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SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2014, Montréal, Quebec, Canada

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ABSTRACT

In June 2012, Euclid, ESA's Cosmology mission was approved for implementation. Afterwards the industrial contracts were signed for the payload module and the spacecraft prime, and the mission requirements consolidated. We present the status of the mission in the light of the design solutions adopted by the contractors. The performances of the spacecraft in its operation, the telescope assembly, the scientific instruments as well as the data-processing have been carefully budgeted to meet the demanding scientific requirements. We give an overview of the system and where necessary the key items for the interfaces between the subsystems.

Keywords: Euclid Mission, cosmology, sky survey, near infrared survey, space telescope

1. INTRODUCTION

With the selection of the main industrial partners, the implementation of the Euclid mission is at a stage where the global design solutions are being consolidated. In this paper we describe the choices made since our previous report of 2012 [1], which was written just prior to mission approval by the Space Programme Committee of ESA in June 2012. Besides the space segment we will give a status of the ground segment, in particular the organisation of the science ground segment, to process the Euclid science telemetry into data products.

This paper is organised as follows. Section 2 summarises the science case for Euclid. Section 3 describes the payload module (PLM) and its instruments. An overview of the satellite service module (SVM) and relevant subsystems is provided in Section 4. The mission, survey operations, and ground segment are given in Section 5. Section 6 concludes with the present programmatic status.

2. EUCLID SCIENCE CASE

Euclid is ESA's next cosmology mission after Planck. Whilst Planck mapped the intensity and polarisation of the cosmic microwave background revealing the structure and properties of the early Universe at a redshift of $z\sim1100$, Euclid will

Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann, Jr., Mark Clampin, Giovanni G. Fazio, Howard A. MacEwen, Proc. of SPIE Vol. 9143, 91430H · © 2014 SPIE
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map the evolution of cosmic structures from z~2 until now. Euclid uses the clustering of matter, which includes both dark matter and luminous, baryonic matter, to measure the accelerated expansion of the Universe at different cosmological times. The accelerated expansion is attributed to Dark Energy, a substance of unknown nature. Euclid aims at measuring the equation of state parameter $w(z)$ to an accuracy of 2% for the constant component, and 10% for a possible variation as a function of redshift. If $w(z)$= constant =-1, then the universe can be described by general relativity with a cosmological constant. At the moment such a description cannot be reconciled with the standard model in particle physics. A significant non-zero variation would mean that our understanding of general relativity needs to be revisited. It is the accuracy of the Euclid measurements that will put strong constraints on any fundamental physics theory.

Euclid will use a number of cosmological probes to measure the clustering properties but is optimised for two methods: (1) Galaxy Clustering (GC): measurement of the redshift distribution of galaxies from a Hα emission line survey using near-infrared slitless spectroscopy and (2) Weak Lensing (WL): measurement of the predominantly dark matter distribution from the measurement of the distorted galaxy images due to the lensing caused by matter between the galaxies and the observer. If the redshifts of the lensed galaxies are known then the distribution of the dark matter as a function of redshift can be obtained. In addition, GC would also provide direct information of the validity of general relativity because we can monitor the evolution of structure subject to the combined effects of gravity, which forces clumping of matter, and the opposing force caused by the accelerated expansion. GC maps the distribution of the luminous, baryonic matter whereas WL measures the properties of the dark matter. The complementarity of the two probes will provide important additional information on possible systematics which limit the accuracy of each of the probes.

The mission will address the following items and associated key questions:

- 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?
- 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?
- Dark matter. What is dark matter? What is the absolute neutrino mass scale and what is the number of relativistic species in the Universe?
- 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?

3. PAYLOAD

3.1 Payload Module (PLM)

The Euclid PLM accommodates the telescope assembly and the two scientific instruments. In December 2012, ESA selected Airbus Defense and Space (Toulouse, France) to lead the PLM procurement. The PLM contractor was selected several months earlier than the prime industrial contractor to enable early procurement of the telescope, which is a long lead item. ESA managed the PLM contract until the selection of the Prime Contractor, who took over this responsibility.

The PLM provides optical, mechanical, and thermal interfaces to the instruments. The thermal interfaces consist of radiating areas and heating lines. The PLM consists of a front cavity with the primary and secondary mirrors and their support structure, and an instrument cavity at the other side of the base plate with the folding mirrors, tertiary mirror, dichroic and instruments, see Fig. 1.

