Micro-cameras for space applications

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ABSTRACT

The digital space micro-cameras are compact and lightweight units able to operate in harsh environmental conditions (low temperature, vacuum, resistance to vibrations and shocks) while combining high performances (high resolution, high data rate, standard interface, internal memory) and low power consumption. We present the concept that has been used in several missions from the European Space Agency and the perspectives offered by these miniaturized systems for space applications.

Keywords: Micro-cameras, miniaturized systems, harsh environmental conditions, space application

1. INTRODUCTION

We present in this paper the developments at Micro-Cameras & Space Exploration (MSCE) of different generations of digital space micro-cameras for specific science instruments involved in exploration missions of the European Space Agency (ESA). The micro-camera is a powerful highly integrated miniaturized low-power robust imaging system with no mobile part, with a specific electrical architecture able to operate at very low temperature (–120°C). The opto-mechanical interface is a smart assembly in titanium sustaining wide temperature range. The concept has been used in several missions from ESA, like Rosetta, MarsExpress lander, SMART-1, PROBA1, PROBA2 and also onboard the International Space Station. We present also some of the multiple applications which can take advantage of such miniature system.

The micro-imager is composed of three parts: the optics, the opto-mechanical interface, and the electronics. The design and manufacturing of the imager electronic module have been performed using the high-density 3D interconnect packaging technique. The module includes the analog to digital conversion, a frame buffer, the data and control digital interfaces, the sequencer as well as the sensor itself, for example a 1024 x 1024 pixels CCD-chip (CCD stands for Charge-Coupled Device). The mechanical support for the optics was designed in order to minimize mass, to withstand vibration stresses during launch, and extreme thermal constraints (–150°C to +50°C). A large range of different optics can be mounted on the opto-mechanical interface, with fields-of-view (FOV) ranging from 5° to 110°. The camera delivers images with a resolution between 8 and 16 bits/pixel at a data-rate of 10 Mbit/s. Once an image has been taken, it can be downloaded directly, or stored in a memory buffer (several images can be stored) so as to be downloaded subsequently. The electronic module includes specific power supplies for the CCD and other components. The operating range of the imager is very large, much larger the usual one (–55°C), since it can take images down to –120°C thanks to specific low temperature electrical architecture. Lightness (110 g including 70° FOV optics, opto-mechanical interface, and electronics), compactness, and characteristics at low temperature make it a very effective solution for resource-critical missions.

2. MICRO-CAMERAS AND SPACE MISSIONS

2.1 Rosetta

ESA's Rosetta mission aims at orbiting and landing on the comet Churyumov-Gerasimenko in 2014. It comprises a large orbiter and a lander. One of the instruments of the lander is a panoramic camera: a lightweight imaging system designed to characterise the cometary surface near the landing site, from anchoring legs at spatial scales not achievable by the orbiter cameras, to the local horizon [1]. It is composed of seven micro-cameras with wide-angle optics having a field-of-view of 70° (cf Figure 1 – left). Six of them are equally spaced by 60° to record the full panorama without mechanical rotation. The seventh camera is co-aligned with one of the above to offer stereoscopic capability in one of the six fields-of-views.

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These micro-cameras must survive a long cruise in interplanetary space and operate in the very hostile environment of a cometary surface where temperatures will vary from –110°C to –50°C. To validate the technology for this extreme environment conditions, successful thermal testing, including thermal cycles, has been performed on these micro-cameras.

Rosetta, with its lander Philae on which the micro-cameras are fixed, has been successfully launched from Kourou on 2 March 2004. During a mars flyby on its journey to the comet, the micro-cameras have been operated and gave images of a spacecraft's solar panel with the planet in the background, as shown in Figure 1.

