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THE AVANTI EXPERIMENT: FLIGHT RESULTS

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ABSTRACT

This paper presents the in-orbit performance of the spaceborne guidance navigation and control system which enabled the AVANTI experiment, a technological demonstration conducted by the German Aerospace Center in autumn 2016. AVANTI proved the viability to perform far- to close-range autonomous proximity operations with respect to a noncooperative flying object using only optical angle measurements. Within AVANTI, the Earth-observation BIROS satellite played the role of a chaser spacecraft, which autonomously approached down to circa 50 m of inter-satellite distance the BEESAT-4 picosatellite, simply using a head of its star-tracker as monocular camera.

1 INTRODUCTION

The AVANTI (Autonomous Vision Approach Navigation and Target Identification) experiment, successfully conducted in November 2016 [1], realized the first fully-autonomous close approach of an unmanned spacecraft to a noncooperative target object in low Earth orbit. The main peculiarity of this demonstration is that a low-cost minimalistic design strategy has been adopted for the chasing spacecraft: the star-tracker, already onboard to support the conventional attitude determination task, has been re-used as far-range camera to take images of portions of the sky. In the absence of any communication between satellite and target body, such images constituted the *unique* source of observations available in real-time. In this framework, the AVANTI spaceborne guidance navigation and control (GNC) system carried out autonomously the following activities: image processing and target identification to extract the angle-measurements of the line-of-sight (LOS) to the target; real-time relative navigation; computation of the impulsive maneuvers' profile required to perform a rendezvous in a safe, fuel efficient manner [2].
With the completion of the AVANTI experiment, the German Aerospace Center (DLR) enhanced its expertise in the field of vision-based noncooperative rendezvous, to pave the way to future on-orbit servicing and debris-removal missions. DLR, in fact, already exercised angles-only (AO) relative navigation activities within the PRISMA (Prototype Research Instruments and Space Mission Technology Advancement) formation-flying test-bed [3]. In August 2011, in the frame of the Formation Re-acquisition experiment, a rendezvous from 60 to circa 4 km of separation had been accomplished, refining two-line-elements (TLE) in the cross-track plane with the solution coming from a prototype LOS-based navigation filter that processed on-ground 5-hour-slot of pictures per day [4]. Afterwards, during the extended phase of PRISMA (April 2012), DLR executed the Advanced Rendezvous

Demonstration using GPS and Optical Navigation (ARGON) experiment [5]. In this occasion, a non-cooperative approach between 30 to 3 km of inter-satellite distance had been performed, and a dedicated ground-based flight dynamics system carried out the routine processing of the camera images collected onboard, for the estimation of the relative orbit of the chaser with respect to the target vehicle, and for accomplishing the maneuver planning. With respect to these two precursors, AVANTI (1) developed a complete vision-based rendezvous-specific GNC system; (2) moved from a ground-based approach to fully autonomous onboard operations; (3) stretched out the AO applicability limits to the close-range domain.

Differently from other multi-satellite technology demonstrations that involved *ad hoc* testbeds (e.g., XSS-10 [6], Orbital Express [7], PRISMA), AVANTI exploited the opportunity that the BIROS spacecraft embarked a single picosatellite launcher device to release in orbit the BEESAT-4 one-unit CubeSat: a target would have been generated for free to support the experiment without the need of spending propellant to fly to an existing object. Moreover, BIROS met the remaining minimal prerequisites to perform vision-based proximity activities: it featured a propulsion system and a star-tracker sensor. In this sense, AVANTI pursued a low-cost approach, and no further formation-flying specific sensors and actuators have been embarked on the already designed BIROS satellite. As thoroughly explained in [8], both orbit and platform characteristics of BIROS posed several challenges to develop an autonomous, spaceborne, vision-based GNC system. Nevertheless, from the one hand these challenges embody ordinary requirements for realizing a realistic and general on-orbit servicing mission. From the other hand, AVANTI could demonstrate the viability of the AO approach in a kind of *worst-case* situation.

As a result, compared to the AO in-flight activities that DLR and other companies and institutions carried out on PRISMA (e.g., OHB-Sweden [9] and CNES [10]), AVANTI had to advance both guidance and navigation solutions proposed so far. The implemented guidance policy tackles a delta-v minimum problem to reach a target relative state at a given time which supports the definition of user-defined time constraints and produces a solution continuously compliant with the passive-safety criterion [11]. This last feature, in fact, is a crucial aspect for a *truly* noncooperative scenario [12], leading to the generation of spiraling rendezvous trajectories. The navigation system, on the other hand, implements advanced algorithms to robustly identify the target despite the frequent observation outages [13]. Moreover, it encompasses the estimation of the mean time-derivative of the relative semi-major axis, to catch the strong effect of differential non-conservative orbital perturbations.

After having recalled the constraints that mission scenario and hosting platform induced on the design of the GNC system, this paper focuses on the flight results achieved by the autonomous activities performed in the second half of November 2016.

