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Euclid end-to-end straylight performance assessment

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ABSTRACT

In the Euclid mission the straylight has been identified at an early stage as the main driver for the final imaging quality of the telescope. The assessment by simulation of the final straylight in the focal plane of both instruments in Euclid's payload have required a complex workflow involving all stakeholders in the mission, from industry to the scientific community. The straylight is defined as a Normalized Detector Irradiance (NDI) which is a convenient definition tool to separate the contributions of the telescope and of the instruments. The end-to-end straylight of the payload is then simply the sum of the NDIs of the telescope and of each instrument. The NDIs for both instruments are presented in this paper for photometry and spectrometry.

Keywords: straylight, Euclid, simulation, telescope, performance

1. INTRODUCTION

1.1 Payload description

The Euclid payload comprises a 1.2m class Korsch-type telescope with an off-axis field of view (FOV). The light at the telescope pupil is spectrally separated in two channels, one per instrument. One instrument (VIS) operates in the visible (550 nm to 900nm) spectral range. The second instrument is the Near Infrared Spectrometer-Photometer (NISP) instrument operating in the near infrared (935nm to 2000nm) spectral range. The extreme constraints imposed on the telescope performances by the probes specifications have driven the definition of stringent straylight requirements for the telescope and both instruments. The details of the telescope optical lay-out are shown in Figure **1**, the optical lay-out of the NISP instrument in described in Figure 2. The NISP instrument is a dioptric system including filters (resp. grisms) for the photometry (resp. spectroscopy) mode NISP-P (resp. NISP-S).

The straylight induced degradation of the signal-to-noise ratio and light-pollution of spectrum between two close objects in the sky has a direct impact on the number of valid observed objects in the survey. We will present in this paper a brief introduction to the Euclid payload system. The approach chosen to assess the end-to-end straylight performance and its impact on the scientific outcomes is reported as well. Furthermore we will show the latest assessed performance at system level for both instruments.

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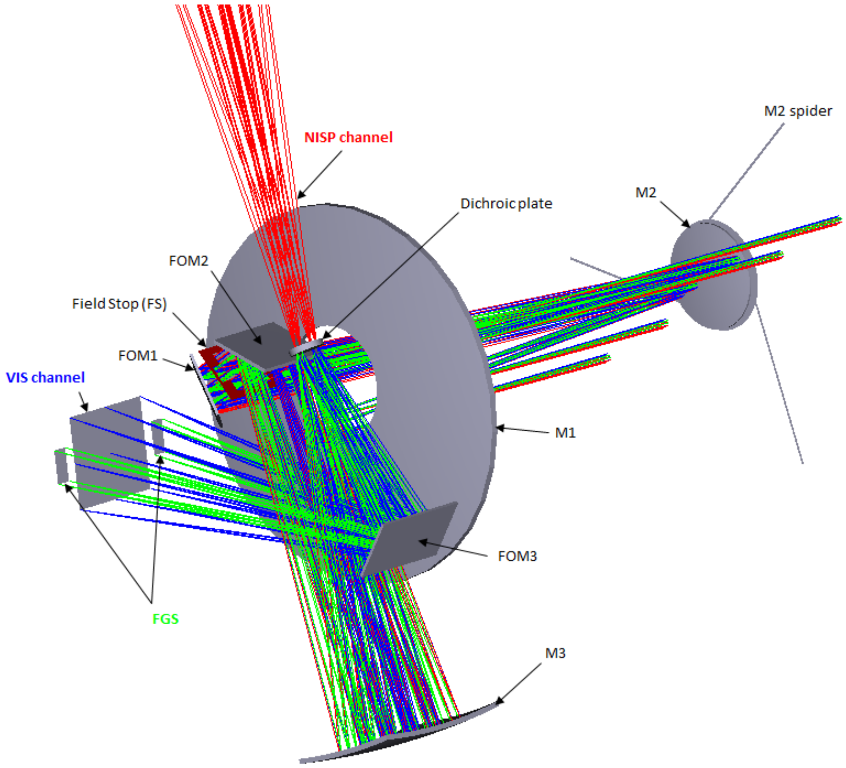

Figure 1. Telescope optical lay-out. The NISP instrument is not represented.

