S-Cam: A Technology Demonstrator for the Astronomy of the Future

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S-Cam is a cryogenic camera developed within the Astrophysics Division of ESA Space Science Department. The camera has been designed as a technology demonstrator, aiming to prove the potential of a new generation of single-photon counting detectors based on Superconducting Tunnel Junctions (STJs). This article provides an overview of the cryogenic detector development, a description of the S-Cam system and a summary of the results obtained both during testing at ESTEC and during actual observations at the William Herschel Telescope in La Palma (Canary Islands, Spain). Initial observations were performed on the Crab pulsar, a neutron star about 10 km in diameter and about 6000 light years from Earth, with a weight equal to that of our Sun and spinning with a period of 33 msec.

Introduction

Modern astrophysics is concentrating on phenomena that only a few years ago were inaccessible. The confirmation of various astrophysical models implies higher and higher precision, thereby requiring more sensitive and accurate instrumentation. Examples of this trend in space are represented by the mapping of the star population of our galaxy with extremely high positional accuracy (Hipparcos and GAIA) or by ever more detailed analysis of the isotropy of the Cosmic Background Radiation (COBE and Planck). Such efforts are being made in all portions of the electromagnetic spectrum, from submillimetre waves to X-rays, covering a photon energy range which varies from meV (at wavelengths of order 1 mm) to several tens of keV (at wavelengths of order 1 angstrom), c.f. XMM.

At all wavelengths covered by astronomical observations, the overall scientific performance is determined by two main factors: the telescope collecting area, which determines the signal that can be detected in a given time, and the detailed properties of the associated detectors placed at the telescope's focus. Photon detectors play a central role, representing the main diagnostic possibility available to astrophysics, and in the end determining the ability to achieve ever more ambitious scientific goals.

The possibility of detecting individual optical photons has been available for a number of years (exploited, for example, by ESA's Faint Object Camera on the HST), but only with low detection efficiency and no wavelength information. Within the Astrophysics Division at ESTEC, we have exploited the physical phenomenon of superconductivity to propose and develop the most advanced optical detection system, allowing individual optical photon counting at high event rates, with very high efficiency across the ultraviolet (UV) to infrared (IR) range, and very low noise. Most importantly, this work has led to the first optical detector that can determine, intrinsically and without the use of dispersive elements or filters, the energy of each individual photon.

While several detector technologies allow single-photon counting at higher energy (UV and X-ray), in the recent past only detectors such as photomultiplier tubes could do the same at lower energies, in the extreme ultraviolet (EUV), visible and near-IR (NIR) range. More recently, cryogenic detectors, such as superconducting tunnel junctions and bolometers operating at temperatures below 1 K, have allowed a drastic performance improvement, with very high responsivities, excellent energy linearity and large count-rate capabilities. As a result of the strong responsivity (as high as 10^4 e^-/eV for Superconducting Tunnel Junctions, or STJs), it is possible to count single photons at wavelengths up to a few microns (NIR). By operating the sensors in photoconductive mode (i.e. collecting the electric charge induced in the detector electrodes by the photo-absorption event), it is possible to measure the energy (i.e. the wavelength) of the detected photons. The resolving power ($E/\Delta E = \lambda/\Delta\lambda$) is of order 10 –100, depending on the intrinsic detector characteristics. The fast response time allows for high count rates and for the capability to associate a well-defined time of arrival to each detected event.

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Once the fabrication technology is mature enough, it will be possible to produce larger arrays based on such individual elements (pixels), providing the possibility to record an image at the focal plane of dedicated optics. In such a configuration, we have an instrument defined as an ‘imaging spectrometer’, i.e. a camera that can provide two-dimensional images in addition to spectroscopic information on the detected photons. An important aspect that needs to be highlighted is the fact that these detectors provide spectroscopic information without the need for any additional device in the optical path, operating in a non-dispersive mode, i.e. with the highest possible photon detection efficiency.

Space-based observatories operating over a wide wavelength band provide an ideal platform to fully exploit the capabilities of this new generation of photon detectors. This is due to the absence of any filtering induced by the Earth’s atmosphere and by the reduced thermal background radiation present in space when looking at faint objects such as stars and distant galaxies.

The recent advances made by cryogenics have drastically simplified the installation of cryogenic equipment on board spacecraft, as clearly demonstrated by the success of ISO (the Infrared Space Observatory) and by several other missions presently being developed (such as FIRST and Planck) or under study (such as XEUS). In order to simplify the future integration of cryogenic instrumentation on board spacecraft, a number of research and development activities have been undertaken by the Astrophysics Division in collaboration with the Directorate of Technical and Operational Support. These include a series of technical developments in the area of mechanical coolers, ^{3}He sorption coolers, Adiabatic Demagnetisation Refrigerators and related cryogenic wiring. In parallel, another series of activities are dedicated to the development of suitable IR filters, allowing high throughput in the visible and EUV and high suppression of any residual thermal radiation.

The development of this first ground-based camera has proved extremely important in identifying the critical aspects of a future space-based cryogenic instrument and in highlighting the operational constraints deriving from its use for astronomical observations. With this goal in mind, S-Cam has been designed as a technological demonstrator for operations at the William Herschel Telescope, in La Palma, Canary Islands (Spain).

The Astrophysics Division has been involved in the development of STJ-based detectors for about a decade, within an R&D programme that has produced world-class devices with excellent spectroscopic performance, from the X-ray to the NIR. The detectors have been manufactured under ESA contract by Oxford Instruments (UK) and operate at a temperature of about 300 mK. The detectors are fabricated according to ESA requirements and are tested in the laboratories of the Astrophysics Division. The latter’s interest in this activity is mainly related to the potential scientific exploitation of these devices and to their utilisation on board future astrophysics missions.

