G.V.M. Gaias, J.-S. Ardaens
In-Orbit Experience and Lessons Learned from the AVANTI Experiment
Acta Astronautica, Vol. 153, 2018, p. 383-393
doi:10.1016/j.actaastro.2018.01.042

In-Orbit Experience and Lessons Learned from the AVANTI Experiment

Gabriella Gaias[1], Jean-Sébastien Ardaens

DLR, German Aerospace Center, 82234 Wessling, Germany

Abstract

This work addresses flight results and practical challenges of the Autonomous Vision Approach Navigation and Target Identification in-orbit demonstration. This endeavor realized a fully autonomous rendezvous to a noncooperative target in low Earth orbit, in the separation ranges between tens of kilometers to 50 meters, relying exclusively on angles-only observations extracted from pictures collected by a monocular, far-range, camera system. By considering experiment commissioning and execution phases, a total of two months of in-orbit experience could be collected, making AVANTI the most authoritative benchmark for designing the first phase of the approach for future active debris removal missions. Accordingly, this work revisits how crucial design decisions revealed decisive to the success of the mission and how they impacted the obtained experiment performances. As conclusion, such lessons learned gained from the flight campaign are reshaped as design guidelines for handing over the peculiar guidance navigation and control system - referred as to AVANTI-concept - to future rendezvous missions.

Keywords: active debris removal, noncooperative rendezvous, angles-only navigation, autonomy, formation-flying, flight demonstration

---

Email address: `gabriella.gaias@dlr.de` (Gabriella Gaias)

[1] Corresponding author.

Preprint submitted to Acta Astronautica, Elsevier *January 11, 2018*

1. Introduction

The AVANTI (Autonomous Vision Approach Navigation and Target Identification) experiment recently demonstrated the viability of a purely vision-based approach to autonomously rendezvous a passive target in low Earth orbit (LEO), to reach its close vicinity, where a more comprehensive assembly of sensors is required to prepare and carry out contact interaction phases [1, 2]. Within such in-flight demonstration, in fact, the Earth-observation small satellite BIROS has been used to chase the BEESAT-4 CubeSat, from far-range down to circa 50 m of inter-satellite distance, in a fully autonomous fashion [3].

The introductory section of Reference [2] presents a critical assessment of commonalities and innovative aspects presented by AVANTI compared to other multi-satellite missions flown so far in LEO like Orbital Express [4] and PRISMA (Prototype Research Instruments and Space Mission Technology Advancement) [5], which performed several vision-based navigation experiments [6, 7, 8]. Beyond many specific details, both Orbital Express and PRISMA were cooperative multi-satellite missions; whereas the main peculiarity of the AVANTI demonstration was its incontrovertible noncooperative mission scenario [9, 2]. As a matter of fact, the images taken by BIROS constituted the unique source of observations available in real-time to perform the relative navigation task. This was due to the absence of any form of communication between BIROS and the target body and to the lack of external navigation sources usable a/o accurate enough for inter-satellite distances below few kilometers.

To meet its ambitious goals, AVANTI pursued a low-cost minimalistic design approach with no impact on the design of the chasing spacecraft: BIROS already featured a propulsion system and a star-tracker sensor. This latter has been used as far-range camera and no further formation-flying specific sensors and actuators have been embarked on the already designed BIROS satellite. In addition, AVANTI exploited the opportunity that the BIROS spacecraft embarked a single picosatellite launcher device to release in orbit the BEESAT-4 one-unit CubeSat of the Technical University of Berlin [10]. So far pico/nano satellites have been usually deployed from the upper stage of a launch vehicle or from the international space station with the goal of getting as far as possible from them to reduce the collision risk. In this case, instead, the BEESAT-4 ejection has been considered as an appealing opportunity to generate in a low-cost way a target to support proximity operations activities. The aspect of employing a standard ejection mechanism to enable confined formation-flying activities embodies a further innovation brought by AVANTI. Nevertheless, this required the development of a specific separation strategy addressed in References [11] and [12], which lead to the in-flight events described in [3].

Originally planned to start immediately after the release of BEESAT-4, the AVANTI experiment could only take place two months after it. Due to some scheduling conflicts in the mission timeline, the experiment commissioning could not be performed before the BEESAT-4 deployment deadline. The latest possible time-limit to eject the picosatellite, in fact, was a hard constraint driven by the endurance of its battery, which had been recharged for the last time before the satellite integration at the launchpad. As a matter of fact, postponing the experiment commissioning phase already with the target satellite free-flying in space turned out to be an extremely valuable situation. On the one hand, it extended the flight-time allocated to AVANTI. On the other hand, AVANTI became a unique testbed to stepwise familiarize with the vision-based approach, with increasing levels of complexity and autonomy.

Indeed the vision-based approach demonstrated by AVANTI is very appealing for future on-orbit servicing and debris removal missions: simply using a passive monocular camera has no impact on the spacecraft system design but it allows to safely carry out the first phase of the rendezvous. AVANTI itself is an example of the high level of portability of such guidance navigation and control (GNC) concept: *de facto* its spaceborne GNC system has been integrated into a satellite not specifically designed to support formation-flying activities. At the same time, AVANTI has been an extremely realistic technological demonstration for future LEO applications, since it took place on a general orbit scenario, strongly perturbed by differential aerodynamic drag and presenting eclipses that lead to periodic outages of the visibility of the target satellite.

This paper sheds light on some practical aspects encountered during the course of the flight activities. After an overlook of the whole flight campaign, Section 3 focuses on the key-role that the architecture of the spaceborne GNC system played to enable the achievement of AVANTI's goals. Afterwards, Sections 4 and 5, describe practical challenges respectively related to visibility issues and close-range aspects, deriving from both orbit scenario and platform characteristics. Finally, in Section 6, design decisions and consequent lessons learned turn into design guidelines to exploit the successful *AVANTI-concept* in possible future missions.

2. In-orbit experience

AVANTI was one of the secondary scientific experiments to be accomplished within the FireBird mission [13]. This is a small-scale scientific mission of the German Aerospace Center (DLR) for Earth observation and hot spot detection comprising a loose constellation of two satellites: TET-1 [14], already launched in July 2012, and the Bi-Spectral InfraRed Optical System (BIROS), launched on the 22nd of June 2016. BIROS has been injected into an almost circular, Sun-synchronous local time of ascending node 21:30, 515 km high orbit. Afterwards, on the 9th of September 2016, BIROS released BEESAT-4 in-orbit by means of a single picosatellite launcher device which provided an equivalent separation delta-v of circa 1.5 m/s [11, 12, 3]. While carrying out its independent experimental activities, BEESAT-4 has been used as noncooperative target for the sake of the AVANTI demonstration.

The timeline of the whole in-orbit experience collected to prepare and support AVANTI is shown in Figure 1 against the explored inter-satellite ranges. The experiment commissioning phase began shortly after the ejection of BEESAT-4, in parallel to the completion of the BIROS bus validation. Its overall duration occupied the majority of the flight-time since it comprised the stepwise verification of all the interfaces and functionalities required to support autonomous formation-flying activities. Particularly, the AVANTI GNC system made use of the following essential capabilities of the BIROS platform: attitude determination and control, absolute orbit determination, power/thermal/communication management, and activation of the propulsion system (interfaces and implementation details are presented in [2]). From the AVANTI GNC side, instead, the following functionalities have been verified: the core relative GNC and safety monitoring tasks (*e.g.*, interfaces with the star-tracker and behavior of the flight SW), the attitude guidance function (*e.g.*, selection of the best-suited attitude mode in compliance with the autonomous GNC activities), and experiment data handling (*e.g.*, pictures and data storage and down-link). At the same time, the preliminary phase has been also used to verify the experiment ground-segment, that is all the specific tools required for monitoring and supporting this technology demonstration (*e.g.*, post-processing relative precise orbit determination facility).

