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WIDE FIELD IMAGER TECHNOLOGY REFERENCE STUDY

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ABSTRACT

In response to ESA's call for space science themes in the frame of Cosmic Vision 2015-2025, the scientific community identified a Wide-Field Optical and Near Infrared Imager as a potential future science mission for Europe. Such a mission would search for Type Ia supernovae at low redshift in the optical and near infrared 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.

To investigate the feasibility of this potential future mission the Science Payload & Advanced Concepts Office (SCI-A) at ESA initiated the Wide Field Imager (WFI) Technology Reference Study (TRS). The WFI would have a 2 m class telescope, a 1 square degree field of view imaging camera and a low-resolution integral field spectrometer.

This paper summarizes the results of this ESA internal feasibility study of the WFI. The paper focuses on the spacecraft design and the critical subsystems and provides an overview of required technology development activities for such a mission.

INTRODUCTION

ESA is currently defining its future science programme; Cosmic Vision 2015-2025 [1]. In October 2004, a call for themes in space science was issued. The response from this call identified a Wide Field Optical Near Infrared Imager as a candidate project for

Europe within this program. 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. Based on the interest demonstrated in the call for themes by the scientific community, ESA decided to study such a Wide Field Imager (WFI) as a technology reference study (TRS), with specific emphasis on its scientific payload, including a space telescope, a wide field camera and a spectrometer.

In a TRS a feasible mission concept is established through a proper mission level study. In such studies the critical technologies required to enable potential future missions are identified. This allows a coordinated and consolidated approach for technology developments

SCIENCE

Recent cosmological work shows that the universe's expansion is apparently accelerating rather than decelerating as expected due to gravity. Einstein's General Theory of Relativity requires the existence of a mechanism driving 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.

Supernovae Type Ia (SNe Ia) provide convenient 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. The comparison of SN Ia red-shift and peak brightness (magnitude) provides information on the changing rate of expansion of the universe; the apparent magnitude is a measure of the distance and hence of time back to the supernova explosion, while the red-shift measures the total relative expansion of the universe since that time. The goals of the WFI mission are (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.

WFI measurements will be used to establish a Hubble-diagram plot (red-shift vs. magnitude) with supernova events looking back over a fraction of the age of the universe (Figure 1). By fitting this experimental diagram with models, albeit will be possible 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.

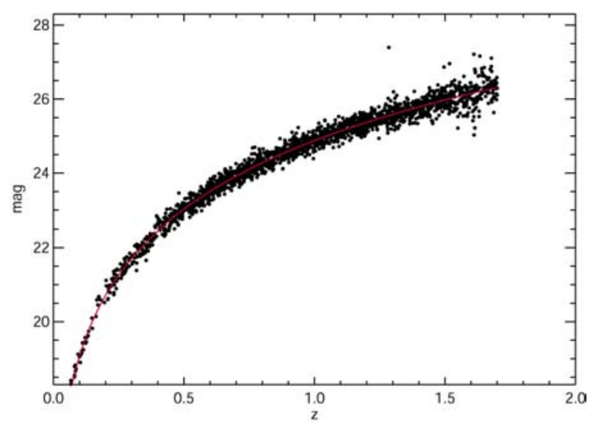

Figure 1 WFI magnitude vs. redshift diagram

In order to accomplish these goals, the WFI reference payload would consist 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 focal plane area (FPA) of the camera 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 (Figure 2). Each step corresponds to 300 arc seconds on the sky and comprises either two or four dither exposures of 1000 seconds, depending on the selected scanning mode. 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 to take into account that performance are limited by the zodiacal background emission in the NIR. In this way, the integration time in the NIR is effectively twice as long as in the visible. A complete sweep takes 144 steps and about 4 days in fast scanning mode (or 8 days in slow scanning mode), including data downlink, provision for telescope slewing, dithering and 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 could 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.

On the basis of this observation strategy 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.

