Preliminary Image Compression Results from the Mars Exploration Rovers

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We report on how image compression has been used to date on the Mars Exploration Rovers. We discuss the statistics on usage, parameter selection, and compression performance.

I. Introduction

The Mars Exploration Rovers "Spirit" (MER-A) and "Opportunity" (MER-B) arrived safely on Mars on January 4, 2004, and January 25, 2004 (Universal Time), respectively. Onboard image compression is used extensively to make best use of the downlink resources. Most of the images were compressed with the ICER image compression software [1]. The remaining images that were compressed made use of modified Low Complexity Lossless Compression (LOCO) software [2–4]. A summary of the compressed image data volumes is given in Table 1. The terms used in the table are explained later in this article.

ICER is a wavelet-based image compressor that allows for a graceful trade-off between the amount of compression (expressed in terms of compressed data volume in bits/pixel) and the resulting degradation in image quality (distortion). When the compressed data volume is allowed to be large enough, ICER will produce lossless compression. The development of ICER was driven by the desire to achieve state-of-the-art compression performance while meeting the specialized needs of deep-space applications. In

Table 1. Summary of compressed image data volumes as of February 7, 2004. The data volumes given are volumes of compressed data for each row except the last. Note that a Mpixel is 10^6 pixels while a Mbyte is 2^{20} bytes.

Compression	Image type	Number of images	Combined image area, Mpixels	Data volume, Mbytes	Average rate, bits/pixel
ICER	Regular	5132	2867.9	387.3	1.13
ICER	Thumbnail	6075	24.9	3.8	1.27
LOCO	Regular	489	124.5	92.7	6.24
LOCO	Reference pixels	1114	36.5	9.2	2.12
No compression	Regular	4	4.2	6.0	12.00

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particular, ICER incorporates a sophisticated error-containment scheme to limit the effects of data losses seen on the deep-space channel. ICER also features progressive compression: compressed information is organized so that as more of the compressed data stream is received, reconstructed images of successively higher overall quality can be reproduced.

When lossless compression is desired, the MER mission generally uses a software implementation of a modified version of the LOCO image compressor [3,4]. Although ICER can also perform lossless compression, the simple predictive approach used by LOCO is several times faster, with similar compression effectiveness.

In addition to conventional image compression, MER is using a handful of other techniques to reduce image data volume. These include sending only subframes of interest of certain types of images (while possibly sending the whole image at much lower quality); performing pixel averaging to reduce the size of images; companding images from 12 bits/pixel to 8 bits/pixel before compression; and sending only row sum data, column sum data, or histogram data. Also, for each image acquired, the rovers produce a small 64×64 pixel "thumbnail" image by pixel averaging; these thumbnail images are compressed by ICER prior to transmission. The thumbnails serve as previews of the full-sized images, which may not be transmitted as soon due to the larger data volume they occupy.

The statistics presented in this article encompass all images downlinked to Earth as of about February 7, 2004. We do not include data produced by any instruments other than the cameras, and we have omitted various small one-dimensional image data sets for which ICER and LOCO are not applicable. The rates and compressed data volumes presented here do not include packetization overhead.

II. Imaging Uses and Image Types

Each rover is equipped with nine visible-wavelength cameras: a mast-mounted, high-angular-resolution color stereo camera pair for science investigations (the panoramic cameras, or Pancams); a mast-mounted, medium-angular-resolution stereo camera pair for navigation purposes (the Navcams); a set of body-mounted front and rear stereo camera pairs for navigation hazard avoidance (the Hazcams); and the Microscopic Imager, a high-spatial-resolution camera mounted on the end of a robotic arm. In addition, each lander had an entry-descent-landing (EDL) camera that, as planned, acquired three images of the Martian surface during descent. All rover cameras produce 1024-pixel by 1024-pixel images at 12 bits per pixel.

The images acquired by the rovers are of a variety of targets and have a variety of purposes. Special types of images include images of a calibration target, Sun-finding images, and the descent images. Naturally, a large portion of the images have been of the Martian landscape, for various navigation and science purposes.

References [5–7] give more information on the cameras and the purposes of the images they acquire.

III. ICER Compression Results

The majority of the images acquired by the rovers were compressed by ICER prior to transmission.

ICER parameters include the choice of wavelet filter, the number of wavelet decomposition stages, the number of error-containment segments, the byte quota, and the "minimum loss" parameter. The choice of wavelet filter and number of decomposition stages determine how the wavelet decomposition is applied. The number of segments is used for partitioning the image for robustness against packet losses. The byte quota and minimum loss parameter control the trade-off between image quality and compressed data volume. See [1] for a detailed description of ICER's parameters.