2 THE AVANTI DEMONSTRATION

The primary objective of the BIROS (Bi-Spectral InfraRed Optical System) spacecraft is to detect hot-spots on the Earth surface in the frame of the DLR FireBird mission [14]. To this end, it has been injected on the 22nd of June 2016 into an almost circular, Sun-synchronous local time of ascending node (LTAN) 21:30, 515 km high orbit. As secondary mission objectives, BIROS embarked several hardware and software technology demonstrations, among which the BEESAT-4 one-unit CubeSat built by the Technical University of Berlin [15] and AVANTI, conceived, developed, and operated by

the German Space Operations Center (GSOC).
BEESAT-4 has been released in-orbit on the 9th of September 2016 by means of a single picosatellite launcher device which provided an equivalent separation delta-v of circa 1.5 m/s [1, 16, 17]. While carrying out its independent experimental activities, BEESAT-4 has been used as noncooperative target for the sake of the AVANTI demonstration.

2.1 The BIROS Spacecraft

Evolved from the ancestor platforms of the DLR small satellites family BIRD and TET-1 [18], the BIROS spacecraft has wet mass of ≈140 kg and an envelope size of $670 \times 580 \times 880$ mm in launch configuration (see Fig. 1). Electrical power for the operation of bus and payload is generated by three solar panels (two deployable) delivering a maximum of 220 W end-of-life. A nickel-hydrogen, 250 Wh capacity, battery provides the energy in the eclipse phase or during peak power demands. BIROS power thermal system (PTS) has been sized to support its primary 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. Communication is based on an S-band transmission system. It features two receiver/transmitter pairs which can be switched to an omnidirectional low-gain antenna system or to the high-gain antenna. This latter configuration allows achieving the maximum downlink rate (i.e., 2.2 Mbps) though requiring a special attitude orientation: the high-gain antenna in Nadir pointing.

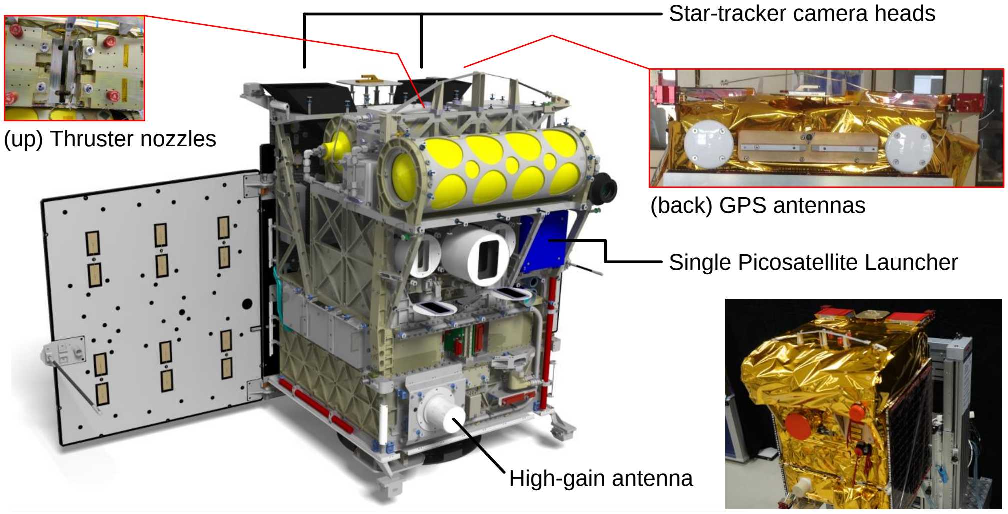

Figure 1: BIROS bus and payload assembly (left); in pre-launch configuration (bottom-right).

BIROS inherits onboard computer (OBC), attitude sensors and actuators gear, and attitude control system (ACS) from the preceding platforms [19, 20]. The propulsion system, instead, is a novelty, as well as a precondition for enabling AVANTI. BIROS is equipped with a Microjet 2000 cold-gas resistojet developed by Aerospace Innovation GmbH and DLR, configured into two independent lines comprising all the functional elements from the nitrogen tank to two thruster units. Since nozzles are activated one at a time, this system generates thrust in a single direction (i.e., one-axis delta-v capability), with a nominal value of 0.1 N and minimum impulse bit of 1 s (translating to single velocity increment of approximately 1 mm/s). During in-orbit operations a correction factor to the total activation time can be applied/updated via telecommand, based on the precise orbit determination calibration products.

Another advance of the BIROS platform is the pre-processing unit (PPU): a supplementary payload computer primarily meant to operate the main payload (i.e., the infrared camera sensor). Relevant for AVANTI, the PPU hosts an experiment-dedicated memory partition (80 MB of space) to store collected pictures and telemetry data.

The primary sensing instrument used within AVANTI is the micro Advanced Stellar Compass (μASC) star-tracker built by the Danish Technical University. It features two camera heads and two, cold redundant, digital processing units (DPU) to deliver the two camera-to-inertial-frame quaternions at 4 Hz. In addition, it can export pictures with different compression formats. Given the combination of DPU-OBC serial connection and software extraction of the image, it became impossible to directly process raw-bitmap images. The supported transfer data rate (1-2 KBps), in fact, translated into a picture every 3 to 4 minutes, which was not acceptable to fulfill angles-only relative orbit determination, considering that the number of observations is already strongly limited by the action of eclipses and camera-blinding phases (i.e., orbit geometry constraint). Among the image compression formats offered by the μASC sensor, AVANTI made use of the regions-of-interest (ROIs) one. According to it, only the fixed-size area around the brightest luminous spots is kept (without loss of information), while discarding the remaining, less-meaningful, quantity of data. By keeping 80 ROIs, for example, an image corresponds to $\approx$20 KB. Finally, the μASC sensor implements an electronic shutter to regulate the exposition time. Given the selected compression format, this feature is crucial to reduce the centroiding error at close-range distance: the target luminous spot fits better into the ROI-size limitation.

