EUCLID ASSESSMENT STUDY

EXECUTIVE SUMMARY

Written by	***Responsibility*** + handwritten signature if no electronic workflow tool
A. Anselmi	Study Manager Alberto Anselmi
Verified by	
Approved by	
P. Musi	Manager, TAS-I ESA Programs Division
Documentation Manager	
R. Cavaglià	RC 05 11 2009

Approval evidence is kept within the documentation management system.

CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
01	30-10-2009	End of Assessment Study Issue	aa

TABLE OF CONTENTS

1. BACKGROUND

Euclid is one of five medium-class space science missions under consideration as candidates for the 2017-2018 launch slots in ESA's Cosmic Vision plan. The objective of Euclid is to elucidate the geometry and the nature of the dark energy and dark matter components of the universe, with unprecedented accuracy, in a large survey of the extragalactic sky by two complementary techniques.

The Assessment Phase, just completed, was to provide all the elements for enabling the selection to proceed. After the down-selection, to be announced in January 2010, a definition phase will be carried out, to be completed by the end of 2011, followed by adoption of the two M-class missions and their implementation phase and launch. The industrial studies had to contribute to the assessment by providing a definition of the space segment (satellite including payload) and programmatic assessments, including development schedule and industrial costs. This document summarizes the results of one such study performed between September 2008 and September 2009 by a team led by Thales Alenia Space (I) and including Thales Alenia Space (F), Kayser-Threde and Deimos Space.

2. SCIENTIFIC MISSION CONCEPT

Over the last decade, astronomers have accumulated conclusive evidence that the Universe's expansion is accelerating [1]. Within the framework of the standard cosmological model, this implies that 70% of the universe is composed of a dark energy which counters the attractive force of gravity. Dark energy ranks as one of the most important discoveries in cosmology, with profound implications for astronomy and fundamental physics. ESA's Euclid mission focuses primarily on two powerful and robust probes of the dark Universe. The baryonic acoustic oscillations (BAO) method relies on the distribution of ordinary (baryonic) matter, deduced from a massive galaxy redshift survey. The weak gravitational lensing (WL) method uses the distortion of the apparent shapes and orientation of galaxies to infer the distribution of mass along the line of sight. The combination of WL and BAO will provide very strong constraints on the dark energy equation of state and allow sorting out systematic uncertainties and biases that are inherent to each individual probe.

The mission carries a telescope with a primary mirror of 1.2m diameter, feeding three scientific instrument channels: a CCD based optical imaging channel (VIS), a NIR imaging photometry channel (NIP), and a NIR slitless spectrometric channel (NIS). The mission will survey 20 000 deg² of the extragalactic sky (Wide Extragalactic Survey, WES) in the visible down to AB=24.5 mag. Two types of redshift will be collected. For all galaxies, photometric redshifts will be obtained from the broad band visible and near-IR measurements. For the sub-sample of galaxies brighter than H(AB)= 19.5 mag, redshifts will be measured directly with the NIR slitless spectroscopic channel.

Moreover, a deep survey (DS) of several tens of square-degrees will be performed. The DS will provide the calibration of the photometric redshifts of the wide survey, as well as additional science. The approach to this survey still has to be worked out; as a guideline, the DS should be obtained by stacking images taken at different times in the course of the WES (multiple revisits of the same sky).

Table 1: Instrument bands

Instrument	Band	Wavelength (nm)	Limiting AB mag	Resolution
VIS	R+I+Z	550-920	24.5	0.1" pixel
NIP	Y	920-1146	24.0	0.3" pixel
	J	1146-1372	24.0	0.3" pixel
	Hp	1372-2000	24.0	0.3" pixel
NIS slitless	Hs	1000-2000	19.5	R=500±20 (point source)

3. MISSION DESIGN

The reference orbit of Euclid is a large-amplitude, free-insertion libration orbit about Sun-Earth L2. The nominal mission lifetime is 5 years, with scientific operations taking at least 4.5 yr.

The s/c will be launched from the Guiana Space Centre, Kourou, on board a Soyuz-Fregat launcher, providing direct insertion into transfer orbit. The launch window analysis showed free-insertion launch opportunities can be found almost through the whole year, when considering a desirable Sun-Spacecraft-Earth (SSE) variation of around 30°. Transfer to L2 shall be completed within 30 days, and the Commissioning Phase shall be completed within 2 months after the end of the Launch and Early Orbit Phase. The instability inherent in the motion about L2 requires periodic corrections. The orbit maintenance strategy shall provide non-escape orbits with variation of SSE angle within the range covered by the on-board antenna during the scientific mission (30° baselined). Orbit maintenance manoeuvres shall occur once every 30 days and take less than 1 day. Mission analysis for Herschel, Planck and Gaia shows Δv requirements between 2 and 3 m/s/year.

The scientific mission consists of a Wide Extragalactic Survey (WES) and a Deep Survey (DS). The WES shall cover 20,000 deg² in the regions of the North and South galactic poles (Galactic latitude $|b| > 30°$). The DS shall cover by multiple visits 40 deg^2 in the vicinity of the ecliptic poles. The sky survey is accomplished by collecting daily strips made up of contiguous, partly overlapping fields. Patches of contiguous strips cover at least 20°x20° (Figure 1).

Cebreros is the prime site for tracking the operational phase of the mission. An L2 mission is observed in the night time. The duration of a daily visibility session from Cebreros shows the typical seasonal pattern, and ranges between 6 and 18 hours, at 5° elevation mask. The useful seasonal minima of the visibility may however become <<6h, assuming the 20° elevation mask required for reliable K-band telemetry. The prescribed duration of the daily communications slot, driving for the telemetry rate, is 4 h.