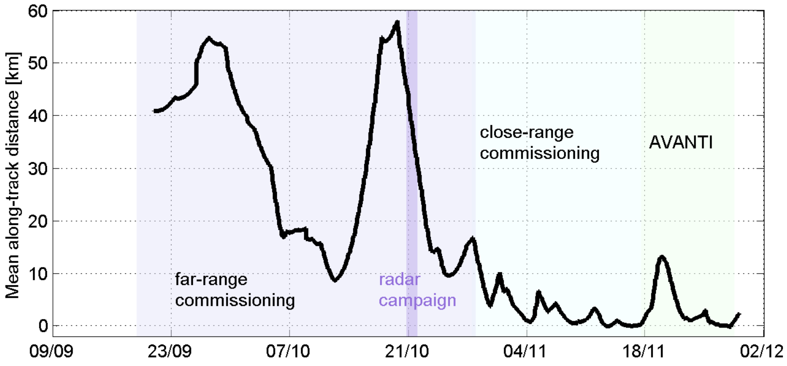

Figure 1: In-orbit phases for the preparation and execution of AVANTI.

In parallel to these functional verifications, the experiment commissioning phase was meant to investigate several aspects of the visual-based angles-only navigation, critically exposed in References [15] (*i.e.*, ground-based reprocessing) and [16] (*i.e.*, performance of the onboard navigation system). To this end, the first phase of the commissioning focused on the far-range domain (*i.e.*, above 3 km of separation distance), whereas the second part has been used to investigate the mid- (*i.e.*, from 3 km to 200 m) to close-range regions (*i.e.*, below 200 m). At far-range the main difficulties lay in the ability to distinguish the target and to perform a meaningful orbit determination given the hardly observable variations of relative motion at such distance. As independent verification of the line-of-sight relative navigation results a radar campaign has been conducted on the 20-21 October with the support of the German Tracking & Imaging Radar facility. Such radar observations have been used to perform radar-based picosatellite absolute orbit determination, thus obtaining a relative reference solution, with respect to the BIROS GPS-based absolute orbit. Results revealed to be consistent, achieving the same accuracy at least for the two lateral components [15]. The first two weeks of November, instead, have been dedicated to collect experience in imaging BEESAT-4 at closer distances, traveling through the mid-range domain (*i.e.*, from 10 km to few hundreds of meters), and reaching two times a relative distance below 200 m. At close-range, the main challenges are related to the fact that the target starts appearing very bright and large in the pictures, and the differential aerodynamic drag perturbation drastically changes, due to the tracking observation attitude profile that is required to keep BEESAT-4 in the camera field of view.

Once completed the aforementioned preparatory phases, in the second half of November, the fully autonomous activities could begin and the AVANTI experiment could be successfully carried out. References [1, 2] present the guidance, navigation, and control flight results achieved during such autonomous activities.

3. GNC architecture aspects

The first lesson learned from AVANTI corresponds to the main achievement of such demonstration: a purely angles-only (AO) navigation approach is feasible and safe despite navigation uncertainties and maneuver execution errors, even in the challenging environment of targeting a noncooperative object in LEO. As mentioned in the introduction, the major benefit of exploiting solely a monocular camera is the minimal impact on the chaser spacecraft design. Nevertheless, this comes at the cost of solving the weakly observable problem of reconstructing the relative state out of a sequence of bearings-only observations. Basically, complexity moves from the spacecraft design (*i.e.*, sensors, mass/power, thus costs) to the algorithms of the GNC system.

The key of success of AVANTI is to be found in the peculiar design of the GNC system, customized to cope with the intrinsic drawbacks of an AO approach: a passively safe guidance profile is generated to compensate navigation and, consequently, control performance anisotropy. Out of the relative orbit determination, in fact, the achievable lateral accuracy (*i.e.*, perpendicular to the line-of-sight) is way better than the longitudinal accuracy (*i.e.*, corresponding to the along-track direction at far-range). At the same time, the overall navigation accuracy remarkably improves when the distance between the satellite decreases. In such a situation, a collision-free approach can be achieved exploiting a smoothly-drifting transfer trajectory that presents (anti-)parallel relative eccentricity and inclination vectors and that shrinks its size in the plane perpendicular to the orbit velocity to reduce the overall 3D distance to the target [17, 9]. The GNC system designed to support AVANTI realizes - and demonstrated in-flight - such strategy, deserving the appellation of *AVANTI-concept*. It, in fact, embeds the generation of delta-v optimum passively safe rendezvous trajectory with an on-line independent monitoring of the one-orbit minimum lateral inter-satellite separation, with the authority to preemptively break the rendezvous in case of any contingency (thus exploiting the intrinsic advantage of a passive collision avoidance strategy).

The peculiar design of such AVANTI-concept can be explained with the support of Figure 2. Here, the left side presents a detail of the overall functional view discussed in Reference [1]. Highlighted are the main modules, referred as to AVANTI and OSM (onboard safety monitoring), and their input and output interfaces to the BIROS AOCS system. These latter, denoted as commands in the picture, are instructions for the AOCS higher software level, in charge to translate them into commands to the different hardware devices. The right view focuses on how the main functions interact with each other: the scheme tries to condense functional relationship with sequential connections (more details in [2]).

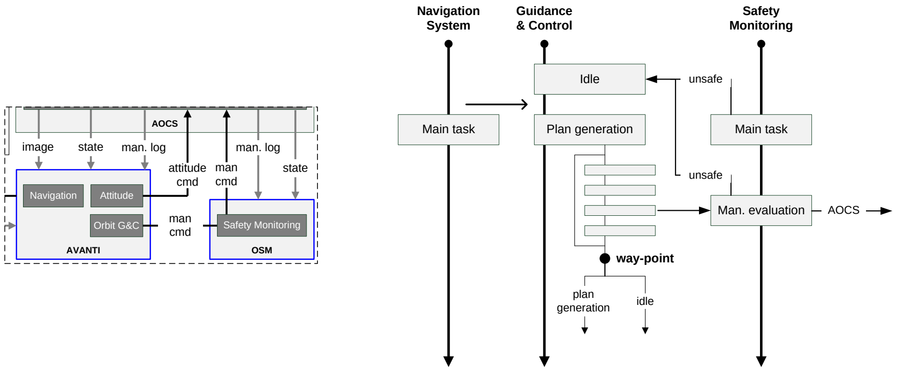

Figure 2: Left: Detail of GNC SW functional view (zoom from Figure 3 of Reference [1]). Right: time and logic connections among the main GNC tasks.

