Angles-Only Relative Orbit Determination during the AVANTI Experiment

By Jean-Sébastien ARDAENS,[1] and Gabriella GAIAS,[1]

[1] *German Space Operations Center (DLR/GSOC), 82234 Wessling, Germany*

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This paper presents the key results of the angles-only relative orbit determination activities performed during the AVANTI experiment. This in-orbit endeavor was conducted by DLR in autumn 2016 and aimed at demonstrating spaceborne autonomous rendezvous to a noncooperative target using solely optical measurements. In view of the complexity of the experiment, a ground-based verification layer had been built-up to support continuously the experiment with the best possible knowledge of the formation state.

Key Words: Formation-flying, Orbit determination, AVANTI

1. Introduction

The AVANTI (Autonomous Vision Approach Navigation and Target Identification) experiment[1,2] represents an important milestone on the way to autonomous navigation to a noncooperative target. This technological demonstration was conducted in autumn 2016 and could successfully show in orbit the ability to approach fully autonomously a passive object in a safe and fuel-efficient way using only line-of-sight measurements provided by a single camera.[3]

In order to limit the costs and time required to develop a dedicated formation-flying testbed, AVANTI had been implemented on BIROS, a German Earth observation satellite launched in June 2016 as part of the FireBird constellation.[4] This choice was motivated by the fact that BIROS was carrying a third-party picosatellite (BEESAT-4[5]) to be released in orbit using a dedicated ejection mechanism,[6] which means that an appealing target was generated for free to support the experiment without the need of spending propellant to fly to an existing object. In addition, the BIROS spacecraft was already equipped with the hardware devices required by the experiment: a camera and a propulsion system. No additional formation-flying sensors or actuators were embarked, so that the entire experiment had been designed to use one of the star cameras as unique sensor for the onboard autonomous relative navigation.

A dedicated standalone spaceborne application had been designed to reach this ambitious goal, requiring the development of novel complex algorithms to handle autonomously the attitude profile of the satellite, to acquire and process images in real-time, detect the target spacecraft and derive a relative state estimate, and finally to compute and execute maneuvers according to a guidance plan satisfying numerous constraints. In view of the complexity and experimental status of the onboard software, it appeared early obvious that a ground-based verification layer would be needed to support the characterization and validation of the onboard algorithms, giving the birth to the ground facility for precise vision-based relative orbit determination. It has to be emphasized that the experiment has been conceived to deal with a truly uncooperative target, relying only on pictures to estimate precisely the state of the formation. As a matter of fact, the images collected in orbit were really the only available observations, since the GPS receiver embarked by BEESAT-4[7] was unfortunately not yet operational during the time slot allocated to AVANTI.

Compared to the onboard real-time navigation,[8] the ground-based orbit determination benefits from larger computational power (allowing thus for more advanced and accurate algorithms) and from the critical eye of the human operator, able to better assess the plausibility of the solution. As a consequence, the resulting reconstructed relative trajectory becomes the best possible post-facto knowledge of the state of the formation, which can serve as reference to characterize the performance of the onboard algorithms and of course as ultimate instance to monitor the safety of the formation during the close approaches.

This optimistic statement should not lead us to overlook that angles-only relative orbit determination in low Earth orbit remains a delicate problem. The design of the relative orbit determination process could partly rely on the experience already collected in 2012 using the PRISMA formation-flying testbed.[9] At that time, the so-called ARGON (Advanced Rendezvous demonstration using GPS and Optical Navigation[10]) experiment had already tackled the problem of angles-only relative navigation by performing a ground-in-the-loop approach to a noncooperative target using optical methods. As outlined in the first section, AVANTI is however confronted to new challenges since it flies on a more demanding orbit, in view of the future possible applications of such a technological know-how: rendezvous to space debris or to a noncooperative satellite to be serviced.[2]

Compared to ARGON, the relative orbit determination supporting AVANTI has to deal with degraded visibility conditions and strong orbit perturbations which are difficult to reproduce faithfully in a simulation environment. As a result, collecting valuable in-orbit experience regarding the system behavior and the achievable performance was also part of the experiment. A short ground-based radar tracking campaign has been conducted during AVANTI, providing an independent assessment of the accuracy of the relative trajectory reconstruction. After a brief description of the design of the facility in the second section, the key results and performance validation are presented in the final section.