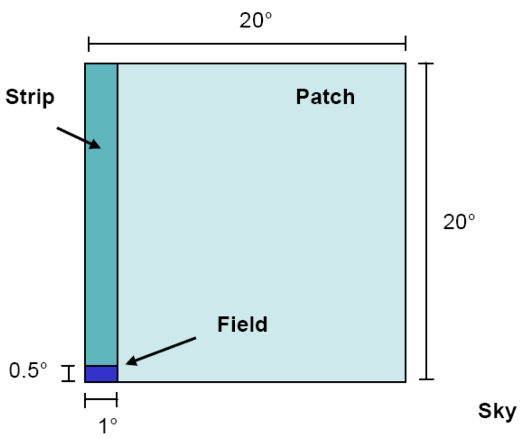

Figure 1: Sky survey nomenclature

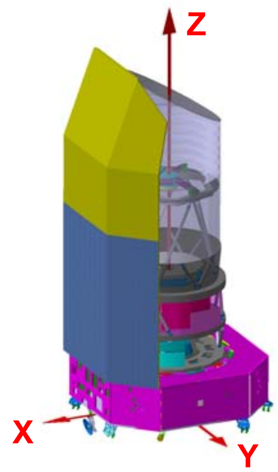

Figure 2: Spacecraft Reference Frame

3.1 Sky Survey Strategies

The basic strategy of sky mapping consists in performing sequential observations by rotating about the spacecraft X-axis, nominally pointed at the sun (yaw rotation), each day covering a strip along the intersection of a great circle perpendicular to the sun line with the extragalactic caps. A longitude step of ~1º (if measured at the ecliptic equator) is taken every day, ensuring the contiguity of the strips. This strategy naturally follows the sun and thus has yearly period. In the basic strategy, complete coverage is achieved in 6 years, violating the 4.5 yr maximum time requirement. This occurs because of lesser efficiency in the vicinity of the ecliptic poles, due to strip overlapping, as well as dead time around the equinoxes.

To overcome these drawbacks, a modified strategy was introduced [2]. In this variant, the X axis is allowed to make an angle of up to 30º with the direction of the sun, by rotating the spacecraft around Y (pitch rotation). Relaxing the constraint allows observing sky areas at longitudes different from those of the great circle perpendicular to the S/C-Sun direction. As a consequence one can now explore the dead zones of the basic strategy. In the modified strategy, the standard scanning sequence is used for the "optimum" zones (those where no loss of efficiency occurs due to excessive strip overlaps), while the dead zones are covered by tilting the SC around its Y-axis. The latter time is called "flexible time" because the scan direction is selectable in a number of ways. The modified strategy shows a drawback too: there appears an unreachable zone in each of the galactic caps. Imaging that zone requires extending the mission beyond 4 yr.

In order to bring the WES to less than 4 yr, more variants were studied. The selected option consists in extending the flexible intervals in the 4th year, by a corresponding reduction of the 'optimum' scanning phase. The areas of the sky not imaged due to the shortening of the optimum interval can anyway be covered during the flexible times. This strategy succeeds without requiring a wider range of Solar Aspect Angle (SAA); see Figure 3.

The results mentioned above hold for field dwell time of 2400s. Longer times would be difficult to accommodate within 4 yr, especially if one considers that the WES ought to allow sufficient "redundant" time at high ecliptic latitude to meet the requirements of the DS (Figure 3). The flexible time extension is the best option devised so far to improve the strategy initially proposed by ESA. It achieves the required sky coverage in 4 years while complying with the 30°-SAA constraint, without additional roll rotations. The pointing angle evolution during the flexible times does not need to be specified in a unique fashion; different yaw-pitch combinations can be used. An objective for the next study phase will be developing a more formal approach to the problem of making optimum use of the flexible times. Further study will be devoted, too, to the DS strategy and the handling of contingencies.

