From Monitoring Camera to Mars Webcam – Producing Outreach from Ops

Thomas Ormston[1]
VEGA, Darmstadt, 64293, Germany

Michel Denis[2] and Sibylle Peschke[3]
European Space Agency, Darmstadt, 64293, Germany

and

Jonathan Schulster[4]
SciSys, Darmstadt, 64293, Germany

The European Space Agency mission Mars Express has been in orbit around Mars since December 2003. The mission comprised two spacecraft – the Mars Express orbiter and the Beagle 2 lander. Shortly prior to Mars orbit insertion the orbiter released the lander on a descent trajectory to the Martian surface. 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 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.

The Visual Monitoring Camera (VMC) is carried on several ESA spacecraft, including Cluster, XMM-Newton and Herschel-Planck. It consists of a small CMOS based optical camera which can be fitted with a Bayer pattern filter for colour images. The camera produces a 640x480 pixel array of 8-bit intensity samples which are recoded on ground to a standard digital image format. The camera has a basic command interface with almost all operations being performed at a hardware level, not featuring advanced features such as patchable software or full data bus integration as found on other instruments.

In 2007 a test campaign was begun to study the possibility of using VMC to produce full disc images of Mars for outreach purposes. The results to date have been very encouraging, with an extensive test campaign to verify the camera's capabilities in-flight followed by tuning of optimal parameters for Mars imaging. October and November 2007 featured the first regular operations, with observations occurring approximately every three days. VMC observations are now routinely inserted into the planning cycle by Mission Planning at ESOC, on a non-interference basis to other science observations (for pointing-attitude, power, data storage and dumping).

[1] Mars Express Spacecraft Operations Engineer, ESA/ESOC OPS-OPM, VEGA, Europaplatz 5, 64293 Darmstadt, Germany
[2] Mars Express Spacecraft Operations Manager, ESA/ESOC OPS-OPM, ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany
[3] Mars Express Spacecraft Operations Engineer, ESA/ESOC OPS-OPM, ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany
[4] Mars Express Spacecraft Operations Engineer, ESA/ESOC OPS-OPM, SciSys, Robert-Bosch-Straße 7, 64293 Darmstadt, Germany

From the beginning of this phase of regular operations the images will be made available on the ESOC website as rapidly as possible to provide a 'webcam' image from Mars orbit that can be enjoyed and studied by the public and may be of particular interest to amateur astronomers and university students. A first case study was undertaken with undergraduate students who interacted with the flight team in order to use a VMC picture as the 'experiment' in a project at school.

It is hoped that this constantly changing view from a spacecraft around another planet will provide a huge draw to the general public. The aim is to improve the awareness for routine operations where science results are impressive but operations run on the principle of 'no news is good news'. The visual connection is one of the most direct ways the public can experience the excitement and wonder of an interplanetary mission and with a simple monitoring camera this excitement can be delivered by the operations team at ESOC.

This paper covers the operational and technical issues concerned with rejuvenation of this monitoring camera in 2007. The paper then goes on to describe how the camera's new use as a 'webcam' around Mars will be used for the purpose of public relations and outreach.

Nomenclature

CCSDS	=	Consultative Committee for Space Data Systems
DoY	=	Day of Year
ECSS	=	European Cooperation on Space Standardization
ESA	=	European Space Agency
ESOC	=	European Space Operations Centre
HRSC	=	High Resolution Stereo Camera
IRIS	=	Integrated Radiation-tolerant Imaging System
OBDH	=	On Board Data Handling
VMC	=	Visual Monitoring Camera

I. Introduction

THERE exists a fundamental difficulty within spacecraft operations that concerns the public relations and outreach connected with the work that is done. Spacecraft payloads generate tremendous interest, whether it be with scientific breakthroughs, images of other worlds or even provision of communications, navigation or remote sensing services to Earth. However, with the exception of critical mission phases such as launch, there few outreach opportunities for operations proper. This lack of information is indeed an indication of a well operated routine spacecraft, where its services can be taken for granted. This is by no means a bad thing, but spacecraft operations is still an exciting and inspiring field and it is of benefit to both the public and the operator to have a closer relationship with one another.