2. Angles-Only Navigation in Low Earth Orbits

It is probably well known to the Reader that the problem of relative navigation based on line-of-sight measurements is weekly observable. In order to improve the observability, it is sufficient to execute maneuvers which alter the relative motion.[11] Even in this case, angles-only navigation will always remain affected by a strong anisotropy: the achievable lateral accuracy (that is, perpendicular to the line-of-sight) is always much better than the longitudinal accuracy. This explains why the results presented in the paper will often be expressed in the Radial-Tangential-Normal (RTN) comoving orbital frame: when observing a target over distances of several kilometers, the flight direction is indeed more or less aligned with the line-of-sight.

Flying in low Earth orbits results in additional difficulties for the relative navigation. Contrary to the ARGON experiment which, thanks to the dusk-dawn orbit of the PRISMA satellites, benefited from optimal illumination conditions, AVANTI is meant for target objects flying on any kind of low Earth orbits. This has dramatic impacts in terms of visibility, since the target object is eclipsed during a large part of the orbit and the camera becomes blinded by the Sun during another large part of the orbit. As a result, only a tiny portion of the relative motion can be observed as depicted in Fig. 1, weakening thus the observability. For AVANTI the situation is even worse, because the experiement was allowed to take images only every 30 s, so that very few measurements were available.

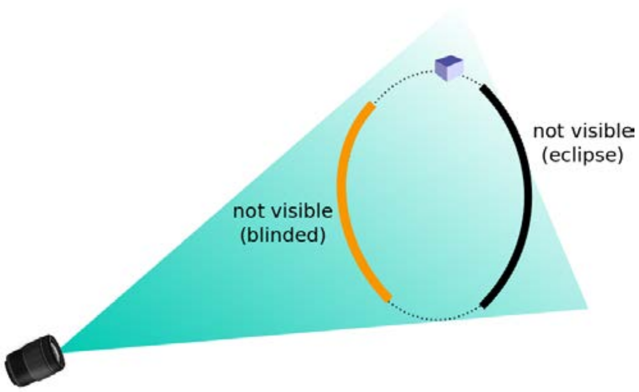


Fig. 1.: Limited visible relative motion in low Earth orbits.

The second major difference with respect to ARGON is due to the low altitude (500 km) of the BIROS orbit. Combined with the fact that BIROS and BEESAT-4 differ greatly in shape and mass, featuring thus a very different ballistic coefficient, this induces a strong unknown differential drag which has to be estimated as part of the orbit determination process. The atmospheric perturbation affects especially the relative semi-major axis Δa, which is used to control the mean along-track separation $\Delta\lambda$ of the formation. Special attention will be paid to these relative orbit elements in the sequel, since the precise knowledge of Δa is the key to ensure a smooth approach.

3. Relative Orbit Determination Facility

3.1. Overview

Fig. 2 provides a graphical description of the precise relative orbit determination facility. In principle, such a facility could (and should) also take advantage from alternative sources of measurements, fusioning several kinds of observations depending on their availability. As mentioned in the introduction, this was unfortunately not possible during AVANTI: the relative orbit determination task could only reprocess the same set of measurements as already collected onboard.

Contrary to the onboard real-time navigation, the reconstruction of the relative trajectory is done a posteriori on ground and is thus not subject to any restriction concerning the computational and data storage resources. As a result, in view of the sparse observations and the weak observability of the problem (cf. previous section), a batch least-square approach has been preferred to improve the robustness of the solution.

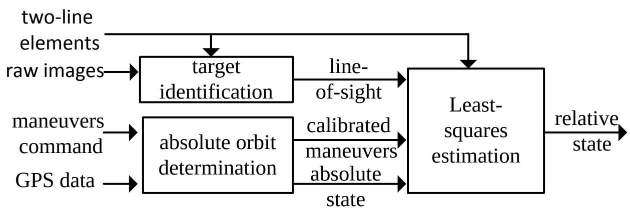


Fig. 2.: Functional description of the relative orbit determination.

The least-squares adjustment is facilitated using a reference solution, around which the quantities are linearized. It has been chosen to make use of a two-line element set (TLE) to derive an approximate value of the state, which can easily be justified by the fact that almost all orbiting objects larger than 10 cm are catalogized as part of the space awareness activities, so that any rendezvous with a noncooperative satellite can rely on TLEs for initial target acquisition. Moreover, as described in section **4.2.**, the TLEs appear to be the ideal companion for angles-only navigation at far range: while the latter is extremely precise in lateral positioning, but has trouble estimating properly the intersatellite separation, the former provides a valuable estimate of the distance. The position error of the two-line elements amounts typically to several kilometers, which corresponds to a few percents error when starting the approach at 50 km distance.