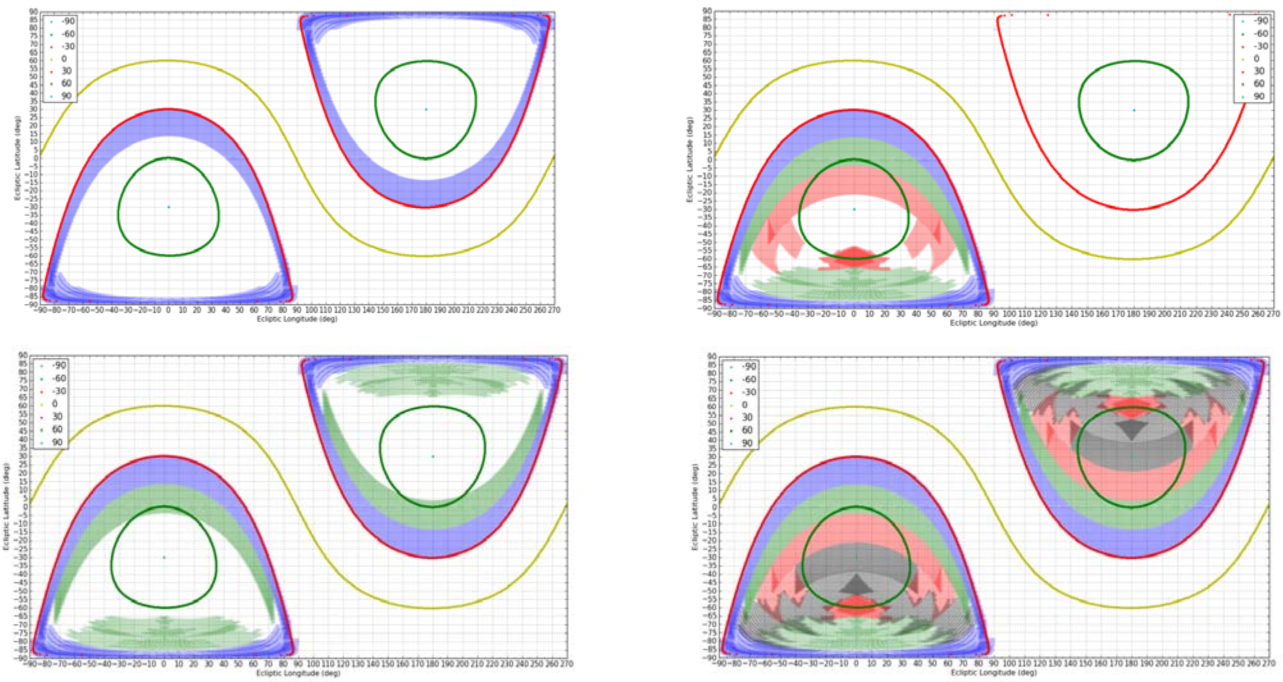

Figure 3: Sky-mapping strategy, years 1 to 4

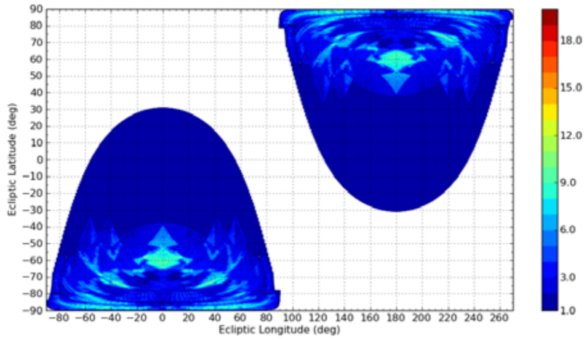

Figure 4: Visit count after 4 years

3.2 Sky Survey Performance

The WES time budget performance depends on the dwell time per field (which in turn depends on the elementary integration times in the different bands) and on the non-operating times (slews, interruptions for manoeuvres). Under spacecraft-level dithering, observations must be synchronized across all channels, hence the channel requiring the longest integration time is the driver. The minimum required dwell time per field is found to be 2250s (Figure 5). 2400s was taken as input for the WES strategy analysis, providing 7% time margin per field. 36 steps are allowed each day, that is a strip of about 17° if the field small side is 0.48°. Under consideration of the housekeeping operations (reaction wheel unload, antenna re-pointing, calibrations), a total WES time budget of about 4.5 yr results, compliant with the requirements.

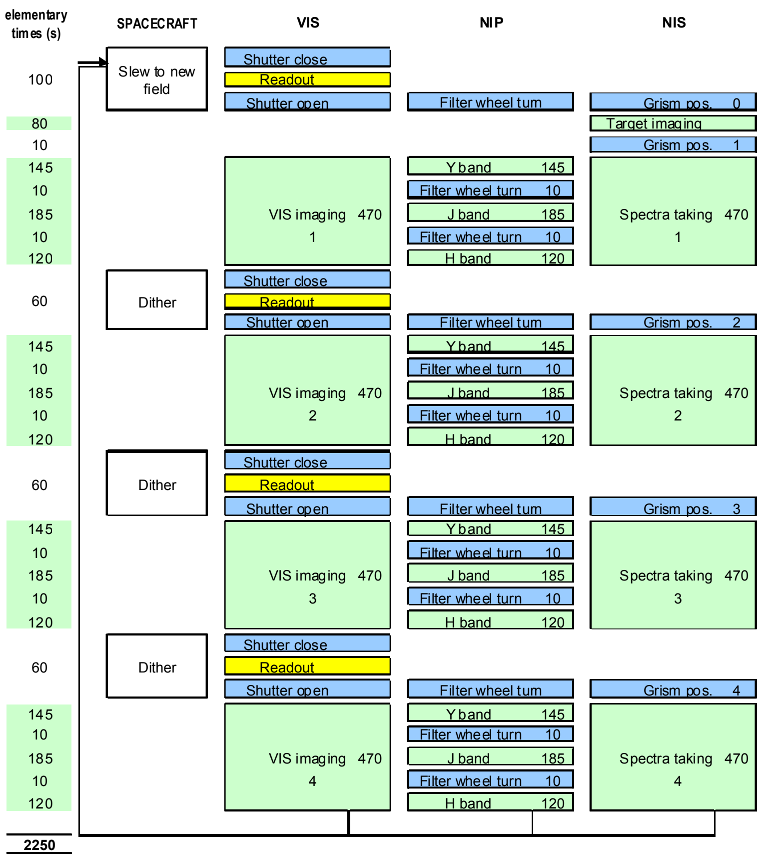

Figure 5: Example of synchronized observation plan of the three instruments

4. SYSTEM DESIGN CONCEPT

4.1 Key Requirements and Design Drivers

The Euclid system is driven by the diverse Dark Energy probes, each with its own specific requirements; by the width and speed of the envisaged sky survey; by the survey depth and signal to noise ratios; and, last but not least, by programmatic constraints.

The multiple DE probes are accommodated by one telescope feeding three instruments. The requirements on size reconstruction and stability of the Point Spread Function (VIS instrument) lead to high image quality, in turn producing large data rates, and to demanding requirements being placed on the pointing and thermoelastic stability.

The survey speed is guaranteed by the combination of a large field of view, about 0.5 deg², an optimized sky mapping strategy, and minimized dead times such as attitude transitions, leading to a requirement for fast slews. The survey depth and SNR requirements lead to a well baffled design, low temperature optics and detectors, and, driven by the NIR instruments NIP and NIS, a cold telescope for low thermal IR background, and extensive on board data processing for noise limitation.

Finally, the chief programmatic constraints include the M-mission cost ceiling and target launch dates, a telescope diameters limited to 1.2 m, and an upper limit on the number of NIR detectors. To contain costs, well established designs are to be employed unless the mission objectives demand otherwise; and anyway, any new technology must be demonstrated by test (Technology Readiness Level ≥5) by 2011.

4.2 System Definition

The generic configuration requirements of Euclid call for a modular configuration, with a Payload Module and a Service Module well separated from both a physical and a functional point of view (Figure 6). The mission specific configuration requirements are dominated by the demanding payload requirements in terms of rejection of straylight, low detector temperature, and high temperature stability.

The proposed solution consists of:

- Herschel-like Sunshield, protecting the PLM from illumination by the sun and Earth in all nominal attitudes of the spacecraft, and providing structural support to the solar array;
- Hollow cylindrical Baffle encapsulating the upper part of the telescope, sliced at the aperture end at an angle of 60° from its axis, endowed with a contamination cover, closed through the launch and EOP and permanently opened once on the way to L2;
- PLM mechanical-thermal concept based on a double truss for low deformation and ease of AIT, providing separate, easily controlled thermal environments to the telescope M1-M2 cavity and the instrument compartment (Figure 7);
- Optical Bench accommodating three pre-integrated instruments allowing independent parallel developments to relax the schedule constraints, with focal planes oriented towards the permanently shaded part of the configuration;
- a clean interface structure consisting of a bipod assembly supporting the PLM base plate,
- Herschel-like SVM for design and development heritage, providing modular accommodation of the platform equipment and allowing wide room for the warm payload electronics.

