VIRTIS
VISUAL AND INFRARED IMAGING SPECTROMETER FOR THE ROSETTA MISSION

R. Bonsignori[1]; A. Coradini[2]; P. Drossart[3]; G. Arnold[4]
[1] Alenia Difesa - Officine Galileo, Florence, ITALY; [2] CNR-IAS Planetologia, Rome, ITALY;
[3] Observatoire de Paris - Département d'Études Spatiales, Meudon, FRANCE; [4] DLR - Institut für Planetenerkundung, Berlin, GERMANY

Abstract. The VIRTIS instrument has been confirmed as one of the most important experiments for the ESA *Rosetta* mission to the comet P/Wirtanen. VIRTIS is a spectrometer in the visible to mid-infrared spectral range, devoted to spectroscopic measurements and mapping of the nucleus and the coma. It is composed of an imaging spectrometer at moderate resolution - the Mapper optical subsystem or *Virtis-M* - and a high-resolution echelle spectrometer - the High-resolution optical subsystem or *Virtis-H* - complementary to each other. Both optical subsystems are passively cooled to 130 K. The infrared detectors are further cooled to 70 K by means of closed-cycle minicoolers. Virtis-M provides a visible and an infrared data channel using the same optical system, with scan capability. Two covers driven by reversible mechanisms protect the optics of both instruments against contamination. The Optics Module (including both optical heads, the cryocoolers and the proximity electronics) is electrically connected to the Main Electronics Module, which is internally mounted to the spacecraft. This paper describes the Virtis system architecture and main technological issues, relating the instrument performance to the mission and scientific requirements.

INTRODUCTION

VIRTIS is one of the major experiments foreseen for the ESA interplanetary mission *Rosetta*, scheduled for launch in 2003. Main target of the mission is the comet P/Wirtanen, which is orbiting around the Sun with a few years period. The primary mission objective is to characterise as far as possible the various component of the comet, in particular its nucleus and coma, by close-distance observations and in-situ analyses.

The mission includes a total of 8 years of cruise before rendez-vous with the comet, during which the Rosetta spacecraft undergoes three gravity assist swing-by manoeuvres and the close encounter with two asteroids. Rosetta will reach the comet at four astronomical units

(AU) from the Sun, and will follow it until perihelion at about 1 AU. The payload on board the Rosetta *Orbiter* (among which VIRTIS) will perform remote observations, while a *Surface Science Package* will land on the comet nucleus to perform in-situ experiments.

VIRTIS, like all other experiments, is funded by the individual national agencies participating to the team, namely Italy, France and Germany. Scientists from the US and other Nations also contribute.

As far as hardware development is concerned, the Italian company Officine Galileo is the prime, with responsibility for the VIRTIS-M subsystem, structure and thermal control, interfaces, ground support equipment, experiment integration and test. The Observatoire de Paris provides the VIRTIS-H subsystem, while the DLR institute in Berlin is responsible for the main electronics.

VIRTIS REQUIREMENTS

Scientific Objectives

The primary scientific objectives of the VIRTIS during the Rosetta mission are:

- study of the cometary nucleus and its environment
- determination of the nature of the solids in the nucleus surface
- identification of gaseous species
- characterisation of physical conditions of the coma
- evaluation of the nucleus surface temperature.

Secondary objectives include helping with the selection of landing sites and providing support to other instruments. Tertiary objectives include the detection and characterization during fly-by of the asteroids Mimistrobell and Rodari.

The above objectives are achieved by VIRTIS through a combination of the following two kinds of scientific data:

- Hyperspectral maps at moderate resolution;

- High-resolution spectra on small regions not necessarily contiguous.

<u>Operation Concept</u>

The spectral maps are acquired by the *Mapper* optical subsystem (VIRTIS-M), an imaging spectrometer in a broad band from the near-UV to the mid-IR.

Spectroscopy in small regions is provided by the *High-Resolution* optical subsystem (VIRTIS-H), an echelle spectrometer providing a resolving power of 1000 to 2000.

VIRTIS-M is designed for the main purpose of nucleus science (mapping function), with limited capabilities for coma science (moderate resolution). VIRTIS-H is designed for spectroscopy of the coma, with some limited capability in nucleus science (non-contiguous pixels).

In this sense, the two channels (-M and -H) are partially overlapping in their scientific return. Therefore, from a scientific point of view, the accidental loss of one of the two channels would not determine a complete failure of the mission but only a (major) degradation. In view of this, it has been chosen to avoid any redundancy in the -M and -H optical heads and to duplicate - in cold redundancy - only the common electronics (instrument control, data handling and power supply).

The VIRTIS operation is programmable in such a way that the scientific return can be maximised versus the available data rate with a great flexibility, depending on the (largely unknown) characteristics of the comet. In the “default mode” VIRTIS-M provides a general-purpose mapping at moderate spectral and spatial resolution with the widest swath possible, along with high-resolution spectroscopy of the central region by VIRTIS-H. Besides that, high spectral and/or spatial resolution modes are implemented along with spectral and spatial editing (selection of spectral regions or narrower swath) for detailed observation of selected sites or features.

In the “pushbroom” mode the map is obtained by exploiting the spacecraft relative velocity, while in the “scan” mode the primary mirror is rotated in order to form the image even while the spacecraft is fixed with respect to the comet.

