Optical navigation sensor platform for high accuracy formation flight spacecraft

John L. Jørgensen(1), Finn E. Jørgensen(1), Peter S. Jørgensen(1),Mathias Benn(1), Troelz Denver(1), Lars Timmerman(1), Raphael Rougeot(2), Daniel Serrano(3)

(1) DTU Space, Measurement and Instrumentation Systems, Elektrovej B327, Lyngby 2800 Denmark, jlj@space.dtu.dk, fj@space.dtu.dk, psj@space.dtu.dk, mb@space.dtu.dk, td@space.dtu.dk, ltim@space.dtu.dk
(2) European Space Research and Technology Center, European Space Agency, Keplerlaan 1, 2201 Noordwijk, The Netherlands, raphael.rougeot@esa.int
(3) Flight Systems Division, SENER AEROSPACIAL, S.A., Servero Ochoa, 4, 28760, Tres Cantos-Madrid Spain, daniel.serrano@aeroespacial.sener

Abstract

The ESA PROBA3 formation flying mission is designed to form a solar Coronagraph with a baseline of 150m. The mission consists of two free flying spacecraft which by means of high accuracy formation flight will form the largest science instrument of it class [2]. This paper discusses the design and performances of one of the navigation instrumentation which has been developed to enable the required formation flight with the required accuracy and robustness. The navigation instrumentation solution arrived at, possesses a performance envelop substantially larger than required, and will support a wide range of future formation flying missions. Several advanced features of the instrument suite is thus also discussed, e.g. non-cooperative rendezvous and docking, ultra-fast target detection and inter-satellite synchronization techniques.

PROBA3, a coronagraph mission

The study of the Corona of the Sun, the outermost region of the Sun's atmosphere, is difficult from observatories inside Earth's atmosphere, because of the intense light from the sun disk itself and its scatter in the atmosphere, relative to which the corona intensity is faint by several orders of magnitude - except on the rare occasions of full lunar eclipses. Space-borne corona observatories where a disk is used to mask out the direct sunlight from the sun-disk itself, Coronagraphs, are benefitting from the light scatter free environs, are only limited by their ability to limit edge diffracted light from the mask itself. Since the light diffracted from an edge is decreasing with distance as r^{-2}, as is the inner field vignetting, a large separation between the masking disk and the corona detector, imager, itself is desirable. These facts form the basis of the ESA PROBA3 formation flying mission, which will pave the way for other space-borne applications by getting the benefits of formation flying.

The PROBA3 formation flying mission [1] consists of two spacecraft operating together, in a mode where the one spacecraft, the Occulter or OSC, is placed at 150m from the other spacecraft, the Coronagraph or CSC, such as to precisely mask of the Sun disk as observe by the other spacecraft, the Coronagraph or CSC, in order to unveil the faint inner corona to be studied in full details by a scientific optical system. Additionally, the PROBA3 mission is designed to demonstrate in-orbit Formation flying maneuvers such as resizing from 25m to 250m, retargeting, roll, rendezvous experiment etc… All in-orbit activities of the spacec segments is fully autonomous, and ground intervention is nominally restricted to science commands.

Figure 1, The PROBA3 formation flight Coronagraph. The distant Occulter spacecraft mask the sun disk, enabling the nearby Cronagraph spacecraft to study the corona. Source ESA

To ensure long undisturbed observations, PROBA3 will be launched into a highly elliptic orbit, inclined such as to avoid the major part of the Van Allen belt ionizing radiation. The launch is scheduled to 2023 into a 600km x 60,500km 59deg inclined orbit, where the 19.6h orbit period, enables long, quiet and stable observation periods when near apogee. When approaching perigee, the formation is broken up, to enable intrinsic safe passages when close to Earth, after which the formation is reacquired when disturbance forces are again small.

The PROBA3 formation flight thus encompasses all elements of close, high accuracy, formation flight: Target detection, formation acquisition, formation maintenance, formation break up, and dilution.