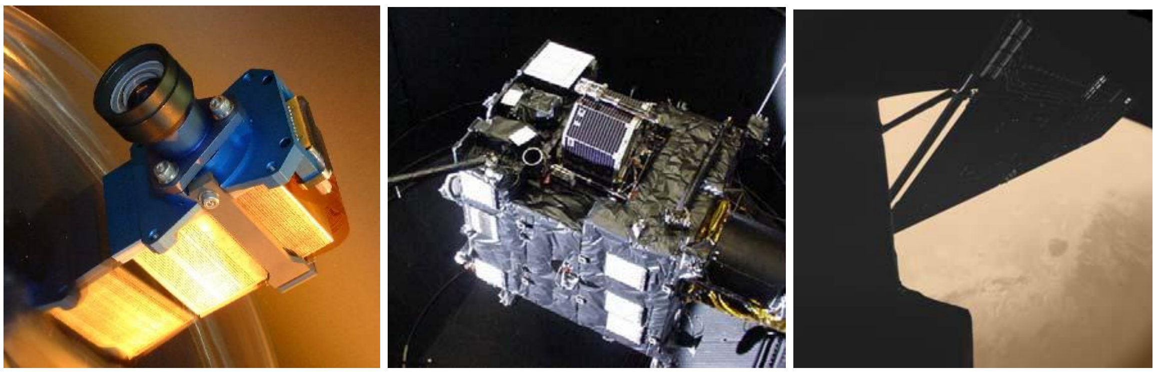

Fig. 1. Left: One of the 7 Rosetta Lander micro-cameras with rad-hard optics. Center: Rosetta spacecraft with the Philae Lander attached to it. Right: Mars taken by one of the lander cameras during flyby (image credits CIVA/Philae/ESA Rosetta).

2.2 Beagle 2

The lander of ESA's Mars Express mission, Beagle 2, was the smallest, most heavily instrumented soft landing spacecraft ever produced. As such it is a possible precursor for other missions for example a network of geophysical stations on Mars or studies of other solar system bodies like Europa, asteroids, Mercury, etc.

MCSE was involved in this project and has delivered micro-cameras for Beagle 2's robotic arm (PAW): a stereoscopic camera composed of two identical units with 48° optics and a micro-camera with specific mechanical interface to realize a microscope (cf Figure 2 – left). The main specifications for the cameras of the Mars Express Lander Beagle2 were: low mass (as less as possible); all electronics included, converter, clock, memory, drivers, communication protocol, direct link to Beagle2 common electronics; low power; resistance to the landing shocks; resistance to Mars thermal environment without thermal control; operation at ~ – 120°C. The imagers for the "Stereo Camera System" are equipped with filter wheels for multi-spectral imaging and a specific lens for close-up images.

Figure 2 demonstrates the ability to see biogenic fabrics using the micro-cameras images. Characteristic textures of rocks and of fossil microbial fabrics are generally well discernible in images taken with the Beagle 2-type cameras. Characteristic features often are visible only when using the close-up lens. This increase in resoluion would have allowed a much more detailed interpretation of the petrology of rocks than was possible during earlier missions.

The probe was launched with MarsExpress on 2 June 2003 and ejected from the orbiter on 19 December 2003. Beagle 2 was due to land on Mars on 25 December 2003. Unfortunately, nothing has been heard from Beagle 2.

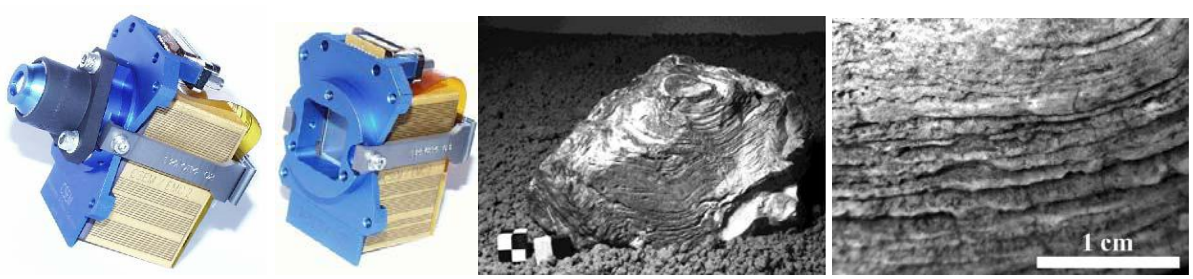

Fig. 2. Left: Micro-cameras for Beagle 2 stereo camera with 48° FOV and Microscope head. Right: Stromatolite (Carboniferous age, Wyoming) (close-up view on the right)

2.3 PROBA and PROBA-2

In the framework of demonstrating the feasibility of small and low-cost missions by increasing operational autonomy, ESA has proposed a mission called PROBA (PRoject for On-Board Autonomy). PROBA intends to demonstrate the benefits of autonomy and to validate the supporting advanced technologies in orbit.

