Optical Synchronizing Formation Flying Spacecraft Systems by Optical Integrating Synchronization Module

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1 Abstract

ESA's mission Proba-3 consist of two space segments, the Coronagraph spacecraft and the Occulter spaceraft operated at a distance between 25m and 250m, and co-aligned to the sun direction. In addition to in-orbit Formation Flying demonstration, one science objective is to achieve science observation of the Sun's corona close to the solar rim at a specific inter-satellite distance of 150m. This configuration creates challenging illumination conditions for optical instruments which are needed to control the Formation at various operations scenarios, e.g. when cameras on the Sunwards Occulter are pointed to the Coronagraph, with the fully sunlit Earth in the background. To achieve robust and reliable operations of these cameras, high accuracy and robust relative timing information between the spacecraft are required. The solution developed for Proba-3 is the topic for this work.

The Vision Based Sensor (VBS) extension of the micro Advanced Stellar Compass (µASC) enables general optical rendezvous and docking navigation capabilities in-between formation flying satellites – in both cooperative and non-cooperative modes. The robustness of the cooperative pose and position determination method by the VBS system rely on high accuracy synchronization between the camera system, located on the observing spacecraft, and the pulse-powered LED mires, located on the target spacecraft.

In order to achieve high accuracy synchronization in between satellites, an optically based Integrating Synchronization Module (ISM) and an Acquisition Mire Unit (AMU) have been developed. The AMU transmits a Hadamard based coded light pulse sequence using an array of LEDs. The ISM samples the incoming light by a band-passed photodiode followed by an amplification stage and fed into an FPGA, performing correlation matching towards the known coded pulse sequence of the AMU. This enables the ISM to determine the pulse train alignment with high accuracy, enabling the µASC camera system to synchronize the image capturing timing. The ISM and AMU are fully integrated with the heritage µASC system as plug-on peripherals to the existing camera port connections.

We discuss the design aspects of this system, outlining its performance envelope, and discuss the technology 's applicability to cover future space mission synchronization needs, e.g. Lisa, Starshade etc.

2 The Proba-3 Mission

The Proba-3 mission consists of two satellites: One Coronagraph Spacecraft (CSC) and one Occulter Spacecraft (OSC). The two forms the high precision formation flying mission, where the OSC will support the Coronagraph instrument on CSC by occulting for the centre part of the Sun.

Proba-3 will function as a technical demonstration mission, demonstrating acquisition, rendezvous, proximity operations, formation flying, at distances of 25m to 250m **Error! Reference source not found.**

In order to achieve formation flying capabilities, the OSC is equipped with stellar inertial attitude determination cameras using the μASC instrument (Refer to Section 3), which are in close cooperation with the pose and position determination Vision Based Sensor (VBS) system (Refer to Section 4).

The CSC is likewise equipped with a μASC for inertial stellar attitude determination. Additionally, in order to cooperatively support the VBS system with optical mire points, the CSC is equipped with 8 redundant Mire Optical Heads (MOHs) placed in a known pattern and are powered through the μASC DPU.

