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Euclid: ESAs mission to map the geometry of the dark Universe

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ABSTRACT

Euclid is a space-borne survey mission developed and operated by ESA. It is designed to understand the origin of the Universe's accelerating expansion. Euclid will use cosmological probes to investigate the nature of dark energy, dark matter and gravity by tracking their observational signatures on the geometry of the Universe and on the history of structure formation. The mission is optimised for the measurement of two independent cosmological probes: weak gravitational lensing and galaxy clustering. The payload consists of a 1.2 m Korsch telescope designed to provide a large field of view. The light is directed to two instruments provided by the Euclid Consortium: a visual imager (VIS) and a near-infrared spectrometer-photometer (NISP). Both instruments cover a large common field of view of 0.54 deg^2, to be able to survey at least 15,000 deg^2 for a nominal mission of 6 years. An overview of the mission will be presented: the scientific objectives, payload, satellite, and science operations. We report on the status of the Euclid mission with a foreseen launch in 2019.

Keywords: *Euclid*, space telescope, astronomy, satellite, dark energy, dark matter, CCDs, near-infrared detectors

1. INTRODUCTION

In the concordance cosmological model, the Universe has evolved from a homogeneous state after the Big Bang, to a hierarchical assembly of galaxies, clusters and superclusters at our epoch. Remarkably, the energy density of the resulting Universe is dominated by two components, see e.g. [8]. First, 76% of the energy density is in the form of Dark Energy, which is causing the Universe expansion to accelerate. Another 20% of the energy is in the form of dark matter, which exerts a gravitational attraction as normal matter, but does not emit light. While several candidates exist in particle physics, the nature of dark matter is unknown. One possibility to explain one or both of these puzzles is that Einstein's General Relativity, and thus our understanding of gravity, needs to be revised on cosmological scales. Together, dark energy and dark matter pose some of the most important questions in fundamental physics today.

Euclid is designed to accurately measure the expansion history of the Universe and the growth of cosmic structures using a large area optical and near-infrared imaging survey and a massive spectroscopic survey in the wavelength range 1.1 − 2.0 micron. The mission yields comprehensive maps of the Universe, tracing the distribution of both its luminous and dark components over more than one-third of the sky and out to epochs when the Universe was less than 3 billion years old. The statistical properties of these distributions will also constrain properties of dark matter, including the contri-

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bution from neutrinos. Euclid is unique in the combination of its two primary probes, namely weak gravitational lensing and galaxy clustering: they not only allow the experiment to reach unprecedented statistical precision, but provide a crucial cross-check of systematic effects, which become dominant at these levels of precision. Euclid aims at improving the dark energy Figure of Merit (defined by $1/(\Delta w_p \times \Delta w_a)$). From the Euclid weak lensing and clustering information alone a FoM of ~430 can be derived, which is a factor ~20-40 higher than what is presently achievable by merging *all* known observations. The following topics with their key questions are addressed by Euclid:

1. **Dynamical Dark Energy:** Is the dark energy simply a cosmological constant, or is it a field that evolves dynamically with the expansion of the Universe?
2. **Modification of Gravity:** Alternatively, is the apparent acceleration instead a manifestation of a breakdown of General Relativity on the largest scales, or a failure of the cosmological assumptions of homogeneity and isotropy?
3. **Dark Matter:** What is dark matter? What is the absolute neutrino mass scale and what is the number of relativistic species in the Universe?
4. **Initial Conditions:** What is the power spectrum of primordial density fluctuations, which seeded large-scale structure, and are they described by a Gaussian probability distribution?

The fourth question helps improving our understanding of the physics that caused inflation, the first period of accelerated expansion when the Universe was only a fraction of a second old. Euclid complements the high-redshift picture of cosmology from the ESA Planck experiment by completing our census of the Universe at lower redshifts.