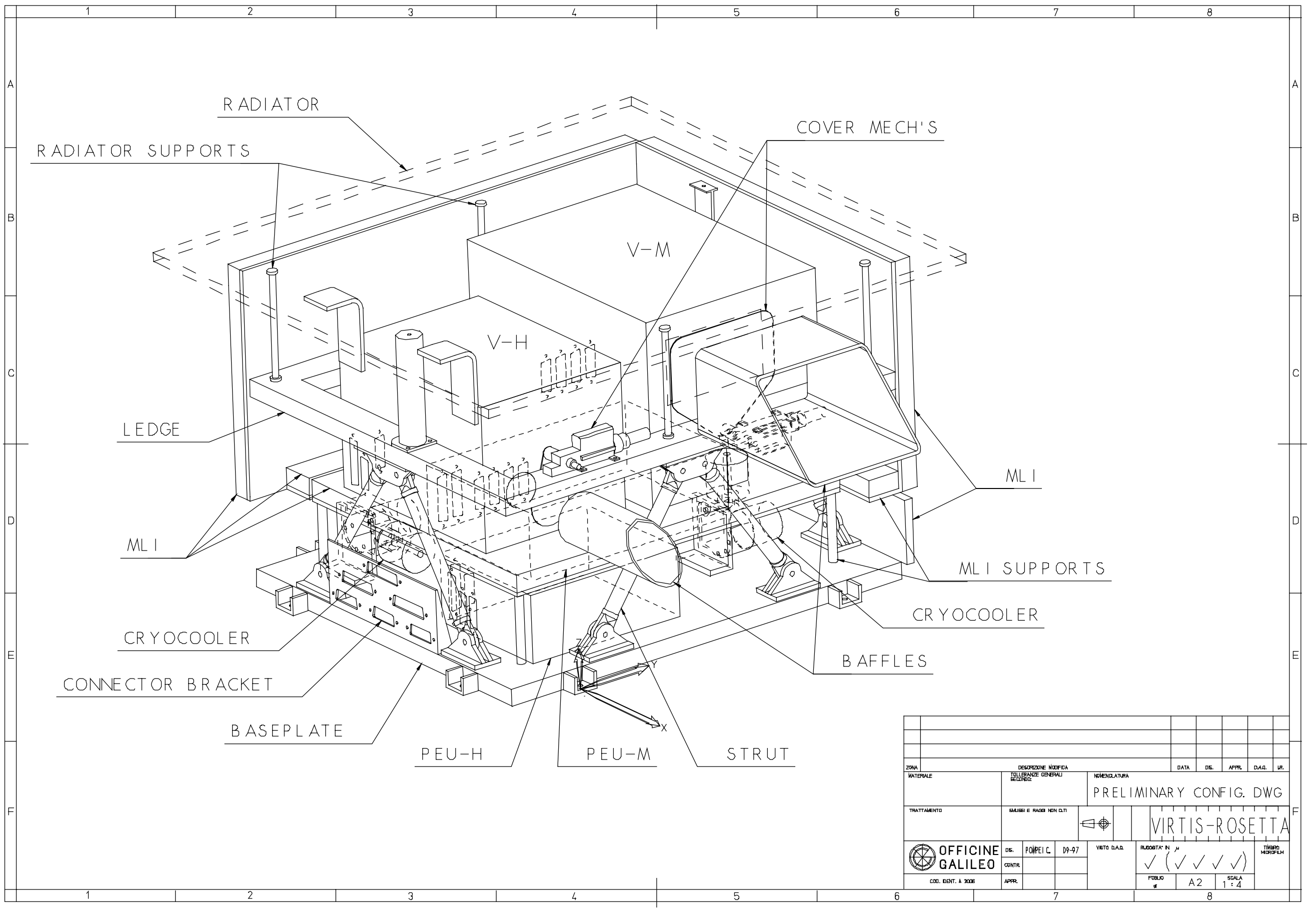

Fig 1 - VIRTIS Optics Module overall configuration

Performance Requirements

VIRTIS has to maesure very low radiation fluxes, since the Sun irradiance is >9 times smaller than on Earth, the comet nucleus is very dark and the radiation is resolved in spectrum. Therefore, the integration time both for Virtis-M and -H has to be of the order of seconds. Both infrared focal planes have to be cooled down to 70 K, while the thermal background coming from the instrument internal walls has to be kept low by cooling at 130 K.

The imaging channel VIRTIS-M is required to provide a minimum signal to noise ratio (SNR) of 100 in both spectral ranges, 0.25 - 1.0 μm and 1-5 μm at the nominal sampling under the measurement baseline conditions relative to the *mapping and close observation* phase, which is considered as the design driver for VIRTIS-M.

The high-resolution channel VIRTIS-H is required to perform high resolution spectroscopy in the spectral range between 2 and 5 μm. The above mentioned scientific requirements imply for VIRTIS-H to provide a SNR better than 100 and a minimum resolving power of 1000 to resolve molecular bands. VIRTIS-H design is driven by the requirements in both the mapping phase and the coma observation phase, that lasts until the comet is escorted to its perihelion.

In Tab. 1 are reported the general top-level instrument requirements for VIRTIS.

REQUIREMENT	**VIRTIS -M VIS**	**VIRTIS-M IR**	**VIRTIS - H**
Spectral Range	0.25 - 1.0 μm	0.95 - 5.0 μm	2.0-5.0 μm
Spectral Resolution	6 nm (default) 2 nm (high resol.)	30 nm (default) 10 nm (high resol.)	1 - 2.5 nm ($\lambda/\Delta\lambda$ = 1000÷3000)
Spectral Calibration	0.6 nm	3 nm	< ½ pixel
Field of View - pushbroom mode (mrad) - scan mode	64 * 0.25 64 * 64	64 * 0.25 64 * 64	0.45 * 2.25 -
Spatial Resolution (mrad)	1.0 (default) 0.25 (high resol.)	1.0 (default) 0.25 (high resol.)	1.0
Radiometric Resolution (SNR) at typical albedo = 4%	> 100	> 100	> 100
Radiometric Calibration - absolute - relative	< 20 % < 1 %	< 20% < 1 %	< 20 % < 1 %

Tab. 1 - VIRTIS Instrument Requirements

INSTRUMENT CONFIGURATION

Both the Virtis-M and -H optical heads are housed in a common structure - the *Cold Box* - kept cooled at 130 K by means of a radiative surface, sustained by a truss having low thermal conductivity. On the *Pallet* supporting the truss are housed the two proximity electronics and the cryogenic coolers necessary to cool the infrared detector to the required temperature of 70 K. The pallet with the cold box form a compact structure called the *Optics Module*, that is mounted on the spacecraft (see Fig. 1).

