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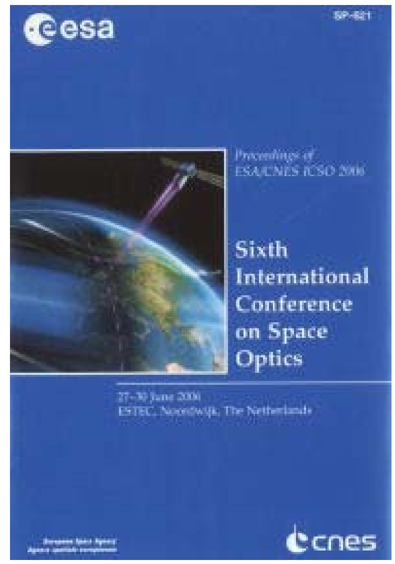

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ESA STUDY OF A WIDE FIELD IMAGER FOR SUPERNOVAE SURVEYS AND DARK ENERGY CHARACTERIZATION

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ABSTRACT

This paper summarizes the results of an ESA feasibility study of a Wide-Field Optical Infrared Imager (WFI) that would search for Type Ia supernovae at low redshift with the aim to measure the changing rate of expansion of the universe. WFI multi-spectral images of the deep universe could also benefit to many other research area in astrophysics. The WFI payload includes a 2 m class telescope, a 1 square degree field of view imaging camera and a low-resolution integral field spectrometer. A mission concept was identified that consists of a 2000 kg spacecraft launched by a Soyuz-Fregat into a L2 halo orbit. The WFI mission could benefit from the technology developed for the ESA Herschel and Gaia missions and for the NIRSpec ESA instrument. A fully European WFI mission would require improvement of existing European detector and on-board processor technology as well as some effort to support the utilization of the 26 GHz Ka band.

1. INTRODUCTION

In October 2005, based on a massive response by the Science Community to ESA's call for themes in space science, a Wide-Field Optical Infrared Imager was identified as a candidate project for Europe within the frame of the 2015-2025 Cosmic Vision program[(1)]. Such a mission would search for Type Ia supernovae at low redshift in the optical and near IR part of the spectrum with the aim to measure the changing rate of expansion of the universe and to determine the contributions of decelerating and accelerating energies such as the mass density, the vacuum energy density and other yet to be studied dark energies. The paper summarizes the WFI science objectives and the result of an ESA feasibility study on a possible mission and scientific payload including a space telescope, a wide field camera and a spectrometer. The paper also specifies the technology development activities for the payload and for the spacecraft that should be initiated in case ESA would decide to develop such a mission.

2. SCIENTIFIC OBJECTIVES

In the past few years the study of cosmology has brought surprises. The universe's expansion is apparently accelerating rather than decelerating as expected due to gravity. Einstein's General Theory of Relativity requires that some mechanism must drive this expansion rate either through a new form of energy, such as a new vacuum energy density (cosmological constant), or a yet unknown kind of particle or field fundamental to the creation and formation of the universe. The Wide Field Imager (WFI) mission objective aims to characterize this new form of energy.

Type Ia supernovae (SNe Ia) provide simple cosmological measurement tools since most observed SNe Ia have nearly the same peak luminosity. The wavelengths of the photons that they emitted are red-shifted in exact proportion to the stretching of the universe since their explosion. Thus the comparison of SN Ia red-shift and peak brightness (magnitude) provides a measurement of the changing rate of expansion of the universe: the apparent magnitude indicates the distance and hence time back to the supernova explosion, while the red-shift measures the total relative expansion of the universe since that time. The objective of the WFI mission is (i) to search for Type Ia supernovae (SN Ia) in the optical and near IR part of the spectrum, (ii) to determine the maximum brightness of their light curves and (iii) to measure the red-shifts of their host galaxies. The WFI measurements will be used to establish a Hubble-diagram plot (red-shift vs. magnitude) dense with supernova events looking back over a fraction of the age of the universe (see Fig. 1). By fitting this experimental Hubble diagram with models, the WFI mission will be able to determine the contributions of decelerating and accelerating energies - mass density ΩM, vacuum energy density $\Omega\Lambda$, and/or other yet-to-be-studied dark energies" as the expansion rate changes over time.

