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# CORNELL UNIVERSITY

*Center for Radiophysics and Space Research*

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Final Report

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## "Development of a Mars Surface Imager"

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S.W. Squyres, Principal Investigator

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# 1 Introduction

This report describes Mars Surface Imager (MSI) instrument developed under NASA grant NAGW-3283. In the most recent version of the instrument, which we call "PIDDP-cam", we have integrated a compact lens, a very long multi-line color CCD, an innovative high-performance drive system, and a state-of-the-art wavelet image compression code into a single package. It is, to our knowledge, the best-performing digital panoramic imager ever built.

# 2 Flight Instrument Functional Requirements

The MSI is a multispectral, stereoscopic, panoramic imager that allows imaging of the full scene around a Mars lander from the lander body to the zenith. It has two functional components: *Panoramic imaging*, and *sky imaging.*

The flight version of the MSI instrument will meet the following requirements:
*For panoramic imaging:*

- *Clear view of all terrain around the lander, from on the lander body to above the horizon, with azimuthal actuation only.*
- *Stereoscopic coverage at all azimuths, and at elevations ranging from the nominal horizon to near the lander body.*
- *0.28 mrad IFOV.* For restored images, this value is slightly better than 20/20 vision in humans.
- *Repeatable pixel placement with an RMS error of no more than 1/4 of a pixel.* Geometric control of this quality is important for correct image restoration and stereo analysis.
- *Spectral range of 400-1100 nm.* This covers a broad range of anticipated spectral variations on Mars.
- *Nine or more spectral bands.*
- *Signal-to-noise ratio of 200:1 under nominal imaging conditions.*
- *Minimal blur from less than half a meter to infinity with no active focus control.*
- *Very high data compression ratios (hundreds to one) possible with minimal image degradation.*

*For sky imaging:*

- *Clear view of the full sky.*

- *Imaging of the sky to within 1° of the sun.* Imaging close to the sun is necessary to define the shape of the diffraction peak of aerosol particles.

- *5 mrad IFOV.* Close to the sun, a sampling interval of 3 to 4 samples per degree is necessary to define the shape of the diffraction peak adequately.

- *Direct imaging of the sun.* This yields daytime optical depth.

- *Imaging of bright stars at night.* This yields nighttime optical depth.

- *At least six bands specifically selected for sky imaging objectives, over the range 400-1100 nm.*

# 3 Description of "PIDDP-Cam" Instrument

## 3.1 Introduction

We have developed, built, and tested a very capable panoramic imager that incorporates a number of innovative design features, particularly in its drive system and data compression technique. It produces images of very high radiometric, geometric, and visual quality, and in its present form it meets many of the functional requirements for panoramic imaging.

## 3.2 Overview

The MSI is a line-scan imager, forming an image by rotation of the camera head. In the current version there is one set of primary optics and one detector array. The detector consists of three parallel silicon CCD line arrays, each covered by a color filter. The optics do not require active focus control. The mast that supports the camera head is rotated by a small torque motor coupled directly to the mast and controlled by an optical encoder. Data compression is carried out in software on a processor that mimics the lander processor, and makes use of a sophisticated new compression algorithm that is not available in custom hardware.

*Instrument design: area vs. line-array imaging:* The most basic choice to be made in design of a panoramic imager is what kind of detectors to use (area arrays or line arrays). We have chosen a line-array imager because of the following weaknesses of area arrays:

- They require significantly more mass to be placed atop the mast than do line arrays.

- For an area array of a reasonable size, high angular resolution requires actuation in both azimuth and elevation.

- They require significantly more complex and expensive CCD drive electronics than do line arrays.

- For good multispectral imaging, an area-array imager requires a filter wheel, imposing a significant penalty in mass and mechanical complexity.

- They either require a shutter, which is an added mechanism, or they must be operated in frame-transfer mode, which degrades radiometric performance and requires still more complex drive electronics.

- They complicate geometric correction of images because lens distortions occur in two dimensions rather than one, and because substantial image mosaicking is required.

- They are more susceptible to array defects than line arrays.

- They are more susceptible to radiation effects than line arrays.
- Because of their much larger number of pixels, they are far more complex and expensive to design, fabricate, test, and calibrate than line arrays.

*End-to-end system optimization:* An important way in which the MSI differs from previous spaceflight cameras is that we treat image gathering, coding, and restoration as a whole, rather than as independent tasks. When the total system is designed for optimal restoration, the restored image improves significantly in quality over a reconstructed or restored image from a conventionally-designed instrument. Image gathering is optimized when the relationship between spatial-frequency response and sampling passband is selected to optimize the information capacity for the minimum design requirements [*e.g.*, Huck *et al.*, *J. Opt. Soc. Am.* **A5**, 285, 1988]. We therefore match the MTF of our optics very carefully to the pixel spacing of our CCD to yield this kind of optimization. As a result, the fidelity of our restored images significantly exceeds that possible with a conventional camera design.

