HRSC: the High Resolution Stereo Camera of Mars Express

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The High Resolution Stereo Camera (HRSC), originally developed for the Russian-led Mars-96 mission, was selected as part of the Orbiter payload for ESA's Mars Express mission. The HRSC is a pushbroom scanning instrument with nine CCD line detectors mounted in parallel in the focal plane. Its unique feature is the ability to obtain near-simultaneous imaging data of a specific site at high resolution, with along-track triple stereo, four colours and five different phase angles, thus avoiding any time-dependent variations of the observational conditions. An additional Super-Resolution Channel (SRC) – a framing device – will yield nested images in the metre-resolution range for detailed photogeologic studies. The spatial resolution from the nominal periapsis altitude of 250 km will be 10 m px^{-1}, with an image swath of 53 km, for the HRSC and 2.3 m px^{-1} for the SRC. During the mission's nominal operational lifetime of 1 martian year (2 Earth years) and assuming an average HRSC data transfer share of 40%, it will be possible to cover at least 50% of the martian surface at a spatial resolution of ≤ 15 m px^{-1}. More than 70% of the surface can be observed at a spatial resolution of ≤ 30 m px^{-1}, while more than 1% will be imaged at better than 2.5 m px^{-1}. The HRSC will thus close the gap between the medium- to low-resolution coverage and the very high-resolution images of the Mars Observer Camera on the Mars Global Surveyor mission and the *in situ* observations and measurements by landers. The HRSC will make a major contribution to the study of martian geosciences, with special emphasis on the evolution of the surface in general, the evolution of volcanism, and the role of water throughout martian history. The instrument will obtain images containing morphologic and topographic information at high spatial and vertical resolution, allowing the improvement of the cartographic base down to scales of 1:50 000. The experiment will also address atmospheric phenomena and atmosphere-surface interactions, and will provide urgently needed support for current and future lander missions as well as for exobiological studies. The goals of HRSC on Mars Express will not be met by any other planned mission or instrument.

1. The Challenge

Europe will make a major contribution to the international programme of Mars exploration with the launch of Mars Express in 2003. The scientific objectives of the orbiter include the significant task of completing the high-resolution reconnaissance of Mars from orbit and the partial recovery of the scientific objectives of the lost Russian Mars-96 mission.

Imagery is the major source for our current understanding of the geologic and climatologic evolution of Mars in qualitative and quantitative terms. It has the potential to enhance our knowledge of Mars drastically and is an essential prerequisite for detailed surface exploration. Therefore, a prime objective of the Mars Express orbiter is the photogeologic analysis of the martian surface at high resolution. For this task, the existing second flight model of the High Resolution Stereo Camera (HRSC) developed for Mars-96 was selected. This pushbroom camera will provide simultaneously high-resolution, stereo, colour and multiple phase-angle coverage and thus will acquire imaging data of unprecedented scientific quality. In response to the urgent demands for very high-resolution imagery in the metre-range, a complementary Super-Resolution Channel (SRC) was added. This boresighted channel serves as the 'magnifying lens' by providing image strips nested in the wider swath of the HRSC stereo and colour scanner.

The reconnaissance task is quite challenging: in only 2 Earth years – the nominal operational lifetime of Mars Express – at least half of the martian surface shall be covered at a pixel resolution better than 15 m, three quarters of the surface at 30 m per pixel and almost the entire surface at least at 100 m px^{-1}. In addition, about 1% will be observed at about 2 m px^{-1}. The images will allow surface distances, heights and the colours of different rocks to be measured. During imaging, the camera is 250 km or more above the martian surface. The camera processes internally up to 9 million pixels per second; the output data rate (after on-line compression) to the spacecraft memory depends on the altitude and can reach up to 25 Mbit s^{-1}, i.e. 200 Mbit of memory are filled with compressed data within several minutes. Each and every bit acquired by the camera is extremely valuable because most of the covered regions will be overflown only once at the highest resolution.

Such data will not be acquired by any other current or planned mission. The HRSC image data have a high potential for unravelling the geologic and climatologic history of Mars. It will also provide the required database for the preparation and planning of future sample-return missions, as well as other robotic and human exploration.

2. The Science

The HRSC directly addresses two of the main scientific goals of the Mars Express mission (high-resolution photogeology and surface-atmosphere interactions) and significantly supports another two (atmospheric studies and mineralogical mapping). In addition, the imagery will make a major contribution to characterising the landing site geology and its surroundings for the Mars Express and other Mars missions (e.g. NASA's Mars Exploration Rovers). The scientific objectives and measurement goals have been formulated by an international team of 45 Co-Investigators (Co-Is) from 10 countries under the leadership of the Principal Investigator (PI). The image data will focus on:

- characterisation of the surface structure and morphology at high spatial resolution of ≥ 10 m px^{-1};
- characterisation of the surface topography at high spatial and vertical resolution;
- characterisation of morphological details at super-resolution of up to 2 m px^{-1};
- terrain classification at high spatial resolution by means of colour imaging;
- refinement of the geodetic control network and the martian cartographic base;
- characterisation of atmospheric phenomena;
- characterisation of physical properties of the surface through multi-phase angle measurement;
- observation of Phobos and Deimos.

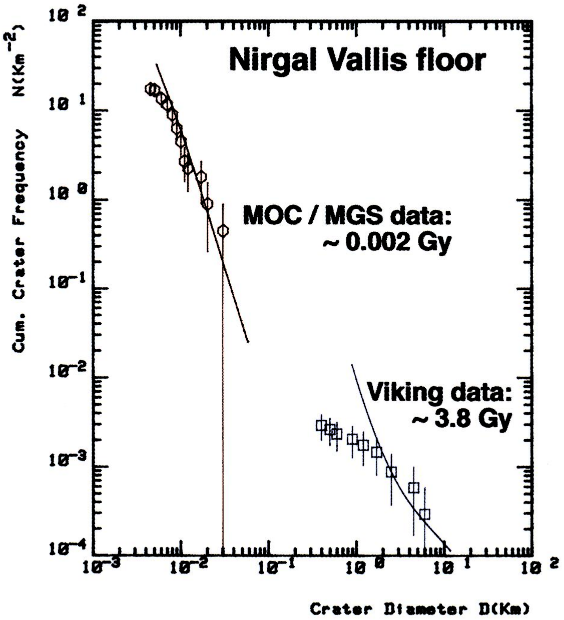


Fig. 1. Nirgal Vallis floor surface ages. Cratering counts on MOC data reveal the near-recent aeolian activity at the floor of Nirgal Vallis, while the formation of the valley more than 3.8 Gy ago can be roughly constrained based on Viking data. Note the obvious gap in spatial resolution to be closed by the HRSC. ***(counts by D. Reiss, DLR)***

These will dramatically increase our knowledge about the planet with special emphasis on:

— the geologic evolution of the martian surface;
— the evolution of volcanism and its influence on the martian environment;
— information on the past climate, its variability and the role of water through martian history;
— the structure of the martian crust and the elastic response of the lithosphere;
— surface-atmosphere interactions (variable features, frost) and aeolian processes and phenomena;
— analysis of atmospheric phenomena (dust devils, cloud topography, aerosol content);
— characterisation of past, present and future landing sites and support for lander experiments;
— support for exobiological studies.

Looking at the previous martian imagery and the expected performance of cameras and altimeters aboard current and planned missions, HRSC's imaging data will close the gap between medium- to low-resolution coverage and the very high-resolution images of the Mars Observer Camera (MOC) on Mars Global Surveyor, as well as the *in situ* observations and measurements by landers. It will substantially increase the very high-resolution image coverage. Such data will not be provided by any other instrument on any other planned mission. The experiment will also contribute significantly to the scientific objectives of past, current and future Mars lander modules (e.g. Mars Pathfinder; the lander missions of 2003 with the Mars Exploration Rovers; sample-return missions) by providing context information on the geological setting of the landing sites. Landing site characterisation will address geological and topographic mapping for scientific interpretation, as well as landing safety and mobility characteristics of future sites.

