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René J. Laureijs, Ludovic Duvet, Isabel Escudero Sanz, Philippe Gondoin, David H. Lumb, Tim Oosterbroek, Gonzalo Saavedra Criado, "The Euclid Mission," Proc. SPIE 7731, Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave, 77311H (5 August 2010); doi: 10.1117/12.857123

Event: SPIE Astronomical Telescopes + Instrumentation, 2010, San Diego, California, United States

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ABSTRACT

Euclid is a high precision survey mission under development by the European Space Agency to investigate the properties of Dark Energy and Dark Matter by means of a weak lensing and baryon acoustic oscillations experiments. The technical capabilities of Euclid are such that it also addresses other cosmological and astronomical topics, providing an unprecedented science legacy. The survey mission will carry out an imaging and spectroscopic survey of the entire extragalactic sky (20,000 deg^2). Euclid carries a meter class telescope which feeds two instruments: a visible imager (VIS), a near-infrared photometer combined with a medium resolution spectrometer (NISP). The two instruments have identical sized field of views (0.5 deg2) and will operate simultaneously in step-and-stare mode. The nominal mission period is 5 years. We describe the mission, the satellite, and the payload concepts, which we have adopted at the start of the definition phase.

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

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 mysterious components. First, 76% of the energy density is in the form of Dark Energy, which is causing the Universe expansion to accelerate. The existence and energy scale of Dark Energy is in conflict with our knowledge of fundamental physics. 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 a high-precision survey mission developed by the European Space Agency (ESA) designed to answer these fundamental questions. Euclid will map the large-scale structure of the universe over the entire extragalactic sky out to redshifts of 2 (about 10 billion years ago), thus covering the period over which dark energy accelerated the universe expansion. The mission is optimized for two primary cosmological probes: Weak gravitational Lensing (WL) and Baryonic Acoustic Oscillations (BAO). Weak lensing is a method to map the dark matter and measure dark energy through the distortions of galaxy images by mass inhomogeneities along the line-of-sight. These distortions appear as shear patterns in the images of the background galaxies. 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. Assuming that the distribution of galaxies reflects the distribution of all matter, 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.

By measuring the two probes simultaneously, Euclid constrains Dark Energy, General Relativity, Dark Matter and the Initial Conditions of our Universe with unprecedented accuracy. Euclid will also make use secondary cosmological probes such as the Integrated Sachs Wolfe Effect (ISW), galaxy clusters and redshift space distortions to provide additional measurements of the cosmic geometry and structure growth. The two primary probes require:

- Determination of the shapes and shear of galaxies with a density of 30-40 galaxies/arcmin^2 over the entire extragalactic sky of 20,000 deg^2.

Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave,
edited by Jacobus M. Oschmann Jr., Mark C. Clampin, Howard A. MacEwen, Proc. of SPIE
Vol. 7731, 77311H · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857123

- Determination of the photometric redshifts ("photo-z") of the weak lensing galaxies with a photo-z accuracy of $dz/z = 0.05$ down to 0.03 (requirement, goal).
- A massive spectroscopic redshift survey over the entire extragalactic sky of the same volume of Universe as the weak lensing experiment by measuring the spectroscopic redshifts with $dz/z < 0.001$ over an area of 20,000 deg^2.

The Euclid mission concept was selected early 2010, to undergo a competitive Definition Phase, as a candidate for launch in the first slice of the Cosmic Vision Plan (with two launch slots M1 and M2), with a possible launch date of 2018. A final selection among the candidate missions for the M1/M2 slots is planned to take place in mid 2011. At the time of the selection it was recognized that the Euclid configuration as presented in the Assessment Phase Study Report (the "Yellow book" [1]) presents significant risk elements, in particular related to mass and schedule. These need to be resolved through an overall mission optimization at the start of the Definition Phase. This mission optimization process has been carried out under ESA leadership with a dedicated team of community scientists.