The *Electronics Module*, containing the digital electronics and the power supply, is mounted in the interior of the spacecraft and connected by cables. An overall block diagram of the instrument is reported in Fig. 2.

The **-M** optical concept is inherited from the visible channel of the Cassini Visible Infrared Mapping Spectrometer (VIMS-V) developed by Officine Galileo. This concept matches a Shafer telescope to an Offner grating spectrometer to disperse a line image across two FPAs.

The **-H**, with a quite different function, uses a cross dispersing prism and a flat diffraction grating to lay several high resolution orders across a FPA.

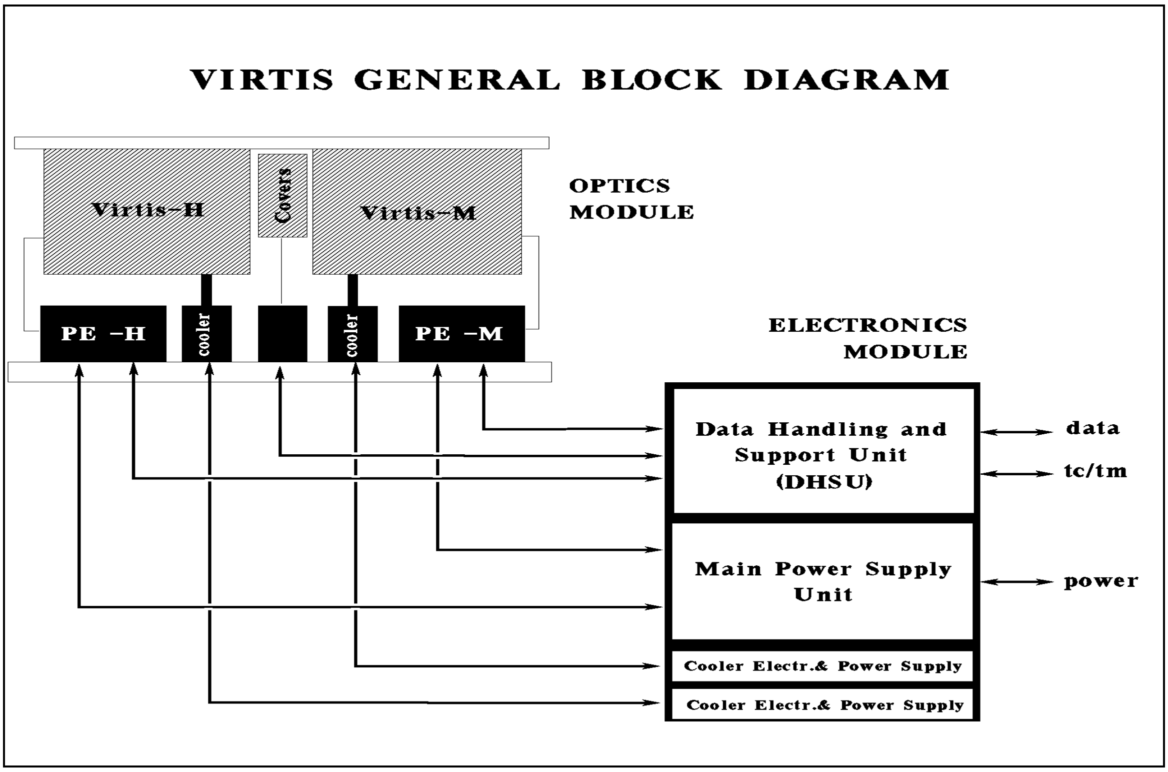

Fig. 2 - VIRTIS general block diagram

The **-M** and **-H** optical subsystems are housed inside the Cold Box of the Optics Module. The Optics Module is externally mounted to the -Y surface of the spacecraft with the **-M** and **-H** co-aligned and boresighted in the positive X direction. Both optical systems have their slits parallel to the Y axis; the **-M** has the ability to point and scan along the Z axis. The Optics Module is electrically connected to the Electronics Module, which is internally mounted to the spacecraft.

VIRTIS -M description

The VIRTIS-M optical system is a Shafer telescope matched through a slit to an Offner grating spectrometer. The Shafer consists of 5 aluminum mirrors mounted on an aluminum optical bench. The primary mirror is a scanning mirror driven by a torque motor.

	VIRTIS-M	VIRTIS-H
Pupil diameter (mm)	50	36
Imaging F/#	5.8 Vis and 3.2 IR	1.67
Etendue (m^2-sr)	$3.7x10^{-11}$ Vis $8.6x10^{-11}$ IR	10^{-9}
Slit dimension (µm)	40 x 10	28 x 142
MTF @ Nyquist (1 mrad).	50 %	N.A.
FWHM (LSF*slit*pixel)	< 60 µm	< 40 µm
Infield stray light	< 5 %	< 5 %
Out of field stray light	< 0.1 %	< 0.1 %