STJ detector development

The development of STJs as photon detectors within the Astrophysics Division started with niobium-based devices, operated as X-ray detectors at a temperature of about 1.2 K. More recently Nb-Al and tantalum-based devices have been optimised for the detection of visible photons, with an operating temperature of about 0.3 K. Such devices have a square geometry, with typical dimensions of order 20-50 µm; they are based on multilayer structures (e.g. Nb-Al-AlOx-Al-Nb), with two superconducting electrodes separated by a very thin oxide layer. The thickness of the electrodes is typically some 100 nm, while the barrier is only 1 nm thick. To achieve the best detector performance, it is necessary to fabricate high-quality devices characterised by a highly uniform isolating barrier and by crystalline thin-film electrodes. Such devices have achieved resolving powers ($E/\Delta E$) exceeding 100 at soft X-ray energies and of order 10 at visible wavelengths.

The 6 x 6 element array detector fabricated for the focal plane of S-Cam is based on Ta-Al devices, having a size of 25 µm. This detector represents the first STJ array capable of providing imaging and spectroscopic information at visible wavelengths; it has been manufactured to ESA requirements, and it is the result of several years of development and testing. The array’s development has required particular effort in ensuring the reproducibility of the current/voltage characteristics of all of its elements and an adequate fabrication yield.

The geometry of the detector is presented in Figure 1; the characteristic 45° rotation of the pixel squares is due to specific operating requirements. Each single element is connected to its own readout electronics by means of Nb wiring 2 µm thick, deposited on top of a passivating SiOx layer. The pixels are separated by gaps 4 µm wide, so that the total filling factor of this Focal Plane Array is 0.74. To maximise the photon collection efficiency, the detector is illuminated from the rear, through the sapphire substrate, which is highly transparent in the visible range. The single-detector quantum efficiency has been modelled theoretically and subsequently measured experimentally at EUV wavelengths, showing a value of in excess of 70% from 200 to 800 nm.

Figure 2 shows, in the form of a 3D histogram, the responsivity of each of the array elements, as measured from soft X-ray tests. The responsivity of the detector is a key parameter, indicating the amount of signal that can be extracted per unit of energy absorbed (in this case, electron/eV, where a visible light photon has an energy ranging from 2.6 eV in the blue to 1.8 eV in the red). The plot indicates a rather high degree of uniformity, with all pixels varying by no more than 5%. Moreover, all of the devices have similar current/voltage characteristics, with very low 'dark-currents' (well below 1 nA at a bias voltage of about 100 μV), thus allowing the signal-to-noise ratio to be optimised.

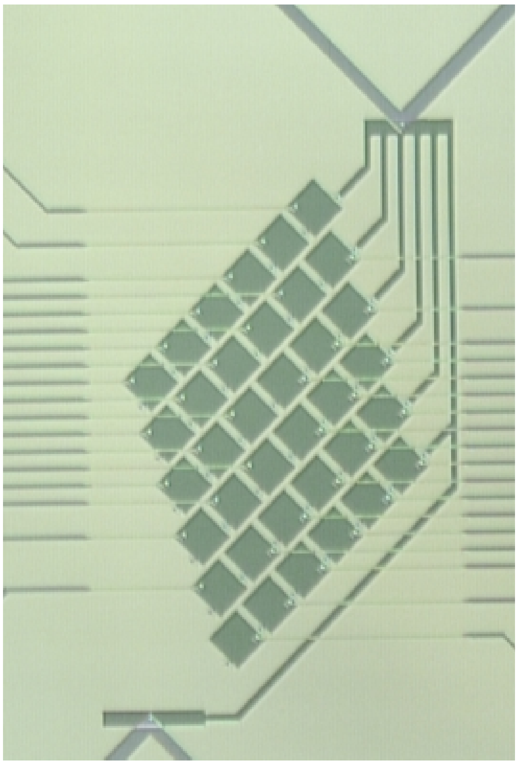


Figure 1. Optical microscope photograph of the 6 x 6 array

Several activities aimed at further improving the array performance are presently underway. There are two main goals to be achieved: (a) a significant increase in the detector active area to allow for a corresponding increase in field of view; and (b) an improvement in the spectroscopic performance by moving to superconducting materials with a lower energy band-gap. Both goals must be achieved while preserving (and possibly improving) the fabrication yield.

Enlargement of the field coverage requires a drastic increase in the number of pixels (from the current 36 to well in excess of 1000) in order to enhance the active area without under-sampling the Point Spread Function of the optical system. Such an increase in number of pixels may imply a corresponding increase in the number of readout channels, thus posing significant challenges in terms of wiring access and cryogenic performance. The adoption of lower band-gap superconductors implies lower operating temperatures (from 400 mK down to below 100 mK) and the need to address materials-science and technological issues related to the controlled deposition and patterning of high-quality thin films.