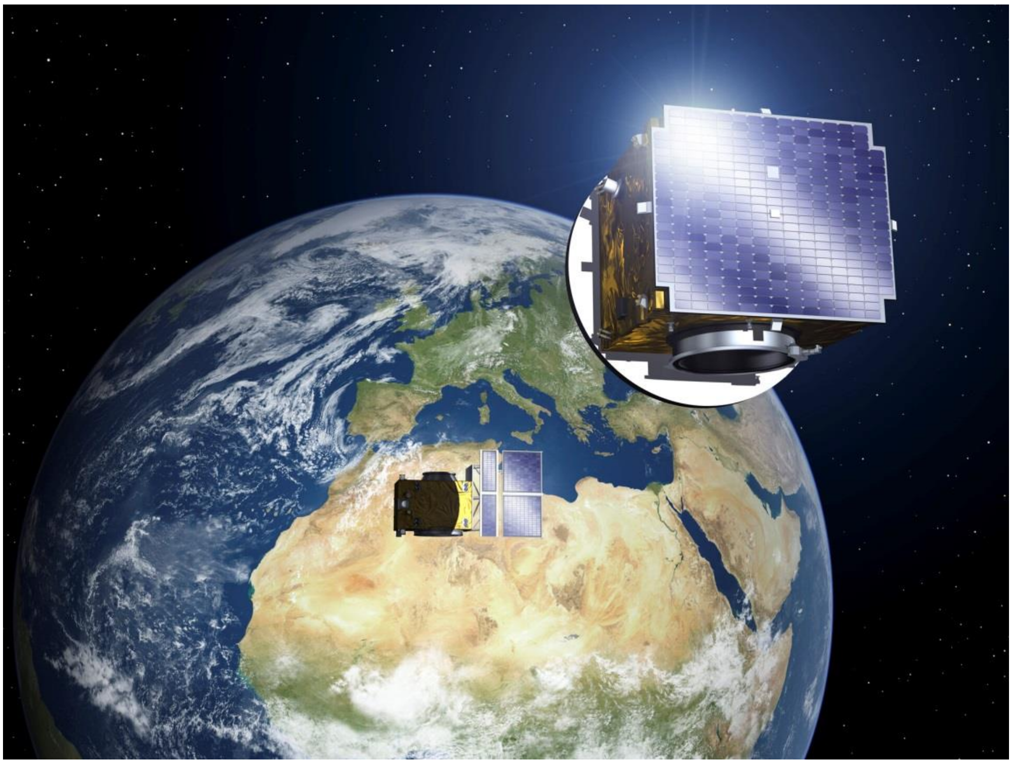

Figure 1: An artistic rendering of PROBA-3. CSC left, OSC right (Source:ESA)

3 Advanced Stellar Compass (μASC)

The μ-Advanced Stellar Compass is an optical navigation system, which is capable of providing attitudes based on detected stars [3]. For the Proba-3 mission, the stellar navigation is realized using three star tracker camera head units (STR CHUs) with a dedicated data processing unit (DPU). A set of three STR CHUs and a DPU is located on the CSC and another set is located on the OSC, providing each spacecraft with high accuracy stellar reference attitudes at a rate of 4Hz.

The OSC features an additional DPU with four dedicated CHUs, where the optical front-ends are modified for performing pose and position solutions of the formation flying satellites [4]. This system is referred to as the Vision Based Sensor (VBS) system (Refer to Section 4).

The µASC supports up to 4 CHUs and 4 peripheral units per DPU. The CHU types can vary based on the optical front-end in place. For the Proba-3 mission three different CHU types are in use:

- STR CHUs: Full bandpass in the visual spectrum, used for determining attitudes based on stars.
- VBS Wide Angle Camera (WAC): Relative pose/position navigation CHU with similar optics as the STR CHU including a bandpass filtering for optimal SNR of the MOHs
- VBS Narrow Angle Camera (NAC): Similar functionality as the WAC, featuring a longer focal length for long distance high precision relative navigation.

The available peripheral units are independent of the attached CHUs. For the Proba-3 mission the following peripheral units are:

- µIRU: Inertial Reference Unit sensors supporting the STR CHUs by propagate attitude solutions.
- ISM: Integrating Synchronization Module provides synchronization information from AMU.
- MICE: Mire Control Electronics handling the MOH and AMU units.
- D2D: DPU-2-DPU communication supporting attitude and synchronization information interchange in between DPUs.

Figure 2: OSC Cupola with three STR CHUs and two NAC VBS CHUs.

4 Vision Based Sensor (VBS)

For pose and position determination, the VBS DPU uses the WAC and NAC CHUs to locate the mire points on the CSC provided by the MOHs. Based on the known location of the MOHs on the CSC, all 6DoF of CSC relative to OSC are determined. Additionally, the attitude information provided by the CSC µASC can, via an inter-satellite link, be provided to the VBS µASC on the OSC. By having the attitude information of both OSC and CSC available to the VBS µASC, only 3DoF needs to be determined based on the optical detections of the VBS CHUs [1][4].

The MOHs on the CSC are pulse driven in order to optimize power yield, extend lifetime and limit power consumption. For optimal SNR, the VBS CHUs needs to integrate only during this pulse powering, and therefore needs to have synchronization knowledge for when this pulsing occurs.

For this, the optical synchronization modules, AMU and ISM, have been developed.

4.1 Acquisition Mire Unit (AMU)

The AMU of the VBS synchronisation system provides a coded light pulse sequence in a rate of 4Hz. The light source of the AMU consist of 32 LEDs with a wavelength of 740nm, powered in 8 separate strings which at standard configuration delivers a total radiated power of ~7.7W (500mA/string). AMU powering is controllable in steps of {62, 125, 250, 500, 1000, 2000} mA/string.

Each individual LED is equipped with an optical front-end in order to optimize the light yield in the desired direction. In Figure 3 and Figure 4 are the AMU hardware depicted, with the intensity distribution as designed for the Proba-3 specifications.

