THE SCIENTIFIC AND PUBLIC OUTREACH VALUE OF LOW RESOLUTION VISUAL MONITORING CAMERAS ON PLANETARY PROBES

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ABSTRACT

Several space vehicles and space transportation systems launched in the recent years were equipped with so-called visual monitoring cameras (VMC), sometimes also referred to as "visual telemetry". These cameras are comparatively inexpensive, low resolution units of webcam quality, that provide engineers with visual feedback on the deployment of structures, vehicles, stage separations and other complex processes. Once these activities have been performed, these cameras are no longer used and remain mostly inactive.
Experience with the VMC installed on the Mars Express spacecraft, as well as comparable units on the REGINA and MIRIAM sounding rocket experiments, has shown however that despite their low resolution, such cameras have unique capabilities. These can enhance a mission's worth scientifically, operationally and from a public outreach point of view.

1. KEY ADVANTAGES

Amongst the key advantages are their inexpensive procurement, the minimal use of on-board resources and the ease of operations and data processing. The low resolution, typically on the order of 640 by 480 pixels, with an 8 bit encoding and a Bayer filter, produce images of moderate data volume, that can be easily transmitted across the solar system even with low performance telemetry subsystems on top of other data. On Mars Express, the additional data generated by VMC operations never caused any data downlink shortages for data acquired during routine mission operations. If on-board image compression is added, entire series of images and even movies can be generated and transmitted with minimal effort. The cameras also produce data that can be directly imported into standard image processing software and the simplicity of the unit itself demands only a minimal support from mission operations.
Further more, images are available instantly and exhibit an outstanding public outreach value.

2. THE VMC CAMERA ON MARS EXPRESS

The visual monitoring camera (VMC) on Mars Express is the only such camera currently in routine operation and the only one to be ever used beyond its original purpose. It was conceived to provide visual feedback for the separation of the Beagle-2 Mars lander.

2.1 The Mars Express Mission

The European Space Agency mission Mars Express has been in orbit around Mars since December 2003. Mars Express represents the contribution of Europe to the scientific exploration of the Red Planet, and is equipped with a comprehensive set of remote sensing instruments targeting all characteristics of Mars and its environment, from solar plasma to atmosphere to surface to sub-surface. Major discoveries about Mars present and past have been made or confirmed from orbit by Mars Express, a few are shown in the timeline in Fig. 1.
Mars Express was even more ambitious than that. The mission comprised two spacecraft – the Mars Express orbiter and the Beagle 2 lander. Shortly before Mars orbit insertion the orbiter released the lander on a descent trajectory to the Martian surface. Beagle-2 was the in-situ component of the mission, which unfortunately failed most likely during the entry descent and landing phase.
Constructing and delivering such a multi-talented mission in time also entailed a number of unique technical challenges imposed by the mission design and sometimes by the circumstances. Some are also listed below and deliberately inserted in the flow of science highlights – as they occurred in reality.
Whether desired or imposed, these extraordinary achievements gave to the mission control team a reputation, a self-confidence and experience that they always entertained by a spirit of permanent improvement. "If the team can do it, the spacecraft can do it" – within the limits imposed by "spacecraft safety first" and operational proven approaches, the teams managed to steadily enlarge the flight envelope and