Orbital imagery in the 10 m px^{-1} range, as obtained by the HRSC, is an essential prerequisite to detailed surface exploration and to solving many of the open questions such as volcanic evolution or the role of water throughout martian history. The

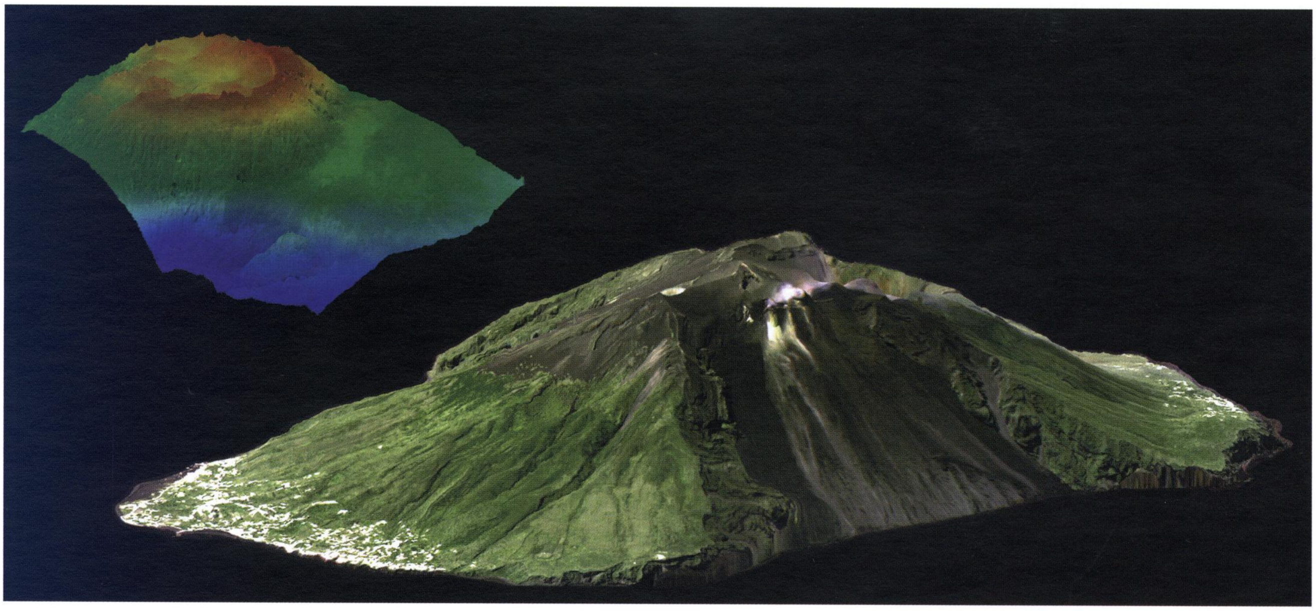


Fig. 2. An example of the expected data return from the HRSC. During standard operations, the HRSC will provide stereo and colour information as shown in this example from the airborne HRSC experiment at the Aeolian island of Stromboli. Here, spatial and vertical resolutions of 40 cm were obtained (main image). For Mars, resolutions in the 10 m range are expected. For comparison, a Digital Terrain Map (DTM) of Arsia Mons in the available DTM resolution of 1 km px^{-1}, derived from Viking data with a resolution of 170 m px^{-1}, is shown (top left).

zoom-in capability of the SRC channel for targeted observations in the metre-range will follow-up these questions at even greater detail.

The ability to study morphologic surface features in more detail by photogeology is complemented by the possibility of deriving ages even for small features like valley floors, surfaces of former lakes, and debris aprons from creep or lavaflows. High-resolution imagery enables the counting of craters much smaller than the features themselves and is essential for reconstructing the geologic history and sequencing of events. The reconstruction of the martian cratering record requires the ability to determine the crater-size frequency distribution at all scales. This is impossible at the moment because 10 m resolution is insufficient and there is little coverage available in the metre-range (see Fig. 1). Closing this gap is a major objective for the HRSC.

The stereo and colour capabilities will both significantly enhance the interpretation of the imaging data (Figs. 1 and 2). For instance, the accurate determination of erosion rates, the modelling of various geologic processes such as water flow, ice-abetted creep, and emplacement of lava flows, is presently limited by the lack of information on local elevation differences. The colour information will be important for terrain classification, detecting compositional layering, variations in surface materials and their composition, and recognising different surface processes.

A key aspect in the evolution of Mars is the role of water in the different epochs. Valley networks and outflow channels provide ample evidence of the existence of liquid water or ice on or in the ancient surface of the planet. Small gullies discovered in MOC images might indicate rather young or even recent erosional activity by water. The present surface, however, is essentially water-free (with the exception of the small residual water ice caps on the poles), and the atmosphere contains only minor amounts of water vapour. Though some water might have escaped into space, the question of water on the surface and where it is now is one of the great unanswered questions in the exploration of Mars.

Permafrost and ground water are considered as the most likely candidates for large water reservoirs in the subsurface. The past or present existence of ground ice is indicated by various morphologic surface features, e.g. rampart craters, terrain softening, and features from the interaction of magma and permafrost. The latitudinal variation of the depth of permafrost has been inferred from the minimum diameter of craters with fluidised ejecta flows (rampart ejecta). Future topographic and morphologic information must be detailed enough to map the exact distribution of ejecta and to determine precisely its volume. If a substantial amount of subsurface ice is present, a terrain can be degraded, or 'softened', by gravity-induced viscous creep of surface material. The degree of such terrain softening can be accurately determined only if the topographic data have spatial and vertical resolutions high enough to discriminate between undisturbed and softened ground (e.g. sharp *vs.* broad slope inflections; concave *vs.* convex slope segments). In a similar manner, the volume of surface features (e.g. thermokarst depressions) caused by the interaction of ground water or ground ice with magma can be calculated only on the basis of sufficiently precise stereo information with horizontal and vertical resolutions better than that of the addressed features (typically of the order of tens or hundreds of metres).

A variety of mechanisms has been invoked to explain the origin of valley networks and outflow channels, including surface water runoff, glacial processes, groundwater sapping and mass wasting. Runoff implies a warmer, denser atmosphere, which places important constraints on the evolution of the atmosphere as a whole. It is a cornerstone not only for the development of Mars' aqueous history but also for the question of life having ever existed on Mars. A critical unknown in the development of valleys and channels is the amount of water needed to create these features and the maximum discharge rates. These can be computed only if reliable cross-sectional profiles through the channels are available; the longitudinal slope of the channel floor also needs to be known.

The existence of ancient palaeolakes and sedimentary basins in the northern lowlands of Mars is one of the most debated topics in martian geology. If ocean-sized bodies of water or mud ever persisted on Mars, they would have had a substantial impact on the atmosphere and global climatic conditions. Even though a lot of effort has been spent in trying to identify evidence for such terminal lakes, into which the outflow channels would have spilled their load of water and sediment, the work suffers from the lack of extended high-resolution imaging data. Lacustrine features that would prove the existence of lakes are very subtle and only a few could be definitely identified in high-resolution Viking Orbiter images. MOC data show evidence for layered deposits in many impact craters, suggesting that standing bodies of water occurred in these locations. Such features are abundant and widespread over the entire planet. If there were lakes, their extent will be determined only by continuous high-resolution coverage to trace faint wave-generated shorelines surrounding them. Once a shoreline has been identified, the volume of water in a lake can be derived from topographic information only. This will help to decide whether lakes periodically covered as much as a quarter of the planet or were comparable in size to the volumes discharged by individual floods. This, in turn, will significantly improve our understanding of the martian water inventory and palaeoclimate.

