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ABSTRACT

The Euclid mission is to be launched in 2022 to survey during 6 years 15,000 degrees^2 of the extragalactic sky in order to characterize the Dark Universe. The mission planning problem and drivers are exposed. The current status of the mission planning software system and infrastructure, its requirements, design, challenges and current implementation are also presented.

Keywords: Euclid, Mission Planning, Space mission, Surveys

1. INTRODUCTION

Euclid (Laureijs *et al.* 2011) is the second medium size (M2) ESA mission of the ESA Cosmic mission 2015-2025 plan, to be launched during the first half of 2022 from the Guayana space centre aboard a Soyuz-Fregat launcher.

Euclid mission is to characterize and understand the dark and expanding Universe by surveying the extragalactic sky. Amongst the questions that the Euclid mission will help to answer are: The nature of dark matter and energy (i.e. the equation of state), how the cosmic structures are affected by the expansion of the universe and the validity of General Relativity over cosmological scales.

In order to answer those questions, Euclid will use two main cosmological probes: Galaxy Clustering (GC) and weak gravitational lensing (WL). In the former case Euclid will measure ~10^7 redshifts to characterize the acoustic baryon oscillations (BAOs) while in the latter it will measure the shape of ~10^9 galaxies (~30 arcmin^{-2}) to characterize the growth rate of structure and the expansion history of the Universe.

Euclid will be also produce a rich wealth of legacy science that will impact several astrophysical areas. Some probably in unexpected ways.

2. THE EUCLID PAYLOAD

The Euclid payload is composed by a large-FoV 1.2-meter Korsch telescope and two instruments comprising 3 channels: VIS (Cropper et al.): a visible imager and NISP: an imager-spectrometer covering the near-infrared (See Table 1 and Figure 2). Both instruments cover a common field of view of 0.54 deg^2 and by the use of a dicroic mirror both can gather data simultaneously.

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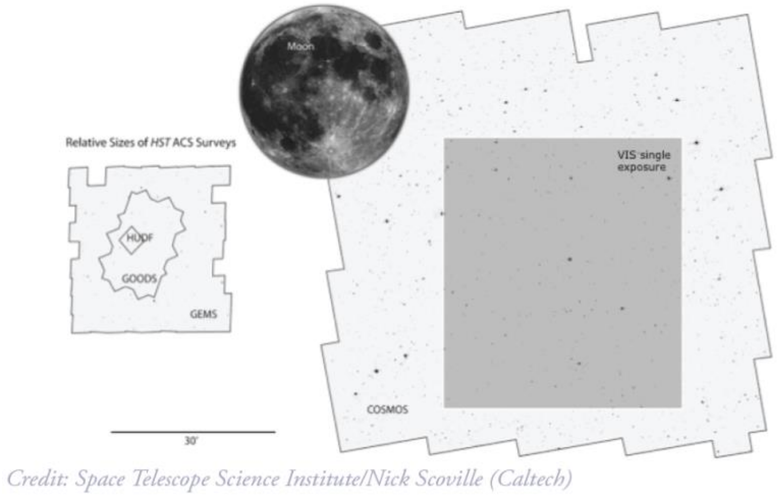

Figure 1 Relative sizes of other cosmological surveys and Euclid FoV

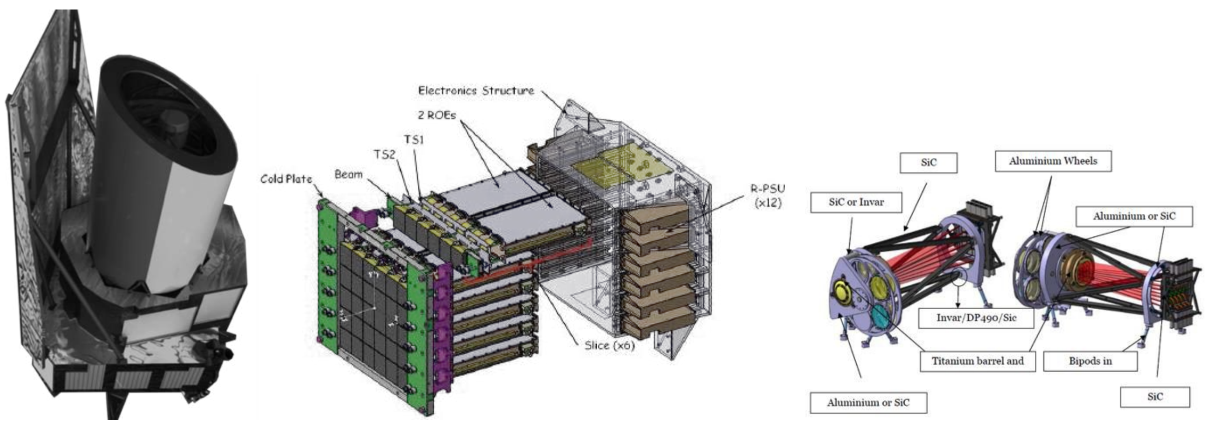

Figure 2 Euclid spacecraft, VIS and NISP instruments

Telescope	1.2m Korsch, 3-mirror anastigmat, f=24.5m				
Instrument	**VIS**	**NISP**			**Common FoV**
FoV	0.700° x 0.787° (0.551 deg^2)	0.727° x 0.779° (0.566 deg^2)			0.700° x 0.779° (0.545 deg^2)
Channels	**Visual Imaging**	**NIR imaging photometry**			**spectroscopy**
Spectral coverage	550-900 nm	**Y** (920-1146nm)	**J** (1146-1372nm)	**H** (1372-2000nm)	1100-2000nm
Sensitivity	24.5(10σ) ext.	24 (5σ) point	24 (5σ) point	24 (5σ) point	$310^{-16}ergcm^{-2}s^{-1}(3.5\sigma)$
Detectors	36x4K^2 CCDs (0.57 Gpix)	16 x 2K^2 HAWAII-2RG HgCdTe detectors			
Plate scale	0.1 arcsecs/pixel	0.3 arcsecs/pixel			0.3", R=250

Table 1 Euclid Payload in number

3. THE EUCLID SURVEYS

The Euclid Survey will consist on two main surveys (see Figure 3): A Wide Survey (WS) of ~15.000 deg^2 and a deep survey (DS) of ~40 deg^2. The latter will consist of three regions: two near the ecliptic poles (EDF-N & EDF-S) of 20 square degrees each and another one of 10 square degrees around the Fornax region (EDF-F). The deep survey will attain two magnitudes deeper (~26.5) thatn the wide survey, allowing performing high-z studies. The observation scheme (number of dithers and exposure times) for the Deep Survey will be identical to the Wide Survey, however each field in the DS will be observed several times throughout the mission and thus going deeper and also allowing transient studies (SNs, SSOs, etc.).

