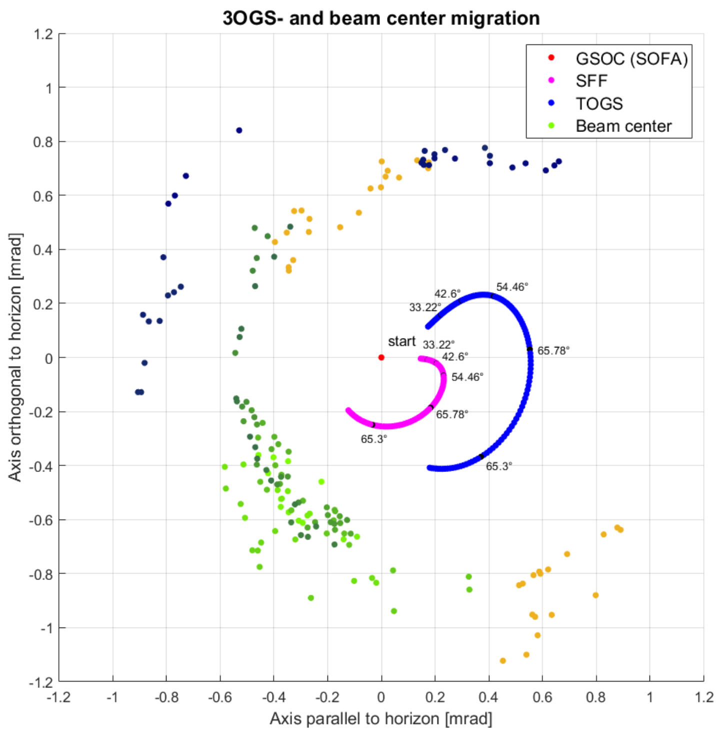

Figure 13. Run of the CoG-offset in *mrad*, on the plane(s) perpendicular to the laser beam, estimated from the three intensity vectors. These positions (dots) are separated by 1s each, starting with green at bottom (at 20:27:30) going to blue on top (at 20:30:20). Orange dots mark the section where intensity from only two OGS where available, resulting in 50% of the solutions appearing ambiguous at the lower right. The positions of the three OGS' can be seen with GSOC-OGS in center (red), and SFF (pink) and TOGS (blue) separated to the right, wandering by their perspective positions. Their locations are marked on their plots every 30 seconds with the according elevation.

The figure shows the run of the calculated beam centers at 1 second intervals. It can be seen that the beam had a relatively large offset from its main target (GSOC), especially at low elevations (up to 1mrad). As the elevation increases, the offset becomes smaller towards maximum elevation (~0.4mrad). In addition, the virtual location migration of the other two ground stations (SFF and TOGS) in the perpendicular plane to the beam can be observed.

3.4 Comparing pointing error with the satellite's attitude measurements

The on-board attitude determination is based on the fusion of attitude quaternions from the star cameras and rotation rates from the fibre-optic gyroscopes. The accuracy during the higher rotation rates of a ground station passage decreases due to the relative movement of stars during the integration time of the star cameras. An indicator of the knowledge error is the inter-bore-sight angle (IBA). The IBA describes the angle between the two star camera bore-sights and it only depends on the relative error of the star camera solutions. If the IBA is close to its expected value, the noise on the star camera solutions is low. The IBA during the whole overflight is plotted in figure 14.

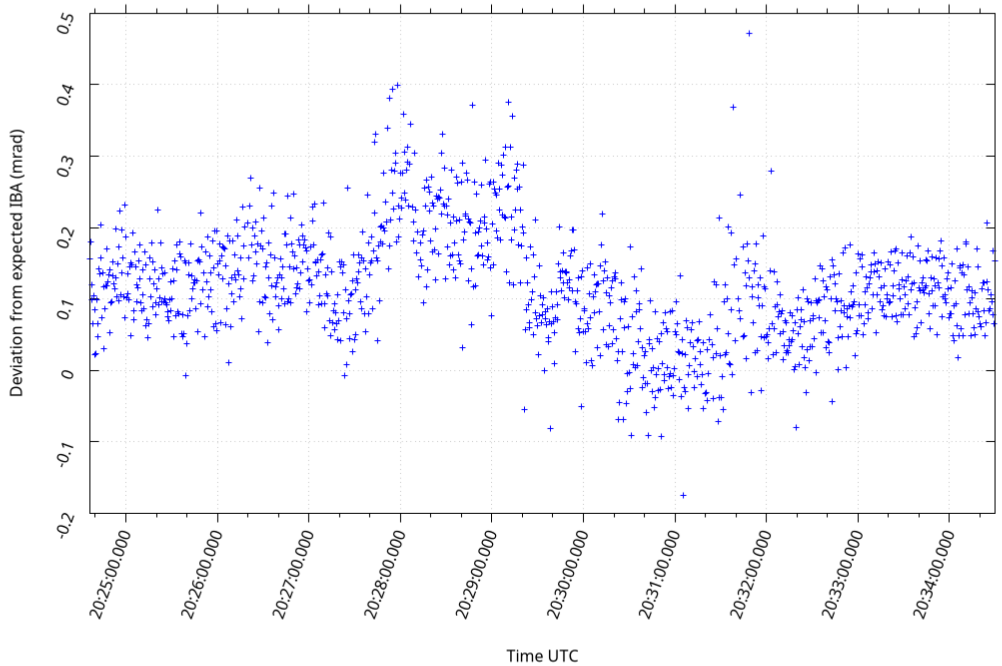

Figure 14. Deviation from expected Inter-Bore-sight Angle of the two Star Cameras, secondwise

With this information we can estimate the knowledge error to be in the same order as the IBA deviation. The following graph, does not include the estimated knowledge error as its direction is unknown.

