NYX: a Night-time Optical Imaging Mission

Executive Summary

ESA/ESTEC CONTRACT: 4000104172/11/NL/AF

Table of content

1. INTRODUCTION

1.1 Context

Astrium was selected by ESA, in 2011, to perform NYX study in answer to AO/1-6598/10/NL/AF ITT. The study has been conducted by a team lead by JJ Arnoux from Astrium AEF in Toulouse with support of C. Aubrecht, European scientist from the Austrian Institute of Technology GmbH (AIT). This mission is dedicated to Earth observation in the visible spectral bands during night-time.

In the first phase of the study, a review of existing and planned missions designed to detect visible nocturnal light was made and various classes of applications were identified:

To get a feedback from the scientific community a questionnaire has been sent to scientists to gather their needs and comments on the different possible missions and the most relevant requirements and performances of the NYX Instrument (e.g. LEO vs. GEO, revisit time, access corridor and FOV, resolution, spectral bands, radiance range, radiometric performances…). Their answers have been analyzed and the preliminary performances requirements have been derived:

- Resolution between 10 and 100 m in LEO or GEO, in five bands (PAN and 4 XS bands), in the range [0.4 µm - 0.9 µm].
- Radiometric performances: MTF > 0.1, SNR > 3 for radiance R_{min}=5.10^{-5} W/m²/sr/µm, and SNR > 10 for radiance R_1=5.10^{-4} W/m²/sr/µm.

Concerning LEO orbit, the instrument shall be compatible with METOP SG platform with the following allocations: Volume: 0.5 x 0.5 x 0.5 m^3, mass below 40 kg, and power below 40 W.

None of existing or planned mission is answering these requirements confirming the interest for the NYX mission.

The instrument study has been conducted for two different orbits with specified platforms: GEO on GEO-Oculus) and LEO on METOP-SG. GEO mission has been discarded at Mid Term Review because of the constraints related to the distortion of the images by the Sun facing the Instrument during night and limiting the operational availability. After having considered a LEO pushbroom instrument which happened to be out of mass and power requirements, a lighter concept has been proposed with a step and stare design. The longer integration time made the MTF very sensitive to METOP jitter. A proposition to decrease the radiance range has been agreed by ESA with a confirmation by Dr Chris Elvidge (NOAA) that the performances are still interesting for such an instrument and reduced radiometric dynamic.[1]

[1] *The initial radiance range requirements was at beginning of this study :*

R_{min} 10^{-9} W/cm²/sr/µm
R_1 10^{-8} W/cm²/sr/µm (SNR>10)
R_{max} 2. 10^{-2} W/cm²/sr/µm

The final agreement on radiance range is:

R_{min} 5. 10^{-9} W/cm²/sr/µm
R_1 5. 10^{-8} W/cm²/sr/µm (SNR>10)
R_{max} 2. 10^{-3} W/cm²/sr/µm

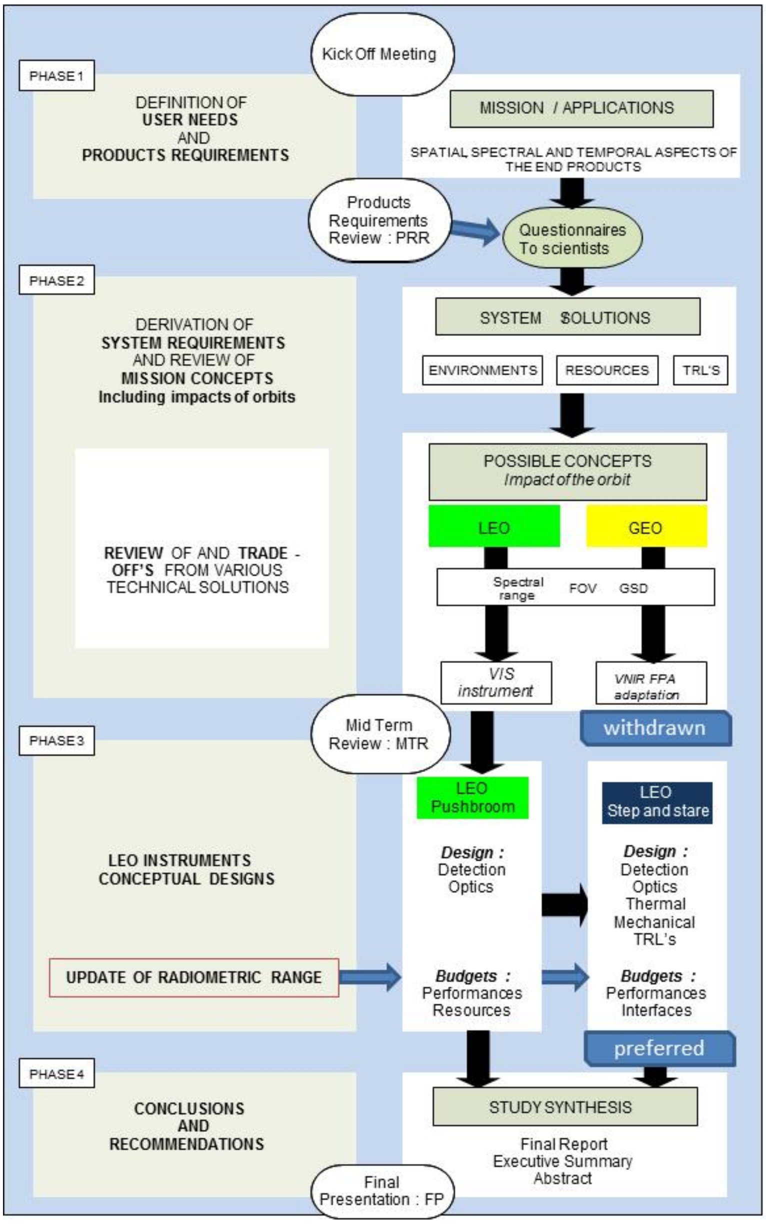

Figure 1.1-1: Study flow chart

1.2 Review of existing and/or planned missions designed to detect visible nocturnal light

At first, we have analyzed the performance of US and European LEO missions similar to the proposed ESA-NYX mission based on existing concepts. The following systems have been detailed:

The DMSP / OLS Precursor System

The Defense Meteorological Satellite Program (DMSP) is the meteorological program of the US Department of Defense, which originated in the mid-1960s with the objective of collecting worldwide cloud cover on a daily basis. DMSP data became available to the public in 1973 and meteorological satellite imagery from the Air Force Defense System Applications Program (DSAP) satellite was made available to the open meteorological community. Data from this system were then called Data Acquisition and Processing Program (DAPP) which was then superseded by the Defense Meteorological Satellite Program (DMSP) which as a total system involves various sensors, data communications and ground processing.

The NPOESS / VIIRS Imaging Suite

The Visible/Infrared Imager Radiometer Suite (VIIRS) is the next-generation radiometer onboard of the NPOESS Preparatory Project (NPP) satellite which serves as bridge mission from NASA's Earth Observing System (EOS) of satellites to the next-generation Joint Polar Satellite System (JPSS), previously called the National Polar-orbiting Operational Environmental Satellite System (NPOESS). VIIRS is a contemporary and technically up-to-date observing system aimed to support the projected operational constellation. The 22 channels featured on VIIRS are derived primarily from three legacy instruments: the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), and the DMSP-OLS. With its low-light nighttime visible sensing capability, the OLS is the only sensor providing heritage for the VIIRS Day/Night Band (DNB).

The Nightsat Program

Nightsat is a concept for a satellite program capable of global observation of the location, extent and brightness of night-time lights at a spatial resolution suitable for the delineation of the primary features laying within human settlements. Based on requirements from several fields of US scientific inquiry, Nightsat was designed to be capable of producing a complete cloud-free global map of lights on an annual basis. To date, this program has not received go-ahead from its administration.

The Nightsat promoters are issued from the community of DMSP/OLS users (initiated by Chris Elvidge from NOAA-NGDC), and have illustrated in many occasions the interest of using night-time imagery as indicator of human activity and in application derivated thereof. The Nightsat mission concept was described by its promoters, by contrast with the situation experienced with the DMSP/OLS system, as unique in its focus on observing human activity, in contrast to traditional Earth observing systems that focus on natural systems.

The MetOp-SG / LLI Imaging System[2]

The Low Light Imager (LLI) represents the more recent instrumental product in low light imaging over current polar-orbiting systems. Building on extensive experience (e.g., NOAA-AVHRR), this sensor results in improved terminator imagery, lunar reflection (clouds, snow, ice) and visible emission based products (city lights, wild fires). Then, through its panchromatic imaging, the LLI is foreseen to be embarked onto the MetOp-SG (A) platform to extend the instrumental coverage to the level required by the MetOp-SG mission needs.

The MetOp-SG / METimage

Aimed in being the European successor of the AVHRR instrument flown on the former meteorological low orbit satellites, the METimage instrumental concept was developed within the framework of a DLR-

[2] *LLI has been withdrawn from METOP-SG since beginning of the study.*

funded feasibility study in 2008. The multispectral radiometer instrument is based on an anastigmatic three mirror rotating telescope athermal design (patented) using a quite innovative material (AlSi). Two technological studies are presently running to ascertain the technical assets regarding both the rotating telescope and the infrared detectors specifically developed for its large spectral range between 1 and 14 micrometers.

1.3 Analysis of the LEO scenario

The first analysis of the NYX LEO scenario highlights the anticipated challenges for implementing such a mission: besides the well understood "low light" / "high dynamics" characteristics of the "day & night" detection and imagery mission, superposes the hard point related to the mass budget. The compliant design will need implementation of sophisticated detection resources in combination with up-to-date optics.

The tables presented here (here-below and on the next page) show some of the very interesting system aspects linked to NYX night-time imagery in a LEO scenario as opposed to a GEO scenario:

- NYX, as Nightsat, are first aimed at the best application / products harvest anticipated by the scientists and the most stringent experts in the field; both projects surpass the already implemented NPP/JPSS-VIIRS mission through the "spatial resolution" (GSD) and "multi-spectral" critical aspects;
- The NPP/JPSS-VIIRS, through its only GSD improvement, together with its proper calibration will significantly ease the data extraction aspects, but will not lead to significant add-ons with respect to the DMSP-OLS; the instrument will participate to a quite continuous and better movement towards the most stringent needs, but will stop at the frontier of the most challenging implementation parameters;
- The MetOp-SG LLI (panchromatic imaging, 500 meters GSD), working in connection with the MetOp-SG METimage (infrared channels), will lead to similar kind of data as NPP/JPSS-VIIRS;
- Implementing 50 meters GSD and multi-spectral imaging should allow to fill the gap between projected optimum use and technical feasibility; however, from the only mass resource viewpoint, the reference of a self-standing HR NYX multi-spectral imager to the LLI example shows the challenge: LLI mass is of 54 kg (500 meters GSD, panchromatic), while the NYX LEO instrument is projected around 40 kg.

Instrument	Nb of Spectral Bands	SSD (m)	Mass (kg)	Power (W)
DMSP / OLS	2 bands (VIS and LWIR)	500 (MR VIS) / 2700 (LR VIS & LWIR)	No figure available	No figure available
NPOESS / VIIRS	22 bands (VIS to LWIR)	300 to 700 (from VIS to LWIR)	275	240
Nightsat LEO	4 or 5 bands (VIS to LWIR)	25 to 100 (from VIS to LWIR)	No figure available	No figure available
Nightsat LEO	4 bands (VIS)	50 (VIS)	30	110
MetOp-SG / METimage	15 to 41 bands **(*)** (VIS to VLWIR)	500 to 1000 (from VIS to VLWIR)	240	200
MetOp-SG / LLI	1 band (VIS)	700 (VIS)	54	60
NYX LEO	4 or 5 bands (VIS to LWIR)	25 to 100 (from VIS to LWIR)	40	40

***(*)** 15 bands with Priority 1 (VIS to LWIR) / 41 bands with Priority up to 4 (VIS to VLWIR)*

Table 1.3-1: Summary of existing and/or planned missions designed to detect visible nocturnal light

Application		Sensors				
		DMSP / OLS	NPOESS / VIIRS	Nightsat	MetOp-SG / LLI	NYX
1	Human settlements					
1.1	Global urban extent	X	X	X	X	X
1.2	Detailed mapping of urban areas			X		X
2	Population					
2.1	Estimating the density of constructed surfaces			X		X
2.2	Estimating population			X		X
3	Human activity					
3.1	Mapping electric power access	X / pan	X / pan	X / µspe	X / pan	X / µspe
3.2	Estimating gas flaring Parts			X		X
3.3	Economic activity	X	X	X	X	X
3.4	Tracking night-time fisheries	X	X	X	X	X
3.5	Tracking night maritime activity	X	X	X	X	X
4	Hazards and Disaster management					
4.1	Fire detection	X	X	X	X	X
4.2	Biomass burning	X	X	X	X	X
4.3	Power outage detection			X		X
4.4	Tracking disaster recovery			X		X
4.5	Volcanoes lava flows		X	X		X
4.6	Volcanoes dust clouds	X	X	X	moonlight	X
5	Light pollution					
5.1	Artificial light sky seen brightness			X		X
5.2	Ecological and Zoological effect					
5.3	Health effects on human beings					
6	Meteorology					
6.1	Urban heat islands			X		X
6.2	Cloud coverage	X	X	X	moonlight	X
6.3	Snow cover mapping	X	X	X	moonlight	X
6.4	Dust storm	X	X	X	moonlight	X
6.5	Lightning detection / auroras	X	X	X	X	X

Legend: *HR only* — *Night only* — *HR & Night*

Table 1.3-2 System concepts and anticipated coverage of the main NYX mission aspects

1.4 Synthesis of the Applications and Derived Requirements

From the large bibliographic survey performed in the scope of this mission study, an extensive recapitulation of night-time imagery applications has been done, which leads to thematic regroupments which will be of interest to understand the main mission topics.