In case of galaxy clustering, by measuring the spectroscopic redshifts of more than 50 million galaxies in the redshift range $0.7<z<2.1$ the *three dimensional* galaxy distribution of the Universe can be mapped to high precision, and quantified in terms of its power spectrum (or correlation function) within several redshift bins over the time interval when dark energy becomes dynamically important. The amplitude, shape and anisotropy of these statistics contain the crucial information on the expansion and structure growth histories of the Universe. The baryon acoustic oscillations (BAO) are the imprint of sound waves from the era of the cosmic microwave background, about 400,000 years after the Big Bang. These waves cause a standard distance between galaxies with the distance increasing as the Universe expands. The details of this “length scale” would carry information about how the Universe has expanded at different epochs since the Big Bang. The length scale of these oscillations can be measured from the spatial correlation of galaxies. The BAO provide Euclid with accurate measurements of the Hubble parameter and the angular diameter distance, putting additional constraints on the Dark Energy.

Euclid uses weak gravitational lensing to determine the expansion and growth history of the Universe. This is possible because the gravitational potential of intervening structures perturbs the paths of photons emitted by distant galaxies. As a result the images of the galaxies appear slightly distorted. The amplitude of the distortion provides a direct measure of the gravitational tidal field, which in turn can be used to “map” the distribution of the dark matter directly. The availability of photometric redshifts for the galaxies means that is possible to study the dark matter distribution in three dimensions, called weak lensing tomography. The distributions as a function of redshift can be used to obtain the expansion and growth history of the Universe.

The Euclid wide survey yields:

- Determination of the shapes and shear of galaxies with a density of at least 30 galaxies/arcmin^2, obtained from high resolution images in the visible over the extragalactic sky of 15,000 deg^2.
- Determination of the photometric redshifts (“photo-z”) of the weak lensing galaxies with a photo-z accuracy of better than $dz/z = 0.05$.
- A spectroscopic redshift survey over the extragalactic sky of the same volume of Universe as the weak lensing experiment by measuring the spectroscopic redshifts with $dz/z < 0.001$ for at least 3500 galaxies per deg^2 over a total survey area of 15,000 deg^2.

The survey data can also be used to measure secondary cosmological probes such as the galaxy clusters, redshift space distortions, and the integrated Sachs-Wolfe effect (gravitational redshifts of the cosmic microwave background radiation).

The Euclid deep survey is two magnitudes deeper than the wide survey. The deep survey is needed for the calibration of the slitless spectroscopy, monitoring the stability of the detectors, and is also unique as a self-standing survey. Beyond the foreseen breakthroughs in fundamental cosmology, the Euclid surveys yield unique legacy science in various fields of astrophysics. In the area of galaxy evolution and formation, Euclid delivers high quality morphologies, masses, and star-formation rates for billions of galaxies out to a redshift of z~2, over the entire extra-galactic sky, with a resolution four times better and three NIR magnitude fainter than ground based surveys. The Euclid deep survey will probe the "dark ages" of galaxy formation as it is predicted to find thousands of galaxies at z>6, of which about a hundred could be at z>10, i.e. probing the era of re-ionisation of the Universe. With Euclid, the majority of the new sources identified by future observatories, from radio to X-rays, will be readily associated to a known redshift, out to a redshift of $z\geq2$.

In this paper we describe the payload and spacecraft (Section 2), the Euclid mission operations (Section 3), the ground segment (Section 4), and the mission management (Section 5). We reported on the status of Euclid in an earlier SPIE paper [1] based on the Assessment Study Phase. The present report describes the baseline mission as studied during Phase A, involving competing studies by two independent industrial consortia. It has been ensured that the performance of the baseline mission fulfills the science requirements. All sub-systems have a high technology readiness level, making sure that the baseline mission is feasible within the programmatic constraints. For further details of the Phase A study, we refer to [2].