MCSE was involved in delivering a micro-camera for the High Resolution Camera (HRC) for PROBA Telescope. HRC performs Earth observations with a resolution of 5-10 m/pixel, realising a mosaic of images of European countries. PROBA was launched in October 2001 and still gives images of the Earth (cf. Figure 3).

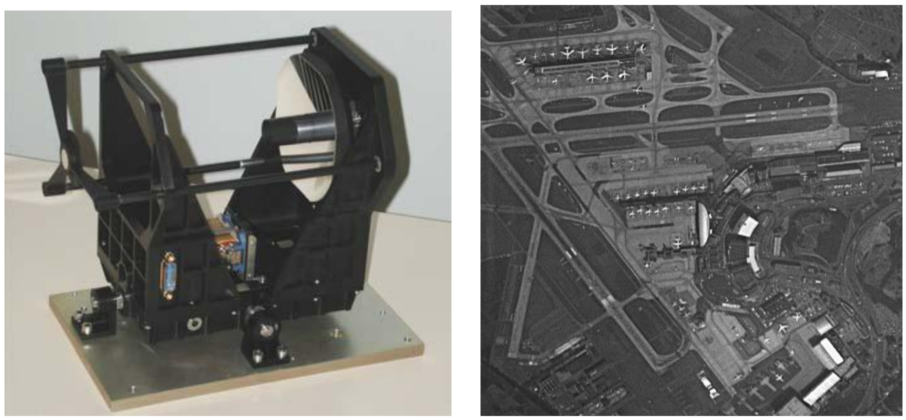

Fig. 3. Left: Proba HRC Telescope. Right: Zürich airport taken by HRC

The second in ESA's PROBA series, called PROBA-2, due for launch end 2008, includes new spacecraft technologies while also carrying scientific instruments for solar observations and for space weather measurements.

The X-CAM instrument developped by MCSE is one of the technology experiments. X-CAM is an innovative concept of a very tiny observation system for generic monitoring purposes, which can monitor the spacecraft separation from the launcher, its attitude, devices deployment, solar panel degradation and so on [2]. It includes a powerful micro-camera equipped with specific optics (Figure 4).

Fig. 4. X-CAM Micro-Camera

2.4 SMART-1

The Advanced Moon micro-Imager Experiment (AMIE), on-board ESA's SMART-1, the first European mission to the Moon, is an imaging system with scientific, technical and public outreach objectives [3]. The science objectives are to image the Lunar South Pole (Aitken basin), permanent shadow areas (ice deposit), eternal light (crater rims), ancient

Lunar Nonmare volcanism, local spectro-photometry and physical state of the lunar surface, and to map high latitudes regions (south) mainly at far side. The technical objectives are to perform a laserlink experiment (detection of laser beam emitted by Tenerife ground station), flight demonstration of new technologies, navigation aid (feasibility study), and on-board autonomy investigations.

The AMIE imaging system is constituted of two units: the camera unit and the dedicated electronics unit. The camera unit, depicted Figure 5, includes an optics with a 5.3° FOV which gives images of 45 km x 45 km at 500 km with a resolution 45 m / pixel. The dedicated electronics allows to achieve data control and power management of the camera, to store image data from the camera into a mass memory buffer, to realize data control and power management of a Digital Processing Unit (image selection and compression), to communicate with the spacecraft through a specific interface and to adapt the spacecraft supply voltage (power bus interface) to the levels required by its electronics and the camera.

SMART-1, with AMIE instrument on board was successfully launched from Kourou on 27 September 2003, and it reached the Moon in November 2004 after a long spiraling around Earth. During the Earth Escape phase, numerous views of the Earth have been obtained, with different scales, depending on the position of the spacecraft on its elliptical orbit.