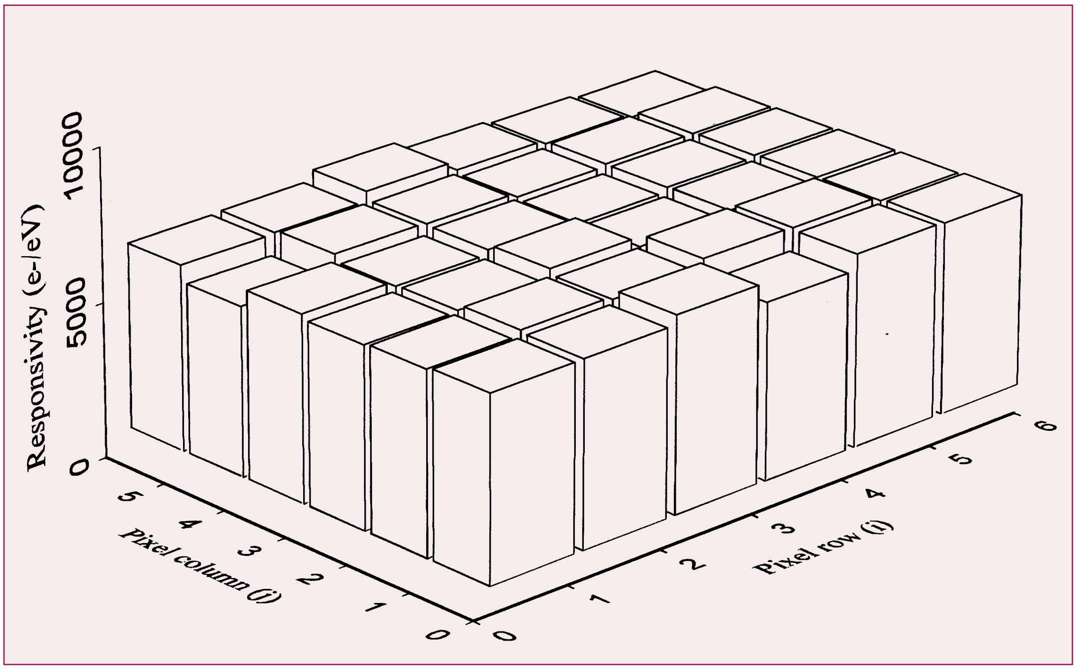


Figure 2. Mapping of the array's responsivity (36 elements)

The array development programme is explicitly oriented towards applications, including future ground and space-based instrumentation for astrophysics. In the ground-based applications category, we can mention the improved versions of S-Cam, which will significantly enhance the performance of the Mark I camera, being designed for operations at a large-diameter telescope. As far as space-based applications are concerned, two different possibilities merit mention: (a) the development of non-dispersive, low-to-medium resolution imaging spectrometers operating in the NIR-Visible range; (b) the development of high-resolution imaging spectrometers for the soft X-ray range (up to 10 keV).

Table 1. S-Cam requirements

Camera band pass	300 – 600 nm
Provided data/event	Wavelength, event arrival time, pixel identification
Typical resolving power	Order 10 (at 300 nm)
Event time accuracy	5 μs (absolute accuracy UTC)
Max. count rate per pixel	1 kHz
Camera field of view	3.6 x 3.6 arcsec^2 (0.6 arcsec/pixel)
Effective observation time	>12 hours (cooler hold time)
Camera focus adjustment	WHT secondary mirror and S-Cam optical unit
Camera guiding	WHT telescope facility (autoguider)
Filter wheel	Two sets of 8 filters on 2 independent wheels
Camera operations	Remotely controlled from the WHT control room
On-line data analysis	'Quick-view' facility running on control computer
Data storage	On control computer (FITS), total capacity >8 GB