The linking between navigation system and G&C determines how the overall control loop is closed. In the AO framework, key point is to stepwise refine both navigation and control solutions, despite a weakly observable navigation. Therefore, it is important to balance the promptness of the control reaction, given the accuracy that is actually achievable and realizable without a useless waste of delta-v. The G&C is implemented with the typical receding finite-time horizon of the model predictive control (MPC). The *prediction horizon* equals the time from the plan update moment (*i.e.*, plan generation state) to the aimed final time of the whole rendezvous horizon. Whereas the *control horizon* is the time to achieve the first incoming intermediate way-point (not shorter than two orbital periods). According to the implemented solution scheme, this requires up to 4 impulsive maneuvers, internally managed as a state machine (more details in Figure 6 of Reference [9]). Thus, the control loop is closed at each refinement of the guidance plan.

The originality of the approach is how to actually solve the optimal planning problem. This prescribes the achievement of an aimed relative state at a given future time, in a fuel efficient, safe, and feasible manner, that is in compliance with several operational constraints dictated by satellite bus and experiment needs. The convenient set of variables represented by the relative orbital elements (ROE) is chosen. These, in fact, allow recasting such time-dependent optimal control problem into a geometrical minimum-path problem in the ROE space [17]. And the guidance solution is the sequence of way-points, corresponding to passively safe relative orbits, to reach the aimed final orbit. To achieve each intermediate way-point, maneuvers are scheduled in time-constraint-free slots through a locally delta-v optimal analytical burns' scheme (*i.e.*, Eq. (8) of Reference [18] for the out-of-plane correction and the option N12 of Table 2 of Reference [18] for the in-plane reconfiguration). As a result, the implemented architecture exploits typical benefits of MPC like the capability to enforce constraints on input (*i.e.*, time constraints on the time of the maneuvers) and outputs (*i.e.*, end-condition and passive safety), and to optimize a performance index (*i.e.*, fuel consumption). At the same time, it mitigates the MPC drawbacks of requiring a prediction model and a larger computational load of classical (linear) control methods. Regarding the first aspect, the ROE-based model for the perturbed relative motion in near-circular orbits of Reference [19] is used. It presents a simple and compact formulation, though being accurate over extended time periods. The planning problem, on the other hand, is reduced to the solution of a linear convex problem in the ROE state [17].

The linking between G&C and safety monitoring, instead, realizes the implementation of the AVANTI safety concept detailed in Reference [9]. OSM constantly monitors the safety, in the sense of collision avoidance, of the BEESAT-4–BIROS formation. To realize a robust approach, safety is assessed independently from the onboard navigation solution: the latest best available knowledge of the relative state produced by the ground-based data re-processing is used as *reference* trajectory and propagated in time. The criterion to assess the safety of the relative trajectory is based on the properties of the uncertainty distribution of the one-orbit minimum radial-normal (RN) distance between the two spacecraft (see Eq. (1) of Reference [9]). OSM exercises an onboard preemptive action since it evaluates each maneuver commanded by the AVANTI module and forwards it to the AOCS of BIROS only if the post-maneuver trajectory is considered to remain safe within a prescribed amount of hours following the burn.

As example of the GNC behavior, results from the close-range commissioning phase are presented in Figures 3 to 5.

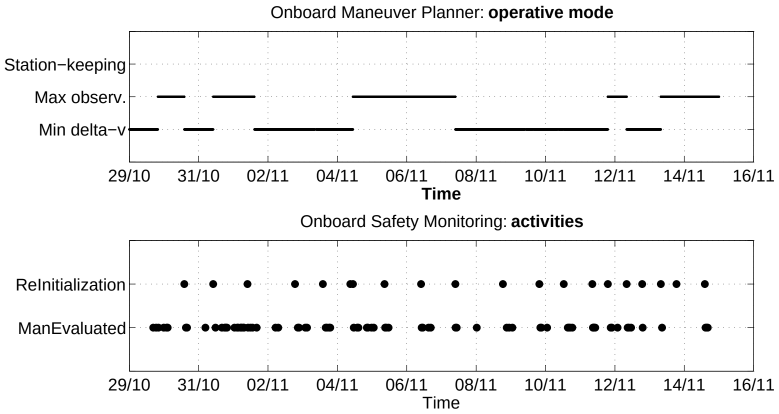

Figure 3: G&C and OSM interaction during the close-range commissioning phase.

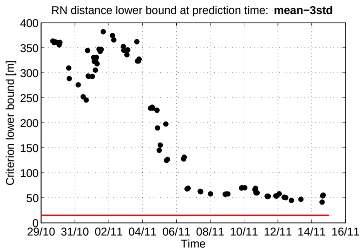

Figure 4: OSM safety criterion based on RN minimum distance at the evaluation times of Figure 3.

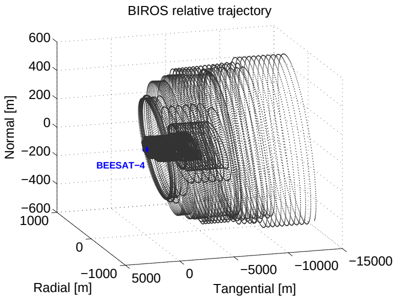

Figure 5: BIROS relative trajectory during the close-range commissioning phase in the BEESAT-4 orbital frame.

Figure 3 presents how G&C and OSM cooperated: a certain number of maneuvers have been evaluated and executed, with OSM re-initialized on average twice per day. Note that, the fact that we were exploring the behavior of the sensor and of the filter for the first time at close-range influenced the frequency of re-initialization of OSM. During the autonomous phase, in fact, OSM has been re-initialized once every two days (see Figure 9-a of Reference [2]). The output of the evaluation process is plotted in Figure 4. With lower bound of the one-orbit RN minimum distance it is meant the mean minus 3 times the standard deviation value of its distribution given the uncertainties in the propagation initial condition and accumulated maneuver execution errors. Around the 5th of November such value decreased in correspondence with the reduction of the magnitude of the relative inclination, to get closer to the target. This can be clearly noted observing the relative trajectory that BIROS performed with respect to BEESAT-4 (Figure 5). It presents the typical AVANTI spiraling profile: more approaches have been carried out with smaller relative orbit size, to achieve the aimed relative states commanded over that ten days. By referring to the upper plot of Figure 3, one can note that the maneuver planner operated in two different modes during the close-range commissioning phase. This is a further degree of flexibility provided by the AVANTI GNC system and it regards how the optimal planning problem is solved. As explained in References [17, 2], the *max-observability* mode is used to intensify the occurrence of maneuvers, being it related to the number of intermediate way-points that are exploited (*i.e.*, length of the control horizon w.r.t. the prediction one). On the other hand, the *minimum delta-v* option uses the smallest number of maneuvers strictly needed by the implemented analytical control scheme (*i.e.*, the control horizon is set equal to the prediction one). Structurally this latter option cannot achieve the same overall accuracy performance of the max-observability operative mode: it is a pure open-loop guidance, sensitive to initial conditions and cumulative maneuver execution errors. Nevertheless, it presented the practical advantage to reduce the number of thruster activations, being the thruster firing attitude mode conflicting with the optimal orientation of the star-tracker to target. This aspect was particularly interesting in some phases of the close-range commissioning, when the maximization of the collection of visual data was sought.

