The E-NIS instrument on-board the ESA Euclid Dark Energy Mission: a general view after positive conclusion of the assesment phase.

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ABSTRACT

The Euclid Near-Infrared Spectrometer (E-NIS) Instrument was conceived as the spectroscopic probe on-board the ESA Dark Energy Mission Euclid. Together with the Euclid Imaging Channel (EIC) in its Visible (VIS) and Near Infrared (NIP) declinations, NIS formed part of the Euclid Mission Concept derived in assessment phase and submitted to the Cosmic Vision Down-selection process from which emerged selected and with extremely high ranking. The Definition phase, started a few months ago, is currently examining a substantial re-arrangement of the payload configuration due to technical and programmatic aspects. This paper presents the general lines of the assessment phase payload concept **on which the positive down-selection judgments have been based.**

Keywords: Cosmology, Space Mission, IR Spectroscopy

1. INTRODUCTION

Euclid[1,2] is a high-precision survey mission to map the geometry of the Dark Universe. To do so, 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 optimised 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. BAOs are wiggle patterns imprinted in the clustering of galaxies which provide a standard ruler to measure dark energy and the expansion in the universe. Surveyed in the same cosmic volume, these techniques not only provide systematic cross-checks but also a measurement of large scale structure via different physical fields (potential, density and velocity), which are required for testing Dark Energy and gravity on cosmological scales.

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WL and BAO require a high image quality for the shear measurements, near-infrared spectroscopic and imaging capabilities to measure galaxies at redshifts z>1, a very high degree of system stability to minimize systematic effects, and the ability to survey the entire extra-galactic sky. Such a combination of requirements cannot be met from the ground, prompted for the design of a wide-field Visible/NIR space mission. A central design driver for Euclid is the ability to provide tight control of systematic effects in space-based conditions and to measure WL and BAO simultaneously.

With its wide-field capability and high-precision design, Euclid is conceived achieve the following science objectives in fundamental cosmology: a) to measure the dark energy equation of state parameters w_0 and w_a to a precision of 2% and 10% from the geometry and structure growth of the Universe, thus achieveing a Dark Energy Figure of Merit of 500 (1500) without (with) Planck priors. b) to test the validity of General Relativity against modified gravity theories, and measure the growth factor exponent γ to an accuracy of 2%. c) to study the properties of dark matter by mapping its distribution, testing the Cold Dark Matter paradigm and measuring the sum of the neutrino masses to a few 0.01eV in combination with Planck. d) to improve the constraints on the initial condition parameters by a factor of 2-30 compared to Planck alone.

The baseline payload design in the assessment phase consists of a Korsch telescope with a primary mirror of 1.2 m diameter. The telescope is designed to provide a large field of view (0.5 deg^2) to an imaging instrument with a visible channel (VIS) and and a NIR imaging channel (NIP) and a NIR spectroscopic channel (NIS)[3]. VIS and NIP support the weak lensing probe whereas NIS is designed to perform the wide spectroscopic galaxy survey.

VIS is designed to measure the shapes of galaxies with a resolution of 0.18 arcsec (PSF FWHM) with 0.1 arcsec pixels in one wide visible band (R+I+Z). NIP contains three NIR bands (Y, J, H), employing HgCdTe NIR detector with 0.3 arcsec pixels. NIS is a slitless spectrometer with $\lambda/\Delta\lambda=500$, which will detect predominantly Hα emission line galaxies. The limiting line flux level is 4 10^{-16} erg $s^{-1}cm^{-2}$ (point source 7σ at 1.6 micron), yielding 70 million galaxy redshifts with a success rate in excess of 35%.

Euclid's primary wide survey will cover 20,000 deg^2, i.e. the entire extragalactic sky, thus measuring shapes and redshifts of galaxies to redshift 2 as required for weak lensing and BAO. To accomplish the surveys within the nominal mission lifetime of 5 years, each instrument has a large field of view and the system design is optimized for a sky survey with fast attitude slews to support a step-and- stare tiling mode. To meet the survey depth and sensitivity, the telescope will have a well baffled design and it is designed to minimize background noise. For the NIR detectors, on-board on-the-ramp processing will be performed, i.e. combining image frames to lower the noise.