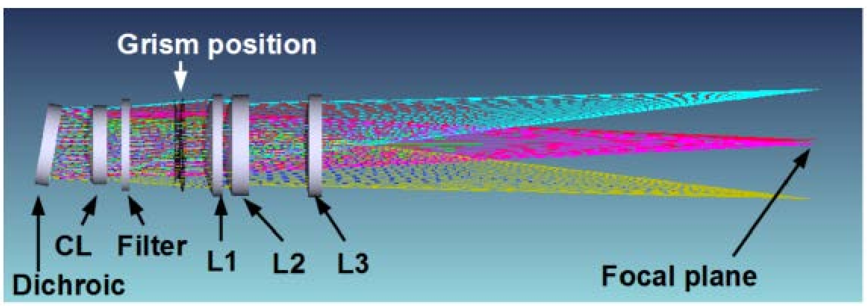

Figure 2. NISP instrument optical lay-out[1].

The mirror M1 lays on side an baseplate made out of SiC, the instruments are in the instruments cavity on the opposite side of the baseplate (Figure 4). The M1-M2 and struts assembly is surrounded by an external baffle (Figure 3).

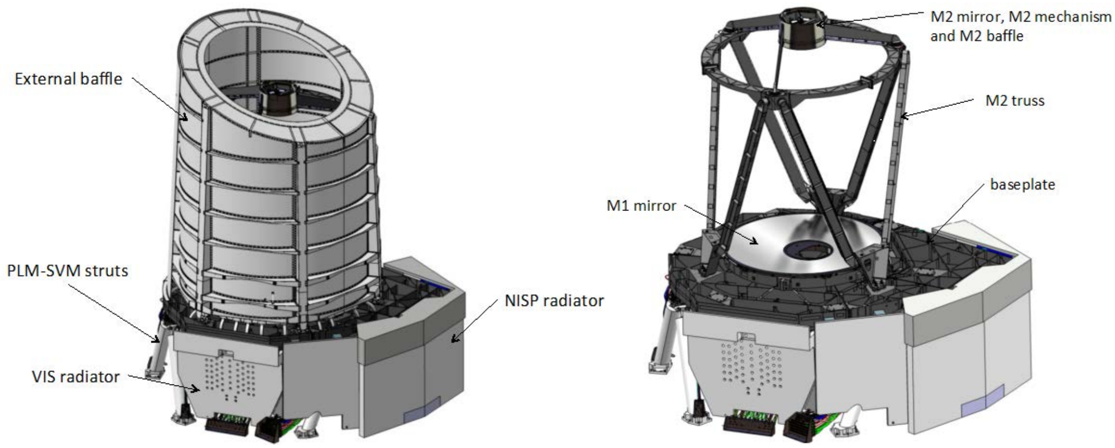

Figure 3. M1 and M2 assembly with (left) and without (right) the external baffle. Courtesy of Airbus Defense&Space.

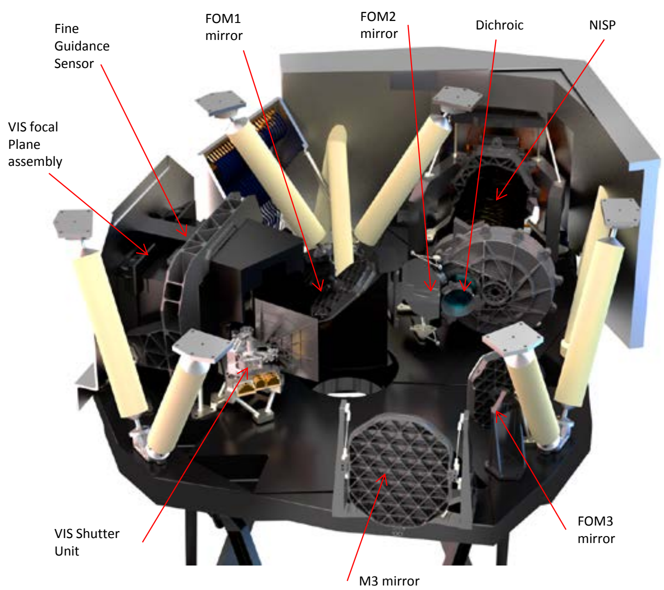

Figure 4. Payload instrument cavity. Courtesy of Airbus Defense&Space.

1.2 Payload main optical properties

The main optical characteristics of the payload are summarized in Table 1. More information on the payload can be found in previous publications[4] and in papers submitted to the present conference[8].

Table 1.

