

Context for the ESA ExoMars rover: the Panoramic Camera (PanCam) instrument

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Abstract: The recently approved ExoMars rover is the first element of the ESA Aurora programme and is scheduled to deliver the Pasteur exobiology payload to Mars by 2015. The 0.7 kg Panoramic Camera will provide multi-spectral stereo images with 65° field-of-view (1.1 mrad/pixel) and high-resolution (85 μ rad/pixel) monoscopic 'zoom' images with 5° field-of-view. The stereo wide-angle cameras (WAC) are based on the Beagle 2 Stereo Camera System heritage (Griffiths *et al.* (2005). *Planet. Space Sci.* **53**, 1466–1488). The Panoramic Camera instrument is designed to fulfil the digital terrain mapping requirements of the mission as well as to provide multi-spectral geological imaging, colour and stereo panoramic images, water vapour abundance and dust optical depth measurements. It can also be used for high-resolution imaging of inaccessible locations on crater walls and to observe retrieved subsurface samples before ingestion into the rest of the Pasteur payload.

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Introduction

The Panoramic Camera (PanCam) imaging experiment is designed to obtain high-resolution colour and wide-angle multi-spectral stereoscopic panoramic images from the mast of the ExoMars rover (as part of the Pasteur payload). Figure 1 shows an artist's impression of ExoMars on the Martian surface.

Launch on a Soyuz Fregat would occur in June 2011 or 2013, with a landing on Mars two years later (to avoid the perihelion dust storm season).

The objective of the ExoMars mission (Vago 2005) is to find evidence of extant or extinct life in the Martian regolith, using a drill system capable of reaching depths of up to 2 m. To achieve this objective it is vitally important to know where to drill. To aid in selecting the correct sample site, the baseline Pasteur payload consists of a set of remote sensing (including

PanCam, an infrared spectrometer and a ground-penetrating radar) and contact instruments (the close-up imager, Mössbauer and Raman/LIBS spectrometers). Once a sample has been acquired it is inserted into an internal analytical suite (i.e. Urey Mars organics detector, GCMS, X-ray diffractometer, microscope and life marker chip) designed to detect a variety of organic compounds.

Therefore, the main scientific objectives to be addressed by the PanCam experiment are:

1. to locate the landing site or most recent rover position and support the ExoMars rover traverse planning;
2. to geologically investigate and map the rover sites;
3. to study the properties of the atmosphere and of variable phenomena;
4. and last, but not least, to support the scientific measurements of other Pasteur instruments, i.e. by identifying the most promising locations for exobiological studies.

The camera system will consist of two identical wide-angle cameras (WACs), arranged on a common pan-tilt mechanism, with a fixed stereo base length of 50 cm. An additional high-resolution camera (HRC), mounted between the WACs, will allow a magnification of selected targets by a factor of 13 with respect to the wide-angle optics.

The camera head assembly will be mounted on top of the rover mast (~1.8 m above the surrounding terrain), which

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Fig. 1. Artist's impression of the ExoMars rover (courtesy of ESA).

can pan 360° about the vertical axis to obtain a full (stereo, colour or multi-spectral) panorama and tilt by $\pm 90^\circ$ in elevation with respect to the horizon. In this way, nearly every possible target can be pointed at by the camera system, in addition to monitoring of the rover's drilling and coring activities.

The PanCam incorporates heritage from the Stereo Camera System flown on the Beagle 2 Mars lander and from the stereoscopic Panorama Camera being presently developed for the NetLander surface modules (Jaumann *et al.* 2000). The baseline PanCam configuration is shown in Fig. 2.

The wide-angle stereo cameras

The wide-angle stereo cameras consist of two identical 'eyes' each composed of a charged-coupled-device (CCD) camera module with 65° field-of-view (FOV) lens and a filter wheel module containing 12 narrow bandwidth interference coated filters. The large WAC FOV is driven by the requirement to minimize the panoramic image data volume that must be returned to Earth (via the Mars Reconnaissance Orbiter for the baseline mission). The Mullard Space Science Laboratory will provide the filter wheel modules (along with WAC science lead and PanCam project management), while the Institute for Space Exploration (in collaboration with Space-X of Neuchâtel) will provide the camera modules.