In this paper we describe the Euclid mission concept (Section 2) spacecraft concept (Section 3) and payload concept (Section 4) which were considered during the optimization process before the start of the Definition Phase. This evolved Euclid concept was taken as the reference baseline for the Invitation to Tender for two competitive industrial studies. The concept also served ESA's Announcement of Opportunity for Euclid payload and science ground segment elements to be provided by a single (community led) Euclid Consortium.

2. THE MISSION CONCEPT

2.1 Mission Description

The satellite is launched on a Soyouz ST-2.1B rocket from ESA's spaceport in Kourou, French Guyana. The launcher capability for the spacecraft is 2150 kg. The spacecraft will be placed in a large second Sun-Earth Lagrange point (SEL2) halo orbit which ensures stable observing conditions. To accomplish the surveys within the nominal mission duration of five years, the instruments have a large field of view of about 0.5 deg2 and operate simultaneously. The system design is optimized for a scanning strategy with fast attitude slews to support a step-and-stare tiling mode. Image dithering is achieved at spacecraft level to fill detector gaps and allow correction for cosmic rays.

2.2 Surveys

Euclid is a survey mission. Euclid's primary *wide survey* aims at covering 20,000 square degrees, i.e. the entire extragalactic sky at galactic latitudes $|b| > 30$ degrees, measuring shapes and redshifts of galaxies to a redshift of $z=2$ as required for weak lensing and baryon acoustic oscillations.

To measure the Weak Lensing shear from the galaxy ellipticities a tight control is imposed on possible instrumental effects. The variance of the shear systematic errors is required to be less than 10^{-7}. The photometric redshifts for these galaxies reach a precision of $\sigma_z/(1+z)= 0.03\text{-}0.05$. They are derived from three Euclid near-infrared bands (Y, J, H in the range 0.92-2.0 micron) reaching 24 mag AB (5σ, point source) in each, complemented by ground based photometry in visible bands derived through collaborations engaged with ground based projects.

The Baryon Acoustic Oscillations are determined from a spectroscopic galaxy survey with a redshift accuracy of $\sigma_z/(1+z) \leq 0.001$. The Euclid baseline is a slitless spectrometer with constant spectral resolution of $\lambda/\Delta\lambda=500$, which will detect predominantly Hα emission line galaxies. The limiting line flux level is 4×10^{-16} erg $s^{-1}cm^{-2}$ (7σ for a point source at 1.6 micron), yielding 70 million galaxy redshifts with a success rate in excess of 35 %. The success rate is the fraction of the total amount of detectable galaxies from which the redshifts can be determined.

Euclid's additional *deep survey* covers 40 square degrees. This survey is 2 mag deeper than the wide survey and is achieved by frequently visiting the same regions in the wide survey observing mode.

The Euclid instrument and pointing capabilities offer the possibility to carry out additional surveys serving a broad range of scientific topics. Depending on the mission performance, additional surveys which are technically feasible shall be selected through a dedicated AO open to the general scientific community. This *open surveys* phase starts after the nominal mission time of 5 years. However, there are presently no technical and funding resources planned for any additional surveys.

2.3 Ground Segment

An important element of the mission is the ground segment. Apart from the up-the-ramp integration for the NIR detectors, no on-board science data processing is performed, due to the complexity of the processing and due to the unprecedented legacy science potential of the raw data. Euclid produces of the order of 100 Tbyte of raw uncompressed data per year of operations.

The raw telemetry data are received at ESA's ground station in Cebreros (Madrid), which is equipped with X and K band receivers. The data are sent to the mission operations centre at ESOC (Darmstadt) where the satellite operations are performed. The science operations centre (SOC) at ESAC (Madrid) performs the science planning and Level 1 processing. The scientific processing at Level 2, 3, and 4, and the instrument health monitoring and maintenance are carried out at the science data centres (SDCs). The SOC together with the SDCs form the Euclid science ground segment (SGS). The Euclid SGS is data centric: it is built around the Euclid Mission Archive (EMA), which is accessible to all parties in the SGS. After the proprietary period the data will be made accessible to the general scientific community by setting the access rights of the public data. This public part of the EMA forms the Euclid legacy Archive (ELA).