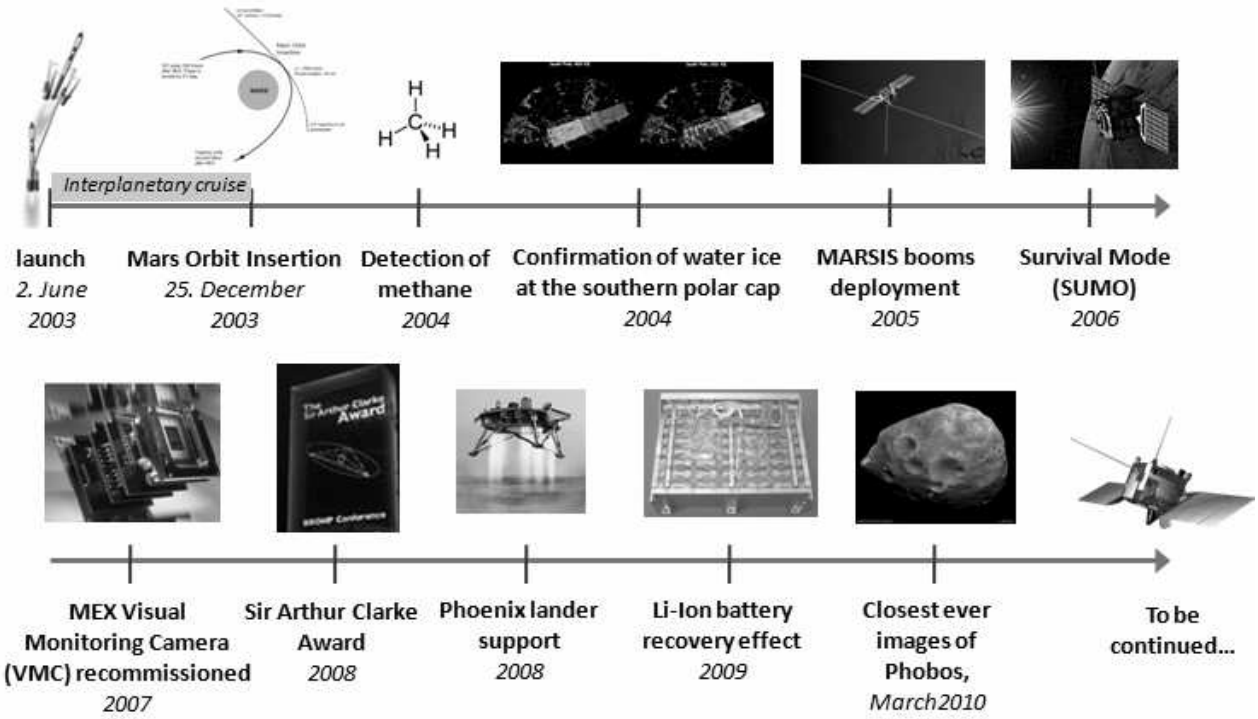

Fig. 1: Mars Express Mission Timeline

bring activities into routine which started as tests, challenges or even cumbersome problems.

For instance the VMC: In order to verify the correct separation and trajectory of the lander a basic monitoring camera was installed on the orbiter to image the retreating lander, and to verify its correct release, spin-rate and coarse trajectory. This technological demonstration was the last and only use of this camera prior to 2007. Usage for science was not considered, given the advanced and highly capable instruments on board the Mars Express orbiter. There was no need for the VMC before it was re-commissioned.

Also many technological reasons pointed towards leaving the VMC unused forever: The camera has a basic command interface with almost all operations being performed at a hardware level, without advanced features such as patchable software or full data bus integration as found on other instruments. Its usage is incompatible with simultaneous other instruments which occupy the mission timeline almost permanently. Also, the intended mission has had an extremely demanding first few years.

However, in 2007 a test campaign was launched to study the possibility of using VMC to produce full disc images of Mars for outreach purposes. The campaign was triggered as a conjunction of two unrelated circumstances. 1) An external request from a group of students to find an original, Mars-related subject including a real experiment designed by them or on their behalf. 2) A team internal request to see "whether the VMC could be used again to make pictures of Mars crescents which cannot be observed from Earth and full planet pictures that cannot be obtained by the narrow field of view of the Mars Express high-resolution instruments.

The MEX VMC has since become "the people's eye on Mars" as part o the "Mars Webcam" campaign, and received an overwhelming popularity through the internet, including forums and amateur-contributed software tools dedicated to VMC image processing.

2.2 Camera Subsystem Description

The Visual Monitoring Camera (VMC) unit is a standard visual telemetry device produced by OIP Sensor Systems of Belgium. The design has flown on several ESA missions to date, including Ariane 502, Cluster-II, XMM-Newton and INTEGRAL.

