18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 221

# Euclid's first year of science operations: Dancing with the unexpected

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## Abstract

The ESA Euclid satellite was launched in 2023, and it is meant to map the sky and reconstruct galaxy formation over the last 10 billion years. The activities of Euclid's Science Operations Centre (SOC) during its first year in flight departed from the ones originally planned during the mission development phase, mostly due to unexpected in-flight problems, but also to late requirements and needs to support a very stringent phase in terms of time and operational requirements for early mission characterization. All this added to a set of programmatic constraints that prevented the SOC to grow its operational capabilities as mitigation means, and to a design of science ground segment that was originally aimed to satisfy a simple and highly repetitive mission profile and not so much to what later demonstrated to be a varying and demanding period. This paper elaborates on a set of complexities found along the early phases of the mission, and how they were circumvented by means of flexibility and adaptability of a limited and skilled set of staff and technical resources, to achieve the current highly productive routine mission phase. It derives some conclusions on how to prepare science ground segments for the unexpected in future missions while not overdesigning or overstaffing them.

**Keywords:** Euclid, pointing, straylight, ice, planning, processing.

## Acronyms/Abbreviations

| | |
|---|---|
| AOCS | Attitude and Orbit Control System |
| ARES | Analysis and Reporting System |
| BAO | Baryonic Acoustic Oscillation |
| CCD | Charged Coupled Device |
| DPS | Data Processing System |
| EC | Euclid Consortium |
| EFC2 | Second ESTEC Frame Contract |
| ESA | European Space Agency |
| ESAC | European Space Astronomy Centre |
| ESOC | European Space Operation Centre |
| ESS | Euclid Survey System |
| ESTEC | European Space Technology Centre |

| | |
|---|---|
| ESTRACK | ESA Tracking Stations network |
| FGS | Fine Guidance Sensor |
| HKTM | HouseKeeping TeleMetry |
| ICR | Instrument Commanding Request |
| IDT | Instrument Development Teams |
| IOT | Instrument Operations Team |
| LE1 | Level 1 Data Product or Processor. |
| MOC | Mission Operations Centre |
| NISP | Near-Infrared Spectrometer and Photometer |
| OBCP | On Board Control Procedure |
| OSS | Operational Sky Survey |
| OU | Organisational Unit |
| PDC | Phase Diversity Calibration |
| PSF | Point Spread Function |
| PV | Performance Verification (phase) |
| QLA | Quick Look Analysis |
| ROS | Reference Observation Sequence |
| RSD | Reference Survey Definition |
| SAS | Science Archive System |
| SDC | Science Data Centre |
| SGS | Science Ground Segment |
| SOC | Science Operations Centre |
| SIS | SOC Interface System |
| SOST | Survey Operations Team |
| VIS | Visible Imager Instrument |
| WebMUST | Web Mission Utility & Support Tool |
| WL | Weak Lensing |

## 1. Introduction

### *1.1 Euclid Mission*

The European Space Agency (ESA) Euclid mission to explore the Dark Universe was launched on 1st of July 2023 and is designed to tackle fundamental questions in the study of the Universe, testing the nature of dark energy and dark matter [1] [2]. Its nominal mission consists of mapping 14000 deg2 of the extragalactic sky over six years [3]. It is equipped with a Korsch telescope with a 1.2-meter primary mirror and 2 science instruments: a visible imager (VIS) and a near-infrared spectrometer and photometer (NISP). From observations of billions of galaxies in imaging and hundreds of thousands of galaxies in spectroscopy, Euclid will derive the distribution of dark matter and test different theories of dark energy in the cosmological parameters. Stability and instrument performance is paramount to ensure that the data acquired along the survey is homogeneous and can be processed with the same level of quality: this is necessary to be able to use a sufficient number of galaxies for statistical analysis suitable to estimate the cosmological parameters that describe the Universe in a given theory.

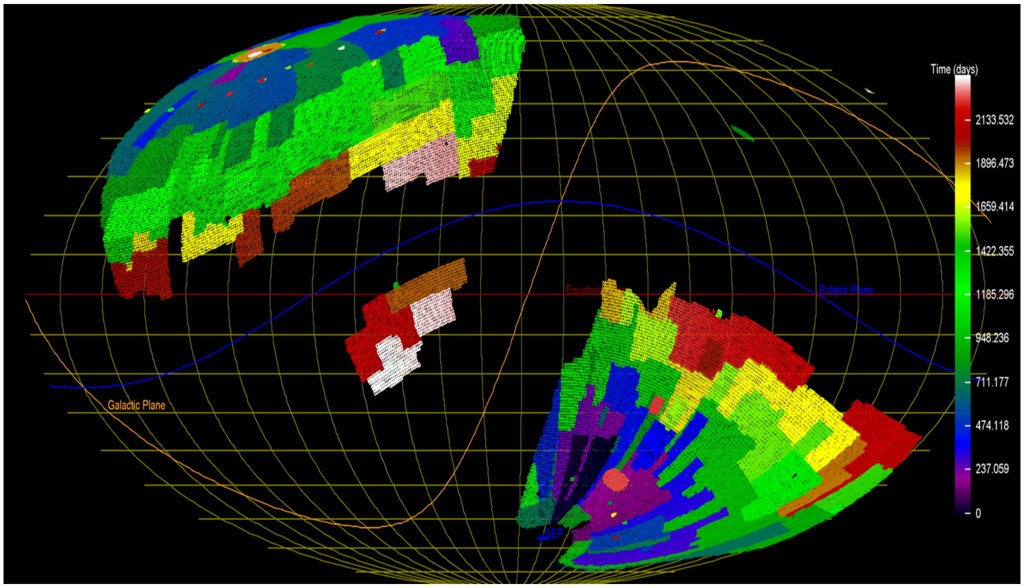

Figure 1 Euclid survey. Realization 2025A (latest available) shown in Mollweide celestial projection. The colour scale exhibits different times of observation. This realization of survey has a coverage of 13000 square degrees of extragalactic sky avoiding galaxy and equatorial planes. The survey is composed of almost 40000 scientific observing fields involving more than 150000 slews, to be implemented over 6 years. Plot extracted from the Ingestion and Analysis Report document.

Euclid combines several techniques of investigation, also called cosmological probes, in a very large survey over the extragalactic sky as seen in **Figure 1**. Among these cosmological probes, two of them play a major role in the Euclid mission concept and the instrumental approach: the Weak Gravitational Lensing (WL) and the Galaxy Clustering (GC; including Baryon Acoustic Oscillations - BAO). The WL measurements consist in observing the distortion in galaxy images, due to the deflection of light as it passes near foreground mass concentrations along the line of sight. GC stands for any 3-dimension statistical description of clustering and motions of galaxies as function of scales time, within an expanding Universe in which gravity (and dark energy) determine the growth rate of structures. It includes baryon acoustic oscillation (BAO). BAO is a series of wiggles generated in the early Universe and still visible in the matter power spectrum, which statistically describes matter distribution in scale and time. Individually, WL and GC are two powerful cosmological probes of the Dark Energy. In combination, they will enable control of many undesirable systematic effects and make it possible to break degeneracies in the parameter space that describes the Universe.