The WAC camera heads will be equipped with a CCD sensor producing greyscale images of 1024×1024 pixels, quantified in 10 bits, in the spectral range 400 to 1000 nm. These detectors have optics with a focal length of 10 mm, yielding intrinsic resolutions of the cameras of 1.1 mrad. The WAC eyes are expected to weigh 200 g (each) and consume 1.5 W of power.

The high-resolution camera

The HRC is provided by DLR/IPF in Berlin and will utilize an active pixel sensor (APS) with 1024×1024 pixels. The HRC optics have a focal length of ~ 130 mm, yielding a FOV

of 5° . The spatial resolution of this camera (IFOV) is 13 times that of the WACs at about $85 \mu\text{rad}/\text{pixel}$. The HRC is expected to weigh 300 g and consume 0.9 W of power.

The colour capability of the HRC is provided by 'stripe' interference filters, each directly bonded over part of the active area of the APS. Thus, with the limited number of colours required, the additional moving parts of a filter wheel mechanism are not necessary – but the additional complication of having to move the camera head (to mosaic each colour swath across the detector FOV) is introduced.

PanCam science goals

Given the prevailing Martian environment, particularly the extreme dryness and oxidizing surface conditions, there is no expectation of finding evidence of macroscopic life on the surface of Mars today (e.g., ESA Exobiology Team 1999). Even the remains of microscopic life from the putative warmer, wetter period of more than three billion years ago would need to be buried beneath the oxidizing layer to be recognizable as such now. Clearly, therefore, PanCam is not a life detection instrument but instead forms the first tier of the Pasteur payloads multi-level strategy for detecting evidence of biological processes on Mars (Vago 2005).

The first stage of this strategy is a thorough geological mapping of the surface (soil, rocks and outcrops) within sight of the rover using PanCam and the infrared spectrometer. Evidence of water-bearing minerals, water-altered rocks or even water-deposited sediments would then be followed up by the next tier of contact instruments to enable a decision on whether or not to acquire samples for further analysis. In addition, the ground-penetrating radar will be used to map the near-surface stratigraphy and look for evidence of ground water or ice to inform the decision on where to drill.

Therefore, the major geo-scientific objectives of the PanCam images are the identification of surface features such as outcrops, ridges and troughs, and the characterization of different rock and surface units based on their morphology, distribution, and spectral and physical properties. The very high-resolution images together with the colour and stereo capabilities of the camera will be of unprecedented quality for the identification of water-related surface features such as sedimentary rocks.

Any qualified search for extant or extinct life requires a careful survey of the ExoMars rover traverse (in fact, such a survey will determine the traverse). The survey will provide geological and topographical data and should aim to achieve several tasks (the following list is slightly modified from Westall *et al.* (2000), here we list only the bullets which will be addressed by PanCam observations):

- to identify the position of the landing site and determine the rover traverse;
- to provide an assessment of the rock density at each site;
- to determine the rock distribution and its heterogeneity;
- to determine the rock size distribution and assess the evidence for bi- or multi-modal distribution caused by different geological processes;