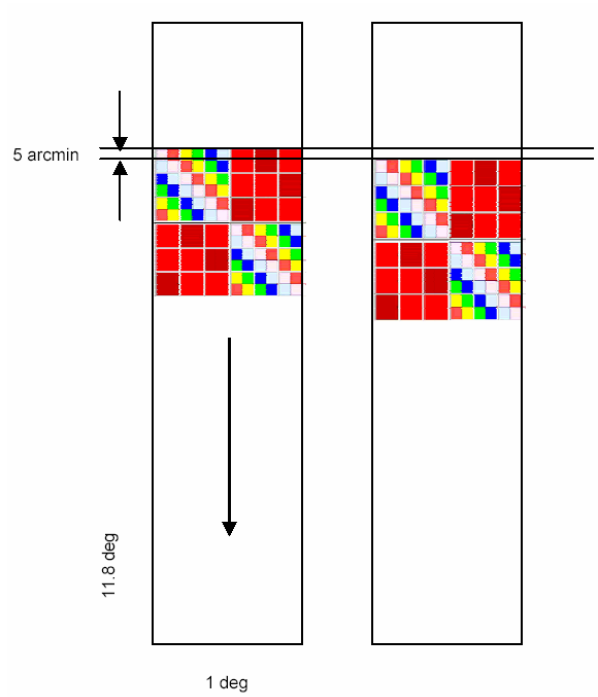

Figure 2 WFI FPA layout and scanning concept

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

- gravitational lenses to trace mass structures in the universe,
- 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.

PAYLOAD DEFINITION

The WFI Telescope design

The science capabilities of the mission depend critically on size of the primary mirror of the WFI telescope. In fact, the combination of the light gathering power of the mirror and of 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; a smaller telescope diameter implies 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 makes best use of the capabilities of the photometric instruments and allows minimizing the exposure times. The wide-field optical photometry will also deliver 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. Dithering allows to improve further performance by improved the sampling.

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 mas
Operation temperature	~290 K

Table 1 Telescope performance requirements

The WFI telescope is based on a three-mirror design with two folding flats (Figure 3) enabling 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 with a 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 20 m is necessary. An important added benefit of the selected design is the location of the focal plane near the outer envelope of the telescope, allowing the focal plane to be placed near a radiator for passive cooling to 140 K. It should be noted that a three-mirror anastigmat (TMA) configuration, developed by Korsch, could provide an alternative solution to the WFI telescope design.

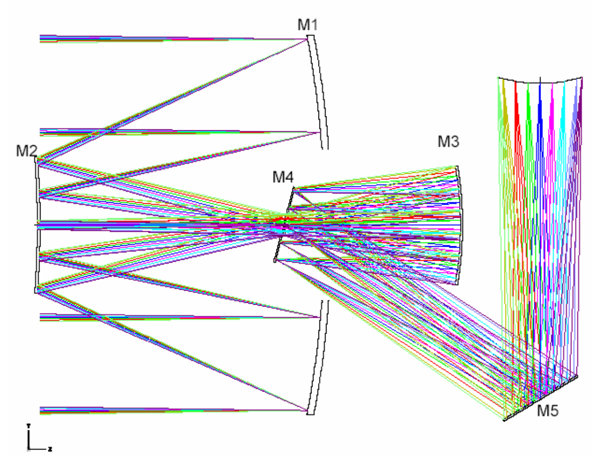

Figure 3 Telescope optical design for WFI

The WFI camera architecture

In addition to the main WFI instruments (wide field camera and the integral field spectrometer), also two highly fault tolerant fine guidance sensors use the throughput of the WFI science telescope, picking-up the light in the outer part of the telescope field of view.

The WFI camera uses two different detector technologies (Table 2). The NIR range (900 nm to 1800 nm) uses 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 use 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 Figure 2.

	Visible detector	NIR detector
Technology	P channel CCDs	HgCdTe
Spectral coverage	300-1000nm	900-1800nm
Array format	2900 x 2900	1450 x 1450
Pixel size	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

Table 2 Detector performance requirements

A typical WFI exposure would last 1000 seconds. After each exposure, the telescope pointing direction is either slewed or offset by a few pixels 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 have to be split again 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.

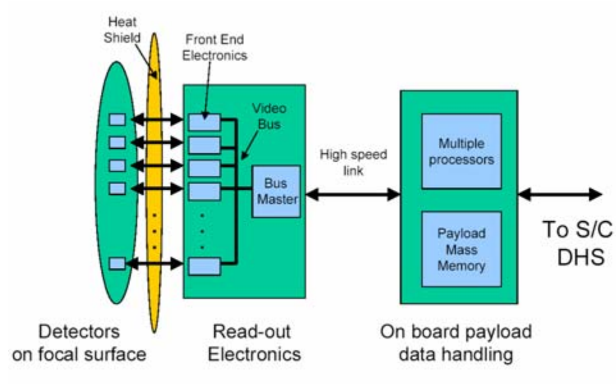

Figure 4 Block-diagram of the WFI camera

WFI SPACECRAFT ARCHITECTURE

To minimize cost WFI should be compatible with a Soyuz-Fregat launch vehicle. The strict constraints that Soyuz has on volume and mass are therefore major design drivers for the overall spacecraft architecture of WFI. A mission summary of WFI is given in Table 3.

