OPERATIONAL CONCEPT OF A PICOSATELLITE RELEASE FROM A LEO SATELLITE

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Abstract: *The Berlin InfraRed Optical System satellite, which is scheduled for launch in 2016, will carry onboard the picosatellite BEESAT-4 and release it through a spring mechanism. After separation, it will perform experimental proximity maneuvers in formation with the picosatellite solely based on optical navigation. In order to start the experiment it is important to create certain initial conditions which assure, that the relative orbit is passively safe and stable, and the Picosatellite is in the field of view of the camera. This is especially challenging, since several design constraints, like a fixed delta-v of the spring mechanism and a limited maximum delta-v of the thrusters, have to be considered. A major design driver is the performance uncertainty of the release mechanism and the on-board thrusters. The developed strategy starts with two maneuvers: the separation itself and a drift reduction maneuver of the Berlin InfraRed Optical System satellite after half a revolution. This is followed by a relative orbit determination performed by on-ground radar tracking. Necessary maneuvers to establish the initial condition will be computed based on the orbit determination and executed. The selected maneuver parameters are validated in a Monte Carlo simulation and the development of an operational plan is presented.*

Keywords: *Formation Flying, Picosatellite, Relative Orbital Elements (ROE), Monte Carlo Simulation, Eccentricity/Inclination Vector Separation.*

1. Introduction

The BIROS (Berlin Infrared Optical System) Satellite [1] is scheduled for launch in spring 2016 and will be operated by the German Aerospace Center (DLR). The satellite which measures 60x80x80 cm and weighs 130 kg will be injected by a PSLV launcher into a sun-synchronous orbit at an orbit height of about 500km. Its primary task will be the observation of wildfires with the on-board infrared camera in the frame of the FireBird mission [1]. On board it carries as a secondary payload the picosatellite BEESAT-4, built by TU Berlin [2] (10x10x10 cm, 1 kg), which will be ejected by a Single Picosatellite Launcher (SPL, [3]) after the successful check-out and commissioning of all relevant BIROS subsystems. In addition, BIROS will host several technology demonstration experiments including the AVANTI (Autonomous Vision Approach Navigation and Target Identification) experiment. Differently from the TET-1 [4] satellite, already operating within FireBird, the BIROS spacecraft will be equipped with a cold gas propulsion system in order to perform orbit and formation control maneuvers.

The AVANTI experiment is intended to demonstrate vision-based noncooperative autonomous rendezvous operations of an active small satellite (BIROS) within separations between 10 km and few hundreds of meters from a Picosatellite (BEESAT-4) making use of solely angles-only measurements [5]. The experiment is intended to start after that the BIROS/Picosatellite formation has been brought to an initial safe configuration at a separation within 5 to 10 km and minimal residual drift, in the along-track direction, towards increasing relative distance. This operational task is solely ground-based and performed by the Flight Dynamics Services (FDS) division of the German Space Operations Center (GSOC), which is in charge of the orbit determination and control of the FireBird mission.

The launch of Picosatellites has become widespread in the recent years as they pose a cost effective orbital platform for low-cost scientific or educational projects. In most cases they are released directly from an upper stage as co-passengers of larger satellites or in a swarm of up to 50 Picosatellites [6]. In order to avoid collisions with the upper stage or other satellites they receive a relatively large delta-v in a single impulse by a deployment mechanism which injects them to a distinct orbit. In this study the scenario is different to usual Picosatellite deployments for two reasons. Firstly the Picosatellite will not be released from the upper stage of a launch vehicle but from another scientific LEO satellite. Secondly, in contrast to usual Picosatellite separations, the goal is not to build up a large separation between the launcher and the Picosatellite as quickly as possible, but rather to keep the Picosatellite in the vicinity of the deploying satellite for formation flying experiments. The fact, that the BIROS satellite uses a standard SPL mechanism with a delta-v of 1.53 m/s poses a certain challenge to the separation design, as usually formation flying reconfigurations employ maneuvers in the order of few cm/s.

In 2014 a preliminary design of the separation concept was presented [7]. The purpose of that study was to demonstrate the design of a maneuvering strategy, which leads to a passively safe relative orbit in the Relative Orbital Elements (ROE) framework [8][9], suitable to start the AVANTI experiment. The design was based on a two maneuver strategy – the first maneuver was the ejection of the Picosatellite by the release mechanism. The second maneuver was planned to be performed by the BIROS propulsion system in order to stop the separating drift between the two spacecraft and to establish passive safety via relative eccentricity/inclination vectors separation. The concept put a special emphasis on the analysis of the effects of execution errors of the two maneuvers in a Monte Carlo simulation. As the behavior of the release mechanism is unknown a performance dispersion with a standard deviation of 10% was assumed. For the propulsion system, instead, a dispersion with a standard deviation of 5% was considered. Additionally, realistic attitude control errors at the time of the maneuver execution and uncertainty on the knowledge of the differential ballistic coefficient were included. As result a strategy was developed which minimized both risks of collision and formation evaporation.

As the satellite integration progressed, it became clear, that this concept would no longer be feasible. This is caused mainly by the three following factors. First, the propulsion system has been meanwhile designed to provide a 1 mm/s discretization capability, considering its more frequently foreseen usage. Consequently, reaction wheels characteristics and allowed maximum continuous firing time limited the maximum delta-v obtainable by a single burn to circa 0.3 m/s. Therefore, the drift stop maneuver originally planned within the former design is no longer realizable with a single burn, since it presented of magnitude of circa 1.33 m/s. Second, the mass of BEESAT-4 is by 8% lower than originally assumed. This results in a higher ejection delta-v (1.53 m/s instead of 1.41 m/s), that has to be taken into account. Third, the analysis of the uncertainties accomplished at that time revealed that starting AVANTI immediately after the drift stop maneuver would have been rather inconvenient, given the effective achievable shape of the relative trajectory and given the size of the unavoidable residual drifts towards increasing inter-satellite distance.

Therefore, in order to provide a solution that satisfies also the aforementioned three factors, a separation strategy involving more than one thruster maneuver after the Picosatellite ejection has been addressed. The design degree of freedom represented by the possibility to distribute the trajectory corrections over multiple burns has been exploited to achieve an overall design cheaper in terms of delta-v consumption. Thus, on the one hand this paper addresses the answer to this following question. *Is there a smart combination of time, direction of the SPL activation, and sequence of maneuvers performed by BIROS so that the majority of the initial conditions required by AVANTI are achieved at the expense of the delta-v provided by the SPL?* On the other hand, the current analysis includes also several further operational aspects, not considered in the preliminary design, such as the illumination conditions at the ejection time, ground contacts coverage, and radar-tracking opportunities. As a result, this paper presents a realistic operational plan for the whole Picosatellite separation phase.

2. Requirements and Constraints

This section presents the requirements advanced by both Mission and AVANTI experiment. These, together with some constraints driven by SPL device, propulsion system, and availability of tracking data from the Picosatellite, bring to the separation strategy concept outlined in Section 2.3.