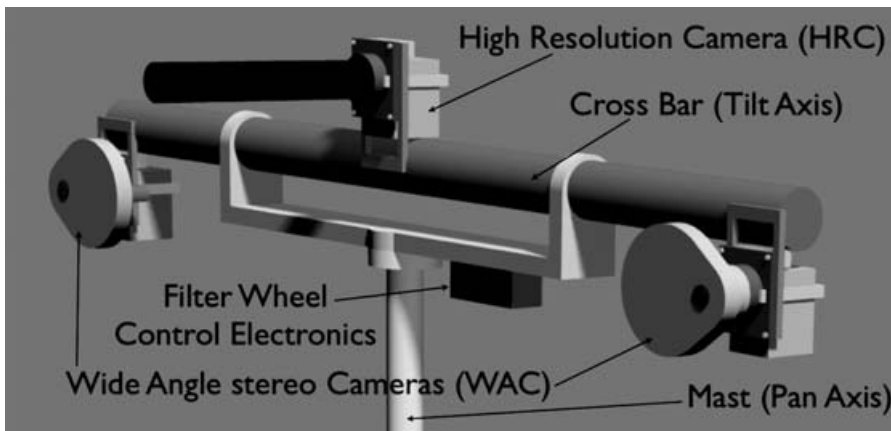


Fig. 2. The baseline configuration of the PanCam system.

- to study the evidence for macroscopic environmental influences on the site (e.g., flooding, impact, volcanism, etc.);
- to investigate aeolian effects (e.g., ripples, wind tails, ventifacts, etc.) for comparisons with global circulation models;
- to study the surface photometric function;
- to investigate the bulk mineralogy of rocks and soils;
- to search for spectral inhomogeneities of soils and compare this to the local morphology;
- to search for spectral inhomogeneities of rocks and investigate evidence for sedimentation and an in-flux of external material;
- to search for potential exobiological targets for the rover, including identification of unusual morphology, to differentiate between weathered and unweathered rock, to study significant colour differences; and
- to identify potential dangers to navigation.

PanCam can perform these essential tasks during the survey of potential exobiological targets illustrating that a flexible, high-resolution colour imager is required for ExoMars. Selected bullet points are discussed in further detail below.

Multi-spectral observations

Multi-wavelength imaging will provide an assessment of the mineralogic inventory of surface materials as well as their weathering state and possible past or present alteration processes (Smith, P.H. *et al.* 1997). The spectral information (see Table 1 for the baseline filter wavelengths) recorded by the PanCam imaging system will be extremely interesting to compare with the results from the Mars Pathfinder and Mars Exploration Rover (MER) (Johnson *et al.* 1999; Squyres *et al.* 2004a, b). Rocks at the Pathfinder landing site have a relatively homogeneous composition, which is rich in silicon and poor in magnesium (McSween *et al.* 1999), whereas at Meridiani Planum the rocks are often rich in sulphate salts with high levels of magnesium (Squyres & Knoll 2005).

At the Pathfinder landing site the composition of the dust is quite different from the rock composition and very similar to dust analysed at the Viking landing sites. This demonstrates that (1) dust is very homogeneous everywhere on Mars and (2) different compositional units exist elsewhere on the planet

(Brückner *et al.* 1999). The characterization of such units is a critical input for resolving the heterogeneity of the Martian crust and to locate sedimentary or at least water-altered deposits. PanCam will observe the dust and rock colours at many sites and will provide clues about the compositional diversity of the upper Martian crust.

Aeolian processes

Wind is known to be the dominant geologic process on the Martian surface (Greeley *et al.* 1992). Evidence for wind-related surface features was visible in image data obtained by the Viking landers and by Pathfinder (Greeley *et al.* 1999). Recent high-resolution images from the Mars Observer Camera (MOC) onboard Mars Global Surveyor (MGS) reveal an abundance of aeolian features such as yardangs or dunes nearly everywhere on Mars (Malin *et al.* 1998), and some of them are possibly active at present (Edgett & Malin 1999). PanCam stereo data will allow the measurement of the orientations of wind drifts and ventifacts (Bridges *et al.* 1999) in digital elevation models at many locations along its traverse. Comparing the results to the orientation of wind streaks seen in orbiter images and to global circulation models (Haberle *et al.* 1999) will help to verify the models and to detect changes in the wind regime over time.

Even before the Pathfinder mission, dust devils were observed in Viking images (Thomas & Gierasch 1985) and were considered as a triggering mechanism for dust storms. During the current MER missions dust devils have been observed many times, particularly by *Spirit* in the Gusev crater (Lemmon *et al.* 2006). PanCam will monitor the horizon for dust devils. By using the windowing techniques, only a thin horizontal band of pixels covering the horizon will be required, reducing the data volume needed to monitor dust devils.