The various identified classes of applications are presented as follows:

- **Human settlements** are analyzed through "Global urban extent" and "Detailed mapping of urban areas".
- **Population** is analyzed through "Estimating the density of constructed surfaces" and "Population estimated from nighttime imagery".
- **Human activity** is analyzed through "Mapping electric power access", " Estimating gas flaring volumes" and "Economic activity".
- **Hazards and Disaster management** are analyzed through "Fire detection and biomass burning", "Power outage detection and tracking disaster recovery", "Volcanoes / lava and fumes".
- **Light pollution** is analyzed through "Artificial night sky brightness", "Fisheries and maritime activity", "Ecological effects" and "Health effects on humans"
- **Meteorology** is analyzed through "Urban heat islands", "Cloud coverage", " Snow cover mapping", "Dust storm", "Lightning detection and auroras imaging"

In the following tables, and along with the applications review as well as drawing upon the additional input from the experts questionnaires, we come up with an assessment proposing major characteristics like "coverage", "resolution", need for "visible or infrared (VIS/IR)" imaging, temporal type (initiation of phenomenon or duration of it) and "night only" (or not) effect which should give input to the specific aspect of such or such effect.

	Application	Light source	Product	Typology					Night only
				Coverage	Resolution	VIS / IR	Initiation	Duration	
1	**Human settlements**								
1.1	Global urban extent	Man-made lighting	Images (cloud free)	Regional to global	1 km	VIS	Slow variations	Week(s) to years	N
1.2	Detailed mapping of urban areas	Man-made lighting	Images (cloud free)	Regional	10-50 m	VIS	Slow variations	Week(s) to years	N
2	**Human population**								
2.1	Estimating the density of constructed surfaces	Man-made lighting	Images (cloud free)	Regional to global	25-50 m	VIS	Population detection limit	Week(s) to years	N
2.2	Population estimated from nighttime imagery	Man-made lighting	Images (cloud free)	Regional to global	25-50 m	VIS	Population detection limit	Week(s) to years	N
3	**Human activity**								
3.1	Mapping electric power access	Man-made lighting	Images (cloud free)	Regional to global	1 km	VIS / multispe	Slow variations	Week(s) to years	Y
3.2	Estimating gas flaring	Flare	Images (cloud free) with detected "hot spots"	Regional	50-100 m	VIS	Slow variations	Week(s) to years	Y
3.3	Economic activity	Man-made lighting	Images (cloud free)	Regional to global	1 km	VIS	Slow variations	Week(s) to years	Y
3.4	Tracking night-time heavy lit fisheries	Fish boat / Man-made lighting	Images (cloud free) with detected "hot spots"	Regional	100 m	VIS	Sudden, not predictable	Hours to days	Y
3.5	Tracking night-time maritime activity	Any boat / Man-made lighting	Images (cloud free) with detected "hot spots"	Regional to global	100 m	VIS	Sudden, not predictable	Hours to days	Y
4	**Hazards and Disaster management**								
4.1	Fire detection	Fire	Images (cloud free) with detected "hot spots"	Regional to global	50 m	VIS / IR	Sudden, not predictable	Hours to days	N
4.2	Biomass burning	Fire	Images (cloud free) with detected "hot spots"	Regional to global	1 km	VIS / IR	Slow variations	Hours to days	N
4.3	Power outage detection	Man-made lighting	Images (cloud free)	Regional	25-50 m	VIS / multispe	Sudden, not predictable	Few days	Y
4.4	Tracking disaster recovery	Man-made lighting	Images (cloud free)	Regional	25-50 m	VIS	Sudden, not predictable	Week(s) to years	N
4.5	Volcanoes lava flows	Lava flow	Images (cloud free) with detected "hot spots	Regional	25-50 m	VIS / IR	Sudden, not predictable	Week(s) to years	N
0.6	Volcanoes dust clouds	Moon (lunar reflection)	Images	Regional to global	25 to 100 m for VIS image rectification	VIS	Sudden, not predictable	Week(s) to years	N
5	**Light pollution**								
5.1	Artificial night sky brightness	Man-made lighting	Images (cloud free)	Regional	100 m	VIS	Slow variations	Week(s) to years	Y
5.2	Tracking night-time heavy lit fisheries	Fish boat / Man-made lighting	Images (cloud free) with detected "hot spots"	Regional	100 m	VIS	Sudden, not predictable	Hours to days	Y
5.3	Ecological and zoological effects	Man-made lighting	Images (cloud free)	Regional	100 m	VIS	Slow variations	Week(s) to years	Y
5.4	Health effects on humans	Man-made lighting	Images (cloud free)	Regional	25-50 m	VIS	Slow variations	Week(s) to years	Y
6	**Meteorology**								
6.1	Urban heat islands	Man-made lighting	Images (cloud free)	Regional	1 km	VIS / IR	Slow variations		Y
6.2	Cloud coverage	Moon (lunar reflection)	Images	Regional to global	25 to 100 m for VIS image rectification	VIS / IR	Sudden, not predictable	Night (day through Météo images)	N
6.3	Snow cover mapping	Moon (lunar reflection)	Images (cloud free)	Regional to global	1 km	VIS / IR	Sudden	Night (day through Météo images)	N
6.4	Dust storm	Moon (lunar reflection)	Images (cloud free)	Regional	25 to 100 m for VIS image rectification	VIS / IR	Sudden, not predictable	Night (day through Météo images)	N
6.5	Lightning detection / auroras imaging	Lightning	Images with detected "hot spots"	Regional to global	1 km	VIS	Sudden, not predictable	Night (day through Météo images)	N

Table 1.4-1: classes of instrument requirements.

1.5 Classes of instrument

To limit the number of classes of instrument, it has been decided to consider only three classes covering the maximum of possible missions. The scientists have been consulted a second time to get their feedback and interest in each class.

The classes listed in next table have been identified and submitted to all scientists identified for the questionnaire.

One of the fact taken into account for the relaxation of the detection limit is the METOP-SG jitter impact on MTF. This has allowed considering a step and stare imager in LEO orbit, with optimized integration times.

	#1	#2	#3	Units
Spatial Sampling (GSD): Goal value	25	100	1 000	m
Spatial resolution : PSF 80% encircled energy	30	120	1 200	m
Swath width	300	700	2 000	km
Minimum Image Extent:	300*300	700*700	2 000*2 000	km
Spectral range and resolution **(*)**	PAN [0.4-0.9] Blue [0.4-0.5] Green [0.5-0.6] Na [0.56-0.61] NIR [0.8-0.9]	PAN [0.4-0.9] Blue [0.4-0.5] Green [0.5-0.6] Na [0.56-0.61] NIR [0.8-0.9]	PAN [0.4-0.9] Blue [0.4-0.5] Green [0.5-0.6] Na [0.56-0.61] NIR [0.8-0.9]	µm
Spectral response homogeneity	5%	5%	5%	
Radiance detection: R_1 Goal value :R_{min}	100 10	30 -100 3- 10	10 1	µW/m²/sr/µm
Max. Radiance	100	100	100	W/m²/sr/µm
SNR	3 @R_{min} 10 @R_1	3 @R_{min} 10 @R_1	3 @R_{min} 10 @R_1	
Inflight radiometric calibration	YES	YES	YES	
Effective revisit time: Goal value	1 to 3	1 to 3	1 to 3	day
Geo-Location Raw image without GCP	35	150	200	m
Geo-Location with GCP and image processing	15 / 200	50 / 200	NA	m
Orbit	LEO/GEO	LEO/GEO	LEO/GEO	

Table 1.5-1: classes of instrument requirements.

2. NYX INSTRUMENT IN GEO

2.1 System requirements

GEO orbit for night-time optical imagery mission allows to track diurnal patterns of lighting. It provides ability to observe year round with greater opportunity to obtain cloud-free observation at a given night. It is an effective way to increase the sensor duty cycle beyond the confines of daylight, and it allows thorough observation of fluctuating gas flares and biomass burning with direct view of Africa and Middle East/Russian fields for a satellite posted at European longitude. But unfortunately severe drawbacks of this particular orbit drastically limit the interest of the GEO orbit, even if NYX instrument could be a simple equipment sharing GEO-Oculus Focal plane. The main constraints come from the position of the Sun during night, with a possible direct illumination inside the GEO-Oculus baffle, requiring to add a large Sunshield and the need to rotate the satellite about noon to avoid Sun unwanted light entering the front telescope cavity. With a Sun avoidance period of 4 hours during every night, the possible observation duration is dramatically reduced. From GEO the platform stability becomes an issue for long dwell time observation of dim lighting, the spatial coverage is also limited to the hemisphere under direct visual access, with a high local incidence angle at target and with resolution being degraded as well.

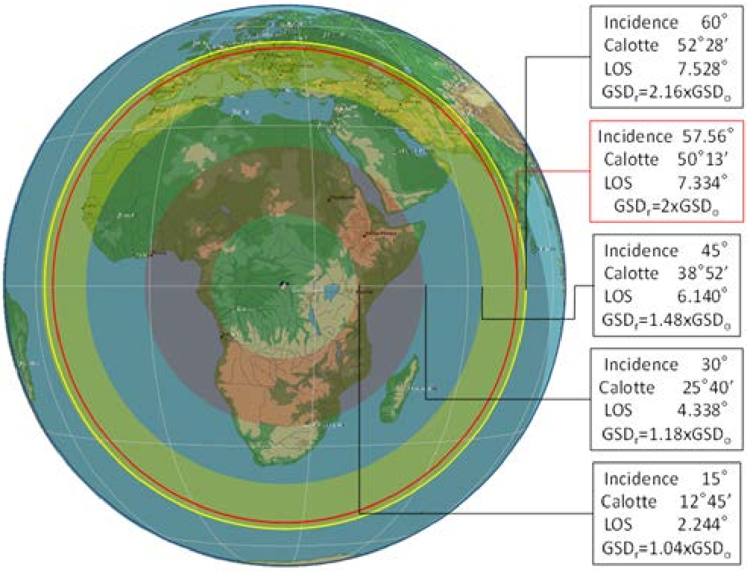

Figure 2.1-1: Observation from GEO Orbit, local incidence and GSD distortion

The main conclusion at this stage was that the GEO and GSO orbits are not ideal for night-time measurement because of seasonal effect, and because of the necessity to have a Sun Aspect Angle greater than 30°. GSD is highly debased when the observation are done with apparent limb pointing.