3. SPACECRAFT CONCEPT

The Euclid spacecraft consists of two main modules: the Euclid payload module (EPLM), which include the telescopes, instruments, and the baffling system, and the Euclid service module (ESVM) which comprise all conventional spacecraft sub systems, the sun shield and the solar arrays (see Figure 1). The attitude and orbit control system of Euclid is designed such that the on ground reconstructed absolute measurement accuracy is better than 0.1 arcsec. To achieve the required relative pointing, Euclid will have a fine guidance sensor which is mounted close to the VIS focal plane array, and integrated in the VIS focal plane assembly. The ESVM is thermally decoupled from the EPLM. The memory unit is seized up to three days of science data in case ground communications is temporarily unavailable.

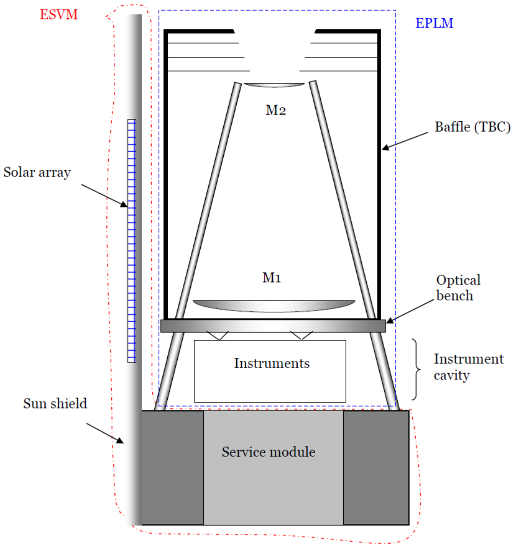

Figure 1: *Euclid system schematics*

To facilitate the unprecedented data rate, Euclid has X and K band transponders to support the tele-commanding and the science data transfer to ground, respectively. The K band section supports a downlink data rate of at most 850 Gbit of compressed science data in 4 hours.

4. PAYLOAD CONCEPT

The payload of Euclid contains a Korsch telescope with a primary mirror of 1.2 m diameter. The telescope is designed to provide a large field of view to two instruments that are placed behind a dichroic filter: a visible imager (hereafter VIS), and a near-infrared photometer-spectrometer (hereafter NISP). A payload concept block diagram is presented in Figure 2a. The VIS instrument in combination with the NISP operating in photometry mode supports the weak lensing experiment. The NISP instrument operating in slitless spectroscopy mode is designed to perform the spectroscopic galaxy survey for the BAO experiment. The VIS and NISP instruments are mechanically mounted on the optical bench inside the instrument cavity (see Figure 1). The optical bench and the payload cavity envelope are maintained at a temperature of 150 K. The instrument temperatures are achieved through passive cooling by means of radiators.

4.1 The Telescope and Optical design

The Euclid telescope baseline reference is a three mirror Korsch configuration with an off-axis field. It has an aperture stop at primary mirror with 1200 mm entrance pupil diameter, a field of view of 0.79×0.83 deg^2, an effective focal length of 24500.0 mm. The primary and tertiary mirror are elliptical, the secondary is hyperbolic. The equivalent diameter of the central obstruction is 350 mm. The reference optical design with a possible folding to accommodate the instruments is presented in Figure 2b.

4.2 The Visible Imager (VIS)

VIS contains a CCD based focal plane with one wide visible band spanning the range ~550-920 nm. The VIS channel will measure the shapes of galaxies with about 0.16 arcsec (FWHM) system point-spread function excluding pixelization. To achieve the high precision for the galaxy shape measurements, stringent requirements are set on the ellipticity, stability and sampling of the point spread function (Amiaux et al. [2])

We are presently considering two possible detector configurations with 0.101 arcsec pixel platescale, with either 30 or 36 CCDs. The two configurations yield geometric fields (which includes the gaps between the detectors) of 0.46 deg^2 and 0.55 deg^2, respectively. More details of the VIS instrument can be found in Cropper et al [3].