These activities are challenging by the fact, that the Occulter spacecraft often will have to observe the Coronagraph spacecraft with the bright Earth in the background, and, that the Coronagraph will have to "observe" the Occulter with the Sun behind it. In the following, one of the crucial instrumentation designed to enable these operations are discussed.

The PROBA3 VBS instrumentation

The science requirements to the Coronagraph, is millimetric accuracy in relative position between the two spacecraft, at all times when in observation mode over the apogee arc, and safe, fast and reliable formation acquisition under all environmental conditions. Since the formation is operating well outside the region where GNSS is available, only optical navigation sensors can offer the required accuracies. Furthermore the relatively limited mass budget of 560kgs for the two space segments, put severe constraint to both thermal control and power usage, yet, the mission requires full redundancy for all navigation sensors. The navigation sensor instrumentation complex developed for the mission by the DTU-Space, a department at the Technical University of Denmark, has been optimized to meet and exceed these requirements.

To ensure robust formation acquisition, the navigation sensor package, is distributed such that potential solar blinding is eliminated. This is achieved by placing the optical navigation sensors, the Visual Based Sensor (VBS) units on the Occulter spacecraft, making this the chaser of the formation, and the navigation fiducials on the Coronagraph spacecraft, the mires, making this the target of the formation. In the following the terms Chaser and Target is thus used, to ease the description of the rather complex instrumentation suite.

Each spacecraft of the formation has a position and attitude, i.e. 6 Degrees of Freedom (DoF), in total 12, but since only the relative position is relevant for the formation, this reduces to 10 DoF, relative position (3), attitude of each segment (3+3) and since GNSS is not available, relative time between the segments (1).

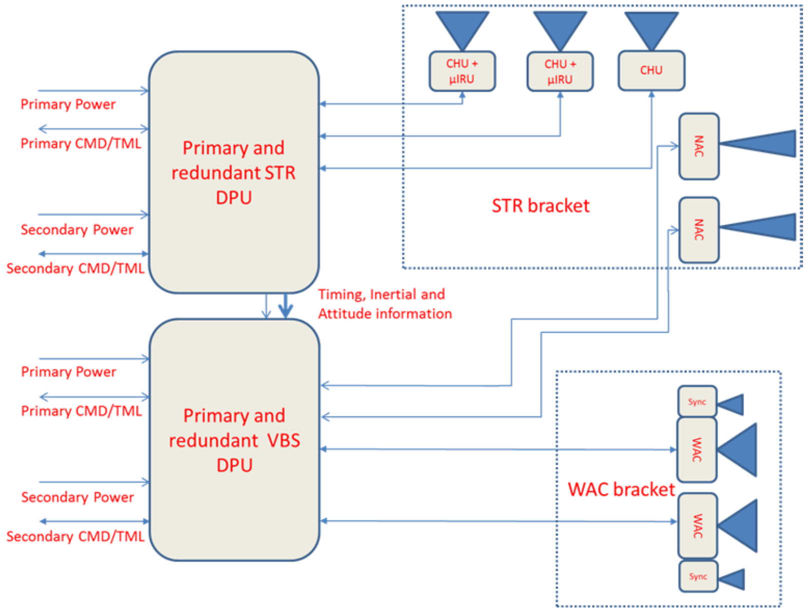


Figure 2, Block diagram of the VBS and STR components on the Occulter space segment, featuring three Star Tracker cameras with internal IMU sensors driven by a redundant processing unit (DPU), and a VBS system with two NAC and two WAC units and the ISM synchronization sensors, all driven by a redundant DPU. The STR DPU communicates timing and attitude information to the VBS DPU via a direct link, whereas all communication is by PUS standard via RS422.

