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THE AUTONOMOUS VISION APPROACH NAVIGATION AND TARGET IDENTIFICATION (AVANTI) EXPERIMENT: OBJECTIVES AND DESIGN

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ABSTRACT

This paper provides the description of the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment currently in development at the German Space Operations Center.
AVANTI is one of the secondary scientific experiments to be accomplished within the FireBird mission which will launch the BIROS spacecraft in 2015.
AVANTI is intended to demonstrate vision-based noncooperative autonomous approach and recede maneuvering making use of angles-only measurements. To this aim BIROS plays the role of the active servicer satellite and performs some proximity operations with respect to a picosatellite, previously released in-orbit by BIROS through a deployment device. Measurements consist of the line-of-sight angles to the picosatellite gained from pictures taken by the star tracker mounted on BIROS.
This paper addresses the experiment design to meet the system's requirements and provides a description of its main flight dynamics subsystems, including the key algorithms they are based on. A simulation of the first phases of the experiment is provided to explain the experiment concept and to show the expected performance.

1. INTRODUCTION

The goal of the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment is to demonstrate the capability to perform rendezvous and receding approaches with respect to a noncooperative client satellite making use of vision-based angles-only measurements. The experiment focuses on far- to mid-range separations. Specifically, the relative motion is confined within approximately 10 km and hundreds of meters in the along-track direction, given the size and visibility characteristics of the spacecraft employed as client.

The capability to approach and rendezvous (RdV) a noncooperative on-orbit object in a safe, fuel efficient, and accurate manner is a key requirement for future on-orbit-servicing and debris-removal missions. In this context, the exploitation of angles-only navigation is appealing since it relies on simple passive low-cost sensors (e.g., optical or infrared cameras) able to provide the line-of-sight (LOS) direction to the target object. To that end, the star trackers usually employed for attitude determination can be advantageously used also to track a space object, if properly oriented [1]. At sufficiently large separations, where it is acceptable to approximate the center of mass of the client satellite with its intensity centroid, angles-only navigation represents a sufficiently accurate methodology to accomplish the first phases of the approach. This leads to a simpler and cheaper design of the servicer satellite, restricting the sensor complexity to close-proximity operations, for which more accurate, costly and power-demanding sensors might be required.

AVANTI is one of the secondary scientific experiments to be accomplished within the FireBird mission [2]. 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, already launched in July 2012, and the Berlin InfraRed Optical System (BIROS), scheduled for launch in 2015. In addition, BIROS will release in-orbit a picosatellite of the Technische Universität (TU) Berlin University. The AVANTI experiment will start straightaway, with BIROS playing the role of the active servicer satellite which uses the picosatellite as noncooperative target for the sake of the experiment.

The development of the AVANTI experiment represents a further step to enhance the expertise of DLR in the field of noncooperative rendezvous, which relies up to now on two recent achievements in the field of

noncooperative far-range approaches: the Formation Re-acquisition experiment in 2011 [3] and the Advanced Rendezvous Demonstration using GPS and Optical Navigation (ARGON) in 2012 [4]. Both experiments took place during the nominal and the extended phases of the Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) mission [5].
The Formation Re-acquisition experiment was meant to re-establish a formation after the conclusion of the nominal mission. At that time, the two PRISMA spacecraft were separated by approximately 60 km, exceeding thus the inter-satellite link range. The experiment consisted in the conduction of a ground-in-the-loop vision-based approach to decrease the separation to circa 4 km after one week. To that end, an early prototype of angles-only relative navigation filter had been developed, processing daily five-hour-long pictures slots of the target satellite taken by the vision-based sensor (VBS) embarked by the servicer satellite. The filter was initialized using two-line-elements (TLE) provided by the North American Aerospace Defense Command (NORAD).
During the ARGON experiment, instead, an approach from 30 to 3 km was accomplished, making use of solely angles-only measurements coming from the VBS system. Priority was given to the refinement and the smooth inter-operations of the different activities necessary to perform such an approach, namely GPS-based precise orbit determination, image processing and target identification, angles-only relative orbit determination, and establishment of a safe guidance profile. Nevertheless all these tasks were still performed on-ground, making use of the dumped telemetry. Moreover the maneuvers were computed to track a pre-computed nominal rendezvous profile.

The main contribution of the AVANTI experiment lies in accomplishing a fully autonomous onboard vision-based navigation and control instead of ground-based operations. Each task has to be accomplished onboard, thus taking into account the limitation of the computational power and the necessary level of robustness to cope with system and environment uncertainties. This involves the onboard processing of camera images and robust target identification, the capability to perform in real-time the relative orbit determination, and, finally the autonomous maneuver planning to accomplish a safe and delta-v sustainable rendezvous towards the aimed final condition.

In contrast to the aforementioned experiments, AVANTI is subject to further challenges coming from the different orbital scenario and servicer system design. First of all the nominal height of the BIROS satellite is 515 km, thus approximately 200 km lower than the PRISMA mission. The greater value of the atmospheric density, together with the considerably different ballistic coefficients of BIROS and picosatellite result in a strong effect of the differential aerodynamic drag on the relative dynamics. As a consequence, the accuracy of the model of the relative dynamics employed in the navigation filter and in the maneuver planning is degraded. Moreover it is difficult to accurately model the value of the atmospheric density, especially when neglecting the solar flux information due to limited computational capability [6].
Concerning the servicer system design, BIROS is equipped with a propulsion system which provides a single-direction thrust vector. Even though the magnitude of the maneuver execution errors can be calibrated on-ground during the commissioning phase, the satellite cannot estimate them onboard in real-time. Thus information on commanded maneuvers is only provided to the relative navigation filter, which could lead to a degradation of navigation performance in case of large maneuver execution errors. Maneuvers are essential for the experiment, because the angles-only relative navigation problem is weakly observable in their absence [7]. The onboard estimation algorithm makes use of the long term effect produced by a known maneuver to resolve the ambiguity in the range to the client satellite [8].
Finally, the AVANTI scenario is fully noncooperative since no GPS data are available from the picosatellite. In the absence of TLE information, the ground segment can rely only on radar tracking campaigns to estimate the absolute orbits of the two spacecraft. Nevertheless, within the FireBird mission it is foreseen to employ the imaging radar tracking (TIRA) station in Germany only immediately after the picosatellite deployment, using two tracking passes spaced by approximately 12 hours [9]. Moreover a minimum along-track separation of 5 km is required for TIRA to be able to distinguish the signal from the two spacecraft. Thus, during the execution of AVANTI, the only source of navigation information is provided by the vision-based sensor. Consequently a strong collision avoidance strategy must be adopted during the whole experiment, in order to ensure the safety of the formation under the most severe uncertainties on the relative navigation. The approach retained by AVANTI is based on the passive safety concept offered by the relative eccentricity-inclination separation [10].

Based on the past flight experience [3, 4], the desired relative navigation accuracy is set to within 10 m for all relative orbital elements except for the relative mean argument of latitude. The error in the mean tangential separation is expected to lie within 10% of the inter-spacecraft separation [4, 8]. Nevertheless, additional uncertainties encountered in AVANTI regarding the maneuver execution and the atmospheric density (i.e., solar activities) can lead to an unavoidable degradation of navigation performance. This sets a limit to the minimum achievable relative tangential separation and sets a further margin on the minimum distance in the radial-normal plane required for passive safety.

In the following, first a description of the experiment and of the space segment is provided. Secondly the main flight dynamics subsystems of AVANTI are presented, including the key algorithms they are based upon. Finally a simulation representative of the first phases of the experiment is reported and discussed.

2. EXPERIMENT DESCRIPTION

The BIROS satellite will be launched in 2015 and injected into an almost circular sun-synchronous orbit at a height of 515 km.
It has a roughly cubic shape 60x80x80 cm with a mass at launch of approximately 140 kg. Fig. 1 provides a detailed view of the spacecraft. BIROS is equipped with a propulsion system whose nozzles provide a single-direction thrust vector aligned with the –Y axis of the body frame and magnitude of 0.1 N. Nominally the total embarked delta-v amounts to 20 m/s. Half of the fuel is allocated to the AVANTI experiment, while the other half is allocated for the primary mission objective.
The two GPS antennas are placed on the surfaces perpendicular to + and -X of the body-fixed frame. The S-band antenna for high data-rate downlink is directed to +Z. The normal to the deployed solar panels is directed as –Z. The two camera head units (CHU) of the star tracker mainly point towards –Y. The heads are mounted so that the boresight are respectively rotated by approximately ±35 deg with respect to –Z and +7 deg with respect to +X.
Finally the Picosatellite Orbit Deployer (POD) faces +Z, providing an ejection impulse nominally aligned with this direction.