The spacecraft will be placed in a large L2 orbit which will ensure stable thermal and observing conditions. The satellite will be launched on a Soyouz ST-2.1B rocket from Kourou. The nominal mission duration is 5 years and the observations will be done in step-and-stare mode. A fine guidance system will provide a relative pointing accuracy of 35mas over a 450s exposure. Image dithering will be achieved at spacecraft level to fill detector gaps, provide sub-pixel information, and allow correction for cosmic rays. The survey speed with a relatively large number of detectors of 36 4k x 4k CCDs and 26 2k x 2k NIR detector arrays, in combination with the dithered exposures yields a data rate of approximately 850 Gbits/day. To accommodate such a rate the K-band transmission is required for data transfer from the spacecraft to the Cebreros ground station.

The Euclid mission is now evolving in a new payload concept, which is described elswhere[1].

2. THE NIS INSTRUMENT

The E-NIS instrument is designed to observe adjacent partially-overlapping areas of sky in each pointing. The baseline for NIS is a slitless spectrograph. An optional multi-slit solution based on Digital Micromirror Devices

(DMD) has also been studied at system and subsystem level by the ENIS consortium[5,6,7]. The NIS slitless spectrograph design is based on top-level requirements listed in Table 1.

Spectrograph Parameter	Value
FOV	0.5 x 1.0 deg^2 = 0.5 deg^2
Plate Scale at Detector	0.44-0.45 as/px
Wavelength Band	1.0 to 2.0 µm (or 0.85-1.7 µm)
Spectral Resolution	R=500 (constant in range)
Mitigation of Spectral Confusion	Multiple Roll Angles or “Multifilter” approach
Imaging Mode	Limited to astrometric mapping

Table 1: General Parameters for E-NIS

At assessment phase level (described in this paper) we kept open the possibility to change the spectral coverage from 1-2 um to 0.85-1.7 um. In the context of Euclid timescale, there is a solid perspective that this could provide a significant gain in the FoM of the spectroscopic survey cosmological results (BAO and growth factor).

2.1 Opto Mechanical Design

NIS is based on an optical system made by a collimator forming a pupil at the dispersive element location and a camera for proper pixel-scale matching. The optical design appropriately folded and materialized in a suited mechanical configuration is shown in Figure 1 and the optical element layout in Figure 2.

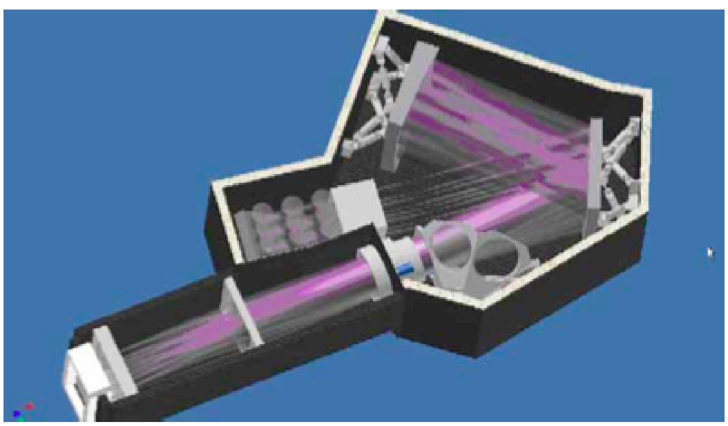

Figure 1: Mechanical Layout of E-NIS

In E-NIS the Telescope beam enters from the center of the image, hits the pick-off mirror (in grey), pass through two corrector lenses (blue), then is directed to the collimator mirror M3 after passing onto a flat folding mirror. After collimation, light is sent to the disperser (violet) passing again onto the flat folding mirror. Finally light is refocused onto the NIR focal plane array by the camera optics, made of four lenses.

