The focal plane instrumentation for the DUNE mission

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ABSTRACT

DUNE (Dark Universe Explorer) is a proposed mission to measure parameters of dark energy using weak gravitational lensing The particular challenges of both optical and infrared focal planes and the DUNE baseline solution is discussed. The DUNE visible Focal Plane Array (VFP) consists of 36 large format red-sensitive CCDs, arranged in a 9x4 array together with the associated mechanical support structure and electronics processing chains. Four additional CCDs dedicated to attitude control measurements are located at the edge of the array. All CCDs are 4096 pixel red-enhanced e2v CCD203-82 devices with square 12 μm pixels, operating from 550-920nm. Combining four rows of CCDs provides a total exposure time of 1500s. The VFP will be used in a closed-loop system by the spacecraft, which operates in a drift scan mode, in order to synchronize the scan and readout rates. The Near Infrared (NIR) FPA consists of a 5 x 12 mosaic of 60 Hawaii 2RG detector arrays from Teledyne, NIR bandpass filters for the wavelength bands Y, J, and H, the mechanical support structure, and the detector readout and signal processing electronics. The FPA is operated at a maximum temperature of 140 K for low dark current of 0.02e−/s. Each sensor chip assembly has 2048 x 2048 square pixels of 18 μm size (0.15 arcsec), sensitive in the 0.8 to 1.7 μm wavelength range. As the spacecraft is scanning the sky, the image motion on the NIR FPA is stabilized by a de-scanning mirror during the integration time of 300 s per detector. The total integration time of 1500 seconds is split among the three NIR wavelengths bands. DUNE has been proposed to ESA's Cosmic Vision program and has been jointly selected with SPACE for an ESA Assessment Phase which has led to the joint Euclid mission concept.

Keywords: Euclid, dark energy, weak lensing, photometric redshift, DUNE, Cosmic Vision, infrared, focal plane

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1. INTRODUCTION

The Dark Universe Explorer (DUNE) is a proposed wide-field space imager whose primary goal is the study of dark energy and dark matter with unprecedented precision using weak gravitational lensing. Immediate secondary goals focus on the evolution of galaxies, to be studied with unprecedented statistical power, the detailed structure of the Milky Way and nearby galaxies, and the demographics of Earth-mass planets. DUNE is a medium-class mission as defined by ESAs Cosmic Vision program, consisting of a 1.2m Korsch-like three-mirror telescope with a combined visible/near-infrared field-of-view of 1 square degree and 0.23 arcsec resolution (visible) in a geosynchronous orbit. DUNE plans to carry out an all-sky survey in one visible and three NIR bands which will form a unique legacy for astronomy. DUNE thus addresses multiple goals of the ESA Cosmic Vision program and would yield major advances in a broad range of fields in astrophysics and cosmology (http://www.dune-mission.net). DUNE is a realization of the wide-field imaging mission recommended by the ESO/ESA Working Group on Fundamental Cosmology (WGFC).

One of the most powerful tools to tackle dark energy is weak gravitational lensing of background galaxies by foreground dark matter: this forms the core of the DUNE mission.[1,2] Gravitational deflection of light by intervening dark matter concentrations causes the images of background galaxies to acquire an additional ellipticity on the order of one percent. Utilization of this cosmological probe relies on the measurement of image shapes and redshifts, or distances, for several billion galaxies, both requiring space observations for point spread function (PSF) stablity and photometric measurements over a wide wavelength range in the visible and especially near-infrared (NIR). These are the driving requirements on the instrumentation of DUNE, and are solved by the separate, large visible and NIR focal plane arrays which will be discussed in more detail in this paper.