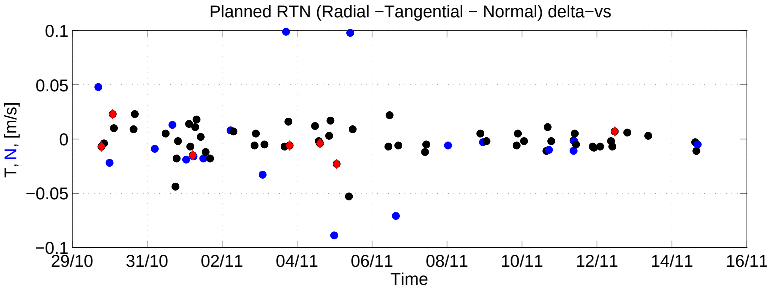

Figure 6: Commanded delta-vs during the close-range commissioning phase.

The commanded delta-vs corresponding to the maneuver evaluations of Figure 3 are plotted in Figure 6. Red diamonds mark maneuvers that failed to occur, due to some temporary communication problems between AOCS and thrusters. The key consideration is that, thanks to the AVANTI-concept, such issues did not pose any danger to the safety of the space segment. To explain this, in Figure 7 the effects of two sequential failures occurred on the 4th of November are shown. Here, in two occasions, the last planned maneuver to achieve the way-point (in blue) did not take place. Thus, referring to the relative semi-major axis and relative eccentricity vector components, instead braking, the drift towards the target continued (gray solution) until new maneuvers were commanded by the planner. Such events, cannot pose any collision danger (as one can see from the trajectory plot of Figure 5), since passive safety allows each maneuver plan being interrupted prior to its completion without any harm. At the system level, OSM receives a feed-back from the AOCS system of BIROS and knows if a maneuver has been skipped, as depicted in Figure 2-left.

Note that during the close-range commissioning phase the maneuver planner was mainly operating in *minimum delta-v* mode, that is why in Figure 7 the logic remains in *idle* for several hours before producing a re-plan. Figure 8 shows maneuvering logic and activity during the fully autonomous phase. As a matter of fact, large maneuver execution errors create similar effects of skipped/not requested maneuvers. As mentioned above, this has no consequences on the

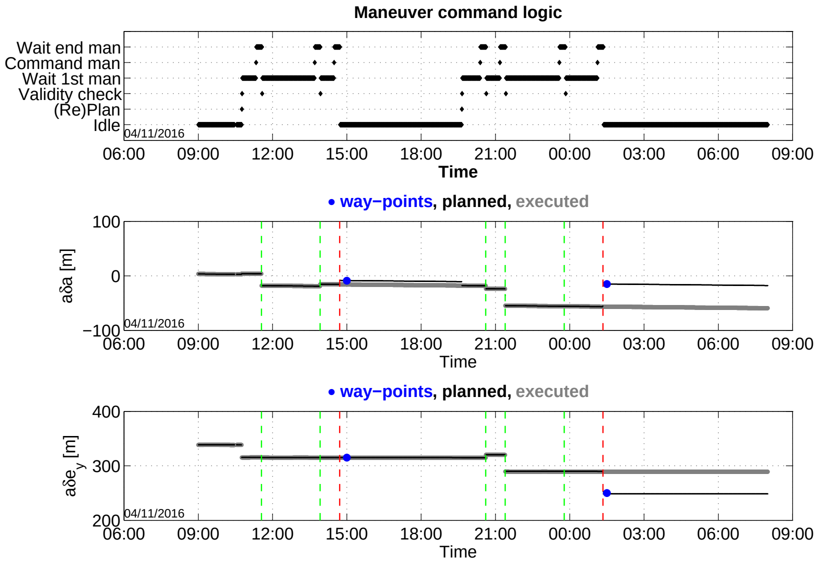

Figure 7: Robustness of the AVANTI-concept solution w.r.t. skipped maneuvers.

safety of the relative trajectory, and from the controller point of view, this is handled by updating the subsequent orbit corrections.

4. Considerations on target visibility aspects

A first obvious consideration regarding the visibility of the target spacecraft is that pictures assume very different aspects depending on inter-satellite range a/o luminosity conditions (see some examples in Figure 9). AVANTI exploited a basic output product of the camera sensor: the regions-of-interest (ROIs) pixel areas around each luminous spot exposed. Such pieces of information were processed onboard by the image processing module to deliver the line-of-sight (LOS) direction to the target in the inertial frame. At far-range the main difficulty lays in recognizing the target among all luminous spots in the image (*e.g.*, faint stars, hot pixels, other satellites). Before the start of the experiment commissioning phase, it was even unknown to which distance the sensor would have been actually able to detect the tiny picosatellite. Radiometry analysis,

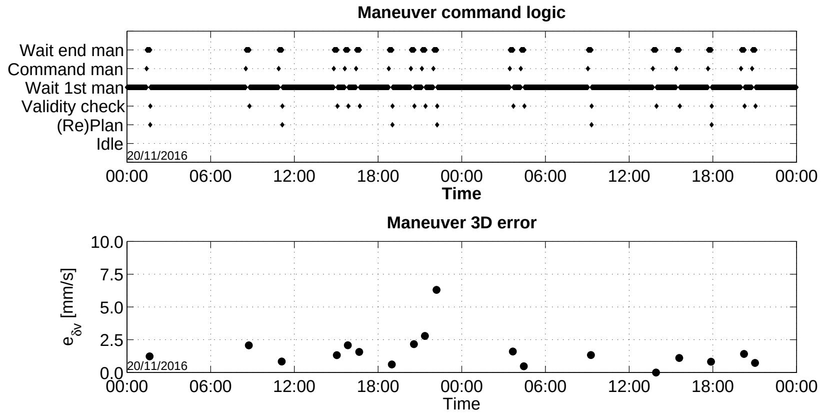

Figure 8: Autonomous re-planning activity.

in fact, provided spread results given the uncertainties on system, orientation, and sensitivity assumptions. The stars in background to each image are used to remove measurement biases to achieve a LOS accurate at sub pixel level. At close-range, instead, the target identification in the image plane becomes trivial but the observations overall accuracy is worsened due to the absence of stars in background a/o increasing centroid errors. The first issue requires the use of the quaternion computed by the attitude determination system of BIROS to determine the direction of the camera. Centroid errors, instead, reflect the difference between luminous center of the spot and target center of mass. Generally, in AVANTI, this error is small given size and symmetry of the target satellite. Nevertheless, at close-range, with the increase of the brightness of the target the luminous spot exceeded the ROI size, when no electronic shutter was used to limit the exposure time (see first view in Figure 9). Despite the robust design of the image processing algorithms, able to handle the various luminosity conditions experienced, the aforementioned sources of noise in the measurements impacted the performances of the navigation solution and a dedicated discussion is carried out in Reference [16] (Figures 10 and 11) for the onboard navigation solution and in Reference [15] (section 4.5) for the ground-based relative orbit determination. Note that, the absence of an accurate relative reference solution (for example obtained from relative GPS orbit determination), a faithful model of the atmospheric drag perturbation, and a realistic optical simulator, make it extremely difficult to isolate the different error contributions to the navigation solution.