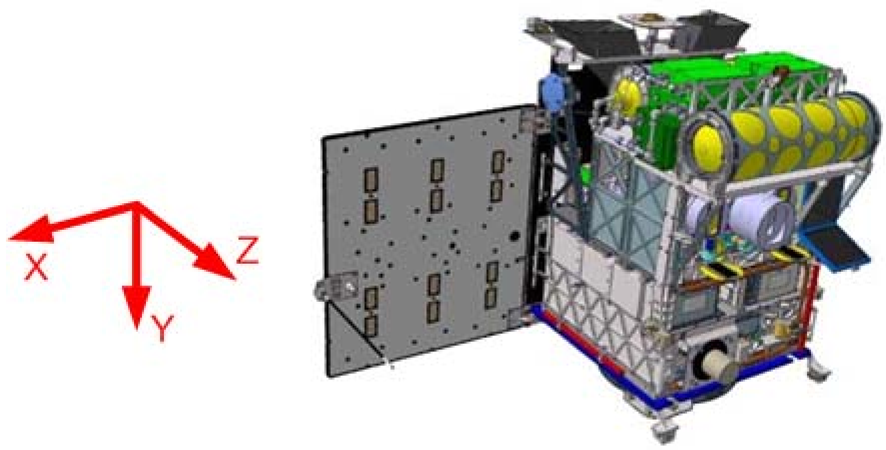

Fig. 1. *The BIROS spacecraft: components view and main orientations with respect to the body frame.*

The AVANTI experiment is planned to start after the picosatellite deployment, as soon as the experiment initial conditions are achieved, with a 30 days duration campaign.
Both separation phase and achievement of the experiment initial conditions are fully ground-based and performed by the Flight Dynamics Services (FDS) division of the German Space Operations Center (GSOC).The POD device imparts a separation delta-v of nominally 1.41 m/s of magnitude. Subsequently the BIROS spacecraft performs a sequence of burns to establish a stable and passively safe formation [11]. At completion of the deployment, the picosatellite leads the formation in flight direction, and the differential drag acts in increasing the mean tangential separation, ultimately towards the evaporation of the formation. Due to the passive safety requirement, the relative motion has a non-zero out-of-plane component. Moreover the mean tangential separation is greater than 5 km, to allow the radar tracking by TIRA and the subsequent orbit determination. Afterwards a further maneuver is to be performed by the FDS to minimize the unavoidable residual drift, hence establishing the proper initial conditions for AVANTI.

At the activation of AVANTI the boresight of one of the CHU of the star tracker is aligned to the +T direction of the local radial-tangential-normal (RTN) frame centered on BIROS. Given the experiment initial conditions, the whole relative motion of the picosatellite is contained in the field of view of the camera. At this stage the target identification task begins and the relative navigation filter is initialized. Several proximity operations are planned to be accomplished during the AVANTI campaign, comprising rendezvous, receding motion, and station keeping. To this end different formation configurations, defined by aimed relative states together with their final acquisition times, are sent to the AVANTI software (SW) via TC from ground. Accordingly the Maneuver Planning and Commanding (MAP) module computes the maneuvers necessary to achieve such aimed configuration, depending on the current estimated relative state, in a delta-v minimum way.

The maneuvering activity prescribed by the AVANTI SW has to take into account constraints coming from the servicer design and from the ground segment. Regarding the spacecraft propulsion, the single-direction thruster system has to be aligned with the aimed delta-v direction before each burn. Moreover, given the limit on the maximum continuous thrust supply, only maneuvers with delta-v magnitude smaller than 0.2 m/s can be commanded. Together these constraints determine the minimum spacing in time between two consecutive orbit corrections.
For what concerns the ground segment requirements, the S-band antenna of BIROS has to be Nadir pointing throughout the scheduled ground contacts, in order to exploit the highest possible downlink data-rate. During AVANTI it is foreseen to use all the four nominally scheduled daily passes, in order to dump both the experiment TM and the VBS images, needed for post-facto replay on-ground. Any maneuver activity during a ground contacts has to respect the aforesaid pointing requirement.

Fig. 2 depicts the servicer attitude modes foreseen during the AVANTI experiment. The default mode is referred to as Client Observation Mode (COM). According to its definition, the boresight of the active CHU (i.e., +Z of the camera frame) is pointed towards a prescribed direction: the current LOS computed onboard or the local tangential direction towards the client satellite (i.e., +T). The attitude definition is completed by a rotation of the camera frame with respect to the boresight axis. This degree of freedom is employed to cope with eventual power, thermal, or GPS antenna pointing requirements, especially during time extensive COM sessions. In the left part of Fig. 2, the boresight points towards +T and the +Y of the camera frame points towards the Nadir, letting the normal to panel to be slightly misaligned from Zenith.
During a maneuver activity the prescribed attitude mode is referred to as Thruster Firing Mode (TFM). Here the thrust direction is aligned with the aimed delta-v unit vector throughout all the maneuver duration. Regarding Fig. 2, whenever a maneuver requires a delta-v in the local T-N plane, the communication pointing constraint is also respected.
Finally, during active ground contacts, the servicer is set to Earth Pointing Mode (EPM) mode, with the S-band antenna directed to Nadir. Consequently, in both EPM and TFM modes, the camera boresight is not aligned anymore with the local flight direction, causing the target to exit the field of view of the active camera head. The attitude mode selection is performed onboard by the AVANTI MAP module.

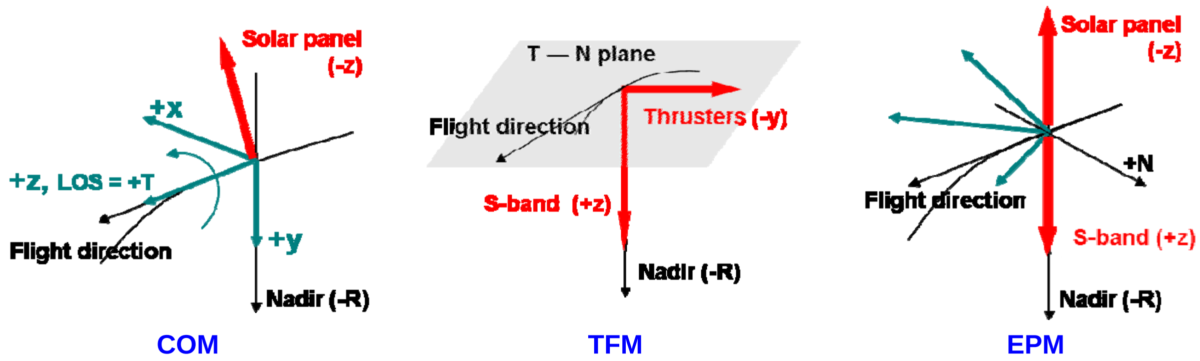

Fig. 2. *Attitude modes foreseen during AVANTI: Client Observation Mode (COM), Thruster Firing Mode (TFM), and Earth Pointing Mode (EPM). The local orbital frame (i.e., RTN) is depicted in black, whereas the spacecraft-fixed and camera-fixed frames are respectively marked in red and green.*

3. AVANTI SW ARCHITECTURE

The AVANTI experiment is implemented on the BIROS onboard computer which is managed by the RODOS real-time embedded operating system [12]. The AVANTI SW consists in a set of C++ applications and is executed every 30 seconds.
Fig. 3 depicts the high level AVANTI SW architecture, including its interfaces to the spacecraft onboard computer, sensors and actuators, and to the ground segment. AVANTI receives the following inputs:

- time-labeled camera images from the processing unit of the star tracker;

- spacecraft attitude and commanded maneuvers from the AOCS system;
- servicer absolute state estimated by the GPS-based Onboard Navigation System (ONS).

At every call of the AVANTI thread three main tasks are sequentially executed. First the Image Processing (IMP) module processes the pictures from the star tracker to identify the target satellite. The resulting LOS to the target is then provided as input to the Relative Orbit Determination (ROD), which implements an extended Kalman filter to estimate the current relative state, expressed in relative orbital elements (ROE). Finally this state estimate is passed to the Maneuver Planning and Commanding (MAP) function, which computes or updates the maneuver plan to achieve an aimed relative state. Moreover it selects the attitude mode required by the plan according to the experiment timeline.
Therefore, the output of the AVANTI module consists of:

- time-tagged center of burn delta-v vectors in the RTN frame;
- attitude mode, with related directions (e.g., LOS or delta-v unit-vectors).

Interfaces to the ground segments are the TM coming from AVANTI and the TC sent to steer the proximity operations.