Mission and orbital requirements

The driving requirements for the mission design of DUNE are from the wide extragalactic survey and specifically the need for the stability of the PSF and the large coverage of the sky. PSF stability puts stringent requirements on pointing and thermal stability during the observation time. The 20,000 square degrees survey demands high operational efficiency, which can generally be achieved either in a step-and-stare imaging mode or by continuously scanning the sky during science acquisition. The pointing accuracy requirement is identical in both cases, namely 0.2 μrad over 375 s integration time per CCD chip (to reach magnitude limits required by science goals), and is essentially driven by the elementary integration time and the spatial resolution. This can be achieved using a drift scanning mode (or Time Delay Integration, TDI, mode) for the CCDs in the visible focal plane, as for GAIA. A continuous scanning mode is by nature more efficient than the step-and-stare mode, since the science measurements can be continuously achieved over a relatively long fraction of a great circle, which reduces the number of maneuvers by one or two orders of magnitude, and is selected as the baseline for DUNE. For the infrared focal plane, using available HgCdTe arrays, TDI mode not feasible and the proposed concept is to stop the image motion during the integration time in the NIR focal plane by using a small de-scan mirror located close to the telescope exit pupil. In practice, the de-scan design is such that this mirror is operated in quasi-static mode with low amplitude oscillations, about 1 degree and a period of 300 seconds.

2. DUNE PAYLOAD AND FOCAL PLANE INSTRUMENTATION

The Payload module (PLM) design uses Silicon Carbide (SiC) technology for the telescope optics and structure. This provides low mass, high stability, low sensitivity to radiation and the ability to operate the entire instrument at cold temperature, typically below 170 K, which will be very useful for cooling the large focal planes. The telescope structure supports the Focal Plane Assemblies. Located behind the passively cooled primary mirror are the two offset focal planes (Visible and NIR), each about 250x500mm and 0.5 deg2 field of view. The visible focal plane is populated by 36 4096x4096 CCD e2V 203-82 (with 4 additional CCDs for use by the attitude control system of the spacecraft), and the NIR focal plane has 60 2048x2048 Teledyne HAWAII-2RG HgCdTe arrays mosaiced together. Defined as part of the payload are also the de-scan mirror mechanism and the additional payload data handling unit (PDHU). Key payload parameters are listed in Table 1.

2.1 Telescope

The optical concept is a Korsch-like f/20 three-mirror telescope (Figure 1). The third mirror is slightly off-axis to separate the two channels: visible and NIR. After the first two mirrors, the optical bundle is folded just after passing the primary mirror (M1) to reach the off-axis tertiary mirror. Then, a dichroic element located near the exit pupil of the system provides the spectral separation of the visible and NIR channels. On the NIR optical

Table 1. Key payload parameters

Instrument	**Value/description**
Optical configuration	Off-axis Three Mirror Anastigmat (TMA)
Pupil diameter	1.2m
spectral range	VIS: 500-900nm NIR: 920-1600nm (3bands)
Resolution	0.102 arcsec
(pixel size)	0.15 arcsec
Visible FOV	$1.08^\circ \times 0.48^\circ$ (array of 9x4 matrices / 4096x4096 pixels per matrix / 12μm pitch)
NIR FOV	$1.04^\circ \times 0.44^\circ$ (array of 5x12 matrices / 2048x2048 pixels per matrix / 12μm pitch)
Focal plane & observing mode	
Visible Channel	TDI through S/C slow rotation (1500s integration time per celestial object)
NIR channel	Step&Stare through de–scan mechanism (600s integration time per celestial object for J, H bands, 300s for Y band)
Focal planes Mass & Power	
Visible + NIR FPA + electronics mass	155kg (CBE)
Visible + NIR FPA + electronics power	369W (CBE)

path, the implementation of the de-scan mechanism close to the dichroic filter allows for a largely symmetric configuration of both spectral channels. After a final folding, the bundles are directed towards the focal planes. This dichroic configuration minimizes the field of view necessary to implement the two large focal planes, leading to a rather compact system.