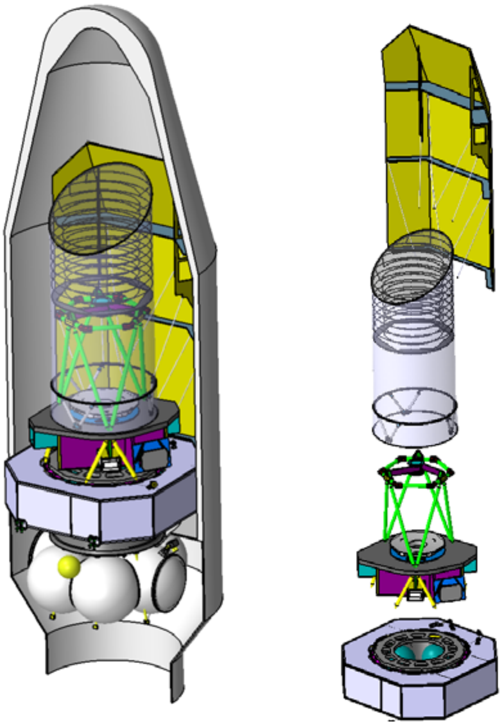

Figure 6: Satellite configuration

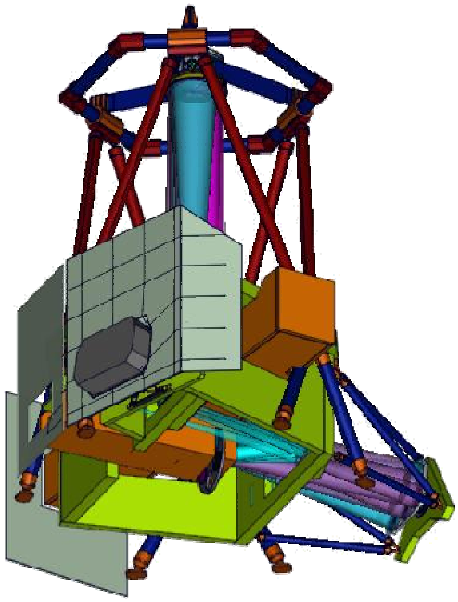

Figure 7: PLM view

4.3 System Trade-offs

Step-and-stare vs. continuous scan

In the Step & Stare Mode (SSM), the required sky map is produced via many contiguous exposures separated by appropriate slews. SSM is easy to implement; each patch can observed with high accuracy, and the sky survey can be planned with a large degree of flexibility. The disadvantages are the dead time accumulated when performing a large number of steps, and the extra complexity of dithering implementation. The Continuous Scan Mode (CSM) consists in mapping the sky by accumulating adjacent strips visited with constant and selectable scanning rate. Slews are only needed between consecutive strips. This approach reduces dead time and dithering is not required, as gaps between sensors are covered by the scan motion. On the other hand, the continuous scan mode was already shown by the CDF study to lead to difficult problems with the NIR instruments (no NIR detectors available with Time Delayed Integration, hence descan mirror required; curved FPA).

SSM was recommended as the more mature implementation, with small development risk and a more flexible observation plan. The recommendation was endorsed by ESA who directed the Phase 2 study to proceed on the basis of SSM.

Instrument-level vs. satellite-level dithering

The VIS and NIP channels require dithering on a field-by-field basis to compensate the effects of the gaps between sensors. Dithering may be performed at individual instrument level, e.g. by a moving mirror, or at satellite level. Analysis showed severe impact on the image quality of dithering performed by a rotating flat mirror. Therefore satellite level dithering was selected. The price to pay is an impact on the observation time budget (dither operations must be synchronized across all channels, hence the channel requiring the longest integration time is the driver) and some extra complication induced on the NIS (source identification in each dithered frame).

Multi-slit vs. slitless spectroscopy

Two options exist for the spectroscopic channel [1]: a multi-slit design and a slitless design. The multi-slit design proposes to employ a MEMS system, DMDs (Digital Micromirror Devices [4]), to observe multiple faint sources over a wide field with high versatility and optimized integration times. By individually reconfiguring on/off millions of optical switches, the slit configuration can be quickly adapted to the distribution of sources detected in each field. Micromirror reconfiguration can provide imaging and slitless spectroscopy modes too. With the multi-slit design, the spectroscopic survey can reach limiting magnitude 22, as opposed to 19.5 magnitude in the slitless option, which is penalized by the sky background. The DMDs are a patented US commercial device that has to be used without modification. In parallel with the industrial studies, ESA initiated a dedicated experimental characterization contract, the results of which are becoming available now.

The DMD design was addressed in Phase 1 of this industrial study. The DMDs place extra design constraints on the instrument (micro mirror-diffused straylight; DMD upper limit temperature of 233K) which are being addressed in the characterization study. The optical design is very complex (anamorphic design; fast beams). Several design approaches were investigated, such as mirror based optics with pick-up mirrors at the Cassegrain focus and in telescope focus behind a tertiary mirror; different lens based design concepts were studied too.

In Phase 2, ESA directed the industrial study to continue on the basis of the slitless option. Meanwhile, the ENIS consortium continued its development of an optimized DMD-based implementation; a working optical design was disclosed at the end of the Assessment Study. The DMD option would require re-design of the instrument accommodation; this exercise will be undertaken in the next study phase if so directed by ESA.

NIS source identification

Sources cannot be identified in the dispersed images; therefore their identification must rely either on NIP observations and very good attitude knowledge (leading to a demanding Attitude Measurement Error requirement), or a short dedicated NIS imaging session must be introduced before each spectrum is taken (requiring an extra mechanism function to move the dispersing element in and out of the FOV). For now, both options are kept open.

Straylight & stray heat protection

The Euclid instrument is very sensitive to both stray heat sources and straylight. Decoupling the two functions of thermal shield and straylight protection has significant advantages in terms of design simplification and improved performance. Lacking a straylight analysis, not in the scope of this preliminary study, a baffle concept based on the SNAP design [6] was provisionally adopted. Depending on a future straylight analysis, this solution will be maintained or it will be replaced with a simpler shade structure. A sun shield can act as solar array support and provide the PLM and the baffle with cold and stable temperature conditions, avoiding the need for complex means to remove heat from one side of the baffle. The radiator accommodation is facilitated too. The telescope is made nearly completely insensitive from the external environment and its variations (internal sources of temperature instability, i.e., variations of thermal dissipation of the instrument front end electronics, will be minimized by design). This is particularly important when considering observations made at widely different epochs and attitudes to the sun (e.g., Deep Survey observations used for calibrating the WES).