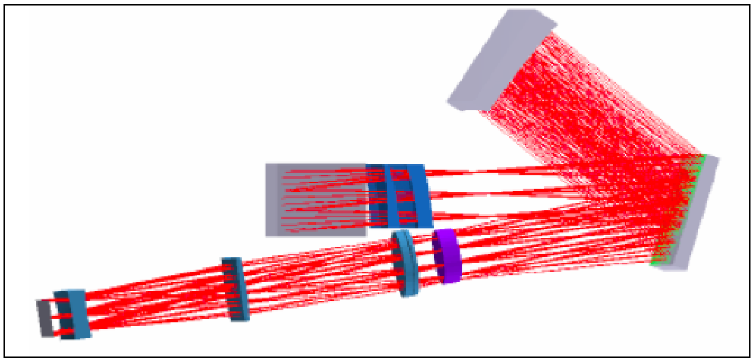

Figure 2: Folded Optical Design of E-NIS

Mirror elements are in light-weighted SiC with JWST heritage, and the lenses derive from developments of many ground-based near-IR instruments, but with special care for radiation-hardened glass. The dispersion for spectroscopy is obtained via a grism permanently inserted in the optical beam. The grism is designed to provide constant spectral resolution along the wavelength range of operation instead of the normally used constant dispersion.

The disperser comprises 2 prisms (ZnSe and Infrasil) and a ruled grating (~17 l/mm). It is mounted in mechanism that allows rotation around its optical axis. This allows varying the orientation of the dispersion with respect to the focal plane coordinates, enabling the multiple roll-angles needed for spectra extraction. Close to the grism a filter wheel allows to insert a blank to collect dark measurements, a counter-dispersion grism for the astrometric mapping in imaging mode. The NIS optical assembly will be operated at a temperature expected between 120 and 150 K, obtained and maintained via passive cooling.

The Filter wheel has been purposely designed and dimensioned with extra positions. This allows an implementation with minor impact on the design of the "multi-filter" option. In this option the dispersion grism is maintained in its position and filters to reduce the spectral range per exposure are accommodated on the filter wheel. A Scientific performance evaluation for the two cases is on-going. The current preliminary design can easily be oriented to one or the other solution.

2.2 Detector Assembly

The Focal Plane of NIS is a single unit accommodating 8 chips (2048×2048 H2RG chips) closely packed and mutually aligned, mounted on a common cold reference plate, made of SiC. It is also connected via a flexi- cable to the proximity electronic ASICS–SIDECAR board. The detector housing is shown in Figure 3.

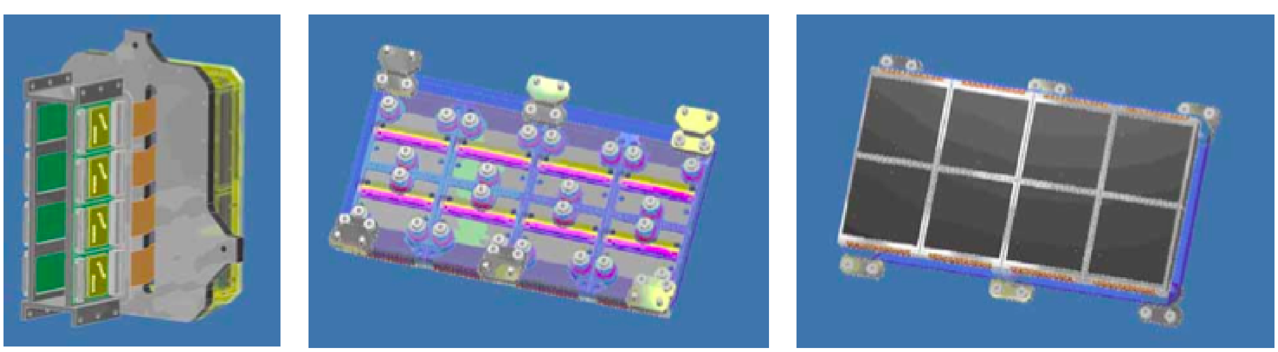

Figure 3: The layout of the E-NIS focal plane

The eight chips forming the E-NIS focal plane are arranged in order to minimize the gap between chips. An unavoidable residual gap of about 2.9 mm (about 80 arcsec) remains and has been taken into account in the performance evaluation.

2.3 Thermal Architecture

The thermal architecture of NIS is schematically represented in Figure 4. NIS will be enclosed in a shielded environment thermalized to about 150 K, passively obtained via a radiator coupled to the cold sky. The detector system needs to be operated at ~90K with very high stability, on the order of 10mK peak-to-peak, in the timescale of an exposure. This is achieved via a dedicated passive radiator and the combination of passive and active thermal control systems.