2.2 Visible Focal Plane Array

The baseline for the visible Focal Plane Array (VFP) consists of 36 large format red-sensitive CCDs, arranged in a 9x4 array (Figure 2) together with the associated mechanical support structure and electronics processing chains. Four additional CCDs are dedicated to the attitude and orbit control system (AOCS) measurements are located at the edge of the array. All CCDs are 4096 pixel red-enhanced e2v CCD203-82 devices with square 12 μm pixels. The CCDs are standard devices requiring no development beyond a rerouting of the connections to eliminate one of the two flexi-lead connections, since only one video output per CCD is required. No development for additional features is envisaged. They are 4-sides buttable with a dead space of 1.6mm between active areas, providing a filling factor of 94physical size of the array is 466x233 mm corresponding to 1.09°x0.52°. Each pixel is 0.102 arcsec, so that the PSF is well sampled in each direction over approximately 2.2 pixels.

The VFP operates in the red band from 550-920nm. This bandpass is produced by the dichroic. If further filtering is required, an optical filter (long-pass such as the Schott GG495) will be mounted near the CCDs. Care will need to be taken with ghost images (which are very important in the case of DUNE), and filters for each CCD will be mounted individually on a carrier to optimize glass thickness. These filters will provide some additional shielding for the CCDs. An alternative being considered in the assessment phase is to add a second filter coating on the optical channel fold mirror.

The optical camera operates in TDI mode, so that the CCD rows are continuously clocked from a single readout node at the same rate as the satellite scans the sky (1.12 arcsec/sec). The CCDs are 4-phase devices, so they can be clocked in 14 pixel steps. The exposure duration on each CCD is 375s, permitting a slow readout rate and minimizing readout noise. Combining 4 rows of CCDs will then integrate for a total time of 1500s. With the broad bandpass this ensures good sensitivity.

The required readout rate from the CCDs is slow, which is advantageous for minimizing system noise. Each CCD will have a dedicated processing electronics module (PEM) responsible for reading out the CCD, bias generation, signal conditioning and digitization. Digitization will be to 16-bit. Each row of 9 processing modules will in turn connect to a common power supply and data routing module, which will transmit the data to the onboard processing for compression and packetization.

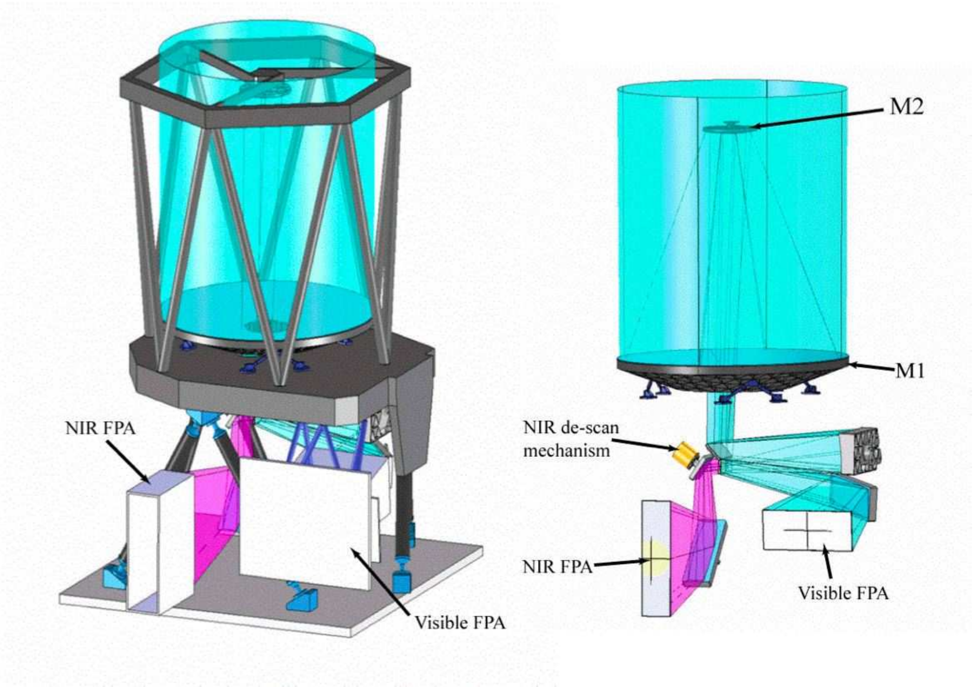

Figure 1. A side view of the DUNE telescope showing the location of the main mirror elements and the focal plane assemblies.