The least-squares method tries to adjust a numerically propagated relative trajectory to best fit the available line-of-sight measurements, which have to be extracted beforehand from the collection of images (cf next section). The adopted numerical model is described in Table 1. In order to reduce the errors of the dynamical model, the maneuvers executed by BIROS are calibrated using the GPS data prior to the relative orbit determination. This calibration is done as part of a GPS-based orbit determination combining code and low-noise carrier phase measurements to reconstruct the absolute trajectory of BIROS with a precision down to a few centimeters.[12] The resulting calibration errors are believed to be reduced to 0.1 mm/s.

As already mentioned, the unknown differential drag is the predominant source of error in the relative motion model. As a consequence, it has been decided to estimate it during the relative orbit determination. This is achieved by setting the drag

Table 1.: Numerical model used for relative orbit propagation.

Items	Values
Gravity field	JGM3 20x20
Atmospheric density	Harris-Priester
Drag model	Cannon ball
Solar pressure	Cannon ball

coefficient of the target spacecraft to a constant a priori value and letting the least-squares process estimate freely the drag coefficient C_D of the chaser spacecraft. The state vector describing the relative trajectory becomes thus

$$\mathbf{X} = \begin{pmatrix} \mathbf{r}^T & \mathbf{v}^T & C_D \end{pmatrix}^T, \tag{1}$$

where $\mathbf{r}$ and $\mathbf{v}$ represent the respectively the inertial relative position and velocity vectors.

3.2. Target Detection

The apparent simplicity offered by passive imagery comes at the cost of additional processing difficulties. Before making use of line-of-sight measurements, it is first necessary to extract them from the pictures. This is not really a problem at mid and close range, where the luminosity of the object allows an unambiguous recognition of the target, but this becomes more challenging at far-range, where it is impossible to recognized at the first glance whether a luminous spot in the image represents a faint star, a hot pixel or a satellite. The use of a star catalog comes naturally in mind to help distinguishing the target from celestial objects. However, this approach is not sufficient, because some stars might not be present in the catalog or simply because additional non-stellar objects might be simultaneously visible. In view of the few available measurements and of the weak observability of the angles-only relative navigation, it is important to ensure that all the line-of-sight measurements refer to the same target, otherwise the additional outliers could prevent the convergence of the solution. The strategy retained to ensure a robust and reliable target detection consists in associating a kinematic and a dynamic approach.

The first step relies on the fact that, flying on a similar orbits, the apparent motion of the target seen by the chaser is very different from the motion of a star or from the motion of satellite flying on a different orbit. As depicted in Fig. 3, when considering the history of the non-recognized objects, some trajectories can be recognized. This is valid only if the camera is fixed in the local orbital frame, which might not be the case, if the orientation of the camera follows the target or in case of large attitude control errors. As a result, it is necessary to consider the history of the non-recognized objects as viewed as a virtual camera which fixed in the local orbital frame. Afterward, the points belonging to the same trajectory are grouped using a clustering algorithm. The Density-Based Spatial Clustering of Applications with Noise (DBSCAN) has been found extremely convenient for this purpose, since it allows grouping the points whose interdistance is below a certain threshold (black stars in Fig. 3), considering the other ones as noise. Since the distance traveled by the target object between two images is much smaller than the one of a non-recognized star or of a satellite flying on a different orbit, this clustering algorithm selects automatically the proper trajectory (cluster on the left in Fig. 3). This kinematic selection might however fail in some cases if a conjunction of random non-recognized objects appears (cluster on the right).

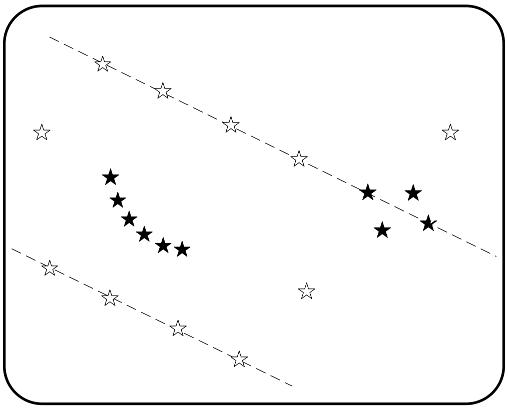


Fig. 3.: Density-based clustering of the non-recognized objects.

The second step complements the kinematic target detection by a data screening based on the a priori reference trajectory. By plotting the line-of-sight residuals between the target detected in the image and the modeled measurements, it becomes possible to discard the observations which are obviously too far from the expected values. As depicted in Fig. 4, this is however not a trivial task, since the residuals can be several orders of magnitude larger than the expected measurement noise if the reference trajectory is affected by some uncertainties. As a result, a simple data screening strategy consisting in discarding the measurements whose residuals are larger than a user-defined threshold is not adapted, since the value of this threshold might be extremely high and depends anyway on the quality of the a priori reference trajectory. Here again, a clustering algorithm provides a convenient means of discriminating the measurements belonging together from the outliers. For simplicity, the DBSCAN algorithm has been recycled for this purpose and worked reasonably well, even if frequent manual adaptations of the data screening parameters were required during the AVANTI campaign, denoting some room for improvement.