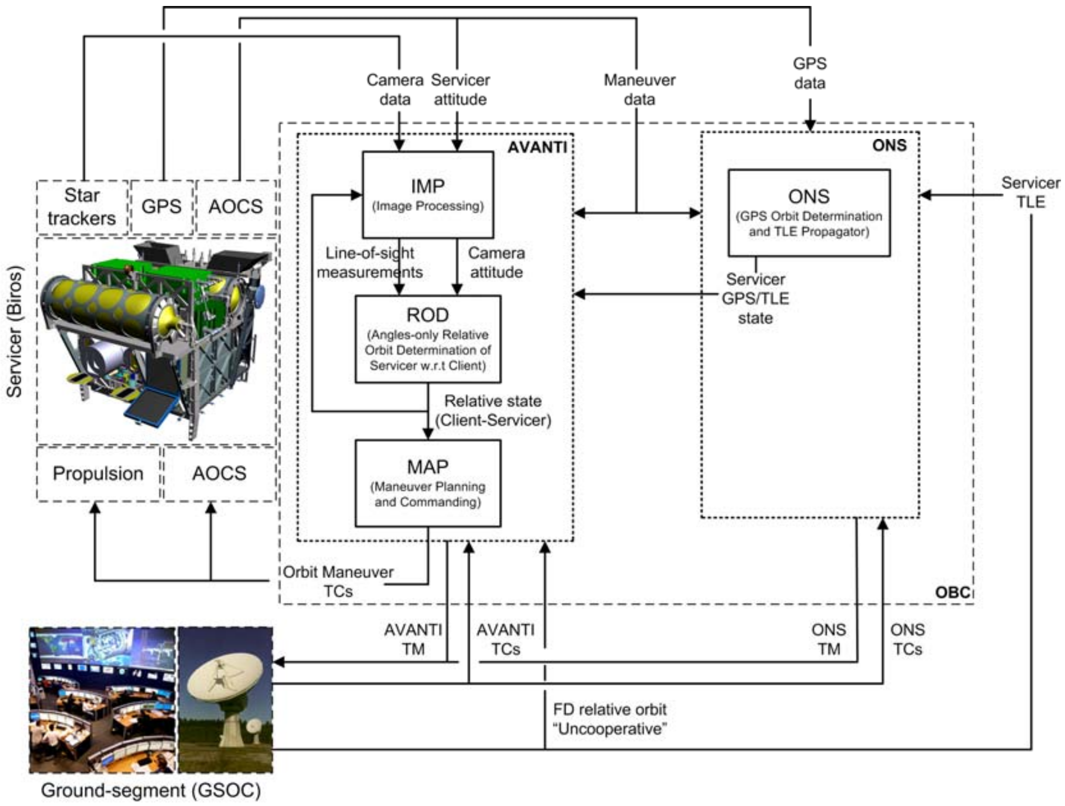

Fig. 3. AVANTI SW architecture and interfaces to space and ground segments.

A. IMAGE PROCESSING

This module is intended to provide line-of-sight measurements as input to the onboard relative orbit determination. In view of the desired working range, the image processing is kept very simple because the shape of the target object can anyway not be analyzed at far and middle range. As a consequence, all the objects imaged by the camera are considered as points. The image processing consists simply in extracting the object centroids comprised in the picture after a threshold-filtering of the background noise. The centroid estimation is done by computing the arithmetic mean of the pixels, which is sufficient to fulfill the desired centroiding performance requirement (0.5 pixel). Further investigations are currently being performed to determine if a more advanced centroiding algorithm implementing a 2D-Gaussian fit shall be used to refine the centroid estimate of the target spacecraft at close distance, when its image does not look like a point anymore.
After the extraction of the centroids of the picture, the target spacecraft has to be recognized among all objects imaged by the camera. The target identification algorithm relies on the fact that the orbit of the target object is very similar to the orbit of the servicer, so that the apparent motion of the target can be distinguished from the apparent motion of stars and non-celestial objects. In order to ease the identification

process, the stars visible in the picture are first identified using a star catalog. In principle, this could be done without any external help using typical star tracker algorithms but it has been decided for simplicity to rely on the onboard knowledge of the spacecraft attitude for the identification of stars. Once the stars have been recognized, the remaining unidentified centroids are composed of the target satellite itself but also of other possible non-celestials objects, unrecognized stars and camera anomalies like hot spots. By combining a sequence of images, it becomes possible to distinguish clearly the trajectory of the target object surrounded by isolated additional centroids and thus to isolate this trajectory using a density-based clustering algorithm. As example, the non-identified centroids of a sequence of 10 simulated images taken every 30s are superimposed on Fig. 4. In this simulation, the camera is constantly pointing in along-track direction and the target relative orbit is a several hundred meter large ellipse at about 10 km distance. In this sequence, a few stars are sometimes not recognized, so that additional centroids are present. Still the trajectory of the target (in red) is clearly recognizable from the other centroids (in blue), simply because their apparent motion are very different. In the very improbable case that another object flies also on a similar orbit, the algorithm selects the trajectory of the brightest object.

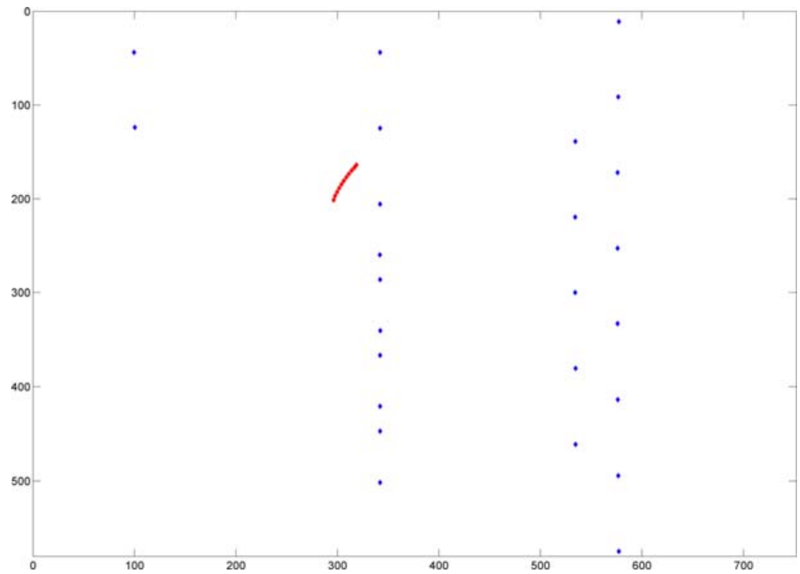

Fig. 4. *Example of unidentified centroids in a sequence of 10 pictures sampled at 30s.*

The advantage of this target identification strategy is that it does not require any feedback from the relative orbit determination and is thus more robust in case of unhealthy relative navigation. The only required assumption is an approximate knowledge of the distance in pixels travelled by the target spacecraft between two consecutive pictures.

The line-of-sight to the target is finally provided after applying a camera distortion model to remove the aberration due to the optics of the camera. The knowledge of the orientation of the camera in space is also refined using the stars recognized in the picture, so that precise line-of sight measurements in the inertial J2000 frame can be delivered to the relative orbit determination task. Further details on the algorithms can be found in [13].

B. RELATIVE ORBIT DETERMINATION

The aim of this module is to estimate the current relative state of the picosatellite with respect to the servicer by processing the time-tagged LOS measurements coming from the IMP unit.

The formalization of the angles-only relative navigation problem is explained in [8]. According to it, the relative state is parameterized through ROE and a linear model of the relative dynamics, which includes the mean effects due to J2, is employed.

In contrast to [8], the AVANTI SW employs an extended Kalman filter instead of a batch least squares method. This choice is motivated by the real-time requirements taking into account the limited computational resources. In addition no camera biases are estimated, since the intrinsic (distortion) and extrinsic (attitude) camera parameters are estimated prior to ROD using the stars visible in the image.

The angles-only relative navigation problem based on a linearized unperturbed model is known to be un-observable [7]. The inclusion of orbit perturbations and or of nonlinearities in the modeling of the

dynamics, or the choice of curvilinear variables to express the relative state, can theoretically provide observability. Though this effect is weak when dealing with realistic scenarios (i.e., measurements affected by noise) and large mean separations (i.e.,. few tens of kilometers to hundreds of meters). Therefore the inclusion of known maneuvers must be exploited in order to solve the ambiguity in the range to the client satellite. Since BIROS is not able to estimate onboard the actually executed maneuvers, the navigation filter uses the commanded delta-v values instead, with a consequent worsening of the achievable navigation accuracy.
In addition to the problem of weak observability, the ROD task has to face other challenges, like the inaccurate initial guess of the relative state for the filter initialization, the sparse measurements due to the occasional spacecraft rotation and the mismodeling due to the maneuver execution errors and differential drag. It is currently being investigated whether the inclusion of the differential drag in the filter dynamics has a significant impact of the navigation performance. Further details about the onboard relative navigation filter are available in [13].

C. MANEUVER PLANNING AND COMMANDING

This module receives the current relative state estimation from the ROD unit and produces or updates the maneuver plan. In addition, it selects the proper attitude mode, in compliance with the relative motion profile and the experiment's timeline.