To this end, the ESA Mars Express spacecraft carried a small camera that was used to provide visual telemetry of the Beagle-2 lander separation. After this event there was no further use for the unit, but it still held the potential to provide this bridge between the spacecraft operators and the public. By re-commissioning the unit and using it to image the spacecraft's environment – the planet Mars – we have created a dynamic, interesting and interactive new view of spacecraft operations to bring to the public.

II. The VMC Unit[1-4]

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. VMC cameras are currently also scheduled to fly on the Herschel-Planck ESA astronomy missions. The main purpose of these cameras was to monitor deployment events or other spacecraft activities where visual feedback is possible. This "visual telemetry" proved to be far more effective than fitting numerous traditional telemetry sensors to a deployment mechanism such as thermistors or contact probes. Just a few frames from a camera can give information on the success or failure mode of the mechanism and in separation events even give flight dynamics information on separation trajectories. This comes at the price of added mass, complexity and cost compared to traditional sensors but, as will be described, the design of the unit has been tailored to minimize these additions.

Figure 1. Photograph of the IRIS-1 System. *This shows the IRIS-1 "camera on a chip" system and power support internals of the VMC camera before application of the housing.*

The IRIS-1 sensor/camera system is fitted inside a housing with power support equipment to become VMC. 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.

III. VMC History on Mars Express

The VMC on Mars Express was originally added to the spacecraft to monitor the ejection of the Beagle-2 lander. This was both for public relations purposes and also due to the aforementioned ability of visual telemetry to give a far more comprehensive picture of such an event than conventional telemetry sensors. To allow the event to be captured the camera was mounted next to the separation mechanism of the lander, inclined towards the base of the lander to capture the separation event.

Figure 2. VMC Image of Beagle-2. *This image was taken shortly after Beagle-2 ejection and shows the spacecraft retreating from Mars Express.*

A. Beagle-2 Ejection

The only purpose of the camera originally was to capture the ejection event, although this use was limited slightly during the design of the separation operations. Due to the criticality of the event (Mars Express could not capture into Mars orbit with the lander attached) it was decided to minimize the ops as much as possible, meaning that the camera could not be switched on until several seconds after the ejection event. This resulted in the capture of only 4 images of the retreating Beagle-2 lander, images which would prove to be the last images of the failed lander. The images nonetheless served their purpose, proving that the lander had successfully separated and was on the expected trajectory. During the investigation into the loss of the Beagle-2 lander, much study was conducted on the VMC images to assess whether any anomalies were present.

B. VMC Re-Commissioning

Following three years of no VMC operations the decision was taken to study the possibility of reviving the VMC camera in a completely different role. With its wide field of view, and unique (for a 'webcam') location around the planet Mars, it provided a very attractive prospect to ESA public relations and of interest even to the science community. However, as it had never been considered to revive the camera, it was as if starting from scratch with a new instrument – no routine planning or data analysis tools existed and the ability of the camera to even image a planet was a complete unknown. Therefore a commissioning campaign was initiated at the end of 2006 to test the camera's abilities and the planning and data analysis processes that would be needed to successfully operate it.

More of the constraints that were discovered in this phase are outlined in the next section. The actual approach to operating the camera was also defined during this period and the automation tools built around this concept. The camera is relatively basic and therefore did not have a great deal of parameters to test in the commissioning phase. In fact the two primary parameters are the number of images to be captured and the exposure time. The first tests covered a wide range of exposure times to try and empirically derive a good generic set of timings. The exposure range of the camera runs from 0.4 milliseconds to 162.8 milliseconds in 0.8 millisecond steps, then from 200 milliseconds to 95800 milliseconds in 400 millisecond steps. A spread right across these ranges was initially programmed but it was then found that the planet was much brighter than expected and overexposed all but the shortest exposure times. A closer packed spread of images was taken at the shortest exposure times and then standard set of exposure times for routine operations was concluded to be 0.4 ms, 2.8 ms and 14 ms. The test campaign also tested the data transfer and auto-imaging capabilities of the camera, with it autonomously capturing the next image after read-out of the last. These tests were all a success and gave the green light to routine operations.