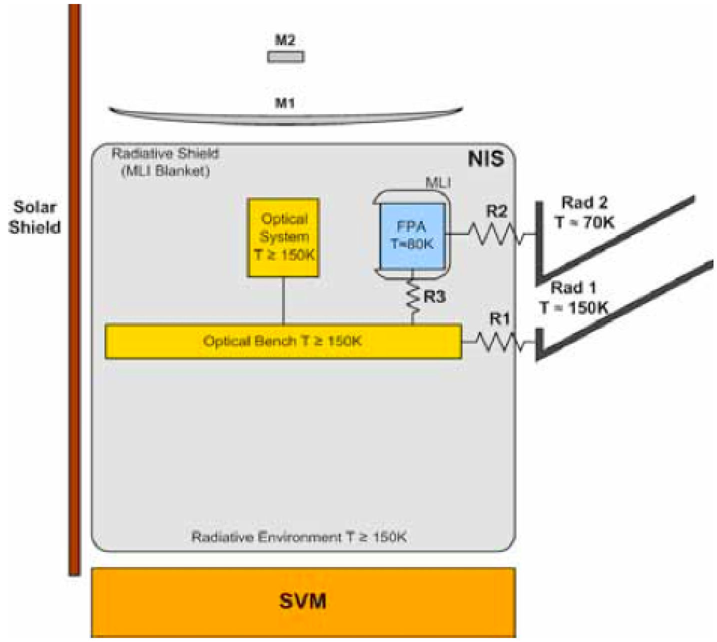

Figure 4: Thermal Architecture of E-NIS

2.4 Electronics Architecture

The electronic block diagram for the spectrograph is sketched in the following Figure 5