## 3.3 Optics

The present MSI optics use a design selected for low mass, compact size, and ability to image over a large FOV. Another consideration was maximizing depth of field; we require imaging from less than half a meter to the horizon with no focus adjustment or zoom capability. We use a four-element, double Gauss design at f/17, with a focal length of 38 mm. The field of view is slightly more than 60°. The lens is rugged, lightweight, and compact. It has a maximum diameter of 2.5 mm, a physical length of 12.5 mm, and a mass (including glass, mounts, and housing) of 9.1 grams. The lens is fully baffled for both field and aperture.

We devoted a great deal of effort in our optical design to tailoring our MTF for optimal image restoration. To suppress aliasing, we designed a lens that fully transmits the lower spatial frequencies while attenuating those higher than the Nyquist frequency, rather than simply maximizing the MTF as has traditionally (and incorrectly) been done for imaging systems. We have met our MTF design goals over the spectral range for which this lens was intended: 400-700 nm. Measured lens MTF at three field positions (0°, 10°, and 20° off-axis) all meet the design MTF goal of 0.20-0.50 at the Nyquist frequency. System MTF (including the limitation caused by the CCD aperture), nicely meets the design goal of 0.12-0.30 at Nyquist. Phase performance in the worst case is substantially better than a quarter of a wave; the on-axis RMS value is 0.016 wave. Geometric distortion across the field is negligible.

## 3.4 Focal Plane Assembly

The heart of our present focal plane assembly is a tri-linear CCD array. The device has three rows of 6000 active elements, each covered with either a red, green, or blue integral filter. Pixel height and pitch are 12 $\mu$m, and spacing of adjacent lines is 96 $\mu$m. The CCD plugs directly into a two-layer printed circuit board that has the essential components and interconnects to simplify the interface to the electronics. Performance of the array has been excellent. Measured read noise is 30 electrons. Dark current is 0.009 pA/pixel at 20°; this corresponds to a dark current of less than 10 electrons/pixel/s at maximum martian polar operating temperatures. Full well is measured at 198,000 electrons, giving a dynamic range of 76 dB.

## 3.5 Drive Assembly

Mechanical simplicity is crucial for the azimuthal drive of a panoramic imager. We use a very simple design, and provide high performance through use of innovative electronics. The mast is turned by a DC motor mounted directly on the drive shaft. The shaft is supported on a pair of dry-lubricated ball bearings and carries an optical encoder at its inboard end. The only moving parts are the bearings. The current instrument uses a brush torque motor, but we will switch to a brushless design in our next instrument. The performance of this drive system has substantially exceeded our expectations. For our angular resolution of 0.28 mrad, we attempted to achieve an accuracy of 70 $\mu$rad in the azimuthal placement of each pixel. In fact, the worst RMS pixel placement error observed is 9 $\mu$rad (about 0.03 pixels).

## 3.6 Electronics

All electronics except the CCD, headboard, and the LED/photo-sensors in the optical encoder reside in a separate electronics housing. The main electronics in the present instrument are implemented on three 20×20 cm breadboards. Two of these are used primarily for drive assembly control, while the third contains correlated double sampling circuits used for sampling the video output signals from the CCD. The key to the performance of the drive system is the electronics. The encoder is read by LED/photosensor pairs that generate a series of 8192 sine/cosine cycles per 360° revolution. We require position information finer than this, so a digitally-generated tangent dither signal is combined with the sine and cosine encoder signals to produce a dithered sine and cosine which increases effective resolution of the encoder by more than a factor of 16. The electronics track the actual position of the encoder by decoding the zero crossing order of the dithered sine and cosine signals. To produce an error signal to the servo loop, the actual position is digitally subtracted from the commanded position. To rotate the camera, the error signal is used to drive the motor to a commanded position that is continuously and smoothly incremented from the starting to the ending position.

## 3.7 Data Compression

The primary compression technique that we use is the Fast Embedded Zerotree Wavelet (FEZW) algorithm. It is a simple, remarkably effective algorithm that orders bits in order of importance. Using it, one can terminate encoding at any point, allowing any target compression ratio to be met exactly. One can also transmit an image at high compression and low resolution, and then select a subregion of interest and transmit additional bits that improve the resolution of that subregion. The algorithm consistently produces results competitive with or better than other compression algorithms, regardless of computational complexity, yet it requires no training, pre-stored tables or codebooks, or prior knowledge of the image source. We believe that it is the state of the art today in image compression. (See Appendix D for a description of the algorithm.) It has been installed on an IBM RS/6000 workstation that very accurately mimics the Mars Surveyor lander processor. Its speed on this processor more than keeps pace with image acquisition.