Euclid will be to some extend self-calibrated, but will also require dedicated calibration observations interleaved with both surveys which will represent an important fraction of the total observation time and hence need to be also carefully planned. The final number of surveys, their precise position, depth and extension could further vary as part of the optimization process that is being performed.

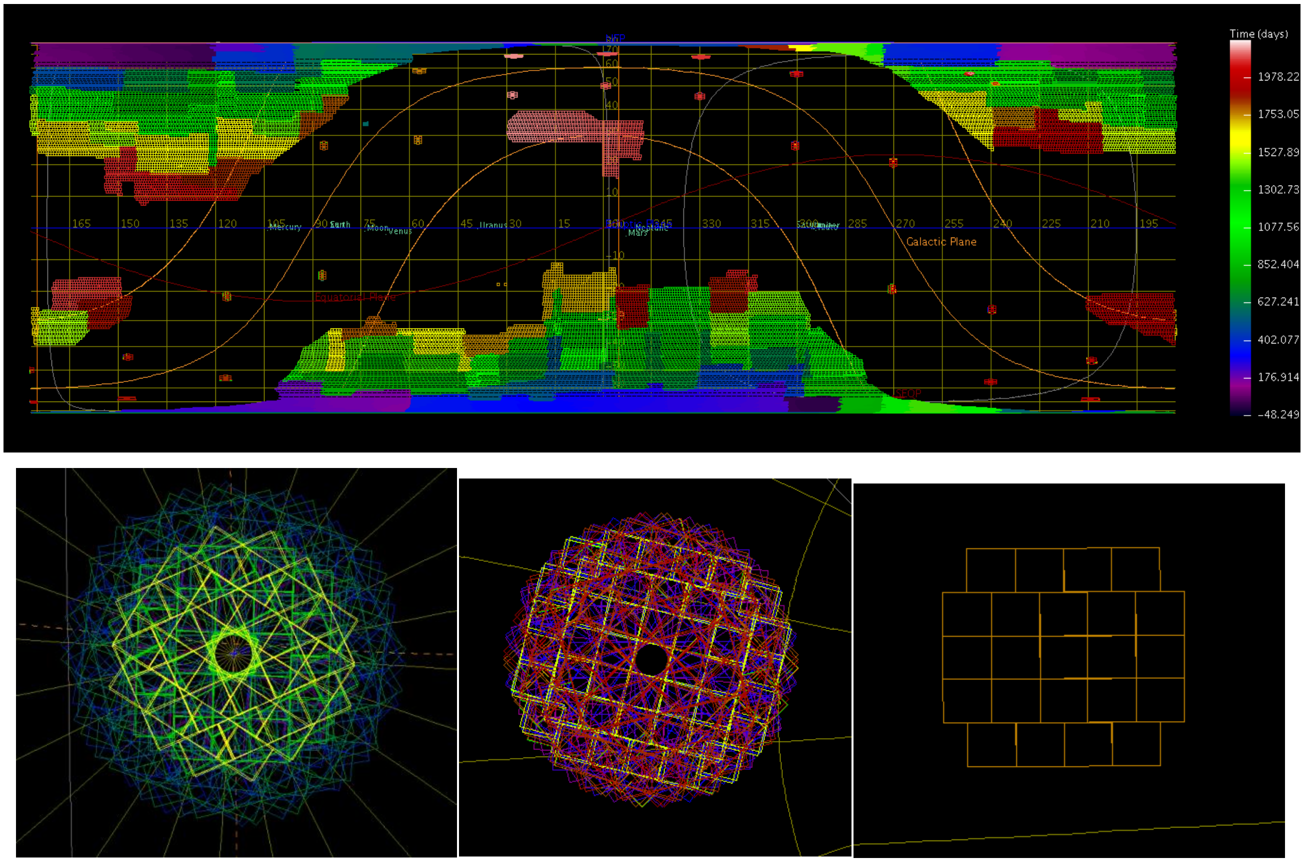

Figure 3 Above: Wide survey and calibration fields. Below: The deep surveys: N, S and Fornax region. All this figures where produced by ESA ESSPT tool

4. EUCLID MISSION PLANNING DRIVERS

Here we review the most important factors that affects Euclid mission planning activities:

4.1 Euclid geometry and thermal management

Euclid mission demands exquisite focal plane stability, which implies careful thermal design and management. This stability is in turn governed by the relative position of Euclid with respect of the Sun. Large and/or fast variations of Euclid attitude with respect to the Sun will produce thermal gradients that will propagate through the Euclid structure, adversely affecting its focal plane stability which is of paramount importance to attain Euclid scientific objectives.

Adopting the following Euclid spacecraft coordinates (See Figure 4): **z**, near the common FoV boresight center, **x**, normal to the solar panels and **y** forming a right-handed triad, we can define two angles that describe the relative position of the Sun with respect to Euclid: **α** and **β**, defined by the angle between **x** and the projections of the Sun in the **xy** and **xz**-planes respectively. The Solar Aspect Angle (SAA) is the angle between the Sun and the spacecraft z-axis.