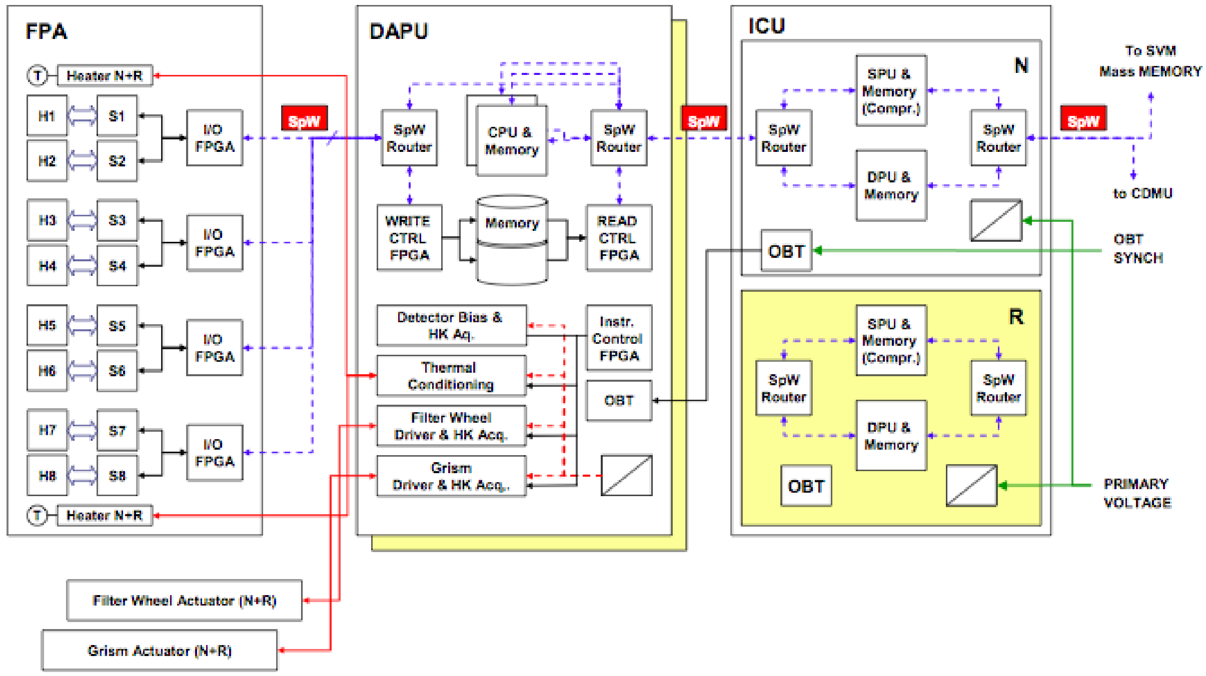

Figure 5: The E-NIS Electronic Architecture

The focal plane assembly is segmented in four groups, each one having two H2RG detectors, two SIDECAR read-out ASICs and one I/O FPGA that handles the communication with the Data Acquisition and Processing Unit (DAPU). Scientific data are sent to the DAPU, where they are multiplexed and stored in the unit's memory, waiting for the CPU to run the deglitching preprocessing algorithm. The detectors are read-out using "up-to-the-ramp" integration. Each pixel is sampled at 16 bit and read-out continuously to allow the ramp reconstruction. The deglitching preprocessing algorithm analyses each pixel to determine if it has been hit by cosmic events[8]. If no cosmic hits have been recorded the net integrated charge value is sent to the ICU. For pixels that have been hit by cosmic rays, all intermediate readings are analysed to preclude the out-liers. On-ground deglitching is foreseen as baseline, while on-board processing is currently considered an option. In the ICU, science data coming from the DAPU are compressed by a lossless algorithm (a 'conservative' lossy method[9] , considered feasible, as an option) and packetized with CCSDS format. Finally data are sent to the S/C mass memory for storage and transmission to ground.

In order to minimize the interconnections between the different units and implement the required redundancies, the adopted communication standard is SpaceWire, that allows high throughput rates and for which routing solutions are already available following space standards.

2.5 Mass and Power Budgets

The overall mass budget (including 20% margin) is given in Table 2. The allocation of functionality, and the definition of structural elements between fixations and supports also varies in all 3 solutions (consortium and 2 industries) and reflects the wide differences between the columns. The budget is hostage to detailed mass allocation for structures that can change with integration approach, but here it is reported on worst-case optical bench estimates.

System	Sub-system	Mass (incl. 20% margin)
NIS		*119 kg*
	Detectors, ASIC +harness	8
	Optics	41
	ICU+harness	15
	DAPU	20
	Thermal	6
	Structure	29

System	Sub-system	Power (incl 20% margin)
NIS		*83 W*
	Detectors, ASIC +harness	5
	DAPU	46
	ICU	32

Table 2: E-NIS Mass budget (left) and Power Budget (right)

3. OPERATIONS

The NIS spectrograph is characterized by one single main observing mode: the acquisition of a slitless spectroscopic image of the monitored field. However, slitless data reduction techniques require that each field is observed at a different orientation of the dispersion with respect to the image coordinates (roll angles) to disentangle confused spectra. Each spectroscopic image is then the association of 4 frames collected at different roll angles.

A possible alternative is to introduce passband filters in order to reduce the length of the spectrum and hence the confusion. This possibility, having negligible impact on the mission architecture, will be possibly studied in the further phases.

Following the need of dithering of the imagers, NIS will synchronize each roll angle with a dither. As a consequence each of the 4 individual frames collected, maps the targeted sky shifted by a dither step and at the given roll angle. In order to make the spectra post processing possible, each step must be reconstructed at a sub-pixel level. This is obtained via reducing relative pointing error in the spacecraft and via astrometric cross-mapping between the NIS and the NIP fields. This requires an additional auxiliary imaging observing mode. Therefore NIS will acquire (at most) a frame in imaging mode every pointing, before the implementation of the dithering sequence. This image will be used to re-construct the astrometric mapping between NIS and NIP by recognition of a number of bright sources. The astrometric matrix will be used in data reduction to achieve the sub-pixel precision needed for spectra extraction.

Performing frequent NIS imaging with a short integration time (tens of seconds) down to H<19-20 ("open exposure") is considered an interesting possibility, provided that it does not impact significantly on the "spectroscopic" integration time and S/N and it does not impact the flight hardware design.