Geological context from orbiter data

High-resolution orbiter images and spectral measurements will provide a regional context of the landing sites, and impact crater counts based on orbiter images will constrain the age of these sites (e.g., Neukum & Hiller 1981). The

Table 1. *WAC baseline filter wavelengths (Beagle 2 Stereo Camera System heritage, see Griffiths et al. (2005)). Note that the Beagle 2 CUL (position R1) would be replaced by a clear filter*

Filter No. ^a	CW ^b (nm)	PB ^c (nm)	Type	Filter No. ^a	CW ^b (nm)	PB ^c (nm)	Type
L1 ^d	481	28	Geology	R1 ^d	720	560	CUL ^e
L2	439	22	Geology	R2	602	21	Geology
L3	532	32	Geology	R3	799	20	Geology
L4	750	18	Geology	R4	906	42	Geology
L5	857	34	Geology	R5	961	29	Geology
L6	930	32	Geology	R6	1003	28	Geology
L7	669	17	Geology/DEM	R7	668	17	DEM
L8	671	17	Far stereo	R8	668	18	Far stereo
L9	928	5.5	Solar	R9	440	22	Far colour
L10	936	5.6	Solar	R10	532	32	Far colour
L11	1000	6	Solar	R11	449	4	Solar
L12 ^f	877	6	Solar	R12 ^f	670	5.5	Solar

^a Filter wheel location (L = left or FM-1, R = right or FM-2 camera).

^b CW = centre wavelength.

^c PB = pass band.

^d Selecting this filter causes the wiper to pass across the front window.

^e CUL = close-up lens (working distance is 8–9 cm).

^f Filter wheel reference home position.

comparison of morphological features at the landing sites with the regional topography derived from orbit by Mars Orbiter Laser Altimeter (MOLA) laser altimetry (Smith, D.H. *et al.* 1998) and High Resolution Stereo Camera (HRSC) stereo imagery (e.g., Neukum *et al.* 1996) will lead to a better understanding of volcano-tectonic and erosional processes, material transport and sedimentation. The mineralogical comparison of multi-spectral data from PanCam and from orbiting instruments, such as the Thermal Emission Spectrometer (TES) onboard MGS (Christensen *et al.* 1998) and especially the Omega mapping spectrometer onboard Mars Express (Bibring *et al.* 2004) and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (Murchie *et al.* 2003), will help to reveal the origin and history of rocks and soils identified along the ExoMars rover traverse.

Atmospheric studies

The major changes on the Martian surface that can be detected by PanCam are caused by aeolian processes and condensation of volatiles, which directly reflect variations in the prevailing near-surface wind regime, and the diurnal and seasonal volatile and dust cycles. Atmospheric studies will concentrate on the detection of clouds, measurements of the aerosol contents and the water vapour absorption at 936 nm (Titov *et al.* 1999). Although currently present at ~30 ppm near the surface, the atmospheric water vapour distribution is vital to understanding the water exchange with the regolith and loss to space. Understanding the water cycle at the ExoMars landing site will provide important clues to the question of extant life in the subsurface.

Scattering by dust particles (aerosols) controls the quantity of light in the sky and its spectral distribution (Thomas *et al.* 1999). Dust particles stripped from dust layers on the ground and ice, nucleated together, are important components of the aerosol load in the atmosphere. The vertical optical depth of aerosols in the atmosphere of Mars varies strongly,

depending on meteorological conditions such as temperature and atmospheric pressure. The results obtained at the Mars Pathfinder and MER landing sites concerning atmospheric conditions are summarized by Smith and Lemmon (1999), Tomasko *et al.* (1999) and Lemmon *et al.* (2006). PanCam will use images of the sky observed near sunrise or sunset to determine single-scattering and multiple-scattering phase functions. The size–frequency distribution of aerosols with altitude can be estimated, when atmospheric layers at various altitudes are successively exposed to sunlight (Markiewicz *et al.* 1999).

