Euclid: The space mission and the spectroscopic sample

F. Passalacqua (1)(2) on behalf of the Euclid Consortium

(1) *Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, Via Marzolo 8, 35131 Padova, Italy*
(2) *INFN-Padova, Via Marzolo 8, 35131 Padova, Italy*

Summary. — *Euclid* is a European Space Agency (ESA) mission, designed to investigate the nature of dark energy and dark matter. The satellite launch took place in July 2023, instrument commissioning and performance verification were completed successfully and data taking started in mid-February 2024. The survey will continue for the next six years covering one-third of the entire sky. It will map the matter distribution by measuring positions, shapes, and colors for billions of galaxies, and also redshift for a subset of tens of millions of those with unprecedented accuracy. This proceeding will present an overview of the mission, with particular attention to the spectroscopic analysis and its systematics.

1. – Introduction

Numerous observation campaigns have been performed to understand the structure and evolution of the universe. These experiments led to the formulation of the current cosmological concordance model, which describes the universe as a fluid composed of different components, including two "dark" elements, namely dark energy and dark matter. Despite the success of the standard cosmological model, different data analyses found tensions of different significance [1, 2, 3, 4], and its description of the Universe is very likely still incomplete [5, 6, 7].

Euclid [8] is an European Space Agency (ESA) mission, which has been designed to investigate the nature of such dark components and the evolution of the Universe. The satellite was successfully launched on the 1st of July 2023 from Cape Canaveral, and it will observe one-third of the sky from the Sun-Earth Lagrangian point L2 for at least six years

In particular, *Euclid* will study the cosmological expansion history, the growth of structures, and the relation between dark and luminous matter to provide constraints on the initial conditions, explore modifications of the theory of general relativity, and determine the neutrino mass scale.

The *Euclid* mission has been optimized for two cosmological probes: weak lensing and galaxy clustering, which are summarized in Sec.**3**. To perform these measurements, the spacecraft has been equipped with two instruments that work in the visible and near-infrared wavelengths and that are presented in Sec.**2**. Finally, this contribution reports the spectroscopic data analysis from raw images to the input catalog for the cosmological analysis and its systematics in Sec.**4** and Sec.**5** respectively.

2. – The Spacecraft and Instruments

The *Euclid* spacecraft is composed of a service module (SVM) and a payload module (PLM). The SVM hosts the warm electronics, the attitude and control system, and telecommunication with the ground. It contains a Sun Shield to protect the PLM from the Sunlight and provides electrical power with the photovoltaic array. The PLM is the core of *Euclid*, it contains the telescope and the two scientific instruments: the Visible Imager (VIS) and the Near-Infrared Spectrometer and Photometer (NISP).

The telescope is a three-mirror anastigmat Korsch with a 1.2 m primary mirror. The two instruments share a common field of view $\sim 0.54\,\mathrm{deg}^2$ and operate simultaneously thanks to a dichroic located at the exit pupil of the telescope that splits the light into the visible and near-infrared ranges:

- VIS [9] performs photometry in a single red passband I_{E} (530–920 nm), combining a wide field of view with a high resolution at the same time. The focal plane is equipped with an array of 6×6 CCD273-82 of 4132×4096 pixel with a resolution of $0\overset{''}{.}1\mathrm{pixel}^{-1}$.

- NISP [10] performs both photometry and slitless spectroscopy in the 920–2020 nm range. The focal plane array consist of 4×4 Teledyne Hawaii-2RG detectors with 2048×2048 pixels with a resolution of $\sim 0\overset{''}{.}3\,\mathrm{pixel}^{-1}$. Two wheels allow NISP to take data in photo or spectro mode, by changing filters and grisms respectively. The photometric channel consists in three passbands Y_{E} (949.6–1212.3 nm), J_{E} (1167.6–1567.0 nm) and H_{E} (1521.5–2021.4 nm). In spectroscopic acquisition, the light is dispersed with four different grisms: three red (1206–1892 nm) and one blue (926–1366 nm). In the main survey, namely Euclid Wide Survey (EWS), only the two red grisms are used, which share the same bandpass but have different orientations ([1]); the blue grism instead is used for calibration purposes.

3. – The Cosmological Probes

To investigate the history and structure of the Universe, *Euclid* has been optimized for two complementary probes: Weak Lensing (WL) and Galaxy Clustering (GC).

GC analyzes the correlation in the 3-dimensional position of the galaxies in space to derive the cosmological information. Currently, the expected size of the sample for this probe is about 25 million galaxies.