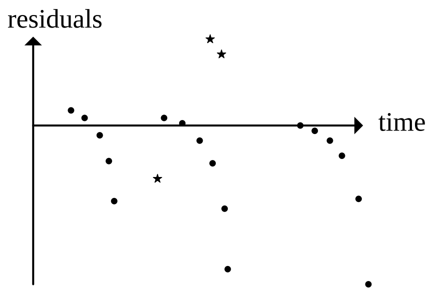


Fig. 4.: On the difficulty to distinguish the proper measurements (dots) from outliers(stars).

Once the target is properly identified, the precise orientation of the camera is estimated using the stars in the background to deliver the inertial line-of-sight measurement to the least-squares process, which is parametrized using a set of two angles (α,δ) named respectively right ascension and declination.

4. Flight Results

4.1. The AVANTI campaign

Two months in orbit were necessary for the successful completion of the experiment, most of the time being dedicated to a thorough commissioning of the spacecraft. Dealing with spaceborne autonomous close-proximity formation-flight, it was indeed necessary to ensure that all subsystems involved in the experiment were working properly before starting an autonomous approach. As depicted in Fig. 5, several rendezvous and recedes with different levels of autonomy could be already exercised during the commissioning phase, generating a valuable collection of images at different ranges. Once the satellite was commissioned, the full featured experiment could start on 19 November 2016, during which two autonomous approaches were performed, first from 13 km to 1 km, then from 3 km to 50 m.[13]

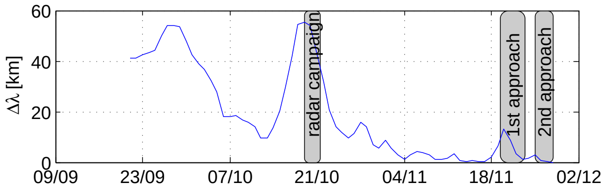


Fig. 5.: Intersatellite distance during the AVANTI campaign.

The formation has been kept passively safe throughout the entire experiment using a proper phasing of the relative E/I vectors.[14] This peculiar formation design, used so far for all formation-flying activities at the German Aerospace Center (DLR/GSOC), induces a spiraling relative motion which ensures a minimal intersatellite distance at any time, minimizing thus the risk of collision.

The problem of angles-only navigation presents different flavors depending on the intersatellite distance. Since AVANTI covered the full range between 50 km to 50 m, the following scenarios could be investigated during the experiment:

- **First acquisition**. This corresponds to the first contact with the target object at far range, typically several dozen kilometers. The main difficulty here is to be able to distinguish the target and to perform a meaningful orbit determination given the hardly observable variations of relative motion at this distance.
- **Far to mid range approach**. This range covers the main objective of the AVANTI experiment, namely the ability to navigate autonomously towards a desired hold point at a few hundred meters distance, far enough to guarantee homogenous visibility and brightness conditions throughout the entire approach.
- **Towards close range**. When decreasing further the distance, the increasing brightness and target size degrade greatly the accuracy of the line-of-sight measurements, posing new challenges to the relative navigation.

4.2. First Acquisition in Far Range

This analysis tackles the problem of approaching for the first time a noncooperative object at far range. In this scenario, it is assumed that a coarse orbit phasing has been already performed by the ground segment based on the available TLEs of the target. In view of the poor accuracy of the TLEs, no passive safety can be enforced at this stage, since the values of the relative eccentricity and inclination vectors cannot be determined accurately enough using TLEs. For safety reasons, a large distance has thus to be kept between the satellites. In fact, substential discrepancies between two consecutive sets of TLEs had been observed during AVANTI (up to 30 m semi-major axis difference!). In view of the poor reaction time of the ground-in-the-loop formation control (at least one day in the case of BIROS), it had been decided to keep a safe separation of about 30 km to avoid any risk of collision.

The strategy here is to keep simply the camera pointing in flight direction, hoping that the target is visible at such a distance (this depends on the object surface properties and camera sensitivity). If the orbit phasing has been done correctly, the large separation ensures that the apparent relative motion is contained in the field of view of the camera. During the AVANTI experiment, this acquisition phase could be investigated as part of the commissioning activities a few days after the separation of the cubesat. In fact, the first attempt to observe the picosatellite was performed twelve days after the ejection. At that time, BEESAT-4 had, according to the TLEs, already escaped to a distance of more than 40 km as depicted in Fig. 6.