The structure of the VFP will provide a stable optomechanical support for the detectors and their processing chains as shown in Figure 2. These will be passively held at 170K to minimize the CTE effects from radiation damage. This temperature also reduces the total heating budget for the payload. The structure material is to be determined and will be selected after a trade-off with due regard to the interface conditions with the optical bench and the CCD package, the thermo-mechanical stability, the ease and cost of manufacture and the cleanliness constraints. The electronics will operate in a warm environment, thermally decoupled from the CCDs and the rest of the payload. A radiator will be used to dump the dissipation from the CCDs (and parasitic heat loads) to space, while the structure housing the electronics will act as their radiator. There are no mechanisms in the VFP.

With a spatial resolution of the PSF in each direction of 2.2 pixels (FWHM), the contribution to the spatial degradation induced by the detector MTF is small, even at far red wavelengths. Additional sources of error including TDI rate errors and the broadening owing to the 1/4 pixel step size during TDI clocking will also be small. The overall sampling including all of these contributions is optimal at 2.2. pixels per FWHM. The effect on image quality as a result of radiation damage will need to be quantified and will draw on heritage from the GAIA program.

The VFP will be used by the spacecraft in a closed-loop system to ensure that the scan rate and TDI clocking are synchronized. The two pairs of AOCS CCDs (see Figure 2) provide two speed measurements on relatively bright stars (V magnitude 22-23, a few thousand total collected photo-electrons). This technique will have been proven in the framework of GAIA, and similar principles will be followed for DUNE, where the requirements are for a slower scan rate but very similar pointing accuracy.

The DUNE VFP is largely a self-calibrating instrument. For the shape measurements, stars of the appropriate magnitude will allow the PSF to be monitored for each CCD including the effects of optical distortion and detector alignment. The PSF will be calibrated as a function of wavelength pre-launch, as it is wavelength dependent, and will differ for different spectral energy distributions. Radiation-induced charge transfer inefficiency will modify the PSF and will need to be calibrated both through the in-orbit self-calibration, and also extensively in the on-ground calibration at CCD level. This effect is being exhaustively investigated in the GAIA program, where centroiding shifts of 0.001 pixel have to be measured. DUNE is mainly sensitive to PSF shape variations and modelling of the effects will be required in order to achieve a detailed understanding and a validation of the overall ground calibration procedure. For throughput measurements, there will be sufficient transits of stars of

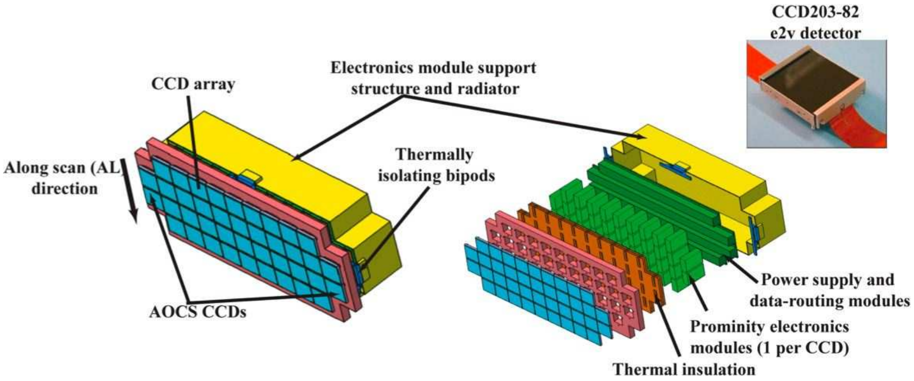

Figure 2. Left: The VFP assembly with the 9x4 array of CCDs and the 4 AOCS sensors on the front (blue) and the warm electronics radiator at the back (yellow). Right: An expanded view of the VFP assembly, including the electronics modules and thermal hardware (but excluding the CCD radiator). Inset: The e2v CCD203-82 4kx4k pixels shown here in a metal pack with flexi-leads for electrical connections. One of the flexi-leads will be removed.

known magnitude to calibrate spatial variations both from the optics and the CCDs. Other calibrations will include scattered light and detector characteristics (noise levels, cosmetics).