Cloud observations are also important since clouds play a crucial role in the dynamics of the Martian atmosphere, redistributing water vapour and removing dust from the atmosphere.

Condensation processes

At the Viking 2 landing site, a bright condensate layer consisting of a mixture of CO₂- and H₂O-frost occurred during the first winter and remained there for 249 sols (Wall 1981). The lifetime of the lower-latitude Pathfinder camera was too short to detect any condensates, and the MERs have also not detected any to date. PanCam will work over a planned lifetime of 180 sols at an as yet undecided landing site up to 45° N. It may, therefore, be feasible to detect seasonal variations that affect the entire area of rover operations (the size of this area is less than 30 km) and to monitor the landing area for changes caused by condensation or sublimation of volatiles. Frost may also form on a daily basis owing to extreme changes of local temperatures. Such changes may be detected during twilight using the PanCam blue filter channels.

Digital elevation models and visualization tools

The primary reason for building a stereo camera system is to use the parallax between the images from each eye to recover the range to objects in the scene (Paar *et al.* 1999). Once

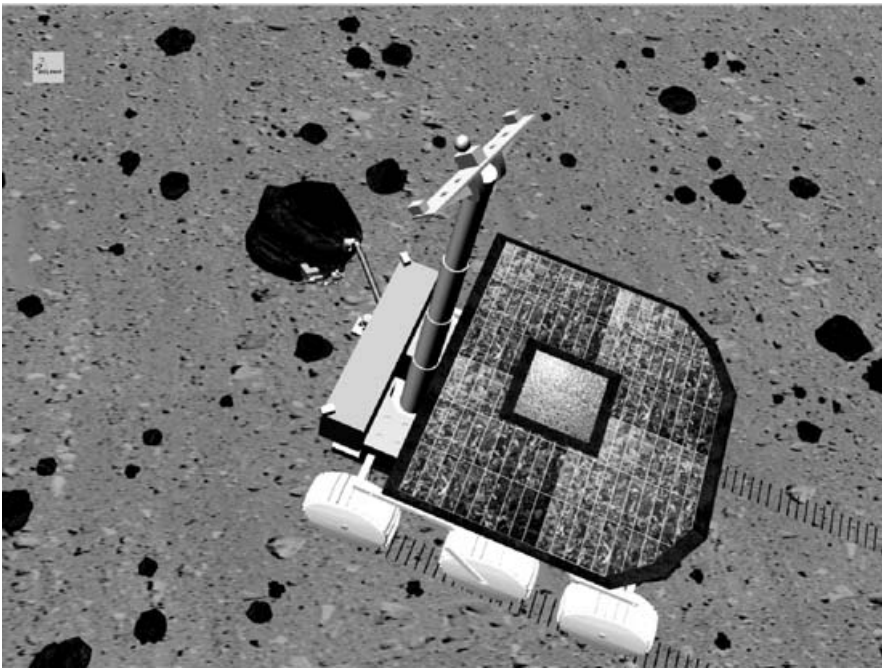


Fig. 3. Example of the rover location external visualization display (for the Astrium Phase A rover designs).

distance measurements (as a function of azimuth and elevation) from panoramas of such stereo image pairs are converted to a digital elevation map (or DEM – with altitude as a function of latitude and longitude), it becomes possible to explore a virtual 3D model of the landscape around the rover.

In addition to this DEM shape from stereo capability, PanCam operators will also have the facility to generate DEM data from single images using photoclinometric techniques. This so-called ‘shape from shading’ provides more accurate information on the high spatial frequencies (Cryer *et al.* 1995; Barnes 2006) ‘than shape from stereo’ but is less accurate for low spatial frequencies (and therefore complementary).