Parameter	Units	Values				
Instrument		VIS	NISP			
FoV	deg^2	0.787×0.709	0.763×0.722			
Capability		Imaging	Imaging photometry (NISP-P)			Spectroscopy (NISP-S)
Spectral range	nm	550-900	935-1192	1192-1544	1544-2000	1100-2000
Plate scale	arcsec/pixel	0.1	0.3			

2. DEFINITIONS AND ASSUMPTIONS

2.1 Normalized Detector Irradiance (NDI)

Due to the intricate nature of the image processing used in the analysis of the Euclid images and spectra, straylight cannot be defined by a single number related to a contrast ratio. Instead the very knowledge of the spatial distribution of the straylight in the instruments focal plane is paramount for objects both in the instruments FOV and out of the FOV. Furthermore, the impact of straylight on the scientific performance of the Euclid mission is derived through a complex process involving the knowledge of the instruments design, the payload system design and the mission design including the survey strategy (see Figure 5) all of which being defined by differents working groups : the assessment of the final performance is performed by the System Working group using the inputs of the Survey Working group, defining the sky survey strategy, and the Straylight Working group which defines the total NDI. In turn, the total NDI calculation uses the inputs from the Contamination control Working group which defines the contamination levels end of life for the different opto-mechanical elements within the payload.

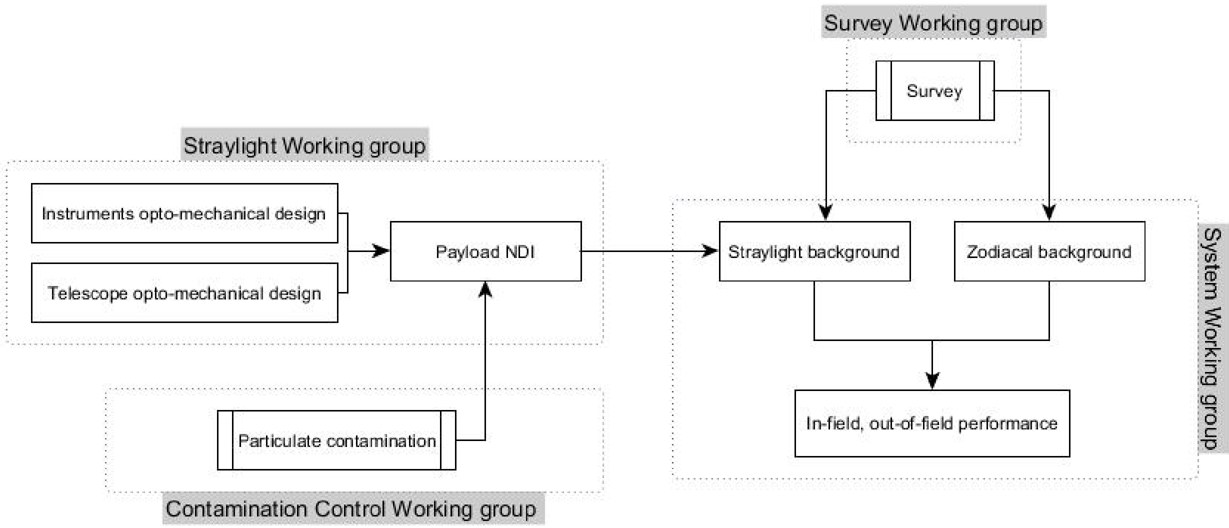

Figure 5. Work flow for the assessment of straylight impact on scientific performance

The definition of straylight must thus enable the scientists to define the straylight spatial distribution in the instruments focal plane resulting from any object distribution in the sky; it must also be usable by the industry partners and testable. For that purpose straylight is defined as a transfer function of the telescope for

input irradiance of objects at different position in the sky. This function is referred to as the Normalized Detector Irradiance[2] (NDI) the principle of which is described in Figure **6**.