The DUNE VFP uses standard technology with essentially qualified detectors. Most of the conceptual design can be adapted from other missions, in particular GAIA. Radiation damage to the detectors is one issue in DUNE that will need careful attention, as the shape measurements have to be made accurately. However, software post-processing and in-flight calibration techniques are being developed to address this issue.

2.3 Near Infrared Focal Plane Array

The NIR system meets the science requirements and is based on mature components with which JPL, MPE and MPIA have had extensive experience in characterizing and integrating into astrophysical instruments. The baseline NIR FPA is composed of a 5 x 12 mosaic of 60 Hawaii 2RG detector arrays from Teledyne, NIR bandpass filters for the wavelength bands Y, J, and H, the mechanical support structure, and the detector readout and signal processing electronics. The FPA is operated at a maximum temperature of 140 K for low dark current of 0.02e-/s[*]. Each array has 2048 x 2048 square pixels of 18 μm size resulting in a 0.15 x 0.15 arcsec2 field of view (FOV) per pixel for the image scale of DUNE. The 5 x 12 mosaic has a physical size of 482 x 212 mm, and covers a FOV of 1.04° x 0.44° or 0.46 square degrees with a filling factor of 89made from molybdenum to match the thermal expansion coefficient of the array mounts. The total weight of the FPA, including the Mo-structure designed for loads of 25g in all axes, is around 40 kg without light-weighting. With the expected availability of a SiC array mounting option from Teledyne, the complete FPA structure can likewise be made from SiC to reduce the weight further.

The HgCdTe Hawaii 2RG arrays are standard devices requiring no development with flight instrument heritage (WISE and James Webb Space Telescope (JWST)). They are composed of a CMOS multiplexer bump-bonded to the HgCdTe sensor layer which is sensitive in the 0.8 to 1.7 m wavelength range with a quantum efficiency of about 0.8. Unlike the charge transfer process used by the CCD, the CMOS multiplexer individually addresses, non-destructively reads, and resets each pixel. Up to 32 data channels are available for parallel output of video data. The array can be read at a maximum pixel rate of 5MHz per channel, but for low read noise operation, the pixel rate is typically limited to 100kHz, resulting in 1.3 seconds to read out the entire array.

For each array, the readout control, A/D conversion of the video output, and transfer of the digital data via a serial link is handled by the SIDECAR ASIC (application specific integrated circuit) developed by Teledyne for JWST. This device has low power consumption (about 100 mW for 100kHz pixel rate and 16-bit A/D-conversion of 32 channels), high flexibility (programmable readout, including windowing), and an operating temperature range from 30 to 300 K. The ASICs will be located within a few centimetres from the arrays to avoid degradation of the analogue video signals, but will be thermally isolated from the arrays and can thus be operated at a higher temperature.

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[*] M.Rao (Teledyne), private communications.