The analysis of the PanCam imagery will eventually result in the generation of precise 2D and 3D map products for the rover landing and exploration sites. To place *in situ* measurements at a landing site into a proper regional context, it is necessary to determine the rover orientation on the ground and to exactly locate the position of the rover site with respect to the available cartographic database. Radio data from the rover alone do not have a sufficient precision to track the rover as it moves across the terrain. Images (including star images, see, e.g., Trautner (2004)) provided by the PanCam camera system will allow the accurate determination of the attitude (tilt and north directions) of the ExoMars rover and the rover location based on landmarks visible to the camera, which can also be recognized in orbital imagery.

Once a DEM of the rover’s surroundings has been generated it will be fed to a suite of software visualization tools. The aim of this software is to display an external view of the rover (based on the manufacturer’s CAD model data, see, e.g., Fig. 3) at its current location, to display the footprints of

the remote-sensing instruments and to demonstrate the workspace volumes of the deployable contact instruments. In addition to providing visualizations of the rover activities for public outreach purposes, such software is vital to enable the rover operators to correctly position both the rover and the contact instruments (including the drill) in order to achieve the mission science objectives.

Finally, although the autonomous ‘minute-to-minute’ navigation decisions will be taken by onboard software based on images from the mast-mounted stereo navigation cameras (and two pairs of body-mounted forward and aft looking hazard cameras), in addition to providing a backup capability PanCam images will inform the ground-based global navigation planning process. The PanCam team therefore intends to supply software tools to assist with incorporating PanCam images into this decision process (Paar *et al.* 1995; Kolesnik *et al.* 1998).

Conclusion

While not specifically a life detection instrument, this paper has demonstrated that the proposed Panoramic Camera for the ESA ExoMars rover will supply a vital part of the Pasteur payload. In addition to the obvious application to mission operations, planning and providing the most easily appreciated dataset in terms of public involvement with the mission; PanCam provides the first link in the Pasteur strategy for detecting evidence of biological activity on Mars. The primary scientific goals of PanCam are as follows (the last four items are also engineering objectives):

- panoramic multi-spectral imaging for a geological context;
- high-resolution imaging of targets of panoramic interest and distant or hard to access features;

- mineralogy/petrology of soil, rocks and abraded surfaces;
- rock abundance and geologic study of the rover traverse;
- the search for evidence of biological activity from rock morphology;
- observation of drilling/coring activities (particularly spectral observation of drill tailings);
- observation of drill samples before internal analyses;
- observation of soil properties from rover tracks and borehole imaging;
- analysis of atmospheric water vapour distribution and dust/aerosol properties;
- multi-spectral observations of Phobos and Deimos;
- DEM creation from stereo image pairs to determine local topography;
- coarse position location from astronomical observations;
- fine position location from comparison of PanCam DEM data and orbital imaging;
- support for route selection and navigation.

The baseline PanCam design achieves these objectives with a 65° FOV stereo pair of 1 megapixel CCD cameras (each equipped with a 12 position filter wheel, see Table 1) producing DEMs and multi-spectral panoramas, and a single 5° FOV HRC to provide ‘zoomed-in’ detail in colour on selected regions.