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)

Table 3 WFI mission summary

To simplify AIV and AIT it was decided to use a separate service module (SVM) and payload module (PLM). Although this would likely cause some mass and volume increase it is expected to save cost in the overall project.

The PLM houses the instruments and the optics. Two main elements drive the size of the PLM; the telescope structure and the baffle. The telescope structure carries the M1, M3 and

M4 mirror isostatic supports and the tripod interface to the secondary mirror (Figure 5). Due to the mirror's low acceptable tolerances, the mirror support structure need to be very stable. Thus it is envisioned that the structure will use materials such as Silicon Carbide (SiC).

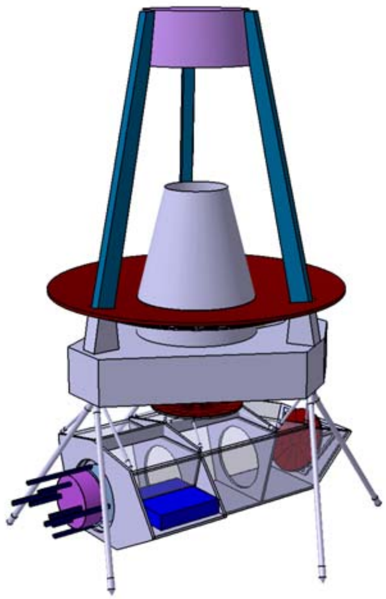

Figure 5 The WFI telescope and instrument

The baffle length required for the selected 2.15 m aperture telescope design can just be accommodated without deployed components. The sun-baffle consists of two main parts; the upper sun-baffle, which is a cylindrical shell, containing a series of vanes against stray-light and the lower sun-baffle that covers the third mirror, the fifth mirror and the focal plane instruments.

The SVM has a hexagonal shape and contains all the spacecraft subsystems. The thick shear panels support the structural interface to the telescope structure at 6 locations while the baffle is connected to the SVM via 12 smaller struts. This effectively decouples the sun baffle from the optical bench of the telescope, which again simplifies the thermal design of the spacecraft. A view of the overall spacecraft is shown in Figure 6.

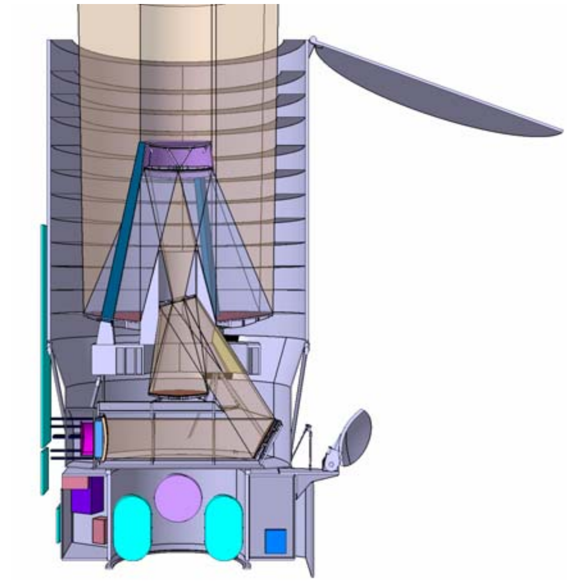

Figure 6 WFI spacecraft configuration

Orbit

Several candidate orbits were investigated for WFI, ranging from LEO to L2 and trailing orbit. The main reason for the selection of the L2 was due to the very high observation efficiency such an orbit would facilitate and the low disturbance environment that the spacecraft would experience. Compared to the trailing orbit the L2 orbit would have the capacity of a much larger data rate, which for WFI is important due to the very large data rate the mission would produce.

Two classes of orbits exist around L2; Halo orbits and Lissajous orbits. The Halo orbit has the advantage of being eclipse free and possible to reach without any significant Delta-V. Lissasjous on the other hand has smaller amplitude, causing the variations in Sun-Spacecraft-Earth angle to be smaller, but would contain eclipses and requires delta-V for orbit insertion. The Halo orbit was selected as baseline for the WFI as the mass in orbit is very critical in the current design.

The Halo orbit is achieved by using a similar transfer strategy to that of the Herschel mission. The spacecraft is launched directly by a Soyuz-Fregat from Kourou towards L2. By using this transfer strategy only minor orbit and launcher dispersion corrections are necessary to obtain the orbit. Once in orbit very little Delta-V is required with a typical value of 2m/s per year. Thus the propellant requirement for transfer and orbit maintenance is very low for the WFI.