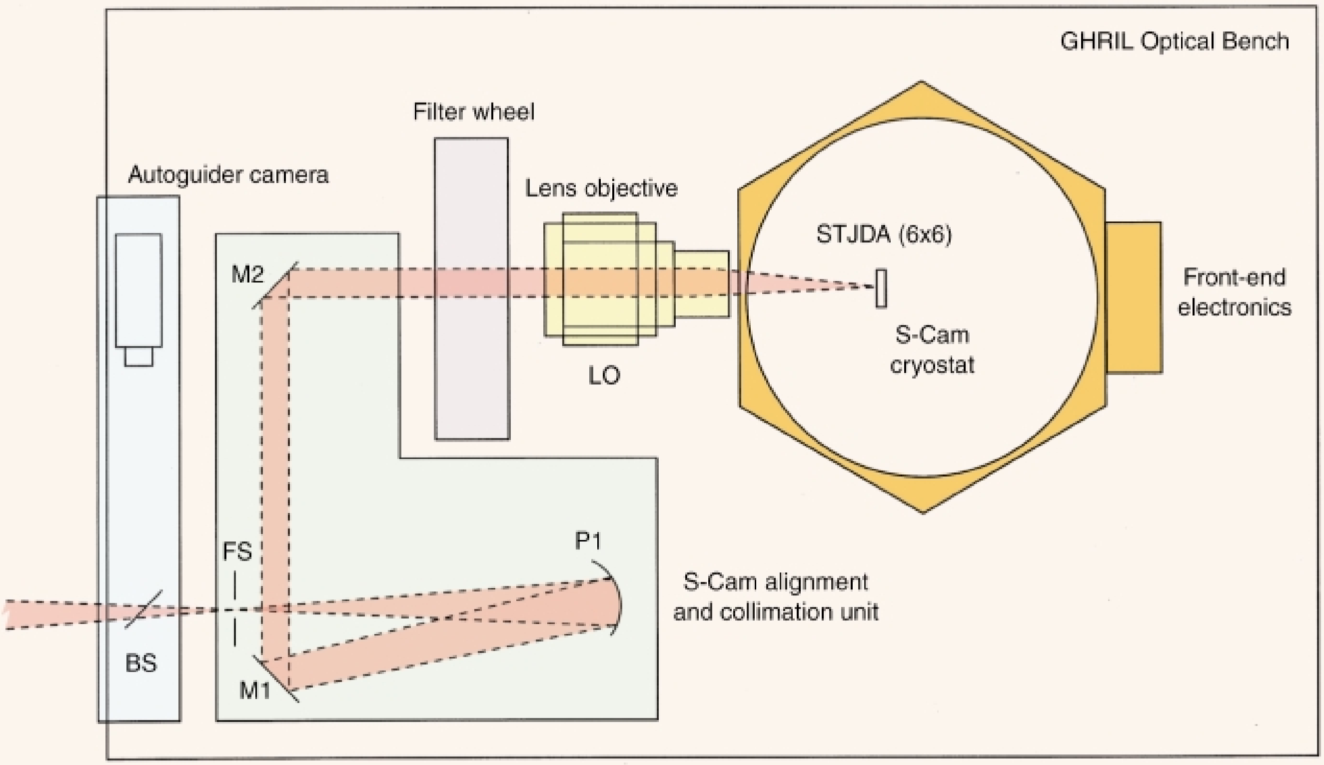
S-Cam development

The S-Cam design is based on the instrument requirements listed in Table 1, which reflect both the operational needs of astronomers using the camera and the observation-site characteristics. Among the most significant issues are the resolving power, the time-tagging, the count-rate and the plate-scale requirements.

The required resolving power matches the intrinsic capabilities of tantalum-based detectors, and requires strict control over the electronics noise and any stray IR radiation impinging on the Focal Plane Array. The latter component is particularly important for a cryogenic camera designed to operate the detector at a base temperature as low as 300 mK. The 5 μs absolute accuracy time-tagging requirement is crucial from an astronomical point of view, since it allows accurate timing analysis for variable sources and the validation of specific astrophysical models. The count-rate performance is also important, since it determines (in conjunction with the plate scale and the image optical quality) the maximum object brightness that the instrument can tolerate without the help of any means of attenuation (i.e. without filters). In addition, the capability to count single photons implies the potential for a large number of events, i.e. the need for adequate data processing and storage performance. Finally, the plate-scale requirement is critical in defining the camera Field Of View. Adequate sampling of the optical system Point Spread Function is necessary, however, in defining the characteristics of the unit interfacing the camera to the Nasmyth focus of the William Herschel Telescope. The cryostat base temperature is linked to the detector choice, while the hold time is determined by operational and logistic requirements.

On the basis of the requirements listed in Table 1, it was then possible to define the detailed engineering of the complete system. The overall architecture is described by the block diagrams of Figures 3 and 4. The complete system is composed of an optical unit, a cryogenic system based on a ^{4}He cryostat and hosting a ^{3}He cryo-sorption cooler, analogue front-end electronics based on 36 charge-sensitive preamplifiers and digital data acquisition and storage equipment.

Figure 3 shows the units located on an optical bench inside the Ground-based High Resolution Imaging Laboratory (GHRIL) room (Fig. 5), a dark cabin which is at one of the two Nasmyth foci of the alt-azimuth telescope. The optical unit of S-Cam includes reflective and refractive units, used to provide a plate scale of 0.6 arcsec per pixel on the Focal Plane Array. There is a filter-wheel unit in the parallel beam portion of the optical path to provide the optional attenuation via different neutral-density and pass-band filters. The main cryostat is also located on the GHRIL optical bench. The analogue, 36-channel Front-End Electronics is mounted directly on the cryostat to minimise noise pick-up and grounding problems (Fig. 4). The output of the charge-sensitive pre-amplifiers is then processed via shaping filters and processed via a dedicated data-acquisition unit, in order to provide the required spectroscopic and time-tagging information (Fig. 6). The latter is provided by a time-reference receiver exploiting the Global Positioning System; such a time reference is within 1 μs of UTC (Universal Time Coordinated, maintained by the Bureau Internationale des Poids et Mesures, in Paris). The data-acquisition system is controlled by a PC-based unit, also located in the GHRIL room. The actual control of the instrument is more than 50 m away from the telescope control room; the Graphical User Interface of the camera and the related quick-look software are running on a second PC, also responsible for the data storage. The data are stored in the



BS: Beam splitter for autoguider camera
FS: Field stop (adjustable)
P1: Parabolic mirror (1x translation, 2x rotation)
M1: Beam folding mirror (2x rotation)
M2: Beam folding mirror (2x rotation)
LO: Lens objective (3x translation)