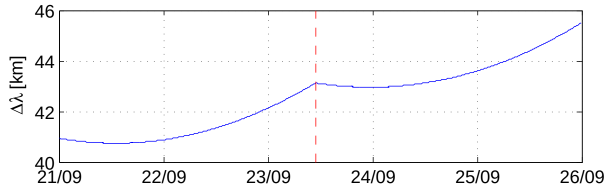
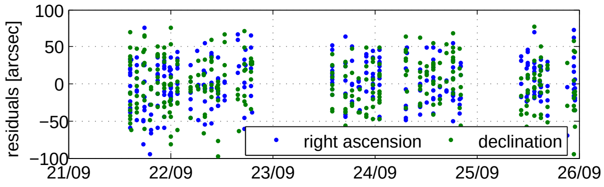


Fig. 6.: Estimated distance during the first acquisition.

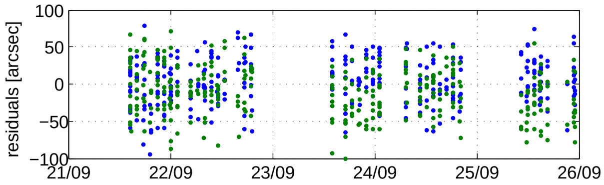
This first attempt could confirm that the star camera was able to track the tiny picosatellite up to a distance of about 50 km. However, determining precisely the relative orbit at this separation revealed itself to be very challenging. In order to improve greatly the observability, the ideal situation would be to alter considerably the relative motion by the means of a large and costly maneuver, which is usually not the preferred approach. In order to keep a reasonable propellant budget, an alternative strategy consists in executing small maneuvers and observing the resulting effect over a longer time interval. This idea was retained in AVANTI, where a single 1.2 cm/s maneuver has been executed on 23 September (represented by the red vertical line in Fig. 6).

Small maneuvers will only improve slightly the observability, requiring thus a longer observation arc (typically several days) to ensure the convergence of the least-squares process. However this comes at the cost of a degradation of the dynamical model over the considered arc, because the mismodeling errors will become predominant. Alternatively, one might be tempted using a priori covariance information to force the convergence close to the solution provided by the TLEs, with the danger of converging to a local wrong solution.

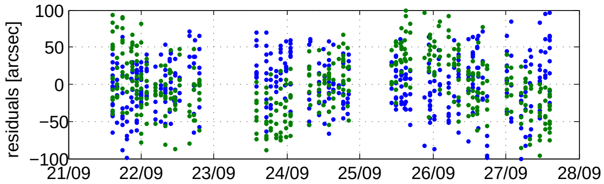
The difficulty here is that only few hints are provided to choose the best strategy. A close look to the line-of-sight residuals out the relative orbit determination process might provide some insight, but is not always sufficient. Fig. 7 depicts the dilemma faced by the user. Fig. 7a and Fig. 7b show the residuals obtained running two orbit determinations on the same data arc, the first time enforcing the convergence close to the



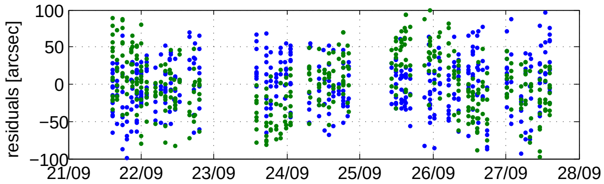
(a) 5-day-long using a priori covariance



(b) 5-day-long without a priori covariance



(c) 7-day-long using a priori covariance



(d) 7-day-long without a priori covariance

Fig. 7.: Line-of-sight residuals obtained using different orbit determination strategies.

solution provided by the TLEs (using 1 km position error and 1 m/s velocity error) and the second time without any a priori covariance.

At the first glance, no anomaly can be detected. The residuals of 30" corresponds to a measurement noise of less than half-a-pixel (one pixel is equivalent to 80"). Some data gaps can be observed. They corresponds to time intervals where the chaser had to interrupt the observation due to thermal problems on the BIROS satellite. Both residual patterns being nearly identical, it is difficult to claim which solution is the best. However Table 2 indicates that the solutions are pretty different (for simplicity the second column indicates only the relative position **r** of the state **X**, mapped in the RTN frame). By inspecting the standard deviation of the least-squares solution (also mapped in the RTN frame), it can be noticed that the expected along-track error of the solution is pretty large (7 km). Extending the data arc reduces the standard deviation, but this might in reality degrade the solution, because the dynamical model is not adapted anymore. This can be observed in Fig. 7c and Fig. 7c, where the pattern of the residuals does not correspond anymore to a Gaussian distribution. From the previous considerations, it appears clearly that angles-only relative orbit determination is not very accurate at far range and can even not compete with fresh TLEs regarding the achievable along-track accuracy. However this assertion has to be complemented by two remarks:

Table 2.: Orbit determination results.