2.2 Operation Concept

The structure of space and ground segments of the AVANTI demonstration is depicted in Fig. 2. The experiment scenario is truly noncooperative since both GPS receiver on BEESAT-4 and inter-satellite link were not yet commissioned, and thus did not function, by the time when AVANTI took place. As a result, the only observations available in real-time were the pictures taken with the BIROS star-tracker (i.e., black arrow labeled Vision-Based).

BIROS is operated from the GSOC premises with support of a ground stations network comprising antennas in Weilheim and Neustrelitz (Germany), St. Hubert (Canada), and O'Higgins (Antarctica). During AVANTI, number and distribution of the supported ground contacts have been traded-off considering: experiment autonomy vs safety, and experiment needs vs data handling constraints. The first compromise balances the autonomy of the spaceborne GNC system, which requires few high-level telecommands per phase, with the needs of the ground-based system to monitor a novel technology demonstration. In addition, according to safety concepts' long-term reaction [12], more sporadic down-link contacts determine a longer reaction time. The second trade-off, instead, is due to architecture and size of the data storage capability onboard on BIROS. Regular high-rate downloads are needed to avoid loss of flight data. Nevertheless, such data-rate is achieved by transmitting through the high-gain antenna pointed to Nadir. The resulting attitude mode, referred as Earth pointing mode (EPM), conflicts with the optimal functioning of the AVANTI GNC. By recalling high-gain antenna and star-tracker camera heads mounting directions from Fig. 1, in fact, EPM determines observations'

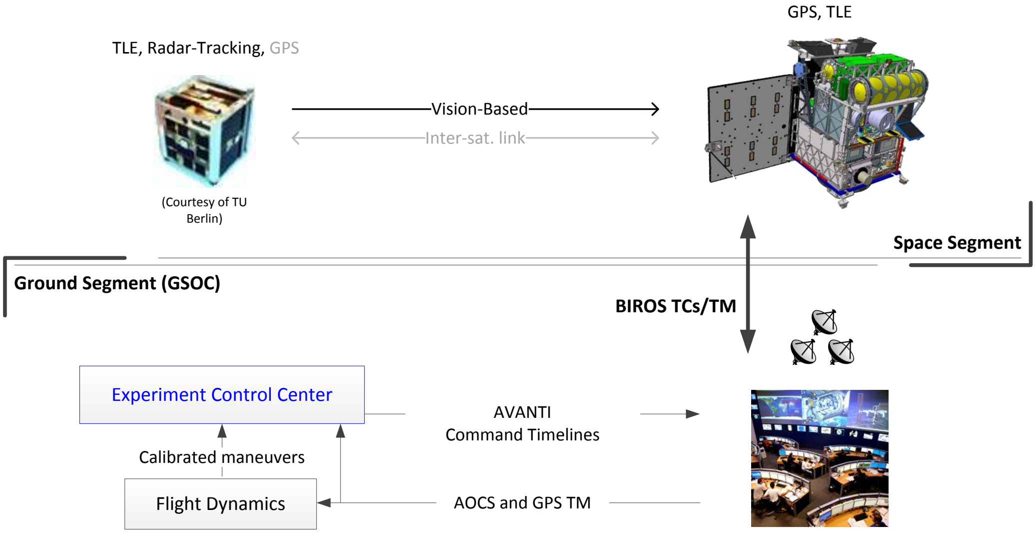

Figure 2: Experiment segments: main elements and information flow (gray items were not available during flight operations).

gaps since the target s/c is no longer in the camera field-of-view. At the same time, the autonomous maneuver planner is forced to avoid scheduling maneuvers that could overlap with an active ground-contact (recall the single-direction thruster system).

According to the upper part of Fig. 2, due to type and refresh-frequency of the available target tracking data, the only way to monitor and assess the performance of the spaceborne navigation system was to re-process on ground the pictures collected onboard. To this end, the ground-based verification layer described in [21] had been built-up to support continuously the experiment execution. Compared to the onboard real-time system [13], the ground based orbit determination benefited 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 obtained solution. As a consequence, the resulting reconstructed relative trajectory became the best possible *post-facto* knowledge of the state of the formation. Moreover, such solution is used as *reference* to characterize the performance of the onboard algorithms later presented in this work.

By referring to the bottom part of Fig. 2, the aforementioned on-ground re-processing of the pictures collected onboard is one of the tasks routinely carried out within the experiment control center. The remaining activities consisted in analyzing the AVANTI telemetry to monitor the whole GNC behavior to detect possible anomalies, and in producing and validating the telecommands that encoded the high-level goals of subsequent phases of the experiment.

3 EXPERIMENT CHALLENGES

AVANTI low-cost design approach, certain characteristics of the BIROS platform, and the orbit scenario posed several challenges to realize vision-based proximity activities. Such aspects were known since the development phase and [8] provided some explanations on how they impacted the design of the algorithms of the flight software. Nevertheless, in order to fully understand the results reported later in section 4, the complete set of constraints is here listed, with meaningful merit parameters and enumeration of the main tasks directly impacted (see italicized items).

