Laser Communication with Alphasat - FD Challenges and First Flight Results

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Abstract: *Inmarsat's geostationary satellite Alphasat, launched on July 25, 2013, is the largest European telecommunications satellite ever built with a weight of 6.6 tons. For technology demonstration it is carrying different payloads, hereunder the laser communication terminal (LCT) built by Tesat-Spacecom and operated by DLR/GSOC. Its purpose is to establish bi-directional data links with data rates of up to 1.8 Gbit/s. Links can be either within space, so called inter-satellite links (ISL) to counter terminals in low Earth orbit (LEO), or from the geostationary satellite to terminals mounted on ground stations on the Earth's surface, space-to-ground links (SGL). This paper gives an overview about the LCT operations aboard Alphasat and its counter terminals. The corresponding work flow from visibility computations over link scheduling until command generation is described. Furthermore, it provides a deeper insight into the flight dynamics tasks that comes along with the operations of an LCT, such as visibility calculations and pointing performance analysis. The results of the first successfully performed links are presented.*

Keywords: *Alphasat, Laser Communication, Attitude Dynamics, Flight Dynamics Operations.*

1. Introduction

Operating a laser communication terminal on-board of a geostationary (GEO) satellite comes along with a pack of advantages for data transmission. An almost constant visibility to the ground station and high transmit rates allow a huge amount of transmitted data. On the one hand the data produced on-board of a GEO satellite can be made available on ground faster than via X-band, Ku-band and even Ka-band radio-frequency transmitters. On the other hand the GEO satellite can be used as a data relay, i.e. receive the data from satellites in LEO and transmit it to the user on ground, acting as a forwarding instance. Also data safety is a factor arguing for optical communications. Less interference with other signals and hampering of data eavesdropping due to the reduced cone of a laser beam improves the security of the data. As drawback and major challenge on LCT operations the requirements on very high pointing accuracies of the laser terminals should be mentioned, which is needed for a successful link. Furthermore, during ground links the atmospheric effects have to be considered and links may be interception by clouds which claims data buffering on the GEO spacecraft [1].

The average visibility time of a LEO satellite to a ground station lies between 10-12 minutes, and is limited to 4-5 passages per day - if the ground station is not located near the poles. Since the amount of data produced on current Earth observation satellites is quickly growing the traditional approach of dumping the data during ground station passes will soon reach its limit and is not sufficient for future missions. An option is to use a data relay service on a geostationary satellite to provide the data to the end-user on ground [2,3].

Alphasat, launched on July 25, 2013, is a precursor mission to the European Data Relay System (EDRS) project. It carries a laser communication terminal (LCT) called TDP1 (Technology Demonstrator Payload 1) developed by Tesat-Spacecom and operated by DLR/GSOC [4]. Since 2007 two similar LCTs are already flying on-board of the LEO satellites TerraSAR-X and NFIRE to demonstrate the applicability of inter-satellite communication [5].

The concept of a data relay is quite elementary as illustrated in Fig. 1. The generated data of a LEO satellite is transmitted via laser to a GEO satellite, here Alphasat, whereof it is directly distributed to ground having constant visibility. On Alphasat this forwarding is done by means of the Ka-band radio-frequency antenna, since there is no data-buffering foreseen, but in general optical communication is feasible for that task, too.