The VMC is a mechanical housing containing the electronics stack - an IRIS-1 sensor/camera system, a small power supply and a basic analogue TM/TC interface. The completed unit is completely self contained and has a mass of 430g, with a size of 65x60x108mm. This compact and light enclosure helps reduce the design impact of adding a monitoring camera to the spacecraft. The first generation VMC used on Mars Express has a basic serial connection to the data bus with only a single image buffer. Current versions of the camera support (in a similar package) much more sophisticated features such as a multiple

image buffer, SpaceWire date interface and CCSDS packet telemetry.
While in no way comparable to the HRSC (High Resolution Stereo Camera) instrument of Mars Express, the camera still produces impressive images for such a resource-light package. The IRIS-1 sensor is capable of producing 640x480 pixel images with 8 bits per pixel sampling depth. The camera produces grayscale images by default but can be fitted (as with the Mars Express unit) with a Bayer pattern filter to allow post-processing to interpolate colour information from the images. The sensor readout time is 100ms, but with the transfer of the data buffer via serial link to the Mars Express mass memory the minimum real interval between images is approximately 38 seconds. The sensor is fitted with an objective that in the case of Mars Express gives sharp images from a distance of 3m to infinity, with a very wide 30x40 degree field of view.

2.3 Camera Observations

The initial observations by the Mars Express VMC were test observations to confirm camera function, calibrate exposures and rehearse the Beagle-2 separation sequence. Four of these observations were made at various points in the Mars Express cruise to Mars. Where the exposure was appropriate these showed a clear view of part of the blanketed back shell of the Beagle-2 lander.
The primary use of VMC was carried out shortly after Beagle-2 separation on the 19th December 2003 at 08:31. The camera captured a sequence of five images showing the lander departing from the orbiter. These images confirmed that the lander had separated successfully and that the trajectory and velocity were well within acceptable limits. These images were in turn studied in the investigation into the cause of Beagle-2 failure to see if they gave any clues to the possible failure causes. Of particular interest was an object that can be seen moving close to the lander in the images. Ultimately this analysis likely showed no failure but this in itself ruled out several possible failure causes.
A typical Mars image, acquired by the VMC around the apocentre of the orbit above low southern latitudes in early May 2010 is given in Fig. 2. Distinctive surface features are visible along with the snow covered South Polar Region. Another noteworthy feature is that the image was acquired directly over the terminator, a perspective that eludes Earth based observatories for geometric reasons (because Mars is an outer planet).
Images that are acquired around the pericentre of Mars Express' orbit can already show a significant level of surface detail. A composite of an image series acquired during a pericentre observation on March 4, 2010 can be seen in Fig. 3. This particular observation was made to cover parts of the North Polar region, Milancovich Crater and Olympus Mons.

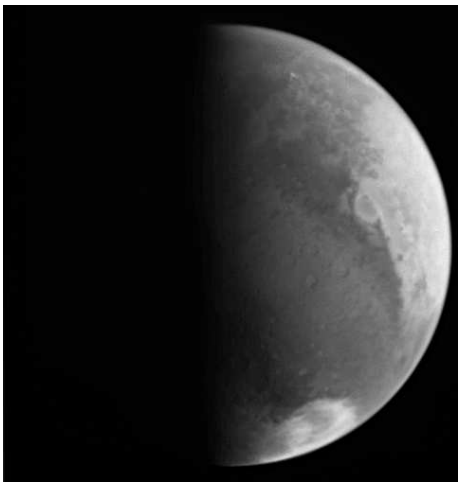

Fig. 2: Image of Mars acquired by the Mars Express VMC on May 7, 2010. (ESA)

Fig. 3: Composite of VMC close-range VMC images acquired on March 4, 2010 ranging from the North Pole (top) to Olympus Mons (bottom right). (ESA)