The aimed relative state to be achieved by the servicer is provided via TC from ground. Depending on the mode of operation, it is described by:
- aimed ROEs at a given final time, if in *reconfiguration mode*;
- aimed ROEs and maximum duty cycle duration, if in *station keeping mode*;

where ROEs are the relative orbital elements of the client with respect to the servicer satellite.
At each plan update, the complete maneuver profile from the current state and time to the aimed final state and time is computed in open-loop. For station keeping the profile is considered as a single step ROE correction. In reconfiguration mode, instead, the final state is stepwise achieved through intermediate ROE sets that guarantee the minimization of the delta-v consumption over the whole reconfiguration horizon. This is based on the fact that the delta-v cost is proportional to the change of ROE caused by an impulsive maneuver. Thus the algorithm minimizes the total ROE variation needed to achieve the aimed state. The details of the algorithm are explained in [14].
The times to acquire the optimal intermediate ROE sets are computed by the AVANTI SW taking into account the *no control windows* intervals defined in the TCs. These quantities identify portions of the schedule where no maneuvers can be performed and can be used to:
- prohibit maneuvers due to requirements of the mission timeline;
- control the distribution of the maneuver activity over the time horizon
- shape the rendezvous profile so that too large drifts (i.e., too big variations of the relative semi-major axis) are avoided.

Each single step (e.g. intermediate piece of a reconfiguration or single station-keeping correction) is established by means of a group of maneuvers, consisting of a set of three analytically computed tangential impulses and a single out-of-plane burn.
Several possible impulsive strategies are compared in [15]. These proposed schemes offer different behaviors with respect to typical planning drivers, such as thrusters' duty cycle, attitude constraints, passive safety, visibility constraints, maneuvers' determinism and predictability, and delta-v minimization. In the frame of AVANTI, the three tangential burns scheme provides the maximum level of determinism and predictability and the minimum delta-v expenditure. Moreover, the fact that single impulses are spaced by multiple of half orbital periods is also compatible with the maneuvers' spacing constraints that arise to slew the single-direction thrusters' system of the BIROS satellite in any appropriate direction. Finally, by exploiting only tangential and normal corrections, the whole maneuvering activity is compatible with the communication attitude constraints that require the BIROS satellite to keep the S-band antenna pointed to Nadir during active ground contacts.

According to [14], the maneuver planning algorithm exploits the state transition matrix of the relative motion expressed in ROE, where the mean effect due to J2 and the differential drag are both taken into account. In particular, the closed form solution of the relative motion is obtained under the assumption that the differential drag produces a constant acceleration in the tangential direction.
Within the AVANTI scenario (i.e., almost circular orbit of the servicer and relative separations confined in few tens of kilometers), this linear model approximates well the real motion, provided that the assumption

of constant differential drag is valid and its value is well modeled. The worse the accuracy of the modeling of the differential drag, the faster the departure of the model from the true motion. This factor can cause a detrimental effect on wide time reconfiguration horizons (i.e., daily plans). Nevertheless, being the open-loop profile updated after every group of maneuvers (i.e., establishment of each intermediate ROE set), a method to counteract such worsening in the control accuracy is to increase the number of intermediate steps. The shortest time slot to accomplish an intermediate reconfiguration is two orbital revolutions (i.e., approximately 3 hours), according to how the triple tangential impulses' scheme is computed [15].

The last action of the MAP unit is to perform the attitude mode selection. To this end the list of initial and final times of the incoming active ground contacts scheduled within the timeline has to be sent via TC to the AVANTI SW. Provided this information, MAP is able to perform the mode selection, according to the following criteria:

- COM is the default mode throughout the experiment;
- TFM is chosen when a maneuver is foreseen, also when it overlaps an active ground-contact;
- EPM is chosen if a ground contact is forthcoming and no maneuvers are planned in that slot of time.

According to the selected mode, MAP outputs either the boresight or the delta-v unit-vector.

D. SAFETY CONCEPT

Throughout the AVANTI experiment, in the absence of TLE for the picosatellite and/or in case of sparse up-link contacts, the only source of navigation information is provided by the star tracker used as a camera sensor. Thus the ground segment is not able to perform any supervision of the AVANTI behavior. As a consequence the principle of passive safety must be adopted during the whole experiment campaign. Then, at the end of the experiment, the formation evaporates following the natural dynamics of the system.

Passive safety consists in keeping a certain separation between the satellites in the radial–cross-track plane. In this way, it is ensured that the second satellite never enters a "safety tube" centered on the trajectory of the first satellite. Passive safety is related to the magnitudes of the relative eccentricity and inclination vectors, to their angular phase separation, and to the magnitude of the relative semi-major axis [10]. This last contribution maps into an offset in the radial direction.
According to the MAP's algorithm [14], the intermediate steps of a reconfiguration are computed to minimize the whole ROE change to achieve the aimed final relative state. Thus, in the ROE space, the intermediate relative eccentricity and inclination vectors move along the direction of the minimum path towards their final value. In addition, the maneuvers performed to achieve each sub-reconfiguration also move those intermediate vectors along the minimum path direction. The mean arguments of latitude of such maneuvers, in fact, are chosen equal to the total vector phase variation to be accomplished throughout the sub-reconfiguration [15].
These features guarantee that if a safe final state is reached from an initial one with similar relative eccentricity/inclination phasing characteristics, then the approach is passively safe during its whole duration, provided that the drifts are small enough (i.e., the reconfiguration takes place over a long enough time horizon), even if the maneuver profile is interrupted prior to its completion.
On the other hand, in the specific scenario of an initial unsafe state, a proper phasing of the relative eccentricity and inclination vectors must be achieved before reducing the tangential separation. In the frame of AVANTI this situation can occur only if the picosatellite deployment experienced a significant error with respect to the nominal strategy [11]. Nevertheless in this situation the two satellites are separated by more than 5 km.

The safety characteristic of a rendezvous can be verified a-priori, when producing the TCs to be sent to the AVANTI SW. Aimed final state, end time, and acquisition times of the intermediate ROE configurations are the degrees of freedom available to tailor any approach. The value of the safety distance in the R-N plane has to be chosen taking into account the expected performance of the relative navigation accuracy and the expected effect of differential drag on the relative semi-major axis over extended portions of time.

4. SIMULATIONS

In order to assess the performance achievable during AVANTI, a realistic simulation environment has been set up, based on the Multi-Satellite Simulator employed at DLR/GSOC to support various projects in the fields of formation flying and proximity operations [16].

The simulation environment consists in a high fidelity Matlab/Simulink model of the space segment, where the behavior of the BIROS spacecraft is emulated and the AVANTI flight software C++ code is embedded through S-functions. The high level of fidelity is achieved by taking into account the following aspects:

- Both the orbits of the BIROS and picosatellite spacecraft are propagated subject to a 30x30 order and degree gravity field together with all the relevant orbit perturbations.
- Errors in the execution of the maneuvers performed by BIROS are incorporated, modeling both the effects in magnitude and direction.
- The BIROS attitude modes are reproduced, together with the slews required to accomplish any mode change. On top of this nominal behavior, attitude errors representative of the characteristic attitude control system (ACS) accuracies are included.
- The functioning of the star tracker is emulated by a camera model that reproduces the tangential and radial distortion of the lens of the optic system, the stellar aberration, and the behavior of the charge-coupled device (CCD) sensor. Regarding this last component, a radiometric model of the visible stars, a Gaussian point spread luminosity function, hot spots, and background noise are implemented.

Given this simulation environment, the AVANTI SW receives realistic inputs. Moreover the interfaces to the simulator allow sending the required TCs to AVANTI. Finally, the data stream produced during each run is assembled according to the TM structure.

The simulation scenario discussed here mimics the initial phases of the AVANTI experiment, immediately after that the FDS achieves the experiment initial conditions at the completion of the picosatellite in-orbit injection. Since at this stage the system is subjected to several uncertainties (e.g., true state conditions after the deployment, accuracy of the orbit determination with TIRA tracking data, delay and/or availability of the orbit determination via radar tracking) and since the relative navigation filter has to be initialized, this scenario represents a critical situation. Thus it can be used to assess the realist performance achievable by AVANTI at the far most end of its application spectrum.

The relative state is parameterized through a set of dimensional ROE (i.e. $a\delta\vec{\alpha}$, being *a* the mean semi-major axis of the servicer satellite), as defined in [17, p 21]. The components of such state vector are:

- $a\delta a$, relative semi-major axis. This measures the drift between the two spacecraft and maps into a shift in radial direction in the local RTN frame.
- $a\delta\lambda$ mean relative longitude or, alternatively, $a\delta u$ relative mean argument of latitude, complete the set and provide the mean separation in tangential direction.
- $a\delta e_x$ and $a\delta e_y$, respectively x and y components of the relative eccentricity vector, whose magnitude $a\delta e$ and phase φ identify the amplitude of the in-plane oscillation and the perigee of the relative orbit respectively.
- $a\delta i_x$ and $a\delta i_y$, respectively x and y components of the relative inclination vector, whose magnitude $a\delta i$ and phase θ identify the amplitude of the out-of-plane oscillation and the ascending node of the relative orbit respectively.