The Euclid telescope consists of a Korsch three mirror anastigmat (TMA) with a primary mirror diameter of 1.2 m (collecting area is 1 m^2) and a focal length of 24.5 m. The Korsch TMA provides a large, slightly off-axis, field of view of more than 0.5 deg^2. A detailed description of the telescope system design can be found in Gaspar Venancio et al. [2]. A dichroic is placed in the exit pupil of the telescope to split the light between the VIS channel (by reflection) and the NISP channel (by transmission). The telescope is diffraction limited at wavelengths longer than 800 nm, and its design is optimised to meet its part of the WL image quality requirements for the system at 800 nm: (1) ellipticity, (2) the squared rms radius (R2) and (3) full-width at half-maximim (FWHM) for the point spread function. The VIS bandpass of 550-900 nm including a stringent out of band suppression of less than 0.1% in the 300-550 nm range and longward of 900 nm, is provided by the telescope mirrors and dichroic, which are all reflective.

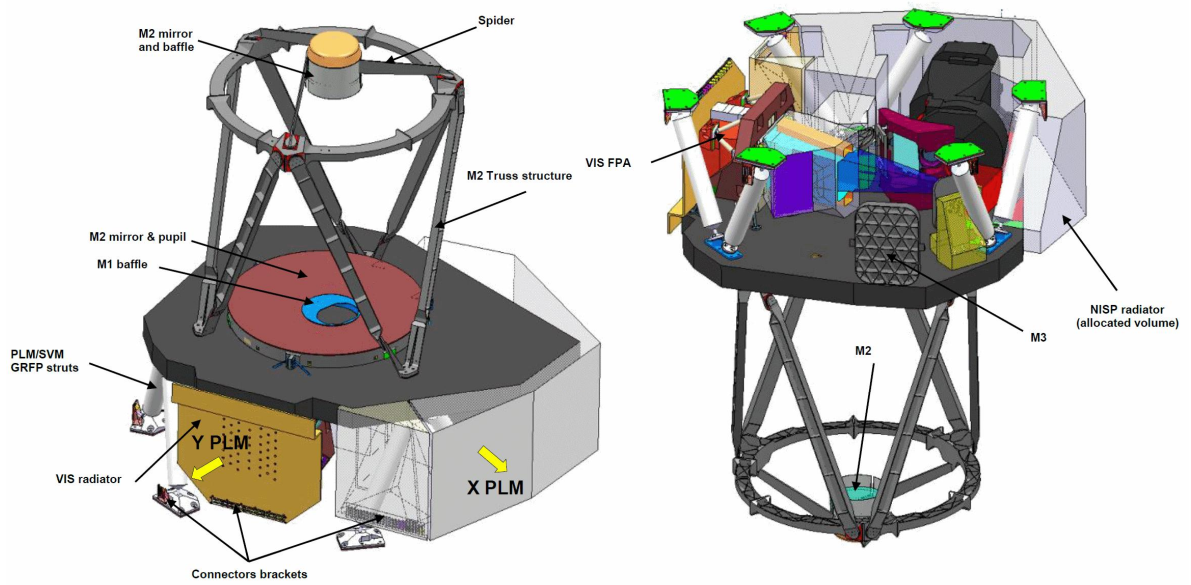

Figure 1: Top and bottom views of the PLM telescope with the VIS and NISP instruments. Image of Airbus Defense and Space, Toulouse.

An important design driver for the payload is to maintain a high and stable image quality over a large field of view. Building on the heritage from Gaia, all mirrors, telescope truss and the optical bench (baseplate) are made of Silicon Carbide (SiC). The telescope structure, baseplate, and instruments are passively cooled to a constant cryogenic temperature of 130 K. This homothetic design provides a high thermo-elastic stability to enable the demanding optical quality and a cold environment to the instruments. The secondary mirror is mounted on a focusing mechanism with three degrees of freedom, which will be employed to re-focus the telescope image on the VIS detector plane after launch and cool down. It is not expected that the focusing mechanism will be used more than once in orbit, but this capability is still anticipated for design and testing.