### *1.2 Mission operational set-up*

ESA and the Euclid Consortium (EC) jointly developed the Euclid Mission. ESA has the overarching responsibility for all aspects of the mission and for the fulfilment of the mission requirements and mission objectives. ESA was directly responsible for the development, manufacturing, integration and verification of a spacecraft capable of accommodating the VIS and NISP instruments, as well as the development, procurement, integration and verification of the Science Operations Centre (SOC) and Mission Operations Centre (MOC). The Euclid Consortium was responsible for the development and timely delivery of the two instruments, NISP and VIS, and for its support during integration and operations. The EC is also responsible for their part of the Euclid Science Ground Segment (SGS). Furthermore, the EC responsibility extends to the provision of ancillary ground-based photometric and spectroscopic data necessary to fulfil its cosmology objectives. Operations are conducted from the European Space Operations Centre (ESOC) in Darmstadt, Germany, hosting the MOC, and from the European Space Astronomy Centre (ESAC) in Villanueva de la Cañada, Spain, where the SOC is located. The SGS operations are distributed along Europe. The EC also provides two operational entities, the Survey Operations Team (in charge of generation of the Reference Survey Definition) and the Instrument Operations Team, that monitors and updates the instrument operations and calibrations. This set-up is shown in **Figure 2**.

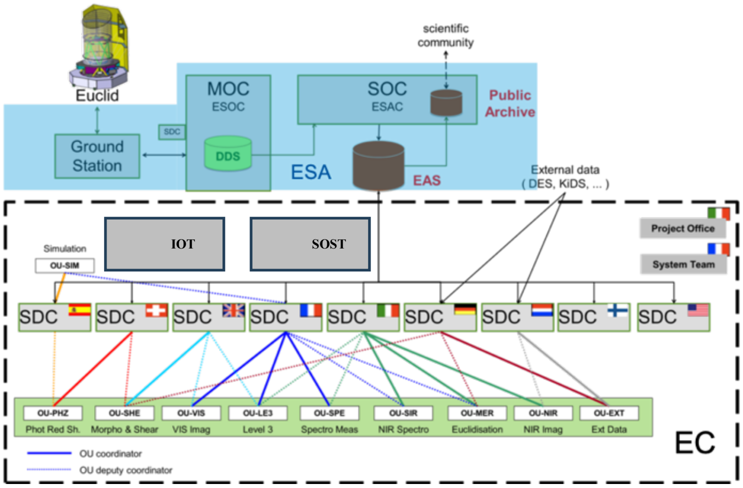

Figure 2 Euclid Ground Segment. Top blue area are the components provided by ESA, the bottom area is the Science Ground Segment involving the scientific processing of data, by Euclid Consortium. Data for processing is placed in the Euclid Archive System EAS Data Processing System (DPS) component, where it is assigned to an SDC.

The MOC conducts all mission operations of the spacecraft from LEOP to decommissioning, including telecomanding, acquisition of space data and mission safety. The SOC is responsible for the maintenance of the Operational Sky Survey, derived from the Survey Operations Team (SOST) inputs, together with Instrument Commanding Requests (ICR) from the Instrument Operations Team (IOT) to implement the routine calibrations. It issues the scientific planning schedule and elaborates and distributes the first level of science data out of the telemetry generated by the spacecraft, called Level 1 (LE1) data. The further elaboration of the data and the generation of the Level 2 and Level 3 science data is performed in the Science Ground Segment (SGS) by several data centres developed and operated by the EC. The SOC is also responsible for the operations and the maintenance of the Euclid Archive System with support and contribution of the EC.

### *1.3 SOC Operations*

The Euclid SOC started its work in 2013, with a small staffing to define interfaces, support mission project and design SOC system’s architecture. The design of SOC operations and its components was fully consolidated after the Mission Critical Design Review in 2018 and subsequent Ground Segment Implementation Review in 2019.

To better exploit the commonalities with the rest of the operations at ESAC, the SOC development and operations were moved to the second ESTEC Frame Contract (EFC2), profiting from the expertise from companies and consortia in archives, science mission’s uplink and downlink system development and operations. This started in ESAC as of the end of 2021. The EFC2 contract brought commonalities from other missions and areas, and more structured but also more rigid processes that were tailored for missions either in early development or well into operational phase. Euclid was the first mission that had to make use of the EFC2 support during critical mission phases such as commissioning and early performance verification operations.

The SOC main operational areas are:

- **Archive**, operating the Data Processing System (DPS) developed by EC and used for the orchestration of the SGS data processing and developing and operating the Science Archive System (SAS) to disseminate data to the science community in general. Both subsystems conform the Euclid Archive System.
- **Uplink**, receiving the Survey Definition implemented by SOST that realizes the scientific inputs and converting it first into a full survey operational realization, and later cut into monthly products to be sent to MOC indicating pointing and instrument activities [4].
- **Downlink,** receiving from MOC the science data in the form of Mass Memory files and the Housekeeping Telemetry (HKTM) and creating the entry products for SGS processing, the LE1 products, that are ingested into the DPS. The SOC also conducts a Quick Look assessment of the data [5].

- **Interface** coordination and operations configuration control, by means of implementing a Mission Operations Coordination Group that ensures that any change is assessed by all parties.

SOC's design assumed a reduced manpower from EFC2 service support and a design of systems based on the assumption of a mission highly repetitive and with fully automatized processing, very infrequent needs for data reprocessing and low mission planning cadence. To cope with the expected extra efforts of the early phases, an enhanced support (around 50% extra manpower) was requested to the EFC2 companies over 4 months following launch.

### *1.4 Mission phases*

A brief description of the early mission phases —as they were intended up to a few months before launch, or even as still considered immediately after it— is provided to better highlight what was changed by later operational considerations as described in subsequent sections [6].

### *1.4.1 Commissioning Phase*

Following launch, which took place on the 1st of July 2023 on a SpaceX Falcon-9 rocket, an early operations phase and a commissioning phase were scheduled, lasting 1 month in total and under full responsibility of the Project Team, and implemented by MOC with the support of Industry and Instrument Teams (still as part of the industrial component of the mission and named Instrument Development Teams, IDT). No SOC intervention was foreseen in the early plans, nor any request for data processing or archive originally required. Commissioning Phase comprised a set of engineering procedures intended to conduct the switch on of the spacecraft and instruments, place the mission on its halo orbit around the Lagrange-2 point, reach thermal equilibrium and conduct a functional characterization of nominal and redundant units, as well as perform the telescope focusing. No scientific objectives were sought nor specific science driven pointing was initially required. Target date for end of the phase was 3rd of August 2023.