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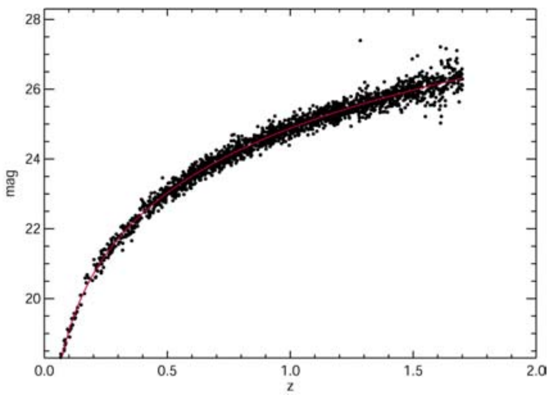

Fig. 1. WFI magnitude vs redshift diagram

To accomplish these goals, the WFI reference payload consists of (i) a 2 meter class telescope with a large 1.0° x 1.0° field-of-view, (ii) a wide field camera sensitive to wavelengths from 350 nm – 1800 nm, and (ii) a low resolution integral field spectrometer operating in the same spectral range. The camera focal plane area (FPA) consists of 18 NIR filters and 72 visible filters deposited on infrared HgCdTe detectors and visible charge coupled devices (CCDs). Each line and each column of the FPA contains nine different filters. The telescope repeatedly steps through its survey zone in such a way that any source located in the 1° x 10° survey area is successively observed through the nine different filters (see Fig. 2). Each step is 300 arc seconds on the sky and comprises either two or four dither exposures of 1000 seconds depending on the selected scanning mode. Since performance are limited by the zodiacal background emission in the NIR, the fraction of the focal plane surface covered with NIR filters is oversized by a factor of 2 with respect to the area sensitive in the visible. In this way, the integration time in the NIR is effectively twice as long as in the visible. A complete sweep then requires 144 steps and about 4 days in fast scanning mode (or 8 days in slow scanning mode) of mission time, including downlink time and provision for telescope slewing and dithering and for antenna re-pointing. One or two additional days are dedicated to follow up spectroscopy of selected supernovae near peak brightness and to calibration. The discovered supernovae can thus be photometrically sampled every 5 or 10 days for the three to six weeks while their luminosity waxes and wanes. The WFI mission can survey 1° x 10° zones located within 20° from the north or south ecliptic poles. These observation fields minimize zodiacal light background and obscuration due to dust in our Galaxy.

The satellite could analyze up to a few thousands supernovae with red-shifts ranging from 0.3 to 1.8. For each object, the WFI telescope and instrumentation shall provide:

- early detection of the supernova.
- B-band rest-frame photometry along its light curve,
- color determination near its peak brightness,
- identification of the supernova type using optical and IR spectroscopy at peak brightness,
- photometric red-shift measurements of its host galaxy.

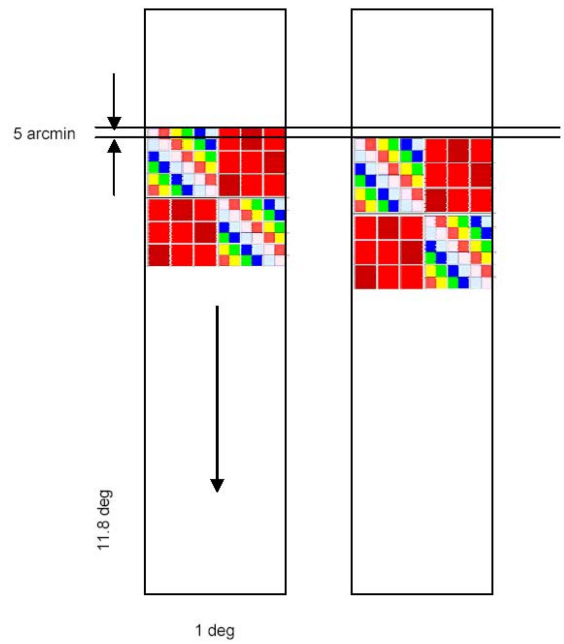

Fig. 2. WFI FPA layout and scanning concept

Although dark energy characterization is WFI primary science objective, the combination of sensitivity, temporal coverage, broad wavelength range, high imaging quality, and wide field make WFI imaging surveys powerful in the study of a wide range of objects and phenomena including:

- gravitational lenses to trace mass structures in the universe including dark matter,
- gamma-ray bursts to probe the ionization states of intergalactic gas in the early universe,
- quasars and galaxy interaction at high red-shift,
- formation of cluster of galaxies,
- faint dwarfs and halo stars to characterize the geometry and substructure of the Milky Way halo,
- solar-system objects such as asteroids and Kuiper-belt objects.

