IN-FLIGHT RESULTS USING VISUAL MONITORING CAMERAS

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ABSTRACT

This paper provides an introduction to in-orbit visual monitoring of spacecraft, followed by a description of the imaging systems used on the European Space Agency missions TeamSat and XMM-Newton with a presentation of related results. New imaging systems which are under development are introduced and future missions using them are discussed.

INTRODUCTION TO SPACECRAFT MONITORING USING VISUAL SYSTEMS

The purpose of external spacecraft monitoring is to provide feedback of spacecraft status during deployment of e.g. antennas, instrument booms and solar arrays. The classical approach using indirect information collection from sensors is becoming impractical when spacecraft and space stations grow larger and have more appendices. A new approach has therefore been introduced using visual systems for direct visual confirmation of spacecraft conditions to complement the classical methods. The use of visual monitoring gives additional benefits such as detection of structural deformation, in-orbit spacecraft surface damage analysis and failure diagnostics.

Since visual information is used for monitoring the spacecraft, the same system can also be used for taking pictures of e.g. separation between launcher and spacecraft or spacecraft and planetary probe. Pictures of the launcher and spacecraft in orbit with Earth in background, are appreciated by the general public and provide the first results from a space mission. Finally, an picture tells more than thousand words, but it also requires more data to be transmitted, making image compression desirable when many images are required. The requirements on visual monitoring smart sensors can be summarised as follows:

- Low power, mass, volume and cost
- Versatility in interfacing to onboard data handling and communications systems
- Image processing such as compression
- Radiation hardness or tolerance

Current systems basically meet the above requirements, but further optimisations are considered necessary. The objectives of ongoing developments are to produce a single-chip camera suitable for visual monitoring, image gathering on planetary probes, rovers etc., where size and power consumption has to be minimised.

THE TEAMSAT MISSION

Cameras for space applications have traditionally been based on Charge Coupled Device (CCD) technology, but this technology is now getting competition from CMOS Active Pixel Sensor (APS) technology. The APS technology offers certain benefits that are directly relevant for potential applications in space. It offers the possibility for integration of system and sensor on a single chip, with resulting gains in system dimensions, mass and power consumption. A new generation of CMOS sensors have shown radiation hardness, making APS interesting for these niche applications.

The most basic application for APS sensors, visual monitoring, has already been demonstrated in space. The first visual monitoring system that was developed for the European Space Agency is the Visual Telemetry System, jointly produced by MMS (UK), OIP N.V. and IMEC (B). It was designed for an Earth observation mission, targeting a spacecraft that has many antennas and booms that needed to be observed. The VTS cameras were based on an already existing IMEC CMOS APS sensor, the FUGA-15. Since the FUGA-15 was not designed with space

Figure 1: *VTS camera*

applications in mind, dating from 1995, the VTS required a separate unit to interface the cameras to the onboard data handling system of the spacecraft and to perform image compression.

The system was finally not installed on the Earth observation spacecraft due to integration and schedule difficulties. The spacecraft was not designed with visual monitoring in mind, making the late add-on integration cumbersome.

The system was however launched on a different mission. On October 30th, 1997, the VTS acquired and transmitted near-life images from the separation between the TeamSat satellite and the upper launcher stage on the Ariane 502 flight. The images produced by the VTS were used on ground for the analysis of the upper launcher stage behaviour. In addition to the separation images, images of the sun were captured, demonstrating the capability of the FUGA-15 sensors to grab extremely high-contrast scenes. Images were also taken of the release and separation of the TeamSat sub-satellite.

Although APS technology was used in the VTS development, the overall system and camera dimensions were large and impacted negatively on spacecraft design. The goal for current and planned developments is to remove the need for a separate processing unit and to produce a stand alone camera that can be directly interfaced to the communication subsystem of the spacecraft.