Cold vs. warm telescope

The factors in this trade-off include (a) the NIR instruments performance, which is sensitive to the thermal background, (b) ground test issues, favouring an ambient temperature telescope, (c) electric power needed to maintain temperature if this is very different from the natural equilibrium temperature. Calculation of the instrument background showed that, with suitable provisions, the requirement that the IR background be less than 20% of the sky background can be met if the telescope temperature is ≤240K. In the given thermal environment (telescope at L2 in permanent shadow of a sun shield), this temperature is close to the equilibrium temperature, leading to little heater power required and small temperature variation over different solar aspect conditions. 240K temperature is not so low as to require special AIT facilities; telescope testing will be for the most part at ambient temperature, relying on thermal model correlation and a final low-T test.

Experiment Mechanical Accommodation

A highly modular instrument accommodation concept was preferred. Each instrument is defined by clear and independent mechanical and optical interfaces. Each instrument can be specified, developed, tested and integrated into the PLM as a self standing unit.

Instrument Data Handing Architecture

The instrument data handling architecture must provide ample scope to instrument autonomy in order to cope with different technologies and individual development and integration constraints. In each instrument, the data processing and the control tasks will be tightly linked in an experiment-specific way; development of the two tasks should not be separated. At the same time, the selected architecture must provide simple and efficient command, control and data distribution interfaces, and minimize power, mass and volume budget impact and operating cost. Based on these criteria, the proposed instrument data processing architecture includes independent Instrument Control Units for control and drive tasks, and instrument DPUs for data processing and compression. Direct interfaces to the mass memory are provided for high-rate science data storage.

Attitude measurement and control trade-offs

The ESA CDF study [2] already identified a Fine Guidance Sensor (FGS) co-located with the VIS focal plane as the only practical solution to the demanding RPE requirement (25 mas in 450s). This study confirmed that choice. To minimize temperature driven mechanical deformations, the FGS must share the VIS optical system; accommodation should be close to the VIS focal plane, with higher distance from the optical centre to improve the accuracy around the boresight. To minimize the impact on the observation time budget, the shutter enabling the VIS readout must not shut out the FGS field of view.

The RPE requirement is the driver, too, of the need for high-resolution, low-noise actuators. Micro thrusters of the GAIA type or magnetic-bearing reaction wheels are the candidates. Because of the step-and-stare mode of operation and the satellite-level dithering, a high proportion of the manoeuvre angular momentum is cyclic. Cyclic momentum has considerable impact on the propellant mass budget if low specific impulse thrusters are used. Because of their performance and better mass budget, magnetic bearing reaction wheels were recommended, subject to continued monitoring of their development status over the next 2 years.

4.4 Telescope and PLM Design

The telescope is driven by the large FoV, feeding a large FPA, by the image quality over the FoV and over the spectral range, and by the volume requirements of the three focal plane instruments. The diameter (1.2m) is imposed by the MRD. The combination of f-number (f/20) and field of view (0.5 deg²) imposes a Cassegrain or Korsch design. The Korsch concept was recommended already in the CDF study and maintained ever since. The optical design adopted at the end of the Assessment Study is based on a reference design received from ESA, common to all industrial and scientific study teams, adapted by the TAS team to improve its accommodability (Figure 8).

The mechanical design is driven by the permissible tolerances, analyzed with the optical model. In particular the M1/M2 distance stability, better than 5 µm, is a major driver. To comply with it, a refocusing mechanism equips the M2 mirror.

The overall concept is based on low CTE materials and flight proven technologies, allowing all together very high stability. The primary mirror is made of Zerodur, light weighed within manufacturing standards. The telescope structure is based on a Si_3N_4 hexapod truss assembly and an optical bench made of sandwich aluminium honeycomb and CFRP skins. The lower part of the PLM houses the three focal plane instruments. The architecture of this part too is driven by the optical stability requirements (relaxed by a factor 10 compared to the M1/M2 stability requirement). NIS is accommodated on the rear part of the optical bench holding M1, while NIP and VIS are accommodated in a structure made of CFRP sandwich panels, designed to stiffen the optical bench, The M3 serving VIS and NIP is supported by a CFRP truss too.

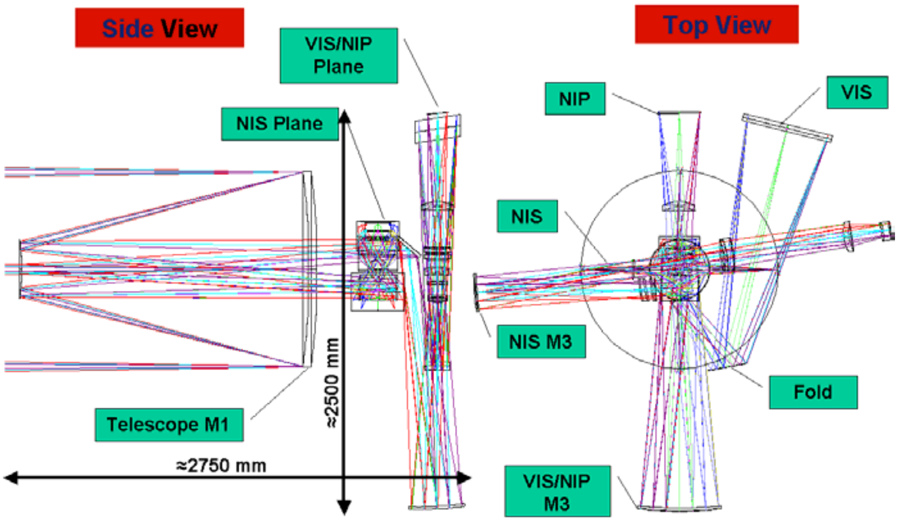

Figure 8: Telescope optical layout at the end of the Assessment Study

4.5 Payload Instrument Design

Visible Imaging Channel (VIS)

The visible imager (VIS) instrument shall observe the sky in the R+I+Z photometric band, from 550 to 920 nm, and reach limiting magnitude AB = 24.5. The instrument is driven by the large instantaneous FoV of 0.5 deg², and by the requirements for a well sampled and stable PSF (<0.18-0.23 arcsec) with small ellipticity <20% (goal: <5%).

The folding mirror may be considered to be part of VIS or not. The latter is the proposed baseline, as it grants some more degrees of freedom for the AIT operations. At least one mechanism (shutter) is part of VIS. Another mechanism (tip-tilt mirror) could be required in order to enlarge the PSF (see below).