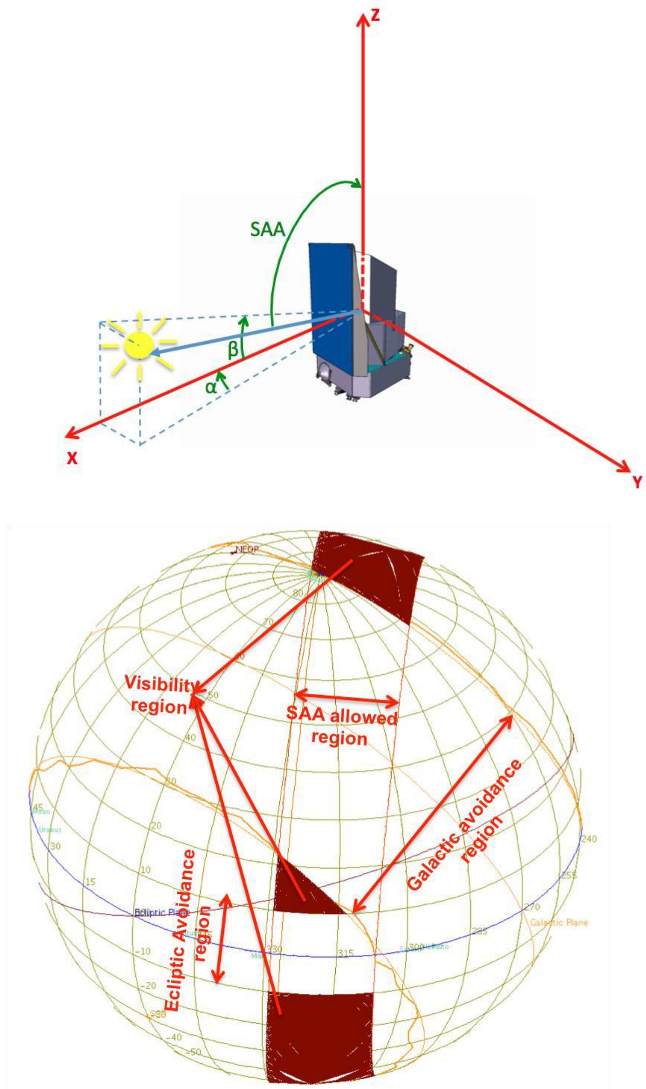

Figure 4 Euclid axes and visibility geometry

Due to Euclid sunshield design and solar power restrictions, the SAA angle is currently restricted to the range `87°-110°`, which defines the "SAA allowed region" band (See Figure 4) which revolves annually around the ecliptic axis, sweeping bi-annually regions at moderate ecliptic declinations. The **α** angle measures the angle of the sun with respect to Euclid symmetry plane and it is currently restricted to the `[-6°, 6°]` interval. The final values of these angles will be refined as part of the undergoing optimization process.

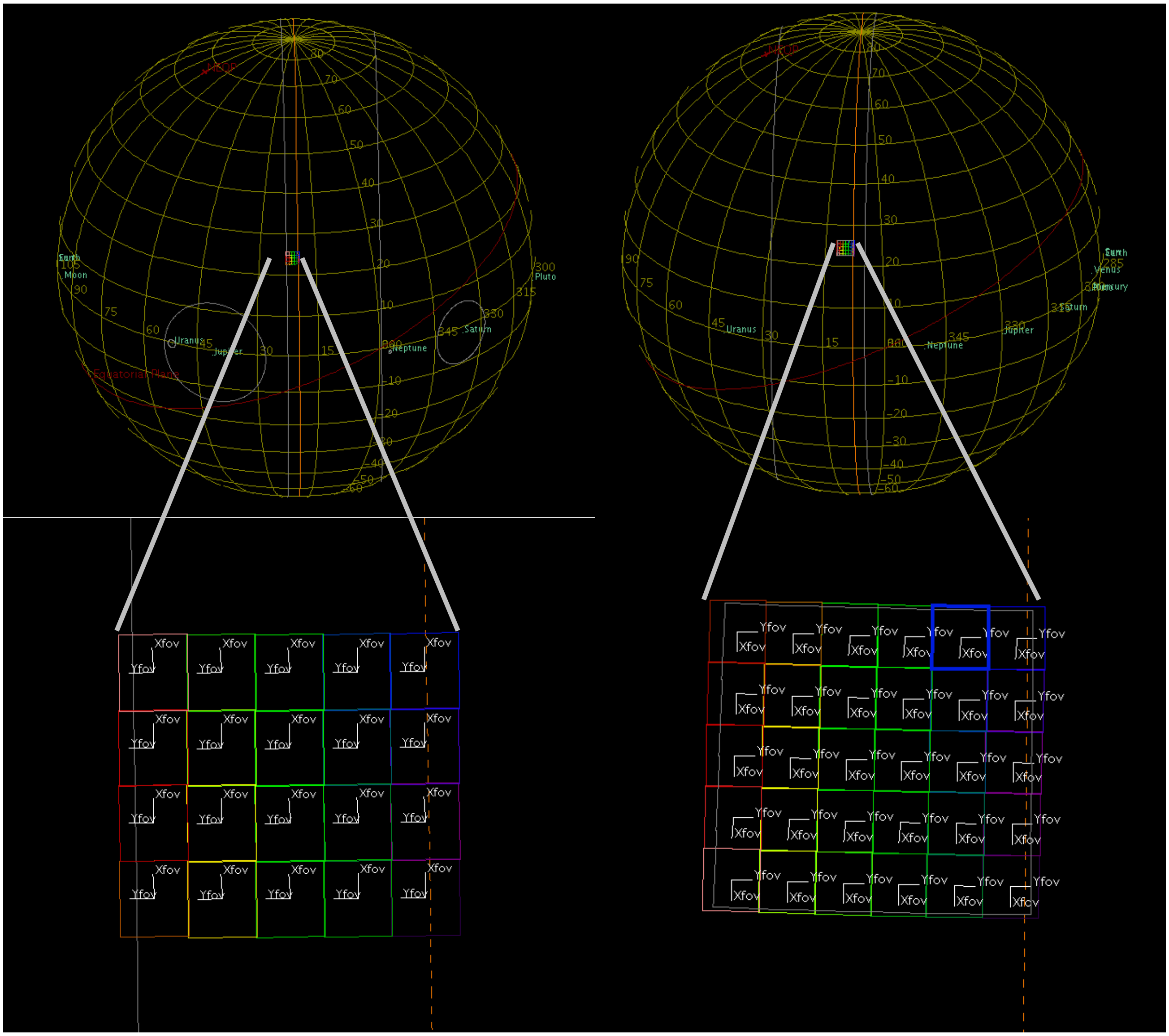

Figure 5 Leading and trailing fields

At moderate ecliptic latitudes a given region of the sky is visible every 6 months. In Figure 5 we can see a small sky patch observed in two configurations half a year apart. In the first case we have the Sun at the West (left) while in the second case, we have the Sun at the East (right). Note that this makes Euclid FoV and dither pattern to observe upside down with respect to each other. Both cases have been denominated as *leading* and *trailing* fields.

Euclid exquisite imaging quality requirements lead to a mission design, which allows the quoted range of alpha and SAA angles. Improvements in galaxy shape measurement accuracies may justify in the future an even more stringent control on thermal disturbances what could be achieved through a restricted range and variability of alpha and SAA angles.