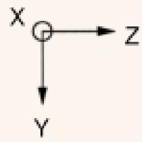


Figure 3. S-Cam block diagram: optical unit and cryostat

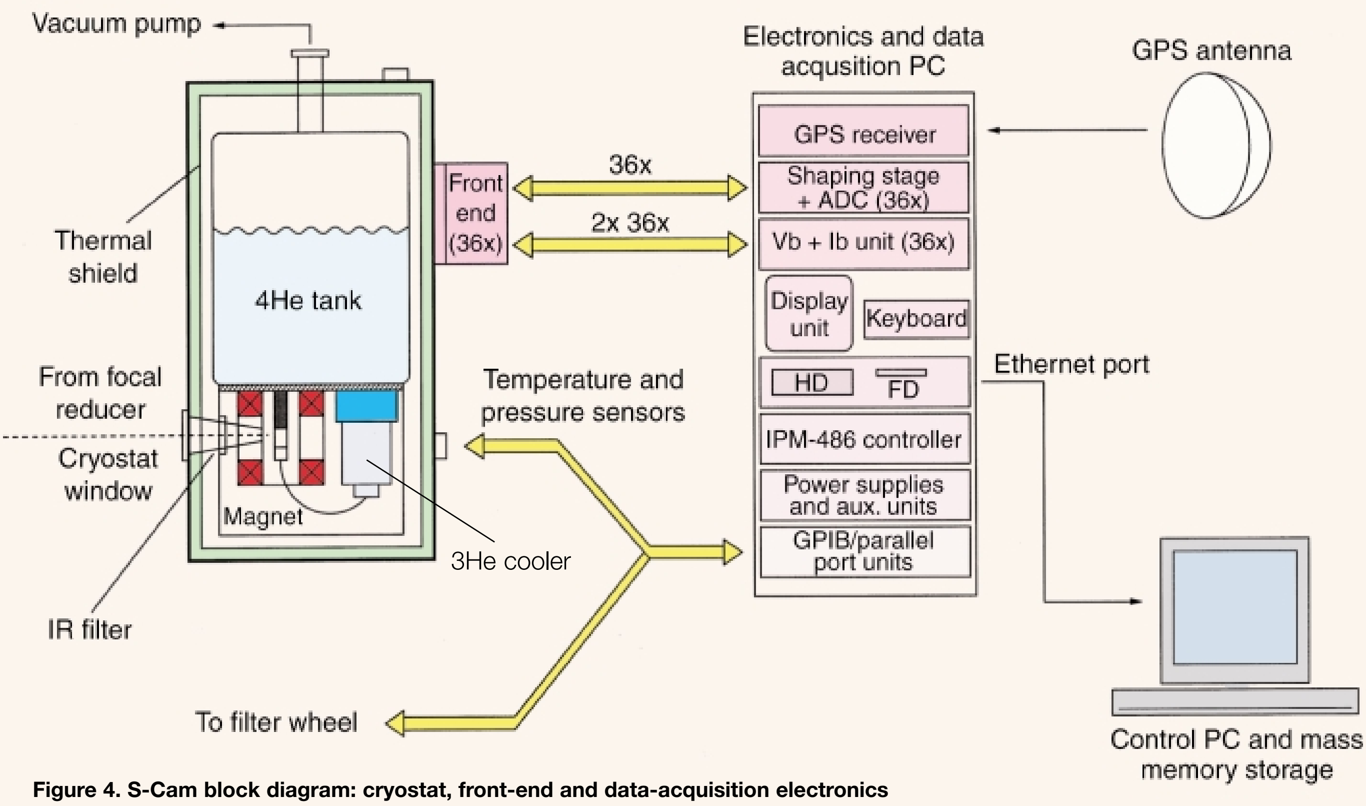


Figure 4. S-Cam block diagram: cryostat, front-end and data-acquisition electronics