- noncooperative scenario: the only source of navigation information is provided by the pictures taken with the BIROS star-tracker (recall Fig. 2). Given the coupling between semi-major axis and orbital period, the uncertainty in predicting the along-track separation of two spacecraft is generally much higher than for the radial and cross-track components. This consideration becomes even more problematic considering the strong anisotropy that characterizes the solution of the angles-only navigation problem.

  1. *safety concept*: in order to mitigate the collision hazard only passively safe relative trajectories are employed to approach BEESAT-4. These necessarily present a (anti-)parallel configuration of the relative eccentricity and inclination vectors, and preserve a certain security margin of the minimum one-orbit distance normal to the flight direction. The uncertainty distribution of such latter value is monitored in real-time onboard [12].
  2. *guidance profile*: the solution outputted by the autonomous maneuver planner is a passively safe rendezvous trajectory [11]. In the local radial-tangential-normal (RTN) orbital frame, this appears as a spiraling trajectory. Hence a certain out-of-plane component is kept during approaches, though decreased while coming closer to the target (to reduce the overall 3D distance).

- differential aerodynamic drag: height and difference in the ballistic coefficients of the two satellites determine a predominant effect of the differential drag perturbation on the relative dynamics (on average 0.7 meter of relative semi-major axis per orbit).

  1. *safety concept*: during AVANTI, BEESAT-4 leads the formation, so that the differential drag always creates a natural drift that increases the along-track separation between the two spacecraft [16].
  2. *guidance*: the maneuver planner takes into account the effect of the perturbations when formulating the delta-v minimum problem [11]. Clearly, rendezvous trajectories are more expensive than receding ones, since they have to counterbalance the differential drag.
  3. *relative orbit determination*: since the modeling of the differential drag is greatly affected by the uncertainties of the unknown attitude and drag coefficient of the target spacecraft, the mean time-derivative of the relative semi-major axis is also estimated onboard [13, 22].

- Sun-geometry: given orbit LTAN and height, during each orbit BIROS is eclipsed by the Earth for approximately 30 minutes. Whereas, the camera head pointed in along-track to image the target is often blinded by Sun and/or Earth, according to the baffle aperture.

  1. *target identification*: to cope with various luminosity conditions and data gaps, a robust approach is adopted exploiting a kinematic identification of the target trajectory throughout a sequence of pictures [13].

2. *relative orbit determination*: observations' gaps and non-even distribution challenge the observability property of the problem: frequent small maneuvers are performed to help reconstructing the relative trajectory [13, 21, 23].

- no-additional camera heads: no major s/c design adaptations have been done on BIROS to support AVANTI. Hence only the two standard camera heads of the star-tracker, with mounting directions designed for Earth observation needs, were available.

  1. *attitude determination*: often achieves a downgraded performance (down to one degree accuracy error) since it works into a suboptimal condition (i.e., one or two heads extensively blinded) caused by the AVANTI pointing geometries.This reflects into a poor attitude control accuracy, especially during maneuvers.
  2. *navigation system*: at close-range, when the luminosity of the target prevents stars to appear on the pictures, the (downgraded) s/c attitude information has to be used to compute observation residuals [21, 23].
  3. *power system*: the image-collection client observation attitude mode (COM) has been designed to use the rotation around the boresight axis to improve the Sun-angle to the solar panels and/or the GPS antennas visibility patterns, depending on need [2].
  4. *thermal system*: keeping a camera directed towards the target (i.e., COM) implies receiving Sun in the radiator once per orbit exactly when the illumination conditions are the most appropriate to image the target. Thus, a cool-down attitude mode (CDM) has been also implemented, to maximize the heat dissipation while recharging the s/c batteries. The selection of CDM is performed autonomously onboard based on current temperature values of some critical devices. During CDM, the target cannot be in the camera field of view (i.e., further data-gaps). Moreover, transitions to CDM determine fluctuations in the cross-sectional area (i.e., variations of differential drag profile).

- 1D-thruster system: the s/c has to slew before each maneuver to orient the nozzle to realize the aimed equivalent delta-v. Such actions are handled by the thruster firing attitude mode (TFM).

  1. *guidance and control*: the autonomous maneuver planner handles several forms of time constraints: minimum time to the first maneuver of a new plan, minimum time spacing between consecutive burns, and no-control windows to prevent maneuvering activities during conflicting phases (e.g., high-rate ground-contacts) [11].
  2. *navigation system*: generally the target is not in the camera field of view during maneuvers; nevertheless, they improve the non-instantaneous observability property of the relative navigation problem (i.e., the capability to reconstruct the relative motion making use of measurements accumulated over long time periods) [24]. Note that the onboard navigation system can only use the information of commanded maneuvers instead of calibrated ones [13, 23].

- onboard computer architecture: the BIROS bus OBC features an industrial Power PC 823e processor without floating point support and 16 MB SDRAM memory for data storing. Star-tracker–OBC and OBC–PPU are connected by a serial connection supporting 115200 bps data rate (recall that PPU hosts the additional experiment data partition).