The optical design of VIS was established as part of the telescope design: the VIS requirements are the most stringent, and the telescope was optimized for them. At this stage, VIS is proposed to be delivered to the PLM in separate parts (FPA, warm electronics, harness) and assembled on an optical bench provided by the PLM. This approach is considered to make the configuration and AIT easier. The optical design is optimized to be limited by diffraction over a 0.5°x1° FOV. The optical PSF FWHM (under consideration of optical misalignments and WFE contributions) is <0.15” at any point of the FOV. The optical ellipticity at the edge of the field of view is less than 4%. Even after consideration of the detector and jitter components, the system PSF remains smaller than the requirement (Figure 9).

The PSF optical performance requirements – FWHM, ellipticity, and encircled energy – cannot be met simultaneously. Indeed, the FWHM is little sensitive to the perturbations considered (misalignments, WFE, jitter) whereas ellipticity and encircled energy degrade quite quickly.

Options for enlarging the PSF without impairing performance were assessed. Purely optical provisions (intentional defocus, spherical aberration, amplitude or phase masks) are not considered promising. Enlarging the PSF by controlled AOCS jitter is in principle possible; however, the amount of enlargement required by NIP would be too large for VIS. Mechanical solutions such as a tip/tilt mirror will be studied further. More generally, this problem has been recognized by ESA and the science consortia and the adequacy of the VIS (and NIP) FWHM requirement is being reconsidered.

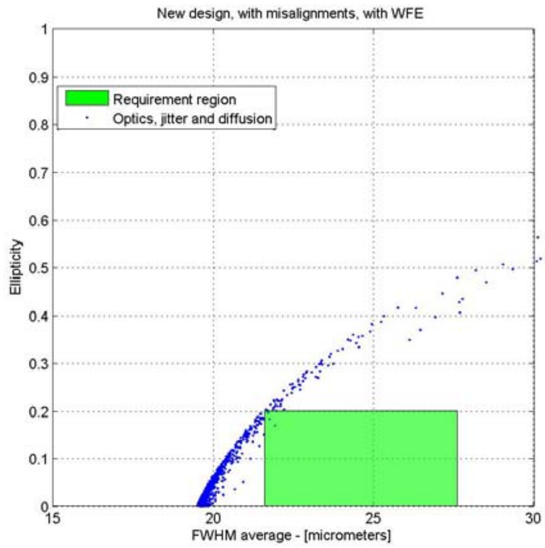

Figure 9: VIS ellipticity performance vs. average FWHM

The radiometric performance was analyzed by means of a dedicated model, in agreement with the guidelines provided by ESA and the science consortia [3]. The objective is SNR≥14.3 with 3 exposures (a final SNR of 10 is required; a factor of 0.7 is introduced to take into account the difference between the radiometric SNR and the post-processed SNR). The calculated SNR is > 14.3 after exposure time > 470s.

The proposed focal plane consists of 36 CCDs, each with 4k x 4k pixels, arranged 9 by 4 because this configuration allows best image quality over the field. The CCD203-82 sensor manufactured by E2V meets the scientific needs in terms of format and performance and, already having high TRL, minimizes risk and cost. A red-enhanced version is particularly well-suited to the 550-920 nm range, with QE higher than 90% at 550 nm, and higher than 40% at 920 nm. The radiation impact on CCD performance is being addressed in a dedicated TDA by ESA.

The proposed detection architecture features one PEM (Proximity Electronics Module) dedicated to each CCD, driven by failure tolerance. Taking into account the SNR requirements, it is preferred to have a readout frequency below 0.5MHz, which means a readout time higher than 18s considering 2 video outputs. Different architectural choices (clustered PEMs, to reduce harness and EM interference, and 4 video outputs to reduce radiation damage) will be addressed in the forthcoming Definition Study. The planned operating temperature of the CCDs is 150K, in order to minimize the impact of radiation and dark current on the SNR. The total mass of the VIS instrument is about 90 kg not including the harness. The power demand is ~170W. Assuming 2.8 compression ratio, the expected data rate is ~500 Gbit/day, the largest contribution to the PLM data.

Near Infrared Photometric Channel (NIP)

The NIR Photometer (NIP) instrument shall observe the telescope FoV in three wavelength bands (Y, J, H). The instrument consists of reducer optics, a filter wheel with three band filters, shutter, calibrator, an FPA and warm electronics. The limiting magnitude H(AB) = 24 drives the design, requiring very low detector noise, low thermal background levels, and extended integration times, in turn leading to an impact on attitude stability and on board data processing.

The optical interface of NIP is the exit pupil of the telescope (1200 mm in front of the telescope focus, diameter < 100 mm). A dichroic filter spectrally separates two beams; the transmitted light feeds NIP and the reflected beam feeds VIS. The dichroic filter is placed in the pupil in order to keep its diameter as small as possible. The bandpass filters, too, are positioned close to the dichroic, because their manufacturing is less critical if the size is smaller. Filters are tilted by a few degrees in order to avoid direct reflections into the optical system.

The NIP optical system has to be diffraction limited and show low wavefront distortion. A lens design is selected to keep the instrument as compact as possible. The optical transmission has to be as high as possible; therefore the number of lenses is minimized, and high transmission Ar coatings are used on the optical surfaces. High quality materials are applied to avoid straylight. The optical system of the photometer consists of 4 lenses (Figure 10), made from materials selected for the L2 radiation environment. This is very important, since any transmission degradation has impact on the instrument efficiency and overall performance.

The optical performance analysis was carried out using the actual telescope beam. The NIP optics imaging shows diffraction limited optical quality at all design wavelengths and field angles. The system has high Strehl ratio (>90%) at all field angles. Optical tolerancing of the lens design was carried out in order to validate the performance requirements. The optical performance remains diffraction limited with ~85 % probability after manufacturing and alignment, and there is margin for other uncertainties such as satellite jitter or thermal instabilities.

The focal plane employs Teledyne's HAWAII 2RG (H2RG) NIR detectors [5] with their SIDECAR front end electronics to perform detector readout and analog-to-digital conversion. The number of detectors depends on requirements such as field coverage, spatial resolution, dithering and cost. The recommended configuration has 18 detectors. The warm electronics functions have been split into an Instrument Control Unit (ICU), performing housekeeping and control, and a Science Data Processing Unit for noise reduction and data compression tasks. NIP produces about 200 Gbit/day of science data, assuming 36 fields a day, 4 frames per field and 2.5 compression ratio.