According to the preliminary deployment strategy assessed in [11], the separation involves first the impulse imparted by the POD device, secondly a maneuver of BIROS to stop the outwards drift and to establish a proper phase separation of the relative eccentricity and inclination vectors. Nominally a stable formation with respectively 590 m and 400 m of magnitude of the relative eccentricity and inclination vectors is planned. Moreover, since the separation has to occur during a predefined ground contact, θ is about 88 deg and due to the passive safety requirement φ is nominally 268 deg. By letting the BIROS maneuver take place half orbit revolution after the picosatellite ejection, the mean relative longitude at completion of the deployment amounts to circa 6200 m, with picosatellite leading the formation in flight direction.
A realistic initial condition for our scenario can be selected taking into account the foreseen performance uncertainties of the release mechanism. Safety and radar tracking conditions require the unavoidable residual drift to increase the relative separation, regardless of the magnitude and of the nature of the POD system's uncertainties. Thus the actual drift-stop maneuver only reduces the drift imparted by the release mechanism. Referring to [11], in the case that the spring provides an actual impulse definitely smaller than the nominal one, a residual drift corresponding to a relative semi-major axis of -50 m can be assumed. The phase of the inclination vector remains almost the nominal one, since the error in the release-direction is negligible compared to the one in magnitude. Nevertheless the magnitudes of the in- and out-of- plane motions result smaller than the planned ones. Furthermore the final phase of the relative eccentricity vector cannot reach a 180 deg shift with respect to θ . By taking into account 24 hours of wait after the deployment completion for accomplishing the

radar tracking campaign and the subsequent orbit determination, $a\delta\lambda$ approximately reaches 12 km. The drift-stop maneuver performed by FDS brings $a\delta a$ close to zero and the following ROE set in meters is selected as *true* initial condition at the initial time t_0 of our scenario:

$$a\delta\vec{\alpha}_{true,t0} = \begin{bmatrix} -3 & 12000 & 153.9 & -422.9 & 12.2 & 349.8 \end{bmatrix} \tag{1}$$

At the start of the simulation (1) represents the relative state of the picosatellite with respect to BIROS. Then, the AVANTI SW is activated with the objective to reduce the mean along-track separation, and to establish an anti-parallel relative e/i configuration. Therefore the aimed relative state to be acquired at a certain final time t_F is chosen as:

$$a\delta\vec{\alpha}_{aimed,tF} = \begin{bmatrix} 0 & 8000 & 0 & -600 & 0 & 400 \end{bmatrix} \tag{2}$$

This formation constitutes a convenient starting point for a closer approach towards the picosatellite, having in the meantime refined the knowledge in the relative navigation. With respect to (1), the relative inclination vector is only slightly changed so that its phase is 90 deg and its magnitude is a little increased. This is motivated by the fact that configurations with $a\delta i_x \cong 0$ are convenient to reduce the mean effects of the J2 perturbation [17, p 35]. Moreover changing the out-of-plane motion is delta-v expensive and a magnitude of 400 m is compliant both with passive safety and with the camera field of view visibility requirements at 8000 m of mean separation. The magnitude of the relative eccentricity vector is increased to 600 m in order to provide some safety margin during the drift phase towards the client. The required relative semi-major axis determines a shift in radial direction thus reducing the minimum distance in the R-N plane.

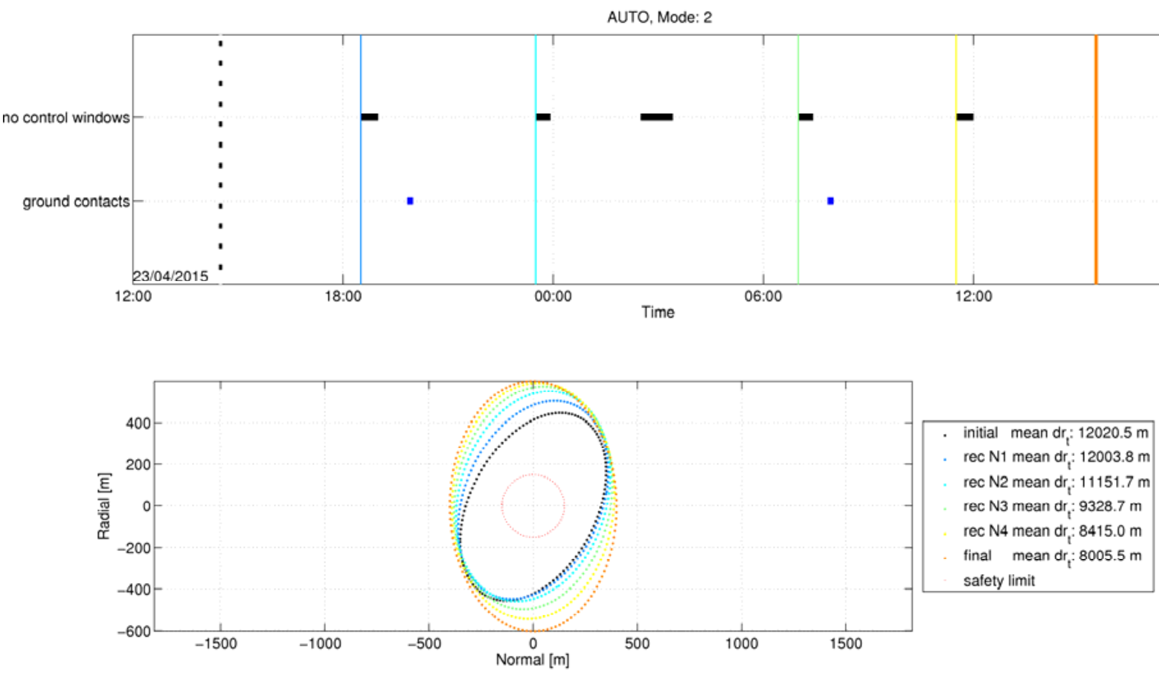

Fig. 5. *Rendezvous design: verification of the TCs to achieve the final relative state of (2).*

The TCs provided to MAP to achieve the final conditions (2) are visualized in Fig. 5, where (1) is assumed as initial state. According to it, the whole reconfiguration is covered in approximately 25 hours; initial time of the scenario t_0 and final acquisition time t_F are respectively marked by black-dashed and orange vertical lines in the top plot. Five intervals where no maneuvers can be performed (i.e., labeled as no control windows *ncw* in the top plot) are scheduled via TC. As mentioned in section C, these can also be used to force the planner to intensify the number of maneuvers and, in the same time, to obtain a gradual change in the required drift. Given such input, MAP schedules 4 intermediate reconfigurations to be achieved at the acquisition times marked in blue, cyan, green, and yellow. No intermediate step is planned between the second and third *ncw* intervals, since that time slot is shorter than 2 orbital revolutions. The corresponding delta-v optimal ROE sets are depicted in the bottom plot of Fig. 5. Here the projections in the R-N plane of the relative orbits corresponding to one revolution time of the optimal intermediate ROE sets starting from the prescribed acquisition times are plotted.

Moreover the legend reports the related mean separation in tangential direction at those times. Fig. 5 can be used to verify that a certain TC set steers the MAP SW to produce an approach compliant with the passive safety requirement throughout the time validity of such TCs. The passive safety limit is set equal to 150 m.

Fig. 5 shows also the presence of eventual active ground contacts in the mission timeline. Concerning our scenario, two 10 minutes contacts are scheduled at about 19:00 and 07:00 of the following day (i.e., labeled as ground-contact *gc* in the top plot).

Concerning the BIROS attitude, during the simulation the star tracker CHU-1 (i.e., boresight in the +X/-Y plane of the spacecraft body-fixed reference frame) is used and the COM is defined to let the camera frame being aligned with the local RTN frame throughout the whole approach. This choice is accomplished since at the beginning of the experiment the LOS computed onboard by AVANTI relies on a relative navigation still affected by the initial error. Furthermore at the tangential separations treated the relative orbit of the picosatellite safely fits in the camera field of view when keeping the boresight aligned with +T (i.e., direction known onboard from the AOCS system).

The initial conditions for ROD are also provided by means of TC. Regarding the AVANTI start scenario, a realistic value can be assessed referring to the expected accuracies of the TIRA tracking and of the subsequent absolute orbit determination. From [9] one can derive an order of magnitude of such error at the end of 24 hours, 3 to 5 contacts tracking campaign. Nevertheless, since within FireBird only 12 hours of tracking is foreseen, we assume a degraded performance. On top of this, a propagation error is included to take into account further 12 hours of delay as a worst case condition of occurrence of the first incoming up-link contact. This is in agreement with the assumption of 24 hours of delay with respect to the completion of the picosatellite deployment, introduced when setting the true initial conditions of the simulation scenario. Accordingly, the following error in meters with respect to the true initial state is employed as initial condition for the relative navigation filter:

$$a\delta\vec{\alpha}_{ROD,t0} - a\delta\vec{\alpha}_{true,t0} = \begin{bmatrix} -10 & -500 & +80 & -80 & +80 & -80 \end{bmatrix} \qquad (3)$$