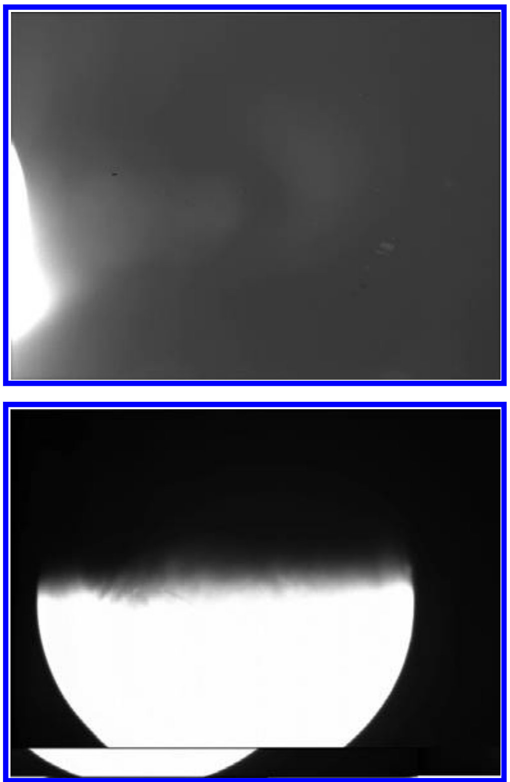

Figure 3. First VMC Mars observations. *The top image was the first attempt at capturing Mars but due to a sign error in the pointing the image only caught an overexposed flare from the edge of the planet! The second test was still overexposed, but much more successful, and proved the viability of the camera.*

Another avenue that was tested during the re-commissioning was one not related to the camera operation. This was the outreach possibility of the camera. To this effect, it was agreed that the VMC re-commissioning would culminate by supporting an outreach project. Three undergraduate science students in a French Lycée had selected as Personal Project the discussion of a question which leaves no young or less young space fan indifferent: "Will the human kind take foot on Mars during the 21st century?" [5] The dissertation for this type of Project has to be supported by an "experiment" of some kind, which was difficult to find considering the ambition of their subject. They had the idea of contacting the Mars Express team for support. We jointly decided that their experiment would be the first VMC image. Their responsibility was to "design" the experiment by understanding and explaining in their memorandum how this picture would be taken with the Mars Express spacecraft and the VMC. The control team responsibility was to deliver this first image so to say "upon request" for an educational purpose. If, already in 2007, unknown young students from about nowhere in France could get an image of Mars just for them, then for sure, the conquest on Mars had seriously started and, with some extrapolation that was the main part of their dissertation, the human kind would step on Mars before year 2100. Quod erat demonstrandum.

The first VMC picture was taken, but Mars was not there, because of a sign error in angle of the camera offset – not the fault of the students, but a valuable lesson learned for the continuation of their studies. The picture was taken again, this time a full success. The three students presented the Project and the Mars picture resulting from their experiment, answered " yes" to their self-chosen question… and got an outstanding mark!

IV. Current VMC Operations

Following a series of initial commissioning tests the next step was to automate the VMC observations as much as possible and schedule the observations so as to exclude any impact on routine Mars Express science observations, including pointing/attitude, data (storage and downlink) and power.