GC is a powerful method to map the large-scale structure of the Universe, but it directly measures only the luminous matter. Indeed, to infer the underlying matter

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([1]) The red grisms are oriented by 0°, 180°, and 270° with respect to the detectors. During the ground test, a non-conformity of the 270° red grism was discovered. The use of the 270° has been replaced by the other two red grisms rotated by an additional angle of 4°; this strategy allows the instrument to meet the quality requirements.

density field in GC, we must assume a relationship between the densities of luminous and dark matter, referred to as 'galaxy bias'. On the other hand, WL can directly reconstruct the total (luminous + dark) matter distribution by observing the distortions in the shapes of distant galaxies due to the presence of massive objects that deflect the path of the light. The WL analysis requires a high resolution, guaranteed by the VIS instrument, which is expected to observe about 1.5 billion objects. Since determining the spectroscopic redshift with NISP for all these objects is not feasible, a photometric redshift is measured by combining NISP photometric images with ground-based observations.

4. – The Spectroscopic Sample

The GC probe relies on the measurement of the angular position and spectroscopic redshift of galaxies. While the former measurement is straightforward, the latter is non-trivial and requires a careful evaluation of the systematics.

In spectroscopy, the redshift z is performed by identifying the emission lines of the sources and comparing their observed wavelengths $\lambda_{\rm obs}$ with respect to the ones in the rest-frame $\lambda_{\text{rest-frame}}$:

$$z + 1 = \frac{\lambda_{\rm obs}}{\lambda_{\text{rest-frame}}}.$$

The redshift and wavelength coverage of the NISP red grism is shown in Fig.1. The main spectral feature that *Euclid* will use for the identification of the redshift is the Hα line, which leads to a redshift $0.9 < z < 1.9$ with *Euclid* red grisms as reported within the dashed gray lines in the figure.

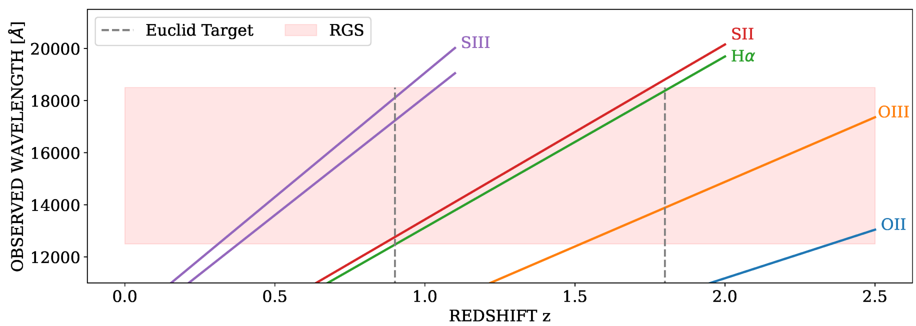

Fig. 1. – Redshift and wavelength coverage for in the EWS. The red-filled area refers to NISP red grisms coverage. Different emission lines are reported with different colors. Gray dashed lines show the redshift range for Hα emitters.

Moreover, as detailed in the *Euclid* definition study report [11], to reach the science requirement, *Euclid* has been designed to measure emission line galaxies up to a line flux of $2 \times 10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ with a detection greater than $3.5\,\sigma$ at 1600 nm.

The spectroscopic measurement, from observations to the catalog for cosmological analysis, can be summarized in three steps: acquisition of the spectroscopic images, extraction of the spectrum for each source, and identification of the emission lines together with the flux measurement of spectral features. The following is a brief description of these steps.

Spectroscopic Acquisition. – The spectroscopic channel enables the simultaneous acquisition of thousands of objects with a technique called slitless spectroscopy. With this technique, all the light in the field-of-view of the instrument is dispersed and each point in the sky leaves its spectral trace on the focal plane as shown in Fig.2. Since nearby objects have overlapping traces, to extract clean spectra, multiple observations with different orientations of the grisms are acquired to disentangle the signal.