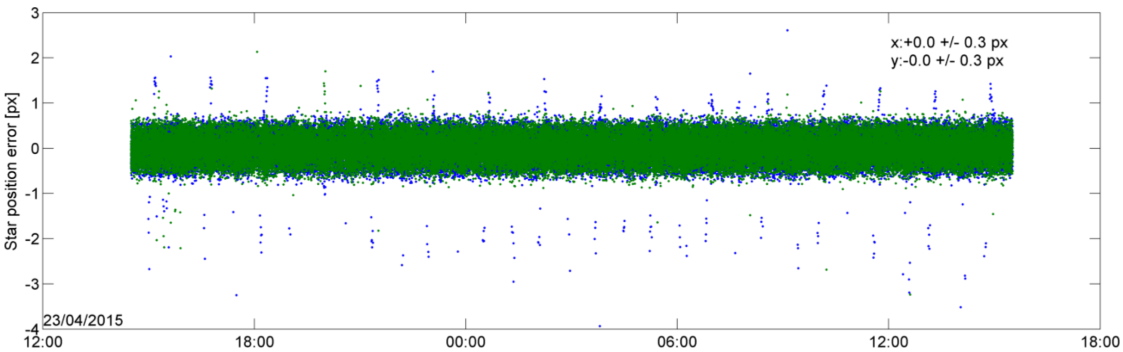

Fig. 6. *Centroiding errors [pixel].*

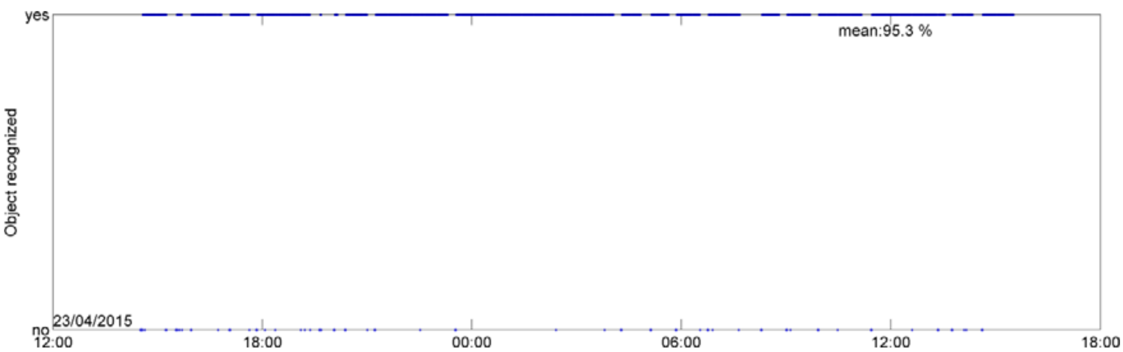

Fig. 7. *Success rate of the target identification function*

The simulated performance of IMP is summarized in Fig. 6 and Fig. 7. Overall of the centroids errors (compared to the reference positions of the celestial objects coming from the camera model used in the simulation environment) are better than the required accuracy (0.5 pixel). The success rate of the target identification algorithm is greater than 95% (Fig. 7). The data gaps on Fig. 7 are due to the fact that the servicer needs to rotate to execute a maneuver in along-track or cross-track direction or during ground contacts, loosing track of the target spacecraft during this period. When the target spacecraft is back in the camera field of view, the target identification algorithm needs to accumulate some observations to identify the trajectory, which explains why the target cannot be recognized immediately after a loss of visibility.

The simulation results of the ROD module are reported in Fig. 8, where the second component of the ROE state is represented by $a\delta u$. The true relative state is marked in red, whereas the estimated one is in black. The convergence process starts with the occurrence of the first maneuver. It can be noted that by the time the first intermediate ROE set is established (i.e., slightly before 18:00), the four executed maneuvers allowed the filter to converge. Thus the first maneuver plan update already benefits from an accurate knowledge of the relative state. After convergence, the magnitude of the navigation error throughout the simulation is respectively contained within 2 m in $a\delta a$, 5 m in all components of the relative eccentricity and inclination vectors, and 200 m in $a\delta u$.

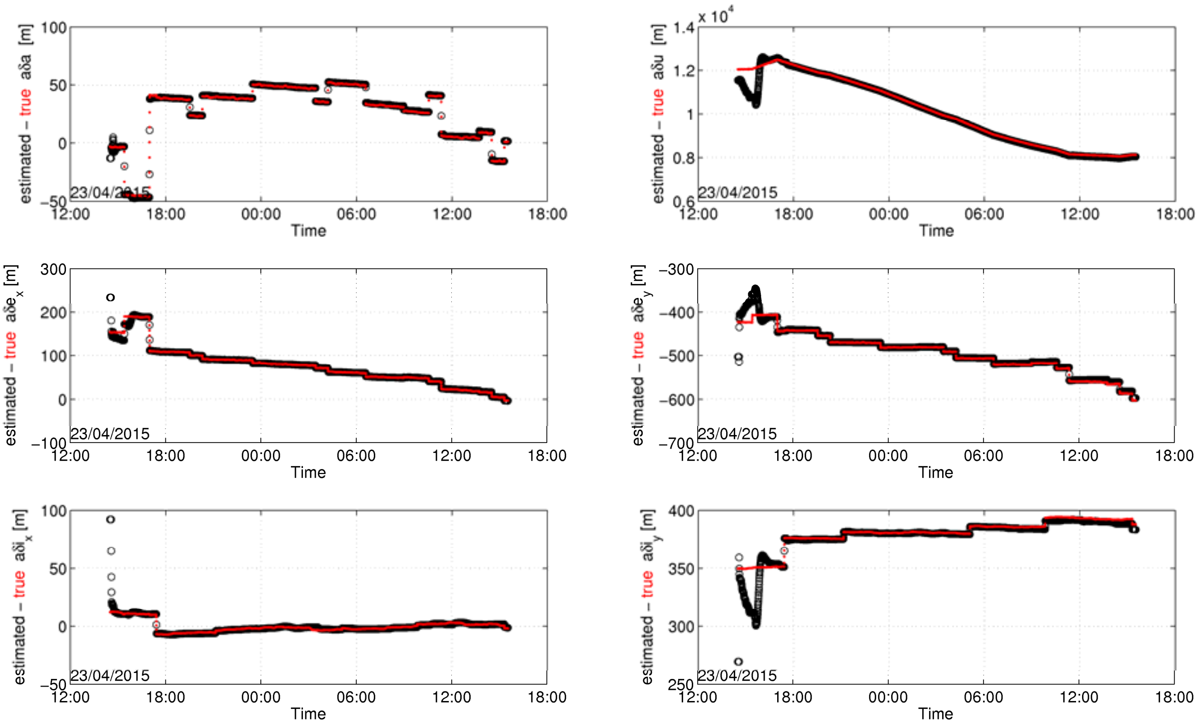

Fig. 8. *ROD results: estimated versus true trends of each component of the ROE state.*

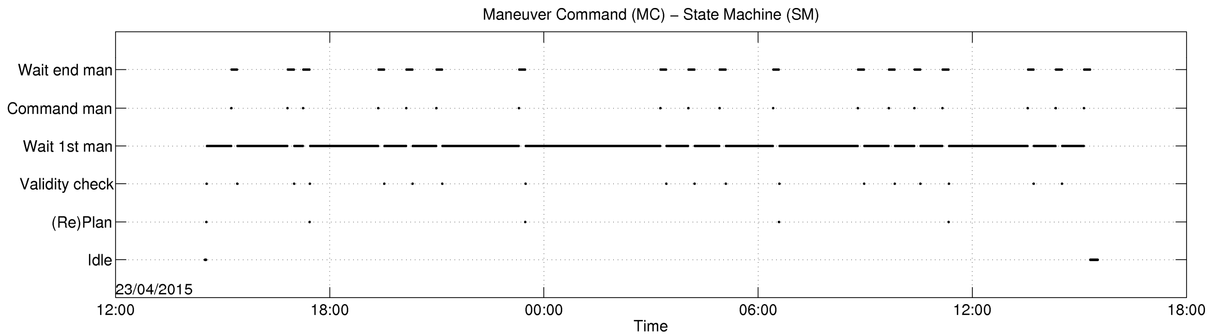

Fig. 9. *MAP results: state flow of the maneuver command state machine task.*

Fig. 9 and Fig. 10 show the behavior of the MAP module. Fig. 9 illustrates the state machine that regulates the maneuver planning task over the complete approach horizon. The maneuver open-loop plan is generated shortly after the AVANTI activation. Then, 4 plan updates are accomplished, after that the scheduled maneuvers' group to achieve each intermediate ROE is performed. At every re-plan the maneuvers' magnitudes and locations are refined, depending on the current estimated state and the remaining time to t_F . Within this simulation, a total of 18 maneuvers were performed with an overall commanded delta-v cost of approximately 0.234 m/s.

The attitude mode assumed over time during the simulation is shown in Fig. 10. As expected the default choice is COM, thus allowing the active CHU to see the client satellite. Slews to TFM mode are commanded prior to the execution of each commanded maneuver. BIROS remains in TFM mode until the AOCS system informs AVANTI that any thrusters' activity has been ceased. The delay between such information and the selection of a different attitude mode is settable via TC. Finally the EPM mode is selected prior to each scheduled active ground contact.