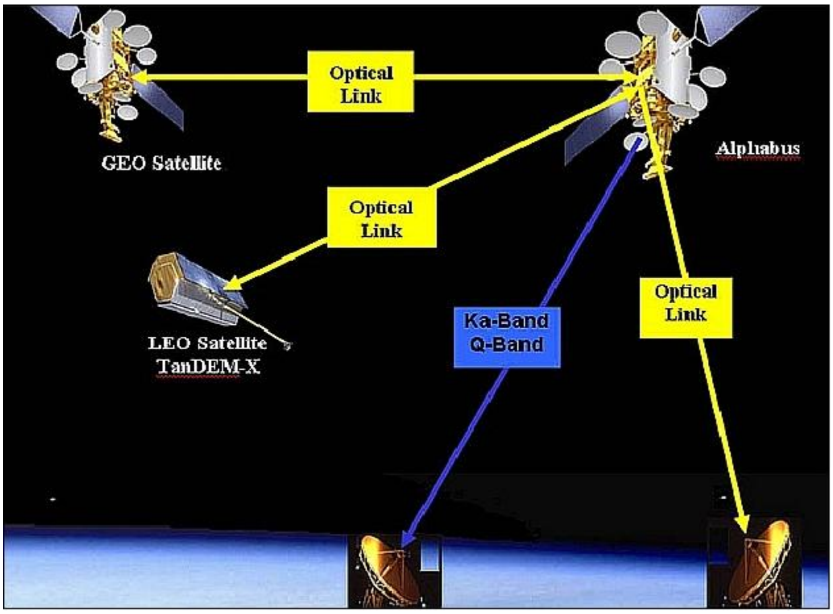

Figure 1. Illustration of communications links with Alphasat [6]

While DLR/GSOC only supported the operations for TerraSAR-X – NFIRE laser communication, it is fully responsible for the operations of the TDP1 terminal on-board Alphasat and all its counter terminals. GSOC acts as Mission Control Center with interfaces to [2,4]:

- Alphasat Mission Control Center (INMARSAT, London),
- ESA TDP Coordination Office (ESOC, Darmstadt),
- Sentinel 1A/2A LEO Platform Operation Center (ESOC, Darmstadt),
- Sentinel 1A/2A Mission Planning Center (ESRIN, FUCINO),
- Ka-Band Ground Antenna (DLR/DFD, Oberpfaffenhofen), and
- Mobile Optical Ground Station (TESAT SpaceCom, Tenerife).

A detailed design of the TDP1 ground system at GSOC is given in [7,8]. The major Flight Dynamics relevant tasks are:

- Computation of possible visibility windows,
- De-conflicting and Scheduling of the communication links considering requests of the costumers (Mission Planning),

- Generation of LCT commands containing coarse pointing information and position data of the counter terminal, and
- Alignment correction computation.

In chapter 2 this paper gives a brief introduction to the Alphasat mission which carries the laser communication terminal TDP1. Furthermore, its counter terminal carriers, i.e. Sentinel and the optical ground station OGS are shortly presented. A detailed insight into the Flight Dynamics related LCT operations and analysis is given in chapter 3. Finally, section 4 presents the first flight results and a short outlook into the future is given in chapter 5.

2. Alphasat's LCT and Counter Terminal Carriers

The geostationary satellite Alphasat was built by Inmarsat and launched on July 25 in 2013. It is the largest European telecommunications satellite ever built with a weight of 6.6 tons and a span width of 40 m. Carrying several technology demonstrator payloads the payload TDP1 consists of a laser communication terminal and a Ka-band antenna, both operated by DLR/GSOC. The Ka-band provides a transmit rate of up to 600 Mbps at a wavelength of 26 GHz, whereas up to 1800 bi-directional Mbps are possible at 1064 nm via optical link [6] – the data rate is reduced to 600 Mbps for user data. A design sketch of Alphasat's LCT is given in Fig. 2.

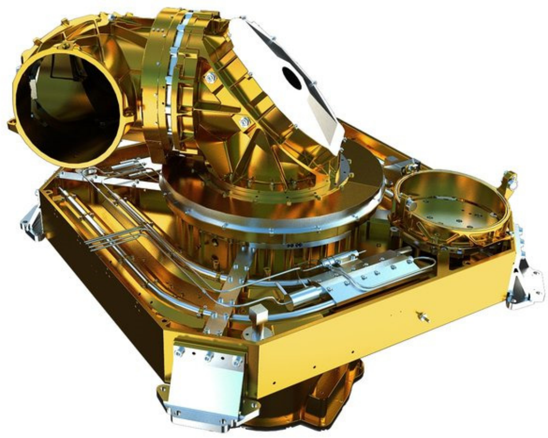

Figure 2. Laser Communication Payload TDP1 on Alphasat [9]