1. *GNC software*: to cope with system's computational load limitations, the AVANTI onboard GNC applications are only executed every 30 seconds (i.e., maximum frequency of observations). In addition, since onboard autonomy requires determinism and robustness, the implemented algorithms make a wide use of semi-analytical formulations developed on purpose [11, 12, 13, 22, 25].
2. *data handling*: ROI image compression format (see section 2.1) is the only employable option to retrieve and process an image every 30 seconds. Despite that this limits to circa 70 MB AVANTI's daily TM and pictures data production, given onboard storage capability and ground stations' support, at least two high-rate downlink contacts are needed per day. These last require BIROS to be in EPM, thus determining observations' data gap (i.e., EPM instead of COM) and interfering with maneuvering activity and/or thermal issues mitigation strategy.

3.1 AVANTI Spaceborne GNC Modules

Fig. 3 shows the functional view of the GNC spaceborne system that supported the AVANTI experiment. It is composed by two main modules, respectively named AVANTI and OSM (onboard safety monitoring), which are implemented on the bus OBC board (two blue-blocks in Fig. 3).

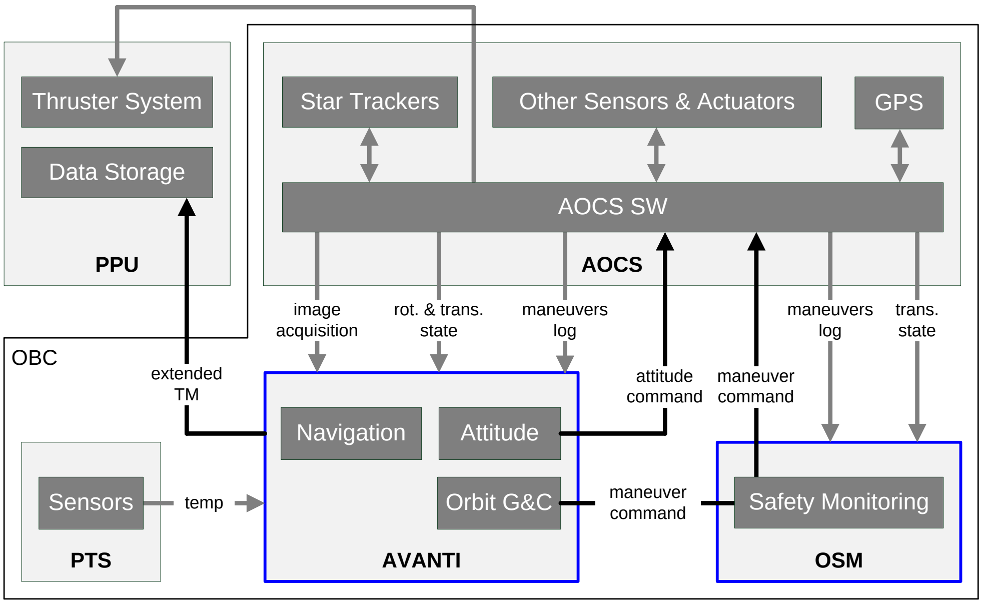

Figure 3: Functional view and main interfaces of the spaceborne GNC SW.

The AVANTI unit features the main relative orbit estimation and control specific functions, as well as the attitude guidance unit in charge of selecting the best suited-attitude mode and, in some cases, of computing the reference time-varying pointing profile. OSM carries out the collision avoidance task [12]. The majority of the interfaces to this GNC system are with the SW layer of the BIROS

AOCS. In addition AVANTI GNC system communicates with BIROS PTS subsystem and with the PPU payload computer. Note that the thruster control unit is also implemented on the PPU, as the propulsion system itself is considered as a technological payload and not as an element of the bus (see section 2.1).

4 FLIGHT RESULTS

The commissioning of the AVANTI GNC system began shortly after the in-orbit release of BEESAT-4, and in parallel to the completion of the BIROS bus validation. It comprised the stepwise verification of several interfaces and functionalities, since AVANTI formation-flying objectives required the following essential capabilities of the BIROS platform: attitude determination and control, absolute orbit determination, power/thermal/communication management, and readiness of the propulsion system. As a result, taking into account all phases of increasing authority and autonomy of the AVANTI GNC system, a total amount of two months of flight experience has been collected. Here, focus is restricted on the fully autonomous phase: the demonstration of the primary goal of the AVANTI experiment [2].

Table 1: Autonomous rendezvous activities.

Range	Start time [UTC]	Start $a\delta\lambda_0$ [m]	Duration time [days]	Target $a\delta\lambda_F$ [m]	Target $a\delta e_F$ [m]	Target $a\delta i_F$ [m]	Commanded δv [m/s]
far-mid	19-Nov-2016 15:30	$\approx$10000	$\approx$3.5	1000	100	60	0.358
mid-close	24-Nov-2016 20:00	$\approx$2500	$\approx$2.5	$<$100	60	30	0.162

Two completely autonomous rendezvous have been performed in the second half of November 2016, exploring far- to mid- and mid- to close-range domains. Table 1 summarizes duration, covered distance, and delta-v cost characteristics. Note that the relative orbital elements (ROEs) nomenclature is used (details in [22] or [25]) to quantify the mean along-track separation ($a\delta\lambda$) covered by the approach. The definition of the aimed final state is completed by the magnitudes of relative eccentricity ($a\delta e$) and of relative inclination ($a\delta i$) vectors; a passively safe configuration is implied. With autonomous operations it is meant that only few high-level commands have been sent to BIROS, namely: the aforementioned target state and target time, planner operative mode, list of scheduled high-rate down-links, and temperature thresholds for triggering the transitions to CDM. In addition, as part of the safety concept, the OSM module has been periodically re-initialized, based on the on-ground picture reprocessing.