2. PAYLOAD AND SPACECRAFT

2.1 Going to space

Weak gravitational lensing requires a high image quality to perform accurate galaxy shear measurements. Galaxy clustering requires near-infrared spectroscopic capability to measure galaxies at redshifts 0.7< z<2.0. Both probes demand a very high degree of system stability to minimize systematic effects, a good understanding of outliers in the galaxy samples, in terms of suppression and knowledge, and the ability to survey the extra-galactic sky at visible and near-infrared wavelengths up to 2 micron. Such a combination of requirements cannot be met from the ground, and demands a wide-field Visible/Near-Infrared space mission. Central design drivers for Euclid are the tight control of systematic effects and the survey speed to complete the surveys at the required depth within the nominal mission time.

The survey speed is guaranteed by the combination of a large field of view and an optimized survey strategy. Ensuring the high image quality leads to demanding requirements on the pointing and thermo-elastic stability. The survey depth leads to a minimum telescope aperture, dedicated baffling design, low temperature optics and detectors, a cold telescope for low near-infrared background, and on-board data processing for the noise and data rate reduction of the near infrared detectors.

2.2 Payload Module (PLM)

The Euclid payload module consists of a 1.2 m aperture telescope with two instruments: the visual imager (VIS) and the near-infrared spectrometer and photometer (NISP). The payload concept block diagram is presented in Figure 2. Both instruments share a large common field of view.

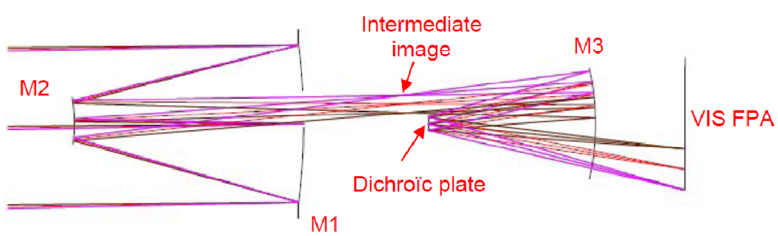

Figure 1. Scaled field of view of the unfolded Euclid telescope design. The NISP instrument, which is placed in the transmitted beam of the dichroic, is not shown.

The driving parameters for the telescope design are the demanding image quality requirements in the VIS channel for the point spread's function ellipticity, full width at half maximum, and the encircled energy. The baseline Euclid telescope is a three mirror Korsch configuration with a 0.45 deg off-axis field and aperture stop at the primary mirror (Figure 1). With three mirrors, there are enough degrees of freedom to achieve a good level of aberration correction and to achieve the required image scale and low distortion. The entrance pupil diameter is 1.2 m, the optically corrected and unvignetted field of view is 0.79×1.16 deg2, with a focal length of 24.5 m. A dichroic beam splitter is located at the telescope exit pupil: the reflected output goes to the VIS and the transmitted output to the NISP. To keep the internal background well below the zodiacal sky background the telescope and payload module operate at a reduced temperature. To minimize dark current noise, the maximum telescope temperature has to be below ~240 K.

The telescope is built on a truss hexapod concept: 6 struts are connecting the secondary mirror mounted on a frame through spiders to the primary mirror optical bench. The upper part of the optical bench supports the M1 and the M2 structure, the lower part supports the other telescope optics and both the VIS and the NISP instruments. The secondary mirror is integrated on a mechanism to correct for possible misalignments after launch, and potentially for any relaxation and thermal changes to focus. Illumination by the Sun is blocked by a sunshield on which the solar cells are mounted. A telescope baffle further minimizes scattered light from outside the field of view entering the telescope.

The VIS instrument consists of a CCD based focal plane array (FPA) with one wide visible band spanning the range ~550-900 nm, a shutter mechanism to close the optical path for read out and dark calibration, and a calibration unit for flat field measurements. The VIS channel measure the shapes of galaxies with about 0.16 arcsec (FWHM) system point-spread function excluding pixelisation. The FPA supports 6×6 CCDs (4k×4k pixels each) with 0.101 arcsec pixel platescale, giving a geometric field of 0.55 deg^2 including the gaps between the detectors. A detailed description of the VIS instrument can be found in Cropper et al [3].