To date, MER has been controlling the trade-off between image quality and compressed data volume primarily with the byte quota parameter, setting the minimum loss parameter to zero. ICER generally overshoots the byte quota by a small amount, so this approach does not yield exact control over the compressed data volume. Because ICER produces progressive compression, the compressed data could be truncated to the exact desired size, but this results in small quality variations between image segments (see [1]). The entire bitstream produced is transmitted to avoid such variations.

Many images are companded from 12 bits/pixel to 8 bits/pixel prior to compression in an effort to improve the fidelity in darker portions of the reconstructed images. This is motivated in part by the fact that the noise is signal-dependent.

Table 2 shows ICER parameter combinations that have been used and provides statistics on the ICER-compressed images. Note that because the image quality has been primarily controlled with the byte quota, the compressed bit rates in Table 2 roughly indicate the amounts of compression selected by the mission and only indirectly reflect the compressibility of different image types. Image sizes smaller than 1024×1024 are obtained by pixel averaging and/or taking a subframe of the original image.

Statistics for thumbnail images are not included in Table 2; they are instead tabulated separately in Table 3. Thumbnail images are obtained by averaging 16×16 pixel blocks of the original 1024×1024 pixel images, resulting in 64×64 pixel images. These are compressed by ICER to an average rate of about 1.27 bits/pixel for a compressed volume of about 650 bytes each. This corresponds to about 0.005 bits per pixel of the original image. In all cases, 4 stages of wavelet decomposition and a single error-containment segment were used, and wavelet filter E was used for all except 22 cases, for which wavelet filter A was used instead.

IV. LOCO Compression Results

Statistics on images that were (losslessly) compressed using LOCO are given in Table 4. Note that a handful of images were compressed losslessly with ICER; they are not included in this table.

In [1] we presented results on lossless compression of 12-bit and 8-bit Mars Pathfinder images using ICER and LOCO. The 8-bit images were formed by linearly scaling the 12-bit originals. As an update to these results, we compare lossless compression performance of ICER and LOCO on 8-bit images from the Opportunity (MER-B) rover. In this case, the 8-bit images were formed onboard from the 12-bit originals by companding, which is a nonlinear operation. The results are shown in Table 5. We see that ICER and LOCO continue to give similar performance. The images are full-frame (1024×1024) Pancam images taken on sol 3. Each of these images was losslessly compressed onboard using ICER, with wavelet filter A, 4 stages of decomposition, and 20 error-containment segments. The LOCO results in the table were generated on Earth, also using 20 segments.

Each row of the charge-coupled device (CCD) detector used in the cameras also includes 32 nonimaging "reference" pixels that allow monitoring of the CCD electronics offset, detector noise, and readout noise [5]. These pixels form a 32×1024 "image" that looks like low-level background noise. Some of these reference pixel images are sent to Earth, in which case they are first losslessly compressed with LOCO using a single error-containment segment. Table 1 includes statistics on the data volume of reference pixel images transmitted.

V. Remarks

We conclude with some additional notes and observations.

Both ICER and the MER version of LOCO partition images into independent segments to limit the effects of packet losses. Since a fair number of packets have been lost, this feature has come into play

Table 2. Parameter combinations and statistics for ICER-compressed images.

Camera	Image size, $w \times h$	Number of segments	Wavelet decomposition stages	Wavelet filter	Number of images	Average rate, bits/pixel	Total image area, Mpixels	Compressed volume, Mbytes
MER-A								
Pancam	1024×1024	1–20	3,4	A,E	1014	1.12	1063.3	141.5
	512×512	2–8	4	A	816	0.81	213.9	20.8
	256×256	1	4	A	82	1.26	5.4	0.8
	128×128	1	4	A	29	0.83	0.5	0.05
	Other	1–16	4	A	507	1.37	59.8	9.8
Navcam	1024×1024	12–20	4	E	235	0.97	246.4	28.6
	512×512	12–32	4	A,E	14	3.21	3.7	1.4
	256×256	1–2	4	A,E	167	1.93	10.9	2.5
	Other	1–16	2,4	E	109	1.04	54.5	6.8
Front	1024×1024	16–32	4	E	56	1.12	58.7	7.8
Hazcam	512×512	4–12	4	A,E	66	0.94	17.3	1.9
Rear	1024×1024	16–32	4	E	50	1.18	52.4	7.4
Hazcam	512×512	4–12	4	A,E	14	1.13	3.7	0.5
Microscopic Imager	1024×1024	24–32	4	A,E	26	1.34	27.3	4.4
Total/average for MER-A					3185	1.08	1817.7	234.2
MER-B								
Pancam	1024×1024	1–20	3,4	A,E	599	1.18	628.1	88.1
	512×512	1–8	4	A	552	1.10	144.7	19.0
	256×256	1	4	A	48	1.11	3.1	0.4
	128×128	1	4	A	21	0.86	0.3	0.04
	Other	1–8	3,4	A	389	1.07	49.3	6.3
Navcam	1024×1024	16–32	4	E	111	1.32	116.4	18.4
	512×512	12	4	A	2	1.07	0.5	0.07
	256×256	1–2	4	A,E	48	1.58	3.1	0.6
	Other	1–16	2,4	E	43	1.04	17.5	2.2
Front	1024×1024	16	4	E	18	2.02	18.9	4.6
Hazcam	512×512	6	4	A,E	50	0.91	13.1	1.4
Rear	1024×1024	16–32	4	E	16	1.03	16.8	2.1
Hazcam	512×512	4–12	4	A,E	18	1.05	4.7	0.6
Microscopic Imager	1024×1024	24–32	4	A,E	32	2.36	33.6	9.5
Total/average for MER-B					1947	1.22	1050.2	153.1