References

- Barnes, D. (2006). Personal communication.
- Bibring, J.-P. *et al.* (2004). OMEGA: Observatoire pour la minéralogie, l’eau, les glaces et l’activité. In *Mars Express: the Scientific Payload (ESA SP-1240)*, ed. Wilson, A., Scientific Coordination Chicarro, A., pp. 37–49. European Space Agency.
- Bridges, N., Greeley, R., Haldemann, A.F.C., Herkenhoff, K., Kraft, M., Parker, T. & Ward, A. (1999). Ventifacts at the Pathfinder Landing Site. *J. Geophys. Res.* **104(E4)**, 8595–8615.
- Brückner, J., Dreibus, G., Lugmair, G.W., Rieder, R., Wänke, H. & Economou, T. (1999). Chemical composition of the Martian surface as derived from Pathfinder, Viking, and Martian meteorite data. In *Lunar and Planetary Science* vol. XXX, abstract #1250. Lunar and Planetary Institute, Houston (CD-ROM).
- Christensen, P.R. *et al.* (1998). Results from the Mars Global Surveyor Thermal Emission Spectrometer. *Science* **279**, 1692–1698.
- Cryer, J.E. *et al.* (1995). Integration of shape from shading and stereo. *Pattern Recognition* **28(7)**, 1033–1043.
- Edgett, K.S. & Malin, M.C. (1999). MGS MOC, the first year: sedimentary materials and relationships. In *Lunar and Planetary Science* vol. XXX, abstract #1029. Lunar and Planetary Institute, Houston (CD-ROM).
- ESA Exobiology Team. (1999). Exobiology in the Solar System and the search for life on Mars. In *Report from the ESA Exobiology Team Study 1997–1998 (ESA SP-1231)*, ed. Wilson, A. European Space Agency.
- Greeley, R., Kraft, M., Sullivan, R., Wilson, G., Bridges, N., Herkenhoff, K., Kuzmin, R.O., Malin, M. & Ward, W. (1999). Aeolian features and processes at the Mars Pathfinder landing site. *J. Geophys. Res.* **104(E4)**, 8573–8584.
- Greeley, R., Lancaster, N., Lee, S. & Thomas, P. (1992). Martian aeolian processes, sediments and features. In *Mars*, ed. Kieffer, H.H. *et al.*, pp. 730–766. University of Arizona Press, Tucson, AZ.
- Griffiths, A.D., Coates, A.J., Jossel, J.-L., Paar, G., Hofmann, B., Pullan, D., Ruffer, P., Sims, M.R. & Pillinger, C.T. (2005). The Beagle 2 stereo camera system. *Planet. Space Sci.* **53**, 1466–1488.
- Haberle, R.M., Joshi, M.M., Murphy, J.R., Barnes, J.R., Schofield, J.T., Wilson, G., Lopez-Valverde, M., Hollingsworth, J.L., Bridger, A.F.C. & Schaeffer, J. (1999). General circulation model simulations of the Mars Pathfinder atmospheric structure investigation/meteorology data. *J. Geophys. Res.* **104(E4)**, 8957–8974.
- Jaumann, R. *et al.* (2000). The Mars NetLander panoramic camera. *Planet. Space Sci.* **48**, 1377–1392.
- Johnson, J.R. *et al.* (1999). Preliminary results on photometric properties of materials at the Sagan Memorial Station, Mars. *J. Geophys. Res.* **104(E4)**, 8809–8830.
- Kolesnik, M., Paar, G., Bauer, A. & Ulm, M. (1998). Algorithmic solution for autonomous vision-based off-road navigation. In *Proc. 12th Int. Symp. on AeroSense, Detection and Remediation Technologies for Mines and Minelike Targets III*, Orlando, FL, 13–17 April 1998. SPIE.
- Lemmon, M.T. & the Athena Science Team (2006). Mars Exploration Rover atmospheric imaging: dust storms, dust devils, dust everywhere. *Lunar and Planetary Science* vol. XXXVII, abstract #2181. Lunar and Planetary Institute, Houston (CD-ROM).
- Malin, M.C. *et al.* (1998). Early views of the Martian surface from the Mars Orbiter Camera of Mars Global Surveyor. *Science* **279**, 1681–1685.
- Markiewicz, W.J., Sablotny, R.M., Keller, H.-U., Thomas, N., Titov, D. & Smith, P.H. (1999). Optical properties of the Martian aerosols as derived from imager for Mars Pathfinder midday sky brightness data. *J. Geophys. Res.* **104(E4)**, 9009–9017.