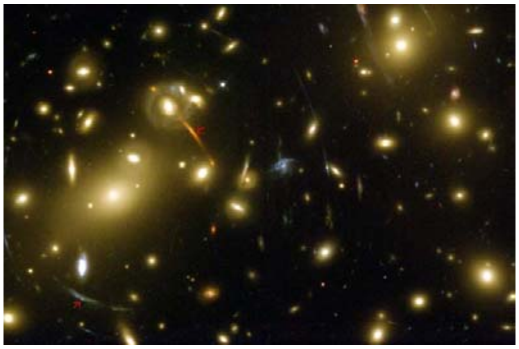

Fig. 3. HST deep field image illustrating WFI performance capability in one single detector (out of 144) and one single filter (out of 9).

3. WFI PAYLOAD DEFINITION

4.1 The WFI Telescope design

The size of the primary mirror of the WFI telescope has a dramatic effect on the science capabilities of the mission. The combination of the light gathering power of the mirror and the diffraction limit imposed by the aperture determine the number of supernovae that can be studied in a fixed time interval. This number varies steeply with the aperture diameter since a smaller telescope diameter means both a lower signal from the supernovae and a higher background contribution from the zodiacal light and host galaxies due to a wider telescope point spread function. The requirement of diffraction limited optics at I-band make best use of the capabilities of the photometric instruments and minimize exposure times. The wide-field optical photometry will also perform with the highest accuracy if the star images are properly sampled. A plate-scale 0.05 arcsec per pixel in the visible and 0.1 arcsec per pixel in the NIR is selected as a best compromise between a wide field of view and achieving the best photometric accuracy. By taking a serie of exposures with pointing dithered by a fractional pixel amount, the scene can be sampled more densely than the pixel grid.

WFI telescope performance requirements	
Primary mirror aperture	2.15 m
Focal length	20 m
Field of view	> 1° x 1°
Spatial resolution	Diffraction limited at 1 µm
Spectral coverage	350 nm to 1800 nm
Plate Scale	0.1 arcsec per 10µm
Survey fields	Ecliptic poles
Solar avoidance angle	>70°
Relative pointing error	10 milli-arcsec
Operation temperature	~290 K

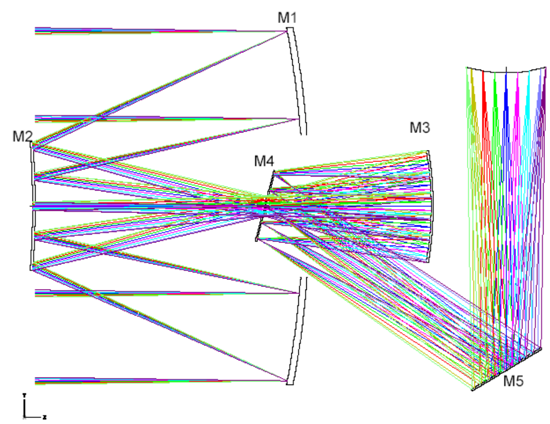

Fig. 4. WFI telescope optical design

The optical configuration of the WFI telescope consists of a three-mirror design with two folding flats (see Fig.4) that provides a large unvignetted field of view corrected for spherical aberration, coma and astigmatism. This choice has been driven by the need for a diffraction limited angular field size of the order of 1.5 degree diameter, combined with the need for rather large telephoto advantage. In order to match the desired plate scale, a telescope focal length of 20m is necessary. An added benefit of the WFI telescope design is the location of the focal plane near the outer envelope of the telescope. This allows the focal plane to be placed near a radiator for passive cooling to 140K. A three-mirror anastigmat (TMA) configuration, developed by Korsch, could provide an alternative solution to the WFI telescope design.

4.2 The WFI camera architecture

The image formed by the telescope in the visible and NIR feed the two key instruments, i.e. the wide field camera and the integral field spectrometer. Two highly fault tolerant fine guidance sensors also uses the throughput of the WFI science telescope and pick-up the light in the outer part of the telescope field of view.