4.2 Constant sky restrictions

The constant factors that further constraints Euclid visibility (See Figure 7) are:

- **The galaxy:** Euclid surveys will be performed at regions of low galactic extinction, where the extragalactic sky is less impeded. As a proxy to this extinction the Schlegel reddening map `E(B-V)` is usually used (see Figure

6), although we plan to use Gaia DR2 (see René Andrae et al.) data as well to derive alternative extinction data. The current wide survey includes regions with reddening $E(B-V)<0.08$ with extensions to $E(B-V)<0.15$ to avoid holes & islands. In Figure 6 we can see how the averaged galactic extinction generally decreases with the ecliptic latitude

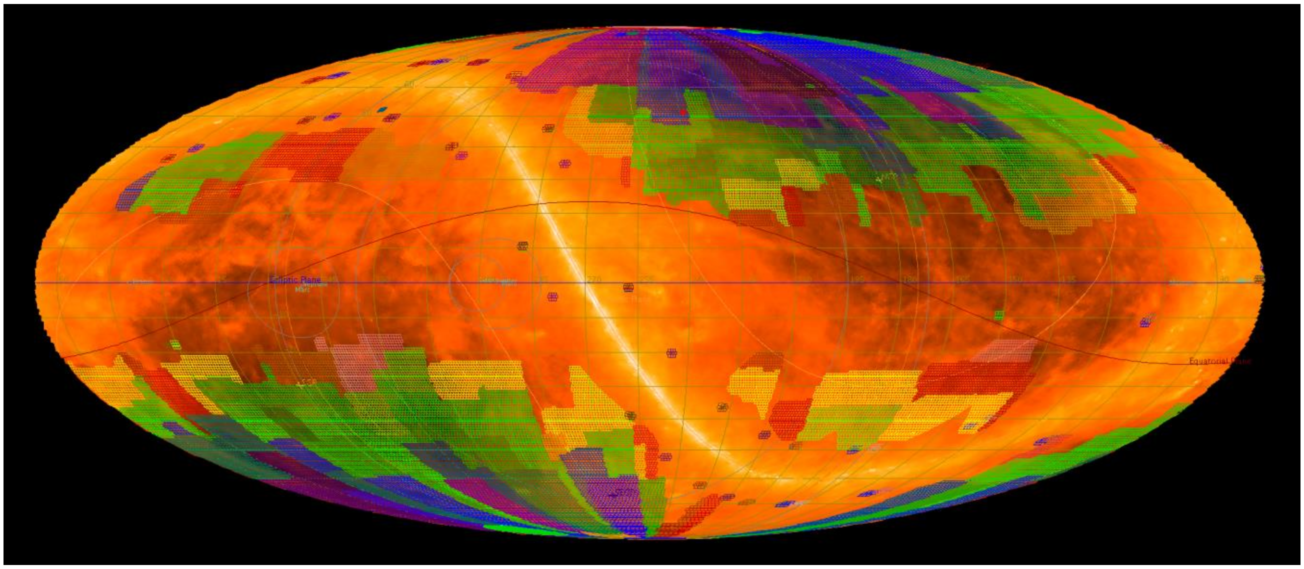

Figure 6 Euclid reference survey over the Schlegel-Finkbeiner-Davis E(B-V) Galactic Reddening Map as seen in ESSPT

- **Zodiacal light:** By excluding ecliptic latitudes in the [-15°, 15°] range. However the zodiacal component is not entirely constant thought the year and it does undego seasonal variations that may be as well taken into account as part of the undergoing optimization process.
- **Straylight:** In-field and out-field straylight from bright stars and/or high star density.

The intersection of these regions roughly defines the area to be covered by the wide survey and the region of the sky that is available at any time in the mission. It is worth to notice that the fraction of the survey that is available at a given time varies substantially across the year (See Figure 8).

4.3 Other drivers

Other aspects that affect the mission planning process are:

- **Best regions** at high ecliptic latitudes should be observed **first** to minimizing the effect of the unavoidable detector degradation by cosmic rays throughout the mission in order to maximize the scientific return of the mission. Therefore, the wide survey is expected to progress from higher to lower ecliptic latitudes (See Figure 7). Of course it will also contribute to optimize the scientific output of the mission in case of partial or total loss of payload capabilities.

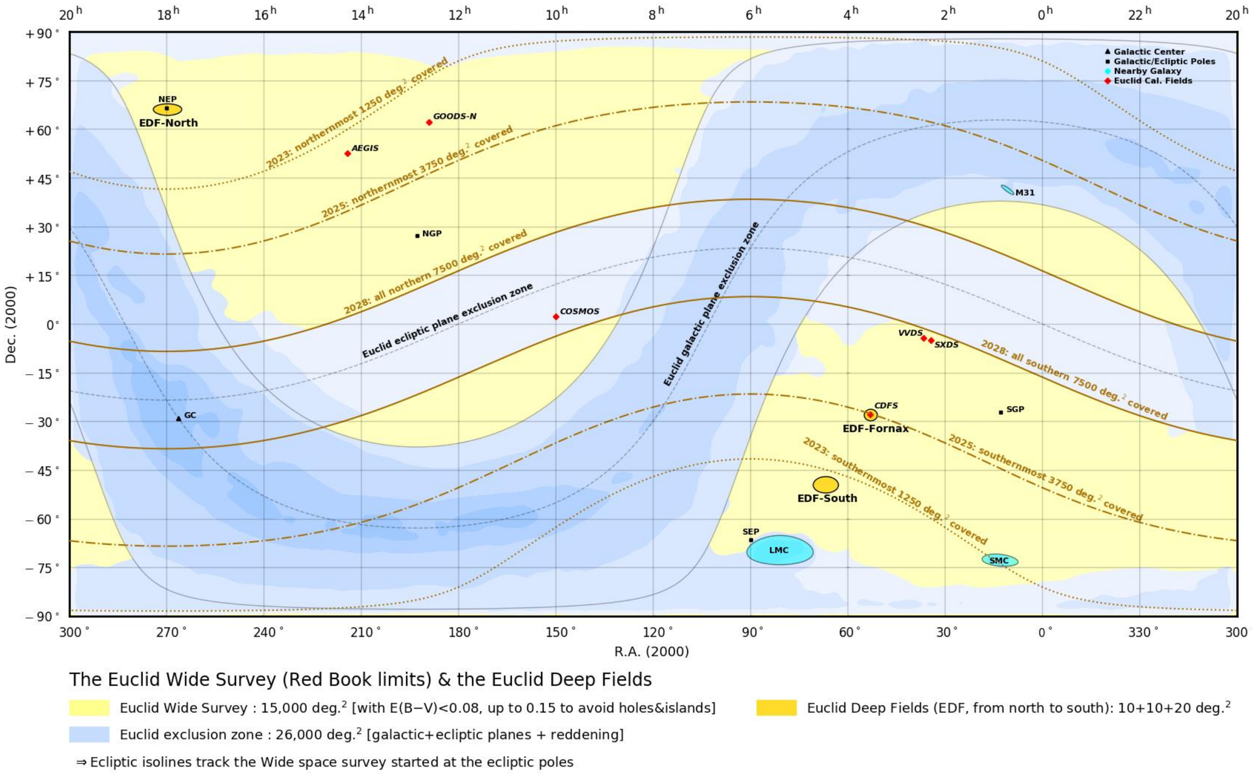

Figure 7 Euclid constraints and regions of interest and overall coverage during the mission