AOCS

The resolution of the visible instrument onboard WFI is 0.1 arcsec. Such a resolution leads to strict pointing stability requirements. In fact, the high resolution is the biggest driver for the AOCS. While the Absolute Pointing Error (APE) is derived from the FOV of the spectrometer and is only 1 arcsecond, the Relative Pointing Error (RPE) is derived from the spatial resolution and is 1/10th of the highest resolution. This leads to a pointing stability of 10 mas over 4000 s, where 4000 s is the maximum duration of 1 observation before the spacecraft moves to the next pointing direction.

To measure the very fine movements of the spacecraft a separate fine guidance sensor (FGS) is used. This sensor uses the telescope optics and thus obtains a very good resolution. The current optical layout makes the FGS quite simple to accommodate and it is assumed that no additional focusing optics is needed. The FOV of the FGS is about 3x3 arcsecond, which should be sufficient to obtain one required guide star in the FOV.

Several actuator alternatives were investigated to meet the stringent stability requirements for a 3-axis stabilized spacecraft. Proportional cold gas thrusters would be able to provide the spacecraft with sufficiently low thrust to not exceed the stability requirement. The main drawback for this propulsion system is the low specific impulse that leads to a large amount of propellant. This causes the propulsion system to not only be heavy but also, due to the low density of Nitrogen, have a large overall size. A more attractive candidate might be using FEEPs, which are under development for Lisa Pathfinder. This system would have very high specific impulse, which causes the propellant mass to be negligible. However, the power required for such a system is much larger than for cold gas. Furthermore, because the Lisa Pathfinder requirements are different than those of WFI there will be a need for some technology development. Mini-ion thrusters were also considered for the AOCS, these thrusters would be smaller versions of the current existing ion-thrusters that have already been successfully flown on telecommunication spacecraft. Such thrusters would also have high specific impulse, but compared to FEEPs they may possibly more easily achieve the thrust levels and the total impulse required for WFI. These mini-ion thrusters are under development at ESA, but are also considered to have a low technology maturity.

All the above thrusters would with some technology development meet the WFI specifications. It was therefore decided that the design of WFI should be compatible with any of these thrusters. This implies that in the current WFI design there are extra mass and volume to accommodate cold gas thrusters and surplus power to accommodate the electric propulsion thrusters. Hence, the thruster selection can be done later when the thruster technology is further developed.

Data handling

During a 1000s exposure frame the imagers will generate about 232 Gbits of raw data. This large amount of data needs to be stored and processed by the data handling system. Due to the large data rate and in order to simplify the interface between instrument and spacecraft, a dedicated payload computer is envisioned. This payload computer needs to perform data acquisition of one frame simultaneously with data processing of the previous frame. Thus the payload DHS need to be able to store two complete 1000s data frames. A redundant mass memory unit is needed thus two 465 Gbit mass memory modules are required.

To perform these two main functions requires a processor capable of performing about 1200 MOPS. In spite of these demanding requirements, several options exist for the design of the payload 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.

The SVM DHS will be responsible for storing the compressed science data between downlinks and thus will require large mass memory storage. Including redundancy, the mass memory of the WFI SVM needs to be 2 times 700 Gbit, assuming an onboard storage of 24 hours. Such large memory modules already exist and are expected to be more widely available at the time of WFI. As no processing on the science data will be done by the SVM DHS, the processing power requirement of the SVM DHS can be obtained by using typical processors such as an ERC32 or a LEON2 based processor.

TT&C

The large data rate is driver for the TT&C system. Assuming a daily 4 hour downlink window, the WFI required data rate is 40 Mbps. Such high data rate resulted in the exclusion of an Earth trailing orbit as a viable alternative for WFI because the link distance would be too large at the end of the mission. At L2 the distance remains more or less constant. However, as L2 is closer than 2 million kilometres the WFI mission is not considered to be a Deep Space mission. The large data rate excludes the use of X-band as there is a 10 MHz bandwidth limitation in the part of the X-band allocated to non Deep Space missions. Also, the use of the Ka-band at 32 GHz is not allowed since it is strictly reserved for Deep Space missions. The frequency band that can be used to meet the data rate requirements for WFI is the part of the Ka-band at 26 GHz. This band is not as frequently used and some developments are therefore required, for instance reception of signals in this band is currently not supported by the ESA Deep Space Network (DSN). Hence upgrades of the DSN are required for this mission. The best suitable ground station for such an upgrade is the ground station at Cebreros.

The 4 hour downlink and 26 GHz band results in the need for an antenna size of 0.7 m and a transmit power of about 20 W. For nominal TT&C operations such as telecommand, housekeeping telemetry and navigation, an X-band transponder is used. The X-band up- and downlink make use of the high gain antenna, which also used for the high speed 26 GHz downlink, and two low gain antennas.