A. VMC Operational Constraints

There are a number of constraints that dictate the operational use of VMC, these largely exist to satisfy the overriding constraint that VMC should cause zero disruption to the routine science operations and engineering tasks of the spacecraft. The primary constraints are, from lowest to highest impact on VMC operations:

1. Power

The power demand of VMC is very low, at approximately 3W average consumption. Given the considerably higher consumption of other instruments and platform equipment the power consumption of VMC is considered largely negligible, although is still modeled for safety during the planning process.

2. Data

The images produced by VMC are relatively compact, but still use up 302 kbytes per image. If multiple images are captured during an observation this can still build up to a non-negligible data volume. While there is usually enough space in the on-board mass memory to accommodate this there is still a problem with scheduling it for dump to ground. Due to this the number of images in an observation is usually limited to ~10 to minimize the requirement for data downlink.

3. Commanding

With finite uplink opportunities and a finite storage space for commands on board the spacecraft there is a limitation on the number of commands that can be allocated to VMC. This also limits the number of images that can be captured in a given observation as each image requires at least one command.

4. Pointing

Because VMC was designed to monitor Beagle-2 eject it is inclined 19 degrees from the normal view direction of the other science instruments. Therefore a special attitude is required that places this boresight directed at the centre of Mars. Unfortunately this is incompatible with communications or science attitudes and so a special pointing must be made for each observation, along with slews to and from that pointing, limiting the maximum duration of an observation to minimize impacting the routine spacecraft timeline. Since the pointing is inertially fixed, the remaining degree-of-freedom of the spacecraft body can be used to ensure power-optimised pointing of the solar arrays throughout the observation.

5. Spacecraft Data Bus

The most limiting constraint on VMC operations is that it cannot be used with any other instruments on Mars Express. This is due to the method of operation that is required for the on board data handling (OBDH) bus that normally operates by polling instruments and using standard CCSDS/ECSS packet telemetry standards. Unfortunately the simplicity of VMC means it has only a basic serial interface and so a large portion of the bus bandwidth which normally would be shared between pollable instruments is monopolized by VMC. Operation of other payloads could overflow the capability of the bus and trigger spacecraft alarms.

By combining all of these constraints the opportunities for VMC observations are limited but sufficient. The data bus constraint has the greatest impact and applies the majority of the filtering effect on VMC opportunities. As payloads on Mars Express are in almost constant operation this leaves only a small window for VMC following spacecraft thruster activities (such as reaction wheel offloading) where the plumes from the thrusters are considered too contaminating for the use of other instruments. This window is always at the orbit apocentre and always lasts one hour, which constrains VMC to high-altitude full disc observations of the planet, with a maximum on duration of about 45 minutes. The frequency of these windows is approximately one per day, but due to other pointing constraints and earth communications windows the real allocation to VMC gives a maximum frequency of approximately 3 observations per week.

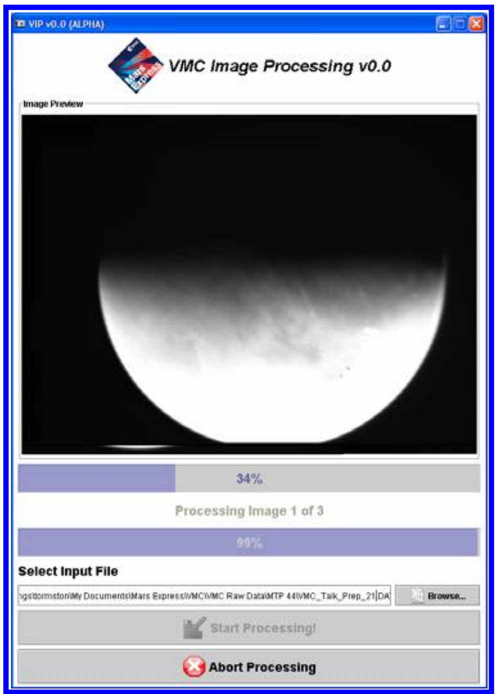

Figure 4. VMC Toolkit Screenshot. *This shows the VMC toolkit software during processing of the data from a VMC observation*

B. End-To-End VMC Operation Description

The end-to-end operations of VMC are following a trend towards automation. This is to relieve the work on the ops team and to speed the latency between observations being made and being available to the public. The following headings detail the end-to-end process of a typical VMC operation.