- **Visibility evolution: The portion of sky that is available to Euclid at a given time during the year is of course variable, due to the moving intersection between the time-dependant SAA constraint and the fixed galactic and ecliptic constraints. In Figure 8 we can see how the available region for Euclid evolves along one year: During the Summer and Winter solstices, the visibility region is maximum in area and is composed by two symmetric bands in the North and South ecliptic hemispheres. During the spring and autumn equinoxes, the visibility is at its minimum and it is mainly composed by a single visibility band on the North and South ecliptic hemispheres respectively. The minimum/maximum values of ~1700/~4500 square degrees correspond to the equinoxes/solstices respectively. This represents a substantial variation (factor ~2.6) of the available region throughout the year. This of course should be considered during the long-term mission planning of the mission: those regions with more visibility (higher ecliptic declination) can be reserved for periods of reduced visibility, but as said these regions are also of the highest scientific value, so a tradeoff is needed.**
- **Already observed** regions are of course discarded as part of the available regions to be observed. This effect will be more important as the mission progress decimating and fragmenting the sky area that is available to observe at a given time.
- **Holes recovery**. As the mission evolves, inevitably some surveys areas would need to be postponed due to a number of operational issues, creating holes in the schedule. This will make the planning progressively less efficient as the survey evolves, since those regions would be visible only during disparate periods of times and therefore larger slews will be needed. It could even happen that the survey run out for available regions, specially at the end of the mission. Another adverse consequence of these hole recoveries, is that those holes, once filled would still be temporally disconnected from their neighbor fields.

- Solar System Objects (**SSOs**): As the Euclid mission will avoid the ecliptic band (See Figure 7), no planet or bright SSO would be never within the Euclid FoV, however these objects should be taken into account as potential out-of-field straylight generators.
- **Orbit maneuvers:** Euclid will be at large halo orbit around the second Lagrange point (L2), which is intrinsically unstable. Orbit correction maneuvers will be needed to maintain the orbit, during which observations are not possible. A guess of one activity per month is estimated but the actual schedule can only be determined when actual orbital telemetry is obtained.
- Fast **SAA** and **α variations** as result of large slews: Large slews could produce large and or fast excursions in SAA and alpha angle which might affect the thermal stability of the spacecraft
- **Slew time estimations:** Initial version of the slew estimation software assumed that any slew would be executed as *eigenslews* i.e. simple rotations around an axis *(eigenaxis*). However SAA and **α** constraints could force to perform some large slews as *sun-safe* slews, for which the rotation axis is not longer fixed to maintain **α** constant and within limits throughout the slew. As this is something that will occur autonomously at spacecraft level, some sort of further modeling will be needed to give an upper boundary of the slew time without sacrificing significant science time.
- Dedicated **calibrations** are needed to attain the scientific objective of the mission and need to be interleaved with the wide and deep survey observations.
- **Mean visibility distribution**: High ecliptic latitudes will be visible during a longer period of time. In particular there will be a always visible circular region of ~20° around the ecliptic poles

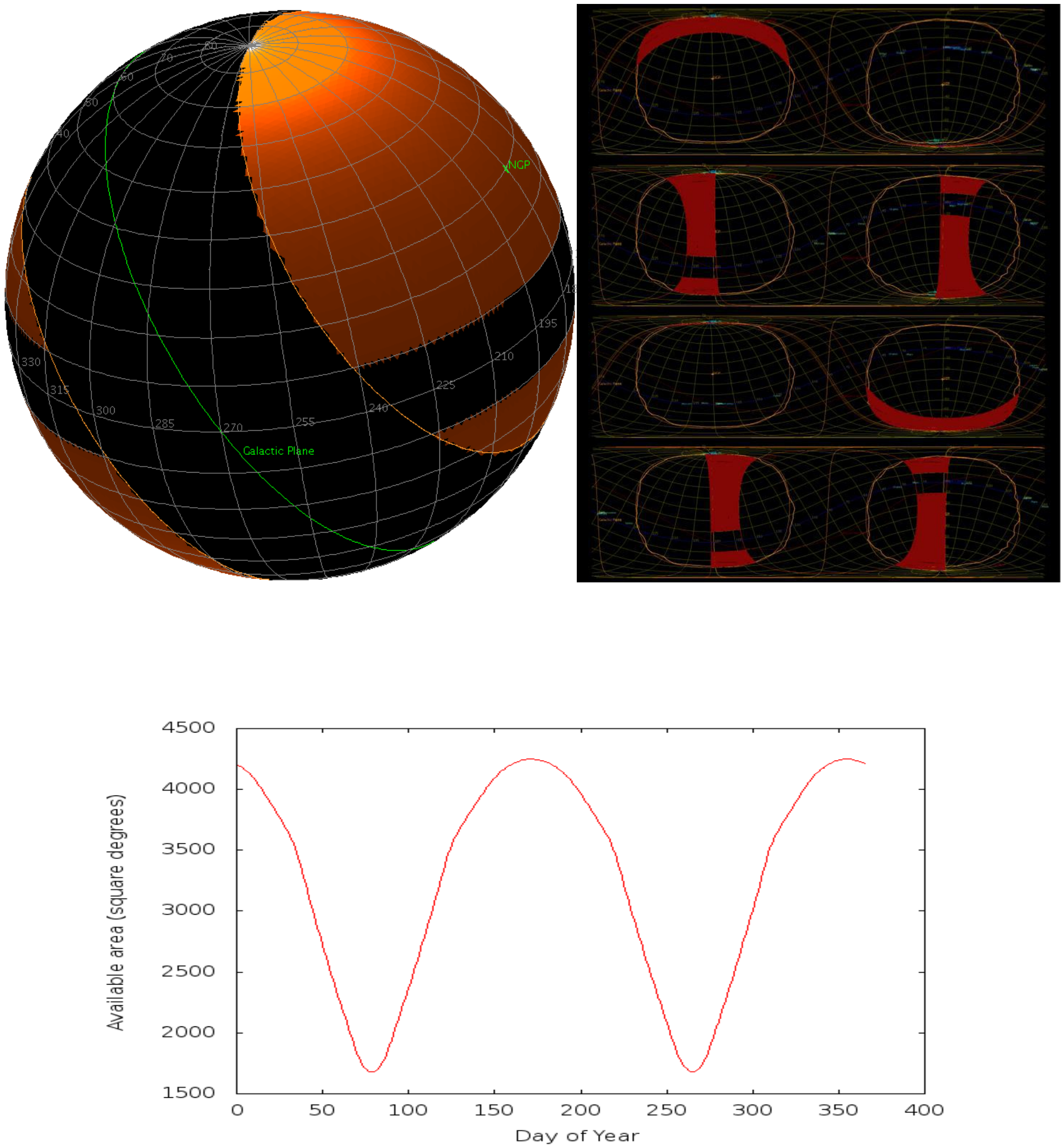

Figure 8 make the planning less efficientMean visibility map, visibility region (red); from top to bottom at the equinoxes (1,3) and Solstices (2,4) and the available observing surface along the year