As OSIRISv1's direction is towards FLPs z-axis the pointing error over the passage can be plotted as deviation to that axis. More precise the axis used in the graph is the beam-direction previously calibrated from past experiments. The fixed deviation of that axis from FLPs z-axis is 17.69 mrad. Figure 15 shows the moving average of the attitude of the GSOC-OGS from the satellite perspective. The data starts with green dots at 20:27:30 and ends with dark blue at 20:30:30. The FLP's x-axis points towards the vector perpendicular to the orbit normal (cross product of position and velocity vector) and the z-axis. The y-axis completes the right-hand system.

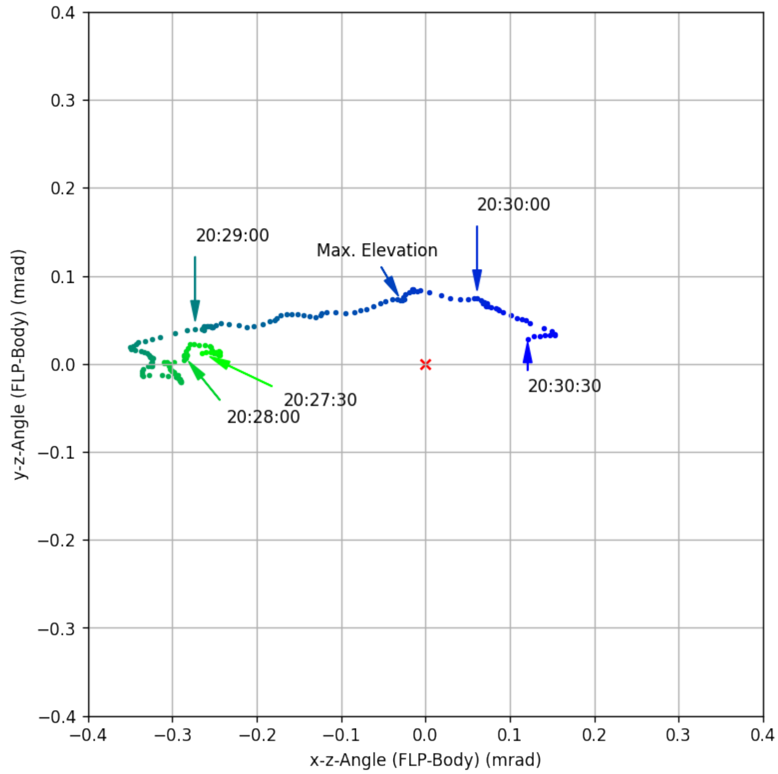

Figure 15. Plot of the pointing-error as measured by the satellite's AOCS, dots are separated by 1s.

The difference between Figure 13 and Figure 15 is caused by the knowledge error described above as well as the uncertainty in the pointing direction of OSIRISv1. While the residual radial error experienced by the satellite through its AOCS is only up to ~300 µrad, the error measured on ground by the 3OGSE becomes up to ~1 mrad, explaining well the intensity-loss observed on ground.

4. RESULTS AND FUTURE APPLICATION

We show the implementation of an automated "Satellite Flash Finder" as a means to identify on ground the time of illumination with an optical satellite signal, to deduce the correct beam exit direction from a fixed satellite terminal. By that, we facilitate and speed up the beam bias estimation, enabling a faster calibration phase of body-pointing laser-transmitters.

To identify the complete position error of a beam wandering on ground, a dynamic triangulation with three Optical Ground Station (i.e. power sensors) has been performed. By back-calculating from measured power to the signal intensity on ground, and estimating the error of the three intensity values with expected distribution form link budget calculation, the dynamic beam pointing error could be resolved. Comparison with the satellite's AOCS data confirmed the measured error, where a broader time-spectrum and precision can be expected by optical measurements. In this specific case, a circular error offset can be identified, arguing for a somewhat fixed offset on one satellite axis.

This 3OGSE verified the feasibility of the measurement, however the proceeding and evaluation-algorithm must be further refined to increase reliability and accuracy.

The information of miss-pointing can in future be fed to the satellite attitude control algorithm to identify offset pointing error directions, and accordingly improve the open-loop pointing. It will then allow the use of even smaller divergent optical signal beams, to increase data rate and thus increase downlink throughput of such simple optical links even further. Moreover, the practical benefit of our semi-automated approach to verify the pointing bias of a laser transmitter opens the perspective to roll out small, low-complexity space-terminals at larger scale at a faster pace.

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