TDP1 is a completely autonomous optical communication terminal. After receiving link information by command from ground the preparations and link establishing runs by itself. The link information is contained in a link start time and duration, coarse pointing assembly angles at the start time, and the state (position and velocity) information of the counter terminal over the link duration. Its own position and attitude is known by on-board system. Prior to the link the terminal autonomously begins with preheating of the instrument, leaves its parking position, moves toward the coarse pointing assembly angles, and starts to search the counter terminal following a defined spiraling search pattern. That way no attitude changes of the spacecraft are necessary and the impact on the AOCS operations is negligible. Of course there are pointing constraints due to the mounting of the LCT, such as the spacecraft body itself and other payloads, and instrument limitations. But these forbidden areas and constraints are already considered during visibility calculations on ground and stated as non-visibility during link planning. When the spiraling laser beams 'see' each other each hit is acknowledged and improves the search until there is a steady visibility connection. Then the instrument goes into lock, which is referred to as 'TRACKING'. Afterwards the frequency acquisition starts to reach the status for a valid communication link and transmit data [1].

For a laser link TPD1 needs a target to point at. Several equivalent laser communication terminals were built by Tesat-Spacecom serving as counter terminals to demonstrate space-to-ground-link capability on the one hand and the end-to-end service of data transfer from LEO spacecraft via a relay satellite in GEO to the final end-user on ground on the other hand. One LCT is mounted on ESA's Optical Ground Station (OGS) located on the island Tenerife, Spain [10]. First space-to-ground links were already performed and 'TRACKING' was in lock as described in chapter 4.

Figure 3. Laser from Optical Ground Station on Tenerife [10]

Other counter terminals are and will be mounted on spacecraft of the Sentinel series. These are Earth observation spacecraft in LEO – which will also be communicating optically with the EDRS fleet. Launch of Sentinel 1A (S1A) was successfully performed on April 3, 2014. First links between Alphasat and S1A are planned for May 2014. Next launch of a Sentinel spacecraft S2A is planned for the winter 2014/2015 [11].

3. FD Operations from Visibility Computation to Command Generation

To start a communication link the first step is the computation of possible visibility windows over a specified time period, e.g. for the next 2 weeks. The flight dynamics system provides this service considering the constraints and forbidden areas of each LCT as described in subchapter 3.1. Also, the attitude and predicted state of each spacecraft/ground station must be taken into account for the covered time period. The calculated visibility windows between different terminals are offered to customers who request links according to their needs. The Mission Planning System considers the incoming slot requests and plans an optimized link schedule which is handed back to flight dynamics [8]. Together with updated attitude and orbit information for each scheduled link the coarse pointing angles are updated and the position and velocity of the corresponding counter terminal are computed and expressed as Chebyshev polynomial. These are translated into command files and finally uploaded to each terminal.

3.1. Visibility Computation

As first step to laser communication, the visibility between Alphasat and a selectable counter terminal has to be computed. This computation is based on the propagated orbital state, the spacecraft's attitude, and LCT mountings and restrictions of both carrier objects and their instruments. From this the line-of-sight vectors (LOS) between the two objects in each LCT-frame are calculated. The LOS vectors are then converted into coarse pointing angles (CPA) expressed in elevation and azimuth angles of the instruments. Both, the LOS and CPA are checked against defined constraints and forbidden areas to identify visibility periods. The computation of the LOS and CPA is described in detail in the following.

Given a position and velocity (r, v) of a spacecraft in the 'True-of-Date' (ToD) reference frame the nominal orbital spacecraft frame expressed in the axes Roll, Pitch, and Yaw (equivalent to tangential (T), out-of-plane (-N), nadir (-R)) is computed by:

$$yaw = -\vec{R} = -\frac{\vec{r}}{\|\vec{r}\|}, \; pitch = -\vec{N} = -\frac{\vec{r} \times \vec{v}}{\|\vec{r} \times \vec{v}\|}, \; roll = \vec{T} = pitch \times yaw. \tag{1}$$