3.1 Observation Sequence

The instrument main observation sequence is composed of 4 dithering steps on the same fields. During each steps, there is 1 frame in the VIS, 3 frames in the NIP (1 in each band) and one rotation position of the NIS grism (or filter in the multi-filters configuration). This scheme implies the NIP FWA is rotating while the VIS and NIS are integrating. Between each frame, the shutter is closed, and dithering steps of ~100" are achieved at satellite level. At the end of the observation sequence, the satellite slews to the following field.

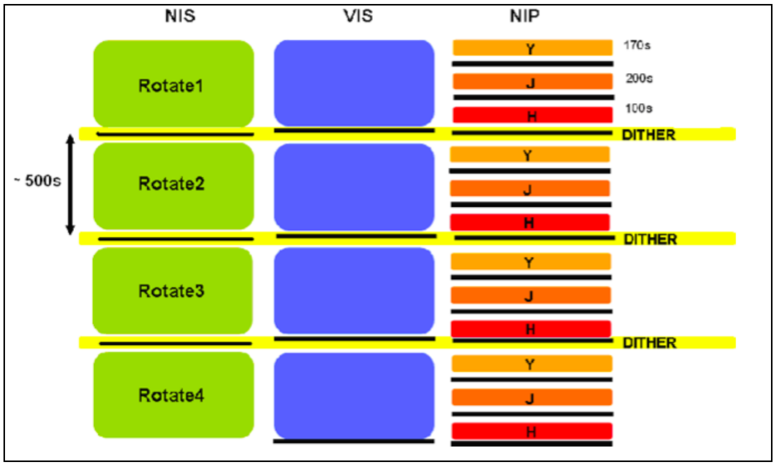

Figure 6: Observing sequence in Euclid.

This sequence described in Figure 6, with approximately 500s observation time per dither step, and after accommodating dither step slews (<60s) and frame step slews (<230s) allows the observation of 36 fields per day. Different assumptions in the radiometric models lead to different analyses of a field duration. Comparison of the data suggests 500s is a comfortable functioning point for overall duty cycle calculations.

The associated instrument daily telemetry rates are given in Table 3. These calculations assume that the data processing for the NIR instruments with Up-the-Ramp sampling include recognition of cosmic ray events.

	VIS	**NIP**	**NIS**	**Total**
# Detectors	36	18	8	
Pixels/detector	16M	4M	4M	
Bits/pixel	16	16	16	
Raw Data/frame	9.7 Gbit	1.2 Gbit	0.5 Gbit	
Frames/field	4	12	5	
Fields/day	36	36	36	
Raw data/day	1397 Gbit	522 Gbit	97 Gbit	2016 Gbit
Compression factor	2.8	2.5	1.5	
Data / day	499 Gbit	209 Gbit	65 Gbit	773 Gbit
Margin/OH				10%
TOTAL				**849 G bit /day**

notes:
(1): 2.8 compression ratio for VIS lossless compression (in PDHU)
(2): 2.5 compression ratio for NIP lossless compression (in PDHU)
(3): 2 compression ratio for NIP lossless compression (in PDHU)
Note: 3% overhead is considered after CCSDS formatting.

Table 3: Euclid payload telemetry rates

	VIS	**NIP**	**NIS**
Plate Scale	0.1 arcsec	0.3 arcsec	R=500 in 2 pixels
Magnitude (AB)	24.5	24	5 10^{-16} erg cm^{-2} s^{-1} (AB mag 19.1 mag)
SNR	14.3	7.1	5 (/spectral element)
Radiometric aperture	1.3 arcsec	0.5 arcsec	3×5 pixels
Sky background	22.3	22.1 (J)	$10^{(-17.75-0.73(\lambda-0.61))}$ erg cm^{-2} s^{-1} Å $arcsec^{-2}$
Overlapping framesto reach SNR	3 out of 4	3 out of 4	4
Frame duration	500 s	170 / 200 / 100 s Y / J / H	480 s

Table 4: Euclid payload performance requirements

3.2 FoV gaps filling evaluation

As the dithering is performed at spacecraft level, NIP imposes the size of the dithering step since it has the largest gap compared to VIS. VIS and NIP have requirements addressing the coverage by 3 or by 4 dither frames. Considering a global optimisation of dither pattern for all instruments together, we only consider the requirement on 3 frames, since the SNR is calculated with 3 frames. The proposed sequence of offsets in *x* and *y* (long and short focal plane dimensions) is (0,0 ; 100,+40 ; +200, +40 ; +300,+40, arcsec). In this case the estimated coverage of each sky pixel by number of dither frames is listed in Table 2.