2.4 Scientific Use

Since images acquired by the VMC instrument are available almost instantly through the Mars Express VMC website [1], both amateur astronomers and professional scientists alike can use these images for

scientific analyses. In the past, VMC images were used to support findings by other instruments as well as primary observations. An excellent example of a scientific contribution by an amateur astronomer can be found in [2].
If routine mission operations allow, dedicated scientific observations are also possible. Fig. 4 shows images of a weather observation campaign targeted at the Hellas Planitia region. The images acquired show changes in cloud patterns for different times of day. Despite the comparatively low resolution, the cloud features are sufficiently discernible to supplement observations made by other instruments, such as spectrometers. If such images are acquired over several hours from around the apocentre of Mars Express' orbit, the dynamics of clouds can be observed. No other instrument is presently capable of such observations on Mars.

Fig. 4: VMC images of Mars acquired within a fortnight in February 2010 directly over the South Pole show changing cloud patterns over Hellas Planitia (ESA).

2.5 Operations and Operational Constraints

Because the VMC instrument is not part of Mars Express' primary scientific payload, its operations are restricted primarily by the requirement of non-interference with primary mission operations. This restriction is further complicated by two facts resulting from its primary intended use:

1. Due to the VMC instrument's design, it can only operate when all other instruments are switched off.
2. The VMC camera has a different boresight vector than other pointed instruments.

These two restrictions require that the spacecraft can only make dedicated VMC observations, rather than "piggy back" observations in parallel to routine operations.

2.6 Programmatic Aspects

Not only good-will, self-confidence and expertise are necessary to insert into a complex system an activity originally not planned; this requires a frame of work that allows for flexibility at all levels, which was already the case for MEX management, planning and technical aspects. The following key aspects are notable and were of paramount importance in the MEX VMC's revival:
- The overall management is flexible: a key is the small size of the teams (not in absolute numbers, but relative to the quantity and complexity of tasks). "Transforming a dead sensor into a living instrument" could also be done easily thanks to the absence of a complex hierarchical structure, by getting higher management to agree to the principle and involve them in a feedback.
- The technical Management is reactive: a long history of ups and downs on the mission has long taught us that "nothing is steady, except change". A good way of mitigating at mission level the "lows" is to get more "highs" even where not formally demanded by mission requirements. Not everything is always possible, but everything possible within the allocated envelope (spacecraft and ground resources, including man hours) should be attempted and, if successful, turned into routine.
- The planning is flexible: this has been imposed by the limitations of the cheap, express, simple and standard spacecraft with respect to its large ambitions. Mission planning at ESOC is permanently checking and ensuring the compatibility of the main instruments between themselves and with the spacecraft resources. Ensuring the "non-interference basis" of the VMC pictures with other science observations (for pointing-attitude, power, data storage and dumping) is therefore a mere extension of processes and tools already in place.
- The planning is reactive: since the beginning of the mission, the MEX planning consists of a series of carefully organised cycles, traditionally long, mid and short term processes, with clearly identified dependencies and independencies. The "opportunistic", reactive VMC planning could be set-up thanks to a solid, structured and pro-active overall planning frame.
- The planning has "lucky gaps": the instrument which is virtually permanently ON (solar wind and plasma analyser) has to be switched off about once a day around apocentre for a wheel off-loading which involves usage of the thrusters. This allows VMC pictures from the highest altitude. Power limitations due do a MEX power anomaly and/or very constrained seasons require reduction of the usage of that

instrument in power limited seasons. This allows for lower altitude pictures (the VMC consumes only 3W). This is an archetypal case of how to benefit from a limitation (insert short shots of a low-power instrument like the VMC when long arks of more power consuming instruments are not possible).
- The technique is flexible: the overall data downlink is controlled by an active data management which checks whether the planned data acquisitions can be returned within the planned ground station passes, including a given margin. One can ensure down to the bit level not only that the data of VMC observations can be returned, but also that it will have no effect on the others. If this is not the case, the VMC observations are simply cancelled or reduced.
- The technique is reactive: there was originally no data store on-board Mars Express for the VMC data. It was temporarily hosted in the unused lander data store thanks to internal spacecraft re-routing; then a dedicated VMC data store was created during re-arrangement of the mass memory to cope with support of the NASA Phoenix Lander. Two years later the VMC store was doubled in size at the occasion of another memory re-mapping.