3.2 VIS instrument

The VIS (visual) instrument is optimised to register resolved images of galaxies in the 550-900 nm passband. A detailed description of the instrument can be found in Cropper et al. [3]. The VIS nominal survey images have a 10 sigma extended source detection limit of AB 24.5 mag and are used to determine the shapes of at least 30 galaxies per arcmin^2 over the survey area, in order to derive the galaxy shear caused by the weak gravitational lensing due to the presence of matter.

The VIS instrument consists of a CCD based focal plane array (FPA) employing one wide visible passband, a shutter mechanism to close the optical path for read out and dark calibration, and a calibration unit for flat field measurements. The FPA supports 6×6 CCDs (4k×4k pixels each) with 0.10 arcsec pixel plate scale, giving a geometric field of greater than 0.5 deg^2 including the gaps between the detectors. The VIS data processing and instrument control units (CDPU and PMCU) are mounted the spacecraft service module. The VIS central data processing unit CDPU has to be sufficiently powerful to fetch data from 144 CCD quadrants, to arrange all of the pixels in the correct order, and then to compress this very large image (24k x 24k), in approximately 250 sec. The VIS power and mechanisms control unit PMCU has to activate the shutter and the calibration unit. To have full control over the sources of systematic errors no additional VIS image processing will be done on board, all CCD data are transferred to ground; see Short et al. [4] for a detailed description of the CCDs in Euclid.

3.3 NISP instrument

The NISP instrument is designed to carry out slitless spectroscopy and imaging photometry in the near-infrared (NIR), see Maciaszek et al. [5] for a detailed description of the instrument. The NISP spectroscopy supports the galaxy clustering probe and is optimised to measure the redshifted Hα (rest wavelength 656.3 nm) emission line of galaxies with redshifts between z=0.8 and z=1.8. NISP will detect redshifts of at least 1700 galaxies/deg^2 in the corresponding wavelength range 1250-1850 nm, at a detection limit of 2×10^{-16} erg/s/cm^2 (3.5 sigma) for a typical source of 0.5 arcsec. The imaging photometry supports the weak lensing probe by photometric measurements of galaxies down to AB 24 mag (5 sigma point source) in three Euclid bands: Y, J, H.

NISP contains an array of 4×4 HgCdTe NIR detectors (2k×2k pixels each) with 0.3 arcsec per pixel. The sensors are of type H2RG; the sensor chip system consisting of the sensor chip assembly, SIDECAR read-out electronics, and flex cable connecting each sensor to each SIDECAR read-out electronic unit, is provided by Teledyne Imaging Systems (Camarillo, CA). The qualification and evaluation phase of the sensors will be completed in 2014. During this phase a batch of customised H2RG sensors with 2.3 micron long-wavelength cutoff have been manufactured and measurements showed that performances are in line with requirements. The 2.3 micron cutoff (and not 2.5 micron) was chosen to minimise thermal noise.

NISP can be operated in either photometer mode or slitless spectrometer mode by means of a filter wheel and a separate grism wheel. In the slitless spectrometry mode, the light is dispersed by grisms in the wavelength range 0.92 to 1.85 micron with a constant $\Delta\lambda$ at a spectral resolution $\lambda/\Delta\lambda > 380$ for an object of 0.5 arcsec diameter. NISP will carry out the detector voltage ramp processing on board providing one photometric or spectroscopic image per exposure. This sets a high demand on the processing capabilities and the power consumption of the NISP warm units.

4. SPACECRAFT

In July 2013, ESA selected Thales Alenia Space (Turin, Italy) to lead the development of the Euclid spacecraft.