1. Observation Opportunity Identification

The first, and to date most manual work-intensive, task is the identification of windows in which to perform VMC observations. This requires careful visual analysis of the timeline to identify where VMC slots can be introduced. To obey the constraints listed in the section above this process is done relatively late in the science planning process, 1-2 months before the observation (in the medium-term planning cycle). This is to ensure that all instrument and engineering activities are captured in the timeline, to minimize any disruption due to VMC observations. Following the identification of windows the pointings are scheduled on the master timeline and distributed. Once the VMC data and power usage predicts are available to the planners, the entire plan is re-run to evaluate the power and data situation to ensure that VMC observations have no effect on other instrument operations. Some VMC observations may then have to be excluded on this second iteration.

2. Planning VMC Unit Operations

The VMC ops toolkit software, developed by the ops team in Java, scans the pointing timeline and produces operations request files based on the available windows. Ideally each request would be tailored to the observation, with optimal exposure times calculated and best phasing of time slot for each image within the observation. However, the software is not yet capable of performing these calculations. Therefore a spread of images is captured with a few steps of empirically derived generic exposure times, to ensure that one of the steps will correctly image the planet. The software automatically schedules the commanding related to these images in a request file and passes this file to the Mars Express Mission Planning for inclusion in the spacecraft commanding products.

3. Observation Execution

Once the request file has been delivered the process is the same as for all Mars Express instrument operations and as such is largely transparent to the VMC operator. The activities that take place in this time include the planning and uplink of command files, based on the requests generated in the last step. This then schedules the observation on board the spacecraft, where it is then autonomously executed. The planning office also plans the downlink of the data, which is initially stored in the Mars Express mass memory. Once this downlink has occurred the VMC operator can then retrieve and process the data.

4. Data Retrieval and Processing

Following the completion of the observation and downlink of the data to ground the VMC ops toolkit software is used by the VMC operator to automatically retrieve the data from the Mars Express data distribution server. This toolkit then performs basic processing of the images, reconstructing the raw data into standard PNG image files. At this stage the processing ends, as it is at present. However, future additions to the toolkit could include more comprehensive data reconstruction methods, including sharpening, deconvolution or colour information extraction. The end result images are then passed to the public relations office for distribution on the website. In keeping with the ‘webcam’ theme of the website the latency of this image production is designed to be as low as possible. The data dump usually occurs within a day or two of the observation and then the retrieval and processing steps take less than half an hour. Therefore the latency makes this camera the most recent available view of Mars from any spacecraft.

V. VMC as a Public Relations and Outreach Tool

At present all VMC images have been undertaken either for testing and commissioning purposes or in routine operations to verify the routine ops concept and build up an initial library of images to release online. The next step will be to launch the VMC data products as the ‘Mars Webcam’, fulfilling the intended new role of the camera as a tool for public relations and outreach from the Mars Express operations team. The following two sub-sections cover these two major activities, outlining the possibilities for the future. The third covers the possible use of VMC as an instrument for providing auxiliary science data to the other science instruments.

A. Website/Public Relations

The base level of public relations with the camera involves uploading images from the camera with as low latency as the operational constraints allow. With an average maximum observation output of three per week this will produce a very dynamic and rapidly updating website. The problem of keeping ops websites dynamic is one identified as a critical issue by the ESOC communications office. The hits received for conventional webcams of ESA ground stations and control rooms have proved to be far in excess of any other part of the site. This re-visit potential is what gives the VMC ‘Mars Webcam’ website such potential.