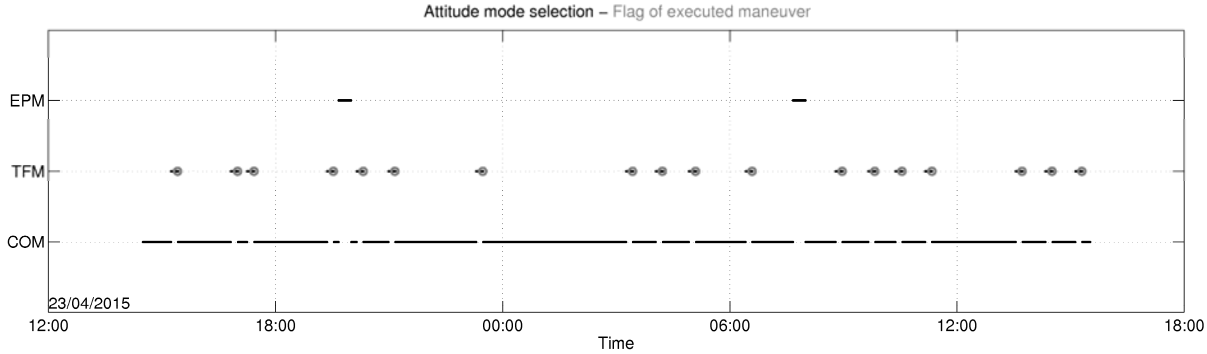

Fig. 10. *MAP results: selected attitude modes throughout the whole simulation.*

The overall control error is reported in Fig. 11, Fig. 12, and Fig. 13. The first two figures show the in-plane components of the ROE set, the last one presents the two components of the relative inclination vector, thus deals with the out-of-plane motion. In all these pictures the true state is plotted in black. The vertical gray lines identify the times at which a change in the values of the aimed ROE occurs. This happens at each re-plan (i.e., first four vertical gray lines) and at the end of the plan, since MAP remains in the *idle* state and no planned ROE are defined. Because the MAP algorithm solves sequences of end-time problems, the control accuracy shall be assessed at the end of each sub-reconfiguration, thus exactly at the times corresponding to these vertical gray lines.

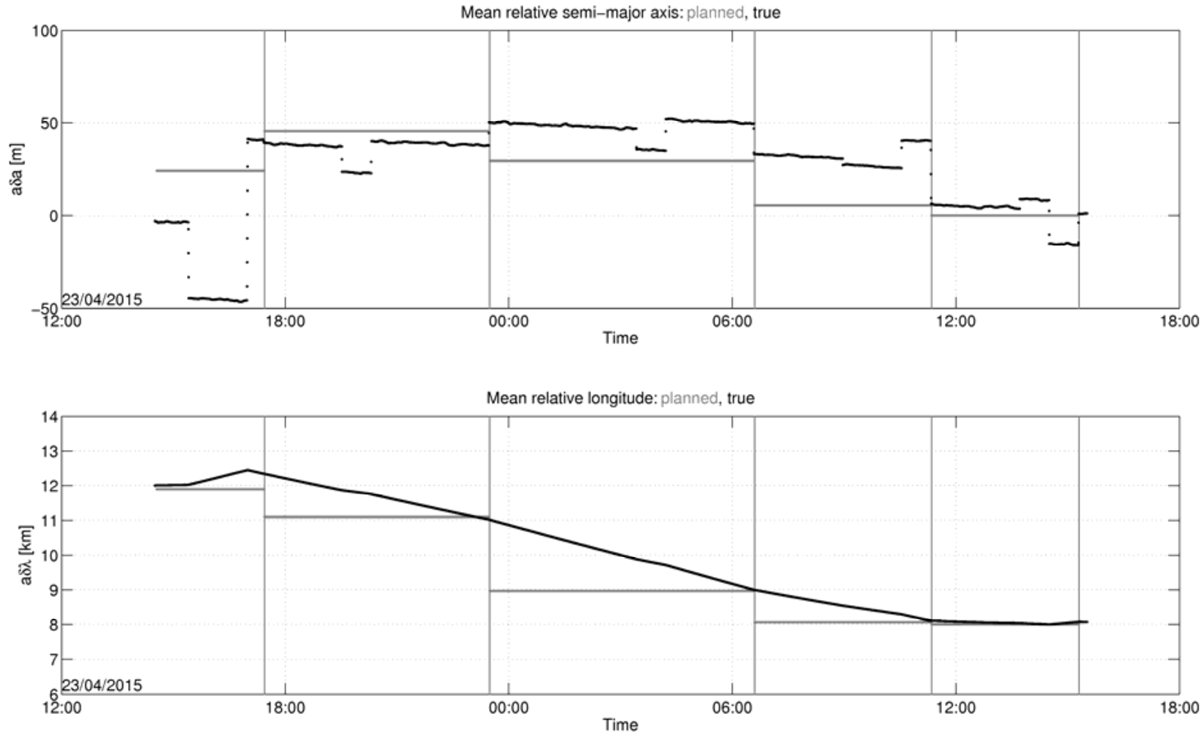

Fig. 11. *Control accuracy: true (black) relative semi-major axis (top) and mean longitude (bottom) versus the stepwise planned values (gray).*

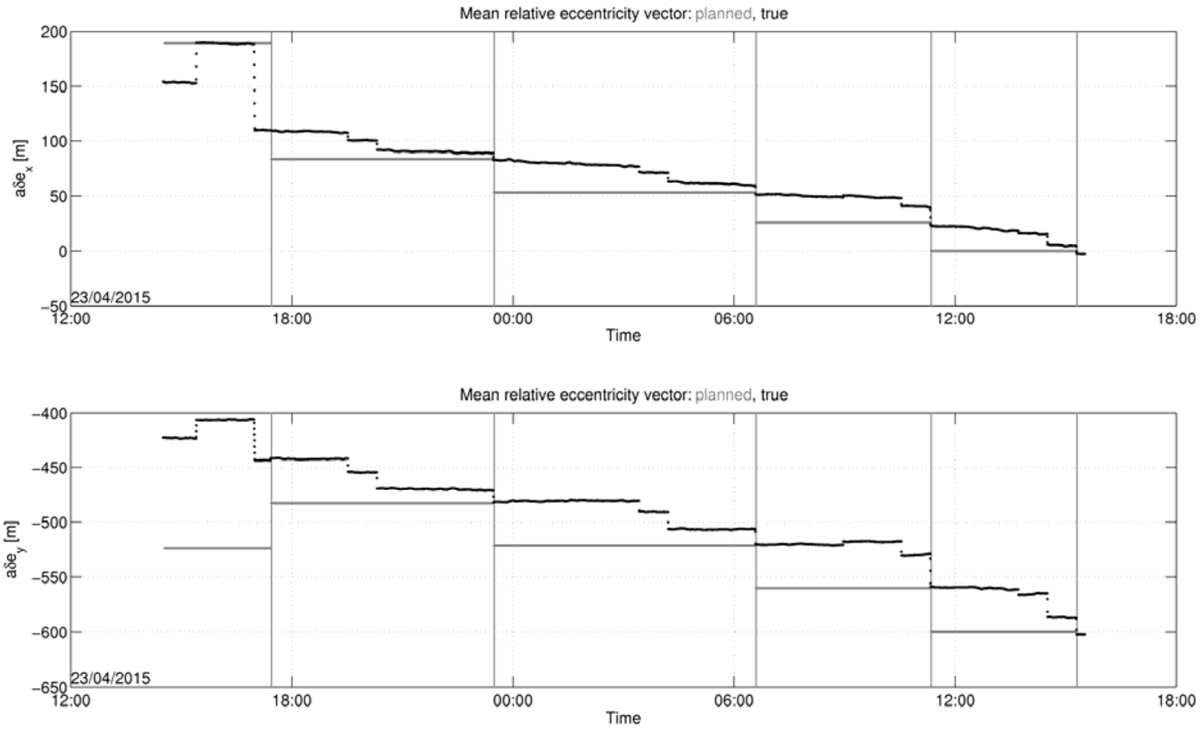

Fig. 12. *Control accuracy: true (black) relative eccentricity vector components versus the stepwise planned values (gray).*