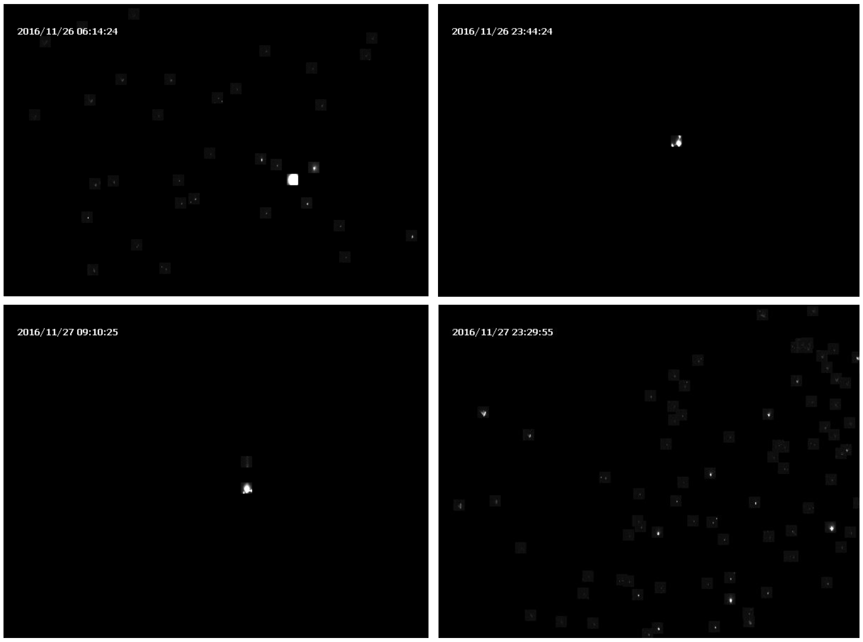

Figure 9: Some pictures taken at close-range during AVANTI.

Another important aspect regards the need of a dedicated attitude mode to satisfy the visual-tracking navigation needs. At design level, its implementation has been required to cope with the high level of autonomy of the onboard maneuver planner and to keep the target satellite within the narrow field of view of the camera sensor, especially at close inter-satellite ranges also considering the spiraling approach of the AVANTI-concept. Nevertheless, the practical implementation and in-flight operation of such attitude profile impacted the optimal functioning of the BIROS platform and the performances of the AVANTI experiment as well. The definition of the so-called client observation attitude mode (COM) is reported in Table 2 of Reference [2]. In COM, the boresight of the active camera head is pointed to the local flight direction (*i.e.*, BEESAT-4 is leading the formation during AVANTI) or tracks the LOS to the target $\mathbf{u}_{\text{target}}^{\text{RTN}}$, with RTN (radial-tangential-normal) denoting the local orbital frame. The remaining degree of freedom constituted by the rotation around the optical axis is exploited to customize the attitude profile to the specific design of the BIROS spacecraft, that is to trade-off between the Sun-angle to solar panels and the visibility angle of the GPS antenna (placed on the same side of the solar panels as shown in Figure 10) to the Zenith. Particularly, a first option is to command a tunable constant rotation angle α of the camera frame y-axis from the point where it is aligned to the projection of the local Zenith on the image plane. The parameter α realizes a compromise between the two aforementioned preferences, during the whole orbit. Its numerical value is derived from simulations, depending on the seasonal Sun geometry. A second option for COM, instead, fosters the power budget aspect, seeking to minimize the angle of the Sun to the normal to panel during the portion of orbit in light. By contrast, while in eclipse, the satellite z-axis is directed to Nadir, to avoid pointing the GPS antennas to Earth. Thus, in this *Sun-optimal* profile, during every orbit BIROS rotates to re-orient its panel w.r.t. the Sun and performs two slews, entering and leaving the shadow region, while keeping the camera sensor towards the target s/c.

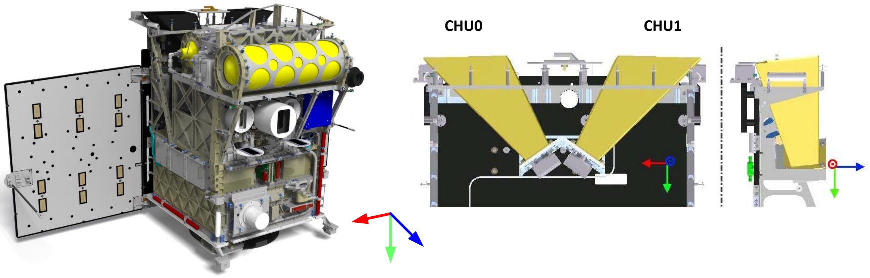

Figure 10: BIROS body-fixed *sat* frame and arrangement of the star-tracker camera heads. CHU0 presents boresight directed in $+x^{sat}$ / $-y^{sat}$; CHU1 in $-x^{sat}$ / $-y^{sat}$.

Figures 11 and 12 show how the COM Sun-optimal profile works, by plotting how Sun (in black during the phase of eclipse and in yellow outside eclipse) and orbital frame directions (*i.e.*, R, T, and Nadir) move in the BIROS body-frame sky-plot. For simplicity an axial-symmetrical baffle is considered, and a relative orbit presenting ≈1 km of mean along-track separation is simulated. Note that the isolated red and cyan points correspond to the attitude during eclipse.

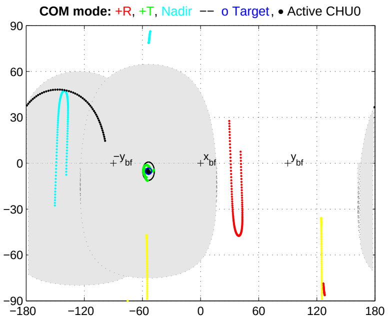

Figure 11: COM Sun-optimal using CHU0.

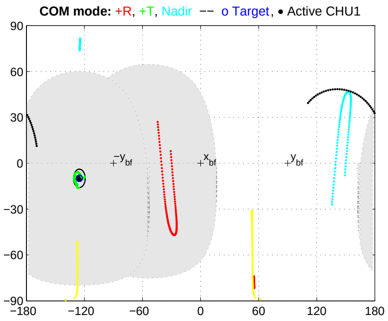

Figure 12: COM Sun-optimal using CHU1.

The selection of which camera head to employ during the experiment could be already performed during the design phase trading-off the following aspects. First, given the absolute orbit of BIROS, the Sun is always blinding the active head during a portion of the orbit, even using simplified geometrical considerations of the baffle geometry. Second, employing the camera head unit (CHU) labeled as 0 (for example as simulated in Figure 11) implies having the remaining one (*i.e.*, the attitude-only camera) continuously obstructed by the Earth. These considerations motivated the choice of using the unit-1 as sensing instrument during AVANTI. And such assumptions could be verified in-flight already during the early check-outs of BIROS, by keeping over few hours a COM-like attitude with CHU0 (see Figure 13) and CHU1 (see Figure 14) respectively pointing in flight direction.

By referring to the scores of delivery of the quaternion, the attitude-only head provides no output when CHU0 is used for relative navigation purposes (see *isActive* flag). Moreover, these plots compare the Sun-blinding flag based on symmetrical geometrical assumption of the baffle effect with the actual delivery of the quaternion, during light and eclipse phases. The availability of quater-

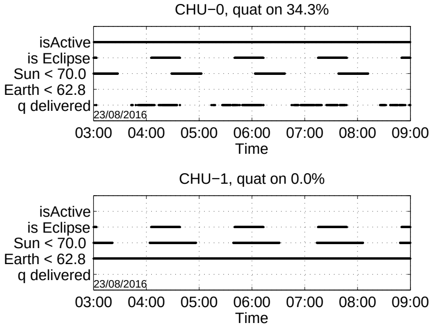

Figure 13: COM effects using CHU0.