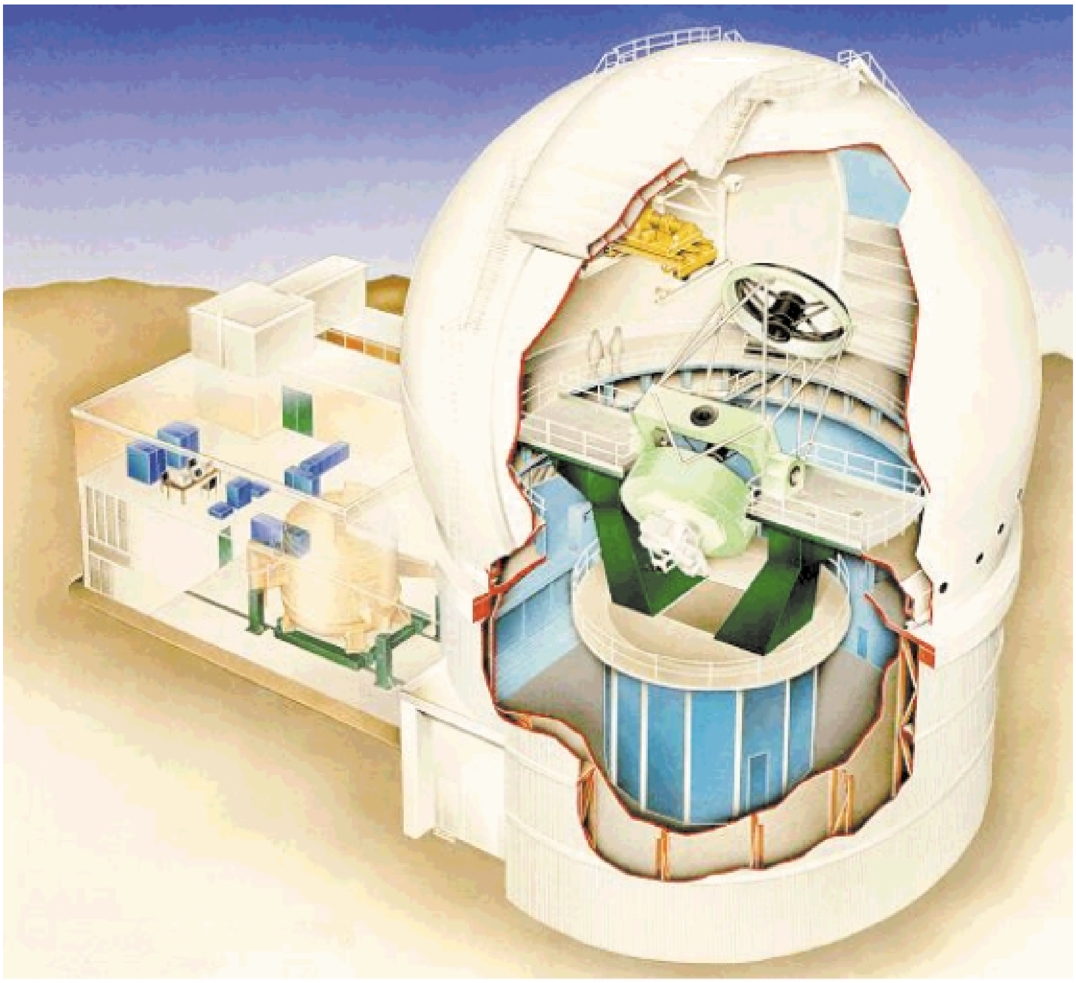


Figure 5. The William Herschel Telescope in La Palma

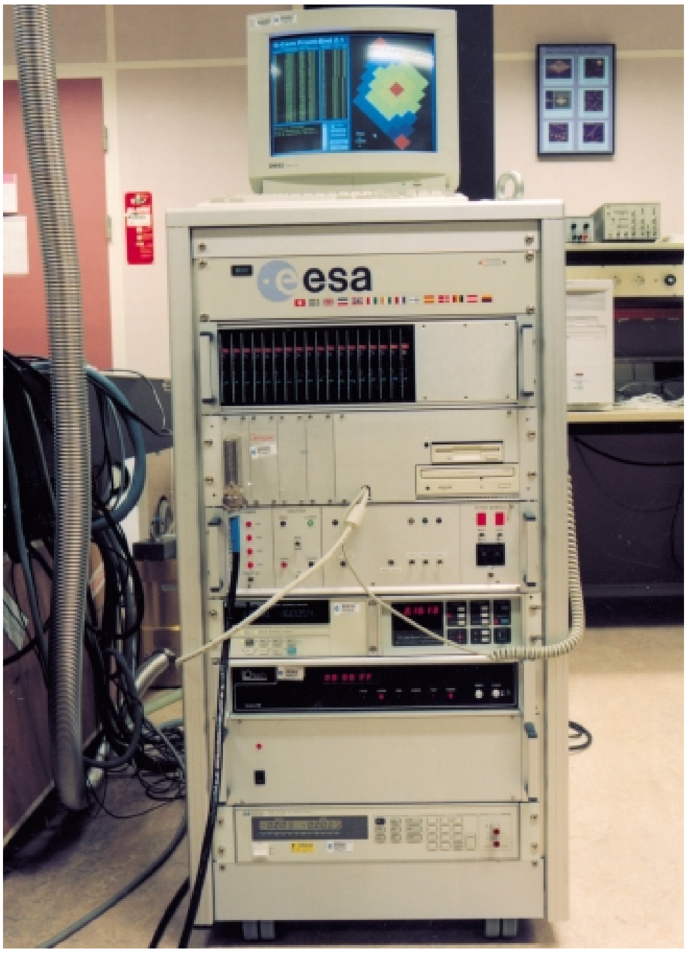


Figure 6. The S-Cam electronics rack

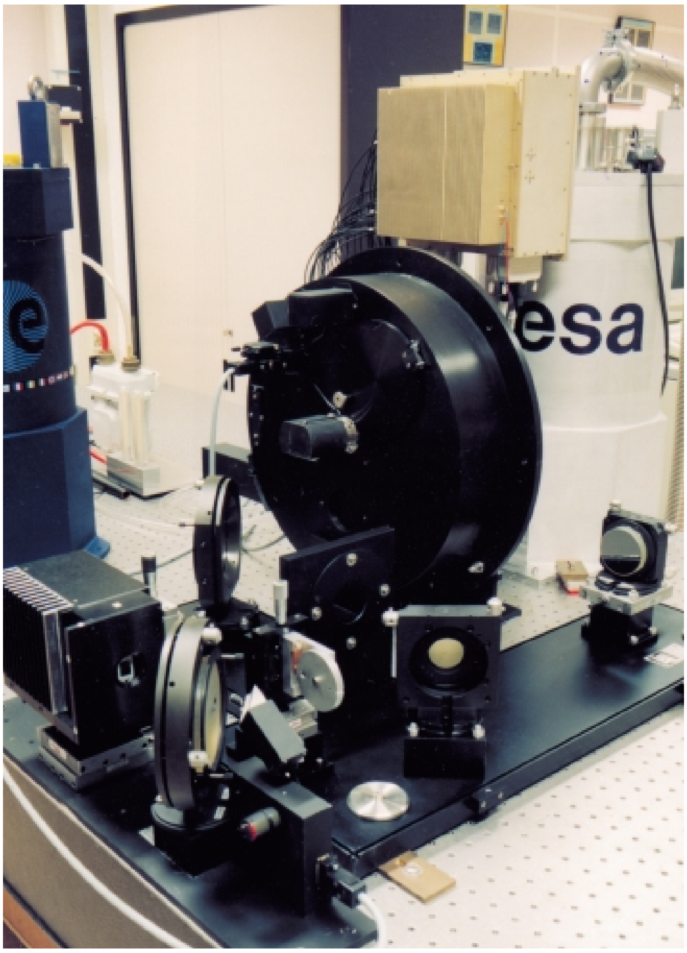


Figure 7. The S-Cam system undergoing testing at ESTEC (NL)