The WFI camera uses two detector technologies. The NIR range (900 nm to 1800 nm) is measured with 72 HgCdTe arrays of 1450 x 1450 pixels each with a pixel pitch of 20 µm. The visible region (300 nm to 1000 nm) could be measured with deeply depleted back illuminated p-channel CCDs that are radiation hard. Seventy-two such arrays with a 2900 x 2900 pixels each and a 10 µm pixel size would be needed. The large (~ 40 cm x 40 cm) focal plane array will be covered with NIR filters and visible filters deposited onto or in front of the detectors as described on Fig.2.

WFI detector performance requirements		
	Visible detector	**NIR detector**
Technology	P channel CCDs	HgCdTe
Spectral coverage	300-1000nm	900-1800nm
Array format	2900 x 2900	1450 x 1450
Pixel sixe	10 um	20 um
QE	>80 %	> 60 %
Read-out noise	4e- @ 100kHz	5 e-
Dark current	0.005 e-/s/px	0.02 e/s/px
Exposure time	8 x 125s	64 x 15.6 s
Read-out time	~20 s	~40 s

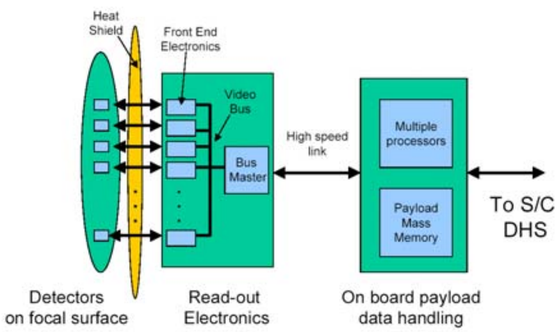

Fig. 5. WFI camera block-diagram

A WFI exposure typically lasts 1000 seconds. After each exposure, the telescope pointing direction is either slewed or offset by a few pixels (and a half) with the objective of improving the spatial sampling of the image and reducing the effect of pixel response non-uniformity and gaps between detectors. Due to numerous cosmic ray impacts, each 1000 sec frame will again be split into sub-frames. The visible p-channel CCDs will be read-out (destructively) every 125s. The 8 x 125s sub-frames will then be re-combined on-board after cosmic rays filtering in order to save as much as possible original data while significantly compressing their volume. For reading the NIR detectors, an up-the ramp sampling technique is assumed that includes 64 non-destructive readouts spaced evenly throughout the 1000 sec exposure. This method enables an expansion of the dynamic range, a correction for cosmic rays and a reduction of the read-out noise. After collection, the 64 sub-frames are re-combined on-board into a frame using intensive on-board processing that requires 465 Gbits memory and a 1200 MIPS processing power including provision for a lossless compression algorithm.

In spite of demanding requirements, several options are possible for the design of the camera processing computer. These include a Maxwell SCS750 processor board, a GINA processor and data compression FPGA (implementing in hardware e.g., the RICE adaptive entropy coder), 2 GINA processors (one for image processing and one for data compression), or a New Power PC board design using the same processor as the SCS750. The payload computer shall include a cold redundant processor module, redundant Spacewire links to the payload mass memory, and to the service module mass memory, and a redundant MIL1553 interface to the service module on-board computer. An additional 700 Gbit memory is needed on the service module for the storage of all the observation data accumulated between two consecutive downlinks and compressed with a factor 1.5. Mass memory could consist of existing boards of 128 Gbits each although significant progress in memory performance is expected in the next few years.

4.3 WFI spectrometer

An integral field spectrometer with an image slicer is a candidate concept for the WFI spectrometer. The image slicer eliminates the need for a slit and greatly reduces the pointing accuracy required to place the supernova within the field of view of the spectrograph while preserving photometric accuracy because of its 100% filling factor. The spectrograph shall have a visible and near-IR arm within a single instrument. Its spectral resolution could be of the order of a 100 and its field of view of about 3 x 3 arcsec square. The maximum number of slices limited by diffraction would be about 15 in the near-IR and 30 in the visible. Gratings or prisms could be used as dispersive elements and the spectrometer camera could also benefit from the p-channel CCD and HgCdTe detector technology. The amount of data produced by such an instrument is not dimensioning for the on-board processing, on-board memory and telemetry data rate of the WFI mission.

4. WFI SPACECRAFT ARCHITECTURE

The WFI spacecraft is made of an upper payload module and a lower hexagonal service module that interfaces to the launcher. The payload module consists of a telescope structure and an outer tube. Both interface directly to the service module. The telescope structure is organized around an optical bench that carries the M1, M3 and M4 mirror isostatic supports and the tripod interface to the secondary mirror. SiC is a candidate material for the metering structures and for the telescope mirrors that shall operate around room temperature. The stability of their temperature should be actively controlled with a high accuracy. The optical bench also carries the instrument bay that contains the last (M5) folding mirror, a calibration unit, the wide-field camera and the integral field spectrometer. The optical bench interface to the service module via an hexapod.