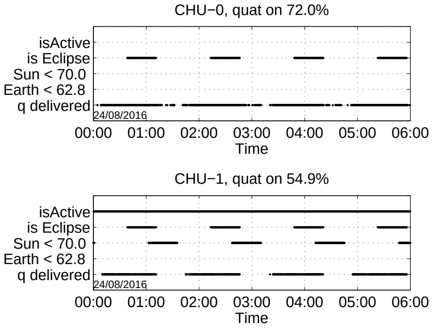

Figure 14: COM effects using CHU1.

nion data from the star-tracker impacts the attitude determination system of BIROS, which process it together with the outputs from inertial measurement unit, magnetometers, and coarse Sun sensors. A degraded attitude knowledge of the chaser generates the following undesired issues. Maneuvers present larger execution errors (see for example Figure 8) disturbing the onboard navigation system which uses the commanded delta-vs to improve the AO observability property. Moreover, at close-range, the noise of the observations remarkably increases, since the attitude of BIROS has to be used to determine the orientation of the sensor, being no stars visible in the picture background (see Figure 15 of Reference [2]).

Figure 15 reports the effects of the rotational dynamic during the autonomous close-range phase of AVANTI; *isActive* flag interruptions denote COM breaks due to ground-contacts and maneuvers. The availability of quaternion data is definitely less than in the case of Figure 14, since BIROS is slewing to track the relative motion of the target and since during satellite cooldown phases both heads are obstructed by the Earth. The *observation* flag in the bottom view has been added to show when the target has been imaged. One can note that, CHU1 hardly delivers a quaternion, as no stars appear together with the very bright target (especially when the electronic shutter is active).

As the more observations are collected the better it is to support AO navigation, BIROS had to spend plenty of time in COM mode. Thus it is important to

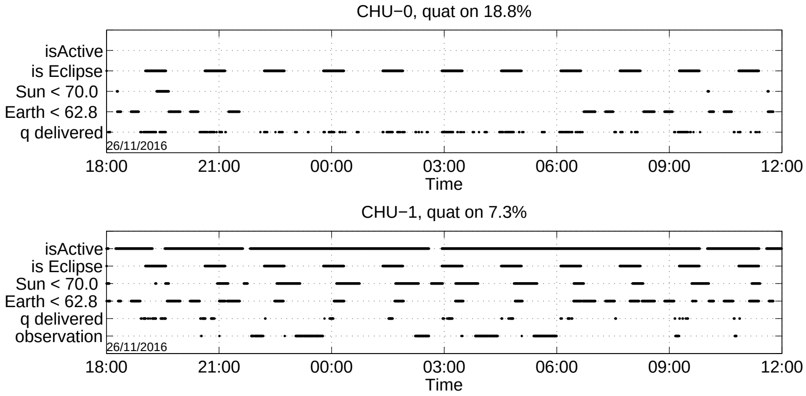

Figure 15: Effects of the rotational activities during the autonomous close-range phase.

consider which consequences this might bring to the functioning of the platform. For AVANTI the major problem revealed to be the thermal balance, since its thermal system has been sized to support the primary Earth-observation mission goal: all the time not dedicated to take pictures of hot-spots on the Earth surface is spent in an inertial-fixed Sun-pointing mode. Moreover, the radiator lays on the opposite side of the star-tracker. A first qualitative understanding of the implications can be inferred from Figure 6 of Reference [2], where LOS to the target and Sun tracks are plotted on the RTN unit sphere. The visual constraint of COM (*i.e.*, directing a camera head mainly in flight direction) implies getting the Sun in the radiator once per orbit, disregarding which head is used. To mitigate possible thermal side effects of lasting persistence in COM, within AVANTI the additional cool-down attitude mode (CDM) has been implemented [2]. This has the objective to dissipate as quickly as possible the heat, and can be entered either via telecommand or following an onboard logic of temperature hysteresis loop monitoring some critical devices. In this latter case, some parameters, tuned during in-flight operations, drive the trade-off between the time required to cooldown the spacecraft and quantity of measurements' loss per each orbit.

Figures 16 and 17 show the functioning of CDM mode respectively during

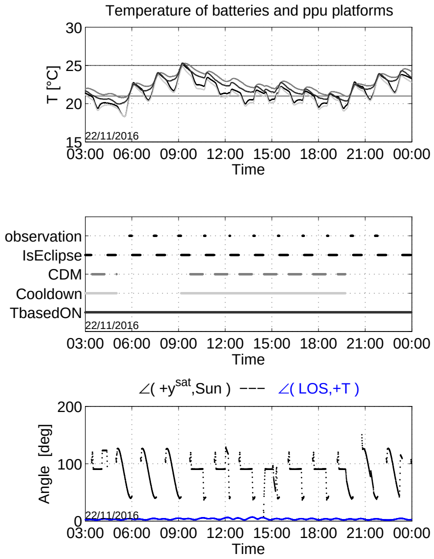

Figure 16: COM-CDM at mid-range.

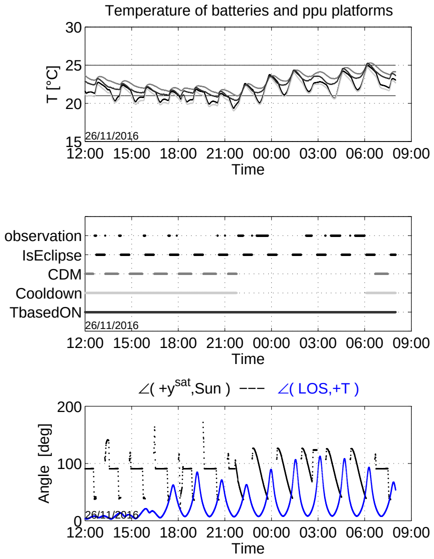

Figure 17: COM-CDM at close-range.

autonomous mid- and close-range phases. One can note that, in COM the angle between radiator (*i.e.*, $+y^{sat}$) and Sun remains below 90 degrees during part of the orbit and reaches its minimum right before the entrance in the shadow region, which is the moment when the target is imaged in the pictures (see *observation* flag). CDM, instead keeps the radiator rotated away from Sun, reducing the time dedicated to observe the target. With the decrease of the inter-satellite separation, the spiraling relative motion requires COM to track the target: this is reflected in larger oscillations of the angle between LOS and the flight direction. As a result, the main side effects of CDM, primarily impacting the performance of the relative navigation solution, are the followings: during cooldown phases the duration of the observations arc is shortened, the BIROS attitude determination is worsened since both heads are obstructed by the Earth, and the differential drag perturbation becomes stronger, due to a larger impact area (see Figure 11-b of Reference [2]).