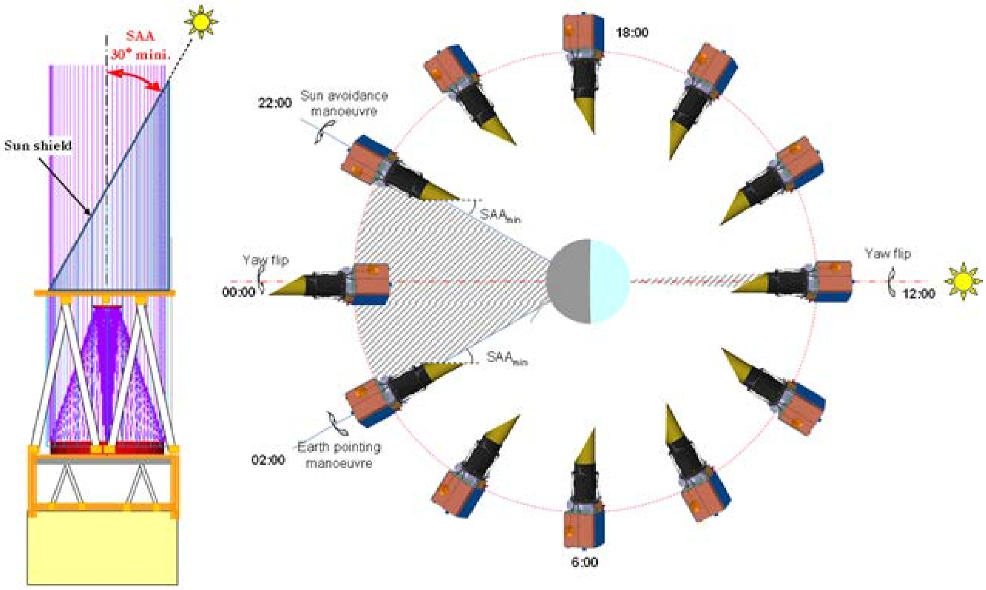

Figure 2.1-2: Manoeuvre and Sun avoidance

Even with the limitation given by the day and night maneuvers, the GEO concept remains an interesting concept especially for fishery monitoring thanks to the long possible observation duration.

2.2 Instrument design

The NYX instrument is implemented on GEO-Oculus platform as an equipment sharing the focal plane assembly.

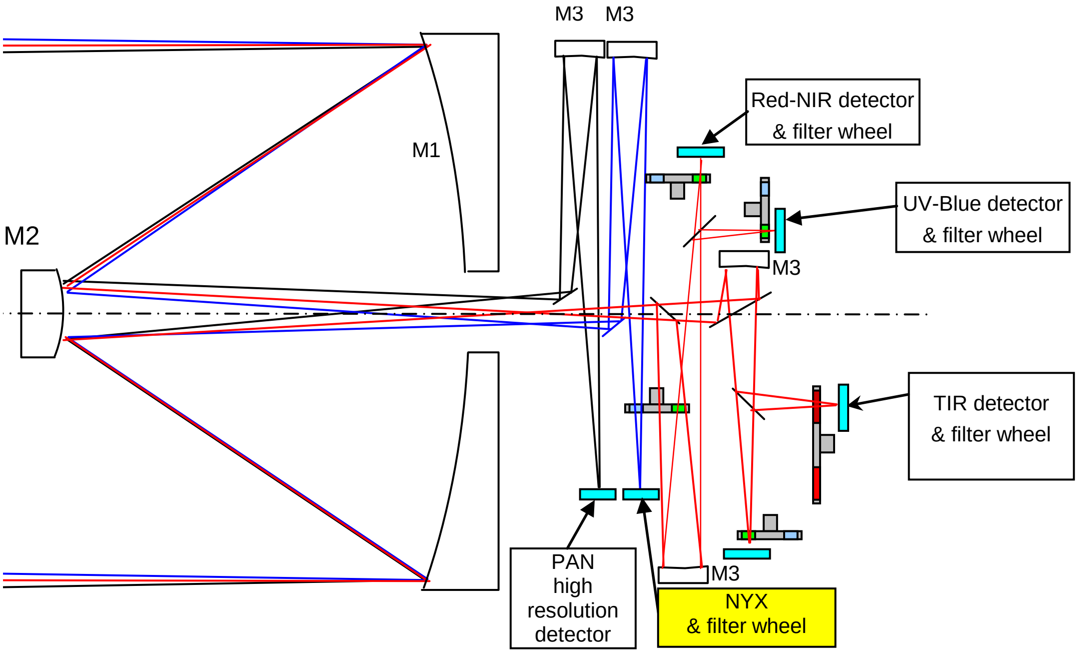

Figure 2.2-1: Preliminary optical architecture Geo-oculus + NYX dedicated channels

The main design drivers are the detection and the derived radiometric performances. An extensive survey of the detector arrays technology is presented, with the associated performance budget.

Shrinking the NYX PAN channel to [0.4 - 0.7] µm instead of [0.4 - 0.9] µm allows allocating VIS1, VIS2, VIS3 and this narrow PAN to the Geo Oculus “UV-blue” detector, being equipped with a double filter wheel with 15 spectral band slots: 11 for Geo Oculus and these 4 for NYX.

This UV-blue and NIR-red channels have a 20 m EW nadir GSD and a 10 m NS nadir GSD, corresponding to a pixel pitch respectively of 8 µm (EW) and 4 µm (NS).

For the 1000 m resolution case, 25 x 50 pixels have to be binned to form the macro pixel, and a flux of 1e-5 W/m²/sr/µm can be detected with a SNR of 10, integrating over 2.2 sec to 7.3 sec, function of the wavelength. Because of the binned pixel Field of View = 28 µrad, such a long integration time is possible even if the assumed worst case pointing stability is 5 µrad/sec. The smearing MTF degradation keeps reasonable and the global MTF is quite good.

To improve the resolution by binning fewer pixels, a flux of 10^{-4} W/m^2/sr/µm is considered, allowing taking a 200 m / 280 m resolution by binning 5 x 10 to 7x14 pixels. A SNR of 10 is reached by integrating between 1.1 sec and 2.6 sec. The MTF degradation is quite high for VIS1 and VIS3 due to the pointing stability impact over the binned pixel reduced Field of view of less than 6 to 7.8 µrad

To decrease the resolution to 120 m / 160 m for the same level of flux, pixel SNR has to be increased: a mean is to propose Digital Correlated Double Sampling, as described in chapter 3.3, which suppresses kTC noise by sampling signal just after reset and then after the integration phase by reading twice the whole array. It doubles the readout time, but it is worth if integration time is sufficient. To reach a better resolution of 40 m / 80 m, the level of flux shall be increased to 10^{-3} W/m2/sr/µm to allow decreasing integration time down to 0.2 ~ 0.3 sec. To meet about the same resolution of 50 m / 100 m, with a level of flux of 10^{-4} W/m2/sr/µm, a dedicated 4T low light level CMOS detector has to be implemented on the Geo-Oculus Focal Plane array.

3. NYX INSTRUMENT IN LEO

3.1 System requirements

The NYX instrument was studied to be compatible of the METOP-SG platforms on a sun-synchroneous LEO orbit with an average altitude of 817 km, an inclination of 98.7° and 14.21 orbits per day. The local ascending node is at 21:30 ± 00:15. This local time has an impact on seasonal possible observation and requires a steering mirror with a 1- or 2-axis gimbal mechanism to improve the access corridor and the revisit time below 5 days. Pointing eastward improves the observation time during days, but the local incidence with a variable GSD across track.

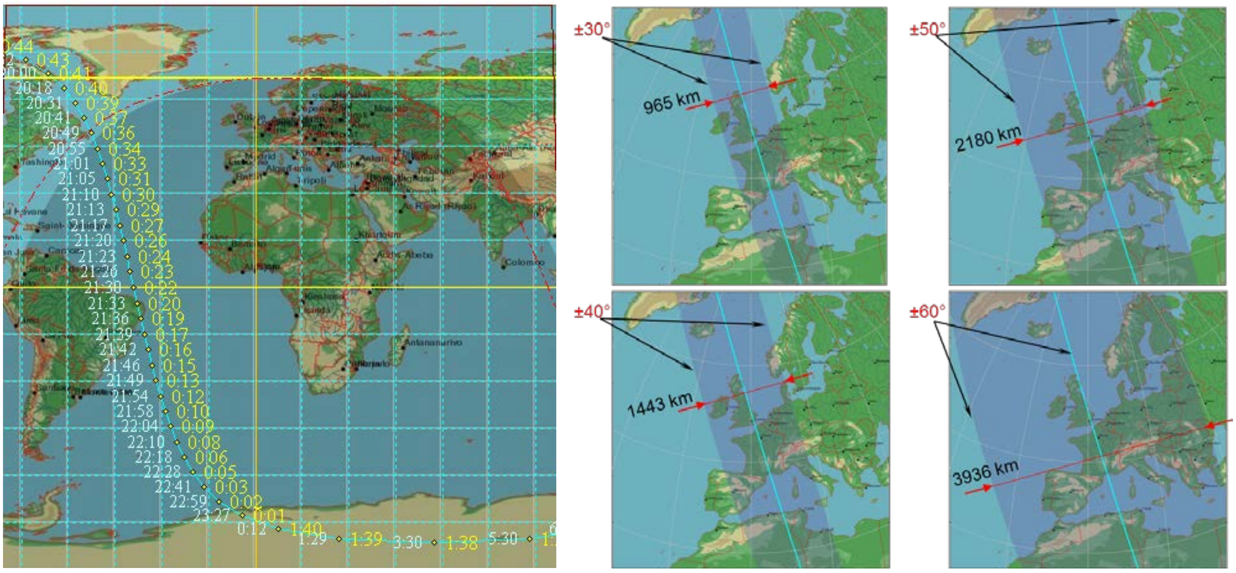

Figure 3.1-1: orbit and local time (left), access corridor and off track pointing over Europe (right)

Limiting the resolution at the edge of the access corridor to twice the GSD at Nadir requires a scanning up to 25° off track (FoV edge LOS depointing ± 30° ACT), this yields to an incidence of about 40° at the far edge of the image.

Because of an ascending node local time rather early in the night, and with a limited across track off-set of the pointing direction; a target at midnight, with a maximum incidence at target of 60°, is only visible southern than 44.4°S. Accessibility and time range during night can be improved by an ascending node at midnight, balancing North and South areas visibility.

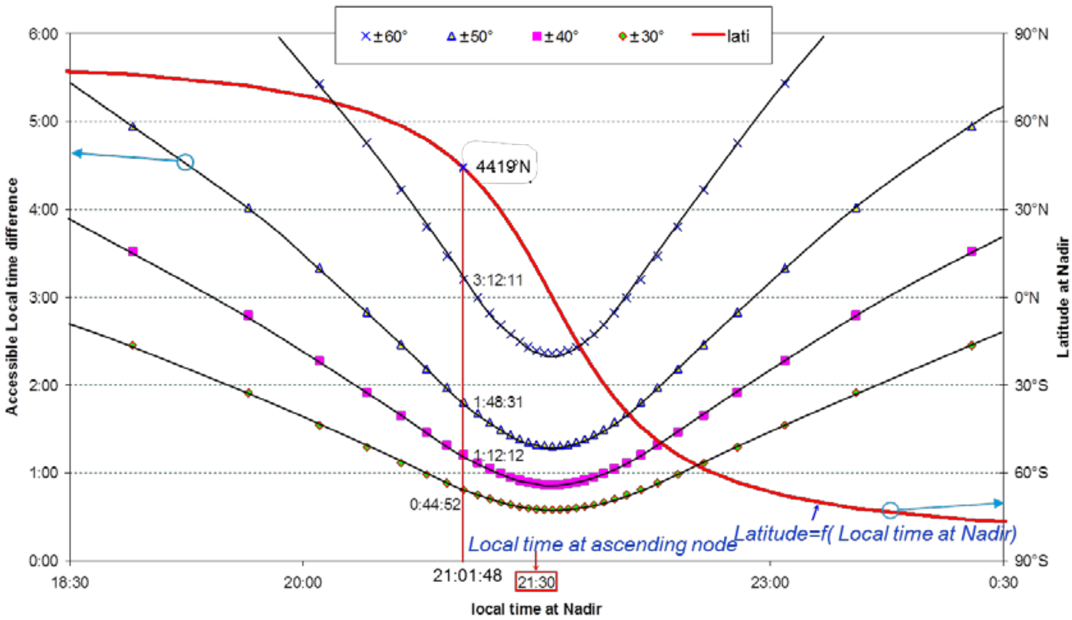

Figure 3.1-2: Accessible local time at target as a function of the off-track angle

In LEO orbit two concepts have been considered: a pushbroom concept and a step and stare concept. The last one is compatible with all NYX main requirements and has been preferred to the push-broom concept which exceeds the mass and volume allocations. After the Mid Term Review, the Nadir GSD has been increased to 25 m in PAN with a baseline of 100 m in XS and an optional 50 m.

3.2 Pushbroom concept

Several cases for the pushbroom concept have been considered resulting in a design which does not meet the mass and power consumption requirements, with optics F-number of F/2 and wide field of view, and very short back focal length without possibility to implement beam splitting by dichroic for example.

The modification of the minimum and maximum spectral radiance made to decrease the radiometric dynamic has improved the radiometric performance of the system, with a detector having only two stages: one TDI detector for low level radiance, with less than 40 lines to limit the impact of de-synchronization MTF; and a single CCD Line for the higher radiance levels.