The instrument mass budget is 72 kg and the power consumption is 42W. About 4W are dissipated at the focal plane (driving for FPA thermal design).

The photometric model calculations led to a focal plane temperature of 90K and foreoptics below 190K. A preliminary system thermal analysis showed these requirements can be achieved with a passive design, using dedicated radiators for detectors and SIDECAR electronics.

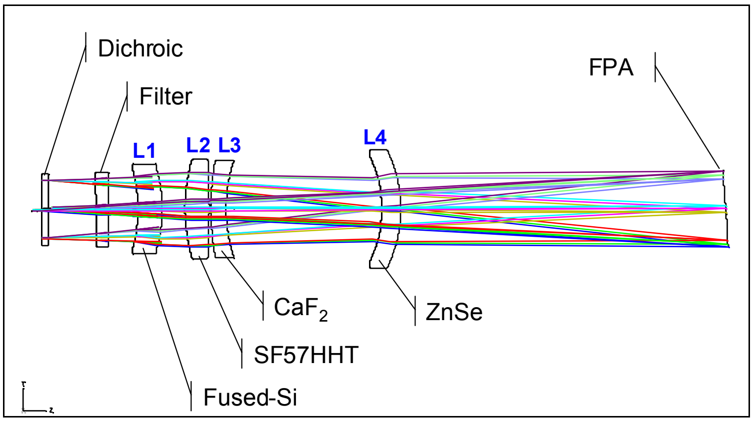

Figure 10: Optical design of NIP as seen from the FoV direction

Near Infrared Spectroscopic Channel (NIS)

The Slitless NIS instrument shall provide spectroscopy in the wavelength range between 1000 and 2000 nm. The instrument consists of a collimating optics, a dispersive element (grism), shutter, calibrator, camera objective, an FPA and warm electronics. In the imaging mode, an additional dispersive element providing dispersion in the contrary direction will be interposed, resulting in imaging operation. The limiting magnitude H(AB) = 19.5 demands a high transmission optical system, low straylight on all the components, cold detector temperature, and high mechanical stability of the optical elements. The instrument should have 0.5 arcsec/pixel spatial resolution and R = 500 spectral resolution at low distortion level. The optical system should reach diffraction limited performance in the imaging as well as in the spectroscopic mode.

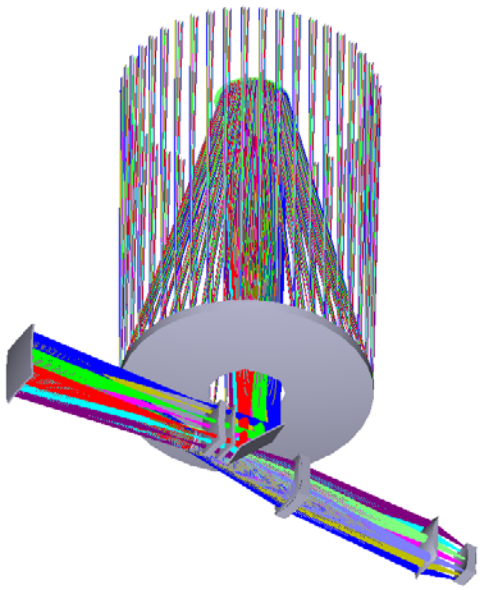

Figure 11: Lens/mirror design of the NIS spectrometer

The NIS instrument uses different telescope fields than NIP and VIS. Field separation is performed by image division at the intermediate or Cassegrain focal plane of the telescope. Therefore, the Cassegrain telescope focus is a possible optical interface of NIS. The telescope beam is then collimated and reshaped by using two lenses and the M3 mirror. The collimating optics shall provide low WFE at the pupil plane, which is essential for the further optical elements downstream. The original ESA design was slightly modified by rotating and shifting the folding mirror behind M2. This was necessary to gain more room for the primary mounting structure and increase clearance between the collimator lenses and fold mirror. The optical design principle has not been modified and no further optimization steps were carried out.

The optical performance analysis was carried out at system level using the real telescope beam. The NIS optics show almost diffraction limited optical quality in the design wavelength range and field. The system has high Strehl ratio (>80%) at all field angles. Optical tolerancing of the lens design was carried out in order to validate the performance requirements.

The focal plane employs eight H2RG infrared detectors with their SIDECAR front end electronics. Similarly to NIP, the housekeeping and control functions will reside in an ICU unit and the data processing functions (noise reduction and data compression) will have a DPU. The NIS produces about 50 Gbit/day of science data, assuming 36 fields a day, 4 frames per field and a compression ratio of 1.5.

The instrument budgets are 97 kg and 40W. About 2W power is dissipated at the focal plane. The photometric model calculations demand instrument operating temperatures of 190K±2K, with the detectors at 90K. Thermal analysis showed these requirements can be achieved with a passive design, using dedicated radiators for detectors and SIDECAR electronics.

4.6 Platform Design, Resources and Budgets

In this Assessment Study the spacecraft platform design was addressed in a preliminary way, focusing on the driving requirements (AOCS, TT&C) and the overall budgets. The Herschel SVM was used to derive design assumptions and budget estimates by similarity.

AOCS

The proposed AOCS configuration comprises sun acquisition sensors, gyroscope assembly, coarse rate sensor assembly, autonomous star trackers, and the FGS. The actuators include reaction wheels and the RCS. The AOCS is driven by the Relative Pointing Error (RPE) requirement, calling for a very high accuracy sensor and low noise actuators. The pointing requirement is best served by an FGS sensor, collocated at the edges of the VIS focal plane and making use of the full telescope focal length. The calculated attitude determination accuracy after gyro hybridization is better than 0.01" (Figure 12).

As noted above, the actuator trade-off has been solved in favour of magnetic bearing reaction wheels. The RPE leads too to requirements being placed on noise sources such as mechanisms (e.g., the NIP filter wheel) acting during the observations. The settling time budgets, driving for the WES duration, have been calculated based on the characteristics of the envisaged control system and the calculated spacecraft inertia.