SMART-1 started its scientific observations of the Moon in March 2005, running on an elliptical polar orbit that ranged from about 500 to 3000 kilometres over the lunar surface. More than 20'000 images were obtained with the AMIE instrument. The SMART-1 Mission was ended on 3 September 2006 with an impact on the near side of the Moon, in a dark area just near the terminator (the line separating the day side from the night side), at a "grazing" angle between 5 and 10 degrees and a speed of about 2 kilometres per second.

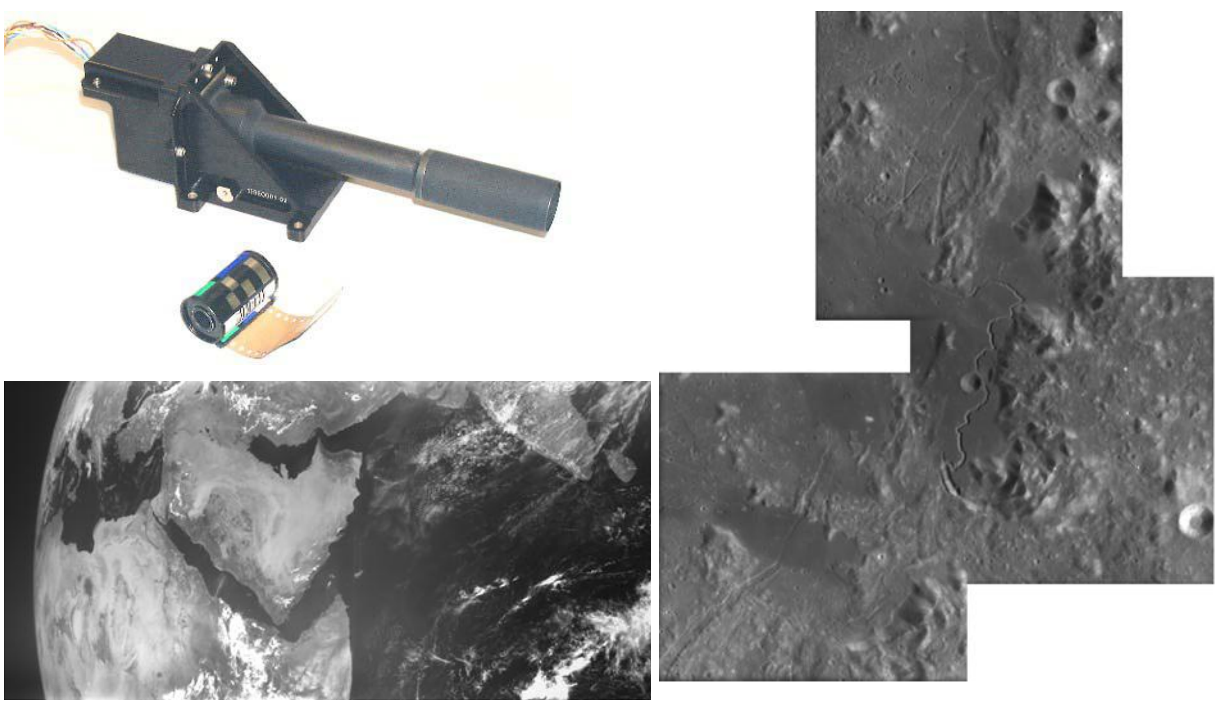

Fig. 5. Top left: AMIE camera. Bottom Left: Earth taken in flight by AMIE in June 2004 at 110’000 km from Earth. Right: Hadley Rilles on the Moon (26.4°N, 3.7°E) taken by AMIE in January 2006

2.5 LSO

In order to prepare a future mission for sprites observations of storms based on lightweight camera units, the French Commissariat à l’Energie Atomique (CEA), with the support of the French Space Agency (CNES), has charged MCSE to manufacture two micro-cameras with support equipment and software to be on-board the International Space Station (ISS), in the frame of the French-Russian Andromède mission. This complete system constituted the experiment “Lightning and Sprites Observations” (LSO), which has been conducted by the French astronaut Claudie Haigneré in

October 2001. One of the micro-cameras was equipped with a filter tailored for sprites observation, the other one imaged lightings in the visible spectrum. The system has been attached to a porthole and operated automatically during night above continents (storms are scarce above oceans), thanks to the software in which time parameters have been entered to enable observations according to ISS's orbit.