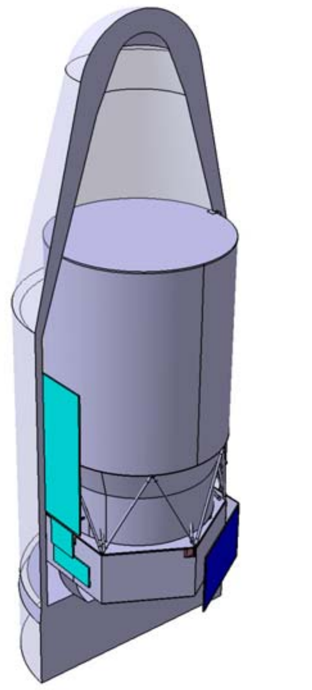

Fig. 6. WFI spacecraft in the Soyuz-Fregat fairing

The volume of the payload module is limited to the fairing dimensions of the selected Soyuz-Fregat launcher. The aperture is not fixed by the fairing diameter, but rather by the total length of the telescope tube that acts as a stray-light baffle and control the telescope thermal environment. A telescope cover protects the optics against contamination on the launch pad and during the early phase of the mission. A baffle length required for the selected 2.15 m aperture telescope design can just be accommodated without deployed components. CFRP with an inner Al foil is a candidate material for the telescope tube. At this size the mission is also mass restricted to the 2100 kg launcher capability to the L2 halo orbit that has been selected for maximizing the observing efficiency and providing a stable thermal environment. The telescope tube carries two radiators that passively cool the focal plane detectors to 140 K and maintain their read-out electronics at room temperature. The telescope tube has no direct contact with the telescope structure but interface directly with the service module.

The WFI service module consists of an hexagonal structure that carries the power subsystem with 6 m2 of GaAs solar cells, the telecommunication subsystem with a 0.4 m diameter high gain antenna, the propulsion subsystem with a monopropellant tanks and the attitude and orbit control subsystem.

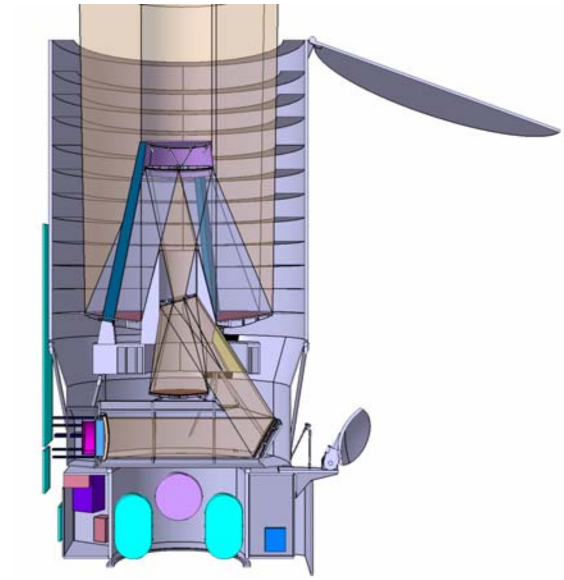

Fig. 7. WFI spacecraft configuration

Attainment of high pointing stability of the telescope is essential for the full completion of the WFI mission science goals. The relative pointing error shall be lower than 0.01 arc sec on a typical 1000 s exposure time. To minimize sources of micro-vibrations, reaction wheels have been avoided and the solar arrays are body mounted. The pointing mechanism of the high gain antenna is the only source of disturbance but does not need to be used frequently.

The propulsion subsystem consists of a hydrazine monopropellant subsystem for launcher dispersion, orbit maintenance, preliminary orbit configuration and safe mode back-up and of a micro-thrusters subsystem for pointing and slews. Provision has been made for enough spacecraft resources (mass, volume and power) such that three micro-thruster options are possible. These include cold gas thrusters similar to those foreseen for Gaia, FEEP thrusters similar to those envisaged for LISA or mini-ion thrusters. Eight mini-thrusters are used for cruise, orbit maintenance and safe mode and twelve micro-thrusters are configured with full redundancy to provide the 3-axis control capability for coarse and fine pointing. The redundant fine guidance sensors located in the telescope focal plane are critical devices for the AOCS.