5. EUCLID MAIN OPERATIONAL SEQUENCE

Both wide and deep surveys will be executed using a fixed main operational sequence. The selected areas will be covered by observations, each one composed by 4 dithers. Several dithers schemes have been tested. The preferred candidate at the time of writing is the so-called "S" scheme, with the following relative offsets (in arc-seconds): `{[0,0];[50,100],[0,100],[50,100]}`

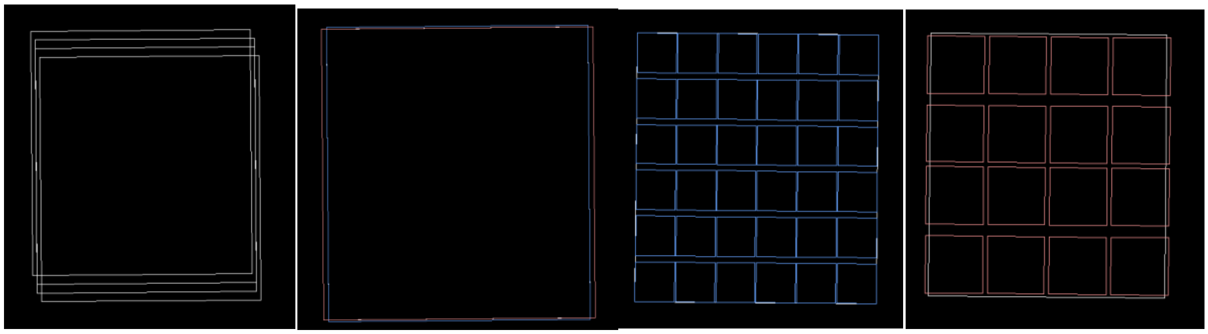

Figure 9 From left to right: Common FoV of Four dithers, VIS and NISP FoVs and focal planes displaying their detectors arrangement

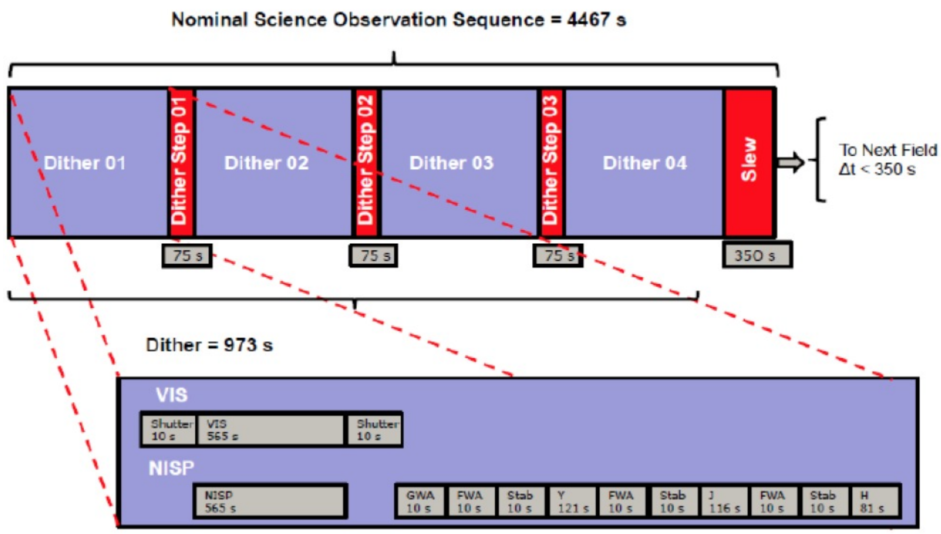

Figure 10 Euclid main operational sequence

- During each dither, the same sequence of activities is performed: Two simultaneous exposures of VIS and NISP spectroscopy channel and then three NISP exposures through the Y, J and H near-IR filters.
- At the end of each dither, a small slew is performed. At the end of the last dither of each observation a bigger slew is performed to the next observation.

Of course, the sequence of activities will be different for calibration observations each one with its particular operational sequence. It is important to note that the bigger operational entropy of the mission will be at those calibration activities.

6. EUCLID OPERATION OVERALL ORGANIZATION

The current mission planning conception starts with the generation, using proprietary tools, of the Reference Survey Definition file (RSDF) by Euclid Survey working group (EC-SURV), See Tereno, I. et al and Figure 11. An ICD based on XML Schemas has been defined between EC-SWG and the Euclid Science Operation Center (SOC) located at ESA Science Operation Center (ESAC).

It is worth mentioning that the RSDF contains both the definition and timeline of the FOVs to be observed.

The Instruments Operation Teams (IOTs) also send their Instruments Calibration Requests (ICRs). Both input are checked for formal correctness and whether it is line with the mission requirements including constraints checking.

The Operational Sky Survey (OSS) is a data entity that contains the most update status of the mission execution, including the past, present and scheduled observations. This entity is continuously updated with new observations coming from EC-SURV, those already scheduled and the ones already observed or even re-observed as a result of previously being considered as failed.

The SSR is a standardized file that is sent to the Euclid Mission Operation Center at ESOC that specifies the scheduled observations.

Once the telemetry of the observations is received back at ESAC, undergo the L1 processing and the Quality Assessment (QLA) is produced the observation metadata is stored at the Euclid Archive at ESAC.

All this processes can be illustrated in both a sequence and state diagrams. See Figure 11 and Figure 12.