These vectors build the transformation matrix for conversions from ToD into roll-pitch-yaw:

$$U = [roll, pitch, yaw]^T. \tag{2}$$

Simple attitude offsets are also taken into account, such as a constant attitude bias on the roll-pitch-yaw axes or attitude steering laws providing attitude offsets on the roll-pitch-yaw axes depending on the argument of latitude in form of a look-up-table.
The argument of latitude AOL is given by:

$$AOL = \arctan\left(\vec{R}(3) / \vec{T}(3)\right). \tag{3}$$

The attitude rotation matrices around each axis look like:

$$R_{roll} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\Delta roll) & \sin(\Delta roll) \\ 0 & -\sin(\Delta roll) & \cos(\Delta roll) \end{pmatrix}, \tag{4}$$

$$R_{pitch} = \begin{pmatrix} \cos(\Delta pitch) & 0 & -\sin(\Delta pitch) \\ 0 & 1 & 0 \\ \sin(\Delta pitch) & 0 & \cos(\Delta pitch) \end{pmatrix}, \tag{5}$$

$$R_{yaw} = \begin{pmatrix} \cos(\Delta yaw) & \sin(\Delta yaw) & 0 \\ -\sin(\Delta yaw) & \cos(\Delta yaw) & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{6}$$

where $\Delta roll$, $\Delta pitch$, and Δyaw are the angle offsets in roll, pitch, and yaw. These form the attitude rotation matrix by simple matrix multiplication:

$$R_{att} = R_{yaw} \cdot \left(R_{pitch} \cdot R_{roll}\right), \tag{7}$$

which has to be applied to get the spacecraft body frame from the roll-pitch-yaw frame.

The LCT mounting matrix R_{LCT}, provided by the spacecraft manufacturer, describes the transformation from the spacecraft body frame into the LCT frame, and is another transformation matrix which has to be considered for the LOS computation.

Having the relative position vector $\Delta\vec{r} = \vec{r}_2 - \vec{r}_1$ between two LCT terminals in ToD the LOS in the LCT frame is finally computed by consecutively applying the introduced transformation matrices:

$$LOS_{LCT} = R_{LCT} \cdot \left(R_{att} \cdot \left(U \cdot \Delta\vec{r}\right)\right). \tag{8}$$

This has to be done for each object at each time step.

For an optical ground station the computation of the LOS looks a little different. The known Earth-centered Earth-fixed station coordinates need to be transformed into the local-tangential-coordinates (LTC):

$$R_{LTC} = \begin{pmatrix} -\sin(lat)\cdot\cos(lon) & -\sin(lat)\cdot\sin(lon) & \cos(lat) \\ -\sin(lon) & \cos(lon) & 0 \\ \cos(lat)\cdot\cos(lon) & \cos(lat)\cdot\sin(lon) & \sin(lat) \end{pmatrix}, \tag{9}$$

where *lat* and *lon* are the station's geodetic coordinates. Furthermore, conversions from the ToD reference frame into the Earth-centered Earth–fixed frame need to be considered:

$$R_{ToD\_ECEF} = P(t) \cdot GHA(t), \tag{10}$$

where *P* is the so called pole-matrix (transformation matrix from pseudo Earth-fixed to Earth-fixed coordinates) at the time and *GHA* is the Greenwich Hour Angle rotation matrix at that time. No further attitude needs to be considered. The final LOS computation in the LCT frame of an optical ground station looks like:

$$LOS_{OGS} = R_{LCT} \cdot \left(R_{LTC} \cdot \left(R_{ToD\_ECEF} \cdot \Delta r\right)\right), \tag{11}$$

again with $\Delta\vec{r} = \vec{r}_2 - \vec{r}_1$ being the relative position vector between two LCT terminals in ToD, where $\vec{r}_1$ is the position of the ground station.

Having the LOS vectors the coarse pointing assembly (CPA) of the instrument expressed in azimuth and elevation angles is computed by the following:

$$azimuth = \arctan\left(\frac{LOS(2)}{LOS(1)}\right), \tag{12}$$

$$elevation = \arcsin\left(LOS(3)\right). \tag{13}$$

The definition of azimuth and elevation in the LCT frame is depicted in Fig. 4.

If the object is a ground station, also the effect of refraction due to the Earth's atmosphere is applied and the elevation angle is adapted accordingly.

The computed LOS vector and CPA angles are checked against a number of constraints to define a bi-directional visibility between the terminals. These checks include e.g. minimum and maximum azimuth and elevation angles, forbidden areas, i.e. excluded azimuth and elevation value combinations due to obstacles in the field-of-view, the distance, i.e. the magnitude of the LOS, the Sun angle and others.