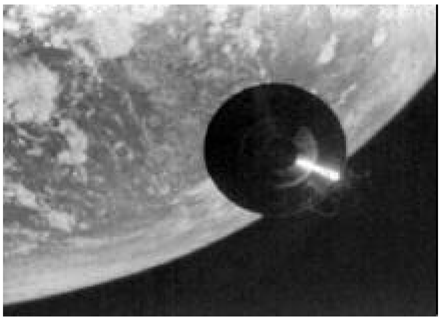

Figure2: *Ariane 502 upper stage seen by VTS/FUGA-15*

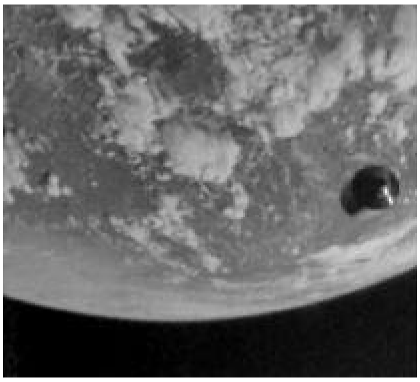

Figure3: *Ariane 502 upper stage seen by VTS/FUGA-15*

THE X-RAY MULTI-MIRROR MISSION, XMM - NEWTON

The first application to use a new CMOS sensor dedicated to space purposes, IRIS-1 from IMEC (B), is the Visual Monitoring Camera (VMC) that was developed for the X-ray Multi-mirror Mission, XMM - Newton. The objective of mounting the VMC on XMM was to observe the deployment of the solar arrays and the sunshield. A secondary objective was to provide visual feedback for public relations purposes.

Two cameras using CMOS sensors of different types were placed on the exterior of the spacecraft's focal plane assembly: a black and white camera with the FUGA-15 chip (as per VTS), its logarithmic transfer curve providing a high dynamic range; and a colour camera with the IRIS-1 chip, its exposure time being controlled by commands from ground. The field of view of both cameras is fixed (40° x 31° and 29° x 29°, respectively), giving a view along the telescope tube towards the service module and the solar arrays.

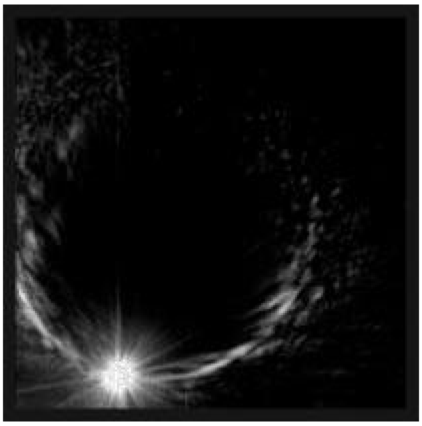

Figure 4: *The Sun seen by VTS/FUGA-15*

On December 10th, 1999, XMM-Newton was launched on the Ariane 504 flight. About five hours after launch, pictures were taken of the left and the right solar array assemblies using the cameras. It should be noted that feed-back on successful solar array deployment had already been obtained in the form of current-readings in the telemetry. The primary objective of the cameras were achieved, providing and confirming information about the status of the solar array deployment. The XMM-Newton spacecraft was at that time at an altitude of 55,300 km above the Earth's surface. Because of constraints due to the spacecraft's orientation at this time, the cameras could not have a view showing our planet.

During early orbit phase manoeuvres, pictures were taken of XMM-Newton’s thrusters in action, commanded by ground control. The thruster unit on the service module appears as a protuberance behind the black thermal insulation and it occults part of the edge of the telescope sunshield. A picture was also taken by IRIS-1 during the second firing of XMM-Newton's thrusters.

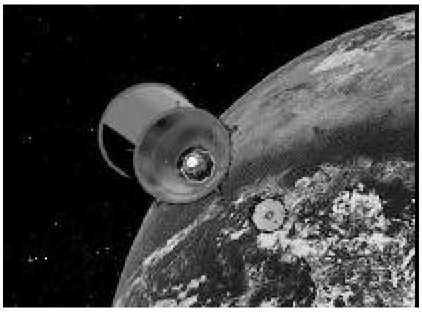

Figure 5: *TeamSat illustration*

During the firing, the thruster nozzles expel gas at high velocity. It is believed that the thruster plumes are visible as two lobes, of different sizes, one upwards and one slightly to the right (see figure 14). Detailed analyses of those pictures could help propulsion engineers to better visualise the expansion of the gas cloud at the exit of thrusters. Placing visual monitoring cameras on spacecraft is a new practice and the views of a spacecraft thrusters working in space are a rare occurrence.