The coded sequence of the AMU light pulse is an extended Hadamard code sequences with low autocorrelation, which eases correlation matching for the ISM even at very low SNR.

Figure 3: Double AMU in Flight Configuration. Primary and redundant side in single mechanical structure.

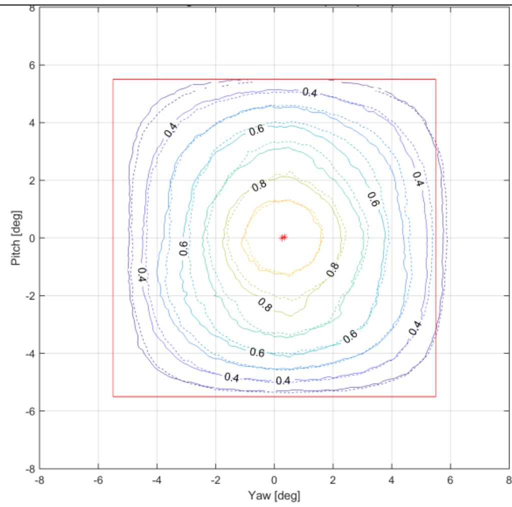

Figure 4: Relative intensity contours of the radiated light power distribution of the AMU.

4.2 Integrating Synchronization Module (ISM)

The AMU light pulse sequence is detectable by the integrating Synchronization Module (ISM). This sensor consist of a precharged photosensor with an optical front-end optimized for the wavelength of the AMU. The photosensor is attached to an EMI protected passive analogue front-end, which dampens exterior disturbances and noise sources. Hereafter the detected light level is passed through a programmable gain amplifier and sampled by an ADC. Both control of the detection train and the correlation to determine the Hadamard code in the photosensor signal, are all handled by a low power FPGA that interfaces to the μASC DPU. The correlator information are hereafter handled by the DPU that locates the 4Hz peak signal and aligns the CHU integration for MOH detection. The ISM detection train is depicted in Figure 5, which are all encapsulated in the mechanical housing provided in Figure 6.

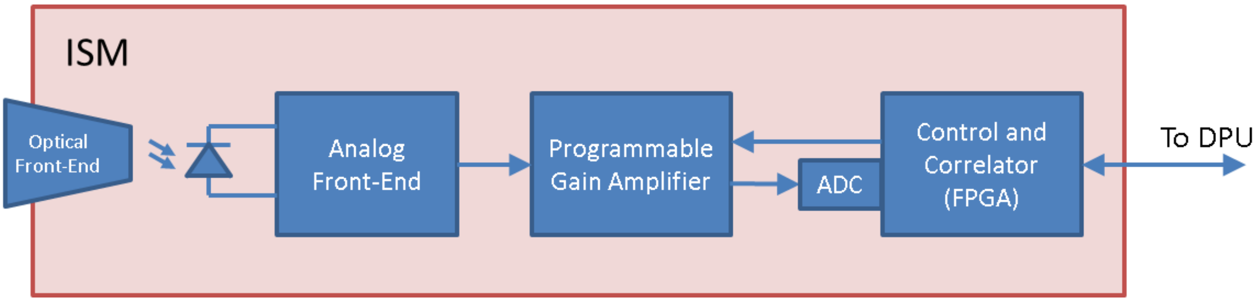

Figure 5: ISM Detection Train

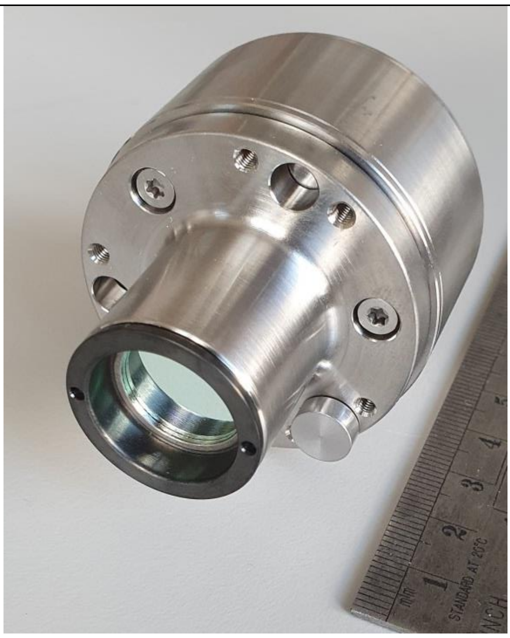

Figure 6: Integrating Synchronization Module housing.