The structure of the website is currently quite basic with a blog-like layout featuring each new observation as a new slot at the top of the webpage, which gradually moves down the page and onto subsequent archive pages as new observations are added to the top of the site. Each observation is in the form of a data card for the observation with the images associated and basic information on the camera settings during the observation such as exposure time and UTC of the image capture. It is hoped to add a script to the VMC toolkit to automatically generate the center point of the image on the Mars surface to allow a generated map showing the surface features visible in the image. It is also possible to add files containing the raw pixel values from VMC, as part of the future website developments mentioned in the next paragraph.

This is the first level of the website design but there are numerous opportunities for expansion. These include more comprehensive image search capabilities, for example based on observation time and location over the planet. Another addition will likely be more in depth articles covering specific interesting observations or explaining details of the design and operation of the camera. Finally, it is the intention to make VMC observations more interactive, allowing members of the public access to raw VMC data to use for educational activities or give basic inputs to the observation planning process via the website.

The primary audience is intended to be educational establishments but there is expected to be a large secondary audience for this VMC website in the public generally but specifically space enthusiasts and amateur astronomers who might take special interest in low-latency Mars images.

B. Education and Outreach

Although creating a dynamic ops website fills the basic public relations requirement for VMC, the use was intended to use this as a vehicle to enhance the resources available to educators, boosting the outreach from the Mars Express ops team. The aim will be to provide as much raw information as possible and allow educators to build outreach activities around this. The most probable destination of most of these projects would be in late school levels or university undergraduate level research.

By providing the raw data there is no limit placed on what these images can be used for. It is thought likely however that the images would be most useful in planetology, studying seasonal variations of the Mars disk and positioning of surface features. The images would also provide an excellent candidate for studies into image reconstruction techniques. In fact due to the lack of expertise within the ops team it is hoped that breakthroughs will be made in the image quality and processing techniques of the images. This can then be fed back, with appropriate accreditation, to the routine imaging processing made by the VMC toolkit. In this way the public and people studying and working with VMC will have a closed loop feedback in the ops process, truly making them feel a part of the operations of an interplanetary spacecraft.

As the operation of VMC and the toolkit is very straightforward it could even be envisaged that the operations planning could be undertaken as an outreach activity. Obviously safeguards would need to be put in place to ensure the safety of the spacecraft and viability of chosen observation slots. It will therefore likely remain that the planning was still undertaken within ESOC but observations could be symbolically ‘selected’ by external parties, again making them feel a real part of the operations of the instrument.

C. Science Utilization of VMC

The VMC was intended originally as a purely ops instrument but having seen the images produced by the camera the Mars Express Project Science Team have shown an interest in acquiring the images for use by scientists on ESA planetary missions. Images from the camera provide excellent context images for the instruments, showing the complete disk of the planet including the state of the ice caps and the cloud cover. This is another task for the future, but it is hoped that the combinations of these context images with the highly detailed readings of the science instruments will provide an even more complete scientific picture of Mars.

VI. VMC Results

The previous sections of this paper have described the technology, operations and purposes for VMC but as it is a camera the end results are also of interest to demonstrate its capabilities. Please find below a series of images captured by VMC with some explanation beneath each.

Figure 5. First full disc image. *This was the first operational full disc image captured of Mars, in 2007 on DoY 57. It shows clearly surface features such as craters and valleys and also a heavy build up of clouds and ice around the south pole (bottom of the image).*

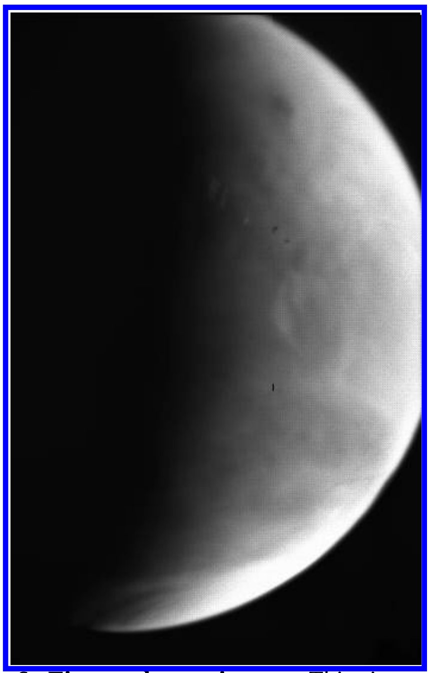

Figure 6. First volcano image. *This image from 2007, DoY 87 was the first image with a Martian volcano, Ascraeus Mons of the Tharsis Montes in the top right of the image. Striped cloud cover can also be seen over the South Pole at the bottom of the image.*