NISP employs 4×4 HgCdTe NIR detectors (2k×2k pixels each) with 0.3 arcsec per pixel covering an area of ~0.55 deg^2. It can be operated in either photometer mode or slitless spectrometer mode by means of filterwheels. In photometer mode NISP images the sky in three filterbands (Y, J, H) covering the wavelength range 0.92-2.0 micron. In the slitless spectrometer mode, the light is dispersed by means of grisms in the wavelength range 1.1 to 2.0 micron at a constant spectral resolution $\lambda/\Delta\lambda \sim 250$. Two kinds of grisms with different passbands are used: two blue grisms transmit between 1.1 and 1.45 micron, while the two red grisms are transparent between 1.45 to 2.0 micron. Both sets of grisms are mounted in 0 and 90 deg orientation. A description of NISP is provided by Prieto et al [4].

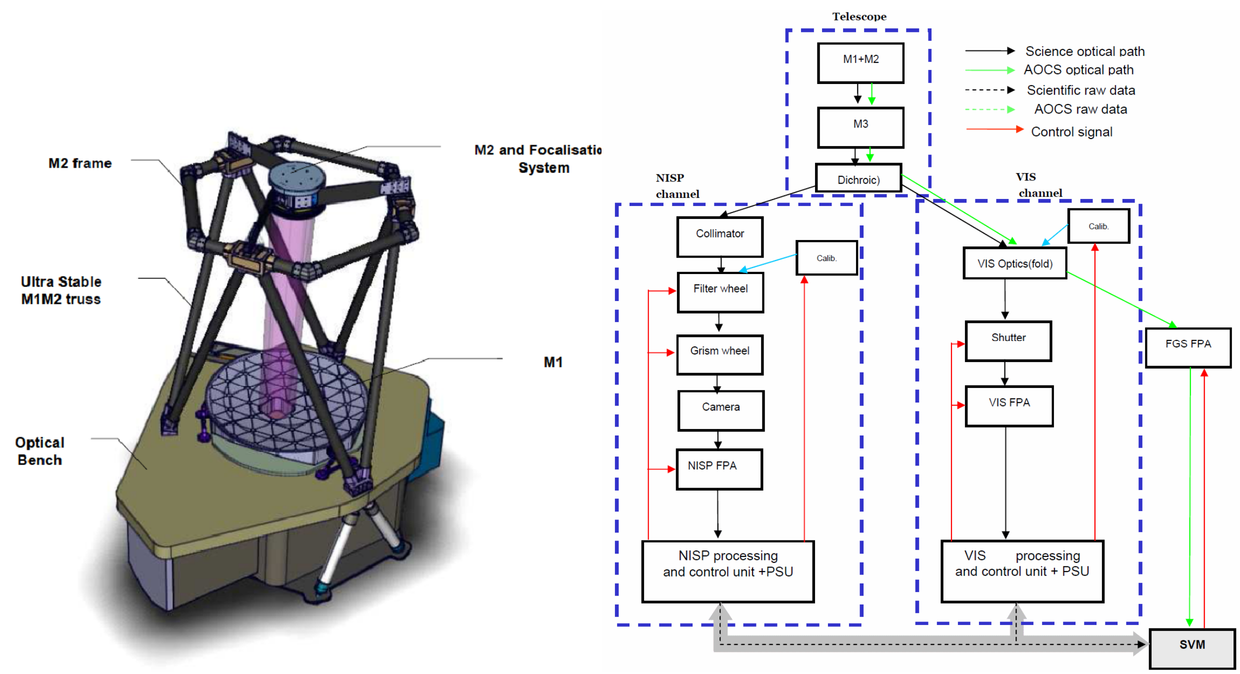

Figure 2. ***Left panel***: Typical telescope mechanical architecture (drawing kindly provided by Thales-Alenia Space). The optical bench supports M1 and the truss hexapod with M2 on one side, and the other telescope optical and the instruments on the other side. ***Right panel***: payload concept block diagram for Euclid showing the main elements of the payload: the telescope, VIS instrument and NISP instrument (blue dashed boxes). The fine guidance sensor focal plane array (FGS FPA) is part of the attitude and orbit control system (AOCS) and is mounted in the same plane as the VIS FPA.