2.1. FireBird Mission Requirements and Constraints

The design requirements posed by the FireBird mission are hereafter briefly introduced:

1. Safe Picosatellite ejection
   Most important for the separation is, that the Picosatellite has to be ejected to a safe trajectory without collision risk. This requirement stands independent of the AVANTI experiment.
2. Enabling to perform AVANTI
   As the AVANTI experiment is part of the FireBird mission, the separation has to be performed in a way that the AVANTI experiment can be performed. This means that certain conditions (which will be introduced in section 2.2) have to be established before the experiment can start.
3. Picosatellite ejection performed during a ground contact
   The separation should take place during a ground station contact – preferably a long contact or an overlapping contact of two or more ground stations. This is driven by the requirements, that on the one hand, some contact time is needed before the ejection for system checks. On the other hand the ejection shall be captured by an onboard RGB camera and the footage should be directly downlinked for an analysis of the ejection.
4. Illumination condition during the Picosatellite ejection
   It is planned to capture the separation with an onboard RGB camera, thus the satellite has to be illuminated by the Sun and not in Earth's shadow during ejection, but, at the same time, the RGB camera must not be blinded by the Sun.

The preliminary design already addressed the requirements 1 to 3, whereas the 4th one is firstly introduced in the current analysis.
As mentioned in the introduction, the separation design has to be compliant with the following constraints:

1. Fixed delta-v imparted by the SPL device
   The delta-v imparted on the Picosatellite is fixed by design 1.53 m/s. The degree of freedom is the vector in which the delta-v will be directed. This is freely selectable as BIROS attitude control allows to assume any desired orientation for the ejection.
2. Features of the BIROS propulsion system
   The BIROS propulsion system has two limitations. Firstly, the pulses have a discretization of 1 mm/s. Secondly, the maximum delta-v which can be achieved in a single maneuver is limited to 0.3 m/s. The second limitation bears the consequence, that the drift-stop cannot be performed in a single maneuver.

2.2. AVANTI Experiment Requirements

The design requirements posed by the AVANTI experiment are hereafter briefly introduced:

1. Relative trajectory at conclusion of the separation and passive safety
   The safety concept retained for AVANTI is mainly based on the passive safety of specific relative trajectories [10]. For almost bounded relative orbits, it is achieved by a determined phasing (i.e., (anti-)parallel configuration) and magnitude (i.e., at least 150 m) of the relative eccentricity and inclination vectors. Accordingly, the AVANTI experiment has to start from an almost bounded passively safe relative orbit, whose remaining characteristics are dictated by the following further aspects. The mean along-track separation should be within 5km (to allow eventual radar tracking support and to allow imaging the Picosatellite with the camera aligned to the local orbital frame centered on BIROS) and 10km (to allow detecting Picosatellite luminous spot on the images). Finally the maximum acceptable magnitudes of the relative eccentricity and inclination vectors are determined so that the motion of BEESAT-4 fits the field of view (FoV) of the camera (i.e., opening angle of 6.8° horizontally and 9.15° vertically) at the start of the experiment. A relative orbit presenting these just mentioned characteristics is referred as to *experiment initial conditions* (ICs).
2. Effect of the differential drag perturbation
   The choice if the Picosatellite should be leading or following BIROS can be decided by looking at the differential drag. The surface to mass ratio of the Picosatellite is larger than that of BIROS by factor 2 to 3 (the effective surface of BIROS varies according to the actual attitude mode). This means that the Picosatellite will be affected stronger by air drag, decay faster and thus move faster in the along-track direction. If it is ejected such, that it will lead the formation, this effect can be used to increase the safety of the constellation, as the differential drag will always create a natural drift, that increases the along-track separation.
3. Stability of the relative orbit
   The stability of the relative orbit is disturbed by the perturbation which is caused by the Earth’s oblateness. The J2 effect on the relative eccentricity vector, for SSO orbit 500 km

high, amounts to a clock-wise rotation of circa 3.6 degrees per day. For a bounded and slowly drifting orbit, the J2 effect on the relative inclination vector affects only its y-component according to: $\Delta\delta iy = 3\ \gamma\ \sin 2i\delta ix$. Therefore, the separation phase has to establish a relative orbit with the x-component of the relative inclination vector the closest possible to zero. This is achieved by an ejection at the “poles” of the orbit, where the mean argument of latitude u = 90° or u = 270° (see equation 2.38 in [8]).

4. Minimization of the separation delta-v
   Furthermore it is desired to save as much fuel as possible. Hence a strategy which manages to reduce the delta-v consumption would be preferred, but not strictly required. The AVANTI experiment has been assigned a fixed delta-v budget. The less propellant is used during the separation and acquisition of ICs, the more is available for the experiment itself.

The preliminary design already addresses the first two requirements. Nevertheless, the assumption to perform just a single thrust with the BIROS propulsion system, in the presence of errors in the execution of both ejection and maneuver, brought to a high expenditure of delta-v and a partial satisfaction of the AVANTI ICs. The current analysis, instead, benefits from the possibility to perform more maneuvers and therefore can aim to pursuing the requirement 4. In addition, the introduction of the 3rd requisite determines a preference on the candidate locations (i.e., mean argument of latitude) of the Picosatellite ejection.

2.3. Separation Strategy

One of the outcomes of the preliminary study is the conclusion that the remaining drift after the thruster-based drift stop maneuver is quite unpredictable. The BIROS maneuver, in fact, has to be performed *blindly* (i.e., the maneuver is pre-computed and will be executed without an orbit determination of the Picosatellite), in order to save time and therefore to prevent accumulating a large mean along-track separation. In this frame, the preliminary study focused on determining a *reduction factor* for the along-track component of the drift-stop delta-v, to cope with possible performance deviation of the release mechanism. As a result, in case of an under-performance of the SPL, an outward residual drift would anyhow be achieved, at the expense of a smaller in size relative orbit but still compliant with the passive safety requirement. In case of an over-performance, instead, the residual drift would be quite large, preventing the immediate start of AVANTI. Suitable ICs, in fact, can be only achieved by further maneuvering, in order to reduce both the inter-satellite separation and relative semi-major axis (i.e., drift), at the expense of further delta-v consumption.

All the above mentioned considerations, together with the whole set of requirements listed before, have led to a new separation strategy concept. Accordingly, the separation phase will consist of the ejection of the Picosatellite followed by a *blind* maneuver of the BIROS propulsion system. Contrary to the original concept, this maneuver is not designed to satisfy the complete set of AVANTI ICs but rather to reduce the along-track drift, so that, even in case of a large under-performance of the separation mechanism, the inter-satellite separation continues to increase. At this time, an orbit determination of the Picosatellite has to be accomplished on-ground, in order to compute the remaining set of maneuvers to establish, in a delta-v optimum way, suitable initial conditions for AVANTI.

In order to enable the ground-based Picosatellite orbit determination, some tracking data of BEESAT-4 have to be collected. Both satellites, BIROS and BEESAT-4 are equipped with a Phoenix GPS receiver [11]. Nevertheless, this option is not considered a reliable data source, since for BEESAT-4 the GPS receiver is only an experimental payload and it is not clear if and how long after separation it will deliver GPS observations. Equivalently, Two-Line-Elements of the BEESAT-4 orbit might not be available in the time frame of few orbits. The images delivered by the RGB camera onboard BIROS can be processed on-ground to deliver accurate 3D pose estimate at the (sub-)centimeter level [12]. The subsequent filtering of the relative trajectory allows estimating the velocity increment encountered during the deployment accurate to 0.2% and subsequent relative orbit prediction accurate at the meter level during the following hours. Nevertheless, a precise knowledge of the orbit at later times and the estimate of the effect of the differential drag perturbation are also required, in order to accomplish the maneuver planning to establish the AVANTI ICs. As a consequence, the orbit determination of the Picosatellite has to be performed based on the solely remaining option of on ground observations: radar-tracking campaigns. To this end, it is scheduled to track the formation with the radar tracking station TIRA (Tracking and Imaging Radar [13]) located in Germany. Due to the large difference in size of the two spacecraft, TIRA will only be able to distinguish them, when they have reached a separation of at least 5km. Furthermore, a reliable orbit determination is only possible, when several passages have been tracked over an interval of 12 hours. Further details on the inclusion of the radar-tracking support during the separation phase are discussed later in Section 5.