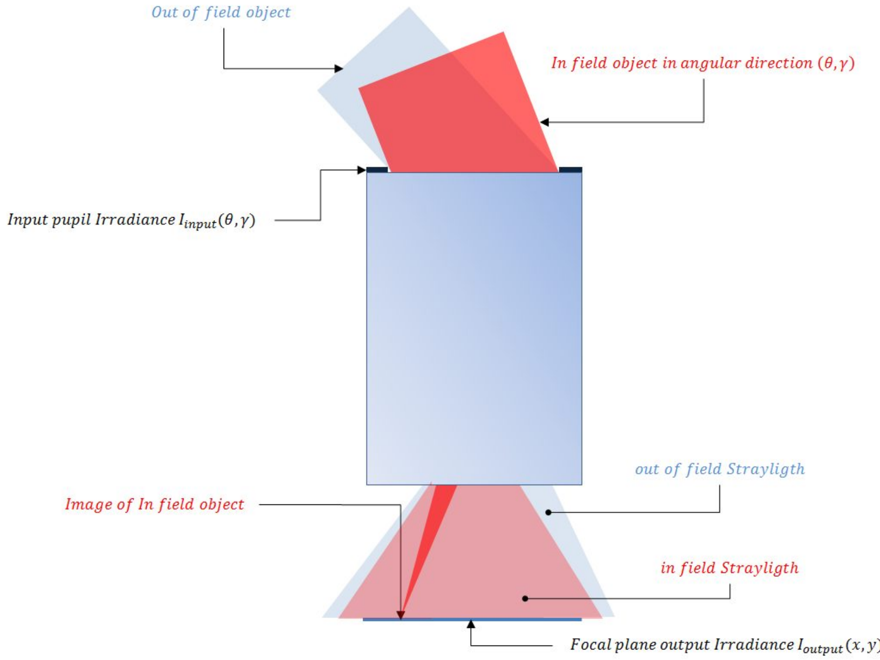

Figure 6. Schematic illustrating the NDI principle.

The NDI is defined as the ratio of the focal plane output irradiance at position *(x,y)* to input pupil irradiance for an object at angular sky coordinates *(θ,γ)* :

$$NDI(\theta,\gamma,x,y)=\frac{I_{output}(x,y)}{I_{input}(\theta,\gamma)} \quad (1)$$

For each sky coordinates (*θ,γ*) the NDI can be calculated for each position (*x,y*) in the instrument focal plane, not including the Point Spread Function itself for objects in the FOV. The NDI includes the contribution of the particulate contamination and scattering by rough mechanical structures including the baffles implemented within the payload module.

2.2 NDI properties and use

- From the definition of the NDI it is straightforward to derive the straylight corresponding to a single point object of magnitude m_{AB} at a position (*θ,γ*) in the sky. Indeed the straylight irradiance is given by $I_{ouput}(x,y) = NDI(\theta,\gamma,x,y)\times\cos\theta\times\cos\gamma\times 10^{(-0.4\times m_{AB}-19.44)}$, with m_{AB} the object magnitude in the AB photometric system[7].

  For an extended object of size (*Δθ,Δγ*) centered on (θ_0,γ_0) then the irradiance on the focal plane is derived by integration of $\int_{\gamma_0-\frac{\Delta\gamma}{2}}^{\gamma_0+\frac{\Delta\gamma}{2}}\int_{\theta_0-\frac{\Delta\theta}{2}}^{\theta_0+\frac{\Delta\theta}{2}} NDI(\theta,\gamma,x,y)\cdot I_{input}(\theta,\gamma)\cdot\cos\theta\cdot\cos\gamma\cdot d\theta d\gamma$.

- The NDI can be considered as an additive function if the different straylight contributors are considered to be independent. Then the NDI of a complex system and/or with multiple straylight sources is derived by simply adding up the NDIs of each straylight contributor. This property is used for the specification of the straylight for each optical sub-systems independently in the Euclid payload.

- The use of the NDI as straylight specification requires that during the design phase are identified the light paths which may have a non-negligible impact on the final NDI. Thus the baffling strategy, the cleaning of the optical components during the on-ground integration activities and the contamination mitigation approach before and during launch are directly driven by the compliance to the specified NDI.

- The NDI is independent of the content (total luminance, spatial distribution,…) of the observed scene.

2.3 End-to-end NDI calculation process

The NDIs of the telescope and of each instrument are calculated separately for wavelengths relevant for each instruments. Since the VIS instrument focal plane is located at the telescope focal plane the NDI calculated for the telescope is also valid for the VIS instrument. For the NISP instrument it is necessary to take into account the magnification *m* of the instrument.

The scattering by the NISP optics of the straylight coming from the telescope is here neglected, the last is supposed to be imaged directly on the NISP focal plane. Such approach allows an improved accuracy and optimizes computation time since the numbers of scattering surfaces can be reduced in the straylight models and the number of rays can be increased wrt models integrating all the scattering surfaces. The entire process presented in Figure **7** has been validated for in-field straylight with the ASAP® software package by calculating for simple cases the straylight with and without the NISP optics. The results were coherent within the calculation error margins.