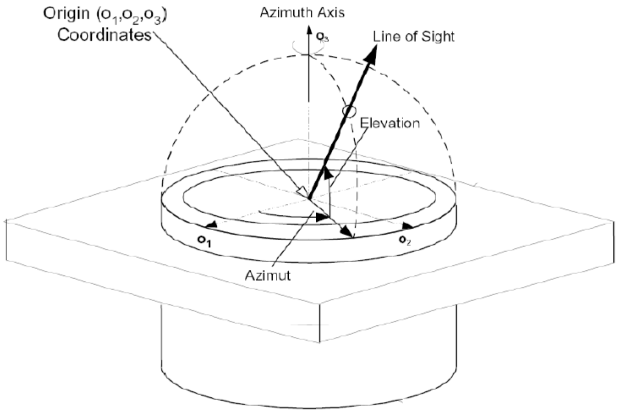

Figure 4. Illustration of azimuth and elevation angles in the LCT frame (O_1,O_2,O_3)

For each nominal pointing assembly a reverse pointing assembly exists, which is computed by:

$$azimuth_2 = azimuth_1 + 180°, \tag{14}$$

$$elevation_2 = 180° - elevation_1 . \tag{15}$$

It is possible that the nominal pointing assemble triggers one of the described limits but the reverse assemble has a good visibility, and vice versa. If either the nominal pointing assembly or the reverse pointing assembly passes all visibility criteria for both terminals, i.e. bi-directional, a visibility for that time can be stated. This way, visibility periods for the next 14 days are computed and provided to the customers to place their link requests within a valid time interval. The requested links are gathered, de-conflicted and optimized by the Mission Planning System and planned into a link list schedule. FDS computes a short-term update of the computed CPA for each scheduled link. The resulting CPA at link start time and the latest available predicted orbit information of the counter terminal is expressed in form of Chebyshev polynomials and included into a command file to be uploaded to the LCTs.

3.2. Alignment Correction Matrix Computation

The alignment of the LCT on each spacecraft is calibrated on ground and expressed in a mounting matrix which is considered during the CPA computation as transformation matrix from spacecraft body frame into LCT frame. Transportation, launch, and other disturbances may result in minor but not negligible errors of the alignment. To compensate these offsets, the spacecraft telemetry data collected during laser links is processed to derive an alignment correction matrix for the space-borne LCT. In the following the theory of how to calculate the alignment correction matrix is demonstrated using the example of Alphasat.

If during a link the pointing is sufficiently accurate to operate the LCT in TRACKING (or higher) mode the telemetry provides the 'true' measured angles azimuth α and elevation β. Based on these angle measurements the unit vector $\vec{p}_{meas}$ in direction from Alphasat-LCT to the counter LCT in Cartesian coordinates is derived by:

$$\vec{p}_{meas} = \begin{pmatrix} \cos(\alpha)\cdot\cos(\beta) \\ \sin(\alpha)\cdot\cos(\beta) \\ \sin(\beta) \end{pmatrix}. \tag{16}$$

Also available from the telemetry are the position and the attitude information of each spacecraft during a link based on GPS or on-board orbit propagator and star tracker measurements. Similar to the computation of the CPA as described in chapter 3.1 the predicted azimuth and elevation angles A and B are computed, including alignment and attitude errors. The predicted unit vector $\vec{p}_{pred}$ in Cartesian coordinates is calculated equivalent to Eq. (16), but replacing (α,β) by (A,B). The goal is to find a correction matrix R which transforms the predicted unit vector $\vec{p}_{pred}$ into the new vector $\vec{p}'_{pred}$ such that the remaining pointing deviation from the measured direction $\vec{p}_{meas}$ is minimized for all data samples.

The calculation of the correction matrix is based on the approach as developed for the TSX – NFIRE LCT link data [12]. The method of least sum squared errors is applied to the error vectors:

$$\vec{p}_{meas,k}(\alpha_k,\beta_k) - \vec{p}'_{pred,k}(\mathrm{A}'_k,\mathrm{B}'_k) = \vec{p}_{meas,k}(\alpha_k,\beta_k) - R\cdot\vec{p}_{pred,k}(\mathrm{A}_k,\mathrm{B}_k). \tag{17}$$

where the index $k \in 1...m$ indicates the sample out of the complete set of m observed data samples.