3. Separation Multi-impulse Maneuver Profile

In continuation with the preliminary study presented in [7], the design of the maneuvers' profile is carried out in the framework of relative orbital elements (ROEs), whose definition is here recalled for completeness:

$$\delta\boldsymbol{\alpha} = \begin{pmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{pmatrix} = \begin{pmatrix} \delta a \\ \delta\lambda \\ \delta e\cos\varphi \\ \delta e\sin\varphi \\ \delta i\cos\theta \\ \delta i\sin\theta \end{pmatrix} = \begin{pmatrix} (a - a_\mathrm{d})/a_d \\ u - u_\mathrm{d} + (\Omega - \Omega_\mathrm{d})\cos i_\mathrm{d} \\ e\cos\omega - e_\mathrm{d}\cos\omega_\mathrm{d} \\ e\sin\omega - e_\mathrm{d}\sin\omega_\mathrm{d} \\ i - i_\mathrm{d} \\ (\Omega - \Omega_\mathrm{d})\sin i_\mathrm{d} \end{pmatrix}, \tag{1}$$

Equation (1) presents the dimensionless set of ROEs, where a, e, i, Ω and M denote the classical Keplerian elements and $u = M + \omega$ is the mean argument of latitude. The subscript "d" labels the deputy spacecraft of the formation, which plays the role of the maneuverable carrier satellite (BIROS) and defines the origin of the local radial-tangential-normal (RTN) frame. The quantities $\delta\mathbf{e} = (\delta e\cos\varphi, \delta e\sin\varphi)^\mathrm{T}$ and $\delta\mathbf{i} = (\delta i\cos\theta, \delta i\sin\theta)^\mathrm{T}$, respectively denote the relative eccentricity and inclination vectors in polar notation. Finally, Figure 1 shows the ROEs with their geometrical relations to the relative trajectory in the RTN frame, when the relative semi-major axis is null. More details can be retrieved in [8].

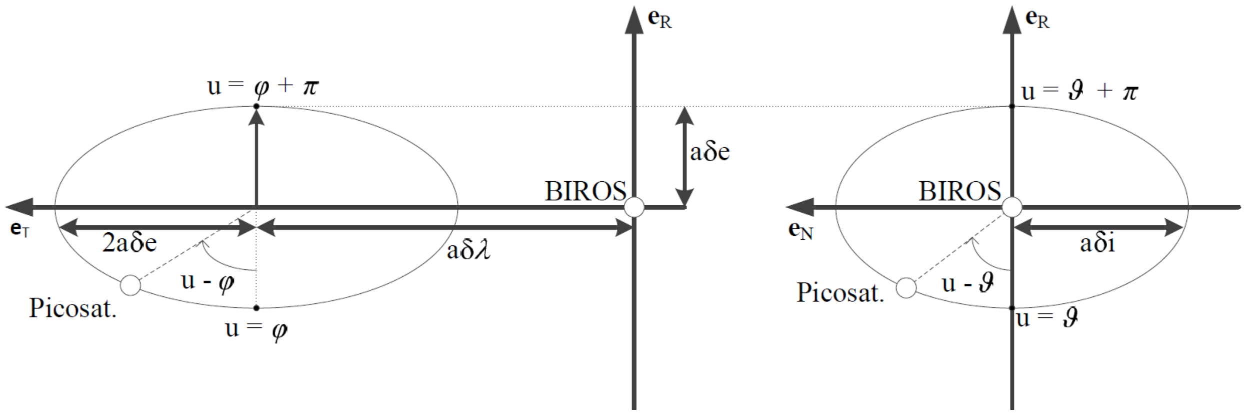

Figure 1. Sketch of ROEs and their relation to the relative motion in the RTN frame

Tackling our maneuvers' design problem in the ROE framework is particular convenient, not only for the geometrical interpretation highlighted in Fig. 1, but also for the following motivations. First, ROEs allow the straightforward inclusion and visualization of the passive safety characteristics of an almost bounded relative trajectory. This, in fact, is simply imaged by plotting the relative eccentricity/inclination vectors in the $a\delta e_x$--$a\delta e_y$ / $a\delta i_x$--$a\delta i_y$ projection of the ROE space (as performed later on in Fig. 2). Passively safe orbits correspond to vectors with mutual phasing of 0 or 180 degrees and a certain size. Second, thanks to the form of the relationships between instantaneous delta-vs in RTN and subsequent changes in ROEs, again a geometrical representation can be set-up, relating location of the maneuvers along the orbit (i.e., mean argument of latitude) and geometry of the post-maneuver relative trajectory. In addition, in the case that in-plane corrections are only performed by means of tangential burns, a linear relation between established orbits and delta-v expenditure is available. In this case, in fact, the minimum delta-v maneuvers are those that achieve a ROE change along the minimum path direction in the ROE space. This framework is extensively explained in [9] and hereafter employed to describe the baseline profile.

The new separation maneuvers' plan, in the ideal case of no errors in the maneuver executions, is visualized in Fig. 2. Here both $a\delta e_x$--$a\delta e_y$ / $a\delta i_x$--$a\delta i_y$ (left) and $a\delta\lambda$ / $a\delta a$ (right) views are reported. The SPL delta-v is prescribed as $\delta v_{SPL} = \{-1.22; -0.28; +0.88\}^T$ m/s, occurring at $u = 90$ degrees (i.e., orbit north pole), and the post-maneuver relative trajectory is marked by colored vectors. Specifically the green segment in the left view corresponds to the relative inclination vector established by the out-of-plane (i.e., normal) component of the delta-v, with size of 800m. Whereas the red segments denote the in-plane quantities, established by the radial and tangential components of the SPL delta-v. Accordingly, the relative eccentricity vector (left) presents both x and y components. The established drift corresponds to a relative semi-major axis of circa -500m (right). Its effect on the relative dynamics is marked by a dashed red segment, corresponding to the obtained increase of relative mean longitude during the time preceding the drift-stop maneuver.