Fig. 6. Left: Micro-cameras, mechanics and filter holding system for LSO. Center: Instrument operated by the astronaut. Right: Images of sprites obtained with LSO (credits CEA).

2.6 ExoMars

First mission of the Aurora Exploration Programme of ESA, ExoMars will demonstrate key flight and in situ enabling technologies, and will pursue fundamental scientific investigations. Planned for launch in 2013, ExoMars will send a robotic rover to the surface of Mars.

The CLUPI instrument is part of the Pasteur Payload of the rover. It is a robotic replacement of one of the most useful instruments of the field geologist: the hand lens. Imaging of surfaces of rocks, soils and wind drift deposits at high resolution is crucial for the understanding of the geological context of any site where the Pasteur rover may be active on Mars. At the resolution provided by CLUPI (approx. 20 micron/pixel), rocks show a plethora of surface and internal structures, to name just a few: crystals in igneous rocks, sedimentary structures such as bedding, fracture mineralization, secondary minerals, details of the surface morphology, sedimentary bedding, sediment components, surface marks in sediments, soil particles. It is conceivable that even textures resulting from ancient biological activity can be visualized, such as fine lamination due to microbial mats (stromatolites) and textures resulting from colonies of filamentous microbes, potentially present in sediments and in palaeocavitites in any rock type.

CLUPI is a complete imaging system, consisting of an APS (Active Pixel Sensor) camera with 27° FOV optics (Figure 7). The sensor is sensitive to light between 400 and 900 nm with 14 bit digitization. The fixed focus optics provides well focused images at a distance of about 10 cm. The camera is an independent scientific instrument controlled via the SpaceWire interface.

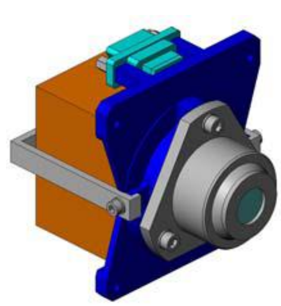

Fig. 7. CLUPI instrument on Exomars

3. OTHER APPLICATIONS

The micro-cameras developed for the different exploration missions, with their low mass, low power consumption and operation in harsh environment, offer numerous advantages for space application outside the field of scientific imaging. Applications like videogrammetry in test chamber or on-board spacecraft, monitoring of deployments, separations or spacecraft environement, etc., can greatly benefit from these miniaturized devices.

3.1 Videogrammetry

Videogrammetry is a metrology method for recovering three-dimensional (3D) coordinates of an object from two-dimensional (2D) pictures. The fundamental principle behind videogrammetry is triangulation, which is the interpretation of 2D pictures as angular measurement. The triangulation can be single point or multi-point (cf. Figure 8 - left). Videogrammetry can measure multiple points simultaneously and with the mathematical intersection of converging lines in space (cf. Figure 8 - right) the 3D coordinates of the monitored points can be precisely measured. The bundle adjustment is the process to provide the final 3D coordinates of the measured points performing at a time triangulation, resection (determination of position and attitude of the camera) and camera calibration.

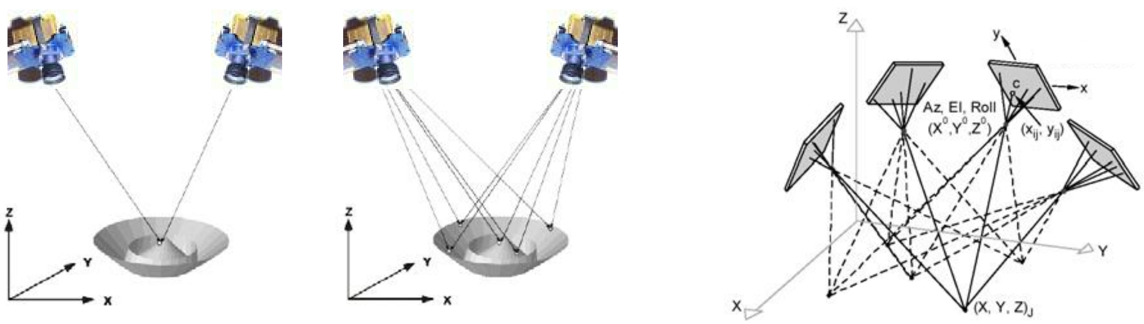

Fig. 8. Single- and multi-point triangulation (left) and line intersection (right)