Tab. 2 - Optics Specifications

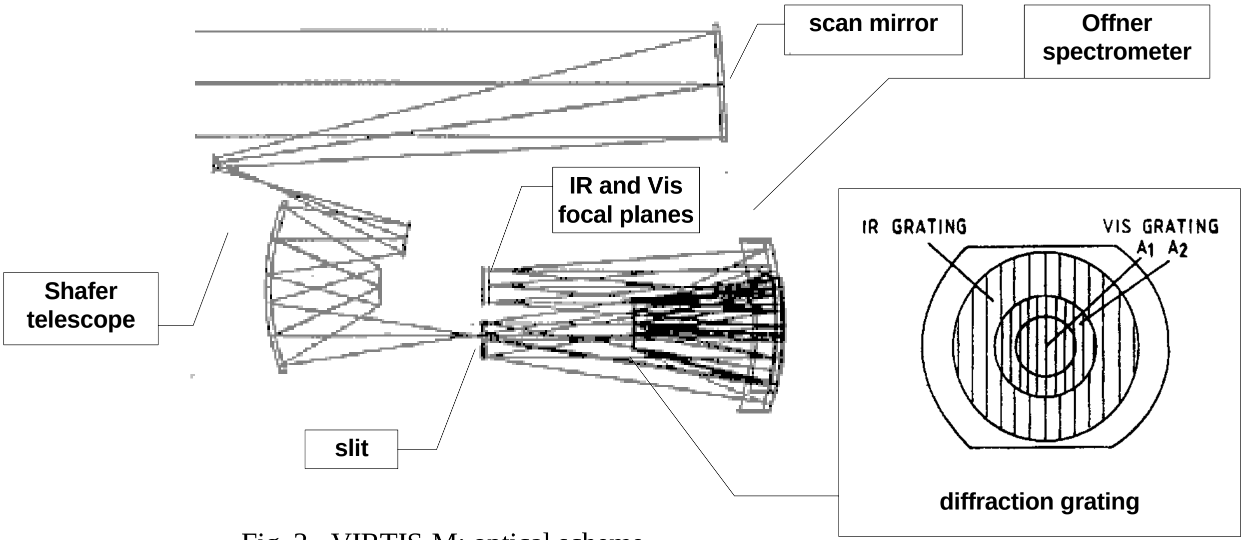

Fig. 3 - VIRTIS-M: optical scheme

The bench is machined from a single aluminum alloy billet and acts as a cold plate and optical support structure that mounts onto the ledge of the Cold Box.
The internal -M box that covers the optics is made of very thin walled aluminum and has no structural support function.
The Offner spectrometer consists of a mirror and a spherical convex diffraction grating housed in an aluminum tube that is flange mounted to the telescope.
The diffraction grating and relay mirror are made of glass. The grating and relays are fixed in place while the slit and FPAs can be rotated for slit-groove-column alignment. The FPAs are also axially adjusted to a tight tolerance. Once the telescope and spectrometer are in independent alignment, the spectrometer is mounted and aligned to the telescope.
The IRFPA is operated at nominally 70 K by means of a Stirling cycle cooler. The cold tip of the cooler is connected to the FPA by copper thermal straps. The CCD is operated at 155 K and mounted directly on the spectrometer.

VIRTIS-H description
The High resolution channel (VIRTIS-H, see Fig. 4) is an echelle spectrometer composed of two off-axis parabolas, a cross-dispersion prism, a reflection grating, and a focusing objective.

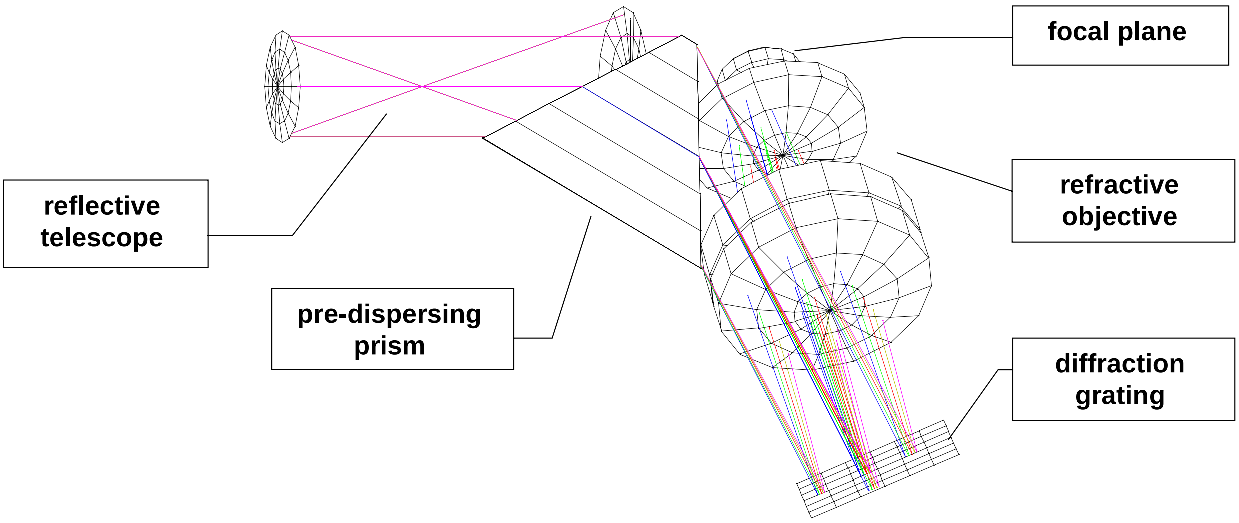

Fig. 4 - VIRTIS-H: Optical scheme

All of these subassemblies are mounted on the optical bench via fixed supports except for the grating subassembly which will be adjusted.
In the -H the light is collected by an off-axis parabola and then collimated by another off-axis parabola before entering a cross-dispersing prism. After exiting the prism the light is diffracted by a flat reflection grating which disperses in a direction perpendicular to the prism dispersion. The low groove density grating is the echelle element of the spectrometer and achieves very high spectral resolution by separating orders 7 through 16 across a two-dimensional detector array. The spectral resolution varies in each order between 1200 and 3000.
Since the -H is not an imaging channel, it is only required to achieve good optical performance at the zero field position. This allows the telescope and collimator to operate with short focal lengths for a considerable reduction in volume and mass. A further reduction in volume is made by using the negative diffraction orders and allowing the objective to be folded behind the primary mirror and form a rigid triangular structure.
The telescope is F/1.6 and the objective is F/1.67 and requires five pixels to be summed in the spatial direction to achieve a 10^{-6} steradian IFOV.