Mars has had a long and varied volcanic history. Based on Viking data, the youngest volcanic deposits were thought to occur at Olympus Mons. Evidence from crater counts and martian meteorites suggest that Mars could be volcanically active even today. MOC images then revealed a number of young lava flows (as young as a few million years) in several volcanic provinces such as Olympus Mons, Tharsis, Elysium and Amazonis Planitia. Models of the formation of Mars indicate that, at the end of heavy bombardment, the global heat flow was about five times the present value and was even higher during heavy bombardment. Such high heat flows imply high rates of volcanism early in the planet's history, yet available morphologic evidence for volcanic activity in this period is rather sparse because the older terrains are highly modified and much of the earlier history is not visible in available images. A multitude of volcanic features reflecting a variety of volcanic processes has been found on the martian surface, which can be divided into central cones and volcanic plains. More than 60% of the surface is covered by plains units of all types. Some are certainly volcanic and some are undoubtedly of other origin. In many cases, however,

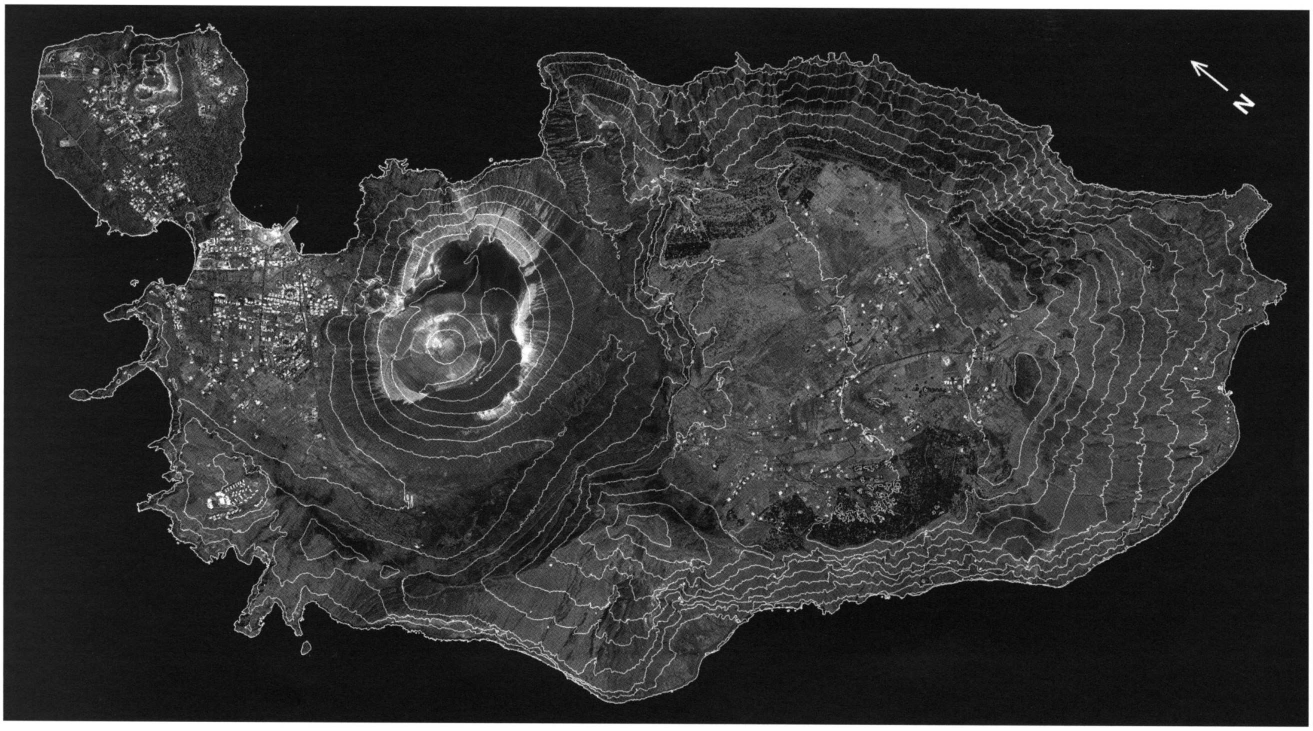


Fig. 3. HRSC orthoimage mosaic of Vulcano Island (I) with 50 m contour lines derived from HRSC stereo data. Obtained during the HRSC flight campaign of May 1997 at an altitude of 5000 m with a spatial resolution of 20 cm px^{-1} for the nadir and 40 cm px^{-1} for the stereo lines.

their origin is interpreted controversially. Volcanic edifices were classified into three different categories based on their morphologies: with shield volcanoes, domes (tholi) and composite cones, and highland paterae. Lava flow deposits are associated with most of the volcanoes. Their morphology suggests high fluidity, which corresponds to a mafic to ultramafic composition by terrestrial analogy. This interpretation is confirmed by the chemical analysis of the SNC meteorites. The results of Mars Pathfinder indicate the presence of more silicic volcanic materials, which implies a higher degree of crustal fractionation than previously thought. The different environmental conditions on Mars, however, with lower gravity and lower atmospheric pressure, could be responsible for a larger amount of explosive activity than on Earth, assuming similar mafic composition and similar volatile content. High-resolution imaging and topographic information is essential for a better understanding of the formation processes and the evolution of volcanic features. The volcanic history is intimately tied to the climatic history and the history of internal processes. Volcanic activity, especially on the Tharsis bulge, could also explain the occurrence of outflow events and the formation of thermokarst features. From Viking imagery we know that a spatial resolution of about 10 m px^{-1} is sufficient to recognise single lava flows within the complex flows found on the flanks and around the shield volcanoes. Quantitative models to estimate the diffusion rate, yield strength and composition of lavas are based on the length, width and volume of a single lava flow as well as on the local topography. The recognition of explosive deposits requires the detailed analysis of erosional features, while many small possible volcanic features like the domes in the lowlands remain enigmatic without higher resolution imagery or have not yet been discovered with existing data.

Wind has played a major role in shaping the martian surface and is still active. Both erosional and depositional landforms are widespread features. The most prominent features are dunes occurring either in large dune fields or as isolated patches. Other aeolian features are wind streaks, yardangs, pits and grooves. It is not clear if dunes

Fig. 4. Example of an HRSC data product. Vulcano Island in a perspective view based on a Digital Elevation Model from HRSC-A stereo and multispectral data. The resolution is 25 cm from 6 km flight altitude.

are still active despite some hints in MOC data. High-resolution imagery and the possibility of analysing the population and degradational state of small craters over a large area are essential for a better understanding of dune formation and evolution.

Atmospheric studies are a prime objective for the cameras aboard the NASA Mars Surveyor missions, which will have increased our knowledge of atmospheric circulation and the cycles of volatiles and dust before the launch of Mars Express. A high-resolution, multicolour and multiphase stereo instrument, however, will make a significant contribution to our understanding of atmospheric phenomena on Mars, especially of cloud properties, local wind regimes, dust devils, variations in aerosol content and the vertical structure of the atmosphere.

Detailed mapping (geology, morphology, topography, composition, etc.) is the prerequisite for the proper characterisation and selection of areas of interest for lander missions, mobile surface activity and sample return. An imaging instrument gathering high-resolution, stereo and colour imagery (Figs. 3 and 4) of large parts of the martian surface will provide the required database. One of the surprising results from MOC/MGS was the discovery that the martian surface appears completely different in images with different spatial resolution. Surfaces that seem smooth at typical Viking scales (60-100 m px^{-1}) show a rough morphology at the very high resolution of MOC (few m px^{-1}) and vice-versa. MOC, however, is observing only a small fraction of the martian surface and much more image data at similar resolution are needed.

Finally, Mars Express will encounter Phobos several times during the nominal mission, when the node of its orbit on the equatorial plane is at the Phobos distance from Mars. There will be periods of about a week when close flybys will occur naturally, with little impact on mission operations. At these times, the HRSC Co-I Team is interested in imaging Phobos at high- and very high-resolution, as well as in colour and stereo. These images will be of higher resolution than the Viking images and will provide an excellent opportunity for detailed geological, compositional, regolith and orbital studies.