The system realises a "canister-free" videogrammetry system that can be used to perform measurements of mechanical deformations of test articles due to temperature in combination with vacuum condition. It can also be used for any metrology applications at ambient and thermal vacuum conditions.

The system, composed of a set of micro-cameras, integrated with the so-called ‘multi-station’ concept, results in a small and light camera hardware, low thermal losses in the thermal-vacuum chamber and no complex feed-throughs required. The goal is to achieve better than 20 parts per million (ppm) as measurement accuracy for large objects inside any suitable test facility in Europe.

The added value provided by the versatility of the micro-camera approach is very high considering the potential tailoring capability for a variety of testing applications, for instance where the dimension of the chamber or of the test object, the possibility of mechanical supports inside the chamber or its access from the outside dictate severe restrictions. There is much less hardware involved. It is easier to access the components for repair and/or maintenance. The required support equipment and harness for testing is very limited also for very specific applications due to the extremely low weight (~ 100 g) and dimensions of the micro-cameras and of the other components. There is no need for special environmental protections. The cameras are already qualified for thermal-vacuum conditions, with very low operational temperature, down to –120°C.

Figure 9 illustrates the system which is installed in the Large Space Simulator chamber at ESA’s technical center (ESTEC) in the Netherlands [4].

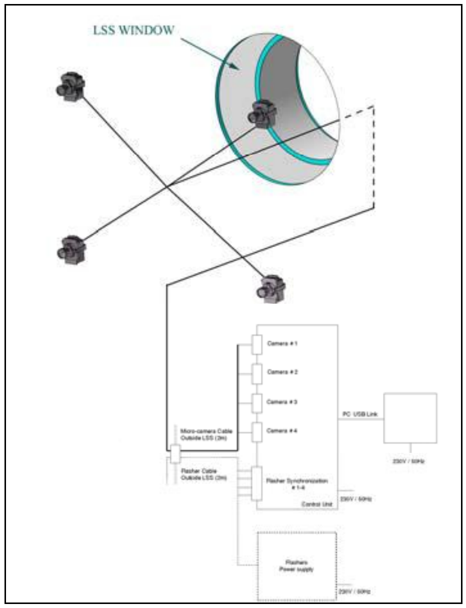

Fig. 9. Architecture of a videogrammetry operational system in the Large Space Simulator of ESA

3.2 Spacecraft subsystems Monitoring

Being compact and demanding few ressources, the micro-cameras can be used on board a spacecraft for health check and monitoring of its subsystems.

An example is given Figure 10, which shows an image obtained during cruise by a micro-camera of the Rosetta lander (cf. section 2.1). Although the lander is attached to the orbiter, two of its micro-cameras have a clear view of the spacecraft's solar panels. The image was taken while the spacecraft was at 35 millions kilometers from Earth. On this image, numerous details about the solar panels can be seen, thus helping in controlling their proper deployment, potential degradation, etc.

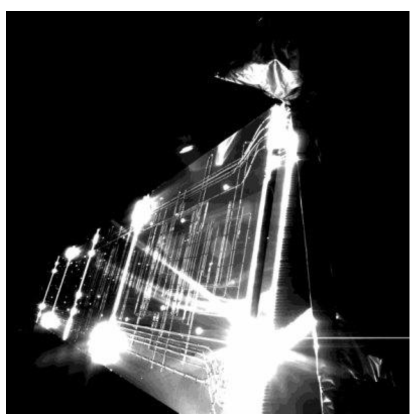

Fig. 10. Image taken by one micro-camera of the Rosetta lander at 35 millions km from Earth (solar panels of the spacecraft). Image credits IAS/CNES.