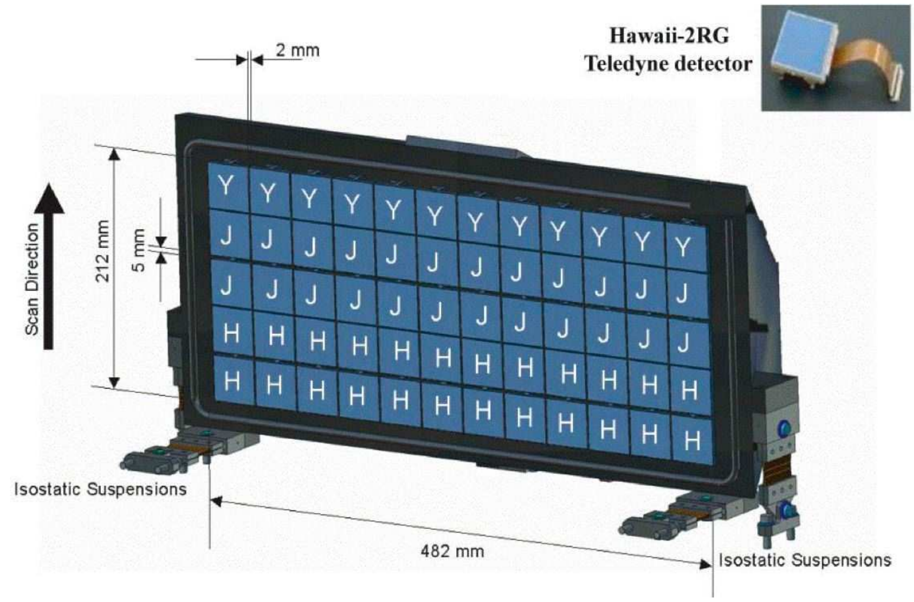

Figure 3. Layout of the NIR FPA (MPE/Kayser-Threde). The 5 x 12 Hawaii 2RG Teledyne detector arrays (shown in the inset) are installed in a molybdenum structure

As the spacecraft is scanning the sky along a great circle, the image motion on the NIR FPA is stabilized by a de-scanning mirror during the integration time of 300s or less per NIR detector. After the initial integration, the mirror flips back to its start position, thus shifting the field from one row of the array to the following exposure. In this way, the total integration time of 1500 s for the 0.4° high field is split among five rows and 3 wavelengths bands along the scan direction. Since two arrays are covered with J and H filters and the other one with a Y band filter, the effective integration times are 600 s in J and H, and 300 s in Y. To achieve the limiting magnitudes defined by the science requirements (24AB, SNR=5, point source) within these integration times, an effective read noise of about 5 e- is required (which would achieve better than 24.4 AB). The read noise of the arrays is about 18 e- for a single read (25 e- for correlated double sampling). For n reads, the effective read noise goes down roughly as the square root of n, implying that a minimum of 13 reads are required to meet the sensitivity specifications. Given that one read takes 1.3s, many readouts are feasible. The number of reads is a trade-off between sensitivity on one side and available computing power and power consumption on the other side. The processing of the digital video signals requires more computing power and memory than provided by the ASICs. Therefore, data are processed on a dedicated unit located in the service module. Images can be 'integrated up the ramp' and stored in 32 bit format in a 1GB memory. For buffering data, another GB may be required. An average processing power of 22 MFLOPS is sufficient to process 13 reads within 300 s. For a larger number of reads, the computing power increases with the number of reads; for permanent readout, 390 MFLOPS are required. For rejection of cosmic ray events and data compression, additional computing power and storage is required.

No specific hardware is required in the NIR FPA for pointing control. The spacecraft will control all attitude and pointing for the NIR channel, including the de-scanning mirror, by using the CCD detectors located in the visible focal plane and dedicated to the AOCS.

The NIR FPA will operate in a step and stare operation with the de-scanning mirror. This is the only science mode. Other modes will be required during acquisition and scan-rate locking. The NIR FPA readout will be operated in one of two modes to be optimised during the assessment phase: either a sample up the ramp mode, or multiple Fowler sampling. Up the ramp means evenly spaced in time non-destructive reads will be made during each integration period. Multiple Fowler sampling clusters a set of reads at the beginning and end of integration times. Additional on-board processing will be required, beyond the SIDECARs, to perform either of these sampling schemes. The primary calibration requirement will be for occasional dark current status. Dark frames will be taken by using the scanning mirror to direct light away from the NIR FPA, effectively acting as like a shutter would for a dark frame.