The navigation instrumentation is thus designed to accurately determine these parameters in a timely and robust fashion. Both the Chaser and Target is equipped with triple star camera units of the microASC family, each of which also features a MEMS based inertial reference unit to recover the attitudes. The chaser is further equipped with a redundant set of Narrow Angle Cameras, NAC, and Wide Angle Cameras, WAC, which by observing the Target, can recover the relative position. While the NAC and WAC may be commanded to find the relative position without any help from the Target, i.e. in non-cooperative mode, the accuracy required, will need guidance from the Target, i.e. cooperative formation flight.

The Target thus features a suite of Mires in the form of small light emitting, the mire optical heads, MOH, placed as far apart as the Target spacecraft and other instrumentation allows. To enable more proximate operations, a special group of MOHs are included, to perform rendezvous and docking manoeuvers, among which one of them is elevated. In total 8 redundant MOHs are placed on the Target, on the side facing towards the Chaser in nominal operations.

Power and thermal constraints preclude operating the MOHs continuously, for which reason they are operated in pulsed mode, with 8 flashes per second, of a duration of 1-50µs. The pulsed operation also ensures minimal ageing of the MOHs, but more importantly, also allow for measuring the relative time between the spacecraft.

The two spacecraft communicates internally via a radio link, the Inter Satellite Link (ISL), the timing and data age of which does not allow for precise timing. The NAC and/or WAC, operating at a 4Hz cadence, may thus determine the time of the transmission of the light pulse from the MOHs on the Target by bifurcation. The 4Hz cycle, i.e. 250ms, is divided up into two 125ms sections, and an image from each interval is acquired. The image interval capturing the flash is then further subdivided into two identical intervals, and the process is then repeated until the exact window of the flash is established. Once the window is found, relative clock drift between the clocks of the two spacecraft is found by simple maximum power tracking by moving the window small amounts back and forth every cycle.

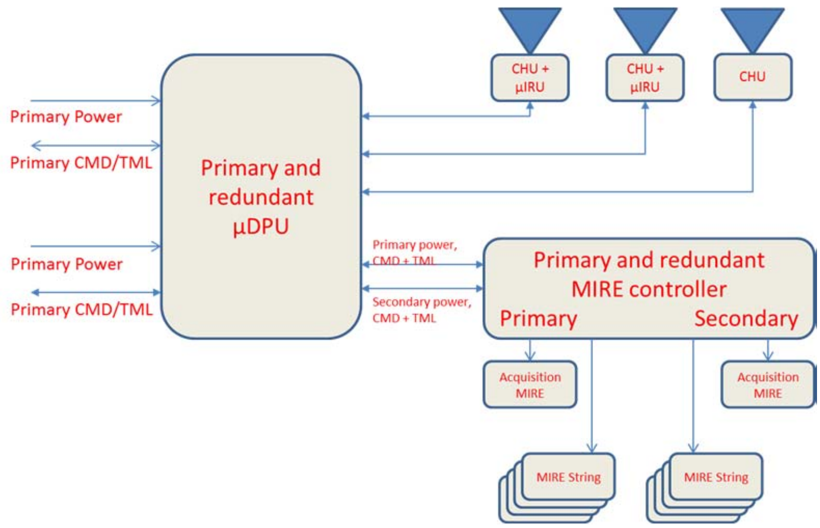


Figure 3, the STR and VBS elements installed on the Coronagraph space segment. The redundant DPU drives three Star Camera heads equipped with internal IMUs, and the redundant Mire controller, which in turn powers and operated the redundant set of MOHs and AMUs.

The aforementioned relative time determination is relatively slow, a few minutes, but worse, signal to noise does not result in robust operations, whenever the bright Earth is near the NAC and/or WAC Field of View (FoV). For this reason, and to allow for timing acquisition, also when the Target is outside the FoV of the NAC/WAC, a precision timing sensor dubbed the Integration Synchronization Module (ISM) [4], has been included on the Chaser, and a redundant Acquisition Mire Unit (AMU), on the Target. The AMU, operating at 4Hz but shifted out of phase of the MOH flashes, transmit a Hamming coded light pattern which is detected by the ISM with microsecond accuracy. The signal strength from the AMU is sufficient to allow reliable detections at large ranges, several km, also when bright Earth is in the FoV. The AMU/ISM is thus the primary relative timing acquisition sensor, and ensures that the NAC/WAC units are perfectly synchronized to the MOH flashes, in less than a second when formation acquisition is attempted.