How the 1.53m/s SPL delta-v is to be distributed among the three RTN components has been decided to fulfil the following design parameters. The tangential component is chosen as the minimum value that, in presence of a 10% under-performance of the spring mechanism, anyway establishes an outwards drift, as already performed within the preliminary study. The normal component is chosen to directly establish a relative inclination vector compliant with the AVANTI ICs, again with some margin in case of under-performance of the SPL device. In this way, in fact, no further delta-v has to be spent to correct the relative inclination vector, which is normally obtained through expensive out-of-plane maneuvers. Therefore, the maneuvers performed by the BIROS thruster will have null out-of-plane components. Finally, the radial delta-v component cannot be arbitrarily fixed due to the constraint on the SPL delta-v size and it absorbs the remaining available delta-v. The originality of the new design concept consists in performing multiple, purely tangential, burns to initially stop the drift and to subsequently establish the AVANTI ICs. Tangential maneuvers, in fact, are extremely convenient in terms of delta-v consumption and allow modifying, either instantaneously or in a certain time span, the complete set of in-plane ROEs [9]. In Fig. 2, the effect of the three performed tangential burns is marked in gray-scale. The lightest point is reached after performing a drift-stop maneuver (i.e., δv_T = +0.28m/s), the two remaining ones are used to achieve a final relative eccentricity vector in anti-parallel configuration with respect to the relative inclination one in a minimum delta-v fashion (i.e., shortest change towards the final configuration, with total consumption of 0.33m/s). Since two burns are used, in the $a\delta\lambda$ / $a\delta a$ plane, this $a\delta\boldsymbol{e}$ correction determines a further outward movement of the mean relative longitude, having firstly set a negative relative semi-major axis.

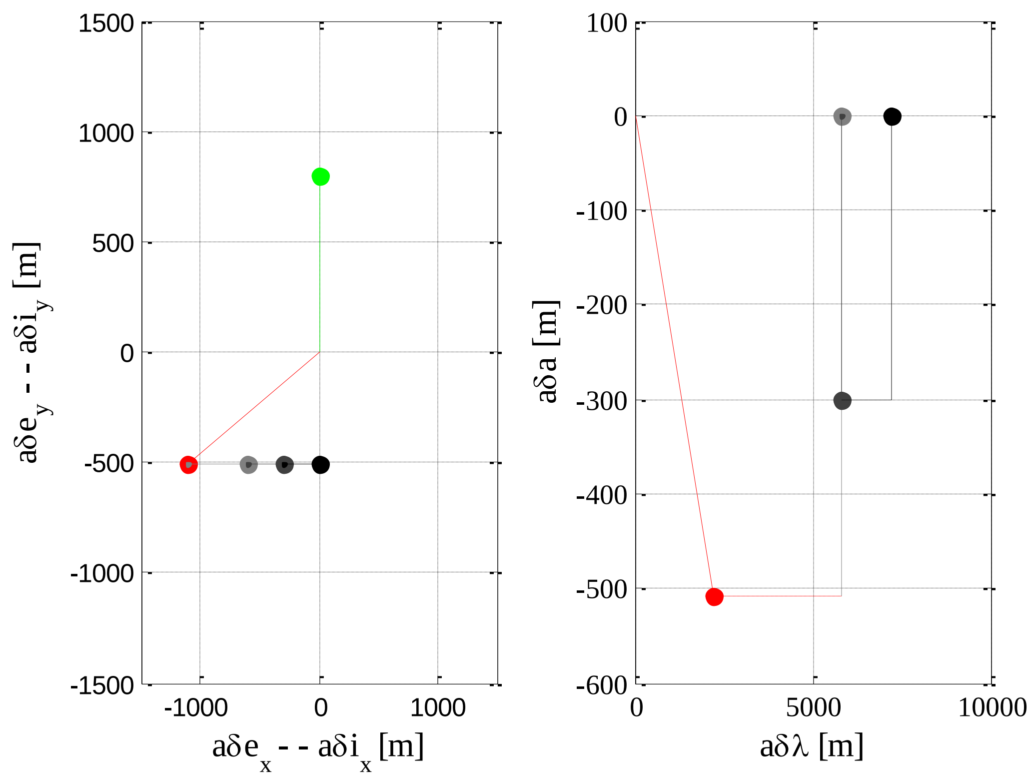

Figure 2. Separation baseline profile (ideal case): left the relative eccentricity and inclination plane, right the local radial—tangential plane

It is emphasized that the percentage of thrusted/ejection delta-v for this new baseline concept amounts to 39.9%, whereas the same parameter of merit in the preliminary design scored 95%. Such a reduction of the delta-v consumption is achieved by avoiding compensating a substantial part of the ejection delta-v by means of a single maneuver, which, in order to satisfy all the design requirements, presents a large radial, expensive, delta-v component.

To conclude, Fig. 3 shows the baseline relative separation trajectory in the RTN frame corresponding to the ideal baseline just discussed. Here, different shades of gray have been used to mark subsequent post-maneuver phases. In addition, in the 2D views, thin-solid-black lines identify the limits of the FoV of the camera employed during AVANTI.

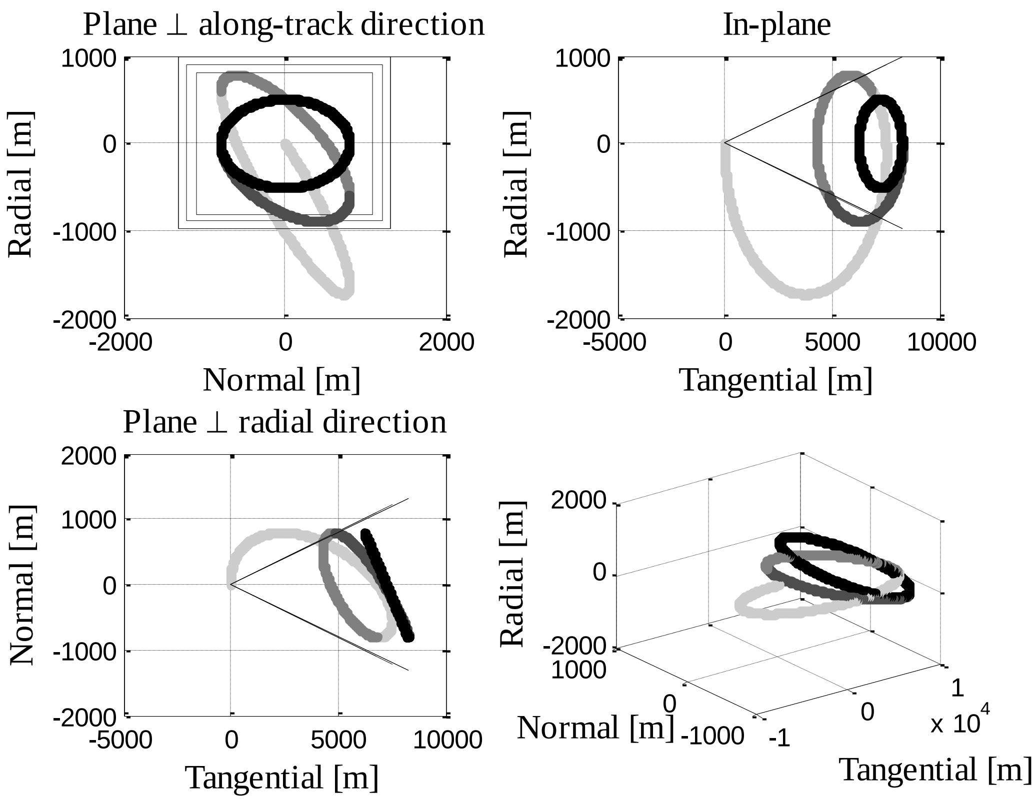

Figure 3. Trajectory of the baseline characterized by the ROEs of Fig. 2

4. Robust Analysis

In order to assess how the uncertainties of the ejection mechanism, the BIROS thrusters, the BIROS attitude control and the differential drag affect the resulting relative motion a Monte Carlo Simulation was performed. It should be noted, that all runs were performed with at least 100.000 runs, but only 1000 samples are plotted in the following figures for readability. The following uncertainties were simulated:

- The force that is imparted by the SPL on the picosatellite is constant by design, but a dispersion of the force is unknown. With an assumed weight of BEESAT-4 of 1kg, the delta-v of the separation would be 1.53 m/s. Nevertheless, the weight of the picosatellite has an uncertainty of a few percent. Together with the unknown dispersion of the spring mechanism, conservative 10% dispersion were assumed for the delta-v in the simulation. This means the delta-v was multiplied with a factor f_1 with the expectancy value of 1 and a standard deviation of $\sigma = 0.1$.