Thermal

The telescope structure requires strict temperature control as the optics is very sensitive to any distortions. To simplify the testing of the optical elements the temperature should be as close to room temperature as possible. The focal plane detectors on the other hand need to be kept at about 140 K to achieve proper sensitivity.

To obtain a stable temperature the SVM and the PLM are thermally decoupled. This facilitates a more stable temperature of the PLM. Furthermore, the telescope baffle surrounding the optics is not connected to the telescope structure but rather to the SVM. By using a proper combination of MLI and paint the telescope tube will keep a rather constant temperature, resulting in only minor temperature gradients in the telescope structure and optics temperature of about 290 K.

To keep the focal plane at 140 K WFI uses a large cold radiator located on the same side as the detectors (i.e. the anti-sun side). To cool the read out electronics and other hardware in the PLM, a separate warm radiator is used. With the current thermal approach there is no need for heat pipes or active elements.

Power

WFI requires most power when in imaging mode, in which about 500 W is required. Because the scanning direction of WFI is inertially fixed and the detectors are asymmetric with respect to rotations about 90 degrees, the spacecraft will only rotate every quarter of a year. Additionally, the spacecraft will need to point in a direction that is +/- 20 degrees from the ecliptic poles. These two operational constraints imply a large variation in sun aspect angle during the mission.

Due to the large angles the solar array needs to be as large as 6 m using GaAs. The solar panels are mounted directly on three of the six side panels of the SVM. Such body mounted solar panels avoids any attitude disturbance and thus simplifies the AOCS.

WFI OPERATION

The WFI Observatory would be controlled from a Mission Operations Centre (MOC) set up by ESA/ESOC and 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.

TECHNOLOGY DEVELOPMENTS

Some technology development activities are required to enable WFI. These are mainly payload developments although a few developments within some of the spacecraft sub-systems are also necessary.

The WFI baseline foresees a telescope using mirrors made of SiC because of the achievable low areal density as demonstrated for example by the SiC-mirrors used in the telescopes of Aladin, Herschel and Gaia. Size limitations of the existing manufacturing facilities for both the manufacturing of the bulk SiC and the application of a SiC cladding layer that is needed to achieve a low surface roughness during polishing require technology developments for the WFI primary telescope mirror. Several alternative options can be envisaged: 1) The technology developments could focus on expansion of both facilities to allow the manufacturing of a monolithic mirror. 2) Brazing techniques could be used to join individual SiC-segments to a single mirror as realized with the Herschel primary mirror already. In this case, only the facility for the application of the cladding layer needs to be expanded. 3) Keeping both facilities and focus the development on a high-precision brazing technique for already cladded mirror segments and on polishing of the joint-areas.

The visible camera is baselining use of p-channel CCDs to increase radiation tolerance. Additionally, the detector needs to be deeply depleted to allow for detection at increased wavelengths. Such detectors are not yet available and would need specific developments for the WFI. The near infrared detector would also need to be developed if the instrument is procured from Europe. HgCdTe detectors with sufficient performance and with the right format do already exist in the US and could alternatively be used instead of European developed detector.

For 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.

The payload data handling system need a very powerful processor and although such processors exist, they are not available in Europe. ESA is developing the GINA processor that would provide around 1 GIPS. This technology would be of interest to use for WFI, although non-European alternatives already exist.

The spacecraft needs very high data rate downlink capability and the baseline is to use Ka-band at 26 GHz. As there is limited availability of equipment such as transponders and amplifiers within this band, it is envisioned that developments of such items will be necessary. Furthermore, as the ESA deep space network, doesn't support this band, upgrade of at least one current ground station is needed.

Also within the AOCS there are some development needs such as the Fine Guidance Sensor (FGS) for the fine pointing. The field of view the FGS needs to be sufficiently large and the sensitivity needs to be good enough that there will always be one guide star in the FOV of the FGS. Without a guide star in the field of view the AOCS will not be able to provide the high pointing stability. The ACOS would also benefit from having a propulsion system with a higher specific impulse. The gold gas system implies a large mass penalty over systems such as FEEPs and mini Ion thrusters. Further developments within propulsion systems would therefore help reducing the overall spacecraft mass, which already is close to the maximum launch mass of a Soyuz Fregat.

CONCLUSION

In the internal study a feasible mission concept for WFI have been identified. The baseline mission concept would use a Soyuz Fregat and an orbit around L2 to provide a large number of supernovae images over the three year lifetime. In addition, the WFI could facilitate several other very interesting science objectives.

The spacecraft design utilizes and benefits from current technology developments for other ESA science missions. Furthermore, the WFI would only require a modest number of technology development activities, thereby greatly reducing the development risk of the current WFI concept.

REFERENCES

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