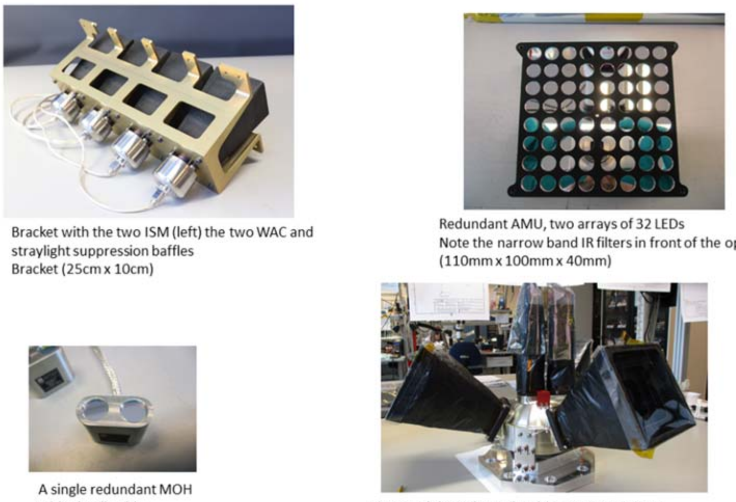
VBS operations in orbit

PROBA3 is launched in stacked configuration to avoid excessive dilution of the formation, and will remain in this configuration until full system verification of the stack has been achieved. Just after separation from the launcher, the µASC star tracker unit is powered on, and will 6s later start to deliver angular rates based on the inertial gyros in the star trackers, and star based attitudes as soon as the angular rate drops below 4deg/s.

After rate detumbling, the optical sensors are performing the post launch checkout and calibration. The three star tracker units will determine and validate the pre-launch internal attitude transfer matrices, and the NAC and WAC units transfer matrices are determined by co-registering the star based attitude of the stack to that of transiting brighter stars or planets through the FoV of the NAC and WAC respectively. Once post launch validation has been achieved, the Chaser and Target may be separated, and full operations may commence.

A typical orbit will then see the sequences of operations:

The formation is broken by a first delta-v, when the disturbance forces from the approaching Earth becomes noticeable, typically 4h after apogee. At this time, the two space segments will be brought to have the segment with the largest ballistic coefficient some 200m forward along their common trajectory to avoid potential collisions near perigee, where the spacecraft often is out of contact with Earth. Throughout, at least one µASC star tracker will have unobstructed view of the celestial vault granting star based attitudes, unless the otherwise unobstructed tracker, happens to have the other space segment in the FoV, in which case, the attitude will be based on the fused inertial solution from the three star tracker units. Since this IRU attitude is constantly autonomously bias corrected, whenever a star based solution is available, the spacecraft may operate virtually bias-free for tens of minutes. Near perigee, the onboard GNSS receivers have an excellent signal resulting in a small DOP enabling accurate post perigee positioning modelling, using relative positioning algorithms.



Bracket with the two ISM (left) the two WAC and straylight suppression baffles
Bracket (25cm x 10cm)

Redundant AMU, two arrays of 32 LEDs
Note the narrow band IR filters in front of the optics
(110mm x 100mm x 40mm)

A single redundant MOH
with pigtail cable
30mm x 18mm x 30mm

The OSC (Chaser) cupola with 3 STR cameras w baffles, and the two NAC center

Figure 4, Photos of the FM units showing the linear bracket hosting the WACs and ISMs, the AMU and 1 MOH, as well as the Chaser cupola with star trackers and NAC units.