### *1.4.2 Performance Verification Phase (PV Phase)*

This phase, delegated to SOC for its planning and coordination took inputs from the Instrument Operations Team and the Science Ground Segment. It was allocated 57 days, up to the end of September 2023, where the different instrument calibrations to be used during the survey, as well as others specific for this phase to characterize scientifically the instruments, were executed, and the processing of the Science Ground Segment as well as the generation of several calibration files was exercised. The data processing followed the nominal path to be used in operations (through LE1 products into the DPS) and the mission planning also followed the standard baseline, with SOC creating products for MOC, though without a baseline survey definition product. This phase involved not only specific instrument commanding and configuration but required pointing to targets on the sky that in some cases had restricted visibility and therefore imposed time constraints. The different blocks composing the PV had internal dependencies, thus not allowing to schedule the phase as any given combination of them. Finally, some of the activities had dependencies on the processing and evaluation of former data, thus requiring a green light from the SGS before further progressing. This phase was organized before launch into a 53-day schedule (plus margin of 4 days) of activities implementing the default realization.

### *1.4.3 Routine Phase*

Also known as Survey Execution, this phase was intended to start early October 2024. It was based on a Reference Survey Definition (RSD) that was provided by the Survey Operations Team. However, it was understood that the results of the PV phase could influence the realization of the survey (either changing the cadence of the periodic calibrations that interleave with the Wide Survey acquisition or by means of adding new ones or altering the ICRs that implement them). Therefore, it was assumed that a new survey would be in place as soon as early PV results would be available.

## 2. Commissioning phase

In this section we address several of the deviations and problems encountered during the commissioning phase, showing its impact on SOC operations.

### *2.1 Telescope best focus*

The original Commissioning Phase plan foresaw one month of technological tasks led by Project and MOC with collaboration from Industry and Instrument Teams, oriented to ensure the operability of the system and characterize the platform. However, relatively late before launch (end 2022) it was identified the need to support industry in the characterization and focus of the telescope.

Euclid telescope contains an M2 mirror that can be adjusted through a set of step motor actuators. Even though originally industry was fully in charge of this task, with some support of the VIS instrument teams, it was found that the processing and availability of the VIS images resulting of different focus status, as well as the identification of target fields with adequate star density, had not been fully considered, and SOC was asked to provide support. This implied the allocation of dedicated manpower to the task, and the development of specific processing chains (portable) to be used at ESOC, different from the nominal processing of the instrument raw data. Furthermore, it required dedicated analysis of pointing strategies and fields to support the focusing.

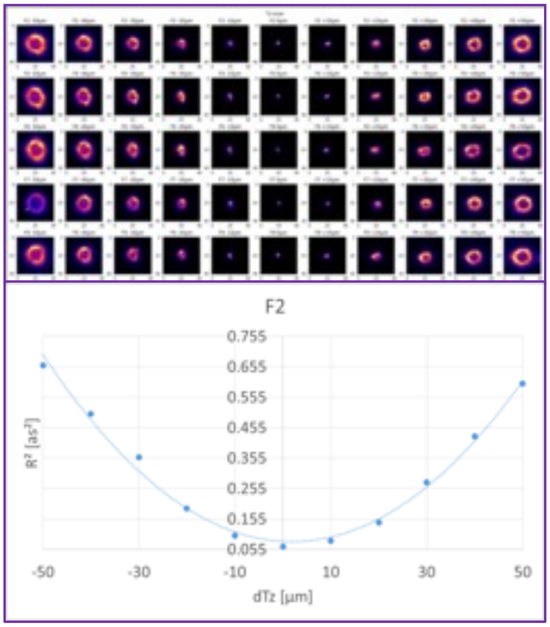

Figure 3 Telescope best focus including cut-outs of the sources under different focus status. Credit Airbus Defence and Space

The solution that had to be implemented was to design quicky and build a dedicated ad hoc best focus pipeline that could take the VIS images, conduct a basic processing on them (to correct for bias, reduce cosmic rays and perform source identification), and extract a set of cut-outs (see **Figure 3**) from them so they could be quickly provided in near real-time to Industry to support the best focus search. This pipeline was built, for redundancy reasons, both to be operated in a dedicated laptop but also making remote use of ESAC's Datalabs [7], that allows to run code over ESAC infrastructure next to the archive and the data. This last path was considered in the light of the need for very fast processing and return of the solutions and required dedicated routing across ESA firewalls. SOC was also asked to provide proposals for targets where the best focus search could be exercised. This required additional unforeseen efforts and script development.

While Industry was conducting the best focus search, SOC also shadowed this activity, to prepare any refocusing needs in the future nominal mission. All these tasks implied 2 persons physically collocated to the MOC for one week, working on a shift pattern.

### *2.2 Pointing selection*

The commissioning phase required preliminary assessment of the Euclid attitude and guiding system, and to validate the Fine Guiding System based on the same CCDs as the VIS instrument is made of. To do so, several fields with different density had to be identified, being SOC the only entity capable to select them and to provide the relevant pointing products to the MOC Flight Dynamics section in the agreed format. A set of unforeseen pointing support tools had to be derived and implemented within some weeks, with some requirements still being consolidated shortly after launch, that involved the capability to select sky regions from Gaia catalogue, estimate the right ascension and declination values and convert them to the spacecraft quaternions that are the required input to Flight Dynamics, ensuring coordination with the MOC, that was building the instrument activities to observe over the selected targets.

Several of these inputs had to be provided towards the end of the commissioning phase, in what was originally intended to be the bridge to the PV phase, and also as demonstrators of the Reference Observing Sequence (ROS), that is the main block used in the observing fields along the Survey, and for the Phase Diversity Calibration (PDC), where mirror is intentionally defocussed.

### *2.3 Data processing, archiving and curating*

The original commissioning phase was designed under the assumption that any activity related to instrument commissioning (i.e. demonstration of their engineering fitness) did not require SOC's support for image processing or archive. SOC volunteered just to archive raw Mass Memory data as legacy. However, the commissioning plan evolved in the last months prior to launch into a more complex set of instrument activities, with preliminary runs of different instrumental modes and a set of runs of the Reference Observation Sequence to ensure that its inner logic was correctly implemented according to instrument constraints (mostly Filter Wheel movements and compression rates). The early switch on of VIS to support telescope focussing, the subsequent switch on of NISP and the longer bridging to PV phase ended up generating over 5000 scientific exposures over the last 15 days of the commissioning phase. SOC was asked to generate LE1 products, though they could not be fully tagged with all the required metadata. Since they had not been fully planned by SOC's nominal planning chain, the enhancement process [8] (information on the pointing, declaring instrument mode, connecting the data products to the planning task activity and flagging any associated problem) could not be automatically run. This forced to build on the fly a cross-matching table to log all the products, that had to be daily maintained manually by SOC personnel. This table was a powerful tool to later validate PV phase activities and to support IOT job.

The data from this phase was archived in the Euclid Archive System, in what meant also an early use of the system weeks before when it was intended, but in a dedicated Commissioning instance, to ensure that it would not be mixed with later PV or Routine phase data.

### *2.4 Straylight and X-Rays*

Immediately after VIS instrument switch-on and first acquisition of science data 2 main problems were identified:

First, Euclid system was designed to operate in a range of Solar Aspect Angle (SAA) and Alpha Angle (AA) values [9]. This was done so to ensure thermal stability of the system and furthermore, to prevent straylight into it. The original range of Alpha Angle values was from -5 to 5 degrees to prevent straylight issues and ensure thermal stability. The definition of these angles is depicted in **Figure 4**.