Case	Rel. Position [m]	Residuals ["]	St. dev. [m]
a	[-757 41872 751]	0±31, 0±33	[17 673 14]
b	[-915 49010 882]	0±36, 0±42	[172 7705 141]
c	[-891 49592 868]	2±31, -11±33	[17 659 14]
d	[-1194 62356 1099]	0±36, 0±41	[105 4236 77]

- Even with several kilometers along-track error, this solution will not endanger the formation (8 km error at 40 km separation corresponds only 20% error). In fact, what really counts when starting the approach at far distance is the knowledge of the relative semi-major axis Δa, in order to ensure a smooth approach, as well as the shape and size of the apparent relative motion to already guarantee a passive safety[15]. As depicted in Fig. 8, all the solutions are still

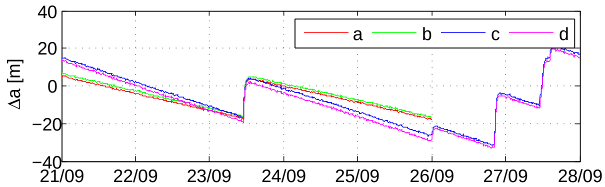


Fig. 8.: Estimated mean relative semi-major axis.

  pretty consistent regarding Δa despite large along-track errors, and tend to indicate a precision definitely better than what can be obtained with TLEs. Note how differently the drag coefficient C_D has been estimated between the 5-day and 7-day long data arcs, resulting in a very different estimate of the time derivative of Δa.
- At far range, the best approach seems to combine the strength of TLEs and optical navigation by constraining the solution close to the solution provided by the TLE. In this case, the solution is locked to the proper distance and benefits from the lateral accuracy of the angles-only observations.

4.3. Far to Mid Range Approach

As soon as larger variations of the apparent relative motion can be observed, the difficulties described in the previous section disappear. The orbit determination becomes able to converge rapidly and consistent results are observed between consecutive data arcs. Here again, the skill of the user is required to select the more appropriate length for the data arc, long enough to ensure observability and short enough to minimize the impact of the errors of the relative motion model.

Fig. 9 depicts for instance more than one month of relative orbit determination, covering a large part of the commissioning phase as well as the first autonomous approach (19 to 23 November). The gray zones correspond to different arcs for the relative orbit determination. The numerous maneuvers have not been represented for clarity. Note at the boundaries how accurately the different solutions match with respect to each other. Small discrepancies can be sometimes recognized (for example between the first and second data arc for Δa) but the errors remained limited to a few percents. In fact, only a closer look to the standard deviation of the solution (last plot in Fig. 9) can provide us with a better insight into the achieved accuracy of the solution.

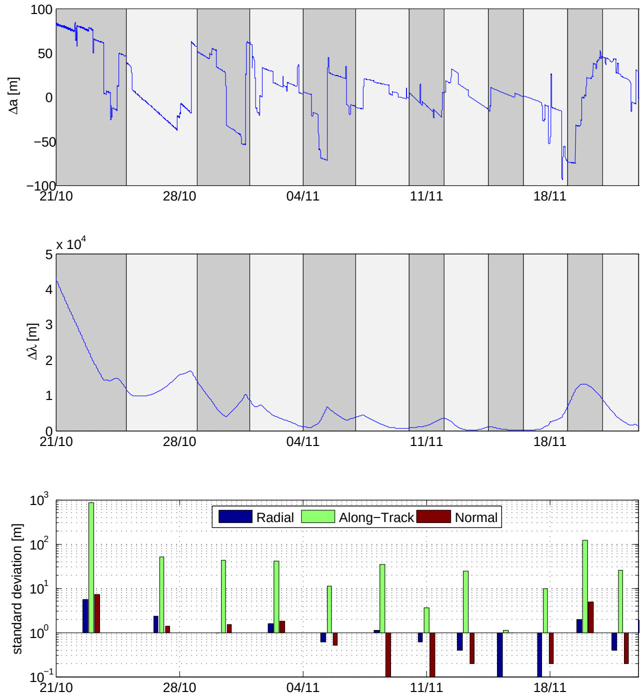


Fig. 9.: Reconstructed Δa and $\Delta\lambda$ during the AVANTI campaign.