Additional results were obtained when observing the telescope tube and the service platform of the XMM-Newton spacecraft with the FUGA-15 camera. Out-gassing was clearly observed as the outer skin of the service module close to the telescope tube is initially inflated and as gas leakage occurs it is deflated (see figure 10).

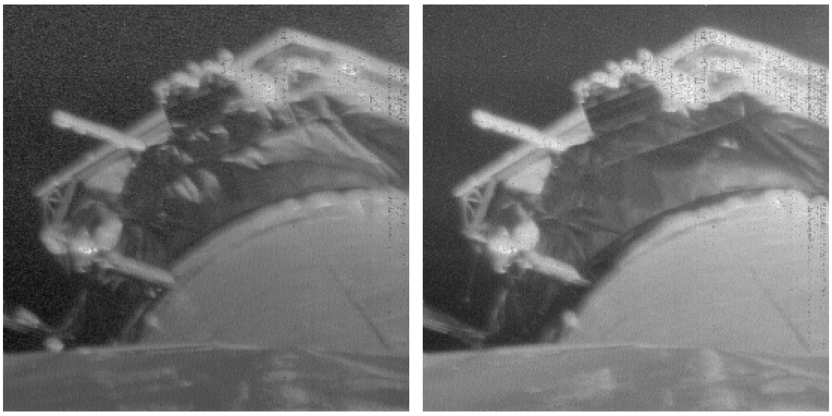

Figure 10: *In-orbit out-gassing as seen by VMC/FUGA-15*

The VMC was developed and integrated with the spacecraft in about one year's time. It was interfaced directly to the instrument controller using a traditional spacecraft interface and power distribution system. There was no space or budget for an additional processing and interface unit, contrary to the VTS development. To enable large images to be relayed to ground, the image frames were buffered to allow low rate readout of pixel data by the data handling system. The VMC contains onboard memory for frame buffering, which is controlled by an FPGA. The VMC has been jointly produced by OIP N.V. and IMEC (B).

Key features of the VMC are:

- IRIS-1 colour sensor or FUGA-15 grey scale sensor
- Autonomous or command-interactive operation with buffering
- TTC-B-01 interface with up to 1 Mbit/s data rate
- Power consumption: 3 W at 28V
- Dimensions: 6 x 6 x 10 cm, 430 g

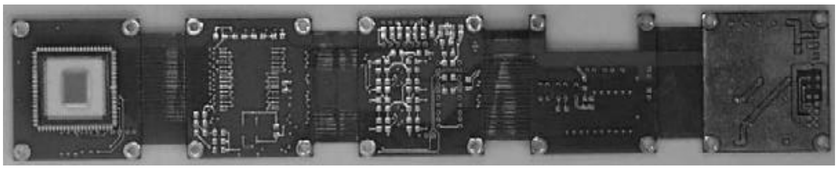

Figure 11: *Visual Monitoring Camera flexible circuit board*

Figure 6: *XMM-Newton illustration*

Figure 7: *Visual Monitoring Camera*

Figure 8: *Visual Monitoring Camera FUGA-15*

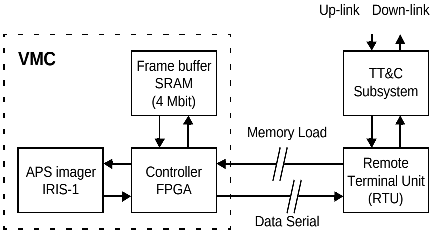

Figure 9: *VMC architecture*

VISUAL MONITORING CAMERA GROUND SEGMENT

Software has been developed for the VMC operations on the XMM-Newton mission. It is connected to the instrument network and extracts the VMC data from the XMM-Newton telemetry frames, which follow a specific implementation of the CCSDS recommendation. The software was developed within ESA at low cost and runs on a simple Intel Pentium III 450 MHz computer under Microsoft Windows NT.