During the far-mid range rendezvous, the inter-satellite distance has been reduced to 1 km, as shown in Fig. 4, where the relative state over time is parametrized in ROEs. The overall GNC error can be assessed by comparison against the reference trajectory (in gray) outputted by the relative precise orbit determination (rPOD) verification layer described in [21]. The navigation error is predominant at the beginning of the rendezvous and at far-range, coherently with the AO convergence and accuracy performances. Particularly, convergence has been slowed down by the challenging combination of few available observations, confined in a limited portion of the relative orbit (unfavorable observation geometry), with the need to estimate also the effect of a varying differential aerodynamic drag (i.e., $a\delta\dot{a}$ component augmenting the state of the filter). Although such navigation error in along-track degrades the lateral accuracy (error in the y-components of δe and δi), the obtained trajectory remains well inside the applicability boundaries of the adopted passively safe approach. Maneuvers are performed to approach the target and to improve the observability property of the AO navigation problem. These are distributed in groups (up to 4 burns) in the time-constraint-free slots (see dashed-green lines in Fig. 4). After each group, the guidance plan to target is updated, refining the sequence of way-points (blue dots). The control error contribution is represented by the distance between the onboard estimated solution (in black) and the way-points targeted by the maneuver planner. The control accuracy degrades due to the cumulative effect of maneuver execution errors, navigation accuracy at re-plan, and guidance assumption of keeping $a\delta\dot{a}$ constant until the next re-plan. Note that within the AVANTI framework, key-point (and challenge) is to step-wise refine both navigation and control solutions, despite a weakly observable orbit determination problem, which from the one hand needs maneuvers to converge, from the other hand cannot benefit onboard from the knowledge of their calibrated values. At 1 km the overall GNC error stays within $\{5, 1, 10, 200\}$ m in $a\{\delta a, \delta *_x, \delta *_y, \delta\lambda\}$ components.

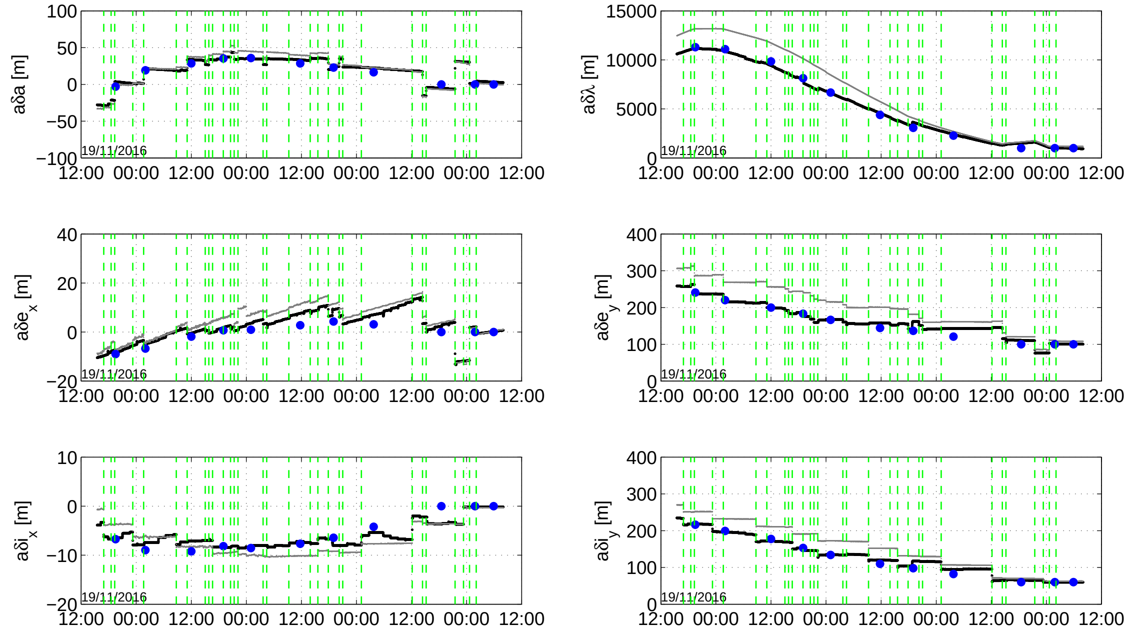

Figure 4: Far-mid range rendezvous - Relative orbit elements over time: onboard estimation (black), rPOD reference (gray), way-points (blue), and times of the maneuvers (green, see Fig. 5-right).

As seen in the RTN frame centered on BEESAT-4, the way-points of Fig. 4 result into a spiraling trajectory that smoothly shrinks in size while decreasing the inter-satellite distance (Fig. 5-left). Such smooth behavior is required to avoid large translations in radial direction (generated by the combined effect on δe and δa changes produced by tangential burns), which can bring the minimum RN distance value close to zero, despite large δe and δi in (anti-)parallel configuration. The commanded delta-vs are plotted in Fig. 5-right. Note that no radial burns are prescribed and out-of-plane (N) components are usually larger than tangential ones, while shrinking the relative orbit. The delta-v minimum guidance policy requires small maneuvers, which sometimes are near to the calibration accuracy limit of the GPS-based precise orbit determination. As mentioned in section 3, the main source of error is driven by the downgraded attitude control (the valve of the cold-gas system is controlled to the ms). Hence, in proportion, small maneuvers are affected by larger errors, a further penalizing factor for the navigation filter.