From Table 5 the requirement for completing the gap coverage of 95% is marginally met. In addition the losses of the NIS spectrograph must be addressed more carefully to account for the complete spectrum length (~600 pixels on a 2048 pixel wide detector) that itself rotates between dither frames

Frames	VIS (%)	NIP (%)	NIS (%)
1	2.6	4	0.4
2	1.3	1.5	8
3	54	47	39
4	41	47	53
>3	96	94	TBC (depends on loss due to rotation of spectra)

Table 5: Gap coverage as a funcion of the number of frames.

4. DMD SPECTROGRAPH OPTION

An optional multi-slit solution based on Digital Micromirror Devices (DMD) has also been studied at system and subsystem level by the E-NIS consortium. The DMD spectrograph design is focused on performance and feasibility issues. Multi-object spectroscopy (MOS) with multi-slits is the best approach to eliminate the problem of spectral confusion, to optimize the quality and the S/N ratio of the spectra, to reach fainter limiting fluxes and to maximize the scientific return both in cosmology and in legacy science.

A promising solution is the use of MOEMS devices such as micro-mirror arrays (MMA). In the timescale of Euclid mission, a dedicated programmable multi-slit mask cannot be developed. This component has to be then already commercially available. The selected component is a DMD DC2k chip from Texas Instruments in order to get more than 2 millions independent mirrors in a 2048 x 1080 "pixels" format, with a pitch of 13.68µm (Fig. 7).

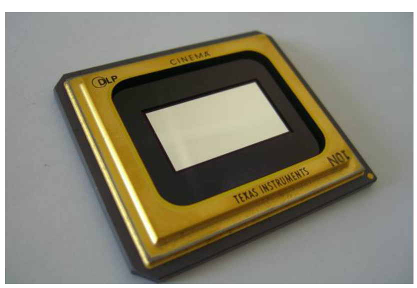

Figure 7: DMD DC2k chip from Texas Instruments (2048 x 1080 micro-mirrors).

The nominal DMD operational parameters are room temperature, atmospheric pressure and mirrors tilting several hundreds times in a second, while for Euclid, the device might work in vacuum, at low temperature, and each MOS exposure lasts approximately 500-600s with mirrors frozen in one state (either ON or OFF) during that duration. ESA has engaged with Visitech and LAM a space evaluation of a DMD chip. A specific thermal/ vacuum test chamber has been developed for test conditions down to -40°C at 10^{-5} mbar vacuum. Imaging capability for resolving each micro-mirror has also been developed for determining any failure for a single mirror. A dedicated electronics and software permit to freeze any pattern on the device for duration as long as 1500s. Tests in vacuum at low temperature, radiations, vibrations, thermal cycling, and life tests have been completed. **The results of this test campaign do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements.** [4]

Designing a spectrograph using this kind of components requires a fore-optics and the spectrograph itself. The fore-optics must accommodate the micro-mirror tilt along the diagonal of each miror. The spectrograph must provide the required spectral resolution, i.e. between 200 and 400. The ENIS Consortium has studied a pool of solutions, reflective, refractive and mixed. Among these, the number of arms, of DMDs, of detectors is varied accordingly to performance and sky coverage. A 4-arms 8 detectors solution has been selected to undergo a deeper analysis for this study. [5]

For geometrical reason (input-output beam respective locations) as well as contrast requirement, a beam of F/3 on the DMD has been chosen. This means a plate scale on the DMD of 0.77" / micro-mirror. For a single DMD, the FOV is then 0.10 deg^2; for covering a maximum FOV with the 8 detectors, 4 spectrographs are foreseen with 2 detectors for each one. The total FOV would be 0.4 deg^2. The slit size is related to the size of the astronomical objects: we can set one micro-mirror for compact objects, while two micro-mirrors will be used for more extended objects. Spectral resolution for one-mirror slit is 400 and 200 for a two-mirror slit.