The wide-field imaging camera generates a huge amount of data that can only be transmitted to ground 4 hours per day. Hence, WFI shall be able to downlink science data with a rate of 40 Mbps. The overall concept for the communication subsystem consists of an X-band transponder for telecommand, housekeeping telemetry and ranging, of a 26 GHz transmitter with traveling wave tube amplifier for science telemetry, one high gain antenna with dual feed, two omni-directional X-band antennas and a radio frequency distribution unit. This approach with no compromise on science return requires an upgrade of ESA deep space network to support the reception of the 26 GHz Ka band as well as some development effort for a high-rate transmitter and a high-power amplifier.

WFI mission summary		
Mission	Launcher:	Soyuz-Fregat
	Orbit:	L2 near-halo
	Lifetime:	3 years (SN surveys) +3 years (extension)
Payload Module	Mass:	1420 kg dry
	Telescope:	2.15 m primary secondary refocusing
	Instruments:	visible/NIR camera low R spectrometer
Service Module	Mass:	560 kg wet
	Propulsion:	monopropellant
	AOCS:	cold gas/FEEP/mini-ion
	Power:	503 W average
	Communication:	40 Mbps (26 GHz)

5. WFI OPERATION

The WFI Observatory would be controlled from a Mission Operations Centre (MOC) capable of monitoring both spacecraft and instrument health and safety, while validating and up-linking WFI observing schedules generated by the Science Operations Centre (SOC). The MOC would receive WFI science and engineering telemetry at the full downlink rate, and temporarily store at least one orbit's worth of data. The MOC would then transfer science and selected engineering data to the SOC.

The SOC would store all WFI Observatory Science Data and all necessary calibration and ancillary engineering data, and provide copies as required to other facilities. The raw science and calibration data consist of sets of 1000 s frames produced by the visible and NIR channels of the camera and spectrometer. WFI calibration data would be acquired using a combination of dedicated observations of astronomical objects, internal lamp calibration and calibration making use of the science data itself. Almost real time on-ground processing of the WFI science and calibration data consist in reconstructing calibrated visible and NIR images of the 10 square degree survey area in 9 different visible filters, reconstructing calibrated low resolution 300-1800nm spectra of supernovae near maximum brightness, archiving and distributing the raw and pipeline processed data, and running detection algorithms on-all calibrated images with the aim to detect new type Ia supernovae and to predict the time of maximum brightness of those already detected. The WFI archival data will be made available to the science community.

6. TECHNOLOGY DEVELOPMENTS

The technology pre-development activities of a WFI mission shall include a conceptual design of the telescope and a subsequent selection of the mirror technology. One candidate for a European mission is the SiC technology based on the experience gained with the Hershel 3m diameter antenna and with the Gaia large aspherized mirrors. The WFI camera has to fulfill demanding requirements with a large focal plane array including many detectors with low noise and low power dissipation. Within the frame of the Eddington and Gaia projects, experience has been gained in Europe for the development of large focal plane areas operating in the visible at low astronomical background levels. The leading NIR sensors in astronomy are HgCdTe focal plane arrays that are normally procured from American suppliers. These devices are produced in Europe but not at the performance level required for deep space observation. The camera electronics would also require 16 bits analogue to digital converter. Regarding the spectrometer, the only critical component is the image slicer that could be of the same type as the one used in the JWST near-IR spectrograph NIRSPEC developed under ESA Contracts. No critical technology has either been identified regarding the spacecraft although some engineering development of a fine guidance sensors and 26 GHz transponder would be needed as well as an upgrade of the Cebreros ground-station to support the reception of the 26 GHz Ka band. The use of this band in ESA ground stations is currently under study including the feasibility of intermediate frequency demodulators able to receive high-rate suppressed carrier modulation format as demanded by WFI.

Based on the heritage of the currently being developed Gaia and Herschel missions, it is concluded that European Industry through ESA is technically capable to either contribute to the science payload on board a space supernovae survey mission or to build a European WFI mission. In such a case, some effort will be required for the development of high performance NIR detectors and for the upgrade of ESA deep space network to support the reception of the 26 GHz Ka band.

7. REFERENCES

1. European Space Agency, *Cosmic Vision: Space Science for Europe 2015-2025*, Document BR-247, ESA publications division, 2005.