2.3 Spacecraft

Measuring weak lensing places stringent requirements on the pointing stability to ensure optimum width and ellipticity stability of the point spread function (PSF). This demands a relative pointing error (RPE) of better than ~25 mas (1 sigma) in spacecraft *x* and *y* direction, and a fraction of arcsec (1 sigma) in *z* (roll) over the image accumulation time of ~600 s. An optical fine guidance sensor consisting of two separated CCDs is mounted close to the VIS focal plane. The dominating error source on the RPE is actuator thrust noise and the dominating control effort is the attitude knowledge noise. Conventional reaction wheels are discounted as the actuator to control RPE, because their noise budget is too high. Instead, cold gas micro-propulsion is considered enabling fine attitude control. The absolute pointing error (APE), governed by a startracker, must also be controlled to minimise overlap between adjacent fields.

The structural and thermal architecture provide a high degree of thermal isolation to the PLM as well as high thermal stability. The sunshield provides the main thermal barrier with respect to the solar heat load. The SVM architecture is derived of that of Herschel with 6 panels and a central cone, in which the propellant tanks are mounted. The Phase A studies of the spacecraft as designed by the two industrial contractors are presented in Figure 3.

Chemical (monopropellant hydrazine) propulsion is used for the transfer corrections, monthly station keeping manoeuvres, and large (180 deg) slew manoeuvres. Low gain antennas in the X-band are used to support the tele-commanding of the satellite and the transfer of instrument and spacecraft real time housekeeping data. The nominal downlink science data is performed by K-band (26 GHz) together with the stored housekeeping data at a maximum data volume of 850 Gbit/day. A steerable K band high gain antenna is used to downlink the science data. To avoid antenna pointing mechanism induced perturbations, antenna re-pointing is allowed in between steps or scans. Euclid is the first astronomy mission of ESA to require K band capability.

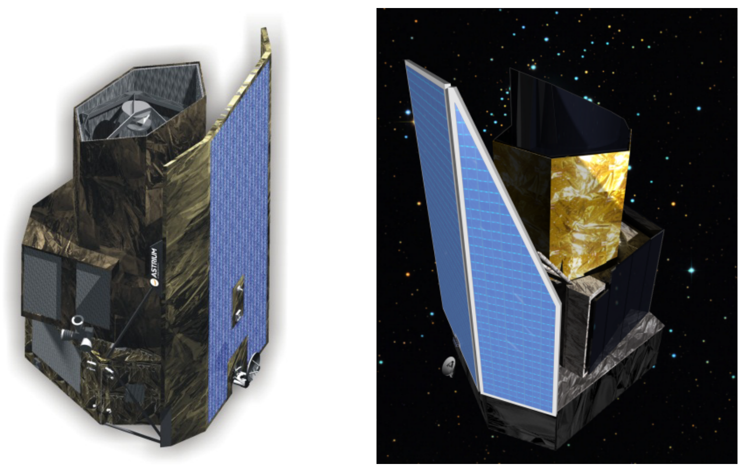

Figure 3. Phase A studies of the Euclid spacecraft. Left panel: design led by Astrium GmbH (Germany), right panel: design led by Thales Alenia Space Italy (Turin) . Distinguishable common features are (1) the sunshield with solar arrays pointing towards the sun and a steerable high gain K band antenna mounted at the bottom; (2) the SVM at the bottom, and (3) the PLM with baffled telescope truss and thermal radiators to regulate the temperatures in the instrument cavity.