The DUNE NIR FPA uses standard technology with qualified detectors and electronics. Most of the con-

Table 2. Technnology readiness levels for key payload subsystems

Subsystem	Heritage status	TRL
Optics	New design derived from Aladin, Gaia, RocSat2 or THEOS	7
Filters	New design	7
Dichroic	New design	6
Structure	Gaia	7
Thermal control	Standard equipment	7
De-scan mirror	LOLA fine pointing mirror	5
CCDs	Minor modifications to design used for NASA-SDO	6
CCD electronic chain	Gaia/Eddington	6
VFPA structure	Herschel/Gaia/Eddington	6
NIR Detector HgCdTe	HST WFC3, JWST NIRCAM and NIRSpec, WISE	6
Hawaii 2RG multiplexer	HST WFC3, JWST NIRCAM and NIRSpec, WISE	6
NIR electronic chain	HST WFC3, JWST NIRCAM and NIRSpec	6
NIRFPA structure	Herschel/Gaia	6

ceptual design can be adapted from other missions, in particular JWST. Though a baseline design has been identified, future trades will be studied, including alternative HgCdTe detector providers both European (eg. QinetiQ and Sofradir) as well as from the United States (eg. Raytheon), as well as the possibility of using InGaAs detectors on the Hawaii 2RG multiplexer with a 1.6μm cutoff. Additional studies will be conducted to determine the optimal method for efficient use of the NIR in the drift scan mode of the mission. These trades include options of controlled scanning of the NIR FPA itself rather than a counter scanning mirror, and fast readout modes of the detector to match the drift rate in a pseudo-TDI mode. Persistency effects on the arrays may be the most critical issues. Tests are already underway under realistic conditions (operating temperature and background cutoff wavelength) to quantify and manage the effect.

2.4 Technological readiness

Table 2 shows the technological readiness (TRL) of the different DUNE components, along with their heritage status. As can be seen in this table, the mission has a low level of technological risk because of the use of only off-the-shelf components and its reliance on the heritage.

While the level of technological risk of DUNE is low, several technological and system studies could be performed early to minimize scheduling risks. In particular, a study of the impact of radiation on the charge transfer efficiency of CCDs and the performance of these detectors at low flux levels should be carried out early as it may impact the orbit choice. The performance of the NIR HgCdTe detectors, whose image quality performance (persistence, pixel cross talk, etc.) needs to be further quantified and its mode of operation optimized (eg. number of multiple reads) The performance of a-posteriori PSF calibration and its impact on shape measurements also needs to be further studied to better specify the requirements on the AOCS system and thermo-mechanical perturbations.

While the VFP is a large array, all aspects of the optical focal plane have significant heritage through other ESA programs, in particular GAIA, which has an FPA three times larger. The e2V CCD203-82 detectors have been qualified by e2v for Lockheed Martin for the Solar Dynamics Observatory (SDO) to be launched at the end of 2008. The technological readiness for the CCD proximity electronics chain and structure has been developed both at Mullard Space Science Laboratory (MSSL) and Rutherford Appleton Laboratory (RAL) for GAIA and Solar Dynamic Observatory (SDO), and these have already demonstrated the required performances (linearity, noise and radiation hardness). Although NIR FPA is a large array which will present specific challenges, all aspects of the NIR focal plane have significant heritage (TRL 6) through other space projects on a smaller scale, in particular NASAs JWST.

2.5 Instrumentation evolution for the Euclid mission

DUNE has been proposed to ESAs Cosmic Vision program and has been jointly selected with SPACE[3] for an ESA Assessment Phase which has led to the joint Euclid mission concept. Euclid extends the DUNE science methodology to include another dark energy probe (baryon acoustic oscillations (BAO)). The expanded science and instrumentation will have significant benefits and impacts on primary and secondary science, as well as payload and mission design. Euclid will have two primary instruments (an imaging channel with visible and NIR

FPAs for weak lensing, and a NIR multi-object spectroscopic channel for BAO), with three separate focal planes. Mission architecture changes include utilizing an L2 orbit, and (probably) a step-and-stare observing mode. The photometric redshift channel (the NIR FPA for DUNE) would be reduced in size compared to the original in DUNE to between 12 and 16 detectors total, with a corresponding plate scale change per pixel to still cover 0.5 square degrees, and a descan mechanism would not be required. Significant effort is ongoing in continuing design trades for the combination of all three focal planes for maximum science return while minimizing cost and risk.

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