Another demanding requirement, driven by NIS, is AME < 0.1 arcsec 1σ. Such attitude measurement accuracy may be provided using FGS and/or other VIS information, with or without gyroscope data (error lower than 0.025" 1σ). The key issue is thermo-mechanical stability between the FGS/VIS and NIS focal planes. Preliminary analyses show that the maximum temperature variation remains well below 10K (worst-cold case and the worst hot-case), and they may be improved by local thermal design provisions. Moreover, FGS/VIS focal plane and NIS focal plane calibrations must be planned to recover misalignment due to mounting uncertainties, launch vibration, 1g/0g, etc. To meet the requirement, the following allocations are preliminarily made: thermo-mechanical stability <0.05", calibration residual < 0.025". Under these assumptions, the requirement will be met (it corresponds to 1 VIS pixel, 0.7 NIS pixel).

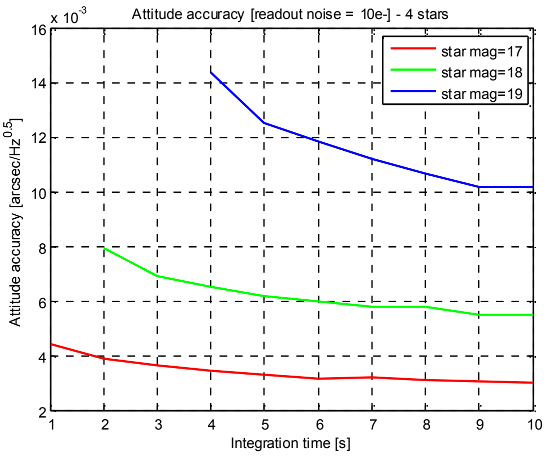

Figure 12: Estimated FGS accuracy

TT&C

The TT&C is driven by the science data rate of 850 Gbit/day, leading to a dedicated K-band (26 GHz) telemetry system with steerable 2-dof 0.4m antenna reflector. A data rate of 66 Mbit/s is needed to support full 1-day telemetry dump in the 3.5 hours (+30 min for set-up and ranging) time allocated with the Cebreros ground station. The high telecommand data rate of 256 kb/s, driven by the requirements for automatic retransmission of lost TM packets, requires another steerable medium gain antenna (X band).The proposed subsystem implementation is based on a dual-band X/X/K transponder with an X band section for housekeeping telemetry and command, and a K band section dedicated to the science telemetry downlink.

System budgets

The mass budget meets the required 20% system margin at launch (Soyuz-Fregat provides direct insertion of up to 2146 kg). The power budget amounts to ~1.3 kW in science mode with K-band telemetry on. An 8.5m² sunshield-mounted solar array is the baseline, delivering 1.4 kW at EOL at 100°C temperature and 30° SAA.

4.7 Technology Assessment

The technology assessment was one of the key tasks of the Assessment Study. Based on such assessments, ESA will initiate Technology Development Activities (TDAs) to run in parallel with the Phase A/B1 Study. During that study, progress in all technologies will be monitored. By 2011, all technologies shall demonstrate TRL≥5, or suitable alternative solutions shall have to be found at system level.

The main items for which TRL=5 is not available today include the FGS, the 26 GHz telemetry system and some optical components (large size dichroic, large size cryo lenses, grism, cryo mechanisms). These elements are proposed for TDAs. For some more items (3-Tbit flash based Mass Memory Unit, 100-GFLOPS level instrument DPUs, magnetic bearing reactions wheels), ongoing developments in the commercial and institutional markets are expected to provide the required advancements in time for the Euclid implementation.

5. DEVELOPMENT APPROACH AND PROGRAMMATICS

The main development drivers include the schedule, constrained by Q3/2012 implementation start and 2017-2018 launch period, the cost ceiling, the procurement of primary mirror and of the payload sensors, subject to limited production rates (visible) and ITAR (infrared) and the demanding payload mechanical-thermal stability and operational temperature requirements, with their implications on the AIT program.

A modular concept is proposed (telescope assembly, PLM, sunshield, SVM) with simple and well-defined interfaces allowing as far as possible separate design, development and test of each module. The number of models is minimized. Further guidelines include early definition of test requirements as part of the design process, selection of existing test facilities, commonality with recent projects to benefit from design, development and test heritage. The proposed system model philosophy, consisting of AVM and PFM models, is driven by the CV schedule and cost ceiling. The instruments are proposed for a full program including development, engineering-qualification and flight models, subject to the schedule constraints.

The overall implementation program takes about 6 years, making Euclid suitable for the 2nd launch slot of the CV plan. The instruments parts procurement is driven by the H2RG sensors, which are long lead items, and would require ESA to initiate the sensor procurement prior to the start of the industrial implementation phase.

The PLM schedule is driven by the telescope and the instruments. The availability of the primary mirror is a prerequisite for starting the PLM AIT sequence. Advance procurement in Phase B2 is required. A second blank of the M1 mirror will be ordered as spare (a classical approach). The entire PLM AIT schedule depends on the schedule of each instrument. The integration sequence is planned to accommodate the instrument in whichever order; then, to some extent, slippage of one instrument can be compensated if another instrument is delivered earlier. Slippages longer than 1Q typically (time foreseen between the delivery dates of instruments) will have a direct impact on the PLM schedule. The assumed average development time needed for instruments is 2 years. The deadline for instrument delivery is the last quarter of 2015. One year and a half is needed for PLM integration and tests. The PLM delivery date to the satellite program is Q1/2017.

6. REFERENCES

[1] Euclid Science Requirements Document (SciRD), SCI-PA/2008-037, Issue 2, rev. 4; Euclid Mission Requirements Document (MRD), ESA SCI-PA/2008-034, Issue 3, rev. 1

[2] Euclid Mission Design, ESA report CDF-73(A)

[3] Radiometric model for the Euclid imaging channels, EUCL-TN-00010-CEA, 24 June 2009; E-NIS Radiometric Sensitivity, EU-NIS-IASFMI-TN-008, 23 June 2009,

[4] M. Robberto et al., Applications of DMDs for astrophysical research, Proceedings of SPIE, Vol. 7210, 72100A (2009)

[5] J. W. Beletic et al., Teledyne Imaging Sensors: Infrared imaging technologies for Astronomy & Civil Space, Proceedings of the SPIE Conference on Astronomical Instrumentation (2008)

[6] C. Akerlof et al., The Supernova/Acceleration Probe (SNAP) Mission, LOI-2003.4, available on the Web.

END OF DOCUMENT