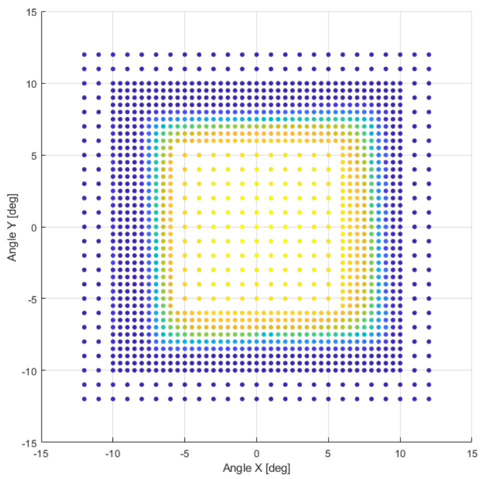

Figure 7: Relative sensitivity distribution for the ISM.

The designed chip length of the Hadamard code and sampling rate of the ISM detection train allows for a correlator peak determination <2µs in precision. In order to verify full system stability, an end-to-end test has been performed, comparing the PPS signal provided to the CSC DPU to the end result of the OSC CHU synchronization. Figure 8 depicts the synchronization stability to vary <18µs for the full end-to-end operation.

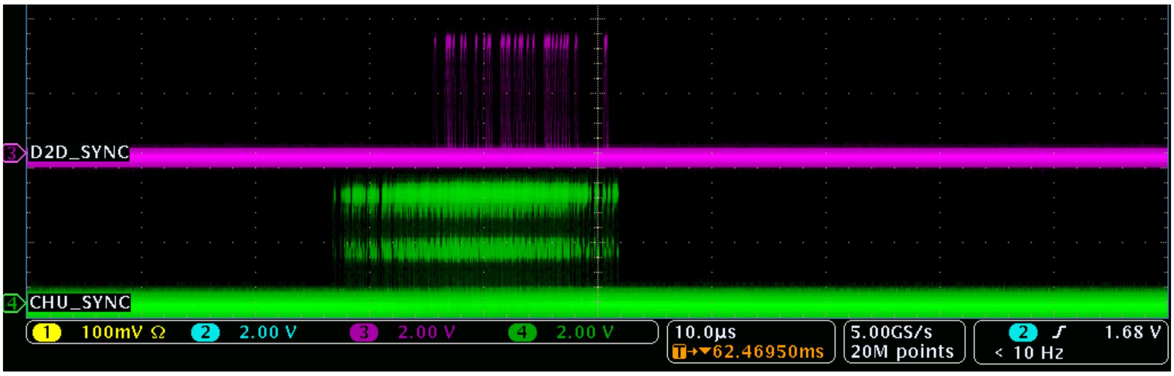

Figure 8.: End-to-end stability from PPS to CSC µASC to OSC VBS CHU sync signals

A 1km distance test of the AMU→ISM synchronization has been performed, realized between two mountain tops in full daylight conditions. Stable synchronization has been achieved over the test ranges provided in Table 1.

AMU current/string	Preamp off (default)	Preamp on
mA		
62	No lock	
125	Occasional lock	Stable lock
250	Stable lock	Stable lock
500	Stable lock	Stable lock

Table 1: AMU → ISM 1km range test results

5 Conclusion

The AMU and ISM combination has shown full operation from 10m to >1km in line-of-sight operation at standard operation configuration.

Multiple unique Hadamard codes are commandable to be used both for the AMU and the ISM, which enables the ISM correlator to distinguish between the different light pulse sequences. The AMU to ISM link is therefore capable of transmitting information over the optical link while keeping the primary functionality of synchronization intact, or service multiple transmitters/spacecraft.

The Integrating Synchronization Module will in combination with the Acquisition Mire Unit provide a stable synchronization between the CSC and OSC for the Proba-3 mission, even in challenging lightning conditions and at distances above the designed operational requirements.

6 Acknowledgement
Proba-3 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] Benn, M. (2011). *Vision Based Navigation Sensors for Spacecraft Rendezvous and Docking*. PhD Thesis, Technical University of Denmark.

[2] 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

[3] Denver, T., Jørgensen, J.L., Michelsen, R. and Jørgensen, P.S,. *MicroASC Star Tracker Generic Developments*, Small Satellite Systems and Services Symposium, Chia Laguna, Sardinia, Italy,25-29 Sept. 2006

[4] Jørgensen, J.L. et al. *Optical Navigation Sensor Platform for High Accuracy Formation Flight Spacecraft,* Small Satellite Systems and Services Symposium, 2022