Optical Filters and Background Radiation

To minimize the effects of background radiation emitted in the form of photons with wavelengths longer than 4 µm, both IRFPAs will be protected by spectral blocking filters with cut-off wavelengths at 5.1 mm. The -M also requires the typical long pass filters to block higher orders, but it has the additional problem of caring for the negative IR orders that fall on the CCD and the positive visible orders that fall on the IRFPA.
The CdTe of the IRFPA naturally blocks the visible wavelengths shorter than .8 mm, but the silicon of the CCD is sensitive to the higher orders of the IR portion of the grating. Fortunately the predicted efficiencies of the higher orders are less than 2% and do not affect the measurement. Since the 4 to 5 µm background radiation cannot be filtered within the same spectral band in which the data are collected, the spectrometers must be cooled to below 130-135 K.
Multi-segment filters will then be necessary on the VIS and both IR focal planes. The possibility of a linear variable filter for improved thermal background reduction is also being investigated.

Contamination and Stray Light

Contamination from the comet is unavoidable. VIRTIS therefore plans to deploy covers across the entrance ports to minimize contamination when scientific data is not being gathered. De-icing heaters will be mounted at the base of the entrance baffle where the cover seals the port and on the primary mirror. Heaters will also be mounted near the FPAs for post-launch outgassing. A soft material, as for the GIOTTO mission, can be used on the primary mirrors to allow high speed particles to pass through the mirrors without damaging the surfaces.
Other than these measures, the most effective defense is to use intelligent optical design methods. Off-axis reimaging systems, such as that contained in Virtis-M telescope, are optimum for stray light suppression, because they do not have obscurations that diffract out-of-field stray light into the FOV, and the forward field stop reduces the number of optical surfaces that are illuminated by stray light.

TECHNOLOGICAL ISSUES

Infrared Detectors

The baseline for both the -H and -M IRFPAs are hybrid two-dimensional arrays of IR sensitive photovoltaic Mercury Cadmium Telluride elements interconnected to silicon CMOS multiplexers.
The growth technique for the CdHgTe crystal is vital for high performance FPAs because structural defects in the material result in defective photodiodes. Therefore the preferred material growth technique for producing the best material, in terms of crystalline quality, electrical uniformity and reproducibility, is the Liquid or Molecular Epitaxy Process.
These devices have the potential to operate at a higher temperature than the more established indium antimonide (InSb) detectors due to dark current reduction by a factor of 10 or more.
Survival of temperature cycling, mechanical shock and high temperature storage are other critical aspects to be considered together with manufacturer space programs experience.
The -H and -M detectors have the same 5.1 µm cut-off wavelength, snapshot [before integration and after readout] operating mode and the specifications contained in Tab. 3.
Currently, there are at least two companies which offer HgCdTe devices with different approach in getting low dark currents - Rockwell (USA) and GEC-Marconi (UK). The lowest achievable dark current is determined by the cut-off wavelength and the area of the junction. However this limit is not yet achieved due to internal leakage currents in the diode structure, caused by crystal defects.

However, fabricating large high performance FPAs often requires that the active material be grown on alternative substrates and hence the need of appropriate device packaging to mitigate thermal expansion mismatch between the substrate material (e.g. sapphire) and the silicon multiplexer.
The Rockwell technology uses epitaxial growth of HgCdTe on a layer of CdTe on a sapphire substrate. Indium bumps connect the individual detectors to the underlying silicon multiplexer elements.
The GEC-Marconi loophole process produces thin dies of HgCdTe bonded rigidly to the silicon multiplexer so that strain due to thermal mismatch is taken up elastically.
The unit cell can be designed either to maximise the full well capacity or to reduce the readout noise using customised detector interface schemes [direct injection, buffered direct injection, capacitive transimpedance amplification, etc]. The process of finding the best compromise between capacity, noise and linearity at low fluxes is not an easy task and implies an iteration with scientific requirements in order to “tailor” the detector to the specific needs of the mission.

VIRTIS IR Detector Specifications (-M and -H)	
Material	HgCdTe
Multiplexer type	CMOS
Sensitive Area Format	341 x 550
Pixel Pitch	30 x 30 μm
Spectral band	1 to 5 μm
Operative temperature range	70 to 90 K
Full Well	$2 \cdot 10^6$ el.
Noise (rms)	300 el.
Power Dissipation	60 mW
Fill Factor	90%
Cross-Talk	3%
Dark Current at 80 K	20 fA
DSNU	± 10 fA
PRNU	± 10%
Quantum Efficiency	60%
Linearity	2%
Defective pixels DSNU >30 fA, PRNU <-10%	≤ 4%
Radiation tolerance	10 Krads

Tab. 3 - IR Detector Requirements

The possibility to use already developed [off the shelf] detectors, for cost/time saving and risk reduction, is being deeply investigated by tailoring the above listed requirements, the front-end electronics and the instrument operative modes to their characteristics. New detector designs will be however addressed to stretch current design to give the right pixel pitch and area format whilst maintaining basic unit cell characteristics.
Cost implications are envisaged for both detectors due to the large area of HgCdTe required, the limited number of chips produced for each detector wafer and the low defects percentage required for astronomy and spectroscopy imaging IRFPAs.

Visible detector

The baseline for the visible FPA is a frame transfer NMOS buried channel CCD with improved sensitivity in UV wavelengths.
To enhance sensitivity in the UV, thinned, backside illuminated CCD technology seems to be hardly viable. The better established front-side illumination technique with an UV coating seems to be the best choice. The UV coating emits light at approximately 540 to 580 nm when excited with light of wevelengths shorter than 450 nm and is quite transparent in the visible and near IR, not significantly affecting quantum efficiency.
The specifications of the visible FPA are reported in Tab. 4.