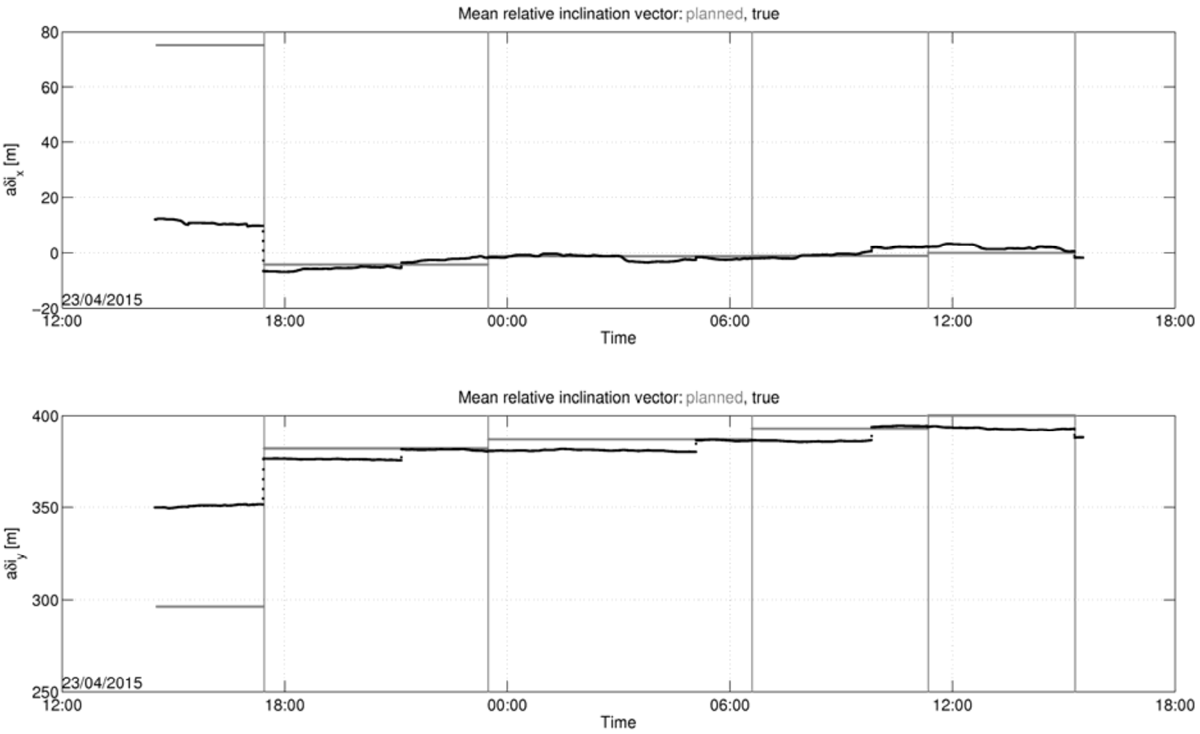

Fig. 13. *Control accuracy: true (black) relative inclination vector components versus the stepwise planned values (gray).*

Graphically this information is summarized in Fig. 14, where the last point corresponds to t_F and its reference state is given by (2). The first value of each sub-plot shows that the true state is far from the planned one. This is due to the fact that the plan was built from a badly estimated relative state (i.e., close to the ROD initial condition (3)), and the subsequent control error reflects such error in the navigation. As soon as the relative navigation filter converges, the magnitude of the control error is confined within 5 m in $a\delta a$, 15 m in the components of the relative eccentricity and inclination vectors, and 100 m in the mean relative longitude $a\delta\lambda$.

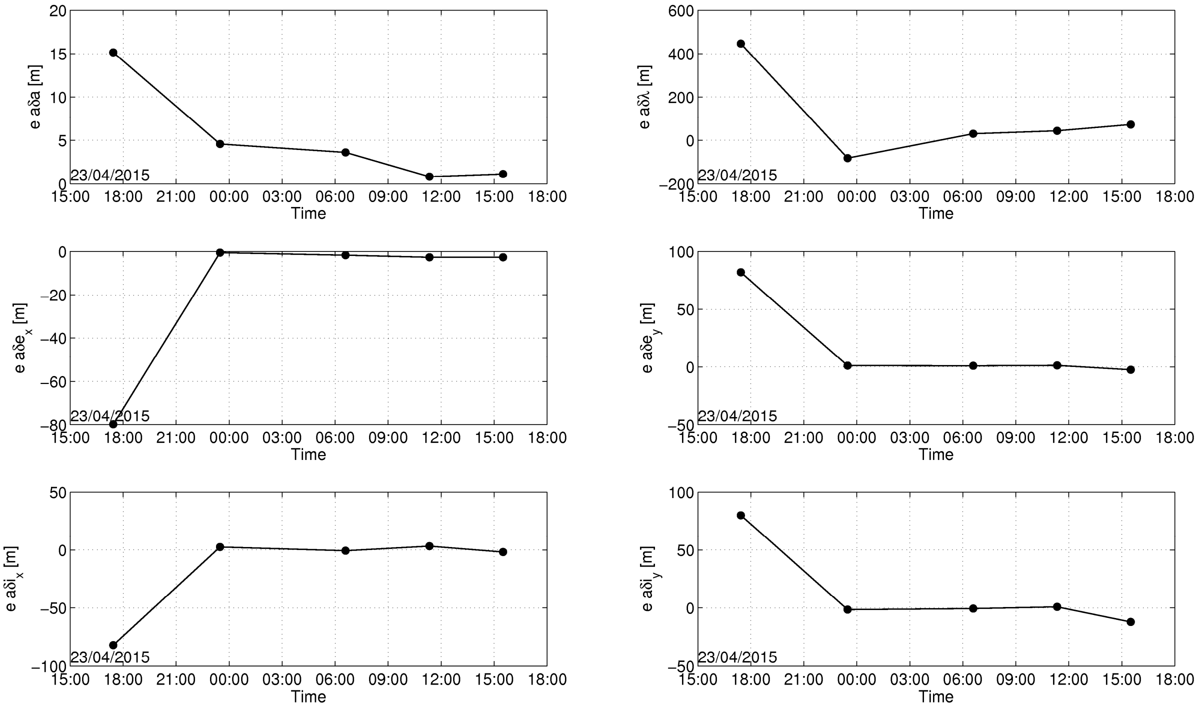

Fig. 14. *Control error at intermediate ROE acquisition times and at final time t_F.*

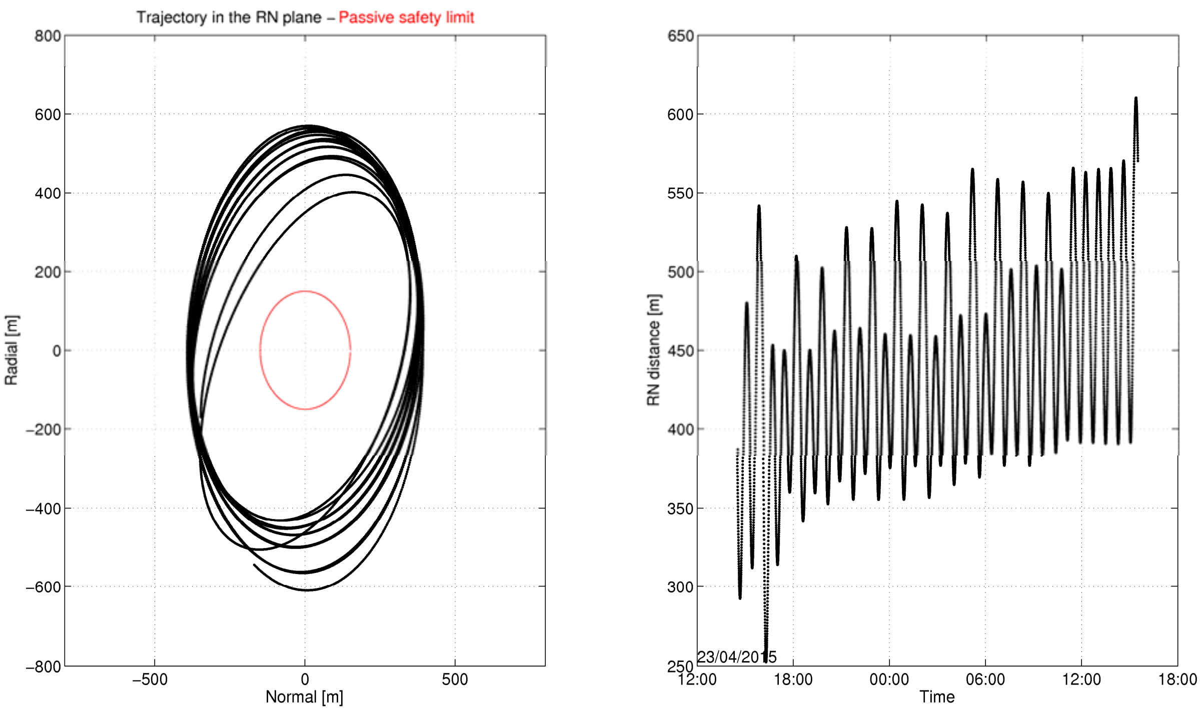

Fig. 15. *Passive safety: relative trajectory and minimum distance to the client in the R-N plane.*

To conclude, Fig. 15 allows verifying a-posteriori the fulfillment of the passive safety criterion.

5. CONCLUSION

This paper provided a description of the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment to be performed in the frame of the DLR FireBird mission.
Focus has been given to the explanation of the experiment's goals and concept. The space segment has been described, together with the main flight dynamics systems of the AVANTI software.
A simulation representative of the initial phases of the experiment has been discussed, in order to show the typical control accuracies achievable during the execution of AVANTI.
Current work deals with the refinement and the robustness assessment of the presented performances.

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