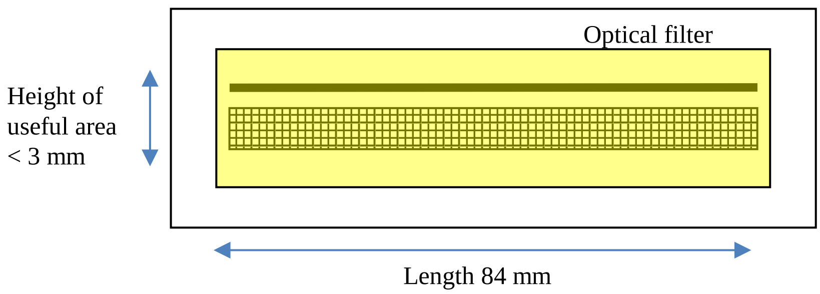

Figure 3.2-1: Detector with two sections: one TDI one single line with read-out line

Band	PAN	B1	B2	B3	B4
GSD	25 m	100 m	100 m	100 m	100 m
Swath	300 km	300 km	300 km	300 km	300 km
Pupil diameter	88 mm	44 mm	44 mm	44 mm	44 mm
F-Number	F/4.50	F/4.50	F/4.50	F/4.50	F/4.50
Radiance detection	0.0005 W/m²/sr/µm	0.0005 W/m²/sr/µm	0.0005 W/m²/sr/µm	0.0005 W/m²/sr/µm	0.0005 W/m²/sr/µm
Max radiance	20 W/m²/sr/µm	20 W/m²/sr/µm	20 W/m²/sr/µm	20 W/m²/sr/µm	20 W/m²/sr/µm
Noise limit (allocation)	14 e-	13 e-	15 e-	12 e-	10 e-
NTDI sized by SNR(R1)	19	13	19	10	5
Radiometric section number required with SNR for overlap of 20	2	2	2	2	2
Rmax section 1	0.453 W/m²/sr/µm	0.528 W/m²/sr/µm	0.481 W/m²/sr/µm	0.556 W/m²/sr/µm	0.618 W/m²/sr/µm
Rmax section 2	66.9 W/m²/sr/µm	78.0 W/m²/sr/µm	70.9 W/m²/sr/µm	82.0 W/m²/sr/µm	91.2 W/m²/sr/µm
Readout frequency section 1	403 kHz	50 kHz	50 kHz	50 kHz	50 kHz
Readout frequency section 2	1613 kHz	101 kHz	101 kHz	101 kHz	101 kHz
Readout frequency section 3	1613 kHz	101 kHz	101 kHz	101 kHz	101 kHz
Number of detector	2	1	1	1	1
Number of video output per detector	6	6	6	6	6
Pixel per line per detector	6000	6000	6000	6000	6000
Pixel pitch	12.0 µm	12.0 µm	12.0 µm	12.0 µm	12.0 µm
binning	No	Yes	Yes	Yes	Yes
N bining	1	2	2	2	2
Operating temperature	-30 °C	-30 °C	-30 °C	-30 °C	-30 °C
Tint	3.79E-03 s	1.52E-02 s	1.52E-02 s	1.52E-02 s	1.52E-02 s
Qsat	200	200	200	200	200

Table 3.2-1: Radiometric budget for the pushbroom concept

The optical combination at F/4.5 with a larger back focal length allows implementing beam splitting and two detectors sharing the focal plane.

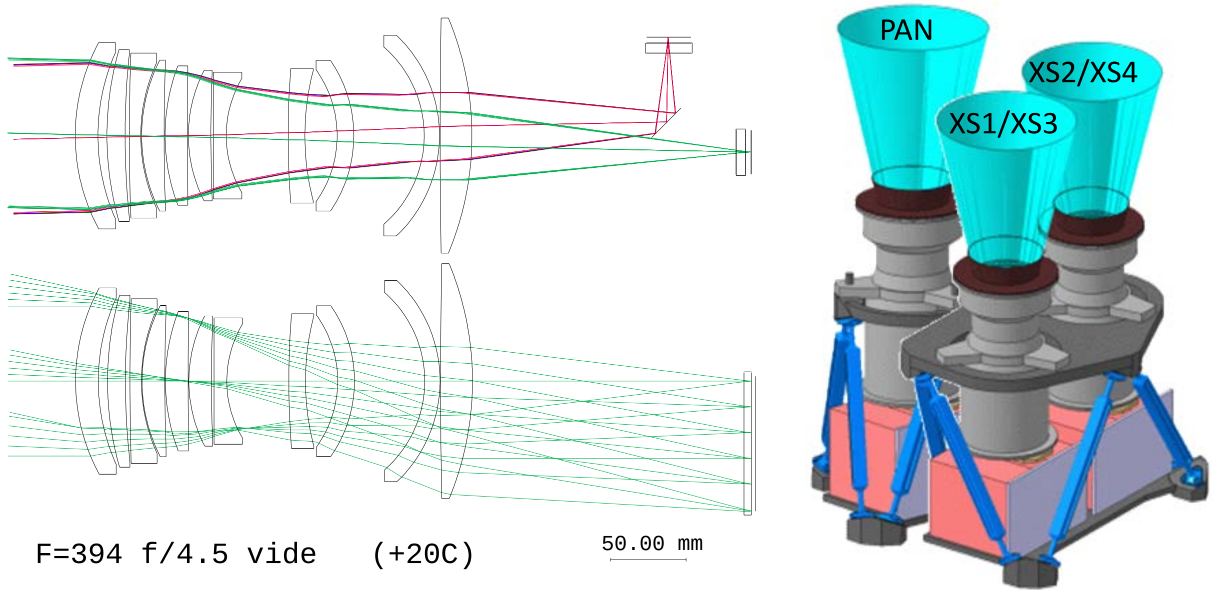

Figure 3.2-2: Pushbroom concept design. (Left) Dioptric lens at F/4.5 with two detectors. (Right) Lens arrangement without the scan/steering mirror, mechanism and structure.

The total mass remains far above the target with 102 kg with three lenses and about 200 kg with five lenses, depending on the number of spectral bands.

3.3 LEO pushbroom concept outcomes

The synthetic outcomes of the LEO Pushbroom concept, with 25 m GSD in PAN and 100 m (baseline) or 50 m (alternative) in XS, are:

- Although not specified for the study, a SNR of 3 at minimum radiance Rmin was suggested by Dr. Chris Elvidge. But the value of Rmin proposed by Chris Elvidge was $2.5x10^{-5}$ W/m²/sr/µm. The equivalent SNR at Rmin should be above 1.9. Keeping SNR of 3 at Rmin is a very stringent requirement especially in B2 band. In the study we kept the SNR of 10 at R1 as the main driving requirement.
- The full dynamic is a key factor..
- Preferred solution: 3 (baseline) or 5 (alternative) lenses
  - One detector with the full dynamic (3 detector arrays on the same chip)
  - 2 bands per focal plane, in-field separation
  - [2 lenses B1+B3 and B2+B4, GSD=PAN GSD] *2 for swath, use of dichroic to be considered
  - PAN image is a combination of the 4 XS images
  - Option: an additional lens system
- Impact
  - Development of a new detector with the full dynamic, even if the technology exists for each of the three types of detector arrays, integration on the same chip shall be developed
- Advantage
  - Same electronics for the 5 bands, adjustment of the gain for each band (mainly number of TDI lines)
  - Same lens objectives for the PAN, B1+B2 and B3+B4, in the case of 5 lenses, two different lenses, one for PAN and one for XS in the case of 3 lenses.
- Drawback
  - Large FOV doubles the number of lens systems in XS
  - Along track separation between bands

3.4 Step & stare Concept

3.4.1 Design overview

The NYX instrument is made of two main sub-assemblies Figures 3.4-1 a) and b) : the imager assembly and the Video and Control Electronics units (VCE).The imager assembly includes:

- a scan mirror mounted on a two-axis mechanism;
- an optical assembly;
- a focal plane assembly including spectral bands separation, optical filters and CMOS detectors;
- the front end electronics associated to the detectors;
- the calibration channel including a folding mirror and a diffuser;
- the mechanical assembly which supports all these items;
- the thermal parts necessary to control the imager temperature.

The electronics units are gathering the following functions:

- power distribution;
- signal processing, compression and mass memory;
- housekeeping and thermal control;
- mechanism drive electronics.

The main features of the instrument are driven by the detector characteristics.

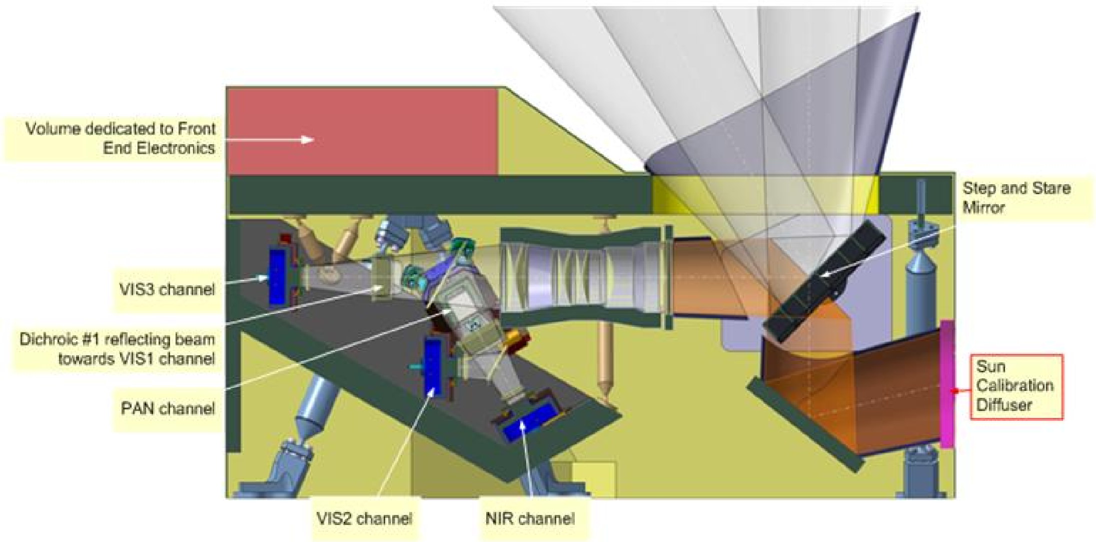

Figure 3.4-1 a: Views of the NYX imager assembly

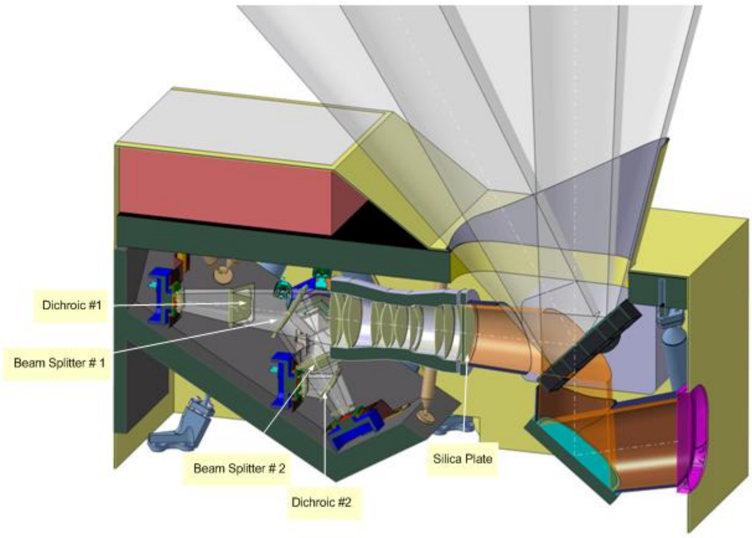

Figure 3.4-1 b: Views of the NYX imager assembly

Mission Characteristics			
Spectral bands / GSD	PAN / 25 m		XS / 100 m (option 50m)
Swath width @ Nadir	332.5 km		332.5 km
Scanning Characteristics			
Time cycle	10.269 s		
Number of steps ACT	6 steps		
Transition from step N to step N+1	0.20 s		3.77 degrees
Transition from Step 6 to Step 1	0.60 s		18.85 degrees
Time allocated to each step	1.245 s		
Space Velocity Compensation angular amplitude	0.652 degrees (Line of sight)		
Optical Assembly			
Focal length	334 mm		
Pupil diameter	90 mm		F/D = 3.71
Field of view	3.94° x 4.8°		
Focal plane assembly			
5 Detectors: CMOS Matrix operated @ 220 K	2800 pixels ALT		2300 pixels ACT
	Pitch ALT: 10 µm		Pitch ACT: 10 µm
3 different exposure times inside each step.	150ms	10 ms	0.1ms
Budgets			
Volume (VCE not included)	o overall dimensions: 625 x 800 x 940 mm^3 o wo local appendices: 530 x 560 x 940 mm^3		
Mass / Power	60 kg / 90 W		

Table 3.4-1: NYX Instrument main features

3.4.2 Optical architecture

The optical design is based on an assembly of nine lenses followed by two beam splitters and two dichroic plates for spectral separation, as presented in Figure 3.4-2.