- The dispersion of the delta-v of maneuvers executed with the BIROS propulsion system is unknown. Similarly to the SPL mechanism, a dispersion of 5% is assumed. This is expressed by multiplying the delta-v of the second maneuver by a factor f_2 with the expectancy value of 1 and a standard deviation of $\sigma = 0.05$. It should be noted, that the execution accuracy of maneuvers of other space missions is often better than 5%. However it was decided to use a conservative value here. A calibration of the propulsion system during the commissioning phase could yield a better estimate, which could then be used if a new planning of the separation strategy is necessary.

- While the two previous items only affect the magnitude of maneuvers, uncertainties in the attitude control of the BIROS satellite at the epoch of the separation or maneuver. The attitude control accuracy of the BIROS satellite is 30 arcsec. This is simulated by multiplying both delta-v vectors by a rotation matrix for infinitesimal angles, where the quantities ε_x, ε_y and ε_z have an expectancy value of 0 and a standard deviation of $\sigma = 30''$. The simulated delta-v for the maneuvers i = 1,2 are obtained by:

$$\begin{pmatrix} \delta v_{\mathrm{R}i}^{s} \\ \delta v_{\mathrm{T}i}^{s} \\ \delta v_{\mathrm{N}i}^{s} \end{pmatrix} = f_i^{s} \begin{pmatrix} 1 & \varepsilon_{zi}^{s} & -\varepsilon_{yi}^{s} \\ -\varepsilon_{zi}^{s} & 1 & \varepsilon_{xi}^{s} \\ \varepsilon_{yi}^{s} & -\varepsilon_{xi}^{s} & 1 \end{pmatrix} \begin{pmatrix} \delta v_{\mathrm{R}i} \\ \delta v_{\mathrm{T}i} \\ \delta v_{\mathrm{N}i} \end{pmatrix}, \tag{2}$$

  where s is the number of the sample of the Monte Carlo simulation.

- Differential drag has a linear effect over time on $a\delta a$ and a quadratic effect on $a\delta\lambda$ [7][8]. The differential drag is dependent on quantities that are difficult to predict, like the atmospheric density, the true effective cross-section (due to attitude maneuvers) and the true weight of the satellites (e.g., due to fuel consumption). Hence an ad-hoc uncertainty of the differential drag with standard deviation of 20% is applied in the Monte Carlo simulations.

From the requirements discussed in section 2.2 arise three acceptance criteria (AC), which have to be fulfilled, before the AVANTI experiment can be started. The Monte Carlo simulation serves to verify, if these conditions can be fulfilled even with execution errors during the separation.

- AC1: the relative semi-major axis after the drift-reduction maneuver must be negative (i.e., residual drift increases the satellite separation) despite all the included uncertainties.
- AC2: The closes transit of BEESAT-4 through the R=0 plane in the vicinity of BIROS must take place at a safe distance of at least 2 km.
- AC3: The minimum distance in the RN plane must be larger than 150 m for a final orbit with almost no drift remaining. In the case that a large negative relative semi-major axis

is present a minimum RN distance of less than 150 m is acceptable. In such a situation safety is ensured by the fact that the satellites are drifting apart in tangential direction.

The results of the Monte Carlo simulation are shown in Fig. 4, 5, and 6. Figure 4 plots the relative semi-major axis ($a\delta a$) and the mean along-track separation ($a\delta\lambda$). The simulated samples are shown after the separation (in gray) and after the drift-reduction maneuver (in black) in the left subplot and 24 hours after the drift reduction maneuver in the right subplot. Furthermore the two limits for the along-track separation at 5 km and 10 km are plotted. It can be seen, that in none of the simulated samples the relative semi-major axis is positive. Thus AC1 is fulfilled.

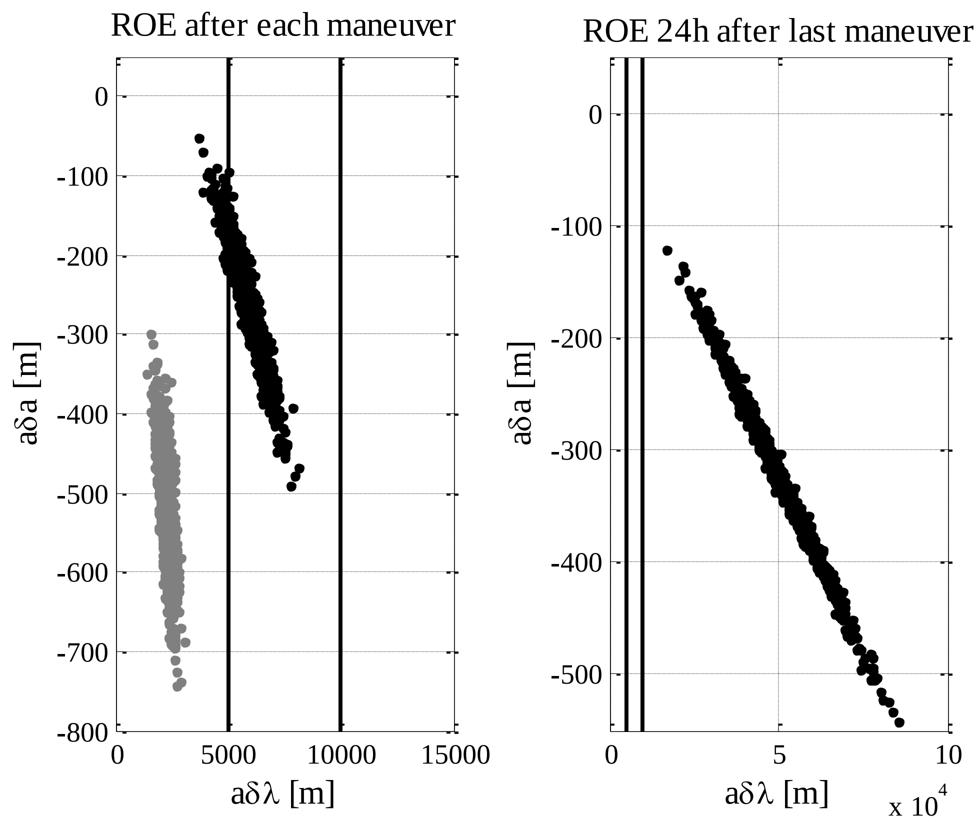

Figure 4. Satisfaction of the AC1 criterion

Figure 5 shows the nearest crossing of the R=0 plane in dependence of the SPL performance factor (f_1). The complete time horizon from the ejection until 24 hours after the drift-reduction maneuver is covered. It can be seen that no crossing closer than 2000 m to the BIROS satellite occurs, which validates AC2.