VIRTIS-M VIS Detector Specifications	
Material	Si
Readout technique	CCD frame transfer
Pixel pitch	20 μm
Format	512 x 824
Temperature range	135K to 155K
Full Well	10^6 el.
Noise (rms)	20 el. with CDS
Linearity	± 2 %
DSNU	± 100 % pk-pk
PRNU	± 5 % pk-pk
Fill factor	> 90 %
Charge Transfer Efficiency	0.99 at 155K
Radiation tolerance	10 Krads

Tab. 4 - Visible Detector Requirements

Effects on charge transfer efficiency due to radiation induced dark current spikes and residual bulk image are minimised when operating at very low temperatures. The challenge is to keep the CCD temperature as close as possible to the cold box (135 K) but preventing degradation of the charge transfer

efficiency due to buried channel freeze-out and bulk traps characteristics. Dedicated x-rays test will be executed to determine the operative temperature, clock overlaps, clock rate, charge pocket size and silicon quality to fulfil vertical and horizontal CTE requirement.
An alternative solution for the visible imager would be the use of radiation hardened CMOS photodiode or photogate (APS, CTIA or similar), the silicon based version of the IRFPA. This approach does not present charge transfer concern and would allow to realise a common encapsulation in which the infrared and visible detectors are working at the same operative temperature. However, no information is available on the use of CMOS visible imager in space programs. Although this technology seems to be sufficiently mature for space application, the conservative approach of CCD based technology gives more confidence from technical and qualification points of view.

Active Cryogenic System

For both IR focal plane assemblies an operating temperature of 70 K or lower is required, with a thermal load of the order of hundreds of milliwatts. Such a temperature and thermal load are judged as not achievable by direct irradiation to the cold space (passive radiator concept).
In view of the general mission characteristics, therefore, the only solution that remains is an active refrigerator system based on a closed thermodynamical cycle.

RICOR K508	
ON/OFF operation (No)	>2000
Operating life (h)	>8000
Cooling power (mW)	500@ 77K
Input power (W)	14
Induced vibration (N rms)	0.1
Mass (kg)	0.45
Volume (mm^3)	71x60x110
Operating temperature (°C)	-40 - +72
Non-operating temperature (°C)	-56 - +85

Table 5 - RICOR cryocooler characteristics

Many space infrared systems overcome the problem using space-qualified Stirling cycle engines. However, the mass and power consumption of such devices is considerably high, especially if we consider an interplanetary mission where spacecraft resources are limited.

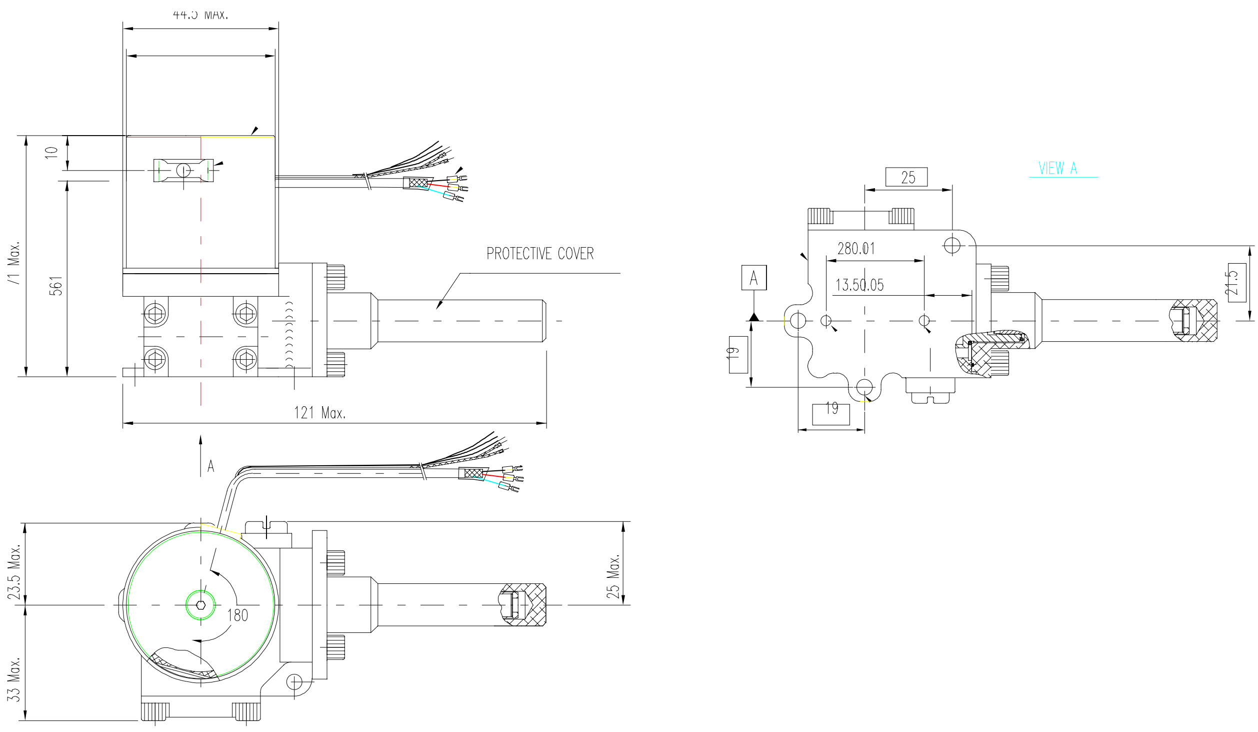

Fig. 5 - RICOR K508 cryocooler - overall view

The small mass, volume and power available on the mission, along with the relatively short active operation requirements (only about 2000 hours, but after 8 years of cruise in "hybernation"), and considerations of cost saving, have led to the choice of "tactical" miniaturised coolers.

Such devices are produced in series by several companies in the world for defense applications. After an extensive evaluation on the coolers available on the market, the preliminary choice has been the K508 by the Israelian company RICOR. By the way, a quite similar type (K506) has been successfully flown on the US lunar mission *Clementine*. In Table 5 the main characteristics are summarised. An external view is shown in the figure. The real possibility of using those refrigerators for VIRTIS is subject to the successful completion of a test campaign, including functional, environmental and life tests on four K508 models, besides a thorough analysis of design and test data provided by the manufacturer.