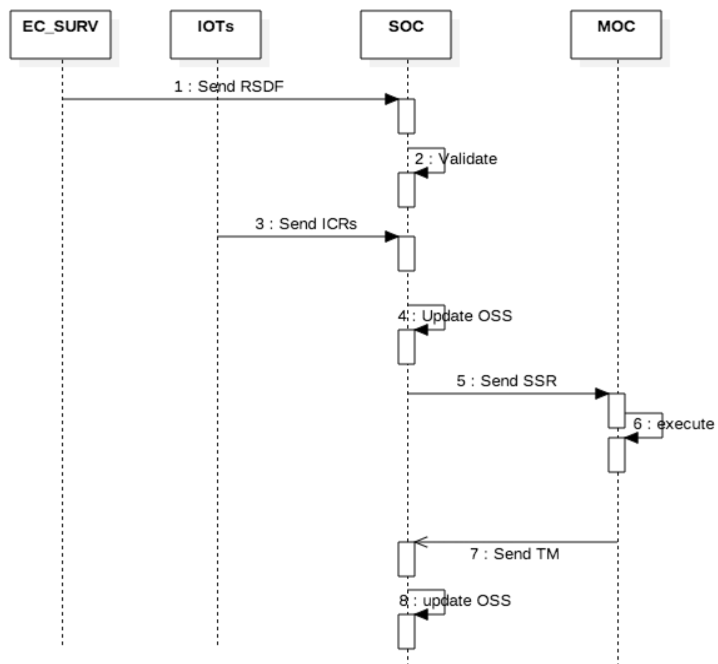

Figure 11 Mission planning sequence diagram

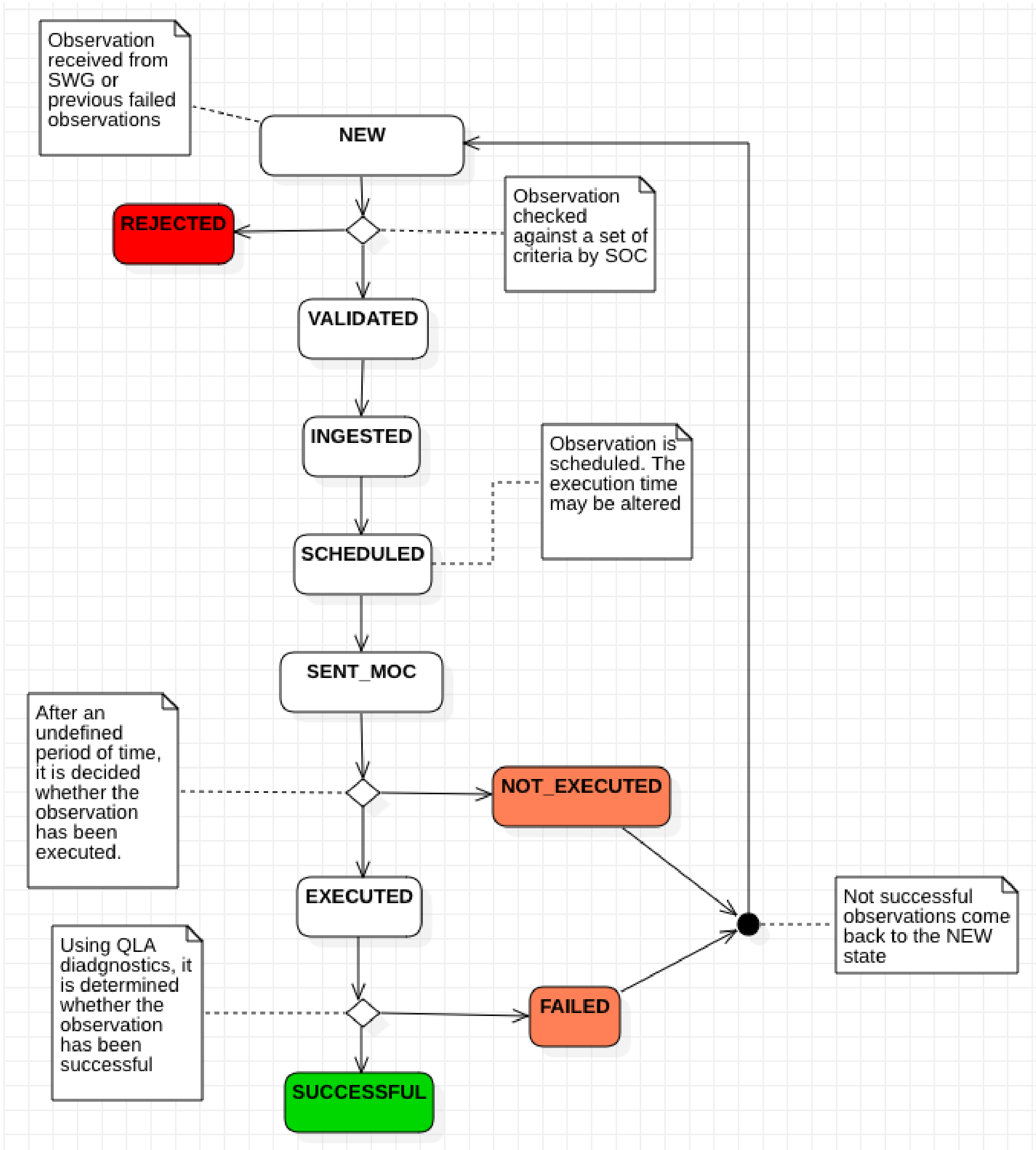

Figure 12 Euclid observation state diagram

7. EUCLID PLANNING SOFTWARE

Initial versions of the Euclid planning software were produced early during the mission development for generating the so-called Reference Survey (RS). These RSs have been used as an input to assess other aspects of the Euclid mission development. This software is an evolution of the Herschel mission planning software (See Gómez-Alvarez et al), which was used during the 5 years of the mission (May 2009-June 2013).