Finally Fig. 6 deals with the AC3 criterion and the minimum RN distance is plotted against the relative semi-major axis value. The dots show the value for a bounded orbit after the drift reduction maneuver. This means, that even if the along-track drift is reduced or even reversed by a maneuver execution error, the minimum RN distance is kept.

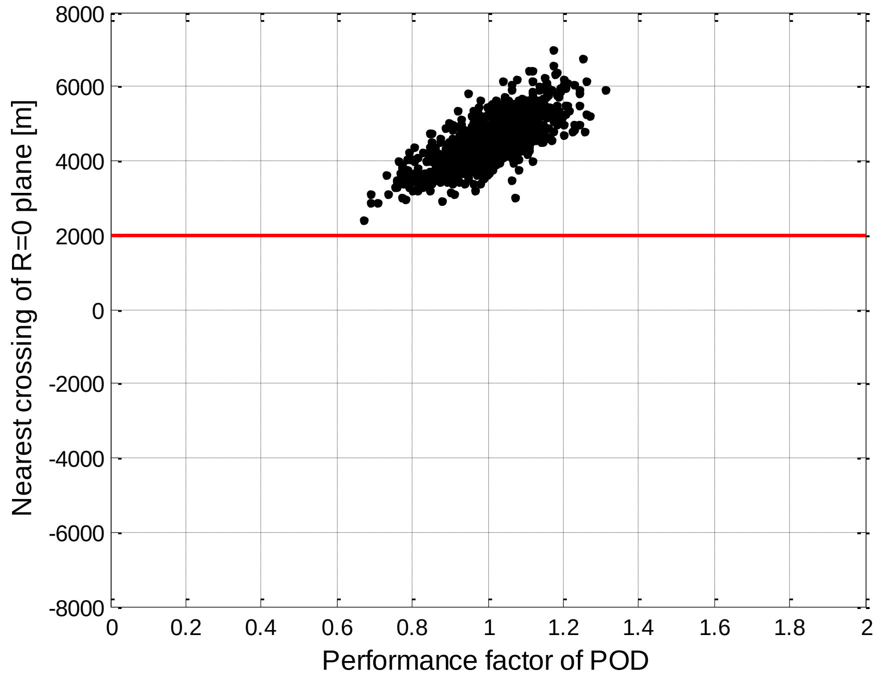

Figure 5. Satisfaction of the AC2 criterion

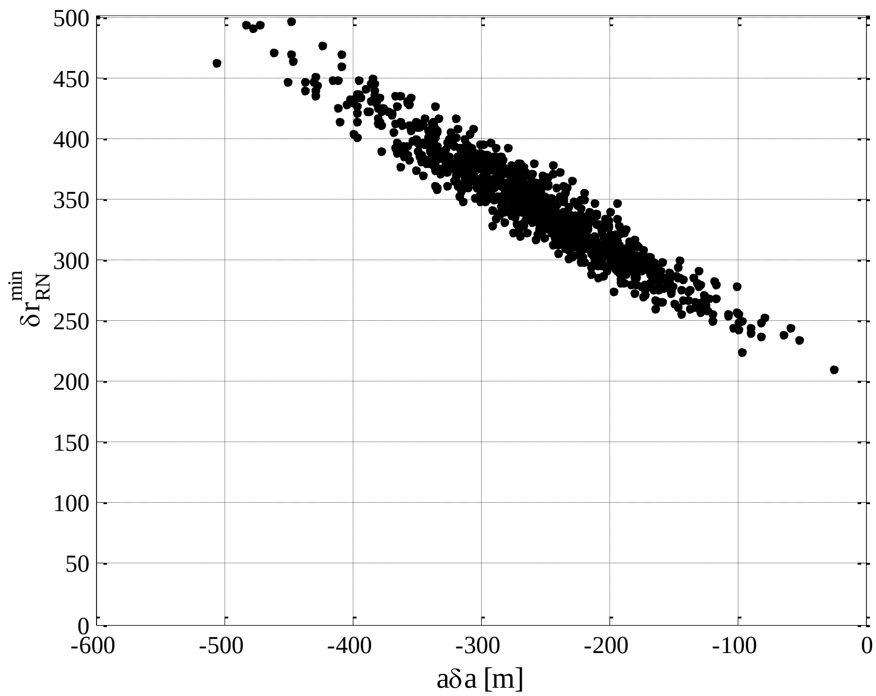

Figure 6. Satisfaction of the AC3 criterion

5. Operational Aspects

Due to the various constraints mentioned above, it is crucial for a successful acquisition of the AVANTI initial conditions, that all operational tasks are planned well in advance. Since the separation strategy will leave the formation slowly drifting apart, it is important to determine the relative orbit, compute and execute the formation acquisition maneuvers within 24 hours. If this fails, it will become more expensive in terms of delta-v to recover the formation at a later stage. The separation has to be planned such, that a radar tracking can be performed as soon as possible.

The analysis is carried out for an assumed separation on 01/07/2016. As the launch is currently scheduled for end of April 2016 and the commissioning phase should take 8 weeks, this would be the first opportunity for a separation. The FireBird ground station network includes the ground stations in O'Higgins (OHIG), Inuvik (INUV), Svalbard (SPZBG) and Weilheim (WHM1). Svalbard is northernmost station, while O'Higgins is the southernmost. As the separation has to take place during a ground station contact, they would both be suitable, as they fulfill the additional requirement that the separation should be close to the poles. Figure 7 shows the visibility of the involved ground stations (empty bars), the TIRA radar (red bars) and the Earth's shadow (solid bars) for the day of separation and the following day. It can be seen, that at ~19:30 on the 01/07/2016 and at ~21:00 on the same day, there are overlapping contacts of the three ground stations WHM1, SPZBG and INUV. They would pose excellent opportunities for the separation with comfortable time for pre- and post-separation analyses. However the TIRA radar has almost the same visibility as the Weilheim ground station, as both are located in Germany. If the separation would take place during the SPZBG contact in the first triple passage at ~19:45, there would be only 1:25 h (or respectively slightly less than one orbit period) until the next TIRA passage. In case of a severe under performance of the release mechanism this might not be enough time for the formation to build up the required along-track separation of 5km and thus the two spacecraft might not be distinguishable for TIRA. In addition, this would be the last TIRA for the next 10 h, so there would be no backup opportunity for a missed pass. Hence the separation during a triple contact has to be ruled out.

It would be better to separate about 2 orbit periods before the first radar tracking is performed. On 01/07/2016, this would be the SPZBG contacts at ~5:40 and ~16:30. Of the two contacts the latter is significantly longer (9 min as opposed to 5min). Hence it is chosen for the separation. Three hours later at ~19:35 is the first opportunity for a radar tracking and ~21:10 another one as backup for the first one. If both passages are successful a first preliminary orbit determination of BEESAT-4 is possible, which allows to draw first conclusions on the separation performance. In order to determine the orbit reliably, the observation data has to be fortified with another passage of radar tracking. The next opportunities are at ~8:30 and ~10:10 on 02/07/2016.