Once, on the outbound leg disturbance forces are at an acceptable level, the formation is going to be reestablished thanks to a second delta-v. It aims bringing the two spacecraft close to optimal position, i.e. near the desired line of sight, and near the desired distance. When approaching this situation where the propagated relative position from perigee is used, the AMU and ISM will first establish synchronization, and the WAC units will be able to locate the Target in their FoV. At more than 100m distance, the WAC is not capable of delivering accurate pose and position of the Target, but will deliver an accurate pointing direction. This direction is then used to rotate the Chaser such that the Target is fully inside the NAC FoV.

Once the NAC has a full view of the Target, it will deliver a 6DoF pose and position solution, which may be used to fine tune the configuration as desired, however as discussed later, the 6DoF is only accurate to the level of 2cm in the science configuration. The star based attitude of the Target is now transmitted via the ISL to the Chaser and forwarded to the VBS unit, together with the star based attitude of the Chaser. With accurate relative information, the VBS may now perform a calculation of the relative position, 3DoF, with full accuracy. I.e. the Coronagraph reacquisition has been achieved.

For the remaining part of the orbit, the Coronagraph formation is maintained with full accuracy, until it is again time to break up the formation.

It is important to note, that the µASC/VBS instrumentation complex have a substantially larger performance envelope than required. This has been implemented to ensure safe return to science operations from anomalies. E.g. in case of a large dilution of the formation, a star tracker unit is capable of, autonomously, detect and track the other space segment at distances above 1000km, the ISM-AMU effectively will synchronize the spacecraft at distances up to 10km, the WAC and NAC operates with shutter times in the µs range giving motion and oscillation free imagery also during thruster firing, and the built in IRUs handles angular rates up to 100deg/s and precise acceleration levels up to $12m/s^2$.

STR and VBS design and performances

For PROBA3, the three star tracker cameras are located on a Cupola which has been designed for minimum thermo-elastic distortion over the operational range for the mission. The Cupola is mounted directly on the optical bench hosting the Coronagraph science instrumentation and protruding on the side of the spacecraft pointing away from the Sun in nominal operations. This placement, ensures low operations temperatures, typically -80C, except from the shorter perigee passages where the temperature may rise some 30K.

On the Chaser, again for maximum accuracy, a similar Cupola also hosts the NACs in addition to the three star tracker heads. This design has been adopted, to give best possible stability in science operations. Each star tracker head, delivers an attitude accuracy better than 2arcsec over the full thermal range in the units pointing direction and about 30arcsec about boresight. To avoid communal blinding of multiple star trackers, their boresights are pointed away from the NAC, and the Target, clocked 120deg about the NAC axis. By combining the attitude from two or all three star trackers, an attitude accuracy of 1.5 arcsecond over the full temperature range, and sub-arcsec precision in all three DoF. I.e. in nominal operations, the NAC will be pointed towards the Target with an attitude knowledge well below 1 arcsec. The NAC, operating on well-formed Mire targets, has a centroiding accuracy of 500milliarcsec.

At 150m separation this configuration, and using e.g. 5 MOHs, theoretically result in a lateral position solution noise accuracy of 300µm and a range accuracy better than 2mm, in the 3DoF mode (in the NAC measurement reference frame, excluding bias). In 6DoF mode, the lateral accuracy is maintained, but the range accuracy is impacted by the poor estimation of the Target pitch and yaw attitude components inherent in all optical measurements from flat targets.

The AMU is made up from an array of 32 high-power infrared LEDs with a center wavelength of 740nm at room temperature, and each MOH feature 1 similar LED. A special issue arises from these units being located on the Sun facing side of the Target. In science operations, some of the MOHs and sometimes the AMU will be exposed to full sunlight, whereas others will be in the shadow of the Chaser. Since LEDs change center wavelength with temperature, they have to be protected from a to large temperature difference, to limit the in band wavelength span. This has been achieved by fitting each LED with an optical bandpass filter just wide enough to allow the light from the coldest and hottest LED to pass. A similar filter is then used on the NAC, WAC and ISM to suppress out of band light to the highest possible level. This, in turn, result in that these optical units operate in a monochromatic fashion, enabling well-formed point spread functions over the huge thermal operations range.