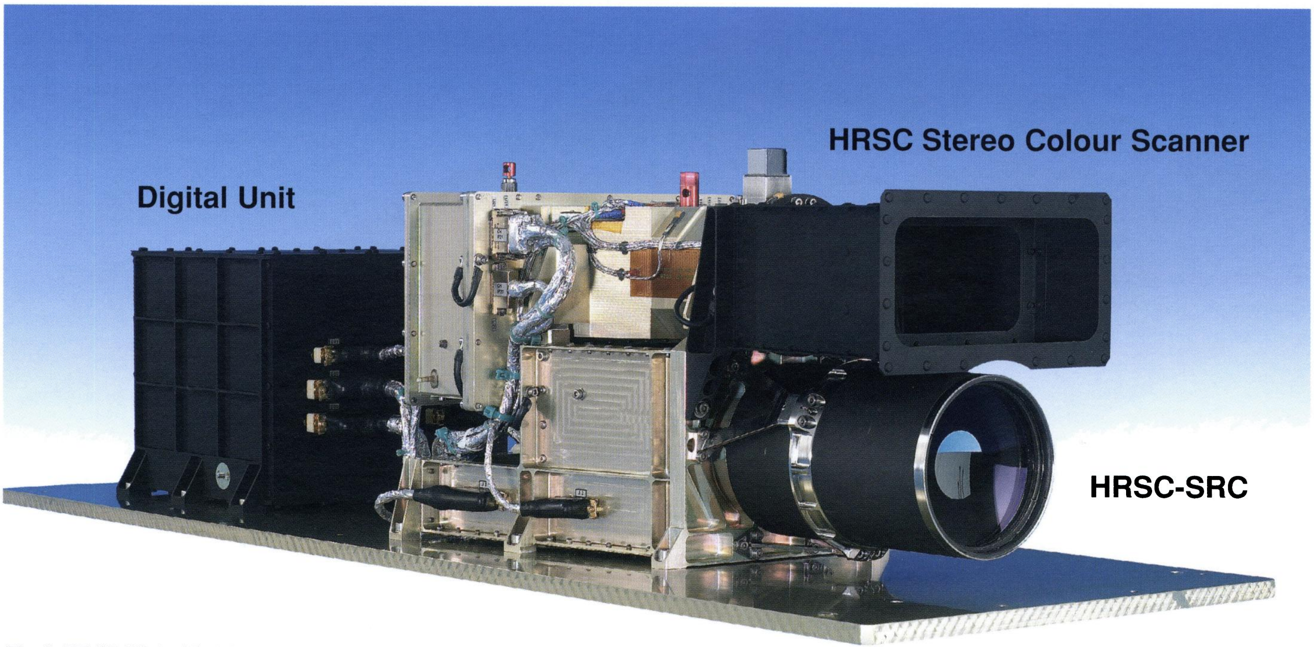


Fig. 5. HRSC Flight Model.

3. The Camera

The HRSC instrument (Fig. 5; Table 1) consists of the camera unit containing the HRSC stereo colour scanner and the Super-Resolution Channel (SRC), and of the digital unit. The unique capability of the HRSC stereo colour scanner is to obtain quasi-simultaneously high-resolution images in three-line stereo, in four colours and at five phase angles. The combination with the SRC makes it a five-in-one camera:

- the along-track acquisition of stereo imagery avoids changes in atmospheric and illumination conditions which so far have caused severe problems in the photogrammetric evaluation of stereo images acquired at well-separated times;
- the triple stereo images permit robust stereo reconstruction, yielding Digital Terrain Models (DTMs) at a vertical resolution similar to the high pixel resolution of the nadir sensor, with 10 m px^{-1} at 250 km altitude (periapsis);
- the colour images (Fig. 6) enable terrain classification and provide information on compositional variations and surface weathering as a complement to the more specific (but with lower spatial resolution) mineralogical information obtained by the imaging spectrometer of Mars Express;
- the multiphase imagery will address the physical properties of the martian soil (roughness, grain size, porosity) via photogrammetric data evaluation by providing a second stereo angle triplet (in essence quintuple stereo);
- the super-resolution imagery, nested in the broader swath of the scanner with a spatial resolution of 2.3 m px^{-1} at periapsis, will serve as the magnifying lens to analyse surface morphology at even greater detail.

The HRSC stereo colour scanner is a multi-sensor pushbroom instrument, with nine CCD line sensors mounted in parallel delivering nine superimposed image swaths. Originally, it was developed as the HRSC instrument for the Russian Mars-96 mission. Two fully tested and calibrated Flight Models were prepared, and only minor modifications to the remaining version were required to satisfy the Mars Express interface requirements.

The stereo colour scanner comprises a baffle, optics, optical bench, spectral filters,

Table 1. HRSC characteristics and performance.

	HRSC stereo colour scanner	*SRC*
Mechanical and Electrical Parameters		
Camera Unit envelope	515 x 300 x 260 mm (height x width x length)	
Digital Unit envelope	222 x 282 x 212 mm (height x width x length)	
Mass	19.6 kg	
Power consumption[a]	45.7 W during imaging	3.0 W during imaging
Radiation shielding	10 krad	
Electro-optical Performance		
Optics, focal length	Apo-Tessar, 175 mm	Maksutov-Cassegrain, 975 mm
F number	5.6	9.2
Stereo angles	–18.9°, 0°, +18.9°	in-track FOV 0.543°
Cross-track field of view	11.9°	0.543°
Number of CCD lines	9: on 3 plates with 3 lines each	1 area array sensor
Detector type	THX 7808B	KODAK KAI 1001
Sensor pixel size	7 x 7 µm	9 x 9 µm
Pixel size on ground	10 x 10 m at 250 km altitude	2.3 x 2.3 m at 250 km altitude
Field of view per pixel	8.25 arcsec	2 arcsec
Active pixels per sensor	9 sensors at 5184 pixels	1024 x 1032
Image size on ground[b]	52.2 km x [# of lines] at 250 km	2.3 x 2.35 km at 250 km
Radiometric resolution	8-bit entering compression	14-bit or 8-bit selectable
Sensor full well capacity	420 000 e^-	48 000 e^-
Gain attenuation range	10.5 dB to 62 dB in 3 dB steps	–
Spectral filters[c]	5 panchromatic and 4 colour	–
Pixel MTF at 50 lp/mm	at nadir: 0.40; at 20°off nadir: 0.33	
SNR for panchromatic lines[d]	>>100 (without pixel binning)	>>70
SNR for colour lines	>80, blue >40 for 2x2 macro pixels	
Digital Features		
On-line compression	yes, DCT: table-controlled JPEG	
Mean output data rate	peak rate 25 Mbit s^{-1} after compression	
Operations		
Pixel exposure time	2.24 ms to 54.5 ms	0.5 ms to 8 s
Pixel binning formats	1 x 1, 2 x 2, 4 x 4, 8 x 8	–
Compression rates	2...20, nominal: 6...10, bypass possible	
Typical data volume	≈1 Gbit/day (compressed data)	
Duty cycle	every orbit; several times/orbit	
Internal data buffer	no	8 x 8 bit or 4 x 14 bit images
Typical operations duration	3 – 40 min	
Expected coverage	≥50% at about 15 m px^{-1}	≥1% at about 2.5 m px^{-1}
Operational lifetime	> 4 years	

Notes

a: including 12 W maximum heating power. *b:* image size is defined by the swath width times the number of acquired image lines, and depends on available downlink capacity. *c:* nadir, outer stereo (2), photometric (2) 675±90 nm; blue 440±45 nm; green 530±45 nm; red 750±20 nm; near-IR 970±45 nm.
d: worst-case scenario (30° solar elevation angle and dark Mars region)

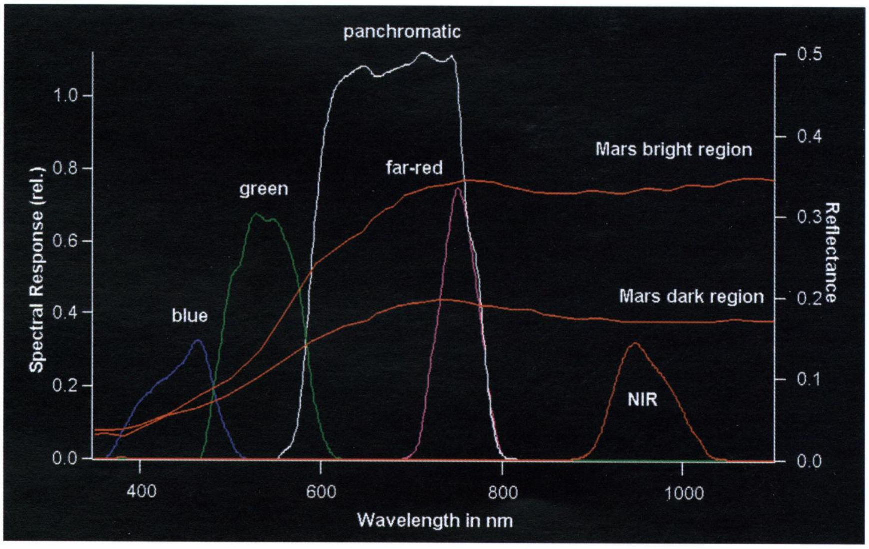


Fig. 6. The HRSC colour filter spectral characteristics.