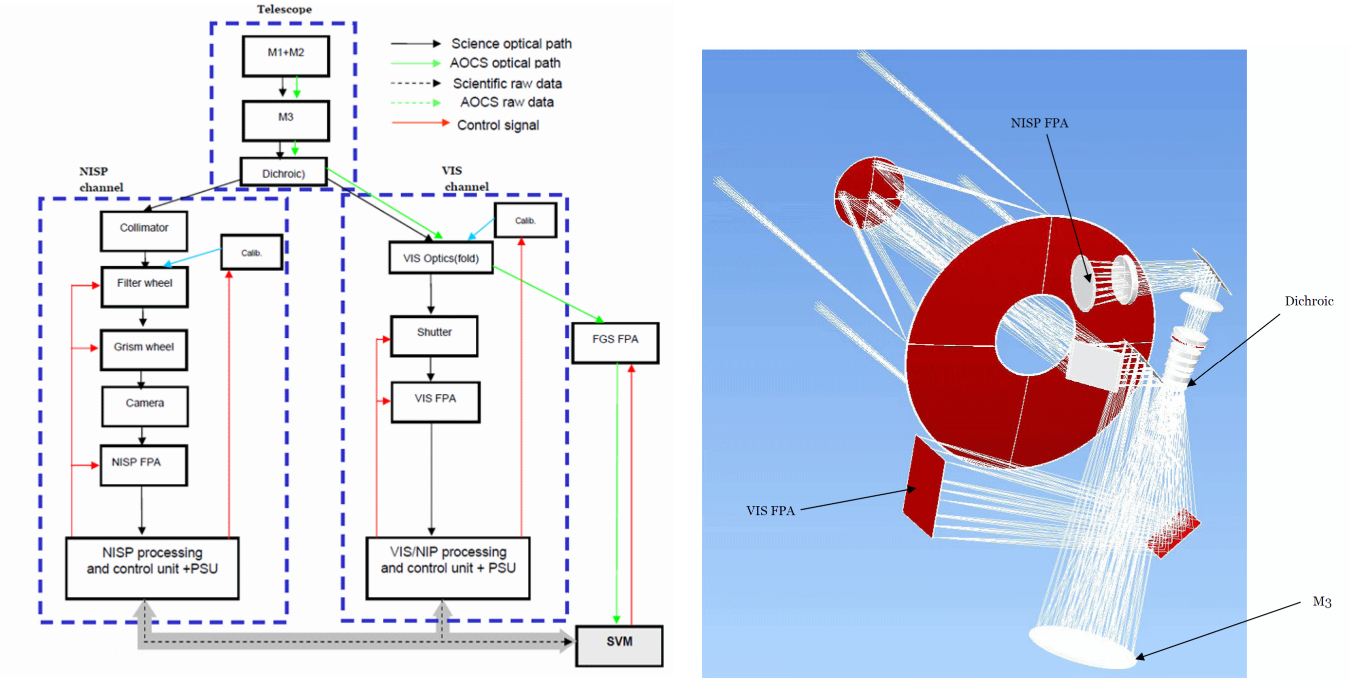

Figure 2: *a. (left panel) Euclid payload block diagram; b. (right panel) reference optical design with possible folding*

4.3 The Near-Infrared Spectrometer and Photometer (NISP)

NISP employs HgCdTe NIR detectors covering an area of ~0.5 deg^2. It can be operated in photometry mode or slitless spectroscopy mode by means of filterwheels. In photometry mode NISP will take images of the sky in three filterbands (Y, J, H), see also Schweitzer et al [4]. When the instrument is operating in photometry mode, the optical components in the light path include the dichroic, the three filters which can be placed in the path by means of a filterwheel, and a lens to replace the grism in the grism wheel. In the slitless spectroscopy mode, a grism is used operating in the wavelength range 1.0-2.0 micron at a constant spectral resolution $\lambda/\Delta\lambda \sim 500$. The optical components include a lens located in the filter wheel, a grism sandwich for each dispersion of the four dispersion directions located in the grism wheel. A description of the spectrometer part of the NISP as considered before the Euclid concept optimization is provided by Valenziano et al [5].