The ISM benefit from this bandpass filter, effectively reducing Earth albedo and thermal emissions to 5%, granting full performance even with its 14deg detection cone. The ISM S/N is further increased by the frequency bandpass enabled by the short pulses transmitted by the AMU, and yet further by the Hadamard coding used to achieve high accuracy timing. The ISM also features an autonomous signal bias compensation, common to all optical detection systems operating with DC suppression.

Extended operations features

The navigation sensors designed for PROBA3, features several advanced features which, not being part of the nominal operations plan will be verified in separate test setups.

One of these is the extended range capabilities supported by the design. If desired, the mission may let the space segments drift apart to very large separations, upon which the sensors allow for fast and reliable formation recovery using the following procedure: The Target is detected as a non-stellar object, a procedure already employed on several missions using the µASC [3], resulting in accurate line of sight knowledge to the target and a measurement of the apparent brightness. This method is useable at distances up to 1000km for a spacecraft with the properties of the Target, and will continue to operate until the Target can be handed over to the NAC at 10km. Similarly the docking MOH pattern will allow the two spacecraft to approach to distance of a few meters, as long as the docking pattern is kept inside the FoV of one of the WAC's.

The AMU/MOH design also supports non-cooperative tracking, at several different levels. The VBS features, besides the MOH model used to derive the 3 and 6DoF solutions, also a full optical model of the Target. If desired, the VBS may be commanded to only use the monochromatic image of the target to derive pose and position, which will be delivered at a cadence of 1Hz. However, since the inherent accuracy of such pose and position solutions are less accurate, and susceptible to mutual shading effects, a special test mode has been included: Using one of the redundant instrument suites in the high accuracy cooperative mode, as nominal, the other redundant instrument suite may be operated in non-cooperative mode, simply by commanding image acquisition to be out of phase with the short AMU/MOH flashes. Even though this operation will not affect nominal science, this mode will only be activated when special approach and recede manoeuvers are planned.

The µASC features a full heritage radiation monitoring capability, where penetrating radiation is detected and reported to ground. This feature is presently used to measure and characterize the radiation belts of Jupiter (Juno) and Earth (Swarm and MMS).

Conclusion

The STR-VBS navigation instrumentation designed for PROBA3 will enable fast, reliable and accurate formation acquisition, and flight. Because of the relative small size and mass of the solution, this instrument suite, will enable a wide range of formation flying missions in the future. Furthermore, the extremely robust acquisition of the Target spacecraft, may be attractive for a further range of missions, e.g. astrophysical spacecraft requiring pointing knowledge, e.g. if the LED of the AMU is changed to a pulsed laser, an identical instrumentation can immediately locate another spacecraft at millions of km separation.

PROBA3 is a project managed by the European Space Agency. The mission is being developed by a large consortium led by SENER Aerospacial as Prime.

References:

1) Galano, D., D. Jollet, K. Mellab, L. Penin, J. Ramon Villa, R. Rougeot, and J. Versluys (2019). “Proba-3 Precise Formation Flying Mission”. In: 10th International Workshop on Satellite Constellations and Formation Flying
2) Galano, D. (2018). Development of ASPIICS: a coronagraph based on the Proba-3 formation flying mission. SPIE proceedings. Doi: 10.1117/12.2312493
3) Benn, M. et al. “Observation of interplanetary dust by the Juno magnetometer investigation”. In Geophysical Research Letters, 44, 10 p. 4701-4708. Doi:10.1002/2017GRL073186
4) Benn, M. et al. *Optical Synchronizing Formation Flying Space System bu Optical Integration Synchronization Module,* Small Satellite Systems and Services Symposium, 2022