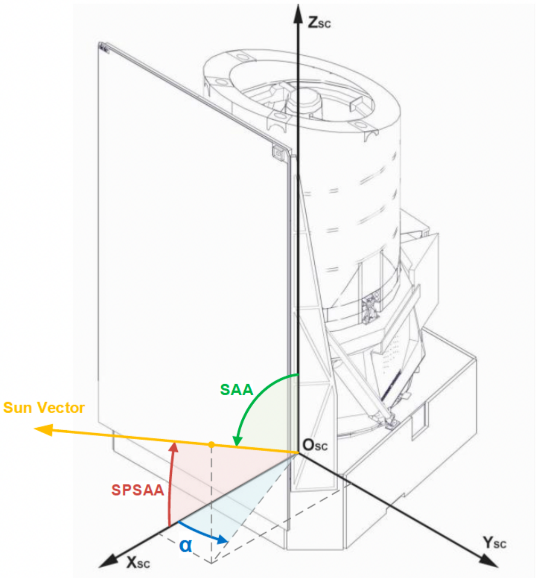

Figure 4 Satellite Solar Aspect Angle (SAA) and Alpha Angle (α) with respect to the Sun Vector. Image from the Mission Operations Concept Document.

However, as can be seen in **Figure 5** VIS images were contaminated by light. The source of this straylight was traced to illumination entering through a pinhole in the cover into the PLM cavity after reflection of sunlight on a thruster bracket.

An immediate impact on SOC's activities was the need to restrict some of the PV phase blocks to avoid positive AAs, and to add to the PV phase a programme to characterize the extent of this straylight contamination over a range of AAs and SAAs to find constraints for the survey construction. This will be further elaborated in the next chapter on PV phase.

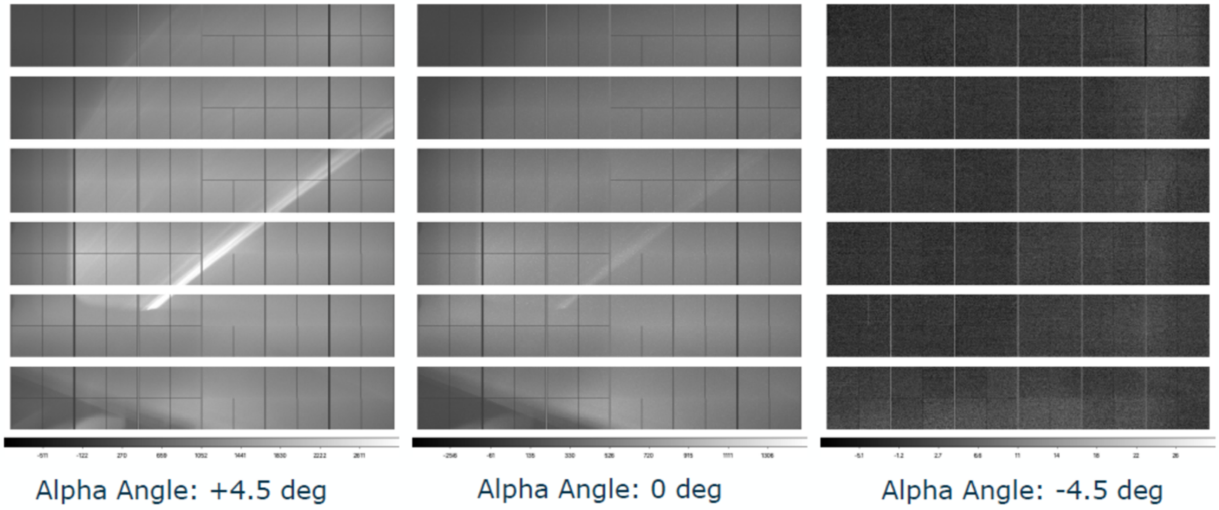
Alpha Angle: +4.5 deg
Alpha Angle: 0 deg
Alpha Angle: -4.5 deg

Figure 5 VIS exposures at different Alpha Angle from the Sun. A dark background as seen in the -4.5 degree image was the expected outcome, while straylight clearly shows up at the other two angles. Credit ESA.

Second, it was found that VIS images were also impacted by solar X-rays connected to cases of elevated solar activity (high class M or class X flares). This was caused by openings in the solar panel structure not sufficiently shielded against X-ray radiation with direct view to the VIS focal plane. No operational corrective action could be taken against this, the impact was estimated around 3% of the images, but it also gave the first information that PV activities may not be successful should they be impacted by this effect.

### *2.5 Guiding*

Euclid's requirements to be able to characterize weak lensing of galaxies imply a high accurate point spread function (PSF) reconstruction and this in turn a very stable and precise pointing over the exposures. This is achieved by means of use of the Fine Guidance Sensors (FGS), which are part of the Attitude and Orbit Control System (AOCS) of the spacecraft and make use of same CCDs as used in the VIS instrument and placed on both sides of the VIS focal plane. This allows to use the telescope light path and conduct a high accurate pointing jitter reconstruction making use of the relative pointing quaternions provided by the FGS.

The FGS, as other units flying CCDs in space, may be impacted by transient signals due to cosmic rays [10]. This was foreseen on its design, and a catalogue of cosmic ray shapes was added to perform removal after image acquisition. However, during the last days of commissioning it was found that in certain cases the AOCS could not achieve a stable pointing solution and rather was drifting randomly during several attempts of stable pointing, see **Figure 6**.

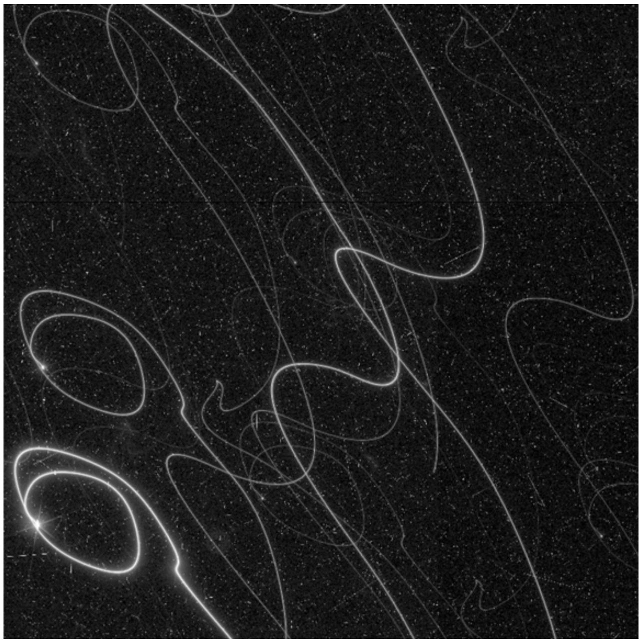

Figure 6 Loss of guiding in one VIS CCD quadrant; trails of stars can be seen over the exposure time. Credit ESA.

The root cause was found to be some cosmic profiles being confused in the FGS with stars, thus leading to the AOCS to abort the science mode and to stop seeking stable pointing. After this was identified, a bridging phase extending Commissioning Phase up to the 12th of August was required to rerun several of the tests originally foreseen at the end of Commissioning (and impacted by guiding) and adding a preliminary test to perform straylight scan analysis. Finally, some dead time was added to allow rescheduling of the PV phase start. This represented a high amount of data to be processed and a required several fast-planning releases to the MOC.