The objective was to keep maximum flexibility and easy maintenance by restricting the developed software to actual data de-packetisation while the operator performs all other functions, e.g. file management, image viewing and post-processing, log files viewing, etc., using standard tools like Microsoft Windows Explorer or Adobe Photoshop. There is no need for a telecommand generation module for the commanding of the VMC since this is done via standard command procedures. Only voice interaction between the VMC operator and the spacecraft operator is required.

For future missions, the VMC ground processing software should be fully compatible with CCSDS Packet Telemetry recommendations and ECSS Packet Utilisation Standard, allowing the use of a unique software with only mission specific customisation. It should also have several possible interfaces to the data source: TCP/IP for a local area network connection, RS232 for connection to the VMC camera via an interface box developed within ESA, or reading of images from source data files.

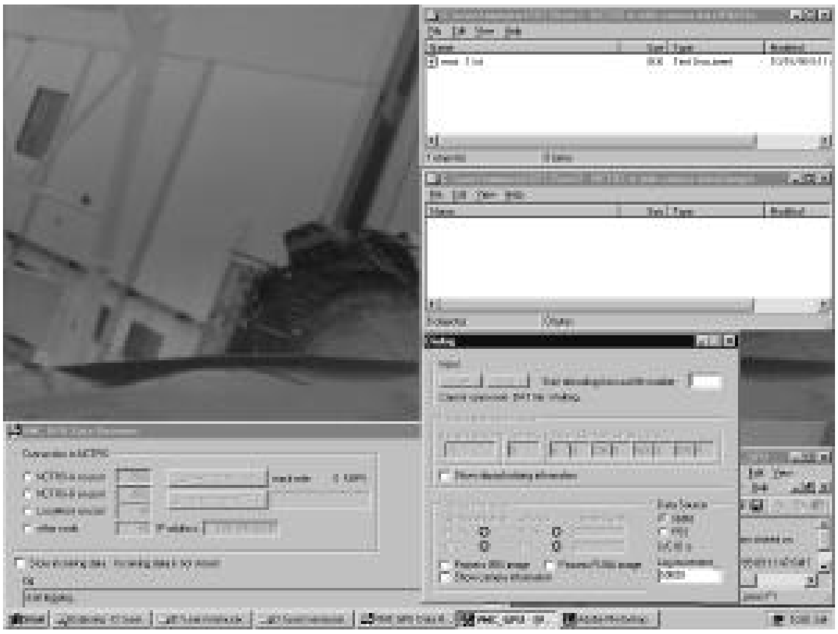

***Figure 16:** VMC Ground Software Graphical User Interface*

INTEGRATED RADIATION-TOLERANT IMAGING SYSTEM

The success of the XMM-Newton camera development is based on the experience from the VTS development for the TeamSat mission and on current CMOS imager developments targeted towards visual monitoring. These

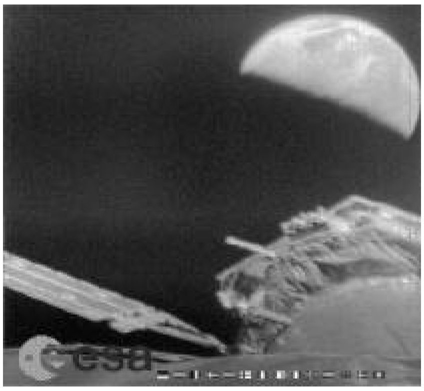

***Figure 12:** Earth seen by VMC/FUGA-15*

***Figure 13:** XMM-Newton seen by VMC/IRIS-1*

***Figure 14:** Plume seen by VMC/IRIS-1*

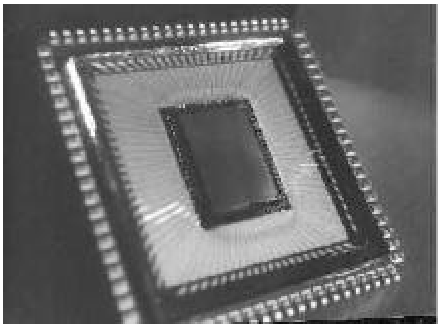

***Figure 15:** IRIS-1 sensor die*

technology developments have been initiated by ESA to enable progression of European monitoring cameras and star trackers based on APS technology.