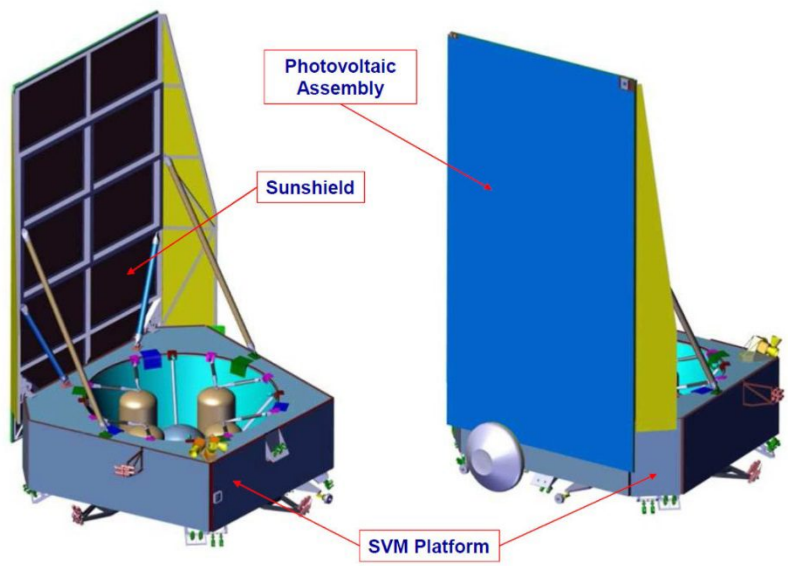

Figure 2: Views of the Euclid service module (SVM) with sunshield. Images of TAS-I (Turin)

The Euclid image quality requirements demand very precise pointing and small jitter, while the survey requirements call for fast and accurate slews. The attitude and orbit control system (AOCS) designed by TAS provides 25 milli-arcsec Relative Pointing Error over 700 s (RPE, 1-sigma), and 2.5 arcsec Absolute Pointing Error (APE, 1-sigma), using the following equipment set. A Fine Guidance Sensor (FGS), consisting of four CCDs of the same type as the VIS detectors, provides the fine attitude measurement. The FGS is mounted at the focal plane of the telescope on two sides of the VIS array; thus it shares the telescope optics and bandpass while working at higher sampling rate. Cold gas thrusters with micro-newton resolution, similar to those used in Gaia, provide the forces used to actuate the fine pointing. The FGS-based attitude control rejects the low frequency noise (less than 0.1 Hz) ensuring that the RPE requirement is met. Three star trackers (STR) provide the inertial attitude accuracy to comply with the APE requirement. The STRs are mounted on the SVM and thus subject to thermo-elastic deformation when large slews are executed. To solve this problem, the FGS will be endowed with absolute pointing capabilities (based on a reference star catalogue), allowing cross-calibration of STR and FGS reference frames. A high performance gyroscope is included to reduce high frequency attitude estimation noise, manage FGS delays and allow recovery from temporary outages. Four reaction wheels execute all the slews (field slews, 50- to 100-arcsec dithers, and large slews between different sky zones). After each slew manoeuvre the wheels are controlled to slow down until friction stops them. The start-and-stop mode of operation ensures noise-free science exposures by eliminating the micro-vibration associated to reaction wheel actuation.

In order to support the data rate of maximum 850 Gbits in 4 hours, a 70 cm diameter steerable high gain antenna is mounted on the spacecraft.

5. OPERATIONS

5.1 Mission operations

Euclid is scheduled for launch in 2020 with a Soyuz ST-2B Fregat combination. Euclid has a daily launch window. One of the key elements driving the launch window duration is the minimum sun angle with the telescope boresight, which should remain above 30 deg.

The spacecraft will be placed in a large halo Lissajous orbit around the second Sun-Earth Lagrange point (L2) with an orbital period of 6 months. L2 provides access to a large sky visibility with reduced thermal modulations and straylight from Sun, Earth and Moon. Seen from the Earth, the orbit describes a Lissajous figure around the anti-Sun direction on the sky with maximum distance from the anti-Sun direction of ~33 deg. Due to this seasonal variation Euclid is nominally tracked by two ground stations of the ESA network, one on the Northern hemisphere located in Cebreros, Spain, and one on the Southern hemisphere located in Malargue, Argentina. Both stations will be equipped with K-band receivers for the downlink of the science data. Euclid is the first astronomical satellite from ESA employing the K band. The commanding and housekeeping data are transmitted in the X band.