Table 3. Thumbnail image statistics.

Rover	Camera	Number of images	Compressed volume, kbytes	Average rate, bits/pixel
MER-A	Pancam	2898	1835.90	1.27
	Navcam	526	319.47	1.21
	Front Hazcam	140	88.95	1.27
	Rear Hazcam	75	50.62	1.35
	Microscopic Imager	43	27.61	1.28
	EDL	3	1.73	1.15
MER-A	**Total/average**	3685	2324.28	1.26
MER-B	Pancam	1952	1249.60	1.28
	Navcam	278	184.61	1.33
	Front Hazcam	82	56.72	1.38
	Rear Hazcam	36	24.50	1.36
	Microscopic Imager	39	25.23	1.29
	EDL	3	2.03	1.35
MER-B	**Total/average**	2390	1542.69	1.29

fairly often. Nearly all lost packets are eventually retransmitted, but this process takes some time, so the segmentation provides the benefit of making large portions of most affected images available immediately. ICER-compressed image segments in which the lead packet is available, but one or more other packets are lost, can still be reconstructed, albeit with lower quality than if all packets were available. This feature also has come into play a few times. The effects of packet losses on a reconstructed image are demonstrated in [1].

Most images from MER are acquired as stereo pairs. The left and right images comprising these pairs are compressed independently. In the future, we hope to provide missions with compressors that exploit the correlation between the stereo pairs, improving the trade-off between image quality and compressed data volume. The rovers also acquire multispectral images with up to seven spectral bands using filter wheels in the Pancams. Currently, spectral bands from the same scene are compressed independently, but a simple method of exploiting some of this correlation may be used later in the MER mission.

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Table 4. LOCO-compressed image statistics.

Camera	Image dimensions, $w \times h$	Number of images	Average rate, bits/pixel	Total image area, Mpixels	Compressed volume, Mbytes
		MER-A			
Pancam	1024×1024	12	7.40	12.6	11.1
	512×512	11	4.44	2.9	1.5
	63×63	161	3.57	6.3	0.3
	Other	5	7.93	0.02	0.02
Navcam	1024×1024	2	6.61	2.1	1.7
Microscopic Imager	1024×1024	16	4.59	16.8	9.2
Front Hazcam	256×256	18	8.43	1.2	1.2
	128×128	2	7.71	0.03	0.03
Rear Hazcam	1024×1024	6	6.71	6.3	5.0
	256×256	2	8.13	0.1	0.1
	128×128	2	6.78	0.03	0.03
EDL	1024×256	3	5.22	0.8	0.5
Total/average for MER-A		240	5.91	43.5	30.6
		MER-B			
Pancam	1024×1024	16	7.50	16.8	15.0
	512×512	16	4.31	4.2	2.2
	63×63	134	3.74	0.5	0.2
	Other	4	5.33	0.9	0.6
Navcam	1024×1024	48	6.46	50.3	38.7
Microscopic Imager	1024×1024	6	5.09	6.3	3.8
Front Hazcam	256×256	18	7.31	1.2	1.0
	128×128	2	6.13	0.03	0.02
Rear Hazcam	128×128	2	6.31	0.03	0.02
EDL	1024×256	3	4.87	0.8	0.5
Total/average for MER-B		249	6.42	81.0	62.0

Table 5. Lossless compression performance on 8-bit MER-B images.

Product ID	Rate, bits/pixel	
	ICER	LOCO
1P128461136EFF0200P2350L7M1	4.21	4.27
1P128461136EFF0200P2350R1M1	4.08	4.13
1P128461820EFF0200P2352L7M1	4.16	4.22
1P128461820EFF0200P2352R1M1	4.03	4.07
1P128462933EFF0200P2530L7M1	5.26	5.27
1P128462933EFF0200P2530R1M1	5.24	5.22
Average	4.50	4.53

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