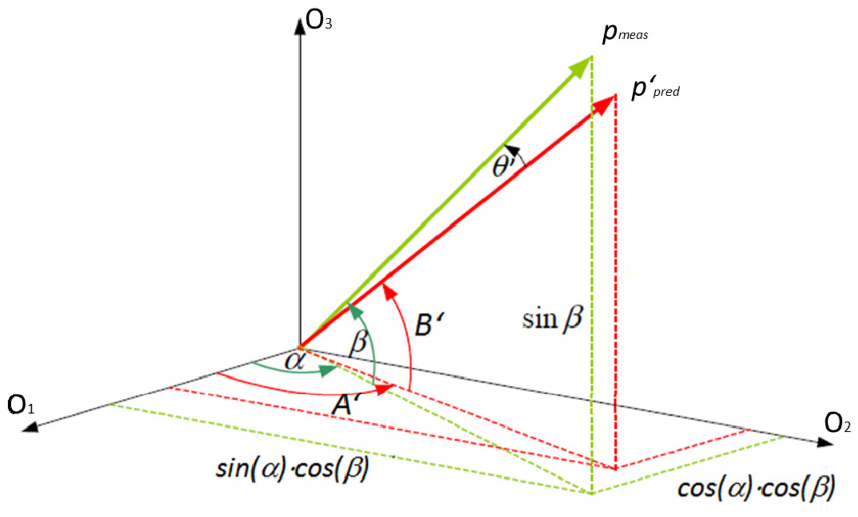

Figure 5. Illustration of the residual pointing error θ' in the LCT frame.

For the correction calculation all telemetry data must be time-synchronized. Not common data arcs are cut-off and proper interpolation is applied to retrieve the data in the expected synchronized manner.
After a correction the residual pointing error θ'_k for each sample is derived from the scalar product of the 'true' measured and the predicted and corrected unit vectors:

$$\cos(\theta'_k) = \vec{p}_{meas,k} \cdot \vec{p}'_{pred,k} \,, \tag{18}$$

which leads to:

$$\theta'^2_k = (\beta_k - \mathrm{B}'_k)^2 + \frac{1}{2}(\alpha_k - \mathrm{A}'_k)^2\left[1 + \cos(2\mathrm{B}'_k)\right], \tag{19}$$

making the assumptions that for small angle differences $|\alpha_k - \mathrm{A}'_k| << 1$ and $|\beta_k - \mathrm{B}'_k| << 1$, also $|\theta'_k| << 1$ and $\beta_k + \mathrm{B}'_k \approx 2\mathrm{B}'_k$ and using $\cos(\theta'_k) \approx 1 - \frac{1}{2}\theta'^2_k$.

To apply the method of least sum squared errors on the residual pointing error angles θ'_k the quantity $S = \sum_{k=1}^{m} \theta'^2_k$ shall be minimized in order to retrieve the best rotation matrix *R*, which represents the alignment correction matrix of the LCT.

Attitude offsets, due to errors in the alignments of the attitude determination instrument, here star trackers, are indirectly considered when applying the described approach. And therefore, mounting offsets of the star trackers are compensated, too.

4. First Flight Results

Since the ending of Alphasat's commission phase in October 2013 the visibility windows between Alphasat and the optical ground station OGS were provided weekly. Due to the satellite commissioning phase and commissioning phases for each single technology demonstration payload (TDPs) and availability constraints of the optical ground station the actual operation start of TDP1 was planned for spring 2014. But some first test and calibration SGL-links during TDP1's commissioning phase were successfully requested and established in November 2013 yielding promising results.

On November 5, 2013, the first sight of a laser beam at OGS was announced by Tesat-Spacecom [10,13], which demonstrated that the coarse pointing assembly and the state of the counter terminal were predicted good enough to get the search algorithm to find its target. On November 8, the LCT even went into lock and stayed in the 'TRACKING' mode long enough to collect valuable telemetry data.