CCD sensors lines, sensor electronics and thermal control system. The technical design is defined by:

— single-optics design;
— CCD line arrays with 5272 pixels each;
— nine detectors for simultaneous stereo and colour imaging, and for multi-phase angle measurements;
— CCDs and sensor electronics implemented in high-reliability hybrid, low-noise and low-power technology;
— implementation of the CCD-control unit in ASICs.

The SRC is a framing device and uses an interline CCD detector to cope with the very short exposure and read-out times. It is based on an instrument development for the Rosetta Lander and the design is characterised by:

— CCD area array interline detector with 1024 x 1032 pixels;
— highly miniaturised and low-power detector and control electronics;
— compact 3D multi-chip module technology using thin-film multilayer metallisation, dycostrate, plasma-etching and chip-on-wire technology;
— selectable dynamic range of 8- and 14-bit per pixel;
— internal data buffer to store eight 8-bit (or four 14-bit) images;
— lightweight Maksutov-Cassegrain telescope with a focal length of 975 mm.

The HRSC scanner and the SRC are boresighted and mounted in a common instrument structure. The common Digital Unit contains a power converter, spacecraft interface, processor for instrument control, data compression unit and heater control unit. It is based on the Digital Unit developed for the Mars-96 mission. Modifications include a lighter housing box, a new camera control processor based on the Mars-96 telemetry controller unit, and new spacecraft interfaces derived from existing parts.

The HRSC is operated in individual imaging sequences. A typical sequence consists of nine HRSC stereo colour scanner images covering the same area on the ground. Image data will be taken during every orbit that offers sufficient illumination conditions for 4-30 min. Data will be compressed on-line by JPEG-based compression hardware with an average (selectable) compression factor of 6-10 and with throughput rates of up to 450 lines s^{-1} in four parallel signal chains (each serving

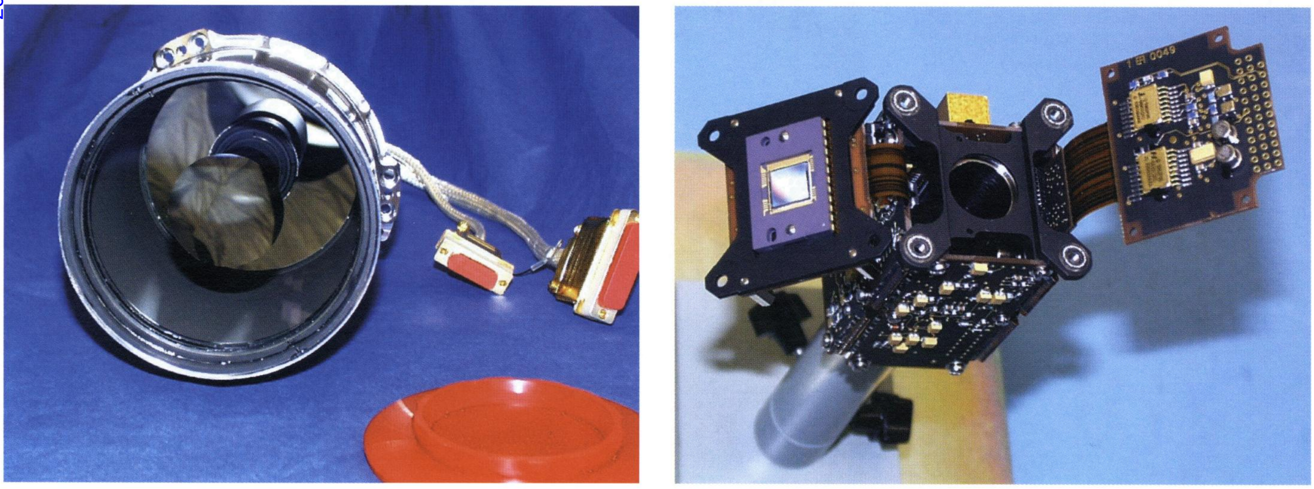


Fig. 7. Above left: SRC optics (Maksutov Cassegrain, focal length 975 mm, optics length 210 mm). Above right: the SRC electronics and detector section.

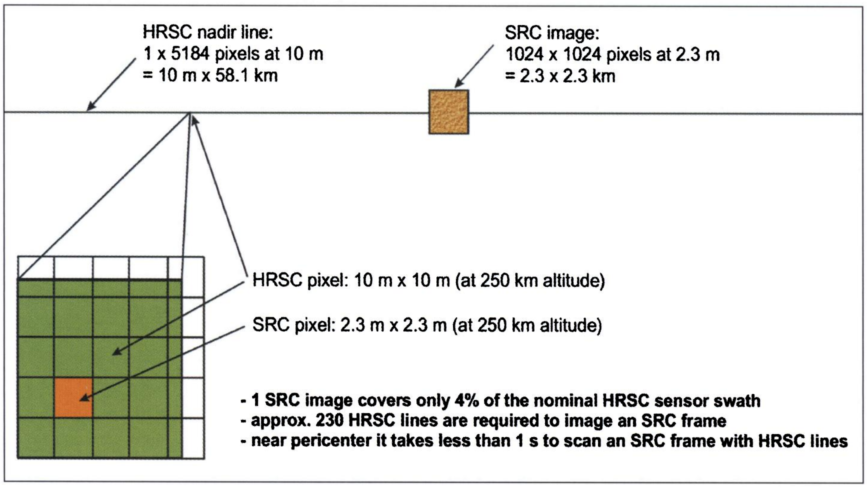


Fig. 8. HRSC scanner and SRC footprints.

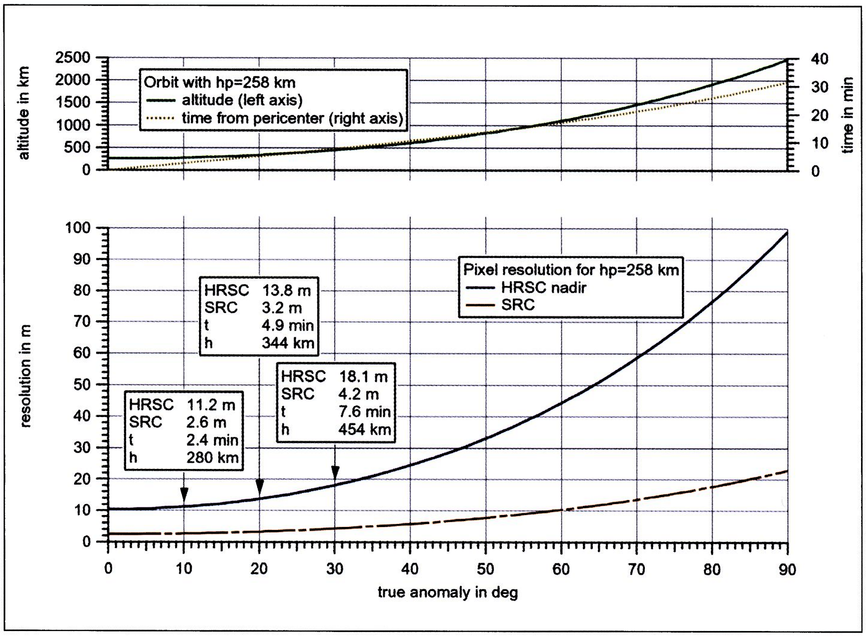
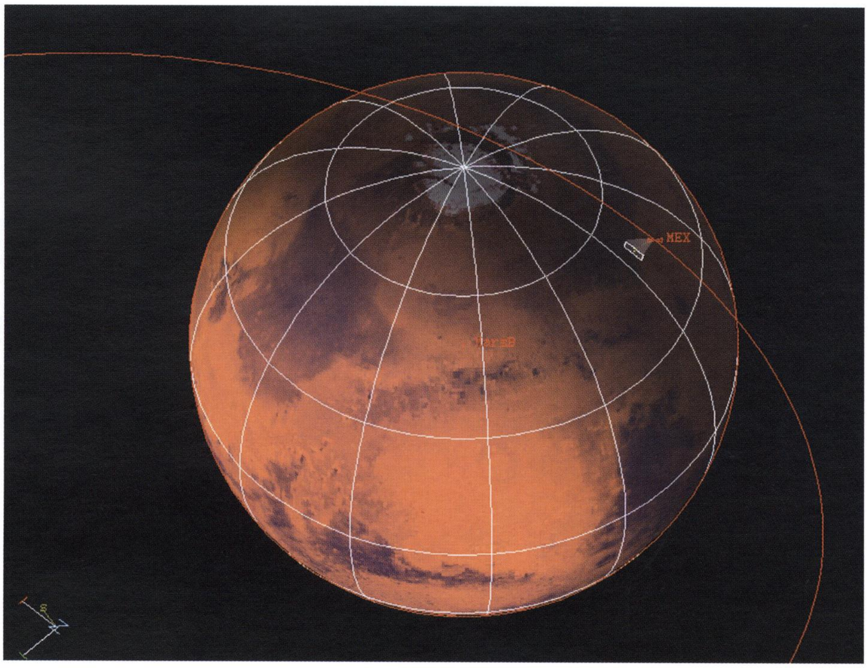