## 3. Performance Verification Phase

Like the previous section, in this one we list the set of operational deviations and problems found during the run of the Performance Verification Phase.

### *3.1 Planning and processing operations*

As already mentioned, PV phase was possibly the most complex one to schedule and plan before launch, involving execution of tenths of complex calibration blocks with interdependencies, pointing constraints and stringent processing needs to evaluate them. Even though the nominal mission planning of Euclid is based on an agreement SOC-MOC to deliver products every 4 weeks covering 4 week's worth of activities, it was understood that this could not satisfy possible deviations during this phase, originally aimed to last 53 days, and fast deliveries with 2 weeks' notice still covering 4 weeks were agreed in case of need. The realization of these planning inputs to the MOC required a significant validation effort for the uplink team as demonstrated during dry runs conducted prior to launch, taking over 1 week of work each. **Figure 7** shows the planned PV phase before launch.

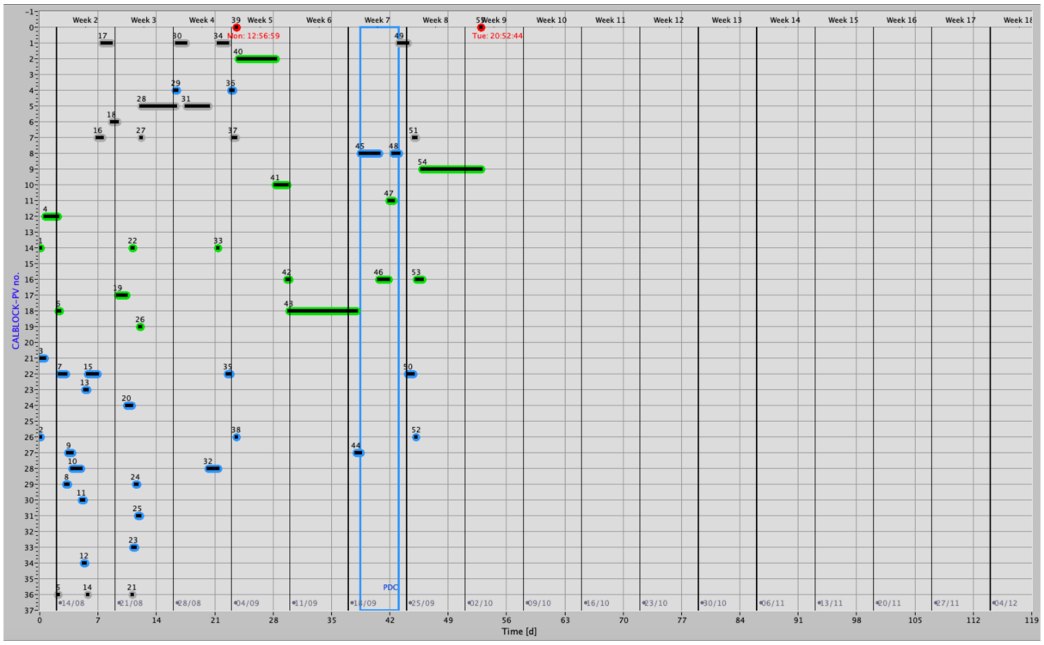

Figure 7 PV phase timeline as planned before launch. Different entries represent calibration activity blocks for VIS, NISP or combined. Area encircled in blue is the Phase Diversity Demonstrator. Even though only 8 weeks in duration, 18 shown for later comparison. Credit R. Kohley

This phase involved the exercise of all possible data formats from the instruments, many of them intended to be used once during the mission and also included a Phase Diversity Calibration (PDC) demonstrator. The downlink chain at SOC was built under the assumptions of automatism and no reprocessing needs (the generated products should be correct on the first attempt, being the processing a very simple handling of the raw data and some further enhancement).

These two assumptions proved wrong, as we may see later.

### *3.2 The real PV phase*

PV phase, as stated, was originally thought to last 53 days. In the end, it doubled its duration, amounting 113 days in total. It added technological activities not originally intended (to fix and validate the spacecraft pointing issue and to characterize the straylight in VIS), and it implemented an Early Release Observation (ERO) programme for legacy science and public outreach.

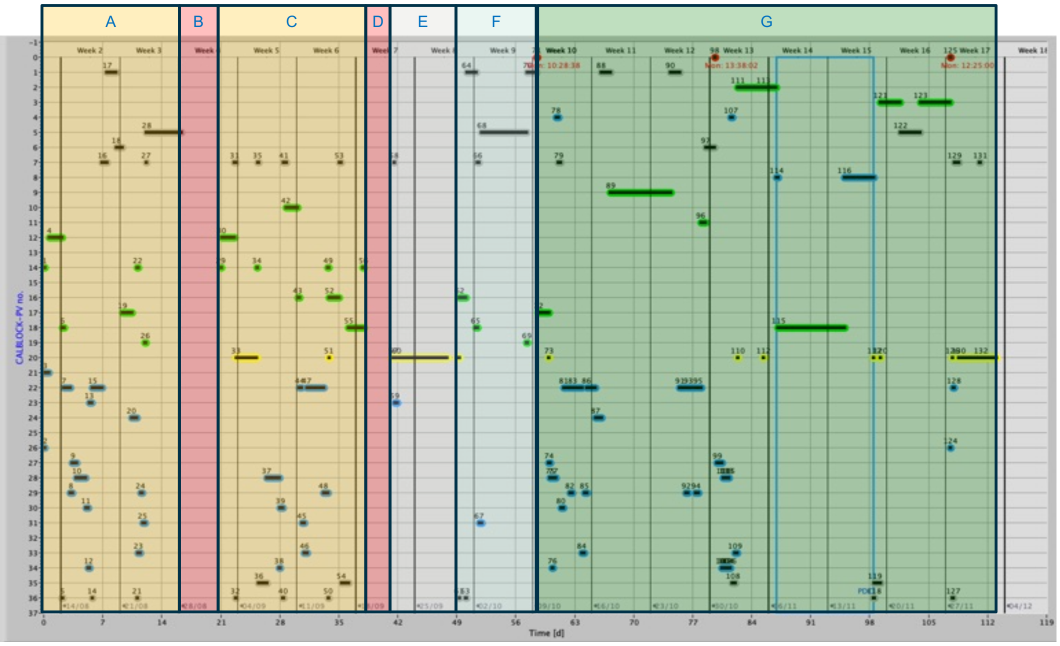

Figure 8 Overall view of the PV phase. The graph shows the phase as implemented, with different calibration activities colour coded and, shading them, the different phases into which PV ended. Yellow activities are added representing time spent in guiding system calibration. Blue encircled area is the PDC demonstrator. Credit R. Kohley.