A further important consideration on target visibility aspects concern the actual number of observations that can be collected each orbit. From the early experiment design phase, it was clear that the constraints deriving from both absolute and relative orbits, together with BIROS platform characteristics could not allow imaging the target spacecraft during the complete orbital period, as happened instead for the vision-based experiments carried out on PRISMA [6, 7, 8]. The geometrical evidence is for example provided by Figure 12, which show the occurrence of eclipse and camera blinding geometrical conditions. The assumptions adopted in the simulation environment used to develop the flight software, however, revealed to reproduce a more optimistic scenario than the in orbit conditions. At far-range, in fact, the observations' arc lasted up to only 10-15 minutes, immediately before the entrance in the shadow region. This is highlighted by the *observation* flag in Figure 16. It is believed that such result is the joint effect of the camera baffle, possible light reflections from the BIROS surfaces, camera integration time, and target reflectivity. Note that before the entrance in eclipse, the Sun comes almost from behind BIROS, thus the coarsely Sun-pointing BEESAT-4, which is leading the formation, directs its solar panel towards BIROS. At close-range, instead, the measurements data arc lasted up to 35 minutes, when the electronic shutter was active and no conflicting activities took place (*e.g.*, maneuvers, ground-contacts, CDM), as shown in Figure 17. Thus, the shorter integration time allowed the much brighter target to appear in the image, despite a partial attenuation of the Sun light by the baffle. Clearly, the limited number of observations has a major impact on the relative navigation filter [15, 16].

Last considerations regard in which portion of the orbit observations are actually obtained, that is putting together illumination conditions and attitude profile with the geometry of the relative motion. A spiraling trajectory presents a one-per-orbit oscillation in out-of-plane that varies the angular displacement between the boresight and the Sun direction, which describes a cone around the normal orbital axis. In-plane-wise, on the other hand, the relative eccentricity vector determines which part of the relative orbit is traveled during the phase of eclipse. Figure 18 shows the relative trajectory of BEESAT-4 w.r.t. to BIROS

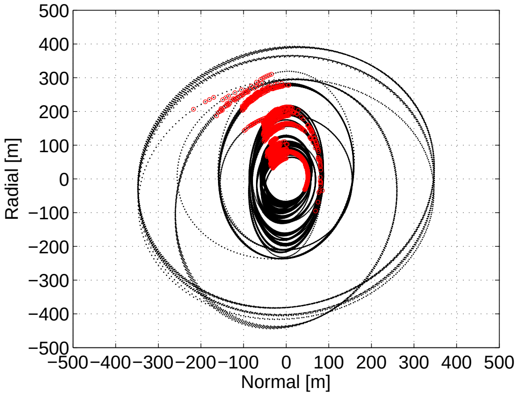

Figure 18: BEESAT-4 relative trajectory during the close-range commissioning phase.

projected on the local RN plane; red dots mark where observations are obtained. The relative eccentricity vector established by the BEESAT-4 in-orbit release strategy presented a negative y-component. At the time of the start of the experiment, the sign of the target relative eccentricity vector has been chosen based on delta-v budget and safety considerations, taking into account the effect of orbital perturbations during the time elapsed after the release of BEESAT-4. As a result, the point of minimum along-track distance (*i.e.*, R=0 and N<0 in Figure 18) occurs during eclipse (*i.e.*, the target cannot be imaged in the pictures). Note that, as the primary objective of AVANTI was to demonstrate AO approach in the far- to mid-range domain, getting observations more far way presented the benefit of an easier management of the field of view constraint.

5. Difficulties at close-range

AVANTI demonstrated that the AO navigation approach can be used beyond the mid-range domain, to bring the chaser satellite at a separation distance where close-proximity specific sensors can be used. The main reason is that the navigation accuracy improves when the inter-satellite distance decreases, allowing to accept a larger noise of the measurements (*e.g.*, centroid errors, downgraded knowledge of the orientation of the sensor) [15, 16].

Aside from such peculiarities of the vision-based approach, at close-range difficulties arose due to the following technical constraints of the BIROS platform. First, the star-tracker is a far-range camera whose 18×14 degrees field of view corresponds to an area of solely $10{\times}15$ m at 50 m of inter-satellite separation. Second, onboard computer and data handling of BIROS supported a maximum picture data-rate of 30 seconds [1, 2], even adopting the ROI image compression format. These characteristics are perfectly fine for running the AVANTI algorithms at far- to mid-range (which actually constituted the primary goal of the demonstration). At close-range, instead, these aspects demanded an attitude guidance able to keep the target in the picture, robustly against errors in the relative navigation solution. The design used in AVANTI, however, could not structurally achieve such robustness, since the COM attitude profile is generated propagating over the AVANTI time-step the current onboard navigation solution. Figure 13 of Reference [16] shows the boresight pointing error, which is the onboard navigation error w.r.t. the *true* LOS to target out of the ground-based post facto reprocessing of the images collected in flight.

6. Design guidelines for exploiting the AVANTI-concept

This last section aims at summarizing constraints and degrees of freedom to exploit the AVANTI-concept design to future rendezvous missions. Still remaining in the framework of a minimalistic low-cost approach, few adaptations are suggested based on the experience collected so far.

The orbit scenario of an effective rendezvous mission is determined by the orbit of the target object (*e.g.*, debris or client satellite). A vision-based AO approach can be exploited despite the orbit presents eclipses (*i.e.*, AVANTI worked with 10 to 15 minutes of data arcs per orbit), provided a proper design of the navigation algorithms. On the other hand, an important aspect is to assess the relevance of non-conservative orbital perturbations (*e.g.*, differential drag) acting in the scenario. If these are not negligible, in fact, the navigation system has to estimate them. In the case of differential aerodynamic drag, being its modeling greatly affected by the uncertainties of the unknown attitude and drag coefficient of the target spacecraft, a convenient option is to estimate the mean time-derivative of the relative semi-major axis. This, in fact, catches the one-orbit mean value of such perturbing acceleration [19]. Finally, relevant for the mission analysis study to achieve the far-range initial conditions, is the selection of rendezvous direction. Again the effect of orbital perturbations have to be considered. Within AVANTI, for example, for safety reason the element with larger ballistic coefficient (*i.e.*, the target) lead the formation in flight direction, so that the natural effect of the differential aerodynamic drag made the satellite to drift apart from each other. This fact has been exploited in the design of the satellites separation strategy [11, 12] as well as of the formation safety concept [9]. From the operational point of view, the evaporation risk is less critical than the collision one, since standard two-line-elements (TLE) products can enable a ground-based coarse formation keeping of circa 20 km of along-track separation, disregarding the values of relative eccentricity and inclination components, which are affected by larger uncertainty [20].

Regarding the relative motion, the exploitation of passively safe relative orbits translate in the constraint of setting a specific phasing of the relative eccentricity and inclination vectors (*i.e.*, 0 or 180 degrees). By combining this requirement with the delta-v consumption aspect, the most appealing option is to target $\delta e_x = \delta i_x = 0$ (as performed in AVANTI). With this design, in fact, the secular effect of the perturbation due to J_2 on the out-of-plane motion is nullified for almost-bounded relative orbits (*e.g.*, cheap control of inspection orbits). Therefore, the remaining degrees of freedom are the signs of y-components of the relative eccentricity and inclination vectors. Recalling the considerations of previous sections, these can be used to optimize the distribution of observations actually achievable across the orbit, given Sun-geometry and attenuation characteristics of the baffle of the optical sensor.

Regarding the chaser system design, care has to be paid on the number of camera heads and/or their location and mounting direction in the platform. A design exploiting three heads (like performed in PRISMA), gives the advantage to dedicate two heads exclusively for the attitude determination task. If not possible, the image-collection attitude mode has to be designed trading off the achievable attitude determination accuracy and the impact on other sub-systems of the chaser.