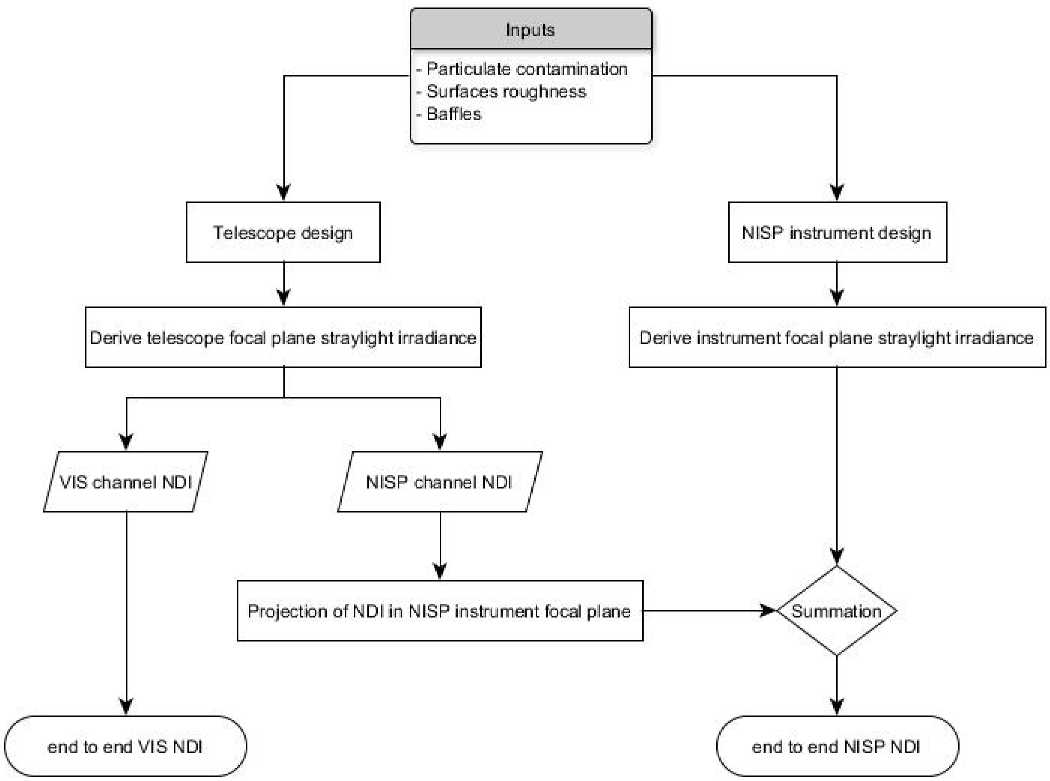

Figure 7. End-to-end NDI calculation process.

2.4 NDI specification

The specified NDI is assumed to have a rotation axis of symmetry centered on the centroid of the PSF in the focal plane. The specification is then limited to the definition of the maximum NDI achievable for any object position (θ, γ) in the sky to reach the performance set by the scientific community. The NDI wavelength dependence is also a function of the angle θ. The exact definition of the NDI specification if a complex equation and will not be reported here. The specification for the total NDI for both instruments is shown in Figure 8.

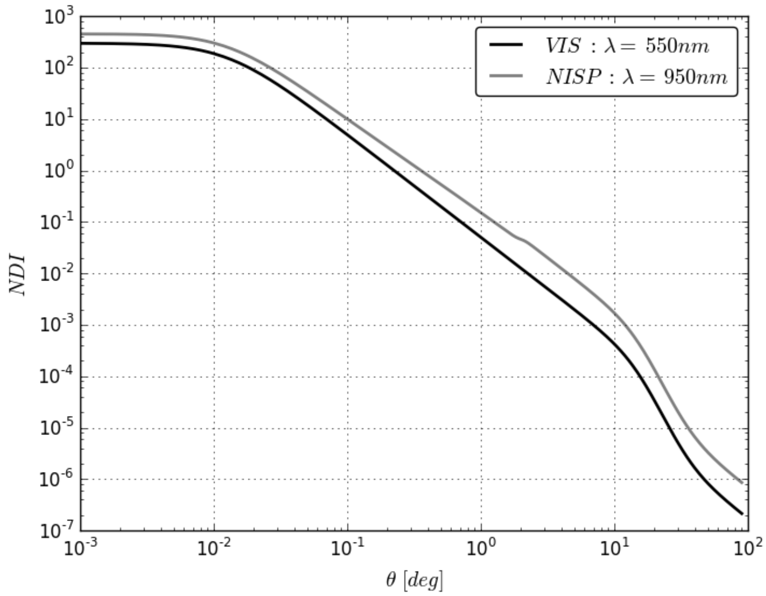

Figure 8. NDI specification for both instruments for a wavelength relevant to each instrument.

The specification can be applied as is for the NISP photometer mode. For the NISP-S instrument the NDI must be applied specifically to each diffraction order and scaled to the corresponding wavelength.