A clear correlation between the intersatellite distance and the performance of the orbit determination can be recognized. Starting with a pretty large along-track error of about 1 km at 40 km (cf. previous section), the accuracy improves when the distance between the satellite decreases, reaching relative positioning performance at the meter level when the separation drops below 1 km (for example on 16 November). This feature belongs to the magic part of angles-only navigation: the relative navigation accuracy improves when it is needed.

4.4. A radar campaign as independent validation

The discussion of the previous section is based only on the analysis of the covariance of the solution, which provides a measure of the achievable orbit determination accuracy. Practically, this measure "is often found to be too optimistic in the presence of systematic force and measurement model error".[16) In order to assess the validity of the assumptions used for relative orbit determination, a radar campaign has been conducted as independent means of verification using the German Tracking & Imaging Radar (TIRA) system.

The radar on ground suffers however from the difficulty to discriminate the signals reflected by the chaser and target satellites if the intersatellite distance is too small. Consequently, it has been decided to conduct this campaign when the satellites were far away (more than 40 km distance). Three radar passes have been scheduled on 20-21 September, following the recommendations of the in-house expertise already available in this domain.[17) The resulting radar-based orbit determination is expected to be affected by an error of about 2 m in the radial direction and 20 m in the other directions.[17) For the angles-only orbit determination, a data arc spanning 5 days (18 to 22 November) has been selected for relative orbit determination, where a controlled approach had been initiated from ground to bring the formation back to 15 km separation.

Fig. 10 depicts the relative orbit determination errors com-

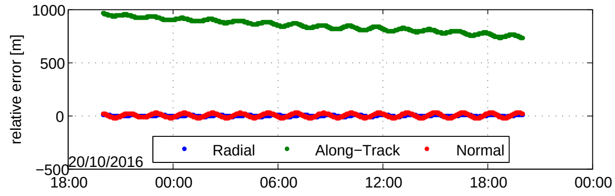


Fig. 10.: Orbit determination errors.

pared to the radar-based solution in the local orbital frame. As expected as this distance, the longitudinal error is much larger (two orders of magnitude) than the lateral error. Looking at the covariance of the solution, the relative orbit determination claims to be accurate to [5.5 873.8 7.3] m in the RTN frame, which is perfectly consistent with the observed errors, giving thus confidence that assumptions retained for relative orbit determination were correct.

A close look to the relative orbit elements gives more weight to what has already been emphasized: at this distance, what counts is to control smoothly the rhythm of approach and to establish a safe relative orbit, not really to know exactly the intersatellite separation (which is in our case anyway estimated accurately to 2%). Fig. 11 shows that, already at this distance, the relative semi-major axis is estimated accurately at the meter level! Its decay due to the differential drag is as well estimated pretty decently.

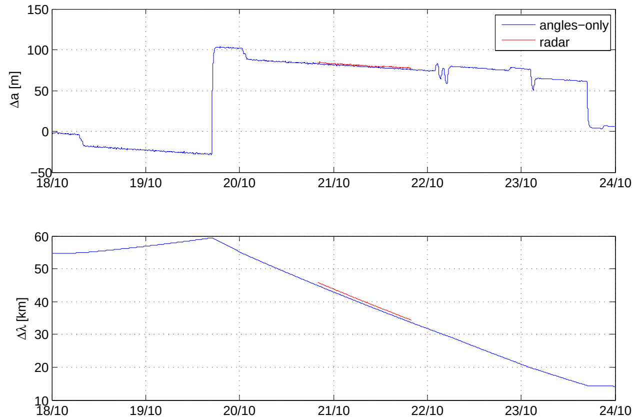


Fig. 11.: Angles-only vs. radar-based solutions

4.5. Towards close range...

Angles-only navigation comes naturally in mind to support far-to-mid range rendezvous. In this case, the target spacecraft is imaged as a point whose centroid matches accurately the actual center of mass, and the stars visible in the background ensure a precise knowledge of the orientation of the camera. All these aspects contribute to provide line-of-sight measurements accurate at the subpixel level and allow for accurate relative orbit determination throughout the entire rendezvous.

In view of the satisfying performance obtained during the far-to-mid range approach, it was tempting to also investigate what would happen at closer distance. Can angles-only navigation also be used to bridge the mid-range gap, that is, to bring the target in the working range of close-proximity sensors?