The **Figure 8** above gives a preliminary view of the PV phase, out of which only the last green part represented the intended original schedule. More insight on what happened on each of the inner phases is given in following **Table 1**

Table 1 Detailed description of PV subphases

| PV subphase | Dates 2023 | Main issues |
|---|---|---|
| **A** | 12/08 to 28/08 | Due to the guiding problems only activities scheduled, which were relatively uncritical with respect to guiding errors. Nevertheless, a lot of data loss due to Attitude Hold Modes (AHM) and many VIS flat fields failed due to large pointing offsets. |
| **B** | 28/08 to 02/09 | No further PV activities scheduled due to continuing high chance of AHM causing data loss and need for recovery. |
| **C** | 02/09 to 18/09 | MOC worked with industry on an On-Board Control Procedure (OBCP) to reduce chance of entering AHM, while industry worked hard on an FGS update. Re-scheduling of PV internal calibrations started in three batches including stray light scans down to an AA limit of -9 deg. |
| **D** | 18/09 to 22/09 | No further PV activities scheduled due to first FGS software update and industry-driven FGS/AOCS re-commissioning activities. |
| **E** | 22/09 to 30/09 | Dedicated SOC-driven FGS tests, which required IOT/SOC to create completely new observation sequences and target areas with different star densities including a sparse field. |
| **F** | 30/09 to 09/10 | First week of PV restart was scheduled with caution, but the FGS software update showed a dramatically improved guiding performance allowing pointing-critical PV observations and Phase Diversity Calibration (PDC). |
| **G** | 09/10 to 03/12 | True execution of all (remaining) PV observations including PDC (demonstrator). High-level NISP calibrations with critical pointing requirements were successful. A lot of VIS failed Flat Field observations were repeated. Stray light scans to advise the survey definition were carried out. Early Release Observation programme conducted. |

### *3.3 LE1 data processing and archive*

A total of 12398 VIS images and 24476 NISP images were generated over the full PV phase. This represented a significant load of SOC's processing chain, close to those expected in routine mission [5]. Being the first time this load was exercised implied different problems in the parallelization, arrival and monitoring of the completeness of the processing that had to be adjusted or corrected. It also created a load test of the Data Processing System, that acts as interface and processing data handling node for the Science Ground Segment, also several issues were found.

However, the main problem related to this phase at SOC was the need to reprocess a significant fraction of the products, something that was not foreseen (at least at that level) in the original plans. Around 20% of the data went through reprocessing in over 20 different reprocessing campaigns. They were mostly due to problems in the instrument processors (SW that was provided by the SGS and instrument teams to convert the raw input files into LE1 exposure data) or in the enhancement process at the SOC, where extra information from HKTM stream or from the planning products were added [8]. It must be considered that the PV phase, as already indicated, exercised a multiplicity of instrument modes that could not be fully tested in a real end to end environment including associated true planning data and HKTM values prior to launch.

The replanning campaigns forced SOC to identify other alternative processing means and resources, to derive processes for data invalidation and deletion on the Euclid Archive System, and to also identify and fix on the processing SW the problems related to the enhancement or deploy new instrument processors on short notice. Again, these tasks involved high stress on the downlink teams.

### *3.4 Planning cycles*

As reported in Table **1**, the FGS issues leading to guiding problems were solved by Industry through a complex SW fix on the FGS unit that led to a double image acquisition to discriminate cosmic ray impacts from real stars.

This, however, involved some telecommand adjustment on the well-tested and predefined Reference Observation Sequence (ROS), that represents the activities of the spacecraft and instruments when conducting the sky survey on tenths of thousands of pointings. The ROS was the result of several years of analysis and tests of instrument and pointing constraints, and any adjustment involved complex tailoring on ground of the different scheduling and commanding systems. The change, at the end of September 2023, led to multiple iterations on the next planning cycle, conducted while the SOC systems involved were also being upgraded through SW and configuration changes. 5 different deliveries to MOC and internal SOC planning had to be exercised to reach a valid solution.

Many other findings or last-minute changes in the PV schedule led to over 25 deliveries of planning products to MOC, in a period where at most 4 or 5 were originally conceived. It must be considered that for the uplink team, though enhanced in support, 1 week of work per planning release was nominally required; satisfying these ancillary needs imposed by the phase and the different changes involved extra work and the support of all team members available, and in many cases waiving validation or acceptance steps in the planning process to meet the deadlines.

### *3.5 Straylight scan*

As mentioned in the Commissioning Phase section, finding straylight in VIS images led to a redefinition of the PV phase to incorporate a straylight scan and identify the new allowed ranges to operate the mission. These values would have a deep impact on the Survey definition and its capability to fulfil the mission goals.

The scan was conducted along 5 different runs from September to end of November 2023, the result of the scans conducted over different Alpha Angle and Solar Aspect Angle values is shown in **Figure 9**. The result found that the valid range was restricted to -8.4 to -3 degrees, which meant a significant reduction (around 50% from the original 10-degree range) on the Survey construction freedom.

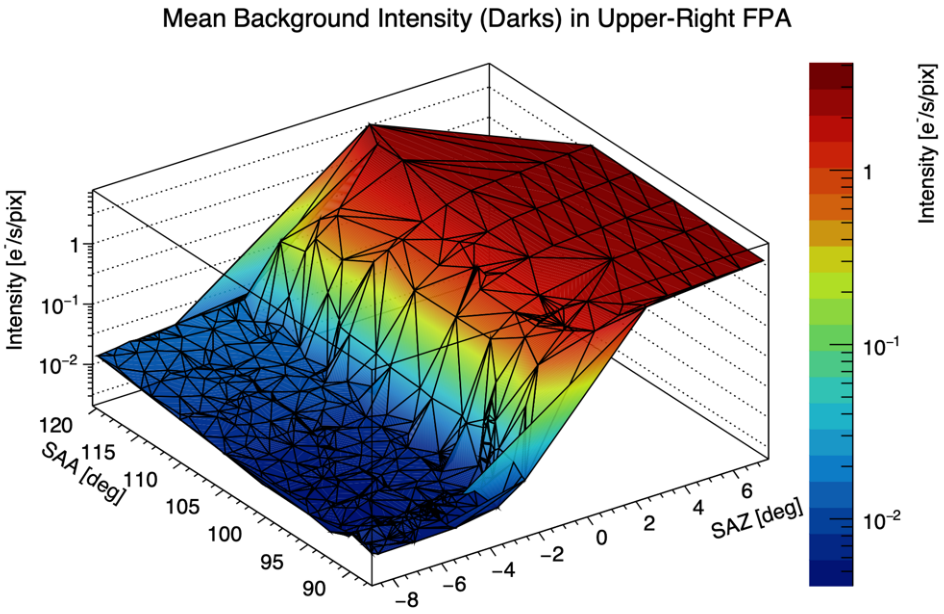

Figure 9 Upper part of VIS focal plane, map of intensity of signal in dark images along scans on different Solar Aspect Angle (SAA) and Alpha Angles (SAZ). Dark blue zones represent valid regions. Credits: Patricia Liebing, VIS IOT.

This immediately triggered a need for Reference Survey Definition analysis and redesign. Further, it triggered the need to adapt SOC's Euclid Survey System (ESS) [4] tool to the new configuration, to ensure that verification on new limits was conducted.