Other possible applications in this field are antenna deployment and other mechanisms motion monitoring, as well as spacecraft surfaces status check (structural deformation due for example to heavy thermal load and surfaces anomalies could be monitored during the spacecraft life).

3.3 Separation Monitoring

An on-board visual system could follow launch vehicle separation, S/C release of probe, and parachute opening. They would bring significant help to assess nominal operations or failures.

3.4 Navigation support

Although attitude and orbit verification are provided by the spacecraft Attitude and Orbit Control System (AOCS), visual based systems could provide a backup solution for navigation support whenever the AOCS is experiencing failures.

An experiment of On-board Autonomous Navigation (OBAN) has been conducted with SMART-1 during the cruise phase to the Moon. The navigation concept was based on measurement information provided by the AMIE camera (cf. section 2.4) pointing to celestial bodies. Due to its peculiarities (low-thrust trajectory with prolonged coast arcs, and multiple fly-bys with the Moon), SMART-1 and the AMIE camera, represented a remarkable opportunity to test and validate the autonomous navigation concepts of the encounter phase, by supplying real images acquired in space and actual star tracker data. Currently, navigation for interplanetary missions is performed on-ground through use of radar tracking and complex filtering techniques. This requires frequent involvement of ground personnel, for long periods of time, for tracking the spacecraft and for computation of manoeuvres. Such operations are quite costly. With an autonomous system, the required time for ground personnel for navigation purposes can be drastically reduced, and ground navigation tasks can be simplified to monitoring/supervising of the spacecraft navigation system. In order to determine the spacecraft position with the help of a camera, images of celestial bodies with known ephemeris, such as planets and asteroids, must be taken along the trajectory, and the attitude of the spacecraft must be known at that time. Figure 11 shows images of the Earth and the Moon limbs obtained during the experiment with SMART-1.

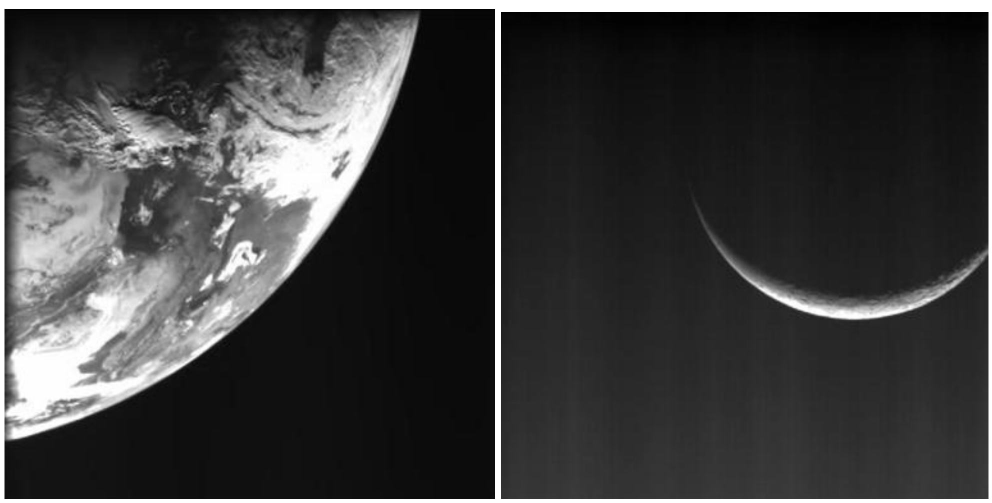

Fig. 11. Earth and Moon limbs obtained with AMIE camera on board SMART-1 in the frame of OBAN experiment

4. CONCLUSION

Due to its very low mass and low power, the Digital Space Micro-Camera can be considered as a "Mission enabling technological element", meaning that it is a key element that opens the door to new highly demanding space missions. The recent successes of its utilisation in several space missions is a proof that the concept is attractive and reliable for resource critical payloads. The modularity of the system allows utilisation for numerous applications, ranging from space missions to spacecraft monitoring or on-ground harsh environement testing. Relying on its previous developments and experience, and in order to meet the challenges of future missions, MCSE is currently developing new generation of imagers with enhanced embedded capabilities, like image compression, etc., that is likely to widen even further the range of applications.

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