On that day three consecutive links of roughly 20 minutes duration each provided the data for a first alignment analysis, which showed that the azimuth was quite well aligned. But there was a constant offset of about -0.08 degree on the elevation, as depicted in Fig. 6 for one link. The other links that day showed similar values and based on the collected data the first alignment correction matrix was computed.

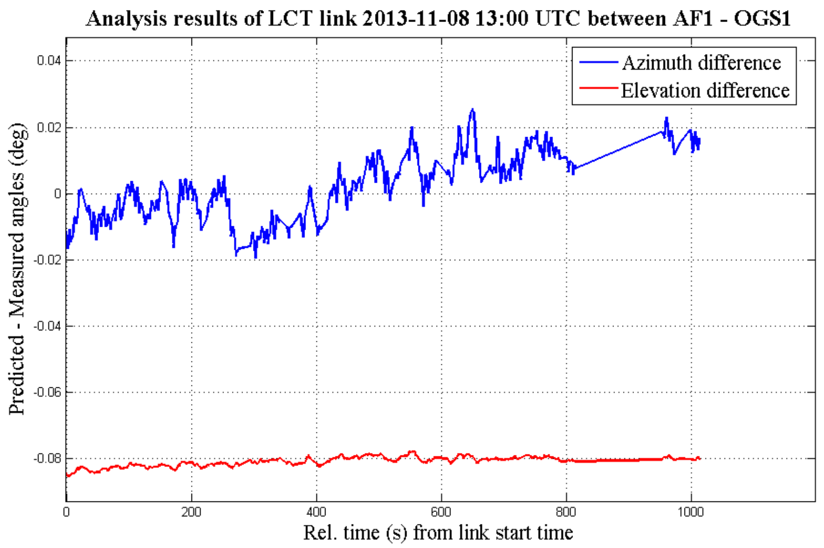

Figure 6. Analysis results of the link on 2013/11/08 13:00 UTC showing the differences between the on-board predicted and measured azimuth and elevation angles in degree.

Finally, in March 2014 the next SGL-links were scheduled, now taking into account the previously computed alignment correction. The pointing was very accurate now and the radius of the spiraling search pattern could be reduced already in order to retrieve quicker results. An analysis of telemetry data of the link on March 27, 2014, showed that the correction matrix was computed and applied correctly. Without correction the offsets in azimuth and elevation looked worse than during the links analyzed before, but after the correction the offset of the elevation was corrected by 0.081 degree as expected due to the results of the first analysis (see Fig. 7 & Fig. 8).

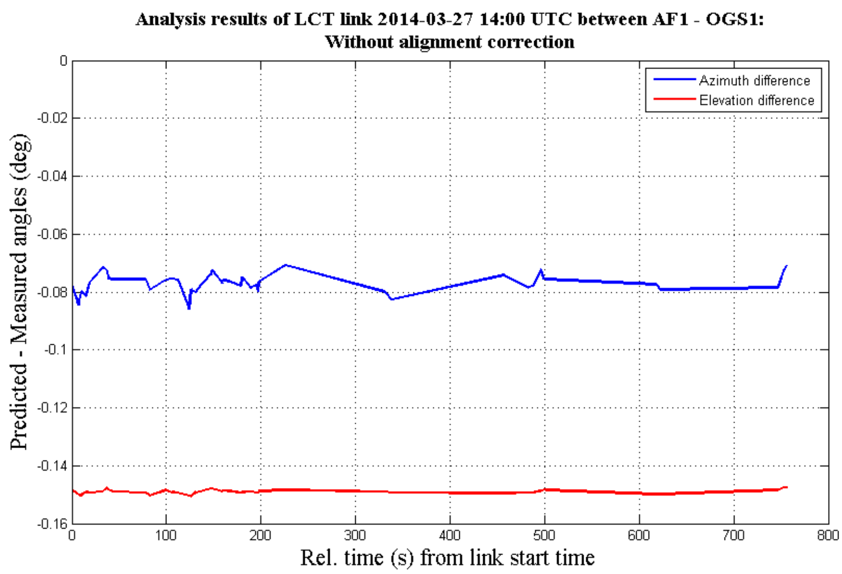

Figure 7. Analysis results of the link on 2014/03/27 14:00 UTC showing the differences between the on-board predicted and measured azimuth and elevation angles in degree - without applying the previously computed alignment correction matrix.