In PAN band the rms diameter of the spot diagrams is about 5 µm which is compatible with the pixel elementary area of 10 x 10 µm². For all the others bands, the rms diameter of the spot diagram is below 10 µm which is compatible with the binned pixel elementary area of 40 x 40 µm² (GSD XS baseline of 100 m) or even 20 x 20 µm² (GSD XS option of 50m).

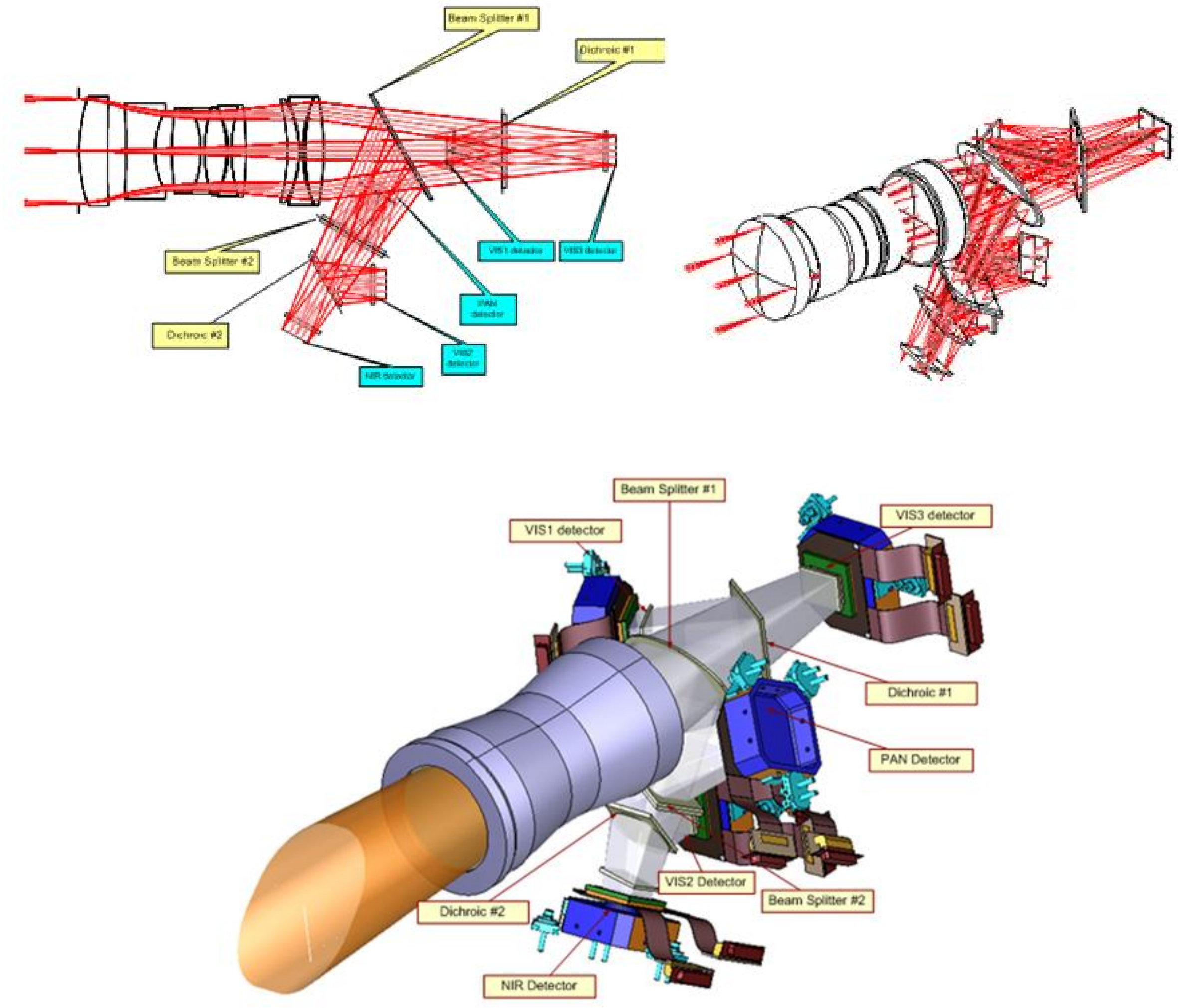

Figure 3.4-2: Different views of the NYX optical assembly

3.4.3 Focal plane architecture

3.4.3.1 Focal plane overview

The focal plane is composed of five CMOS detector matrices; each matrix being dedicated to a spectral channel. The pixel characteristics and CMOS detectors size proposed for the NYX mission are summarized in the table below.

CIS technology	CIS 0.18 µm with 10 µm epi and high resistive substrate, operated in BIL
Detector size	28 x 32 mm²
Pixels array size	23 x 28 mm²
Pixel pitch	10 µm
Pixel architecture	4T pixel architecture with pinned photodiode, low noise source follower transistor and on-chip dual column amplifiers with fixed gains (low/high radiances)

Figure 3.4-3: Description of the proposed pixel architecture for the NYX mission (GSD baseline)

3.4.3.2 Integration time and detector gain tuning to cover the dynamic

The 4T pixel CMOS detector matrix shall be operated in rolling shutter mode to easily implement the CDS for noise minimization. With such readout mode it is possible to integrate and read several images in the same slot. The number of images that need to be acquired at each slot is linked to the radiance dynamic on one side and on the detection chain dynamic on the other side. The SNR specification is met at 220 K for all the specified radiance levels for the 100 m GSD XS baseline and the 50 m GSD XS option.

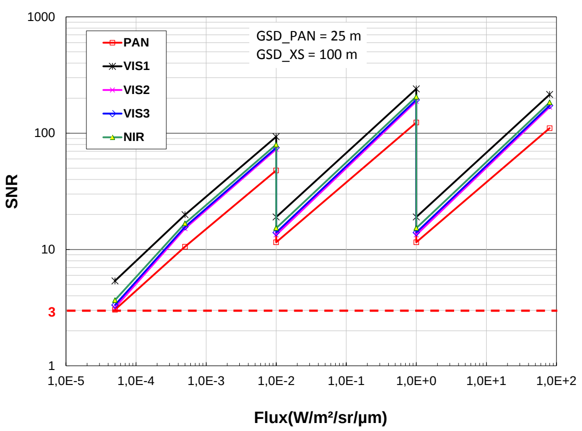

Figure 3.4-4: SNR values over the radiance dynamic for the 100 m baseline GSD XS

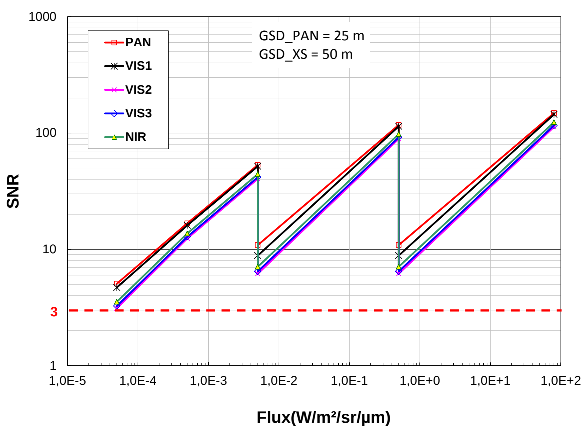

Figure 3.4-5: SNR values over the radiance dynamic for the 50 m option GSD XS

3.4.3.3 CMOS detector operating conditions

The total frame readout of each CMOS matrix is the outcome of the trade-off between the number of analog outputs and the readout frequency. It is proposed to design each CMOS matrix with 8 analog outputs operated at 5 Mpixels/sec resulting in a frame readout duration of 175 msec.

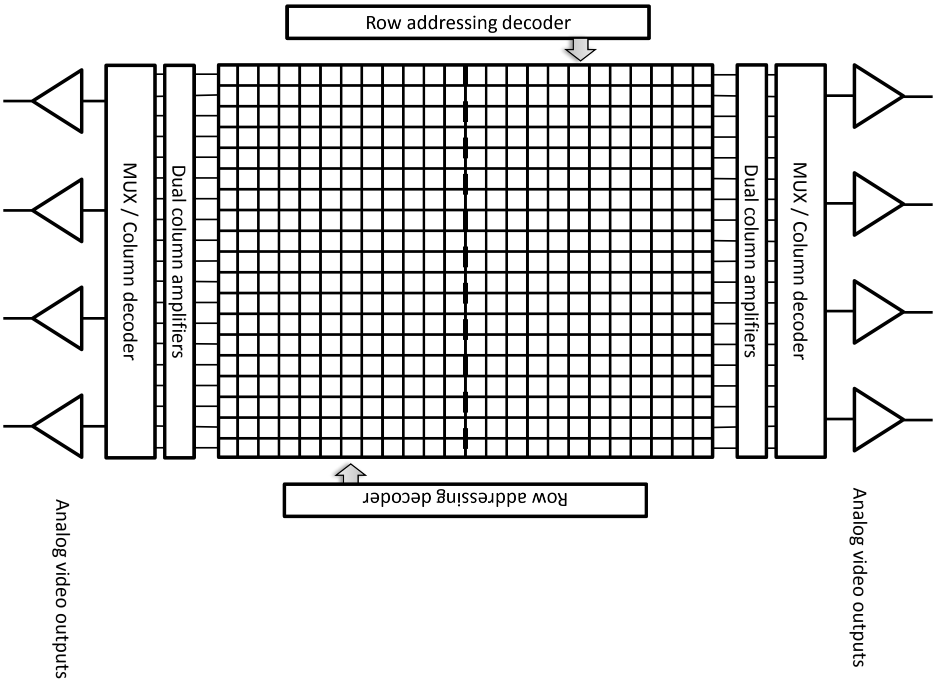

Figure 3.4-6: Detector block diagram with 8 analog outputs

It is proposed to integrate and readout 3 images during each ACT step sequence resulting in 685.1 msec sequence duration. This overall 3 images sequence duration is comfortably within the 1.245 sec allocated time per ACT step. The remaining time can be used in several ways:

- The horizontal swath can be increased with 1 or 2 additional steps;
- The image quality for the low radiance can be improved by acquiring and processing one additional image with the same integration time;
- The margins allocation can be further increased for:
    - Better stability at platform and/or mechanism level by increasing the integration time for low radiance levels;
    - Improved XS GSD (50 m) by increasing the integration time;
    - Relaxing some design parameters such as the stabilization time.

Thanks to the flexibility of the step and stare concept, the above listed optimizations can be selected at a late stage of the programme.

3.4.3.4 Detection chain architecture and sizing

The detection chain overall architecture is presented in **Figure 3.4-7**. As a recall, the NYX step and stare instrument encompasses five CMOS detector matrices, each one being associated to one spectral band. Each CMOS detector is divided into two identical and independent sub-matrices having each four analogue outputs (see Figure 3.4-8). To prevent single point failure, each sub-matrix is connected to a dedicated Front-End Electronics (FEE) via a dedicated flexible link (see Figure 3.4-9).Each FEE encompasses 20 video chains (4 per sub-matrix of each CMOS detector) up to digitization. Each FEE interfaces with the Video and Control Electronic (VCE) which is cold redounded. With the proposed detection chain architecture, a single failure does not result in the loss of a complete CMOS detector (i.e. loss of a spectral channel). In case of failure, half of every detector matrices is still operational and provides images over a horizontal swath equal to half of the nominal one thanks to a re-calibrated OTS mechanism.