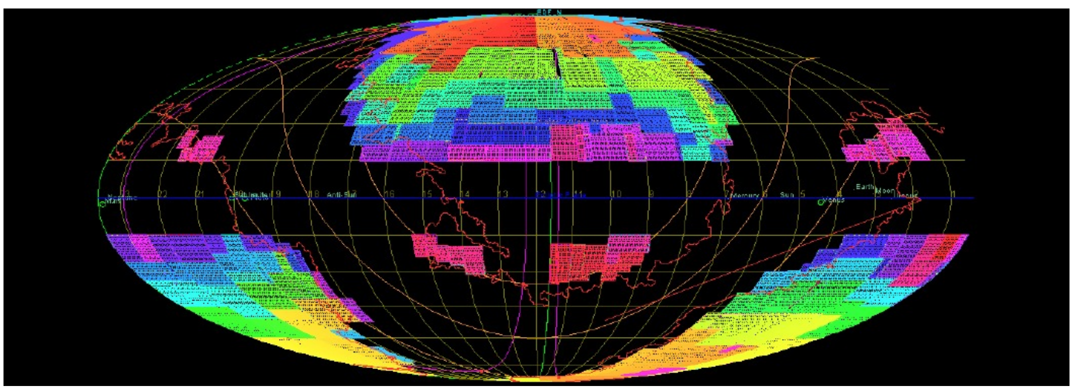

Figure 3: Mollweide projection of the Euclid reference survey for a 6 years nominal mission. Different colours indicate different years during the mission.

During routine operations, Euclid has a daily commanding and data transfer period of 4 hours, with a maximum down-link telemetry rate of 74 Mbit/s. Euclid will be observing autonomously by executing an uplinked timeline, but in case of data transfer contingencies, Euclid has enough mass memory (over 4 Tbits) to ensure a continuous storage of data without ground contact for three days. The science data are transferred using the CFDP file transfer protocol between the satellite and the ground station. This file based transfer (and not using conventional packets) is new for operations by ESA.

The commissioning phase already starts during transfer to the L2 orbit. In this period the spacecraft and payload systems and interfaces are commissioned. In the subsequent Performance Verification Phase the performance of the scientific instruments is verified, and the initial instrument calibrations are carried out. Some three months after launch, the routine phase of nominally 6 years is started in which the survey operations take place.

The Euclid mission operations are done from the European Space Operations Centre (ESOC) in Darmstadt, where also the ground stations at Malargue and Cebreros are operated. The science operations are done from the European Space Astronomy Centre (ESAC) in Villanueva de Canada, near Madrid, which hosts the Euclid science operations centre (SOC). The planning of the survey is performed in close collaboration with the Euclid Consortium, in charge of investigating survey strategies, including the calibration observations, and survey optimisation. At ESAC the first processing is performed of the science telemetry data. The resulting products are distributed to the Science Data Centres (SDCs), which are responsible for the scientific processing of the data.

5.2 Survey operations

Within its 6 year nominal mission, Euclid will carry out a Wide Survey of 15,000 deg^2 and a Deep Survey of at least 40 deg^2. Due to the required image quality, the spacecraft is three axis stabilized, and operates in a step-and-stare mode. With a VIS and NISP common field of view of 0.54 deg^2, the survey will contain at least 30,000 survey field pointings. The Deep Survey imaging has a detection limit at least 2 magnitudes deeper than the Wide Survey; this corresponds to about 40 Wide Survey exposures on the same sky position.

To meet the required galaxy density of more than 30 galaxies/$arcmin^2$ for the wide weak lensing survey, the plane of the Milky Way is avoided (i.e. galactic latitudes $|b| < 30$ deg are excluded, but also regions of high galactic extinction) as well regions of high zodiacal background emission at ecliptic latitudes $|\beta| < 20$ deg. It should be noted that these zones of avoidance are not strictly followed: Euclid will observe calibration fields in the galactic plane and fields at low ecliptic latitude. The Deep Survey will have at least two regions close to the two ecliptic poles, which guarantees an all-year visibility. In Fig. 3 shows the reference survey based on the latest spacecraft constraints and calibration requirements.

Per field Euclid observes 4 pointing “dithers”. We define a dither as a pointing close to the field position to fill the gaps between the detectors in the focal plane and to improve the pixel sampling of the sky. Per dither Euclid will measure one VIS image, one NISP grism spectroscopy measurement, and three NISP (in Y, J, H) photometry images. In addition, per field VIS may collect one short exposure obtained in parallel during one of the NISP photometry measurements, the technical feasibility of this exposure is under investigation. This extra exposure would improve the dynamic range of the VIS imaging, and - besides its scientific value - can be used to improve the VIS calibrations, in particular the calibration of the point-spread function using bright stars. A schematic overview of observational procedure during a field pointing is given in Fig 4.