Diffraction Grating

The VIRTIS diffraction grating (Fig.3), designed by Carl Zeiss Oberkochen and based on the heritage of VIMS-V[1] for the Cassini mission, is holographically recorded on a convex surface in a Rowland circle configuration. The central circular region and the intermediate annular region are used for the visible channel, the outer annular region for the infrared. The two visible regions have a laminar construction with a rectangular groove profile, with two different groove depths, in order to optimise the overall instrument efficiency versus wavelength. The infrared region has a blazed groove profile, its blaze angle changing through the surface.

The spectral dispersion is different in the Vis ans IR regions in order to match the requirements for the two focal planes. Thanks to the pupil position of the grating, the two channels have the same FOV, free of vignetting.

In order to achieve the spatial separation of the IR and VIS focal planes, the VIS path uses the +1 diffraction order of the two central regions, while the IR uses the -1 order, for which the blaze angle of the outer region is optimised.

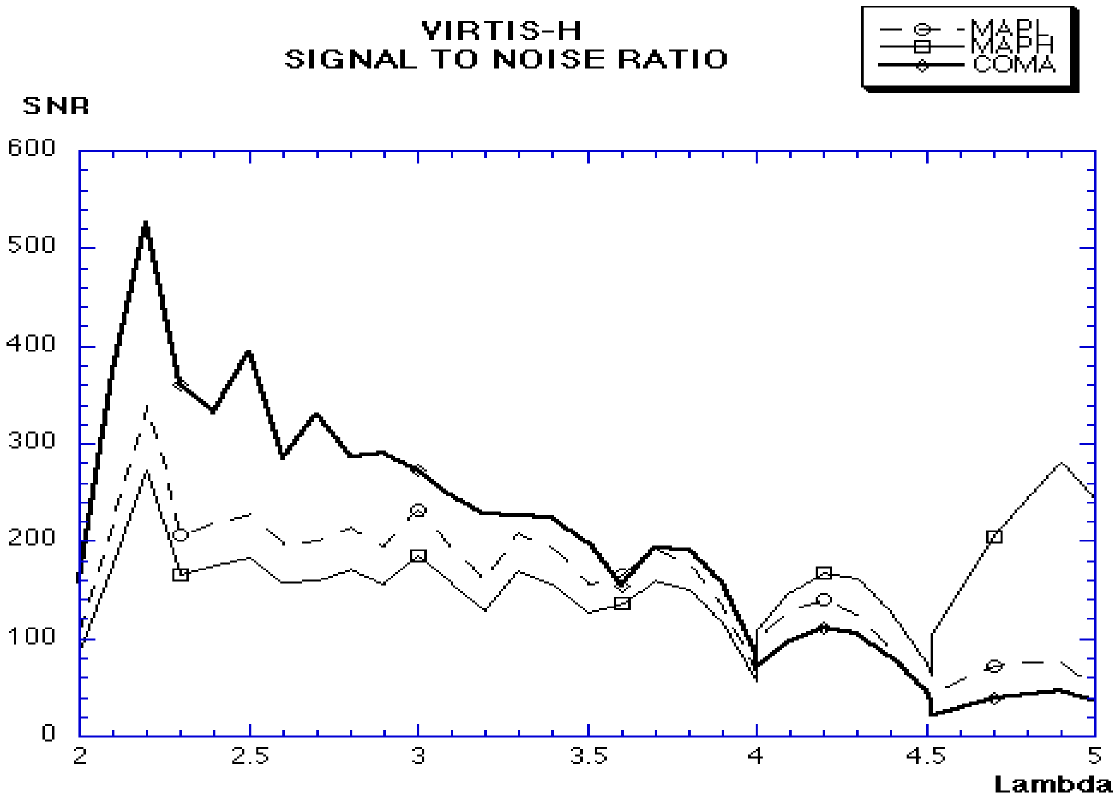

Fig. 6 - VIRTIS-H predicted SNR for observation of the coma (dwell time 60 sec) and the nucleus (dwell time 1 and 10 sec)

INSTRUMENT PERFORMANCE

In this chapter a summary of the results of the radiometric calculations is given, in order for the reader to have an idea of the instrument sensitivity.
The parameters used for the calculation are in most cases still preliminary and based only on analysis and design. In particular, the IR detector data are subject to change depending on theichoice of manufacturer.
Only some examples are included here, referring to the most important phases of the mission, namely:

- Comet nucleus mapping, in the 2-months “Mapping and Close Observation” phase after the rendez-vous manoeuvres, while Rosetta is nominally at 3.25 AU from the Sun;
- Coma observation, during the “Escort to Perihelion” phase, lasting almost two years and ending at 1.05 AU, i.e. near the Earth orbit.

The -H charts (Figs. 6 and 7) the signal to noise ratio in different conditions and the spectral resolving power $\lambda/2\Delta\lambda$ are given.