2.5 Particulate contamination

The Bi-directional Reflectance Diffusion Function (BRDF) for a mirror with particulate contamination is derived thanks to the Lallo&Petro empirical equation derived for the Next Generation Space Telescope (NGST) and based on the data reported in the series of papers by Spyak&Wolfe[3].

The particulate contamination levels End Of Life (EOL) considered for the different optical elements are shown in Table 2.

Table 2. Particulate contamination levels EOL.

<table>
<tr><th>Telescope</th><th>PAC [ppm]</th><th colspan="2">NISP-P</th><th>PAC [ppm]</th></tr>
<tr><td>M1</td><td>3000</td><td rowspan="2">L1</td><td>Front</td><td>900</td></tr>
<tr><td>M2</td><td>3000</td><td>Back</td><td>900</td></tr>
<tr><td>M3</td><td>1200</td><td rowspan="2">L2</td><td>Front</td><td>900</td></tr>
<tr><td>FOM1</td><td>3000</td><td>Back</td><td>900</td></tr>
<tr><td>FOM2</td><td>1200</td><td rowspan="2">L3</td><td>Front</td><td>900</td></tr>
<tr><td>FOM3</td><td>1200</td><td>Back</td><td>900</td></tr>
<tr><td>Dichroic Front</td><td>1200</td><td rowspan="2">CL</td><td>Front</td><td>1800</td></tr>
<tr><td>Dichroic Back</td><td>1200</td><td>Back</td><td>900</td></tr>
<tr><td></td><td></td><td rowspan="2">Filter</td><td>Front</td><td>900</td></tr>
<tr><td></td><td></td><td>Back</td><td>900</td></tr>
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3. STRAYLIGHT ANALYSIS

3.1 Contamination and rogue paths

It is clear that the NDI can be driven by different straylight sources and/or paths depending on the position (θ,γ) of the considered object. The first step of the NDI analysis is to identify the main drivers accordingly to the sky coordinates. The NDI can then be divided in three well defined regions (see Figure 9) :

1) close to the PSF centroid up to 1 degree from it the straylight is dominated by the scattering of the particulate contamination on the optical elements,
2) for angles larger than 1 degree up to about 30 degrees first scattering from the mirrors mounting and rogue rays entering in the payload module cavity through the primary mirror opening are dominating,
3) for $\theta \geq 30$ degrees, the light scattered by the baffle entering in the PLM cavity and reaching the VIS and NISP focal plane is driving the NDI.

At this stage the NDI includes the scattered light only. The diffraction effects were analyzed but are not included here as the diffraction due to the pupil function is included in other imaging performance metrics[4].

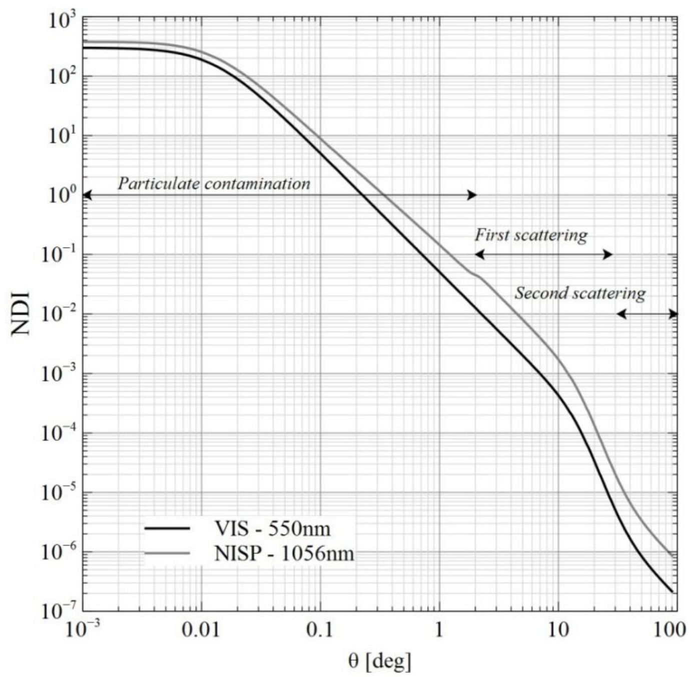

Figure 9. Main contributors area of impact in the NDI.

3.2 End-to-end NDI

The baffles detailed definition is not yet consolidated and will be finalized in 2017. However the main baffles properties and location in the payload module are identified and implemented in the straylight analysis model built with the ASAP® software package.

The considered particulate contamination levels for the optical elements are those reported in Table 3.