3. SPACECRAFT DEPLOYMENT OBSERVATIONS ON THE REGINA AND MIRIAM SPACE TESTS

3.1 Background

During the development programme for the hypersonic drag balloon project ARCHIMEDES [3], a novel atmospheric sounding probe for Mars based on the concept of using a ballute (an inflatable drag body) for planetary atmospheric entry, two spaceflight tests were carried out that relied on visual monitoring. The flight test REGINA, launched in April 2006, carried a complement of cameras that confirmed the correct separation of the flight test article from the rocket and the correct automatic deployment of the balloon package from its storage container. During the space test MIRIAM in October 2008, the complement of cameras was augmented with a set of 3 television cameras of slightly lower resolution.

3.2 Camera Subsystem Description

The cameras used on both REGINA and MIRIAM were 2005 model Aosta DV480 consumer cameras with a solid state memory and a standard VGA resolution (640 x 480). The units were stripped of their plastic housing and modified to be usable in vacuum as well as under the high-load environment on board a rocket. They were then tested in a thermal vacuum chamber as well as a vibration test bed according to launcher specifications. The television cameras were PAL standard TV camera heads, which were modified in the same way and underwent the same qualification tests.

3.3 Camera Observations

Typical observations made with these cameras are pictured in Fig. 5 and Fig. 6.

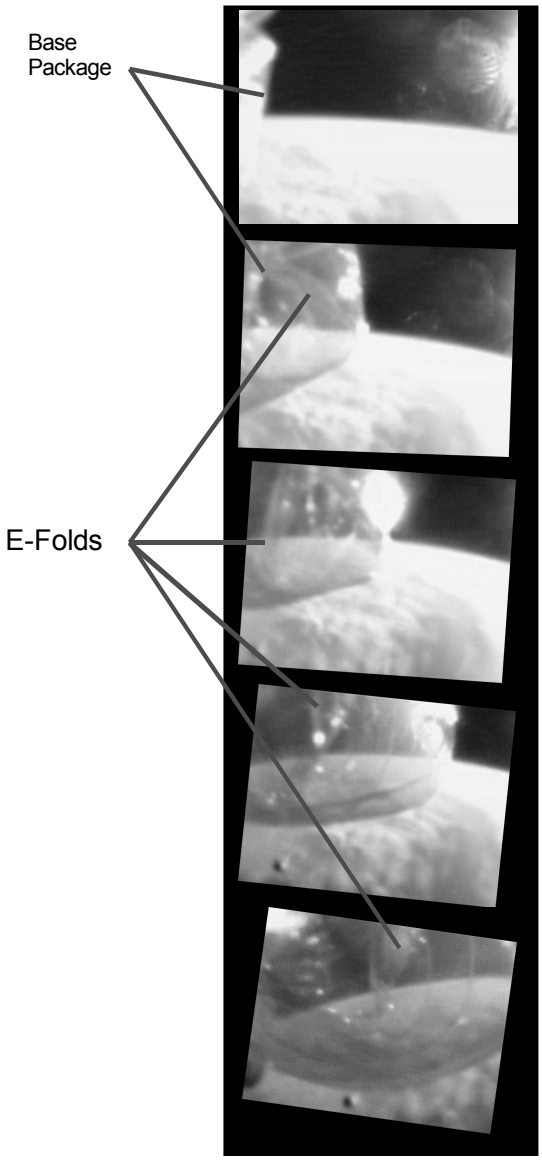

Fig. 5: Deployment sequence of the MIRIAM ballute spacecraft as seen from the PAL standard boom cameras of the service module.