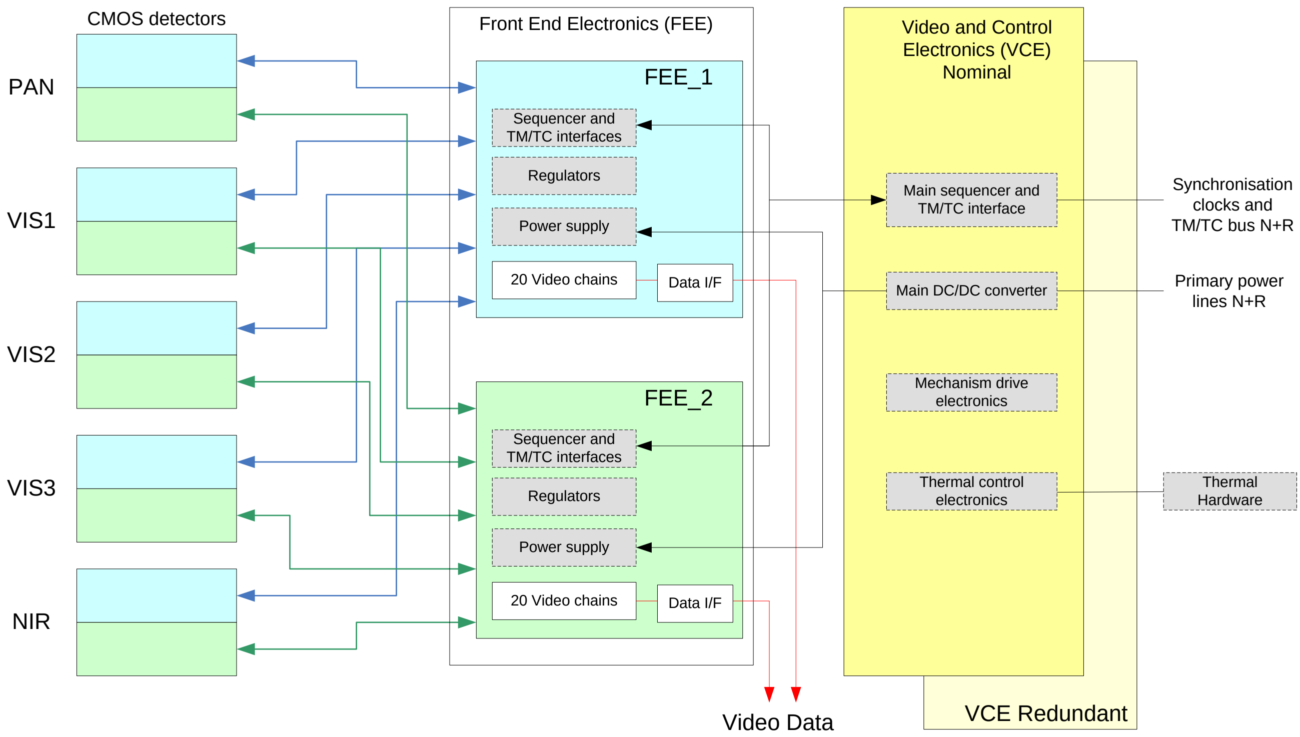

Figure 3.4-7: Detection chain architecture

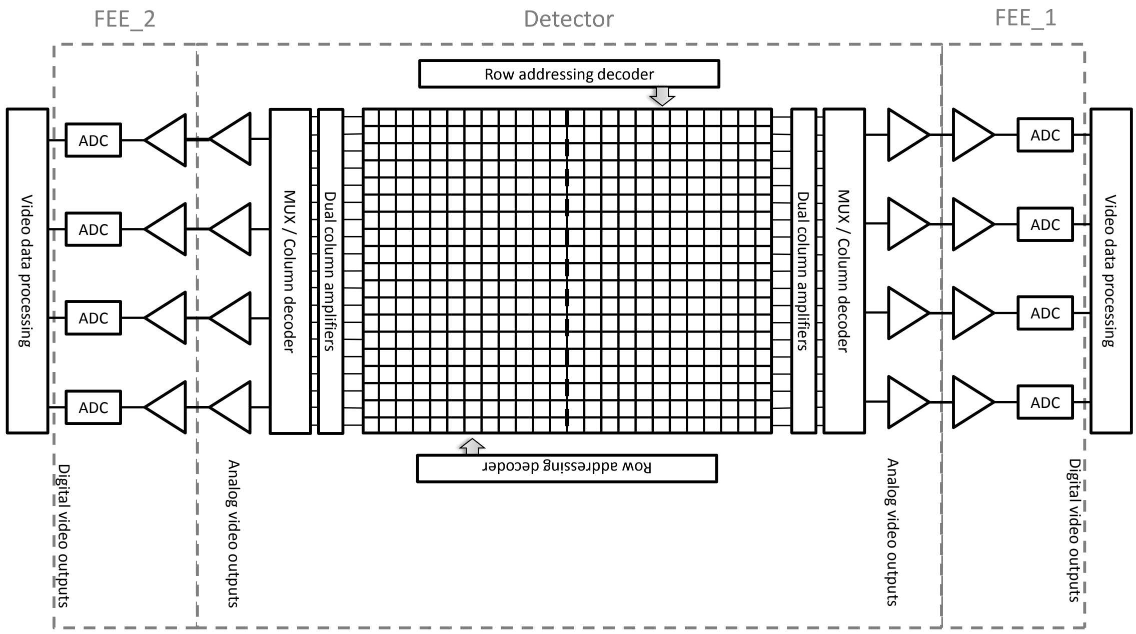

Figure 3.4-8: Detection chain block diagram

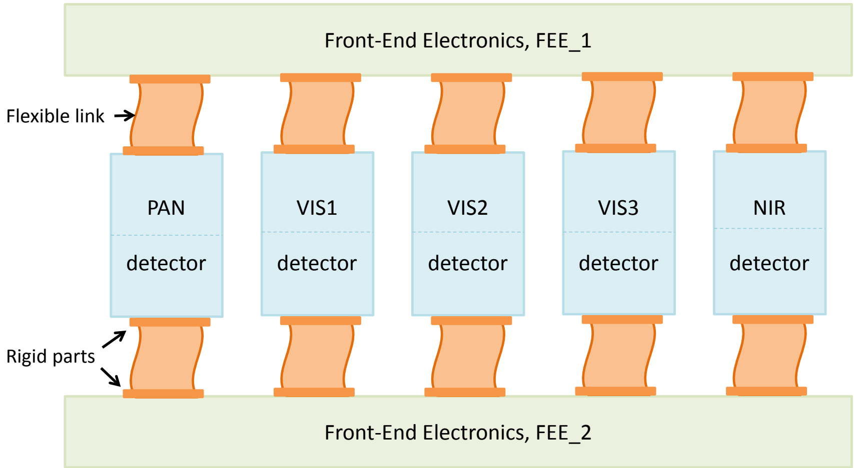

Figure 3.4-9: Schematic of the detectors / FEE modules assembly

Thanks to the detector on-chip column amplifier with high gain at detector level, the architecture of the video chain is simplified. Indeed, for the low flux images, most of the overall analogue gain is performed in the detector to improve the SNR and make the video chain noise contribution more negligible.

3.4.4 SCAN mechanism and pointing mirror

The scan mechanism is located at the instrument entrance. It is a bi-axis mechanism equipped with mirror scanning the Earth across track while the second axis is compensating the Spacecraft Velocity along track.

The scan mechanism assembly benefits from Astrium heritage on several missions. It is based on the mechanism studied in the frame of IASI NG instrument and benefits from MTG scan mechanism bread-boarding activities (SVC/ALT design & performance aspects).

The swath width is covered in 6 steps of equal duration. The Across Track (ACT) axis is powered by a DC brushless torque motor and the large angular ACT rotation guidance is ensured by ball bearings while the small ALT line of sight compensation (< 0.7 degrees) is ensured by flexural pivots associated with a Limited Angle Torquer (LAT). Two optical encoders are used to control the angular position on each axis. A feed-forward open loop installed in the Mechanism Drive Electronics FPGA controls the movements on both axes.

	ALT Satellite Velocity Compensation	ACT Scanning
Guidance	Flexural pivots	Ball bearings
Motor	LAT (Limited Angle Torquer)	DC brushless torque motor
Optical Encoder	Codechamp 24 bits	Codechamp 24 bits
Pointing accuracy	+/- 200 µrad (*)	+/- 200 µrad
Pointing stability	**ΔLOS < 3,2 µrad @ 1 σ (*)**	**ΔLOS < 3 µrad @ 1 σ (**)**
	Compatible with a 20 µrad ΔLOS PtP allocation on each axis	
Range Angle (at mechanism level)	+/- 0,2 °	> 90 ° ('infinite' by principle)

(*) Demonstrated on MTG BB
MTG scan mechanism predevelopment : design & performance. J Vinals, T Blais and Al.
14th European Space Mechanisms & Tribology Symposium - ESMATS 2011 Constance, Germany 28-30 Sept 2011

(**) Stabilization time has been extended to 0,3 s (instead of 0,1s considered previously)

Figure 3.4-10: Scan mechanism performances

3.4.4.2 Scan sequence

The scanning parameters are driven by the mission parameters (orbit altitude, GSD, swath width), the geometry of the detectors matrix, and the overlap considered between the elementary images. The scan sequence is described below.

Vsat = satellite velocity at ground level	6573 m/s
Npix_ALT: number of PAN pixels of the matrix Along Track	2800
Npix_ACT: number of PAN pixels of the matrix Across Track	2300
Novl_ALT: number of pixels considered for overlap Along Track	100
Novl_ACT: number of pixels considered for overlap Across Track	100
SW: Swath Width at Nadir	332.5 km
GSD_PAN: Ground Sampling Distance at Nadir in PAN band	25 m
Tc: time allocated for a step and stare cycle .	10.269 s
N_steps: number of steps Across Track required to cover the swath width	6
T_stab: stabilization time allocated to the mechanism at each step	0.30 s
T_disp: time allocated required for each elementary displacement (from step n to step n+1)	0.10 s
T_step the time allocated at each step for the imaging sequence	1.245 s

Figure 3.4-11: Scan sequence description

3.4.4.3 Pointing mirror

The pointing mirror is installed on the scan mechanism. It is made of SiC with a mechanism interface in Invar to cope with the SiC thermal expansion coefficient.

The SiC choice guarantees excellent stiffness, thermo-elastic stability with good industrial background.

3.4.6 Mechanical and thermal architecture

3.4.6.1 Mechanical architecture

The camera mechanical architecture relies on proven mechanical and thermal technologies and inherits from development performed by Astrium for similar optical payloads.

The opto-mechanical concept relies upon:

- A main structure which supports all the main elements of the camera;
- An entrance baffle which aims to limit sun illumination and to minimize stray-light effects;
- A step and stare mechanism assembly offering a large capability to scan the whole swath from Nadir up to 30 degrees off-track, and also to provide speed compensation during detector acquisition phase;
- A refractive telescope of 90 mm diameter made of 9 lenses plus one silica plate to protect the lenses from in orbit radiations;
- A cold temperature focal plane assembly made of five identical 6.4MPixelsCMOS detectors and the associated beam splitters / dichroic for the PAN, VIS, NIR channels separation fixed on a monolithic focal plane bench.
- The two Front End Electronics (FEE) connected by low conductive flex to the associated detectors packages and by harness to the Video and Control Electronics (VCE)located within the satellite platform;
- The calibration assembly consisting of a folding mirror and a calibration window which are fixed on the main structure.

3.4.6.2 Thermal concept

Three thermal radiators are used to control the instrument temperature.

- The first one is dedicated to the detector assembly that needs to be controlled around 220K
- The second one aims at controlling the temperature of the refractive telescope around 293 K in order to limit the temperature variations of the lenses and to control the image quality (including focus). The need for an athermal design of the refractive telescope assembly shall be evaluated.
- The last one is dedicated to the Front End Electronics operated around 293 K.

3.5 Step and stare imager performances

3.5.1 Radiometric budgets

The SNR specification of 3 at Rmin is met for all the spectral channels with a 4T pixel CMOS detector that includes column amplifiers with a fixed gain of 8.