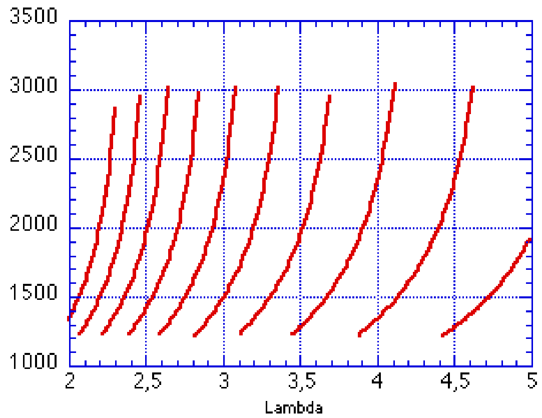

Fig. 7 - VIRTIS-H resolving power in the diffraction orders 7 to 16 as a function of wavelength

For -M only the simulations for the IR channel are shown. The four charts in Fig. 9 describe, respectively:

- SNR at 3.25 AU for 1 sec integration time (the allowed dwell time per pixel is 20 seconds) for elementary pixels (high resolution mode) and composite pixels (default mode)
- Noise budget in electrons r.m.s. on each pixel
- Noise equivalent spectral radiance for typical expected albedo conditions, against the requirement
- Electrons budget on the single pixel for typical and maximum albedo, showing the dynamic range and the saturation level

In the chart in Fig. 8 the capability of mapping the surface temperature by VIRTIS-M in the long wavelength region (4-5 µm) is shown, in terms of noise equivalent temperature as a function of the temperature of the nucleus in Kelvin, for different integration times. The choice of integration time is done phase by phase, according to the maximum foreseen photon flux, which must not saturate the pixels.

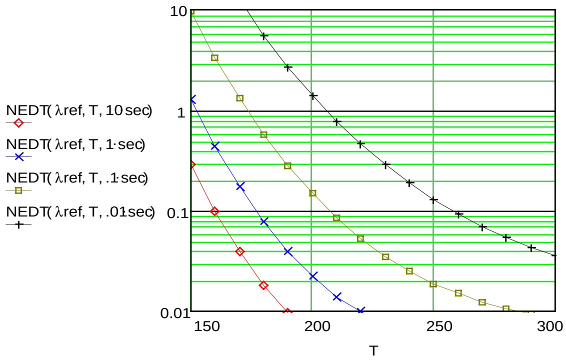

Fig. 8 - Thermal mapping by VIRTIS-M: predicted sensitivity versus comet nucleus temperature and integration time

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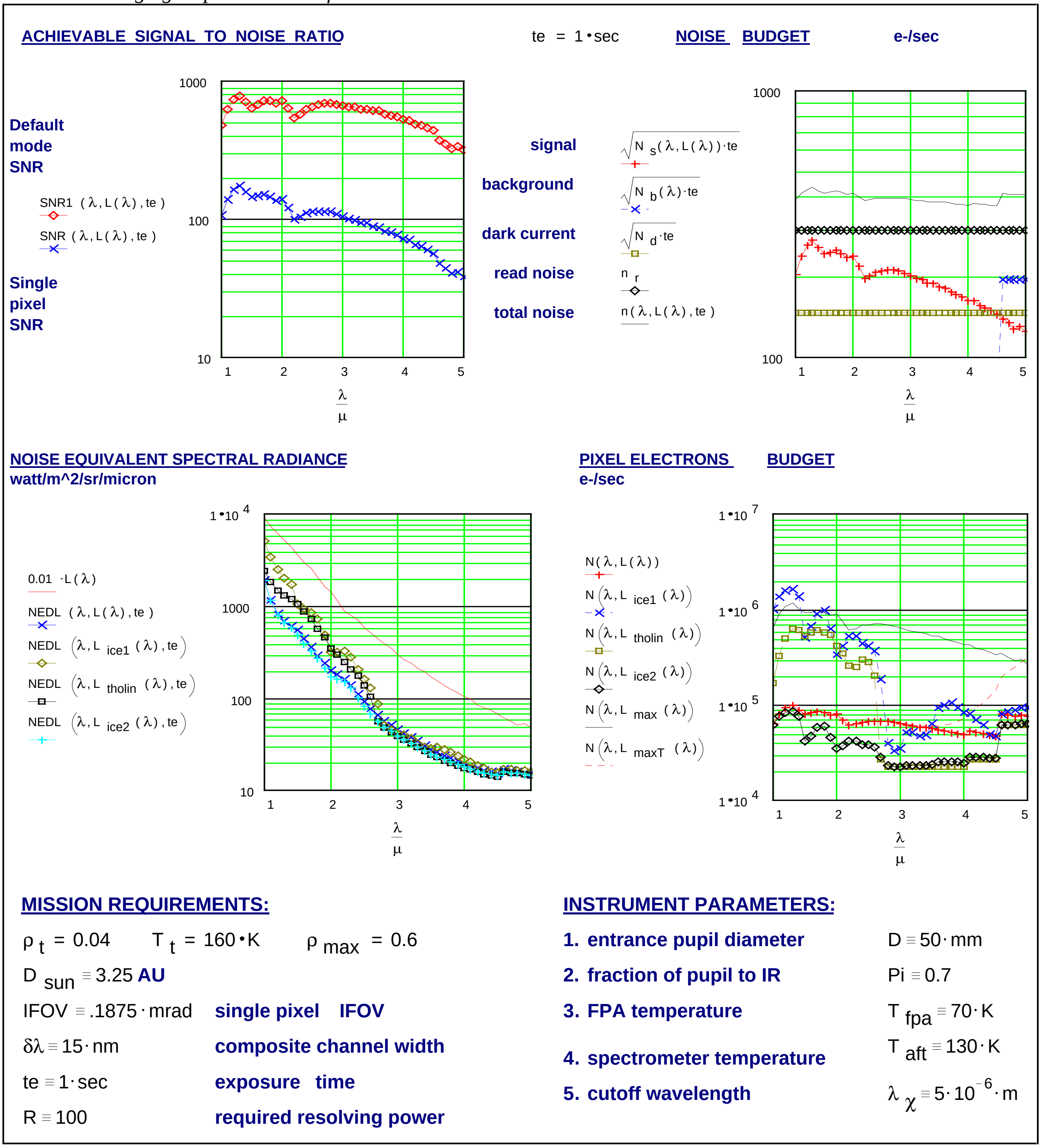

Fig. 9 - VIRTIS-M IR channel predicted performance (at 3.25 AU) - The upper charts (SNR and noise budget) are referred to the comet nucleus as a dark, grey body with albedo 4%; the lower charts consider also the maximum expected albedo (60%) and typical spectra of materials (ice, tholin)