A series of CMOS APS smart sensors targeted towards space applications, the Integrated Radiation-tolerant Imaging System (IRIS), is being implemented in several steps. Firstly, a imaging sensor part has been developed in 1997/1998, based on an integrating APS previously developed by IMEC (B). The first new sensor (named IRIS-1) has been tailored to meet specific requirements posed by the ESA, such as an increased resolution of 640 x 480 pixels, on-chip analogue-to-digital conversion and the possibility for reading out sub-windows of an image at high rates. IRIS-1 is the first technology prototype in the IRIS series of imagers. Prototype devices are available for interested parties through ESA. The key specifications are the following:

- 640 x 480 pixels, 14 micrometer pitch
- Integrating photo diode pixel, double sampling amplifiers
- 8 bits digitising on-chip, 10 images per second
- 20 krad (measured on the same image technology family)

In the second step, the sensor is integrated with all timing and control logic required to operate the sensor itself and to support multiple variants of serial and parallel interfaces and protocols. Although the smart sensor can be used in a multitude of applications, special attentions has been given to the aspect of interfacing it with modern spacecraft communication systems. The resulting smart sensor (named IRIS-2) will be a camera-on-a-chip capable of taking images and directly communicating with the spacecraft. The additional key specifications of IRIS-2 are:

- Sub-windowing and interleaving, digital pixel averaging
- Serial and parallel digital pixel data and command interfaces
- Analogue data output, raw data or CCSDS packets
- Standard spacecraft interfaces

The only electrical parts required to turn an IRIS-2 sensor into a camera are line transceivers and passive components. The IRIS-2 sensor is being fabricated at the time of writing. Demonstration cameras are expected by the end of year 2000 and will be made available to interested parties through ESA.

The next generation IRIS-3 smart sensor will also support local image storage, capable of handling between ten and hundred images depending on the compression factor used and be radiation hard. The imager, together with a dedicated compression device and local synchronous dynamic memory, will enable new applications by providing low rate grey scale video capability while maintaining simple user interfaces adapted to spacecraft requirements.

IMEC has developed, partly funded by ESA, a new pixel architecture that preserves the electro-optical sensitivity, while adding to it an increased tolerance towards gama irradiation, showing only a gradual deterioration up to doses exceeding 20 Mrad.

The new IRIS devices are being jointly developed by FillFactory and IMEC (B) and manufactured in commercial mixed-signal CMOS 0.7 and 0.5 μm processes from Alcatel Microelectronics (B). In parallel to the IRIS development, FillFactory and IMEC have produced imagers with resolutions up to 6 million pixels, for studio photography, and sensors with an image rate up to 1000 full frames per second, for motion analysis.