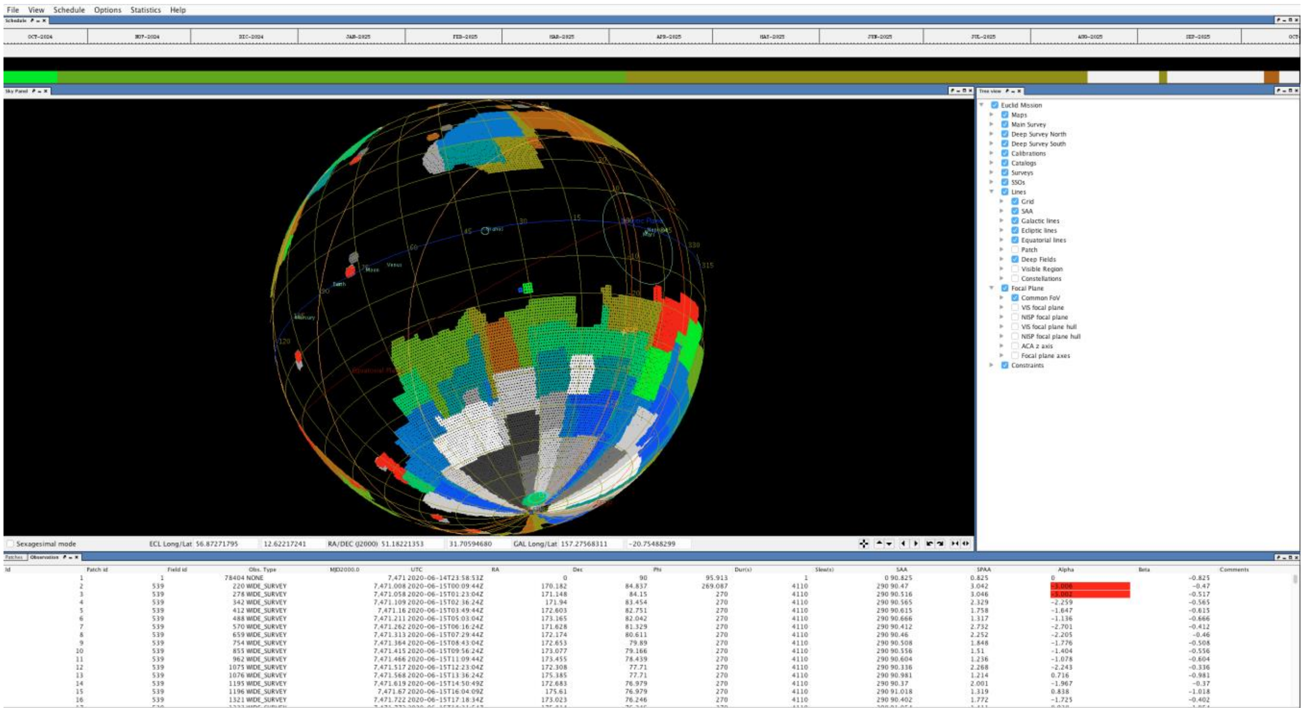

Figure 13 The Euclid Sky Planning software

The Euclid planning tool is distributed in two flavours: The ESSPT (Euclid Sky Survey Planning Tool) for the general Euclid community to visualize, inspect and check any survey conformant to the XML Schema accorded and the ESSOT (Euclid Sky Survey Operational Tool) which is a functional superset of the ESSPT plus specific SOC functionality. Here a brief description of the ESSPT is performed:

The ESSPT tool (see Figure 13) is composed by a number of panels:

- **Sky panel:** were all the relevant artefacts are displayed: observations, pointings, patches, coordinate grids, Solar System Objects (SSO), constraints, main circles, maps, catalogues, instrument focal plane, etc. Both the coordinate system in use and the preferred projection can be selected by the options item in the menu bar.
- **Time panel:** where the observation timeline and the calendar is represented. Also unused time and time violations are also represented. In addition it allows to select the current time, so the rest of the panels are updated accordingly or select a time interval and thus only observations within that time interval are represented. It is draggable and zoomable
- **Tree panel:** where the different elements to be represented in the sky panel can be selected or unselected in line with the intended functionality required by the user.
- **Patches panel:** where a tabular view of all the defined patches.
- **Pointing panel:** All the attributes of each pointing is displayed
- **Query panel:** where different query criteria are present: Time interval selection, survey selection, dither selection, leading/trailing selection, observation duration selection, scientific merit selection, angles selection (SAA, alpha, beta, Solar panel aspect angle, field orientation, etc.)
- **Issues panel:** Upon loading a new survey a standard set of correctness tests are performed. Amongst the most important are: SAA and alpha angles and their time variation within limits, time between observations are enough to perform the needed slew. Each issue is individually reported.

All the panels in the tool are interconnected, for example all the observations selected in the query panel are automatically represented in the time and sky panel. The time selection is synchronized with the object selection at sky and pointing panel level.

The tool also sports as usual a menu bar from where usual operations can be performed, as for example, loading and saving schedules, exporting to other formats, load the most recent reference survey which is embedded into the software bundle, take a sky panel screenshot, change projection or the reference frame, clear the schedule, change the color assignment to observations (time, SAA, alpha angle, etc.).

The tool also contains a statistics menu, from where several statistics can be generated: amongst the most representative: the amount of cumulated area with time, spatial and time holes present in the survey, the histograms of several figures in observations (angles, slew time, slew excess, slew size, idle time, etc.)

The software is highly modular and is composed by a set of libraries (See Figure 14) that implements domain-related functionality as ephemerides, spherical geometry, vector calculation, focal plane management, schedule representation, time management, persistence, etc. Using these components several subsystems has been or will be implemented as for example the operational mission planning tool for performing the routine planning of the mission.

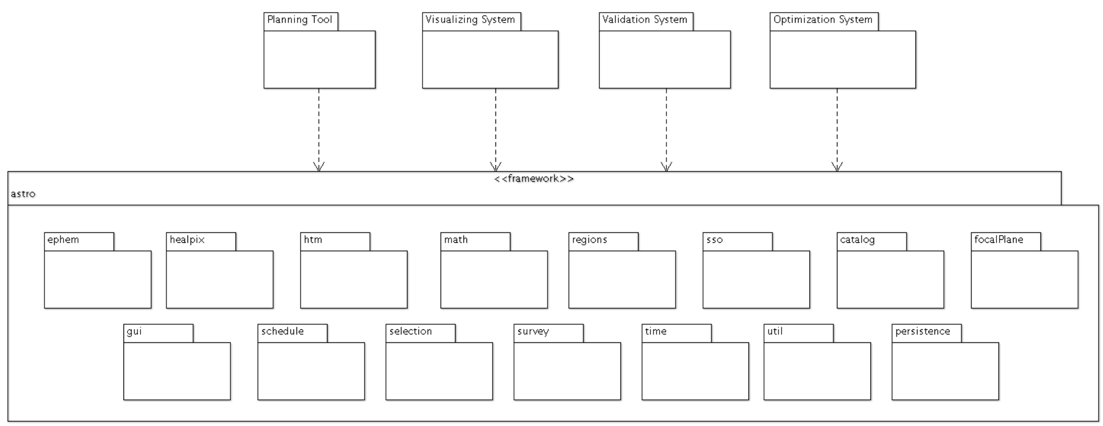

Figure 14 Euclid mission planning software framework

8. CONCLUSIONS AND FUTURE WORK

The Euclid mission planning problem and the adopted solution solution has been presented. The mission planning software was prototyped early into the mission which has been extremely useful both for receiving early feedback from a wide community which have been continuously retrofitting the development effort in very valuable ways. Thanks to its modular design, the software has been also used to generate a large number of artifacts (reports, statistical calculations, etc.), which produced added value in addition to the pure mission planning functionality to be performed during the mission. Agile methodologies has been used but has been tailored to each stage of the development phases. Euclid mission planning has been also a story of successful software reuse from Herschel mission planning software, beneficing from a previous 10-year development effort and from 4 years of testing, debugging and refining during its mission execution.

In the near future other related software modules will be developed. In particular in regards with the operability and reporting of the survey.

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