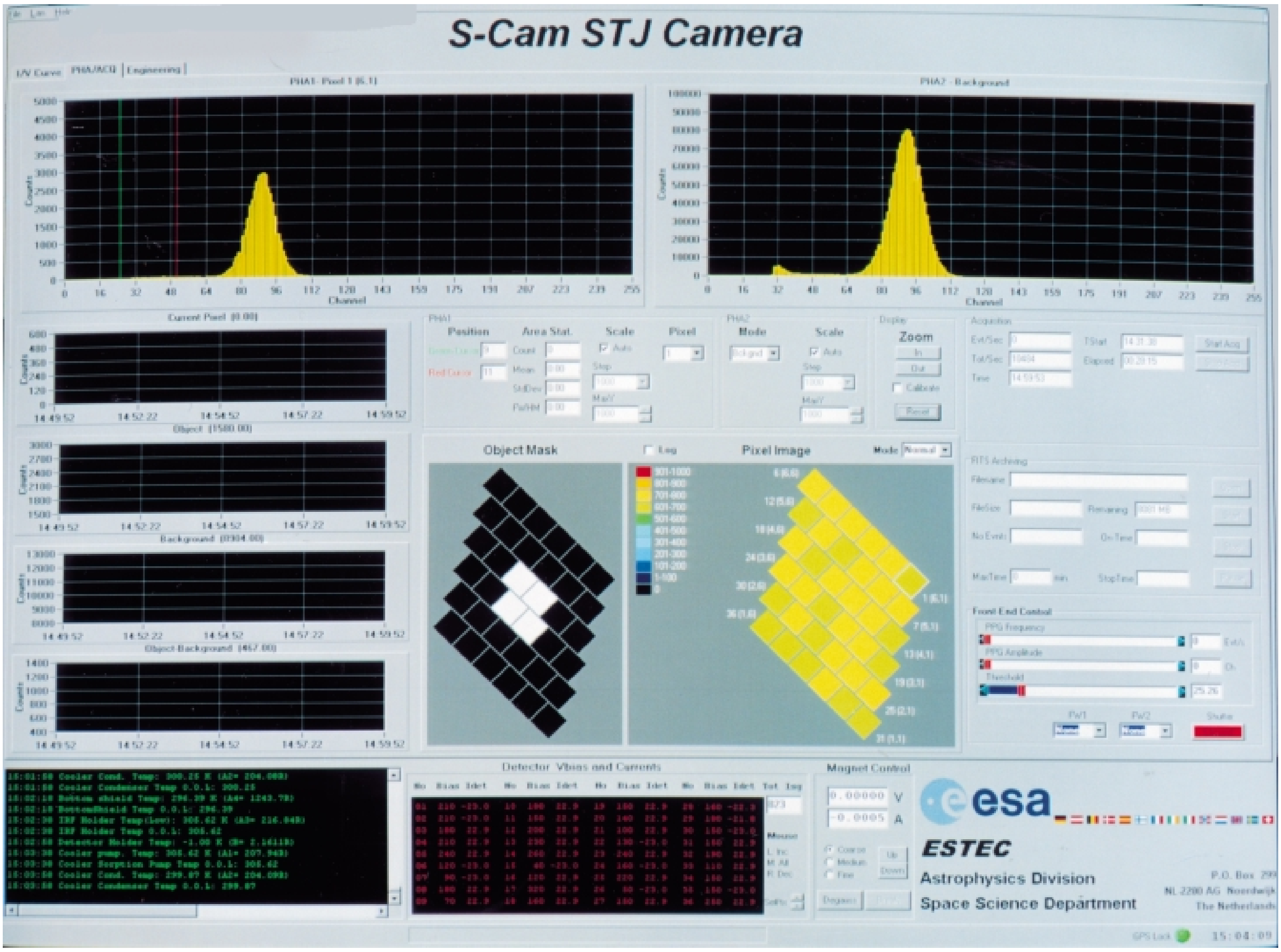


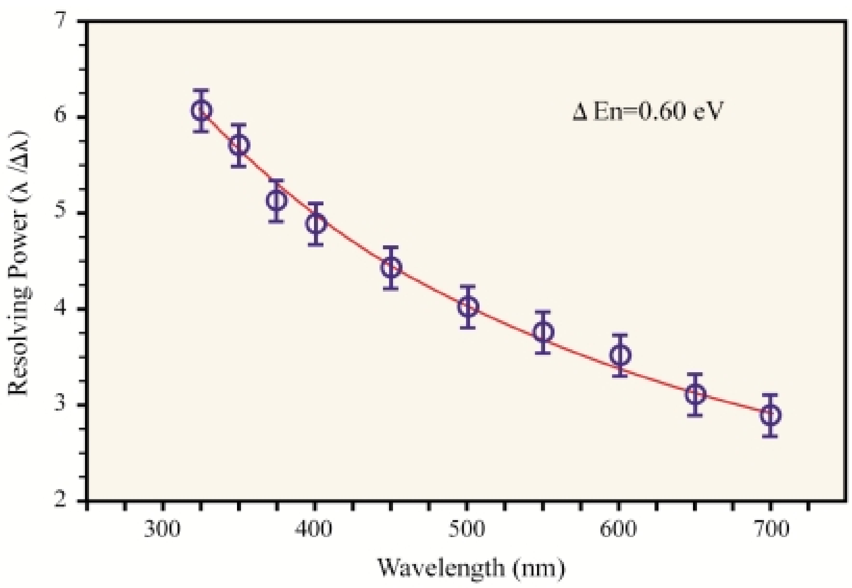
Figure 8. The main panel of the S-Cam Graphical User Interface software

FITS (Flexible Image Transport System) format in order to allow immediate access by means of standard astronomical data-analysis software.

Figure 7 is a photograph of the system while undergoing integrated system testing in the laboratory; the main system components are clearly visible. Figure 8 shows the main panel of the Graphical User Interface software.

The system tests took place at different levels of integration, between January and May 1998 at ESTEC. The integrated system tests were conducted in the period July to December of the same year. Such tests allowed us to verify the main system performances, including the instrument's resolving power, prior to the first observation campaign at the telescope site. Figure 9 shows the resolving power (expressed in the form of the ratio $\lambda/\Delta\lambda$) in the wavelength range of interest. This result, as a consequence of several degrading mechanisms, corresponds to a moderate spectroscopic resolution; nevertheless, it allows one to perform astronomical measurements never attempted before. Specific tests have addressed other aspects, such as the uniform array response to a flat field illumination, the capability to properly image, the maximum sustainable count-rate, the accuracy of the event timing, the linearity of the energy response and the related calibrations. The cryogenic system has shown excellent performance, with a base temperature of 320 mK and a hold time in excess of 8 hours.