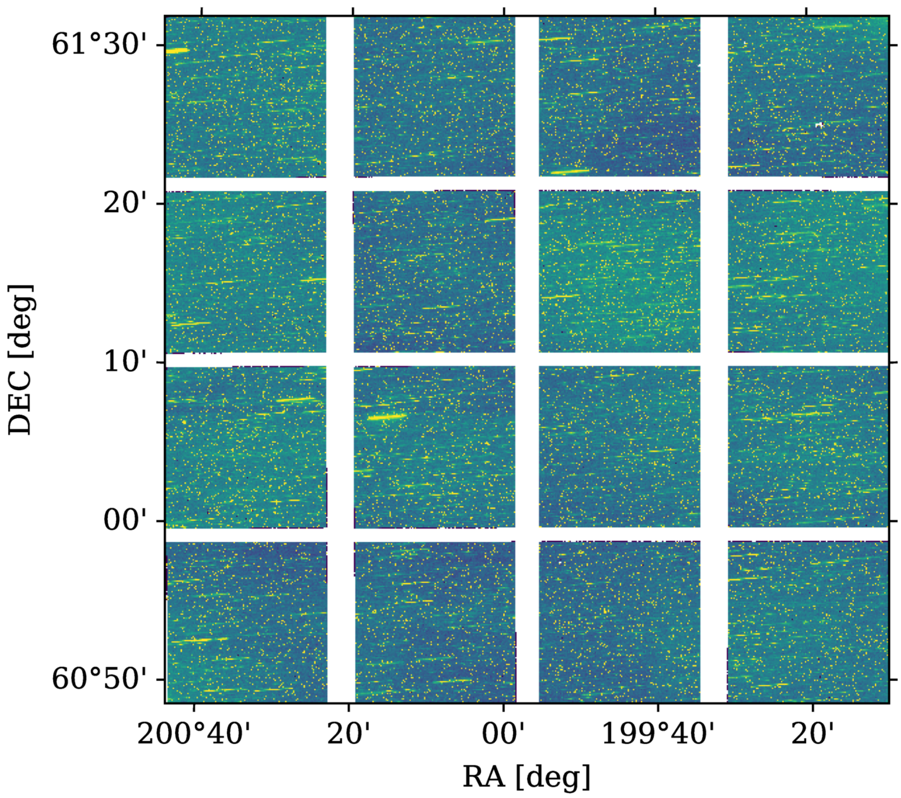

Fig. 2. – NISP 4 × 4 detector array in spectroscopic mode (simulation). The axes report the coordinate of the pointing in Right Ascension (RA) and Declination (DEC).

Extraction of the Spectra. – Once the spectroscopic images are acquired, spectra are extracted with the following operations:

1. Pre-processing: mask of bad pixels (*e.g.* saturated or disconnected), non-linearity correction, dark current subtraction, cosmic ray identification;
2. Measurement of the angular position and photometry of the sources from VIS and NISP;
3. Decontamination: modelling of contaminants and subtraction of overlapping spectra;
4. Extraction: computation of a one-dimensional spectrum and conversion to physical units;

5. Combination: computation of a stacked spectrum from the different observations.

Redshift Measurement. – Finally, the redshift estimation is performed through template fitting over a grid of redshifts, which provides a probability density function for each galaxy model [8]. This framework also allows the possibility of including priors in the computation of the redshift probability density function. The pipeline has also been trained with a deep learning algorithm to provide an indicator of the reliability, which is essential when dealing with huge amounts of data such as *Euclid*.

5. – Systematics with Slitless Spectroscopy

Slitless spectroscopy is a really powerful technique to observe a wide area of the sky, but it has also two main limitations:

- self-contamination: degradation of the resolution of a spectrum with the size of the object;

- cross-contamination: degradation of the signal-to-noise ratio of the spectra due to the overlap of traces from different sources.

Whereas the former translates into a reduction of the number of sources that can provide a suitable resolution, cross-contamination must be accurately characterized. In fact, there could be some density-dependence systematic effects due to the cross-contamination of faint spectra in dense regions. To investigate and characterize this effect, *ad hoc* simulations have been performed with a specific tool called `SPRING` [12] which runs end-to-end spectroscopic simulation by using *Euclid* official data processing described in Sec.**4**. Other sets of simulations were also designed to combine real data with simulated data to account for any unknown systematics by inheriting them directly from the data.

Although simulations are powerful tools to investigate and characterize systematic effects, they are not complete and calibration surveys are necessary. For this reason, a deep program of observations, called Euclid Deep Survey (EDS) was designed and it will cover an area of $50\,\mathrm{deg}^2$ with repeated observations. EDS will characterize the spectroscopic sample, by assessing the purity and the completeness of the redshift measurement.

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The authors acknowledge the Euclid Consortium, the European Space Agency, and a number of agencies and institutes that have supported the development of *Euclid*, in particular the Agenzia Spaziale Italiana, the Austrian Forschungsförderungsgesellschaft funded through BMK, the Belgian Science Policy, the Canadian Euclid Consortium, the Deutsches Zentrum für Luft- und Raumfahrt, the DTU Space and the Niels Bohr Institute in Denmark, the French Centre National d'Etudes Spatiales, the Fundação para a Ciência e a Tecnologia, the Hungarian Academy of Sciences, the Ministerio de Ciencia, Innovación y Universidades, the National Aeronautics and Space Administration, the National Astronomical Observatory of Japan, the Netherlandse Onderzoekschool Voor Astronomie, the Norwegian Space Agency, the Research Council of Finland, the Romanian Space Agency, the State Secretariat for Education, Research, and Innovation (SERI) at the Swiss Space Office (SSO), and the United Kingdom Space Agency. A complete and detailed list is available on the *Euclid* web site (`www.euclid-ec.org`).

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