The analysis above is only valid, if the launch and the commissioning phase are performed as scheduled. Launch delays of several months are not uncommon for satellite projects. If the launch is only slightly delayed or the actual orbit is slightly different than planned, the analysis has to be updated. In order to show, how strongly the separation scenario is affected, the analysis is repeated with an assumed launch delay of six months. The separation should then take place on 01/01/2017, which is shown in Fig. 8. In both figures, the black bars indicate, when the

BIROS satellite is in Earth's shadow. It can be seen, that for the summer separation scenario, the satellite is always illuminated by the Sun, when in contact with the SPZBG ground station. In the winter scenario, the SPZBG contacts are partially in shadow. Hence, in this case the Antarctic ground station OHIG has to be used to perform the separation online in order to fulfill the lighting requirements.

Finally it has to be verified, that the RGB camera which will capture the ejection is not blinded by the sun. Figure 9 shows the BIROS body-fixed frame at separation for the summer scenario (01/07/2016), while Fig. 10 shows the same view for the winter scenario (01/01/2017). The boresight axis of the camera is at (0°/90°) which coincides with the ejection vector. The dotted line at the top indicates the field of view of the camera, while the other dotted line indicated the area that is obstructed by the Earth. The grey dot shows the location of the Earth's center and the yellow star shows the location of the Sun. It can be seen, that in both cases, the Sun is about 90° of the boresight axis of the camera. Hence the camera will not be blinded during separation.

6. Conclusions

In this study, a separation strategy of the picosatellite BEESAT-4 from the LEO satellite BIROS was developed. The strategy serves the purpose of a safe separation and the establishment of safe and stable initial conditions for the Autonomous Vision Approach Navigation and Target Identification experiment. The strategy was the enhancement of a preliminary concept which had become obsolete due to changed pre-conditions.

The design had to incorporate several external requirements and constraints. These requirements originate either from the FireBird mission or the AVANTI experiment. These requirements comprise safety concerns, initial conditions for AVANTI, ground station contacts, lighting conditions, radar tracking opportunities and design parameters of the separation mechanism and the BIROS propulsion system. In order to take all these factors into account relative orbital elements were employed. They provide an efficient framework for relative trajectory design that allowed adapting the strategy to all design parameters. Finally it was not only possible to expand the preliminary strategy for additional constraints, but also to improve the concept and reduce the delta-v consumption.

In order to validate the separation strategy a Monte Carlo simulation was performed considering several uncertainties like performance dispersion of the separation mechanism, the BIROS propulsion system and attitude control and differential drag. It was demonstrated, that the formation is safe at any time due to relative eccentricity/inclination vector separation and a residual drift towards larger separations. Even if planned maneuvers are not executed, the formation will drift apart. This effect is supported naturally by the differential drag of the two spacecraft.

Finally an operational plan for the separation has been developed. The plan takes into account the ground station network, visibility, illumination conditions and the radar-tracking station TIRA. It has been shown that there is a seasonal dependence, and the plan will vary according the actual separation date. It is likely that the operational plan has to be updated after the launch of BIROS satellite and prior to the actual separation in order to adapt to unforeseen events like a launch delay or a deviation from the planned orbit. Nevertheless this study presented the tools that were used in the development of the separation strategy. As these tools are now in place an update or even a re-design of the strategy can be performed on short notice.