The radiometric and quality image computations for the baseline (GSD_XS = 100 m) for each spectral band over the whole radiance dynamic are presented in the following tables. The SNR specifications for the five spectral channels are met with good image quality as the detector MTF at Nyquist is above 0.4 for all the channels.

channel	PAN	PAN	PAN	PAN	PAN	PAN	PAN
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25	25	25
pixel binning factor	1	1	1	1	1	1	1
Binned pixel GSD (m)	25	25	25	25	25	25	25
binned pixel FOV (µrad))	29,9	29,9	29,9	29,9	29,9	29,9	29,9
Altitude (Km)	835	835	835	835	835	835	835
Space Velocity (km/sec)	7,43	7,43	7,43	7,43	7,43	7,43	7,43
Vertical pixel number (row number)	2800	2800	2800	2800	2800	2800	2800
Vertical overlap pixel number	100	100	100	100	100	100	100
Vertical elementary Swath (Km)	67,5	67,5	67,5	67,5	67,5	67,5	67,5
OTS period (sec)	10,27	10,27	10,27	10,27	10,27	10,27	10,27
Horizontal pixel number (col number)	2300	2300	2300	2300	2300	2300	2300
Horizontal overlap pixel number	100	100	100	100	100	100	100
Horizontal elementary swath (km)	55	55	55	55	55	55	55
horizontal swath (Km)	332,5	332,5	332,5	332,5	332,5	332,5	332,5
number of horizontal slot	6,00	6,00	6,00	6,00	6,00	6,00	6,00
actual horizontal swath (Km)	330,00	330,00	330,00	330,00	330,00	330,00	330,00
SVC profile period (sec)	1,71	1,71	1,71	1,71	1,71	1,71	1,71
Detection allocated time (sec)	1,245	1,245	1,245	1,245	1,245	1,245	1,245
Pixel ReadOut Frequency (MHz)	5	5	5	5	5	5	5
T frame (sec) - 4x2 outputs	0,175	0,175	0,175	0,175	0,175	0,175	0,175
Dtel(m)	0,09	0,09	0,09	0,09	0,09	0,09	0,09
focal_lenghth (m)	0,33	0,33	0,33	0,33	0,33	0,33	0,33
aperture number	3,7	3,7	3,7	3,7	3,7	3,7	3,7
instrument trans	20%	20%	20%	20%	20%	20%	20%
instrument Gain (ph/sec/W/m2/sr/µm)	1,91E+6	1,91E+6	1,91E+6	1,91E+6	1,91E+6	1,91E+6	1,91E+6
R1 (W/m2/sr/µm)	5,0E-5	5,0E-4	1,0E-2	1,0E-2	1,0E+0	1,0E+0	8,0E+1
pixel flux (ph/sec)	95	953	19053	19053	1905349	1905349	152427888
temperature (K)	220	220	220	220	220	220	220
pixel pitch (µm)	10,0	10,0	10,0	10,0	10,0	10,0	10,0
integration time (sec)	0,150	0,150	0,150	0,010	0,010	0,0001	0,0001
Pixel							
Total pixel charge (e-)	11,5	114,4	2286,5	152,4	15242,8	152,4	12194,2
Column amplifiers on chip							
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	0,800	0,800	0,800	0,800
Ampli on det chip Output signal (mV)	7,79	77,52	1549,43	10,33	1032,92	10,33	826,34
Detection chain							
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50	2,50	2,50
Video gain (LSB/mV)	490,404	49,303	2,467	369,978	3,700	369,989	4,625
Total readout noise (e-)	1,642	1,643	2,146	4,701	4,790	4,701	4,758
Noise per pixel (e-)	3,8	10,8	47,9	13,2	123,6	13,2	110,5
SNR binned pixel 1 image	3,0	10,6	47,8	11,5	123,4	11,5	110,3

Table 3.5-1: Integration time and gain for the PAN channel to cover the whole radiance dynamic (GSD_XS = 100 m)[3]

[3] *3 images are integrated and readout during each ACT step sequence resulting in 685.1 ms sequence duration within the 1.245 sec allocated time per ACT step*

channel	VIS1	VIS1	VIS1	VIS1	VIS1	VIS1	VIS1
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25	25	25
pixel binning factor	4	4	4	4	4	4	4
R1 (W/m2/sr/µm)	5,0E-5	5,0E-4	1,0E-2	1,0E-2	1,0E+0	1,0E+0	8,0E+1
pixel flux (ph/sec)	20	202	4036	4036	403641	403641	32291262
integration time (sec)	0,150	0,150	0,150	0,010	0,010	0,0001	0,0001
Pixel							
Signal per pixel(e-)	2,7	27,2	544,9	36,3	3632,8	36,3	2906,2
Pixel noise (µV)	89	89	89	89	89	89	89
PhotonicSignalNoise(e-)	1,7	5,2	23,3	6,0	60,3	6,0	53,9
DarkNoise(e-)	0,3	0,3	0,3	0,1	0,1	0,0	0,0
Column amplifiers on chip							
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	0,800	0,800	0,800	0,800
Ampli on det chip Output signal (mV)	1,89	18,51	369,31	2,46	246,17	2,46	196,94
Ampli on det chip electronic noise (µV)	300	300	300	300	300	300	300
Ampli on det chip electronic noise at pixel level (µV)	38	38	38	375	375	375	375
Detection chain							
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50	2,50	2,50
ampli noise (µV rms)	150	150	150	150	150	150	150
Nb of useful bits (ADC 14bits)	12	12	12	12	12	12	12
Dynamic at input FEE (=output det) (V)	0,002	0,019	0,369	0,002	0,246	0,002	0,197
q actual (V/LSB)	0,00000	0,00001	0,00024	0,00000	0,00016	0,00000	0,00013
ADC noise (µV rms)	0,36	3,50	69,74	0,46	46,49	0,46	37,19
Video chain output (LSB)	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703
Allocation for other noises (Truncature, EMI, ..) (µV rms)	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Total readout noise (e-)	1,151	1,642	1,675	4,701	4,706	4,701	4,704
Noise per pixel (e-)	2,0	5,5	23,4	7,6	60,5	7,6	54,1
SNR binned pixel 1 image	5,4	19,9	93,1	19,0	240,4	19,0	214,8

Table 3.5-2: Radiometric computations for the VIS_1 band (GSD_XS = 100 m) over the complete radiance dynamic

channel	VIS2	VIS2	VIS2	VIS2	VIS2	VIS2	VIS2
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25	25	25
pixel binning factor	4	4	4	4	4	4	4
R1 (W/m2/sr/µm)	5,0E-5	5,0E-4	1,0E-2	1,0E-2	1,0E+0	1,0E+0	8,0E+1
pixel flux (ph/sec)	12	123	2467	2467	246669	246669	19733549
integration time (sec)	0,150	0,150	0,150	0,010	0,010	0,0001	0,0001
Pixel							
Signal per pixel(e-)	1,7	16,7	333,0	22,2	2220,0	22,2	1776,0
Pixel noise (µV)	89	89	89	89	89	89	89
PhotonicSignalNoise(e-)	1,3	4,1	18,2	4,7	47,1	4,7	42,1
DarkNoise(e-)	0,3	0,3	0,3	0,1	0,1	0,0	0,0
Column amplifiers on chip							
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	0,800	0,800	0,800	0,800
Ampli on det chip Output signal (mV)	1,17	11,33	225,70	1,50	150,44	1,50	120,35
Ampli on det chip electronic noise (µV)	300	300	300	300	300	300	300
Ampli on det chip electronic noise at pixel level (µV)	38	38	38	375	375	375	375
Detection chain							
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50	2,50	2,50
ampli noise (µV rms)	150	150	150	150	150	150	150
Nb of useful bits (ADC 14bits)	12	12	12	12	12	12	12
Dynamic at input FEE (=output det) (V)	0,001	0,011	0,226	0,002	0,150	0,002	0,120
q actual (V/LSB)	0,00000	0,00001	0,00015	0,00000	0,00010	0,00000	0,00008
ADC noise (µV rms)	0,22	2,14	42,62	0,28	28,41	0,28	22,73
Video chain output (LSB)	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703
Allocation for other noises (Truncature, EMI, ..) (µV rms)	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Total readout noise (e-)	1,642	1,642	1,654	4,701	4,703	4,701	4,702
Noise per pixel (e-)	2,1	4,4	18,3	6,7	47,4	6,7	42,4
SNR binned pixel 1 image	3,2	15,1	72,7	13,3	187,5	13,3	167,5

Table 3.5-1: Radiometric computations for the VIS_2 band (GSD_XS = 100 m) over the complete radiance dynamic

channel	VIS3	VIS3	VIS3	VIS3	VIS3	VIS3	VIS3
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25	25	25
pixel binning factor	4	4	4	4	4	4	4
R1 (W/m2/sr/µm)	5,0E-5	5,0E-4	1,0E-2	1,0E-2	1,0E+0	1,0E+0	8,0E+1
pixel flux (ph/sec)	13	131	2624	2624	262367	262367	20989320
integration time (sec)	0,150	0,150	0,150	0,010	0,010	0,0001	0,0001
Pixel							
Signal per pixel(e-)	1,8	17,7	354,2	23,6	2361,3	23,6	1889,0
Pixel noise (µV)	89	89	89	89	89	89	89
PhotonicSignalNoise(e-)	1,3	4,2	18,8	4,9	48,6	4,9	43,5
DarkNoise(e-)	0,3	0,3	0,3	0,1	0,1	0,0	0,0
Column amplifiers on chip							
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	0,800	0,800	0,800	0,800
Ampli on det chip Output signal (mV)	1,25	12,05	240,07	1,60	160,01	1,60	128,01
Ampli on det chip electronic noise (µV)	300	300	300	300	300	300	300
Ampli on det chip electronic noise at pixel level (µV)	38	38	38	375	375	375	375
Detection chain							
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50	2,50	2,50
ampli noise (µV rms)	150	150	150	150	150	150	150
Nb of useful bits (ADC 14bits)	12	12	12	12	12	12	12
Dynamic at input FEE (=output det) (V)	0,001	0,012	0,240	0,002	0,160	0,002	0,128
q actual (V/LSB)	0,00000	0,00001	0,00016	0,00000	0,00010	0,00000	0,00008
ADC noise (µV rms)	0,24	2,27	45,33	0,30	30,22	0,30	24,17
Video chain output (LSB)	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703
Allocation for other noises (Truncature, EMI, ..) (µV rms)	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Total readout noise (e-)	1,642	1,642	1,656	4,701	4,703	4,701	4,702
Noise per pixel (e-)	2,1	4,5	18,9	6,8	48,8	6,8	43,7
SNR binned pixel 1 image	3,3	15,7	75,0	14,0	193,5	14,0	172,8

Table 3.5-2: Radiometric computations for the VIS_3 band (GSD_XS = 100 m) over the complete radiance dynamic

channel	NIR	NIR	NIR	NIR	NIR	NIR	NIR
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25	25	25
pixel binning factor	4	4	4	4	4	4	4
R1 (W/m2/sr/µm)	5,0E-5	5,0E-4	1,0E-2	1,0E-2	1,0E+0	1,0E+0	8,0E+1
pixel flux (ph/sec)	19	191	3812	3812	381216	381216	30497303
integration time (sec)	0,150	0,150	0,150	0,010	0,010	0,0001	0,0001
Pixel							
Signal per pixel(e-)	2,0	20,0	400,3	26,7	2668,5	26,7	2134,8
Pixel noise (µV)	89	89	89	89	89	89	89
PhotonicSignalNoise(e-)	1,4	4,5	20,0	5,2	51,7	5,2	46,2
DarkNoise(e-)	0,3	0,3	0,3	0,1	0,1	0,0	0,0
Column amplifiers on chip							
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	0,800	0,800	0,800	0,800
Ampli on det chip Output signal (mV)	1,40	13,61	271,29	1,81	180,83	1,81	144,66
Ampli on det chip electronic noise (µV)	300	300	300	300	300	300	300
Ampli on det chip electronic noise at pixel level (µV)	38	38	38	375	375	375	375
Detection chain							
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50	2,50	2,50
ampli noise (µV rms)	150	150	150	150	150	150	150
Nb of useful bits (ADC 14bits)	12	12	12	12	12	12	12
Dynamic at input FEE (=output det) (V)	0,001	0,014	0,271	0,002	0,181	0,002	0,145
q actual (V/LSB)	0,00000	0,00001	0,00018	0,00000	0,00012	0,00000	0,00009
ADC noise (µV rms)	0,26	2,57	51,23	0,34	34,15	0,34	27,32
Video chain output (LSB)	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703	3821,703
Allocation for other noises (Truncature, EMI, ..) (µV rms)	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Total readout noise (e-)	1,642	1,642	1,660	4,701	4,704	4,701	4,703
Noise per pixel (e-)	2,2	4,8	20,1	7,0	51,9	7,0	46,4
SNR binned pixel 1 image	3,7	16,8	79,7	15,3	205,8	15,3	183,9

Table 3.5-3: Radiometric computations for the NIR band (GSD_XS = 100 m) over the complete radiance dynamic

The radiometric performances at Rmin for the 50 m GSD XS option are presented in the table below. The SNR of 3 at Rmin is met for all the channels with an integration time of 370 msec.

channel	VIS1	VIS2	VIS3	PAN	NIR
elementary pixel FOV (µrad)	29,9	29,9	29,9	29,9	29,9
elementary pixel GSD (m)	25	25	25	25	25
pixel binning factor	2	2	2	1	2
Binned pixel GSD (m)	50	50	50	25	50
R1 (W/m2/sr/µm)	5,0E-5	5,0E-5	5,0E-5	5,0E-5	5,0E-5
pixel flux (ph/sec)	20	12	13	95	19
integration time (sec)	0,370	0,370	0,370	0,370	0,370
Pixel					
Signal per pixel(e-)	6,7	4,1	4,4	28,2	4,9
Pixel noise (µV)	89	89	89	89	89
PhotonicSignalNoise(e-)	2,6	2,0	2,1	5,3	2,2
DarkNoise(e-)	0,4	0,4	0,4	0,4	0,4
Column amplifiers on chip					
Ampli on det chip Gain (V/V)	8,000	8,000	8,000	8,000	8,000
Ampli on det chip Output signal (mV)	4,67	2,90	3,07	19,22	3,46
Ampli on det chip electronic noise (µV)	300	300	300	300	300
Ampli on det chip electronic noise at pixel level (µV)	38	38	38	38	38
Detection chain					
ampli gain (V/V)	2,50	2,50	2,50	2,50	2,50
ampli noise (µV rms)	150	150	150	150	150
Nb of useful bits (ADC 14bits)	12	12	12	12	12
Dynamic at input FEE (=output det) (V)	0,005	0,003	0,003	0,019	0,003
q actual (V/LSB)	0,00000	0,00000	0,00000	0,00001	0,00000
ADC noise (µV rms)	0,82	0,51	0,54	3,39	0,61
Video chain output (LSB)	4096,000	4096,000	4096,000	4096,000	4096,000
Allocation for other noises (Truncature, EMI, ..) (µV rms)	200,000	200,000	200,000	200,000	200,000
Total readout noise (e-)	1,151	1,642	1,642	1,642	1,642
Noise per pixel (e-)	2,9	2,6	2,7	5,6	2,8
SNR binned pixel 1 image	4,69	3,11	3,25	5,06	3,54

Table 3.5-4: Radiometric performances at Rmin for the 50 m GSD XS option

3.5.2 MTF budgets

Platform stability is a key point impacting the MTF performance that has to be considered for MTF budgets.