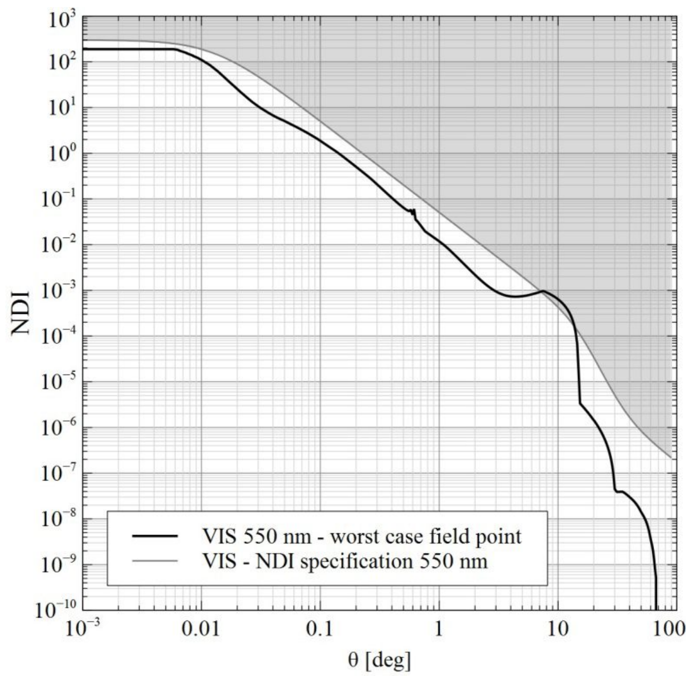

Figure 10. VIS instrument total NDI for λ =550nm.

For the NISP instrument alone the NDI is limited to the in-field area. The instrument internal baffles[6] reduce very efficiently the amount of out-of-field straylight reaching the instrument focal plane. This secondary straylight source is thus neglected. The out-of-field straylight in the NISP instrument is dominated by the telescope alone.

The total NDI is derived from the analyses performed for the telescope and the NISP instrument independently as per the process described in Figure 7. The results for the NISP-P are reported in Figure 11. The straylight analysis for the NISP-S is currently ongoing.

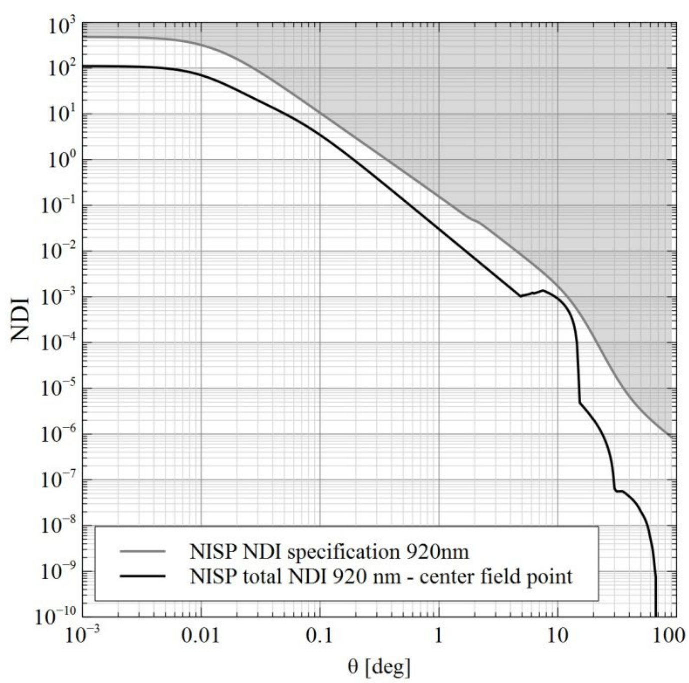

Figure 11. NISP-P instrument total NDI for λ =920nm at the center of the field of view of the instrument.

3.3 NDI sensitivity to particulate contamination

The end-to-end NDI for the NISP-P was found to be dominated by the telescope NDI. Preliminary results for the NISP-S based on Bi-directional Transmitted Diffusion Function (BTDF) measurement on grism prototypes have led to the same conclusion. The cleaning and contamination monitoring efforts during the payload and spacecraft integration and validation activities must then mainly focus on the telescope surfaces. A sensitivity analysis is performed (see Table 3) on the telescope optical surfaces to determine the main offenders and is implemented in a Excel™ worksheet tool based on the work of Peterson(2004)[5]. This tool provides an assessment the maximum levels of NDI for 9 points in the field of view of each instrument. An additional feature of this tool is the calculation of the NDI curves for any PAC levels of the telescope mirrors. The Figure 12 shows an example of calculation for the set of contamination levels defined in Table 2.

Table 3. Sensitivity table for the worst case field point of the instruments detector.