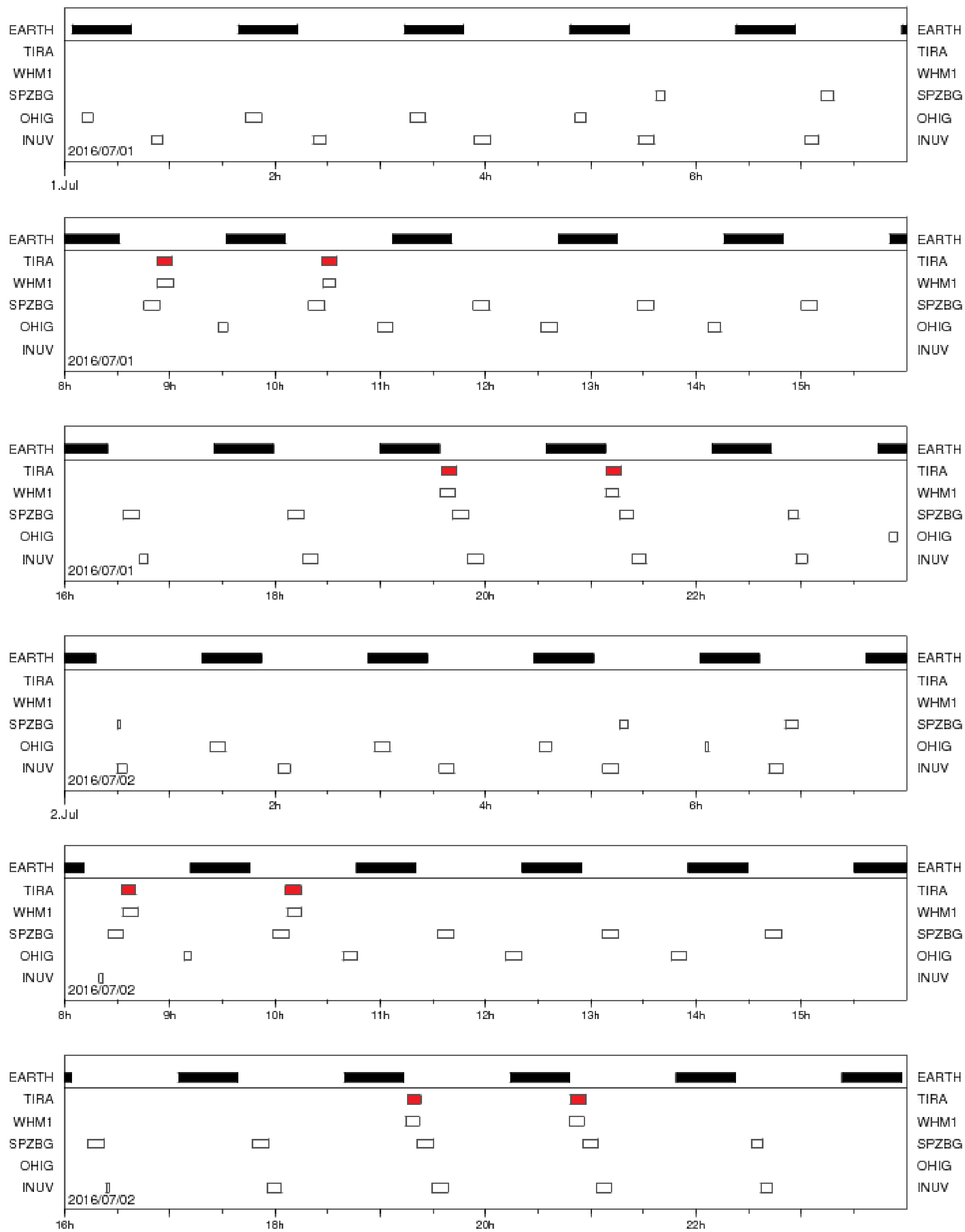

Figure 7. Visibility of BIROS by ground stations and TIRA on 01/07/2016

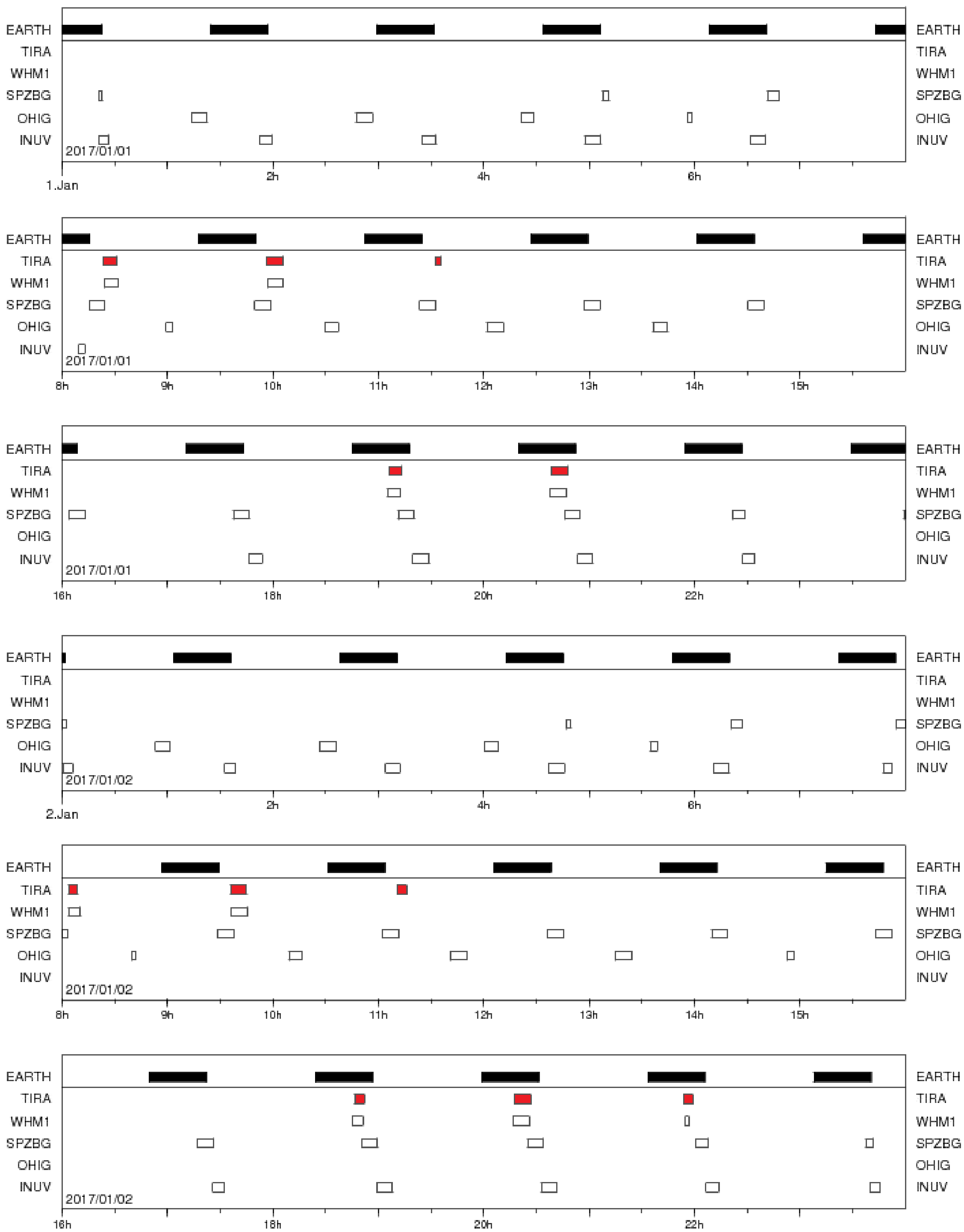

Figure 8. Visibility of BIROS by ground stations and TIRA on 01/01/2017

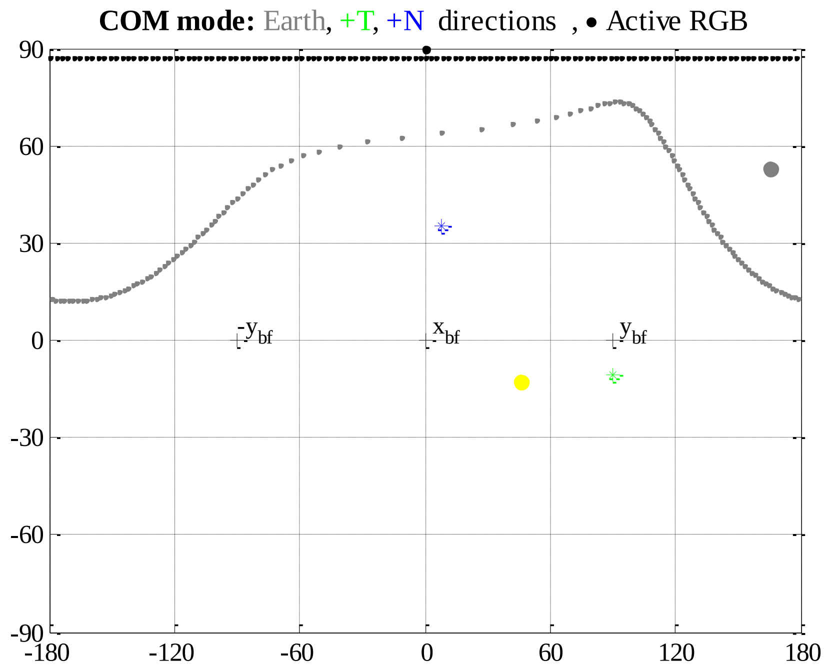

Figure 9. BIROS-fixed frame at separation (01/07/2016)

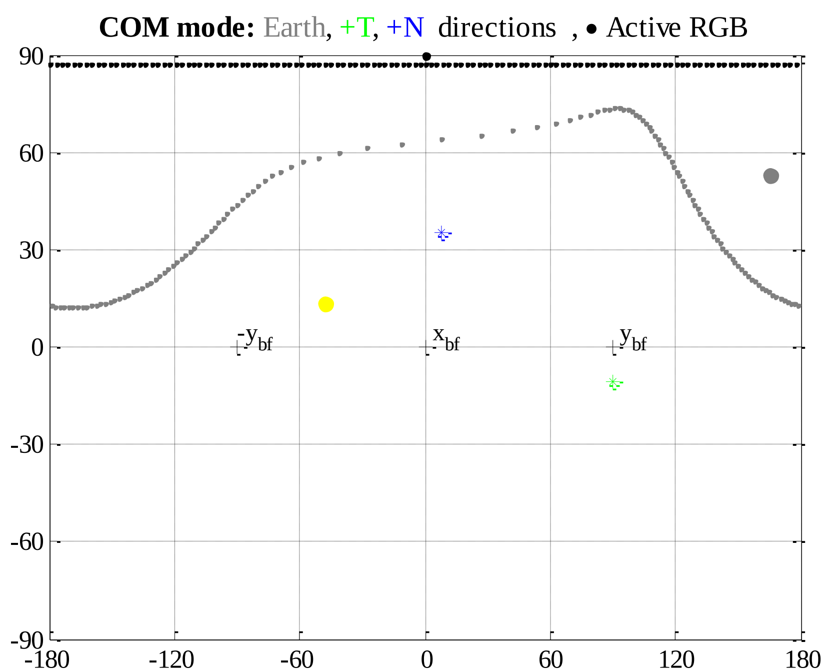

Figure 10. BIROS-fixed frame at separation (01/01/2017)

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