Four spectrographs are designed and folded in a single plane perpendicular to the telescope axis (Fig. 8). Each spectrograph includes a 3-mirror fore optics, the DMD, a 3-mirror spectrograph, a grism for the beam dispersion and the detector; the post-DMD optics is identical for the 4 arms. The optical design is also based only on mirrors with aspherical values within standard values, commercially available from main manufacturers. The optical quality on the DMD and the detector are also reached with this design. The spot diagram is within one micro-mirror in the DMD plane (optical quality of the fore-optics), and around two detector pixels in the detector plane.

The opto-mechanical design of NIS / DMD option is based on a central optical bench with two spectrographs located each side (Fig. 8). Four flat pick-up mirrors are sending the beams towards the spectrographs; they are located within NIS volume and before telescope focal plane. This leads to 4 non-adjacent sub-fields on the sky. The bench is linked to the telescope structure, via 3 bipods. Optical bench and structures are based on honey-combs with carbon skins; optics are made with Zerodur and attached with Invar bipods. All detectors are located in the area of the instrument for a global electronics / thermal design of the focal planes. A preliminary DMD board design has been produced, based on actual boards developed for DMD testing. A specific 2-chip assembly, based on 2048x2048 HAWAII 2RG detectors, has been designed and the detector architecture is identical to the slitless case. The proximity electronics has also to be specific for driving 2 detectors. For the electronics architecture of the DMD option, main features are identical with the slitless design, mainly around FPA electronics and data processing. However, for DMD handling and configuration, specific electronics cards are considered, including a DMD formatter board and DMD thermal control unit. Additional computing power must be also installed for on-board processing of the DMD pattern, after a pre-imaging step. For the thermal architecture, the main difference with respect to the slitless case consists in the need to keep the DMD subsystem at 233 K.

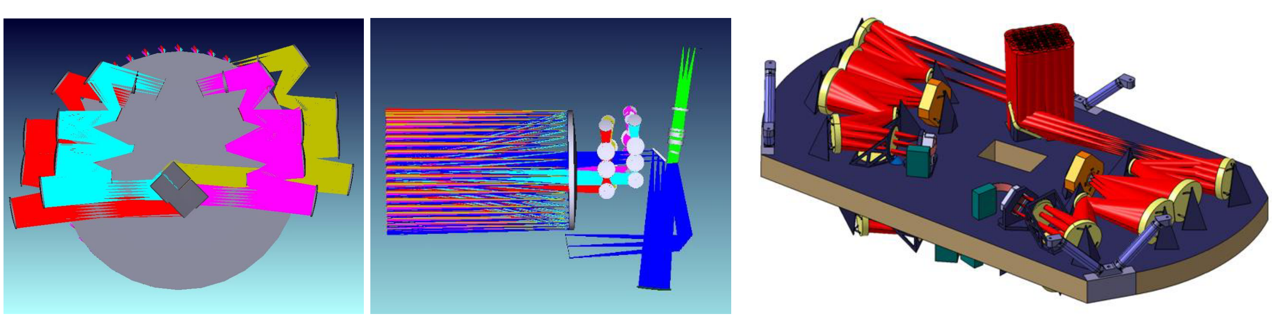

Figure 8: DMD DC2k chip from Texas Instruments (2048 x 1080 micro-mirrors).

Common interfaces for the slitless and the DMD spectrograph option have been developed for the opto-mechanics, the thermal architecture, the electronics, the data handling, most of AIT/AIV and development plan.

In the DMD spectrograph option, all elements are kept within the spectrograph allowed envelop and mass. DMD spectrograph option is fully feasible for a scientific performance much higher than the slitless design.

5. CONCLUSIONS

The E-NIS instrument on-board the ESA Euclid mission has been presented. This paper reports the design made bay the E-NIS consortium during the assessment phase, as described in the Assessment Study Report[2]. The Euclid payload has evolved since then in a different payload concept[1], where the two infrared instrument have been merged into a single, combined one (Near-Infrared Spectro-Photometer – NISP). The Euclid mission is currently undergoing the ‘Definition Phase (Phase A/B1) and will be submitted to the final selection for the ESA Cosmic Vision programme in 2011.

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