### *3.6 ERO programme*

The ERO programme itself was a great success of the PV phase, devoting 24 hours in total of Euclid's time in different selection of celestial targets of public interest while also ensuring science data return and a demonstration of the mission's capabilities [11]. It involved media releases with a wide coverage and impact in November 2023 (disseminating 5 ERO images and different cut-outs and zooms) and May 2024 (where all the ERO images and associated data, plus accompanying scientific papers, were released). These releases required participation of many SOC staff busy at the time with other activities. The ERO is added to this list since, even though the programme was granted on a best effort and return basis, special care was taken to reschedule any of them when guiding issues (that were still present, though at minor rate) or X-ray contamination impacted data. One of the images of the programme is shown in **Figure 10**.

Figure 10 Perseus Cluster, one Euclid observation (~0.5 square degrees). Hundreds of thousands of galaxies can be found in the image. Credits ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi.

## 4. Phase Diversity Calibration

Euclid needs a stringent characterization of its optical performance to be able to calibrate the PSF of detected objects during the processing. Since it was well known that there is a correlation from the overall system (and therefore mirror) thermal values and optical characterization, it was proposed before launch to run a set of calibrations, the Phase Diversity Calibration, where target fields are visited having the system settled into different thermally stable configurations, and then gather data either in fully focused optics or intentionally defocussing them to intra- and extra-focus points with respect to the best focus position. This resulted into a matrix to characterize the system behaviour with respect to different S/C attitudes and thermal settings.

The original idea was to exercise these runs in different moments along the 6 years of mission, ensuring a characterization that could be applied over the last reprocessing campaign of the mission data once the survey were finished. However, it was considered, following findings on the straylight and survey constraints, that it was better to run the calibration before the nominal survey was started.

The campaign was assigned 70 days for its execution, since it involved not only pointing to given fields and conducting focussed and defocussed acquisitions but also stabilizing on a given attitude (from a Sun illumination point of view) so the system could reach a new equilibrium.

New tools had to be built to support the planning of this phase over only a few months, to find the best selection of targets and settings, but also to fill the stabilization periods with useful science observations (since they meant a big fraction of the programme), that were selected following a call for proposals to the scientific community. This was one of the activities not originally foreseen (or at least not so early) that required extra efforts and interfaces from SOC. Significant changes to the Euclid Survey System had to be implemented to validate the scheduling.

But once the calibration started, other hidden complexities were found along its different runs.

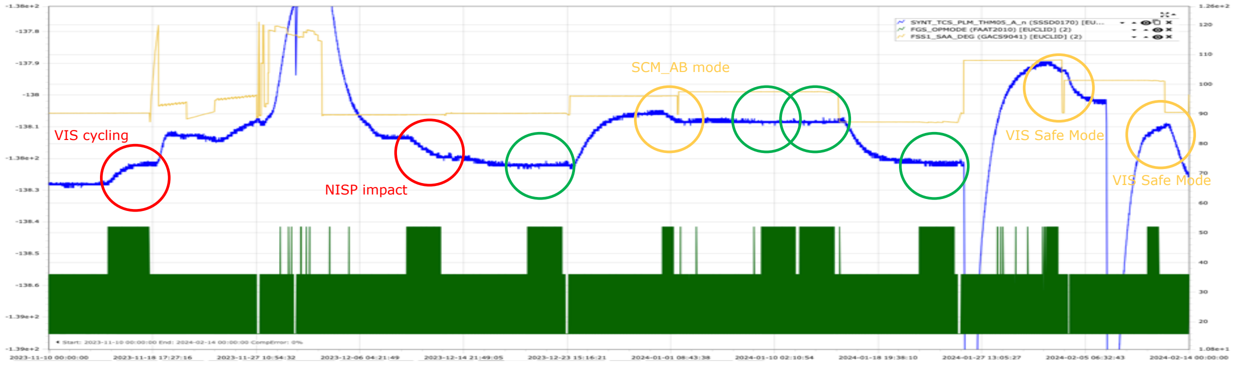

Figure 11 PDC phase summary, with the different 9 calibrations encircled. Only green realizations can be considered fully successful, though some others are also valid to add partial points to the characterization space. In blue, the baseplate temperature (connected to the mirror temperature), in yellow, the Solar Aspect Angle, that was found the main contributor to its changes. Credit G. Buenadicha.

**Figure 11** shows the different realizations of the PDC runs. Prior to the programme start, the Euclid thermal analysis considered that the Alpha Angle was the main contributor to thermal changes on the baseplate where the main mirror M1 is connected through some mounting points. However, it was quickly found that the true main contributor was the Solar Aspect Angle, so this led to an immediate redefinition of the rest of the programme. Then, as different runs happened, it was found that instrument activity changes also influenced the baseplate temperature, and that a constant instrument operation cadence for the VIS instrument prior and during the calibration was required. Further, the PDC runs were activities with only VIS instrument active. This meant that having NISP active in the stabilization phase also created a thermal delta, disabling it prior to the in focus or out of focus activities had to be implemented in subsequent runs. Finally, in one of the realizations several cases of guiding problems led to a fraction of VIS acquired data being invalid, whereas in others unexpected VIS instrument power off created lack of thermal stability, due to VIS having part of its electronics coupled to the baseplate. Still, the programme was successfully completed, and it was not required to rerun some of the missing cases. However, the analysis, investigation and operational reaction to of all these cases consumed lots of SOC resources.

## 5. Routine Phase

Following the PDC campaign, Euclid Survey started on the 14th of February 2024. However, already at that time the analysis of some recurrent calibrations on the self-calibration field, aimed to determine the photometric zero points (the maximum reachable magnitude) of the optical and infrared channels, led to the conclusion that this was changing with time, and that less and less optical throughput was obtained by the system.

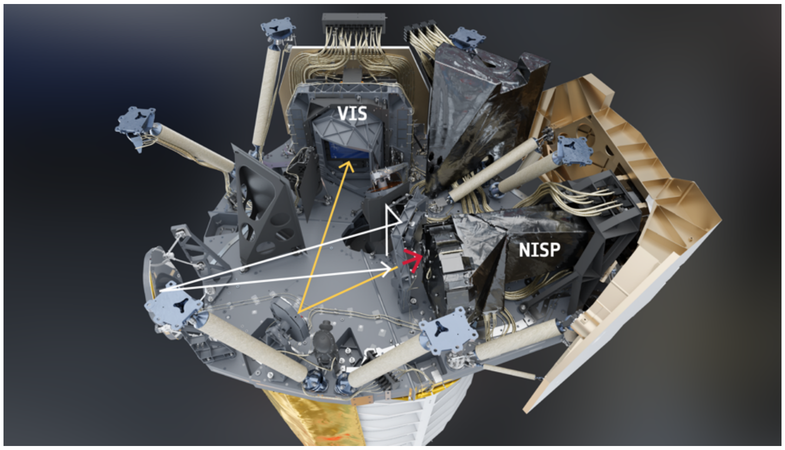

Figure 12 Euclid PLM cavity, showing different mirrors along the optical path to the instruments. Ice could be deposited on different sensitive surfaces. Credits Airbus Defence and Space and ESA.