		NISP focal plane (λ = 1056 nm)		**VIS focal plane (λ = 550 nm)**	
Optical element	**PAC [ppm]**	**Maximum NDI**	**Contribution**	**Maximum NDI**	**Contribution**
M1	3000	0.09	0.03%	0.08	0.04%
M2	3000	0.98	0.38%	0.83	0.37%
FoM1	3000	136.77	52.37%	116.17	51.99%
FoM2	1200	117.92	45.15%	100.15	44.82%
M3	1200	1.00	0.38%	0.85	0.38%
Dichroic front	1200	2.17	0.83%	1.84	0.83%
Dichroic back	1200	2.24	0.86%	n.a.	n.a.
FoM3	1200	n.a	n.a.	3.52	1.58%
	Total	**261**	100%	**223**	100%

The maximum NDI levels calculated were estimated to be higher than the result achieved with ASAP® by 20% at the most. The purpose of the tool is to provide a quick assessment of the expected straylight levels and NDI curves for different contamination levels. In particular it is useful to assess the impact of particulate contamination levels currently being investigated by the Euclid Contamination Control Working Group.

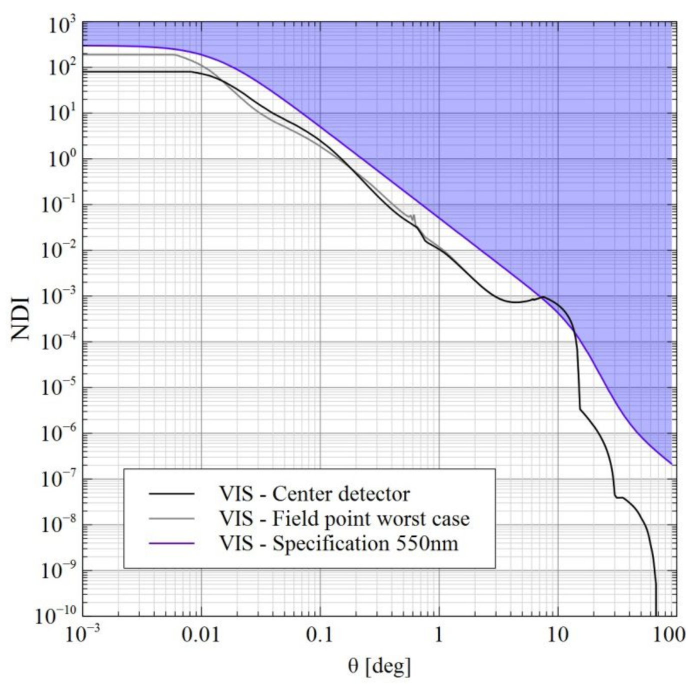

Figure 12. Results for the VIS instrument of the NDI sensitivity tool for λ =550nm and the contamination levels in Table 3.

The following conclusions can be drawn from the sensitivity analysis:

1. The NDI is mostly field dependent for $\theta \leq 1$ degree
2. The in-field straylight is driven by the mirrors FOM1 and FOM2. The mirror FOM2 is the most sensitive surface. However it is well protected while the FOM1, because of its location, is more exposed to contamination falling through the M1 central hole.
3. For 1 deg $\leq \theta \leq$ 20 deg, the particulate contamination from FOM1, FOM2 and M3 is dominating.
4. For 20 deg $\leq \theta \leq$ 70 deg, the NDI main offender is the mirror M1.

4. CONCLUSIONS

During the last two years a significant effort was made to tackle the straylight issue which was identified has a potential showstopper[4] for such a challenging mission as Euclid. In the frame of the Euclid Straylight Working Group all the mission stakeholders, from the scientific consortium to the industrial partners, share the tasks of identifying, assessing and implementing straylight reduction measures in the telescope, in the instruments[6] and in the data post-processing.

From the scientific requirements a definition for the straylight based on the NDI has been derived. A NDI based specification was then flown-down to the telescope and the instruments independently. The results for the total NDI presented here show that the straylight requirements are met in-field for both the VIS and NISP-P instrument; for the NISP-S the analysis is ongoing. For the VIS instrument the NDI is slightly exceeding the specification for $\theta \approx 10$ degrees. This non-compliance is currently under investigation.

The particulate contamination of optical elements is identified as the major contributor for the in-field straylight and out-of-field straylight. A sensitivity analysis has shown that only a few surfaces have significant impact on the NDI. The contamination control activities are thus focused on those surfaces. For the other surfaces a last minute cleaning will be performed before integration in the payload and/or the NISP instrument.

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