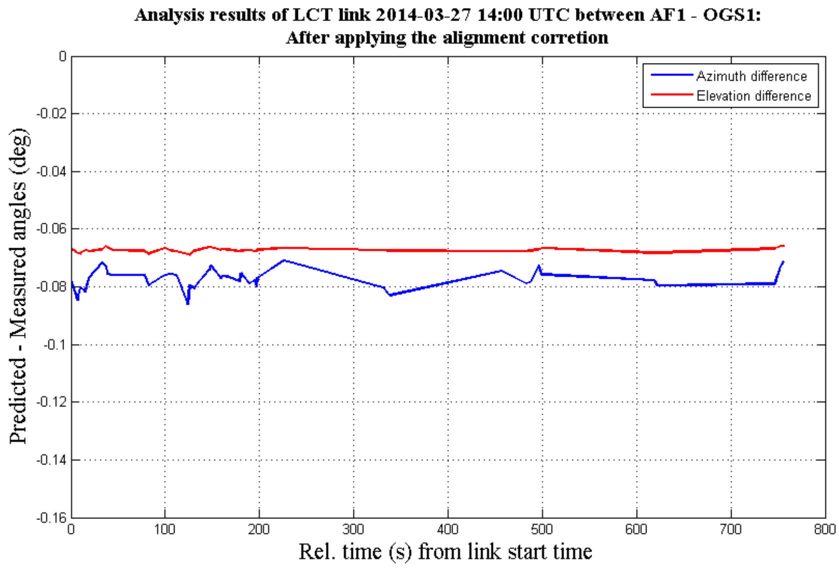

Figure 8. Analysis results of the link on 2014/03/27 14:00 UTC showing the differences between the on-board predicted and measured azimuth and elevation angles in degree - after applying the computed alignment correction matrix.

The overall residual error during the links in November was about 1400 µrad. Even if the angle offsets during the link in March looked worse, due to a high elevation of around 83 degree the influence of the azimuth offset to the residual error is almost negligible. The main effect on the total error comes from the elevation offset, which could be reduced by the alignment correction from -0.149 deg to -0.068 deg, compared to -0.08 deg in the November pass. The overall residual error of the link in March was less than 1200 µrad.

The reason why the azimuth and elevation angle offsets were worse in March than in November is not further analyzed yet, but there are several possibilities. First of all the update times of the on-board orbit propagator is not known to DLR/GSOC, thus maybe a longer propagation period resulting in larger prediction offsets is simply the cause. Besides, more than 4 months lay between the analyzed links, so additional minor alignment offsets may be introduced during that time due to radiation or other disturbances.

5. Conclusion and Way Forward

Within this paper the Alphasat mission operating a laser communication terminal is introduced and its counter terminal carriers are also presented. The advantages and disadvantages of optical communication are listed and the concept of a data relay using a geostationary spacecraft is shortly depicted. The major flight dynamics tasks, i.e. visibility prediction and alignment correction matrix calculation are described in detail and first flight results are presented.

So far, only a limited number of space-to-ground laser links was executed and the results maintained are statistically not very significant. But they indicate good results and nevertheless, already a good performance of the LCTs on Alphasat and the optical ground station OGS could be demonstrated. The visibility computations are correct and the provided LCT commands are accurate enough to successfully find and track the counter laser terminal.

Analysis of telemetry data during links in 'TRACKING' mode resulted in the computation of a first alignment correction matrix which was successfully uploaded to Alphasat. Following links made use of that knowledge and further analysis showed the improvement due to its application.

On April 3, 2014, Sentinel 1A was successfully launched and the first links between Alphasat and S1A are planned for May 2014. Then, for the first time user data of a LEO spacecraft will be transmitted to a data relay servicer in GEO via laser and then directly be forwarded to the ground using Ka-band communication [14]. A successful delivery of the data to ground would be a mile stone for data handling in space missions.

6. References

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