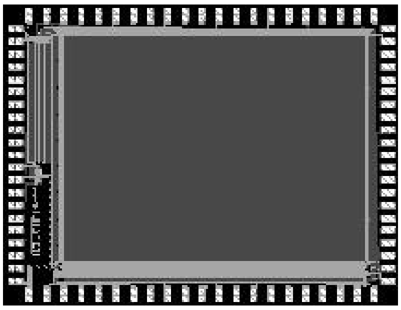

Figure 17: *IRIS-1 layout*

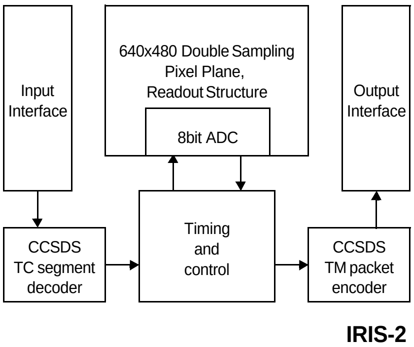

Figure 18: *IRIS-2 architecture*

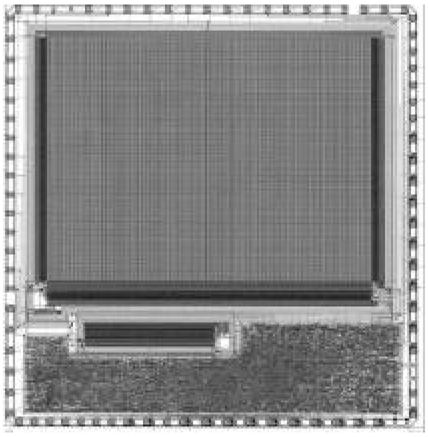

Figure 19: *IRIS-2 layout*

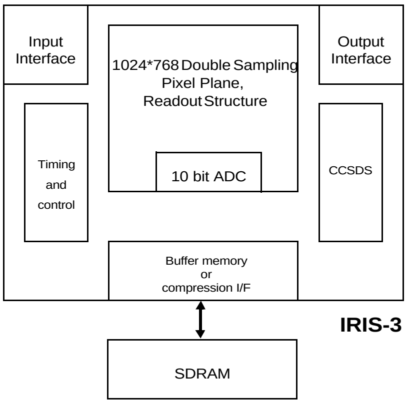

Figure 20: *IRIS-3 architecture*

FUTURE MISSIONS

The VMC, extended with a dedicated 27 image memory module, will be used on the Cluster-II mission. Cluster-II comprises four spacecraft that are launched two at the time. A camera will be mounted on the upper spacecraft and capture the separation sequence. An image will be taken every three seconds, capturing the separation between the upper and lower spacecraft, and between the lower spacecraft and the upper stage of the launcher.

The VMC will be flown on the Proba mission. It will provide the possibility to detect clouds that might obscure the field of view of the compact high resolution imaging spectrometer. It is also considered for Proba-2.

The VMC was originally planned for the Integral mission, but was finally not embarked due to accommodation issues which did not allow monitoring of the solar array deployment without modifying the camera field of view and focus.

The VMC is baselined for the Mars Express mission.

OTHER DEVELOPMENTS

To complement the miniaturisation done with increased integration levels on the sensor silicon itself, an ESA development has been targeted towards the miniaturisation of the mechanical implementation. A matchbox sized camera has been developed by CSEM (CH). This cost effective solution for resource critical missions illustrates the possibilities offered by the most recent microsystem technologies, allowing for improvements in mass and power consumption of imaging systems.

CONCLUSIONS

In-orbit visual monitoring of a spacecraft has been demonstrated successfully on two ESA missions. The expectations are that future spacecraft will use monitoring cameras. The role of the cameras will change with the future improvements in performance.

To further reduce the mass of the cameras one needs to address the mechanical implementation in addition to the reduction of the number of electrical components. Combining the two approaches, mechanical and electrical miniaturisation will lead to cameras that carry a small overall cost overhead when integrated on a spacecraft.

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Figure21: *Cluster-II illustration*

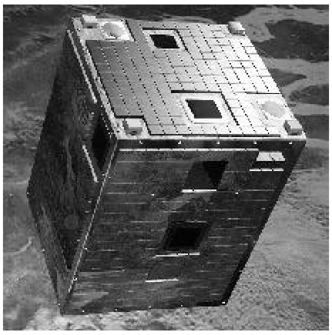

Figure 22: *Proba illustration*

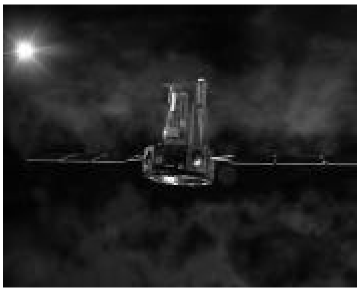

Figure 23: *Integral illustration*

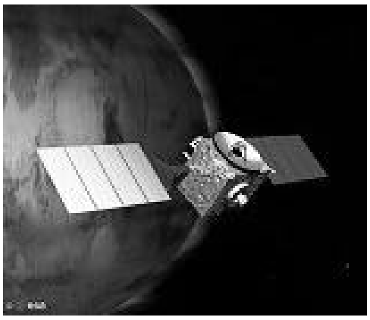

Figure 24: *Mars Express illustration*

Figure 25: *Microimager by CSEM*