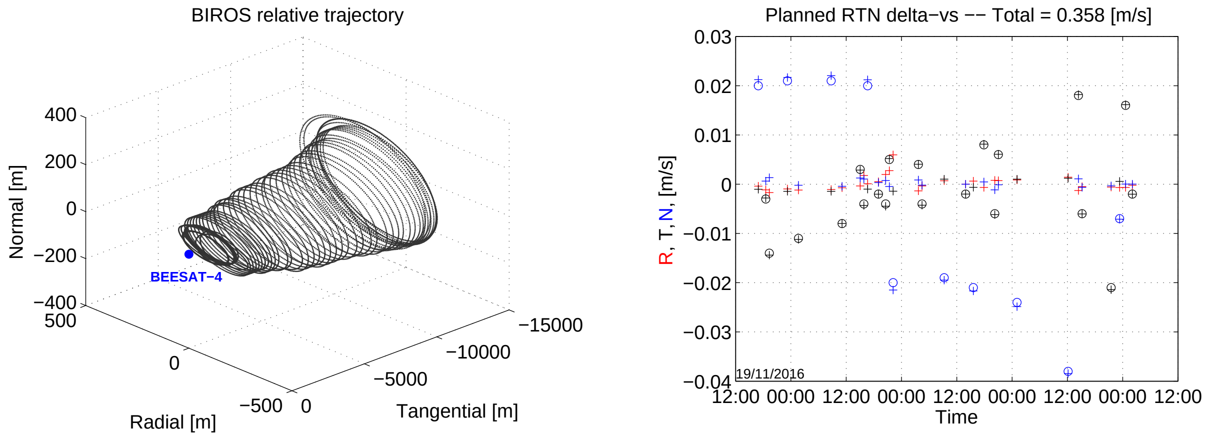

Figure 5: Far-mid range rendezvous - Left: BIROS trajectory in the RTN frame centered on BEESAT-4. Right: commanded maneuvers (o) and values calibrated (+) with GPS-based precise orbit determination.

During the 36 hours break between the two rendezvous, the action of the differential drag perturbation brought BIROS back again to a separation of circa 2.5 km. Within the mid-close range rendezvous, the minimum 3D distance achievable given the operations safety limits and the system's restrictions (section 3) has been targeted. To this end, the relative inclination vector has been reduced to 30 m, and $\delta\lambda_F$ and δe_F have been chosen to allow BIROS overtaking BEESAT-4 during the portion of relative orbit spent in eclipse. The obtained rendezvous profile is shown in Fig. 6 and the overall GNC error stays within $\{0.5, 1, 1, 10\}$ m in $a\{\delta a, \delta *_x, \delta *_y, \delta\lambda\}$ components. Note that no way-points appear during the final phase, since here the natural drift is exploited considering that: the implemented relative orbit control cannot structurally achieve a fine continuous tracking and maneuvers determine picture data-gaps. In addition, the aimed final time of the mid-close range rendezvous has been chosen to synchronize the aforementioned drifting conclusive phase with a period in which no heat dissipation interruptions are required. This is visualized in Fig. 7; according to the attitude management during the mid-close rendezvous, no TFM (for maneuvers) and CDM (for reducing the s/c temperatures) attitude modes have been selected.
The corresponding trajectory in the BEESAT-4 RTN frame is depicted in Fig. 8: the two R-T and N-T views are used to better visualize the geometry of the problem. Absolute and relative orbit characteristics determine that the point of minimum 3D distance is achieved during eclipse (no pictures). In Fig. 8, red dots mark the observations collected during the rendezvous. Generally, observations are limited to 10 to 15 minutes arcs of the orbit, when maneuvers, high-rate down-links, or thermal mitigation strategy do not further reduce them. At close-range, during the conclusive phase of the