Figure 9. Resolving power as a function of photon wavelength for a typical array pixel

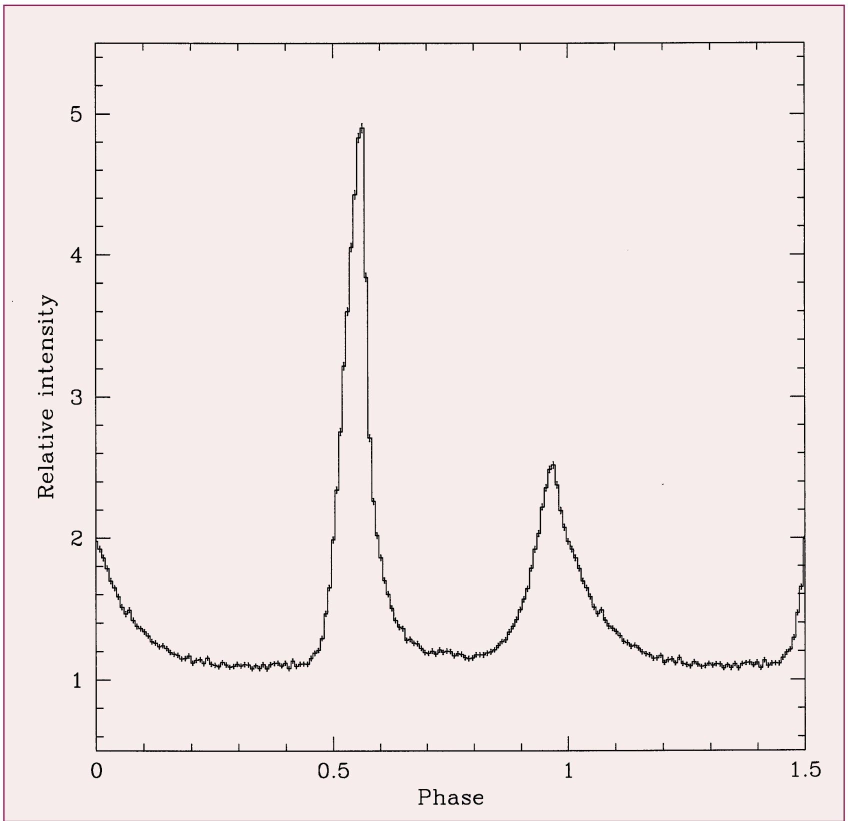


S-Cam was shipped at the beginning of January 1999 to the William Herschel Telescope in La Palma. The system was installed in the last week of January and the instrument saw first astronomical light in the first week of February. The very first astronomical observations took place immediately thereafter. This first campaign was conducted successfully: no major interface problems were encountered, but numerous opportunities for possible improvements and refinements were highlighted.

The William Herschel Telescope is managed by the Isaac Newton Group (ING), which also operates smaller telescopes on the same site. It is the largest telescope in Europe, with a classical Cassegrain configuration and a paraboloidal, 4.2 m-diameter primary mirror. The telescope has an alt-azimuth mount, requiring accurate computer control to track an object on the sky.

During the S-Cam campaign, astronomical observations concentrated on time-varying objects in order to take maximum advantage from the time-tagging performance of the camera. Several celestial objects have been observed, including pulsars, white dwarfs and binary systems. The most interesting results have been obtained by observing the Crab pulsar, a neutron star spinning at about 30 rev/sec and initially discovered in 1968 by radio astronomers. This neutron star, together with its surrounding nebula, is the remnant of a supernova explosion recorded in 1054 AD. The explosion took place in the Taurus constellation, approximately 6000 light years from the Earth. Figure 10 shows the light curve produced by the pulsar over an integration period of 10 min: the two peaks correspond to the emissions from the two different magnetic poles of the spinning neutron star.

Figure 10. Light curve of the Crab pulsar



Conclusions

The development of S-Cam and its commissioning at the William Hershel Telescope represent a significant milestone in the R&D activity programme of the Astrophysics Division. Such a milestone is particularly important in view of the effort being made by ESA to manufacture cryogenic detectors based on STJs with highly innovative performance. In this respect, S-Cam represents a world first in terms of the technologies involved and the performance offered to astronomers. Possible applications of these technologies outside astrophysics include materials-science diagnostics, biomedical instrumentation and remote sensing, with particular relevance to high-speed spectro-photometry, low-light imaging spectroscopy and the study of luminescence phenomena.

Acknowledgements

The S-Cam project has required the combined efforts of several people. We would like to acknowledge the key role played by P. Verhoeve (ESA) in the characterisation of the array detector and by B. Christensen (Unigate Technologies) in the development of the complete camera software. We also wish to mention the support received from D. Doyle (ESA) for the characterisation of the optical unit's performance, and from the ESTEC Transport Office, which took care of equipment delivery.

While the overall S-Cam system was designed, assembled and tested at ESTEC, several contractors were involved in the manufacturing phase. The optical unit was manufactured by SESO (F), the ^{4}He cryostat by Bradford Engineering (NL), and the ^{3}He cooler by CEA/TBT (F). The detector array was manufactured by Oxford Instruments (UK). We also wish to thank Mr. F. van Schaik (Messer Nederland) for the delivery of liquid helium to La Palma.

Last but not least, we would like to acknowledge the excellent support received from the WHT staff, and in particular P. Moore and C. Benn of the Isaac Newton Group.