Fig. 9. HRSC and SRC pixel resolution for the nominal Mars Express orbit with 258 km periapsis altitude.

Fig. 10. The Mars Express orbit, with HRSC's field of view near periapsis.



a part of the nine CCD lines). Bypassing the compression is possible. Data compression techniques have been used successfully on previous planetary missions (e.g. on the US Clementine mission to the Moon based on hardware similar to the HRSC chip-set) and for current Earth remote-sensing and deep-space missions. Up to date, a specific implementation of the JPEG algorithm, namely the Discrete Cosine Transform (DCT) compression, has been applied in most of the cases. Before its implementation in the HRSC, the DCT algorithm was thoroughly tested. No appreciable loss of 'science' arising from this particular method could be detected within the expected compression rates.

The SRC (Fig. 7) is used for targeted observations. It will operate mostly in parallel with the scanner to generate nested super-resolution images in order to avoid any location problems and to obtain the contextual information and the precise position (Figs. 8 and 9).

SRC imaging will be carried out in one of two modes. In the 'internal' mode, up to eight 8-bit images or four 14-bit images can be acquired during one session. The images are stored in an SRC internal buffer and transferred to the spacecraft memory via the digital unit after compression. There are no restrictions on scanner operations for this mode. In the 'connected' mode, one of the four HRSC signal chains is devoted to SRC. This means that, in addition to spot and raster images, contiguous image strips can be formed. However, this requires a reduction in resolution or in the number of operated lines of the scanner.

The operational profile foresees imaging preferably near periapsis and at solar elevation angles of 15-90°. With the Mars Express reference orbit, this will be possible during the first 3 months (January to March 2004) of the mapping phase and after one year with the periapsis in the dark again starting in March 2005. However, high-altitude imaging is also envisaged and solar elevation angles down to a few degrees will be used for specific tasks. The high flexibility in instrument operations (e.g. pixel summation, compression ratio, windowing, integration time) allows optimisation of data acquisition with respect to the scientific goals, the available spacecraft resources and orbital constraints. Multiple imaging sequences during one orbit revolution are being considered for optimum coverage strategies.

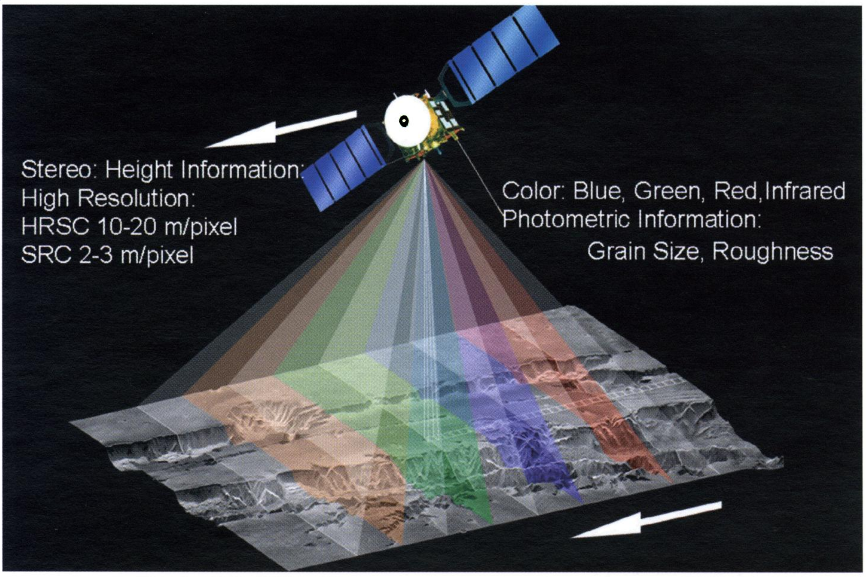


Fig. 11. The HRSC operating principle and viewing geometry of the individual CCD sensors.

The highest image quality is attained by providing accurate spacecraft attitude and orbital data. Combined with geometrical calibration data, they allow the derivation of digital terrain models. Radiometric precision is maintained by thorough on-ground calibration and by periodic in-flight verification over near-uniform targets such as dust storms.

The achievable surface coverage is not restricted by the HRSC instrument but has to be traded-off between available telemetry rates, telemetry sharing and orbit characteristics (Fig. 10). During the nominal mission lifetime of 2 Earth years and within the given mission constraints, at least 50% of the surface will be covered at a spatial resolution of ≤ 15 m px^{-1} and about 1% at a spatial resolution of 2.5 m px^{-1}.

The camera is designed to sustain an operational lifetime of more than 4 Earth years in orbit, consistent with the envisaged mission extension of another martian year.

The martian surface is ‘scanned’ by the nine CCD lines of the stereo colour scanner at frequencies of up to 450 Hz (Fig. 11). Single spot observations by the SRC are gathered at specific times from periapsis while continuous observations are performed at a constant frequency. After internal signal processing and on-line data compression, HRSC data are transferred to the spacecraft mass memory at output rates of up to 25 Mbit s^{-1}.

Instrument operations control (housekeeping and command echo monitoring, data consistency checks) is performed by the DLR Institute of Planetary Research in concurrence with the PI and his project group at FU Berlin.

During the cruise phase, the camera will be operated only for internal health checks (i.e. no imaging will be provided, with the exception of looking back at the Earth-Moon system for a ‘farewell’ picture). During the approach to Mars, HRSC-SRC images of Mars will be obtained for the first time.

For nominal imaging, camera operations focus on the configuration of the camera channels (CCD lines, signal electronics, use of the SRC) and of the on-line data compression. Various imaging strategies will be realised by setting different resolutions for each of the nine CCD lines via pixel summation formats. Pixel summation (or ‘macropixel’) formats of 1x1, 2x2, 4x4, 8x8 (first factor: in-flight direction pixel summation, realised by exposure time variations; second factor: across-flight direction pixel summation, digitally realised by pixel summation/ averaging in the Digital Unit) are possible independently for each line. Thus, under certain restrictions it is possible to read out all nine CCD lines by three signal chains and to devote the remaining one to the read-out of SRC data. The number of possible configurations has been grouped into 64 basic camera macro formats. The macro format is selected by commands and remains constant during one imaging sequence. A number of internal parameters (e.g. sensor integration time for taking into account imaging altitudes, sensor on/off delays for covering the same area on the ground, as well as window size and compression parameters for reducing the data rate, timing for SRC observations) are set depending on the selected imaging strategy. All of them are constant during one imaging sequence (except the sensor integration time, which is automatically adopted according to the orbit profile) but may be changed via commands for subsequent sessions.

4. Relation to Other Mars Express Instruments

The HRSC is a standalone instrument – it does not require operational interactions with other instruments. There are no restrictions regarding simultaneous operations with other instruments except probably the electric ambient field of MARSIS.