The immediate suspect was ice accumulated along Euclid's optical path, that involves six mirrors (three mirrors with optical power and three flat folder mirrors, see **Figure 12**) [12]. The loss was estimated to be around 0.1 magnitude since throughput monitoring started in early August 2023, so a decision to act was agreed, understanding that any alteration of the system was preferable at early start of the survey that halfway into it.

The operational reaction involved selective de-icing through heating of some individual mirrors. There were no procedures originally created for this, so this required careful preparation in coordination with MOC, while at the same time, definition of post decontamination calibrations and measurements were agreed with the instrument teams and the SGS. The first decontamination took place 12th of March 2024 and involved an urgent replanning of the already delivered pointing and instrument activities to MOC, as well as the construction of dedicated ICRs and command sequences for it.

The systematic processing of VIS data at Leiden University led to a very efficient and practical means to monitor the throughput behaviour on the VIS channel. **Figure 13** shows its evolution up to this first decontamination, and how the results brought it back to values even better than expected from the first VIS acquisitions. However, subsequent monitoring indicated that the situation had worsened, with a loss of throughput steeper and with a different profile over the VIS focal plane. The situation was monitored over the following weeks, and it was concluded that another decontamination was required. This was run early June 2024, and the result since then is that ice does not seem to be longer present in the main optical paths in the visible.

Obviously, this situation (2 decontaminations, involving replanning, monitors, definition of calibrations, etc) came once Euclid SOC had undergone stressing previous phases for already 8 months, and it represented a final set of intense efforts (ICR construction, overall activity coordination, mission planning and data analysis support) before a steady operational situation could be achieved in June 2024.

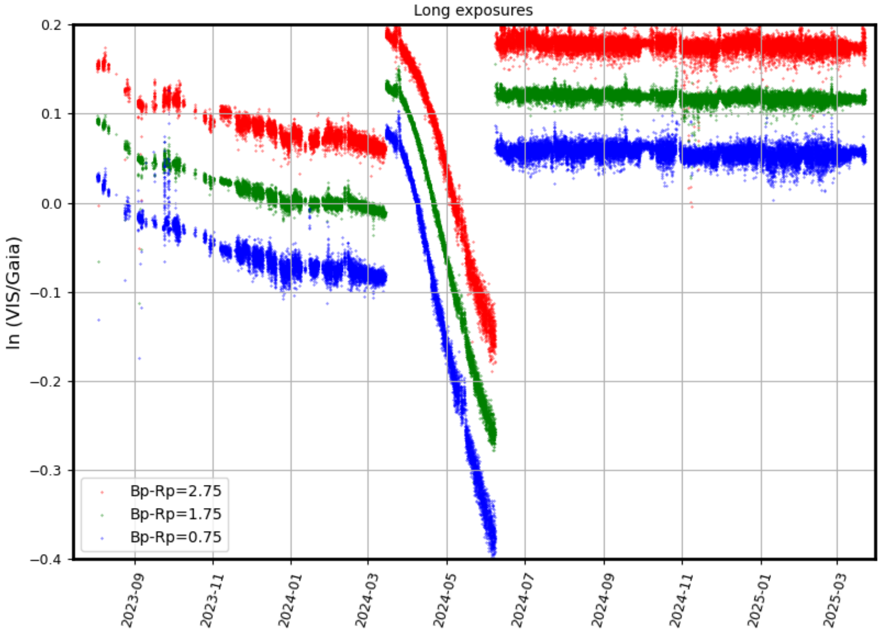

Figure 13 Throughput on different star colours as compared with Gaia on the VIS long exposures. The two decontaminations took place in March and June 2024. Credits K. Kuijken, Leiden University.

## 6. Conclusions

It is not unusual for space missions that the scheduled and planned activities are often overrun by reality and different problems, especially during early characterization phases. Euclid's first year is a very good example, amounting a wide variety of problems of different nature and impact, that have also had the peculiarity of being timed sequentially, converting what was expected to be a complex three months into an almost one year of intense work. This meant, for the Science Operations Centre at ESAC, the need to apply innovative solutions and seek the capability to maintain a full system view while unplanned fast changes had to be deployed to systems and processes. It has also stretched the endurance and resilience of a reduced team.

Some lessons learnt are:

Cross mission service support is thought to bring enhanced flexibility and growth capabilities in case of punctual needs, but this is not so easily achieved in the case of stringent mission phases requiring highly dedicated know-how. The EFC2 contract at ESAC is very adequate to support early developments not connected to critical mission phases or missions in a very steady routine operational phase. However, it is complex to bring rapidly new expertise and capability into a mission in a situation where little margin exists to train or adapt new team members, since exiting personnel is fully occupied. This type of scenarios must be considered when seeking extra support, and flexible formulas ensured to overcome the overheads of nominal workflows.

A stressful phase longer than 6 months is hardly manageable by teams. If a situation appears such that a long period of crisis is envisaged, there must be room to accommodate team rests, even if at the cost of extending certain mission schedules. Some people represent single points of knowledge, and it is hard to build a deputy schema.

When developing a science ground segment one of the main goals is efficiency and cost. Overdesign is often not the best way to mitigate the risks associated to contingencies in early mission phases. However, the SOC interfaces and systems should be thought always with flexibility in mind. It is best to have multiple basic functions (i.e. in the case of Euclid, pointing tools, enhancing tools for LE1 outside the nominal processing pipeline, reuse for ICR composition) at an early development stage that trying to compose mature systems with lots of complex functionality in them, that are hard to maintain and adapt. Possibly a set of dedicated tools for early phases would help.

Labels and surnames are dangerous. Euclid performs a survey, but it is not a surveyor. Some of the SOC design drivers and operational designs were biased by this later, considering that the apparent simplicity of a surveyor with highly repetitive patterns would apply also to the Euclid's SOC and the mission operations. However, when confronted with a mission phase as PV this does not fully work, and it even forces to operate with systems and procedures not suitable at all for the task.

In times of complexities, it is key to ensure configuration control, coordination and to maintain the capability to have a system view and to assess the possible impact due to changes elsewhere. All these things may seem important but tend to be overruled by urgency; in the case of Euclid planning, some of the needs for redeliveries and internal replanning came from trivial configuration issues that were overlooked due to stress and the fast reaction required. A tighter parallel configuration control would have helped. If an area had need to be supported by more personnel, it is probably this one.

Linked to the previous, it is essential to have ready before launch a mechanism of logging and recording unforeseen events, recording not only the operational actions taken by SOC, but capable to host, as it was the case in commissioning, thousands of non-foreseen data products so that they can be later curated and correlated to operational events and situations. This is a relatively small investment that saves a lot of time in the future.

Finally, it is always good to keep in mind that the unexpected may happen. That sometimes many unexpected events may happen. And that all may happen at the same time or, which could be worse, may happen one after the other and pave a long road to normality. And plan for it.

## Acknowledgements

Not all of SOC staff could contribute to this paper, but the efficient and professional solutions to the problems here described were achieved thanks to them. The authors would like to acknowledge the work and dedication of all the teams from the supporting service contracts (SCO02, SCO03, SCO08, SCO11, SCO12), without them the role and success of the Euclid SOC would have never been the same. Also, the great cooperation maintained with, and support received from MOC, EC and Project.

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