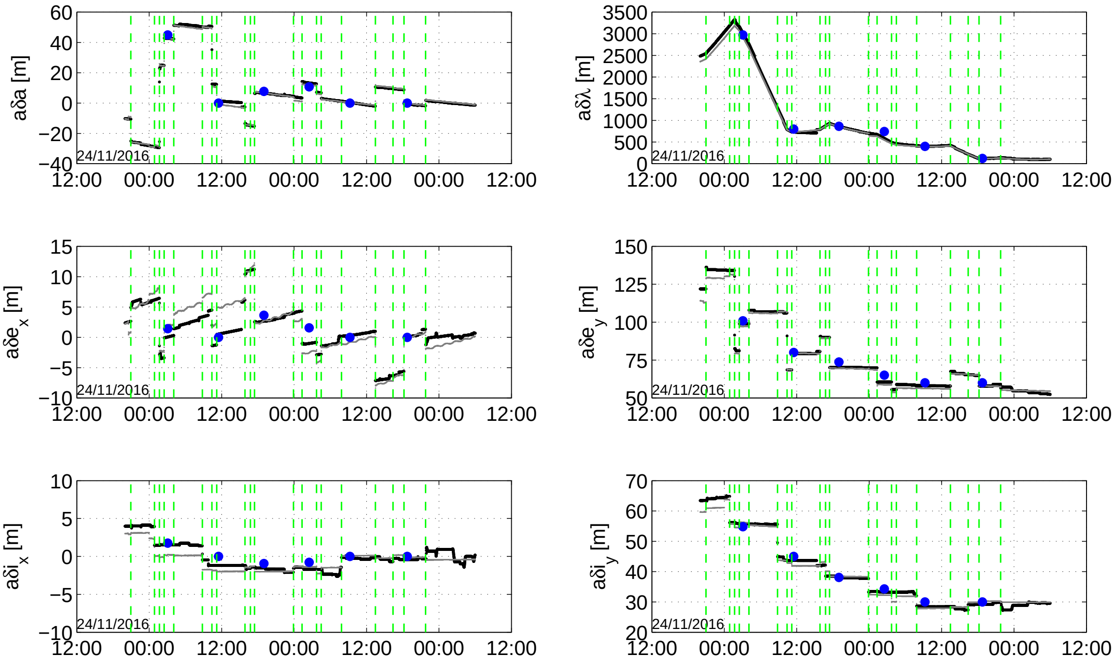

Figure 6: Mid-close range rendezvous - Relative orbit elements over time: onboard estimation (black), rPOD reference (gray), way-points (blue), and times of the maneuvers (green).

approach, orbits presented up to 35 minutes of data arc, given the combination of attitude profile (to keep the target in the field-of-view) and predominant out-of-plane motion.
Nevertheless, the close range domain represented the most challenging working condition for the navigation system, especially considering the system's characteristics in use for AVANTI. As explained in [21, 23], in fact, stars in background are no more visible (i.e., no biases correction and downgraded attitude information) and the image of the target cannot be considered anymore as a point aligned with the center of mass. As an example Fig. 9 shows the ROIs containing the target in two different locations on the orbit though both during a phase in which the electronic shutter was active. A deeper investigation of the resulting navigation performances is addressed in such referenced papers.

5 CONCLUSION

This paper presented the guidance, navigation, and control flight results achieved during the autonomous activities of the AVANTI experiment. Within this endeavor a chasing small satellite approached a noncooperative target in low Earth orbit down to less than 50 meters distance making use of a monocular camera as unique device for sensing the relative state. As a result, AVANTI embodies a milestone in the preparation of future debris removal missions, since it demonstrated the viability of the angles-only navigation approach into an extremely challenging, and representative, orbit scenario.

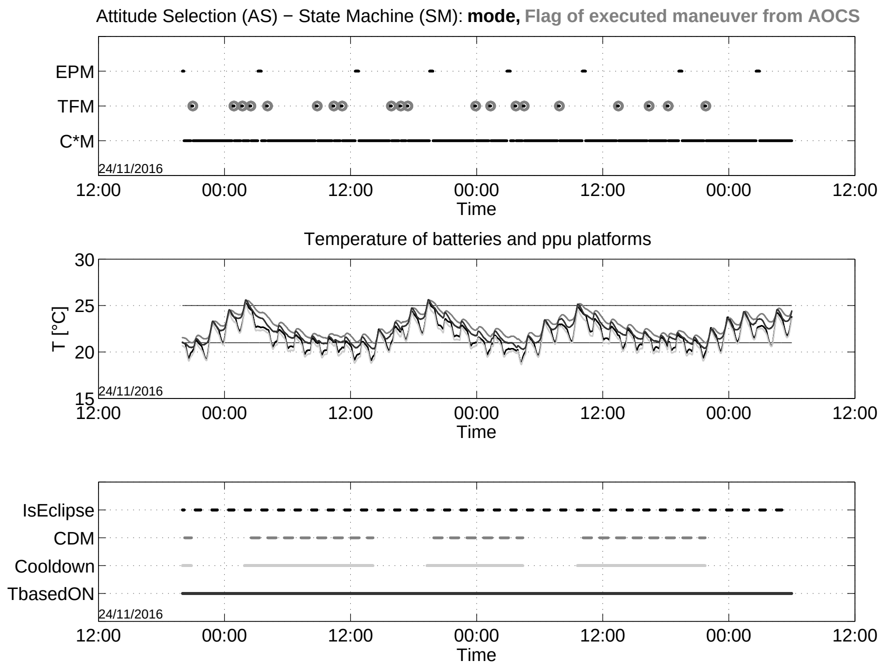

Figure 7: Mid-close range rendezvous - Autonomous attitude management of COM, EPM, TFM, and CDM transitions. Observations of Fig. 8 occur only in COM mode and no eclipse.

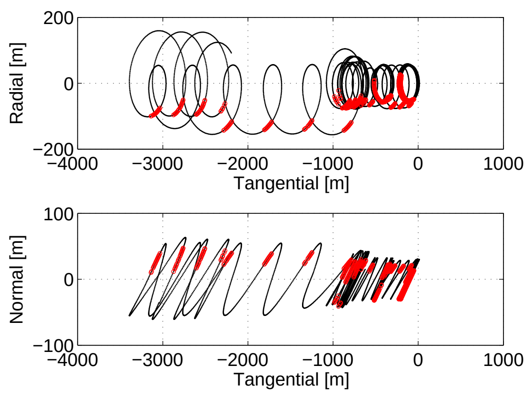

Figure 8: Mid-close range rendezvous - BIROS trajectory in two views of the RTN frame centered on BEESAT-4: target observations (red).

Figure 9: Mid-close range rendezvous - ROIs containing the target with active electronic shutter.

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