3. THE EUCLID MISSION

3.1 Mission Operation

Euclid will be launched by the end of 2019 on a Soyuz ST-2.1B rocket, with an all-year round launch window. A direct transfer of ~30 days is targeted to a large-amplitude free-insertion orbit at the 2nd Lagrange Point of the Sun-Earth system. The nominal survey period is 6 years to complete the wide survey with the deep survey interspersed. Spacecraft commissioning, performance verification and initial calibrations require an additional 3-6 months. The sky mapping mode is step and stare. At least one ground station is available for a daily pass of 4 hours to operate the spacecraft and to receive the science data.

The elementary observation sequence for a given field in the survey is composed of four dither frames with a dither step in between. The dual capability of the NISP instrument, namely spectroscopy and photometry using the same near-infrared detectors, forces the two types of measurement to be carried out sequentially. The integration times per dither is graphically presented in Figure 3. After the fourth dither frame the field of view is slewed to the next field.

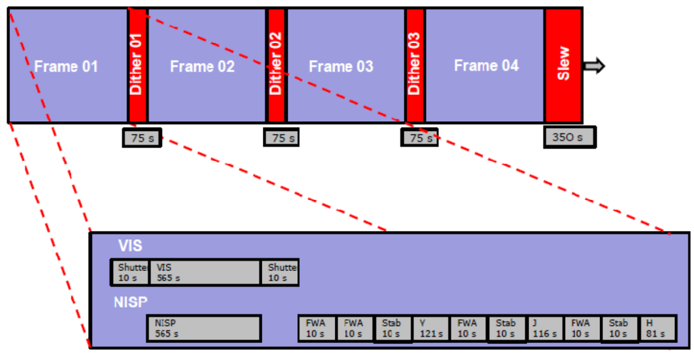

Figure 4. The nominal field observation sequence. The observation sequence consists of four dithers. Each dither is made up by a simultaneous VIS and NISP spectroscopy integration followed by the three NISP photometry measurements.

3.2 Survey properties

The wide survey covers 15,000 deg^2 of the extragalactic sky and is complemented by at least two 20 deg^2 deep fields observed on a monthly basis. For weak lensing, Euclid measures the shapes of resolved galaxies one broad visible band (550-900 nm) down to AB mag 24.5 (10 σ, extended source). The photometric redshifts of these galaxies are determined to a precision of $\sigma_z/(1+z) < 0.05$. These photometric redshifts are derived from imaging data in three additional Euclid near-infrared bands (Y, J, H in the range 0.92-2.0 micron) reaching AB mag 24 (5σ, point source) in each band, and necessarily complemented by ground based photometry in visible bands. Galaxy clustering is determined from a spectroscopic survey with a redshift accuracy $\sigma_z/(1+z) \leq 0.001$. The slitless spectrometer, with $\lambda/\Delta\lambda \sim 250$, predominantly detects Hα emission line galaxies for the redshift determination. The limiting line flux is 3×10^{-16} erg s^{-1}cm^{-2} (1 arcsec extended source, 3.5 sigma at 1.6 micron), yielding over 50 million galaxy redshifts with a completeness higher than 45%.

3.3 Survey strategy

The survey strategy depends on several parameters. The image quality depends on the thermo-elastic deformations of the payload, due to variations of the illumination of the spacecraft by the Sun. By design, the solar aspect angle (SAA), which is the angle between the boresight and the Sun, is allowed to vary between 90 and 120 deg. In general, thermo-elastic variations can be minimized by scanning the sky along lines with approximately constant SAA. During the Phase A study it was found that variations in SAA of less than 10 deg do not require additional stabilization time to maintain the same image quality. The diffuse zodiacal sky background limits the depth of the survey. As a consequence regions with ecliptic latitude |β| < 15 deg, where the zodiacal background is highest, are not included in the survey area. Low extinction and low stellar density regions have high priority, roughly excluding the regions close to the galactic plane with galactic latitude |b| < 20 deg. Eventually, extinction maps and stellar density models will be used to refine the determination of the boundary of the galactic polar caps suitable for the Euclid survey. A detailed description of the Euclid reference survey can be found in Amiaux et al [5].