- McSween, H.Y. *et al.* (1999). Chemical, multi-spectral, and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site. *J. Geophys. Res.* **104(E4)**, 8679–8715.
- Murchie, S. *et al.* (2003). CRISM: Compact Reconnaissance Imaging Spectrometer for Mars on the Mars Reconnaissance Orbiter. In *Proc. 6th Int. Conf. on Mars*, Pasadena, CA, 20–25 July, 2003, abstract #3062. Lunar and Planetary Institute, Houston, Texas.
- Neukum, G., Carsenty, U., Eichentopf, K., Hoffmann, H., Jaumann, R., Oberst, J., Pischel, R. & Schwarz, G. (1996). The experiments HRSC and WAOSS on the Russian Mars 94/96 missions. *Acta Astronautica* **38(9)**, 713–720.
- Neukum, G. & Hiller, K. (1981). Martian ages. *J. Geophys. Res.* **86**, 3097–3121.
- Paar, G., Bauer, A. & Sidla, O. (1999). Near range stereo for Mars landing site reconstruction. In *Proc. of Industrial Lasers and Inspection*, Munich, 14–17 June, 1999 (*Proc. SPIE*, vol. 3827). SPIE.
- Paar, G., Sidla, O. & Pölzleitner, W. (1995). Natural feature tracking for autonomous navigation. In *Proc. 28th ISATA Conf. on Robotics, Motion and Machine Vision*, Stuttgart, Germany, October 1995. *Proc. SPIE* **3827**, 133–143.
- Smith, D.E. *et al.* (1998). Topography of the northern hemisphere of Mars from the Mars Orbiter laser altimeter. *Science* **279**, 1686–1692.
- Smith, P.H. *et al.* (1997). The imager for Mars Pathfinder Experiment. *J. Geophys. Res.* **102(E2)**, 4003–4025.
- Smith, P.H. & Lemmon, M. (1999). Opacity of the Martian atmosphere measured by the imager for Mars Pathfinder. *J. Geophys. Res.* **104(E4)**, 8975–8985.
- Squyres, S.W. & the Athena Science Investigation Team (2004a). The Spirit Rover’s Athena Science Investigation at Gusev Crater, Mars. *Science* **305**, 794–799.
- Squyres, S.W. & the Athena Science Investigation team (2004b). The Opportunity Rover’s Athena Science Investigation at Meridiani Planum, Mars. *Science* **306**, 1698–1703.
- Squyres, S.W. & Knoll, A.H. (2005). Sedimentary rocks at Meridiani Planum: origin, diagenesis, and implications for life on Mars. *Earth & Planet. Sci. Lett.* **240**, 1–10.
- Thomas, N., Markiewicz, W.J., Sablotny, R.M., Wuttke, M.W., Keller, H.U., Johnson, J.R., Reid, R.J. & Smith, P.H. (1999). The colour of the Martian sky and its influence on the illumination of the Martian surface. *J. Geophys. Res.* **104(E4)**, 8795–8808.
- Thomas, P. & Gierasch, P.J. (1985). Dust devils on Mars. *Science* **230**, 175–177.
- Titov, D.V. *et al.* (1999). Measurements of the atmospheric water vapour on Mars by the Imager for Mars Pathfinder. *J. Geophys. Res.* **104(E4)**, 9019–9026.

- Tomasko, M.G., Doose, L.R., Lemmon, M., Smith, P.H. & Wegryn, E. (1999). Properties of dust in the Martian atmosphere from the imager on Mars Pathfinder. *J. Geophys. Res.* **104(E4)**, 8987–9007.
- Trautner, R., Manaud, N., Michael, G., Koschny, D., Griffiths, A., Coates, A., Josset, J.-L. & Beauvivre, S. (2004). Determination of the Beagle 2 landing site. In: *Proc. Int. Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, Lisbon, Portugal, 6–9 October, 2003 (*ESA SP-544*), ed. Wilson, A., pp. 175–181. European Space Agency.
- Vago, J.L. (2005). *ExoMars Science Management Plan, EXM-MS-PL-ESA-00002*.
- Wall, S.W. (1981). Analysis of condensates formed at the Viking 2 Lander site: the first winter. *Icarus* **47**, 173–183.
- Westall, F. *et al.* (2000). An ESA study for the search for life on Mars. *Planet. Space Sci.* **48**, 181–202.