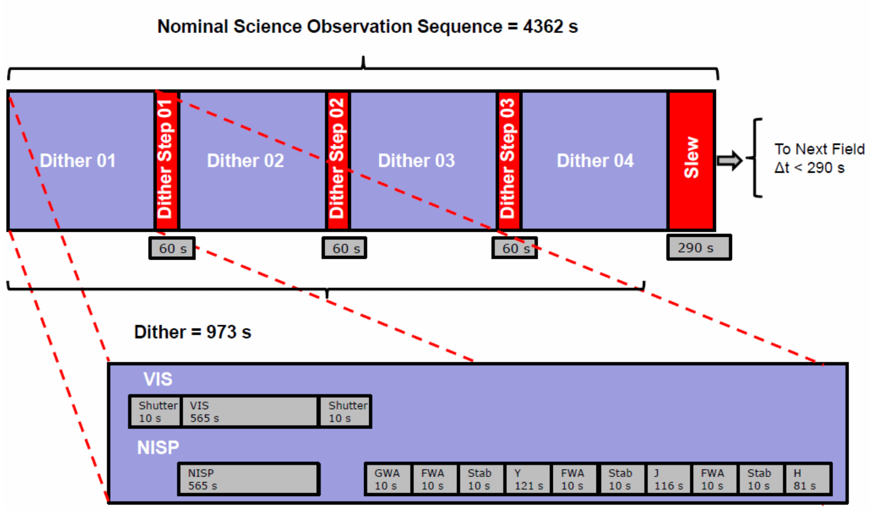

Figure 4: Nominal Wide Survey field observation. One observation consists of 4 dither pointings, each containing a sequence of exposures with VIS and NISP instruments. The VIS short exposure is not included in this diagram.

5.3 Science data processing

Depending on the compression rate, Euclid will produce 50-100 TByte of uncompressed science data per year. Together with ESA, the science community has worked out the SGS operations concept, which has led to an agreed set of science implementation requirements for the SGS. The implementation encompasses the definition of tasks and interfaces of the science data centres and the architecture of the SGS that includes operation of the mission and the data archive. The organisation and the workpackages were kicked off immediately after adoption, anticipating the substantial amount of software development before and after launch, see also Pasian et al. [6] for a detailed description.

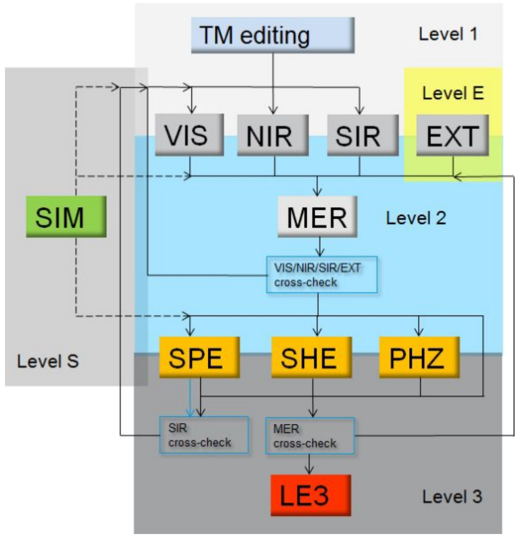

Figure 5: The SGS data processing organisation. Indicated are the different levels and the ten functions providing the data processing stages. The arrows indicate the flow of information between these stages. Level S is responsible for the provision of simulated data. Level E procures the external data from ground based surveys, most of these data are needed to complement the Euclid photometric measurements to derive the photometric redshifts of the WL galaxies down to the required accuracy of 5%..

The Euclid SGS consists of the SOC, the science data centres (SDCs), and the operational units (OUs). The SOC will carry out the Level 1 processing, and pass these data to the SDCs which will perform the Level 2 - the removal of instrumental effects and calibration of the data - and the level 3 - scientific analysis - processing. The SGS consists of ten processing functions (see Fig. 5): the respective pipelines are prepared jointly by the Organisation Units (OUs), large teams of scientists responsible for the development of the data processing algorithms, and by the SDCs that are in charge of the integration of the code within a well-engineered pipeline.

The data products are distributed to the general community by ESA, who will maintain the legacy archive. It has been recognised by the Euclid SGS that the performance of the overall processing is limited by the transfer of data between the SDCs. The data transfer will not evolve as powerfully as the processing speed or data storage capabilities. The pipelining concept where the results of one data centre is subsequently processed by the next centre has been abandoned, instead the concept of micro-pipelining is adopted. This concept assumes that all SDCs can carry out a full processing starting from Level 1 on a given data set. This dataset is preferentially a connected area, or a “patch”, of sky to ensure uniformity of the processing of adjacent fields. This concept is presently being worked out by the Euclid SGS.