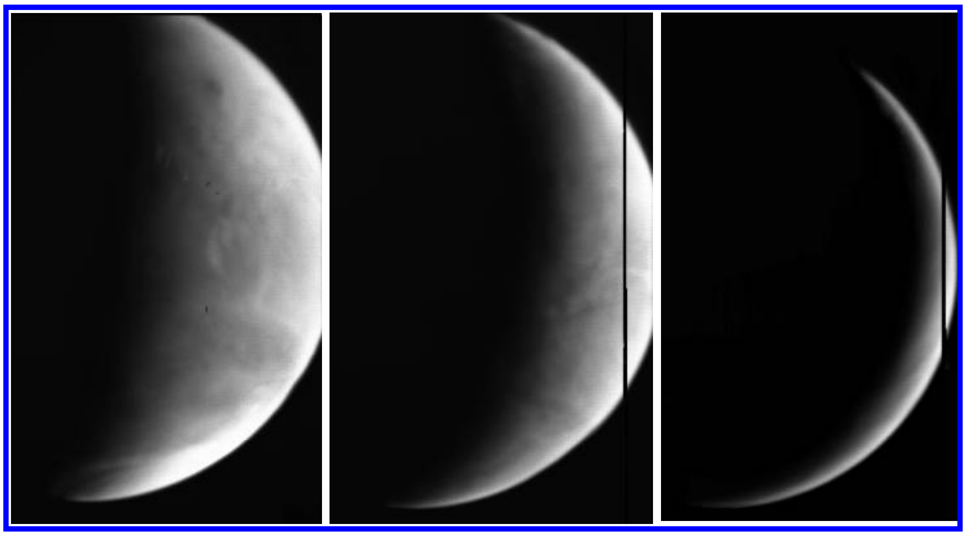

Figure 7. Martian Sunset. *These images are from 2007, (right to left) DoY 87, 99 & 124. They show the planet in various illumination conditions as the phase angle changes. The black lines in the centre and right pictures are artefacts from the camera processing.*

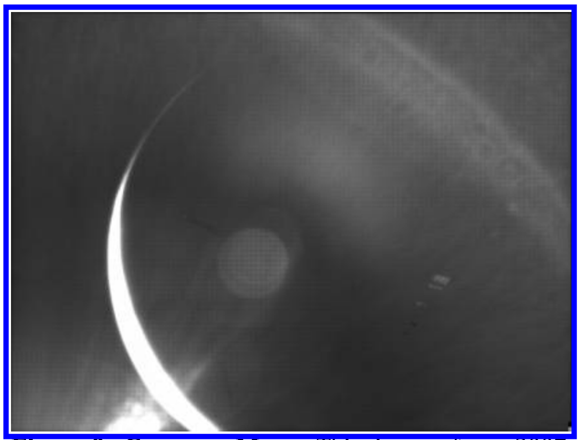

Figure 8. Crescent Mars. *This image from 2007, DoY 140 shows a crescent Mars. The atmospheric horizon glow can be seen in the top left. The bright object in the bottom right is a reflection from part of the spacecraft. The other effects in the top left are lens flare artefacts.*