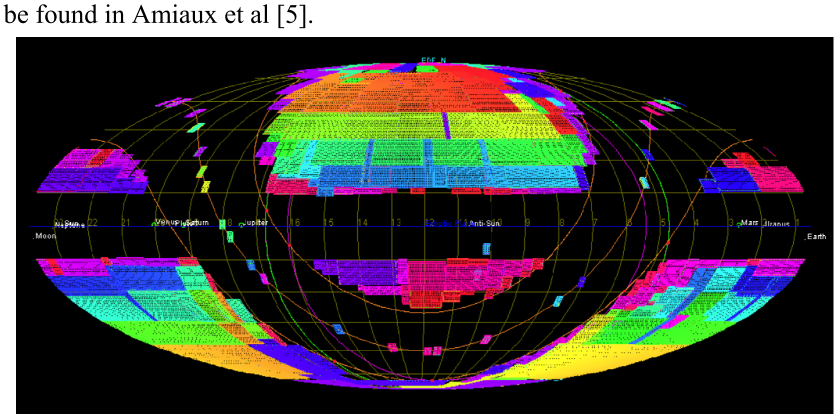

Figure 5. An instance of the Euclid sky survey covering 15.000 deg^2 obtained within a six year mission [5]. The Mollweide map is given in ecliptic coordinates; the orange lines indicate the galactic plane and b=±20 deg. This survey includes the deep fields at the ecliptic poles and the calibration regions. Different colours represent the year in which the regions have been collected (blue, green, red, light blue, purple, and yellow: for the 1st to the 6th year, resp.)

4. GROUND SEGMENT

The spacecraft health and safety and instrument safety are monitored by the Mission Operations Centre (MOC) located in Darmstadt (Germany). MOC controls the spacecraft attitude and handles the telemetry and telecommanding for both spacecraft and instruments. MOC also controls the ground stations. The Science Operations Centre (SOC), located in Madrid (Spain), is part of the Euclid science ground segment (SGS) and is responsible for executing the planned surveys, i.e. scheduling the spacecraft slews, scheduling the observations, monitoring the survey performance, rescheduling, and requesting MOC action via predefined procedures and sequences of telecommands. It receives the telemetry from MOC, does a first level processing and quality check to the science data and delivers these data to the science data centres (SDCs) for further processing. SOC is also responsible for the public releases of the data via its legacy archive. The SDCs will host the instrument operation teams, which are responsible for monitoring the health of the instruments and the understanding of instrumental effects in the science data, see also Valenziano et al [7].