3.5.2.1 MTF Budgets with METOP SG platform

LOS stability of METOP SG Platform has been modelled by SL team and the MTF performance has been computed for different integration times.

Considering METOP SG platform the maximum integration time is adjusted to 0.15 s in order to keep a reasonable MTF level. This value has been considered for the SNR budgets.

X Axis _ PAN GSD = 25 m	Tint = 0,85 s	Tint = 0,5 s	Tint = 0,30 s	Tint = 0,25 s	Tint = 0,2 s	Tint = 0,15 s	Tint = 0,1 s
PAN MTF							
Optical design	0,75	0,75	0,75	0,75	0,75	0,75	0,75
Manufacturing & alignment	0,90	0,90	0,90	0,90	0,90	0,90	0,90
Thermoelastic & Mech. stability	0,95	0,95	0,95	0,95	0,95	0,95	0,95
Detector	0,40	0,40	0,40	0,40	0,40	0,40	0,40
LOS stability impact_drift (mechanism & PF)	0,00	0,00	0,12	0,20	0,29	0,38	0,47
LOS stability impact_jitter(mechanism & PF)	0,97	0,97	0,97	0,97	0,97	0,97	0,97
NYX instrument MTF	**0,00**	**0,00**	**0,03**	**0,05**	**0,07**	**0,09**	**0,12**

Y Axis_PAN GSD = 25 m	Tint = 0,85 s	Tint = 0,5 s	Tint = 0,30 s	Tint = 0,25 s	Tint = 0,2 s	Tint = 0,15 s	Tint = 0,1 s
PAN MTF							
Optical design	0,75	0,75	0,75	0,75	0,75	0,75	0,75
Manufacturing & alignment	0,90	0,90	0,90	0,90	0,90	0,90	0,90
Thermoelastic & Mech. stability	0,95	0,95	0,95	0,95	0,95	0,95	0,95
Detector	0,40	0,40	0,40	0,40	0,40	0,40	0,40
LOS stability impact_drift (mechanism & PF)	0,00	0,22	0,45	0,51	0,57	0,63	0,70
LOS stability impact_jitter(mechanism & PF)	0,98	0,98	0,98	0,98	0,98	0,98	0,98
NYX instrument MTF	**0,00**	**0,06**	**0,11**	**0,13**	**0,14**	**0,16**	**0,18**

Figure 3.5-5: MTF performances with Metop-SG platform

3.5.2.2 MTF Budgets considering other Earth Observation platforms

Stability figures coming from platforms dedicated to Earth Observation high resolution missions (as for Pleiades for example) are improved wrt METOP SG and lead to MTF performance compatible with a higher integration time. In that case an integration time up to 0.3 s can be considered leading to a MTF performance higher than 0.11 for ACT and ALT directions.

PAN GSD = 25 m	Tint = 0,85 s	Tint = 0,5 s	Tint = 0,30 s	Tint = 0,25 s	Tint = 0,2 s
PAN MTF					
Optical design	0,75	0,75	0,75	0,75	0,75
Manufacturing & alignment	0,90	0,90	0,90	0,90	0,90
Thermoelastic & Mech. stability	0,95	0,95	0,95	0,95	0,95
Detector	0,40	0,40	0,40	0,40	0,40
LOS stability impact_drift (mechanism & PF)	0,00	0,22	0,45	0,51	0,57
LOS stability impact_jitter(mechanism & PF)	0,98	0,98	0,98	0,98	0,98
NYX instrument MTF	**0,00**	**0,06**	**0,11**	**0,13**	**0,14**

Figure 3.5-6: MTF performances on earth observation platform other than Metop-SG

The 50m XS GSD option considered in Chapter 6 requires an integration time of 0.37 s which leads to a MTF performance higher than 0.2.

3.5.3 Dimensions and Mass Budget

The overall dimensions of the instrument are: 990 mm (length) x 800 mm (width) x 645 mm (height including the baffle). Mass budget is estimated to 60 kg.

Optical Assembly	7,9
Step and stare mechanism	9
Structure	19
Calibration	1
Detectors	0,8
FEE	6
Radiators	2
Optical Assembly	**45,7**
Video & Control Electronics : VCE (N & R)	**10,0**
Harness	**4**
NYX instrument - Mass budget (kg)	**60**

Figure 3.5-7: Mass budget of the proposed Step and Stare instrument

3.5.4 Power Budget.

The instrument power budget is estimated to 90 Watt, including the front end electronics (FEE) and the Video and Control Electronics (VCE) including cold redundancy.

FEE units		40
VCE (N & R)	Sequencer	2
	TM TC	2
	Thermal Control (monitoring)	3
	Instrument Thermal Control	10
	CV	12
	Step & Stare Mechanism (including Drive Electronics)	21
NYX instrument - Power Budget (W)		**90**

Figure 3.5-8: Power budget of the proposed Step and Stare instrument

3.5.5 Data Rate

The data rate for the proposed baseline (PAN GSD = 25 m and XS GSD = 100 m) is detailed below.

		PAN	XS	PAN + XS
GSD	m	25	100	
Number of pixels ALT for each elementary image		2800	700	
Number of pixels ACT for each elementary image		2300	575	
Number of elementary images		6	6	
Number of bits		12	12	
Number of spectral bands		1	4	
Number of images for each scene		3	3	
Cycle period	s	10,269	10,269	
Mean Data rate wo compression	Mbit/s	135	34	169
Compression ratio		3	3	
Mean Data rate with compression	Mbit/s	**45**	**11**	**56**
Mean Data rate with compression and fusion (1 single image - 14 bits)	Mbit/s	**18**	**4**	**22**

Figure 3.5-9: Data rate of the proposed Step and Stare instrument (XS GSD = 100 m)

The mean data rate is about 56 Mbit/s considering 3 images per scene with a compression ratio of 3 for PAN and MS data. This data rate can be decreased to 22 Mbits/s in case the 3 images are processed on board and mixed in a single image (14 bits). For the option case (PAN GSD = 25 m, and XS GSD = 50 m), the data rate budget is increased by a factor: 1.6.

3.6 NYX imager development overview

The NYX overall development logic is based on risks mitigation and step-by-step verification approach to support instrument design and performances consolidation with a view to secure full qualification and flight model production (see Figure 3.6-1).

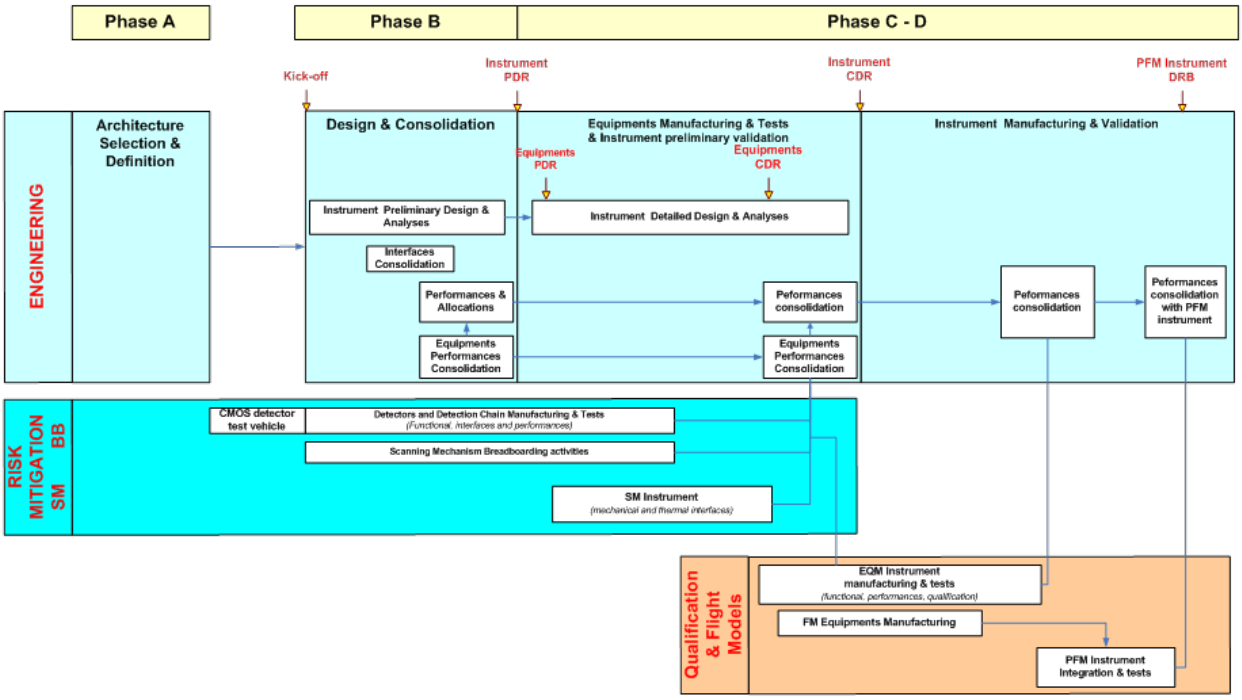

Figure 3.6-1**:** Overall development logic

Most of the NYX imager equipment items rely on flight proven technologies with a Technology Readiness Level (TRL) higher than 6. Only the CMOS detector technology requires specific technology development to reach TRL of 6 before the NYX imager Preliminary Design Review (PDR). A specific mitigation risks programme for the CMOS detectors is therefore to be implemented.

4. DOCUMENTATION ISSUED DURING THE STUDY

	Title	Reference
TN1	Product Requirement Review Report	EF.RP.JJA.11.00239 Iss 04
TN2G	TN2G : GEO NYX System requirements report	EF.NT.JJA.12.00118 Iss 01
TN2L	LEO NYX System requirements report	EF.TN.JJA.12.00117 Iss 01
TN3G	Candidate GEO NYX Mission Concepts Report	EF.TN.JJA.12.00120 Iss 01
TN3L	LEO NYX Mission Concepts Report	EF.NT.JJA.12.00119 Iss 03
TN3LS	A step and stare instrument for NYX mission in LEO	EF.NT.PL.12.00232 Iss 02
TN4	NYX Study Final Report	EF.NT.PL.13.00039 Iss 01
	Instrument Radiometric Model	EF.NT.FK.13.00043 Iss01
	NYX Study Abstract	EF.NT.PL.13.00038 Iss 01
	NYX Study Executive Summary	EF.NT.PL.13.00040 Iss 01

5. CONCLUSION

The proposed step and stare instrument meets the NYX LEO mission and offers high flexibility for possible mission and design upgrades. It includes a single refractive telescope coupled with five identical 6.4 MPixels CMOS detectors operated at 220 K. These detectors are based on CMOS low noise 4T pixel technology. The refractive telescope consists of an assembly of nine lenses and one silica plate for radiations protection. The mass of the instrument is about 60 kg including the VCE electronics located within the platform, and the power consumption is estimated to 90 Watt. Overall dimensions are limited to 0.53 m x 0.56 m x 0.94 m (local appendices not included).

Though the step and stare mechanism benefits from Astrium past developments and recent studies, a robust development programme is proposed based on risks mitigations and step-by-step verification approach. Dedicated development logic is proposed for the CMOS detectors based on the successful GMES Sentinel-2 MSI VNIR detector development programme.

Astrium is therefore confident that the step and stare instrument can be successfully developed for the NYX mission with a high level of performances.