The major difficulty during a close approach lies in the increasing brightness of the spacecraft, making mandatory the regulation of the exposure time. However, when reducing the exposure, the stars in background are not visible anymore and it becomes impossible to derive precisely the orientation of the camera. Another important limitation is due to the image of the target itself, which can not be considered anymore as a point aligned with the center of mass. These two sources of error contribute greatly to degrade the accuracy of the line-of-sight measurements.

During AVANTI, the unknown differential drag was also an important source of troubles at close range. As already mentioned, a spiraling approach had indeed been enforced during all rendezvous. When decreasing the distance, BIROS had to perform large attitude maneuvers to follow the target, resulting in large variations of the cross-sectional area subject to the atmospheric drag. Unfortunately, the current drag model of the relative orbit determination (cannon ball) considers however only a constant C_D and cross-sectional area over one orbit determination arc, introducing thus non-negligible errors in the relative motion model.

As a summary, the orientation of the camera, the line-of-sight measurements and the dynamical model are affected by larger errors at close range. But since the problem depends very much on the distance, these uncertainties are still acceptable for small separations. In fact, one degree measurement error corresponds to less than 1 m error at 50 m distance but translates into 174 m error at 10 km. Similarly, the data arc length for orbit determination can be reduced at close range (a few orbits is enough) thanks to a better observability, reducing thus the impact of the modeling errors.

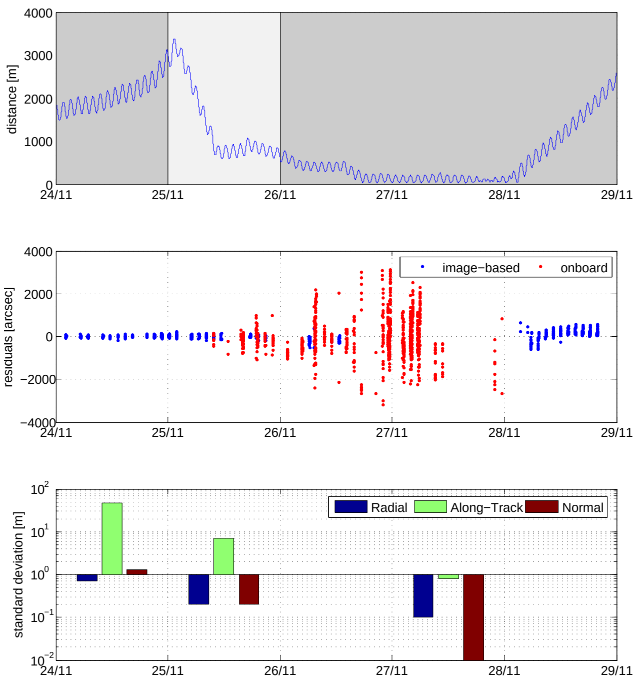


Fig. 12.: Orbit determination results during a close approach

Two close approaches have been exercised during AVANTI, the first one (11-18 November, cf. Fig. 9) with a strong support from the ground as part of the commissioning phase, the second one fully autonomously. This section will only focus on the fully autonomous approach (24 to 27 November). The upper subplot of Fig. 12 depicts the estimated instantaneous inter-satellite distance (not the mean along-track separation $\Delta\lambda$ anymore) during the approach. In the mid-subplot, the residuals in blue refer to angles-only observations which have been derived using the stars in the background to estimate the orientation of the camera.

When approaching too much, it becomes necessary to make use of the onboard attitude to determine the orientation of the camera and to compute the inertial line-of-sight observations (in red). In the case of BIROS, since one of the star cameras was used to follow the target, it was unfortunately not possible to always keep a camera head pointed to the deep sky, so that the onboard attitude was sometimes affected by errors up to one degree! Nevertheless, a proper tuning of the filter parameters (especially the measurement noise) makes possible a precise reconstruction of the relative trajectory. According to the covariance of the solution, relative positioning accuracy at the sub-meter level is achieved at close range!

5. Conclusion

During more than two months, precise post-facto reconstruction of the relative trajectory based only on line-of-sight measurements has been exercised in orbit, covering a range from 50 km to 50 m. Despite the weak observability, the strong dependence of the relative navigation performance on the inter-satellite distance makes angles-only navigation very appealing for approaching a noncooperative target. AVANTI demonstrated that even a tiny picosatellite can be visible at a distance up to 50 km. At far-range, angles-only relative orbit determination exhibits large along-track errors up a few hundred meters but is already able to estimate accurately the relative semi-major axis at the meter level, enabling thus a smooth and safe rendezvous. This statement could be confirmed independently by a dedicated radar-based cross-validation campaign. Afterward, the achievable accuracy improves continuously throughout the entire rendezvous, promising relative navigation performance at the submeter level at close range.

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