If a close-range phase is foreseen, some customized functionalities have to be also developed. In this domain, in fact, image sample rate and robust attitude guidance play an important role. Basically these generate constraints to the onboard data handling sub-system: the faster is the supported time-step the better it is for the navigation system. By exploiting the fact that at close-range the target identification becomes obvious, it would be advantageous (*i.e.*, more robust) to connect the attitude control directly to the image processing output, with the objective to keep the target in the center of the field of view. At a separation distance of 50 m, in fact, the measurements noise is at cm level, whereas the onboard relative navigation solution remains at meter level accuracy, due to observability issues and to the further challenges discussed across this paper. Note that for inspection orbits, a specific attitude guidance might be needed to handle the attitude singularity when the chaser crosses the target RN plane.

7. Conclusion

AVANTI successfully demonstrated the practicability of angles-only vision-based navigation to safely and autonomously rendezvous down to 50 m a non-cooperative object in low Earth orbits, despite severe orbital conditions and sensor and actuator errors. Building from the outstanding quantity of data accumulated across two months of in-flight activity, this paper critically presented peculiarities, advantages, and operational limits of the guidance navigation and control system developed to support such flight demonstration. This analysis resulted in several lessons learned hardly/not obtainable thorough on-ground simulation environments. Moreover, these had been outlined in the form of design guidelines to foster the further exploitation of the flight-proven AVANTI-concept to future rendezvous missions.

8. Acknowledgments

The construction of the BIROS satellite was funded by the Federal Ministry of Education and Research of Germany (BMBF) (project number FKZ 01LK0904A).

References

[1] G. Gaias, J.-S. Ardaens, C. Schultz, The AVANTI experiment: flight results, in: Proceedings of the 10th International ESA Conference on Guidance, Navigation & Control Systems, European Space Agency, ESTEC, Noordwijk, The Netherlands, 2017.

[2] G. Gaias, J.-S. Ardaens, Flight Demonstration of Autonomous Noncooperative Rendezvous in Low Earth Orbit, Journal of Guidance, Control, and DynamicsAccessed, 16 Nov 2017.

[3] The AVANTI weblog, `http://www.dlr.de/rb/desktopdefault.aspx/tabid-11685/#gallery/28310`, DLR Raumflugbetrieb und Astronautentraining, [retrieved 4 August 2017] (Dec. 2016).

[4] T. Weismuller, M. Leinz, GN&C Technology Demonstrated by the Orbital Express Autonomous Rendezvous and Capture Sensor System, no. Paper 06-016, 29th Annual AAS Guidance and Control Conference, American Astronautical Society, 2006.

[5] P. Bodin, R. Noteborn, R. Larsson, T. Karlsson, S. D'Amico, J.-S. Ardaens, M. Delpech, J.-C. Berges, PRISMA Formation Flying Demonstrator: Overview and Conclusions from the Nominal Mission, no. 12-072, 35th Annual AAS Guidance and Control Conference, Breckenridge, Colorado, USA, 2012.

[6] R. Noteborn, P. Bodin, R. Larsson, C. Chasset, Flight Results from the PRISMA Optical Line of Sight Based Autonomous Rendezvous Experiment, in: Proceedings of the 4th International Conference on Spacecraft Formation Flying Missions & Technologies (SFFMT), Canadian Space Agency, St-Hubert, Quebec, 2011.

[7] M. Delpech, J.-C. Berges, S. Djalal, J. Christy, Vision Based Rendezvous Experiment performed during the PRISMA Extended Mission, in: Proceedings of the 23rd International Symposium on Space Flight Dynamics, Jet Propulsion Laboratory, Pasadena, California, USA, 2012.

[8] S. D'Amico, J.-S. Ardaens, G. Gaias, H. Benninghoff, B. Schlepp, J. L. Jørgensen, Noncooperative Rendezvous Using Angles-Only Optical Navigation: System Design and Flight Results, Journal of Guidance, Control, and Dynamics 36 (6) (2013) 1576–1595, doi: 10.2514/1.59236.

[9] G. Gaias, J.-S. Ardaens, Design challenges and safety concept for the avanti experiment, Acta Astronautica 123 (2016) 409–419, doi: 10.1016/j.actaastro.2015.12.034.

[10] Technische Universität Berlin, BEESAT-4 website, `https://www.raumfahrttechnik.tu-berlin.de/menue/forschung/aktuelle_projekte/beesat-4/parameter/en/`, Sascha Weiss, TU Berlin, [retrieved 4 August 2017] (May 2017).

[11] M. Wermuth, G. Gaias, S. D'Amico, Safe Picosatellite Release from a Small Satellite Carrier, Journal of Spacecraft and Rockets 52 (5) (2015) 1338–1347, doi: 10.2514/1.A33036.

[12] M. Wermuth, G. Gaias, Operational Concept of a Picosatellite Release from a LEO Satellite, in: Proceedings of the 25th International Symposium on Space Flight Dynamics ISSFD, DLR, German Space Operations Center, Munich, Germany, 2015.

[13] H. Reile, E. Lorenz, T. Terzibaschian, The FireBird Mission - A Scientific Mission for Earth Observation and Hot Spot Detection, in: Small Satellites for Earth Observation, Digest of the 9th International Symposium of the International Academy of Astronautics, Wissenschaft und Technik Verlag, Berlin, Germany, 2013, pp. 184–196, iSBN 978-3-89685-574-9.

[14] S. Föckersperger, K. Lattner, C. Kaiser, S. Eckert, W. Bärwald, S. Ritzmann, P. Mühlbauer, M. Turk, P. Willemsen, The Modular German Microsatellite TET-1 for Technology On-Orbit Verification, no. IAC-08.B4.7.3, 59st International Astronautical Congress, Glasgow, UK, 2008.

[15] J.-S. Ardaens, G. Gaias, Angles-Only Relative Orbit Determination during the AVANTI experiment, in: Proceedings of the 26th International Symposium on Space Flight Dynamics ISSFD, Japan Society for Aeronautical and Space Sciences, Japan, 2017.

[16] J.-S. Ardaens, G. Gaias, Flight Demonstration of Spaceborne Real-Time Angles-Only Navigation to a Noncooperative Target in Low-Earth Orbit, no. N.A., 9th International Workshop on Satellite Constellations and Formation Flying, University of Colorado Boulder, Colorado, USA, 2017.

[17] G. Gaias, S. D'Amico, J.-S. Ardaens, Generalized Multi-Impulsive Maneuvers for Optimum Spacecraft Rendezvous in Near-Circular Orbit, Int. J. Space Science and Engineering 3 (1) (2015) 68–88, doi: 10.1504/IJSPACESE.2015.069361.

[18] G. Gaias, S. D'Amico, Impulsive Maneuvers for Formation Reconfiguration using Relative Orbital Elements, Journal of Guidance, Control, and Dynamics 38 (6) (2015) 1036–1049, doi: 10.2514/1.G000191.

[19] G. Gaias, J.-S. Ardaens, O. Montenbruck, Model of j2 perturbed satellite relative motion with time-varying differential drag, Celestial Mechanics and Dynamical Astronomy 123 (4) (2015) 411–433, doi: 10.1007/s10569-015-9643-2.

[20] R. Kahle, M. Weigel, M. Kirschner, S. Spiridonova, E. Kahr, K. Letsch, Relative Navigation to Non-cooperative Targets in LEO: Achievable Accuracy from Radar Tracking Measurements, Int. J. Space Science and Engineering 2 (1) (2014) 81–95.