The surface- and atmosphere-oriented instruments of Mars Express are highly complementary. DTMs and images derived from the HRSC will allow registration and map projection with the results of the OMEGA IR mapping spectrometer and the MARSIS subsurface radar to a common reference surface. The combined evaluation of HRSC images and topographic data with the gravity measurements obtained by the MaRS radio science experiment will allow an improved investigation of the martian crust. The HRSC will also produce improved spacecraft orbit and attitude information from high-precision stereo models, which will be shared with the Mars Express project and the other instruments for their data reduction.

While OMEGA will provide surface mineralogy at about 100 m resolution, HRSC's colour capability will detect compositional variations in the OMEGA subpixel range, leading to a better understanding of terrain boundaries and spectral mixing characteristics. The topographic information derived from MARSIS can be used to verify or calibrate the HRSC terrain models and vice-versa.

5. Relation to Other Missions

In order to better understand and validate the achievements and scientific return expected from the HRSC, the instrument has to be placed in a broader context of former, current and planned missions. Almost every planetary mission carries an imaging system for observing planetary surfaces and atmospheres (Fig. 12). In addition, Mars Global Surveyor is carrying a laser altimeter (MOLA) around Mars for the first time.

What will HRSC achieve in comparison with other Mars missions?

The Viking missions provided near-global (95%) coverage at 200 m px^{-1} and 28% coverage at ≤ 100 m px^{-1}, but only 0.3% was observed at ≤ 20 m px^{-1}. The Mars Observer Camera (MOC, initially developed for the failed Mars Observer mission, now on Mars Global Surveyor) provides global coverage with its wide-angle camera at a spatial resolution of 225 m px^{-1}. The MOC narrow-angle camera yields a spatial resolution of up to 1.4 m px^{-1}, but only for a small amount of the martian surface even after the extension of the MGS mission. The spatial resolution of the SRC is comparable to MOC and it will be possible to increase the 2 m-resolution coverage significantly, which is especially important for future lander missions.

Mars Climate Orbiter (MCO) aimed at covering about 80% of the surface at 40 m px^{-1}, but its loss resulted in a major gap in martian imagery. HRSC can fill that gap. Mars Odyssey arrived in orbit in October 2001 and provides a spatial resolution of 20 m px^{-1}. However, the number of images that can be transferred to Earth is severely limited and no more than about 7% of the surface will be covered. The Mars Surveyors carry single-line sensors that lack intrinsic geometrical control. Only Mars Express and HRSC data will close the gap in the high-resolution reconnaissance imagery and provide the link between MOC's small images at very high-resolution and the medium- to low-resolution data of former missions.

Moreover, the HRSC is the only dedicated stereo camera planned for flight. Some

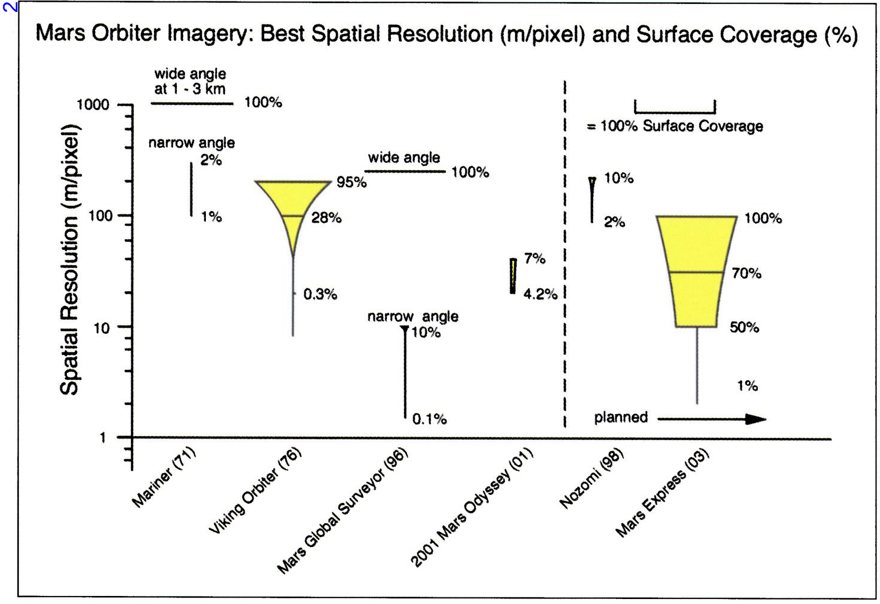


Fig. 12. Best spatial resolution and surface coverage for past, present and planned Mars missions.

high-resolution stereo imagery has been obtained but only by multiple coverage at different times and for a very small part of the surface. From Viking data, a global DTM with 1 km resolution was obtained; better resolution was achieved only locally. MGS has provided stereoscopic coverage with its wide-angle camera at 225 m px^{-1}. Mars Odyssey is focusing on colour imagery and has no dedicated plans for stereo coverage.

A second source for topographic information is the MOLA laser altimeter on MGS. It has produced global topographic coverage with a spatial resolution of about 300 x 1000 m at the equator, and better near the poles. The HRSC with a (nominal) resolution of 10 m is a significant improvement. Furthermore, the individual laser return points (though these cannot be seen in images) can be entered as control information in the HRSC image adjustment procedures to calibrate for absolute heights. The MOLA altimeter and the HRSC stereo information are thus highly complementary.

The Viking cameras were sensitive only in the visible wavelength range. Near-global coverage with 2-3 colours was achieved at 900 m px^{-1} and only a small amount of the surface at 100 m px^{-1} (~1%). The MGS/MOC instrument has only a 2-colour capability for the wide-angle camera, while the narrow-angle camera has no colours at all. The THEMIS camera of Mars Odyssey has five colours, with a maximum resolution of 20 m px^{-1}. With the ability to transfer 15 000 images in total, no more than about 7% of the surface can be covered. The HRSC colour capability will drastically improve the multispectral coverage of the martian surface. Owing to its higher spatial resolution (ratio ~1:5), it will support the spectrometer data obtained by Mars Express and Mars Odyssey.

Furthermore, the HRSC is the only instrument with the ability to obtain near-simultaneous images with multiple phase angles of the surface. Similar information by other cameras/missions has and will be obtained only by multiple coverage with large time differences, producing severe problems in photometric modelling arising from variations of atmospheric conditions, variable surface features etc. The unique multi-angle capability of the HRSC will also support its stereo capability by providing not only a stereo triplet but also a stereo quintuplet.

In conclusion, the orbital reconnaissance of the martian surface is not met by any other instrument or set of instruments. The HRSC is a unique instrument in the international Mars exploration effort and will close the existing gaps and provide the required imaging and cartographic products for future missions.

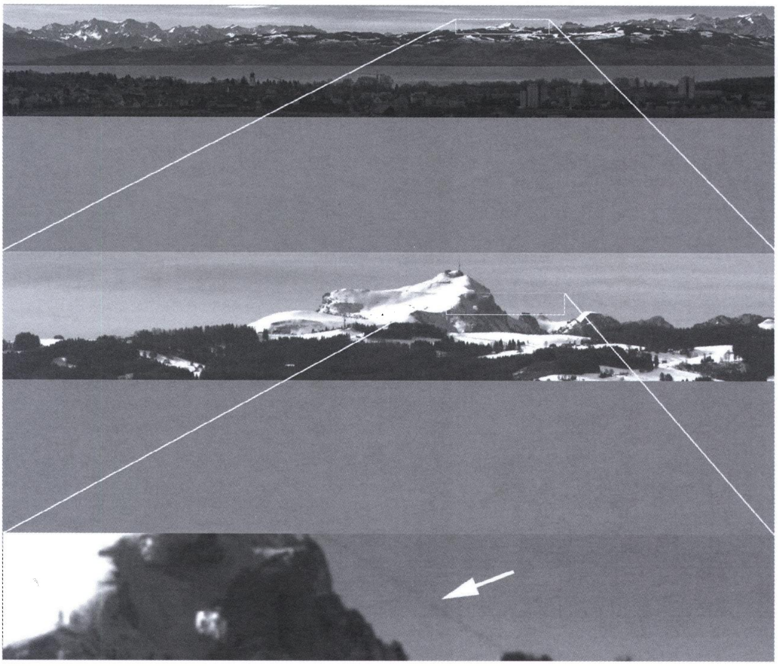


Fig. 13. This test image, looking across Lake Constance in March 1995, illustrates HRSC's resolution. The cable car rope (diameter 10-15 cm) is imaged from a distance of 40 km. The pixel resolution at this range is 1.6 m.