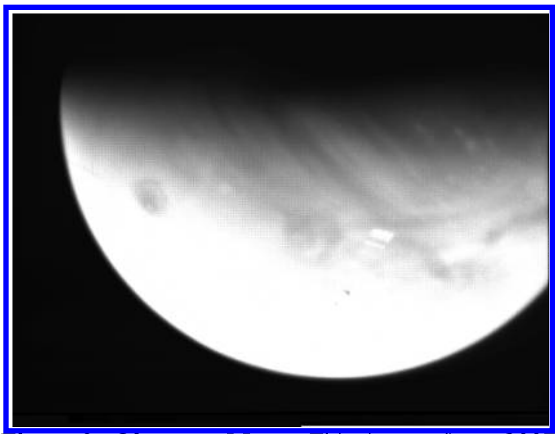

Figure 9. Olympus Mons. *This image from 2007, DoY 288 was the first image by VMC of the largest volcano in the solar system – Olympus Mons. It is the large shadow in the overexposed region to the left of the disc. The spacecraft was over the North Pole at this point, it is in shadow at the top of the image.*

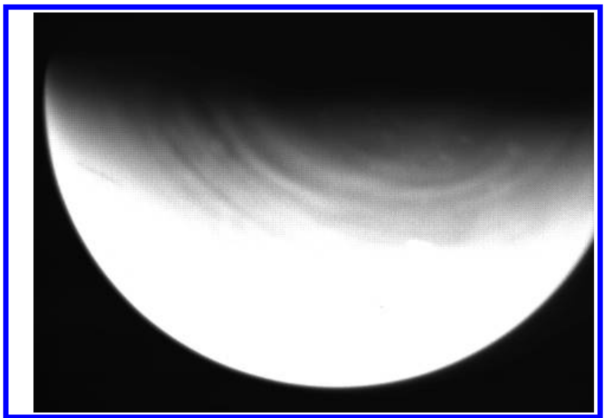

Figure 10. Polar Cloud Vortex. *This image from 2007, DoY 270 demonstrates the weather monitoring capabilities of VMC. It was taken over the North Pole and shows the clouds swept into a spiral vortex pattern by the circum-polar winds.*

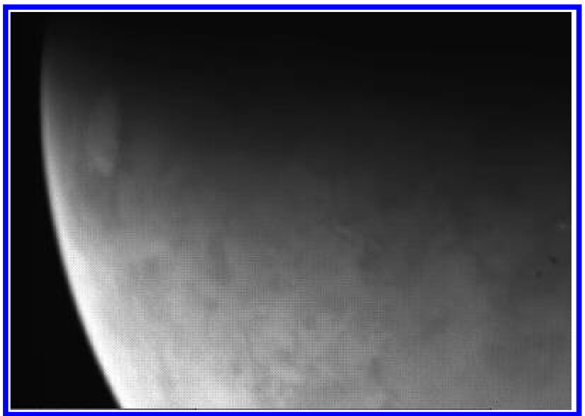

Figure 11. Low Altitude. *This image from 2007, DoY 330 was a rare low altitude (~5000km) opportunity. It shows a dramatic increase in resolution of surface features compared to the high-altitude standard observations.*

Other results from VMC include video montages where multiple images have been stitched together, with corrections for location, and show Mars rotating during a month's worth of images. These types of product are very interesting for public relations and even science; although before they can be reliably produced more work must be done into determining the exact positions on Mars of the image.

VII. Conclusion

The VMC concept of visual telemetry is still a very valid one and one that will hopefully be added to more and more mission as the cost, mass, size and thus design impact of such systems decrease. However, it has been shown that these cameras, while useful for their primary purpose, should not be given up on and indeed can find great success in public relations, outreach or even auxiliary science data gathering. While the VMC on Mars Express images Mars, other VMCs could give similar views and insight into the Earth or give engineering students monitoring capabilities over space mechanisms.

The VMC on Mars Express has captured numerous exciting images purely in its early commissioning stages, the hope is that this impressive production will continue into normal operations when these images and data are made available to the general public and the education and outreach community. Then the goal of bringing the outside world together with the world of spacecraft operations can finally be realized.

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