The MIRIAM ballute spacecraft deployed from an automatic storage and deployment control subsystem inside the service spacecraft. Fig. 5 shows the deployment sequence as seen from the TV boom cameras on the service spacecraft pictured in Fig. 6. The latter image was acquired by the solid state video

cameras within the launch adapter ring, which remained attached to the rocket. The booms that took the picture sequence in Fig. 5 can be seen sticking out from the service spacecraft in Fig. 6. The images show clearly that even such a low resolution camera can depict meaningful details. The base package of the ballute can be clearly identified, as well as the seams and pleats in the skin as the gores deploy. The cameras themselves, although they were of consumer quality, proved to be extraordinarily robust. Those cameras which were recovered after the flight could be refurbished and re-flown, although they were neither protected against the hypersonic flow nor the impact into the ground. Despite both REGINA and MIRIAM trajectories were suborbital and the maximum flow velocity was around Mach 5, it proves that modern consumer grade units are well suited for space applications after only a moderate conversion effort.

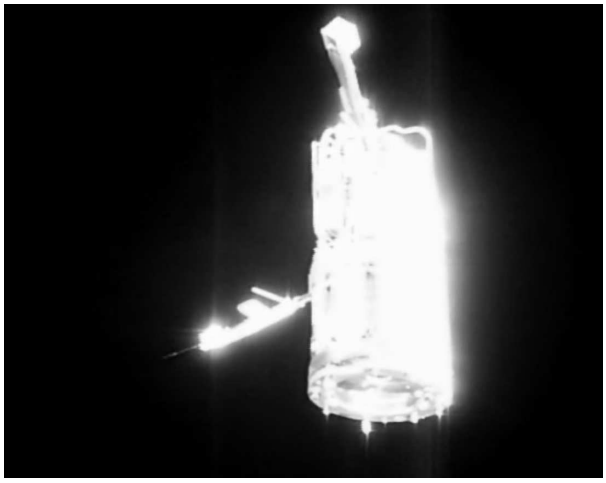

Fig. 6: The MIRIAM service spacecraft after separation from the launch rocket as seen from VGA video cameras within the launcher adapter ring.

4. FUTURE USE ON PLANETARY PROBES AND CONCLUSION

4.1 Engineering and Operational Use

Planetary entry vehicles typically require complex mechanisms to facilitate a soft touch-down, such as parachutes, landing airbags, retrorockets, struts or wheels and possible other deployable appendages. Low resolution monitoring cameras could acquire still images as well as movies that would allow engineers to assess the performance of these systems better. This information could then be used to improve future vehicle designs.

In addition to this, area surveys would help surface operators and mission planners such as rover drivers to plan operations better. This involves the assessment of driving terrain and particularly possible dangers.

4.2 Scientific Use

Images or movies acquired during approach and descend of an entry vehicle would provide scientists with valuable context images that could later be exploited for the following purposes:

1. Assess the landing area with a series of consecutive images that provide an area survey ranging from global to local.
2. Pinpoint the landing site faster.
3. Provide valuable information on interesting targets for surface operations (such as rovers).

4.3 Lessons Learned and Suggestions

Despite the impressive results obtained from these instruments as compared to their complexity, a number of key improvements can be deduced from their operations. These can be summarized as follows:

1. Despite the fact that their intended primary use may be short, integration into the payload suite should be made such that future, secondary uses become easily possible.
2. Possible secondary uses, such as the augmentation of primary scientific observations, should already be assessed at the mission planning stage to identify possible benefits and synergies earlier.
3. Because data losses are less critical than with high resolution scientific cameras and spectrometers, visual monitoring cameras may come with an on-board image compression hardware that may reduce data volume by ratios exceeding 1:10 or even 1:20.

Past experience has shown that simple, low resolution cameras can add a substantial value to the engineering and flight operations of a mission as well as its scientific exploitation and public outreach value.

The robustness of the VMCs and their overall low-demand operations is favourable to expand their usage in flight from one-off sensors to a regularly used payload that can produce thousands of observations.

5. REFERENCES

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