The Euclid products will be released according to a release schedule which was approved by the ESA advisory structure in 2013. The Level 1, 2, and 3 data products are made available to the astronomical community via the ESA archive. In addition, quick data releases are planned: Level Q data consist of Level 2 data and represent products suitable for most purposes in astronomy, except for the core cosmology objectives of the mission. The first Level Q product delivery takes place 14 months after the start of the survey and consists of ~50 deg^2 of survey area. The release of the first year of survey data with products from all levels will happen one year later. Subsequent complete data releases are planned such that each release enables meaningful advances relative to the previous one: the second complete data release covers the first 3 years of the survey and happens 3 years and 14 months after the start of the nominal mission, the third and last complete data release covers the whole survey and occurs 3 years later. Subsequent complete data releases encompass the reprocessing of the previously processed data, this is to ensure that the archived products are homogeneously reduced. Level Q product deliveries are scheduled during the years where no complete data release takes place.

6. PROGRAMMATIC STATUS

The scientific community proposed weak lensing and galaxy clustering missions for ESA's Cosmic Vision call in 2007, and these were combined by ESA into a single mission named Euclid by the combined consortia in early 2008. The Euclid Consortium (EC), funded by national agencies, has been selected to provide the VIS and NISP instruments, and elements of the SGS related to the scientific pipelines for generating the data products and the instrument in-orbit maintenance and operations. The multi-lateral agreement between ESA and 11 supporting funding agencies of the Euclid Consortium member states was signed in November 2013.

The number of EC members has grown to yield more than 1200 individuals, spread over 15 countries, most of them ESA member states, and over more than 120 institutes. The data processing challenge is well-recognised by the EC: the allocated funding of the contribution to the SGS exceed the costs of the instruments. The EC is now one of the largest astronomical consortia ever, reflecting the large interest by the community not only for the core science - cosmology - but also for legacy science projects. The EC has proprietary access to the data prior to the public data releases.

A Memorandum of Understanding between ESA and NASA was signed in January 2013, for the NASA provision of the flight models of the infrared sensors for the NISP instrument. The number of scientists in the US team is commensurate to the NASA contribution to the mission. NASA will also support a US based science data centre at IPAC (Caltech).

Presently we are completing the PLM preliminary design review (PDR), after the instrument PDRs held earlier in 2014. The Mission-PDR is foreseen to take place in the first half of 2015. For the science ground segment the system requirements review is to be finalised by the end of 2014. We are on schedule for a launch in the first quarter of 2020.

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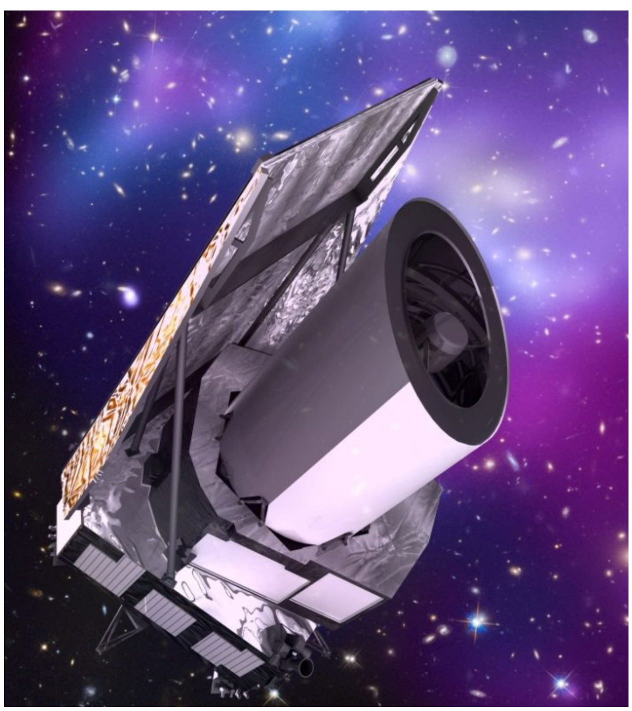

Figure 6: artist impression of the Euclid satellite.