Like for the VIS instrument, we consider two detector configurations with 12 and 16 detectors, and corresponding plate scales of 0.33 and 0.31 arcsec, respectively. The two configurations yield geometric fields of 0.49 and 0.59 deg2, respectively.

4.4 Performances and mission parameters

The computed integration times per dither for the baseline reference payload concept described in the previous sections that have been adopted for the required detection limits are summarized in Table 1.

Table 1: *the derived integration times for the required detection limits have been highlighted in grey. The AB magnitudes and the near-infrared spectroscopy (NIS) emission line sensitivities (in erg s^{-1} cm^{-2}) refer to the 4 dither exposures per pointing field.*

	VIS	**NISP**				
		NIP Y, J and H	**NIS 1.0 um**	**NIS 1.4 um**	**NIS 1.6 um**	**NIS 2.0 um**
Mag/flux	24.5	24	5e-16	4e-16	4e-16	3e-16
Nb. mirrors	7	6	6	6	6	6
Nb. lenses	0	8	7	7	7	7
Overall transmission (incl. QE)	0.59	0.45	0.29	0.42	0.39	0.29
Integration time (s)	542	88.5, 107.4,61.8	408	408	408	408
SNR	14.3	7.1,7.1,7.1	4.2	6.0	7.0	4.7

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. The amount of integration time per dither for the two NISP modes in sequence is significantly longer than the parallel exposure with the VIS instrument. Extending the VIS integration time would saturate the CCDs at a too low detection level, disabling the measurement of bright field stars with S/N > 500 which are used to calibrate the temporal PSF. On the other hand a second VIS exposure per dither would increase the downlink rate beyond the limit of 850 Gbit/day.

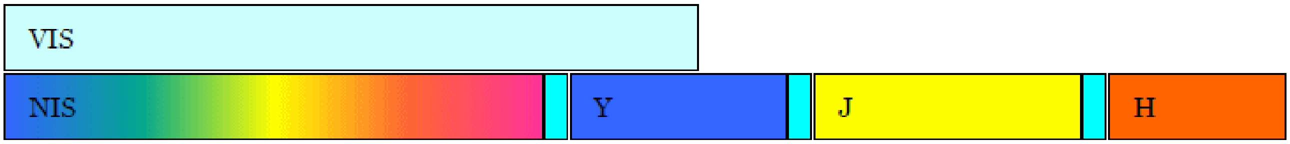

Figure 3: *Integrations per dither for the VIS (top bar) and NISP (lower bar) instruments. The integration time is driven by the NISP performance. For the reference concept payload a complete dither integration last about 700 seconds .*

The mission duration is for a significant part driven by the overheads introduced by repointing and stabilization between dithers and complete fields. We are presently investigating the slew and dithering manoeuvres from two types of systems: cold gas and low friction reaction wheels. The reaction wheels implementation give a better performance in terms of the smaller time overheads and implied spacecraft mass. The required wide survey area of 20,000 deg^2 in the nominal mission time depends on the scanning strategy and the amount of freedom to move the line of sight away from 90 degrees. This freedom is severely limited to a few degrees at most to ensure the VIS image quality due to the considerable stabilization times to recover from thermal variations.

5. THE EUCLID PROGRAM

Euclid is one of ESA's Cosmic Visions Plan M-class mission candidates selected to enter the Definition Phase (A/B1). 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. For the M-class missions, the selection process is being conducted according to the following schedule:

- Assessment Phase in 2008- Aug 2009 (completed)
- ESA internal review: Sep – Oct 2009 (completed)
- First down-selection of M-class missions to enter the Definition Phase (A/B1): Feb 2010 (Completed)
- Second and last down-selection for M1/M2: June 2011
- Completion of the Definition Phase (A/B1): by December 2011
- Final adoption for the Implementation Phase (B2/C/D/E1): before Feb 2012
- Start of the Implementation Phase: by July 2012
- Launch: by end 2018

The readiness for launch by 2018 is a severe demand which in practice requires conceiving the space segment without new basic technology developments and with minimum developments risks. This is conveniently quantified by the standard Technology Readiness Level (TRL) of the space segment. The minimum request is to reach TRL ≥ 5 before the final mission adoption.

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