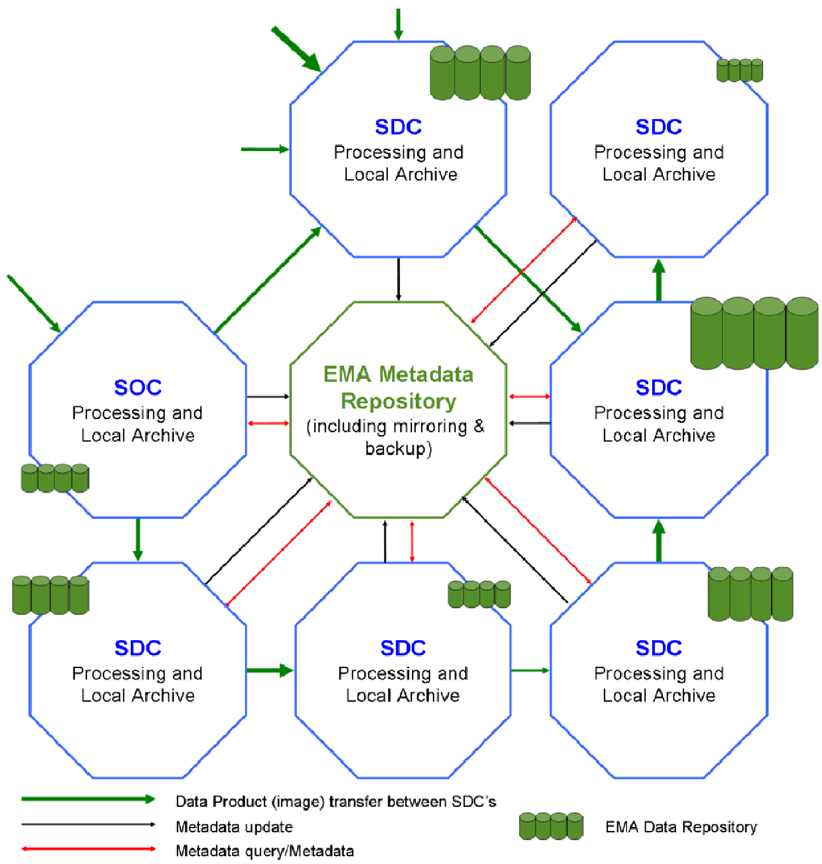

Figure 6. The Euclid SGS logical reference architecture

Since large and reliable computing resources are needed, the backbone of the science ground segment is formed by the science data centres, located in participating countries of the Euclid Consortium. The SDCs are in charge of developing and running data processing functions of the Euclid pipeline. In most cases the infrastructure of these data centres already exists and provides services to the astrophysics or particle physics community. The SDCs are manned with information technology experts such that system maintenance is guaranteed from day one to the last days of the Euclid post-operations phase. The Euclid Consortium is in charge to develop the scientific processing algorithms based on the science requirements and the operational pipelines to produce the scientific data products.

The key features of Euclid are the amount of data that the mission will generate, the heavy processing that is needed to go from the raw data to the science products, and the accuracy and quality control that are required at every step in the processing. This enforces a *data-centric* approach: all SGS operations revolve around the Euclid Mission Archive (EMA) a central storage and inventory of the data products and their metadata including quality control, see also Pasian et al [6]. A schematic depicting the SGS logical architecture is presented in Figure 6. The orchestration of data exchange and metadata update through SOC, SDCs and EMA is performed by a monitoring and control function. The SOC and the EC have the joint responsibility of guaranteeing homogeneity in data access, and of providing integrity, security and the appropriate level of quality control.

5. MISSION MANAGEMENT

The Cosmic Vision Plan objective is to define and implement the future ESA science missions through a competitive process starting from open "Calls for Missions" to the science community and ending by a selection of the missions to be adopted through two down-selection steps. The science return value, the design and technical maturity and the budget are the key mission elements supporting this decision process. In October 2011, the Euclid mission was selected amongst a number of candidate missions for the second medium class launch slot (M2) of the Cosmic Vision Plan. The following development milestones are envisaged:

- 2013: System Requirements Review
- 2014: System Preliminary Design Review
- 2016: System Critical Design Review
- 2017: Instrument deliveries by the Euclid Consortium
- 2019: Launch

For the space segment ESA provides the spacecraft and the payload module, which includes the telescope. ESA also procures the CCDs and near-infrared detectors for the scientific instruments. ESA starts with the procurement of the PLM, and once the PLM industrial contractor has been selected, a tender is issued for a Prime Contractor to develop the spacecraft and system. This process is formally closed with the System Requirements Review (SRR). For the ground segment, ESA is in charge of the MOC and the SOC.

The Euclid Consortium (EC) is funded by the national funding agencies, and has been selected to provide the VIS and NISP instruments, and elements of the science ground segment, related to the scientific pipelines generating the data products and to the instrument in-orbit maintenance and operations. In addition, the EC is deeply involved in the assessment of the scientific requirements and scientific performance of the mission. The EC is composed of more than 900 individuals, of whom more than 500 researchers, residing in more than 100 laboratories from 13 European countries.

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