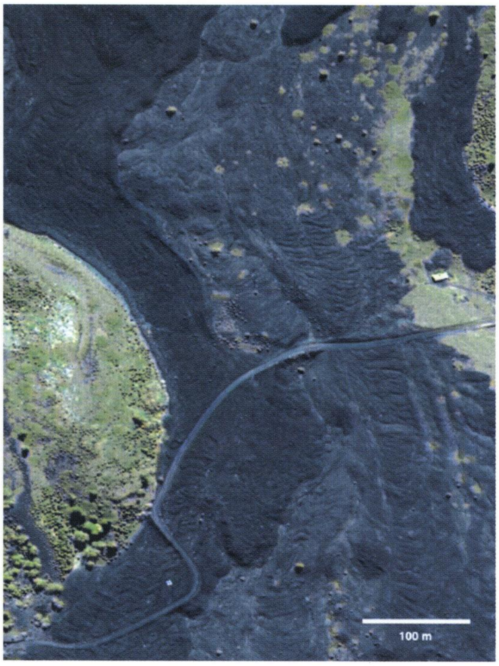


Fig. 14. HRSC test image of Mount Etna lava flows from a flight altitude of 10 km. Resolution is 40 cm px^{-1}.

6. The Test Campaign

The HRSC instrument and its ground data system were extensively tested in March 1995 at Lake Constance (Fig. 13), as well as during airborne experiments near Mount Etna (Fig. 14), Stromboli and Vulcano, Sicily, in May 1997. The tests included the HRSC Flight Model and demonstrated the resolving power and the radiometric quality of the instrument, as well as the reliability of the fully operational software. The airborne campaign verified the entire system in an end-to-end test, including the ground data system. The HRSC Qualification Model was mounted on a stabilising platform and the volcanoes were covered from a flight altitude of 10 km with a spatial resolution of 40 cm px^{-1}, in triple stereo, in colour and at multiple phase angles. These targets were selected specifically for their relevance to comparative planetology. Comparative analysis of volcanic morphologies will shed important light on the origin and mechanisms of volcanic activity on both planets. Images from Etna (Fig. 14) were analysed for their potential to recognise and map surface features typically associated with volcanoes, such as lava flows.

The dataset of the Stromboli airborne test is available in Planetary Data System (PDS) standard format on CD-ROM along with stereo processing software and calibration data.

A further result of this test and other multiple airborne flight campaigns with the Qualification Model was the demonstration of the robustness of the camera system under severe environmental conditions. During these tests, the camera produced excellent imagery which allowed the qualitative and quantitative validation of the camera performance parameters. Since 1997, the HRSC airborne camera has been widely used for Earth remote-sensing applications.

Additional tests have been conducted in order to identify ageing and degradation effects; none has been found. For Mars Express, the HRSC instrument underwent comprehensive and full-scale tests before integration on the spacecraft.

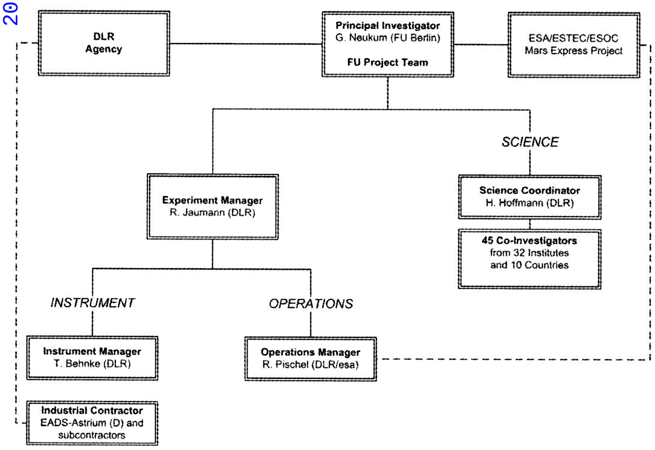


Fig. 15. The HRSC project team structure.

Fig. 16. The Science Team structure.

7. The Data Processing Tasks

Mars Express scientific data will be transmitted to Earth daily. After receipt in Perth, Australia (or at station of the NASA Deep Space Network) and primary decoding and formatting, the image data will be processed at the DLR Institute of Planetary Research, Berlin (D) to a certain level.

The data reduction will be performed in consecutive steps consisting of systematic and scientific data processing. For Mars-96, a fully operational software package for scanning instruments was developed. A modified version of this software that takes into account framing camera characteristics (SRC) has been applied and tested for analysis of Viking Orbiter, Clementine and Galileo images. Only minor modifications to Mars Express-specific needs are necessary.

The results of the systematic data processing step are radiometrically and geometrically calibrated and map-projected images. These data will be transferred to the database of the PI at FU Berlin. After validation by the PI, they will be released electronically to the Science Team at the individual home institutes of the Co-Is. They will be distributed to the Science Team members and the science community. The scientific data processing by the Science Team involves chiefly the photogrammetric and cartographic processing and colour image production, and will result in higher level products, including DTMs, orthoimages, image mosaics, cartographic products (e.g. image maps, topographic maps, thematic maps) and a refined geodetic control network.

After the processing phase, the data will be released as individual images in electronic version or through hardcopy, as offset-printed maps and CD-ROM archives in PDS formats for further use by the general planetary science community and the public. The stereo images are expected to have a great potential for public relations activities.

The processing software was tested and refined as an additional result of the HRSC airborne campaigns. Data handling and data management were also exercised. The amount of data processed for airborne projects since 1999 exceeds the expected Mars data volume by a factor of 10-100.

8. The Team

The HRSC experiment organisation is divided into three functional teams (Science Team, Instrument Team, Operations Team) under the direction and responsibility of the PI, supported by his project team at FU Berlin (Fig. 15; Table 2). The Science Team (Fig. 16) is subdivided into working groups by discipline to meet the

Table 2. HRSC Co-Investigators.

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Table 3. HRSC Experiment Team.

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Subcontractors: A. Zaglauer, U. Schönfeldt, K. Eckhardt, J. Krieger, D, Tennef, S. Govaers, A. Kasemann, M. Langfeld (DLR/Anagramm), E. Rickus (Levicki microelectronic), J. Schöneich (Jena-Optronik)

*left project, **retired

experiment objectives (Geosciences, Photogrammetry/Cartography, Spectrophotometry, and Atmosphere). The Instrument and Operations Teams, led by the Experiment Manager, include engineers and scientists from the DLR Institute of Planetary Research. The industrial contractor is Astrium (D), who built, assembled, tested and verified the HRSC for Mars-96.

The DLR Institute of Planetary Research provides a competent Instrument Team that was especially trained for a similar task in the Mars-96 HRSC experiment, covering the development of the sensor electronics, compression, electrical and optical ground support equipment, mission planning, instrument operations, target acquisition, calibration, data processing and data management. The DLR Institute is in charge of the assembly, verification and testing, for the system integration qualification, testing and calibration, and of the camera system integration with the spacecraft. Astrium (D) was responsible for the development of the Digital Unit and the integration and testing of the instrument subunits.

The PI and Co-Is are responsible for the scientific outcome of the experiment, and the Co-Is have individual responsibilities in areas such as calibration support, data processing, assessment of imaging scenarios, and photogrammetric data processing. All public relations efforts are a primary responsibility of the PI, who also has the primary data rights. The PI will actively support ESA in PR matters.

The Instrument Team includes engineers and scientists from the DLR Institute of Planetary Research and industry (all of whom have built and flown space instruments) and was recruited from the former HRSC Mars-96 Team. Similarly, the Operations Team from the DLR Institute of Planetary Research has extensive experience in running planetary missions and processing, archiving and the delivery of data products; it originally developed the HRSC ground data system on Mars-96.