McGowan_J_2001

VERY LOW BITRATE VIDEO FOR MARS MISSIONS

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ABSTRACT

Neither manned landings nor short-range robotic probes such as Mars Pathfinder can explore more than a small fraction of the surface of Mars, 144 million square kilometers comprising as much surface area as all the continents and islands on Earth. Complete exploration of Mars to find or conclusively rule out important discoveries such a past or present life will require high speed low-altitude or ground-based probes such as airplanes, balloons, or high-speed rovers. These devices will need high frame-rate imaging such as digital video to explore the planet and for remote operation either by astronauts on Mars or mission control on Earth. A major limitation for transmission of video both on Mars and especially between Mars and Earth is the limited bandwidths available, currently less than 100 Kilobits/seconds between Mars and Earth when line of sight is available. One solution is to establish a network of communications satellites in Mars orbit. Even with a communications network, bandwidth will be limited, especially between Mars and Earth. A complementary approach is to develop very low bitrate video compression algorithms, e.g. VHS videotape quality at 56 Kilobits/second. Methods that may be able to achieve this such as the H.26L and MPEG-4 video coding standards, contour-based image coding, and object-based image coding are discussed, including applications and special issues on Mars and in deep space such as the high bit error rates of deep space communication links.

INTRODUCTION

A desirable goal for missions to Mars is real-time or near real-time video coverage of the missions. Video coverage of robotic or manned missions will help build and maintain public support for missions to Mars and other space missions. In the case of a privately funded mission to Mars, video of the mission would probably represent the principal revenue stream from the mission. This probably represents the most important and best recognized use of video for space missions. In addition, video can help achieve and may even be essential for a large number of scientific and engineering goals during missions.

Video may prove essential for life detection by robotic missions. Experience has shown that unambiguous detection of past or present life where it is not expected is difficult. For example, the Viking Lander Labeled Release experiments produced positive signals at both landing sites[1]. However, these results were eventually interpreted by most planetary scientists as the results of inorganic oxidants in the Martian soil. Similarly the current controversies over the Martian meteorites and the past controversies over biomarkers in carbonaceous chondrites such as the Murchison meteorite illustrate the difficulty of unambiguously identifying life. In the case of microbial life, even a detailed still image of a single-celled organism might be interpreted as an inorganic structure of some kind. A microscope with a video camera could observe microscopic organisms dividing or making copies of themselves in real-time. A video camera could also observe microscopic organisms swimming or crawling about in culture. A video of microscopic organisms reproducing would probably be accepted as unequivocal evidence of life. Video could also reveal exotic life based on biochemistry substantially different from terrestrial biochemistry.

Video may also be helpful for engineering goals such as failure analysis and failure prevention. Video of the risky final approach and landing of probes should be helpful in understanding failures. A camera or cameras mounted on a lander could unambiguously determine the cause of a failed landing such as the Mars Polar Lander. Cameras mounted on the interior or exterior of a probe could perform frequent inspections of the probe during the long journey from Earth to Mars. A camera could determine the relative location of the edge of Mars and the fixed stars during the final approach to the planet. The probe or mission control might be able to use this information to determine if the probe is coming in too low as in the loss of the Mars Climate Orbiter (MCO) or too high.

Neither manned landings nor short-range robotic probes such as Mars Pathfinder can explore the surface of Mars, 144 million square kilometers comprising as much surface area as all the continents and islands on Earth[2]. Complete exploration of Mars to find or conclusively rule out important discoveries such as past or present life will require high speed low-altitude or ground-based probes such as airplanes, balloons, or high-speed rovers. These devices will benefit from high frame-rate imaging, such as digital video, to explore the planet and for remote operation either by astronauts on Mars or mission control on Earth.

Video is better suited than a series of slightly overlapping still images to detect and observe transient phenomena such as dust storms, lightning, releases of sub-surface gases or liquids, and so forth. Video provides multiple successive images from differing viewing and lighting angles, which should assist in understanding ambiguous surface features.

Ideally, the exploration of Mars or other planets should seek “something interesting” such as past or present life, geology relevant to terrestrial concerns, or unusual physical phenomena. Some features would be obvious even in a series of slightly overlapping still images. Seepage or venting of fluids or gases from beneath the surface seems like the most likely discovery on Mars and might be difficult to detect or study in still images. In addition to scientific value, subsurface deposits of gases or fluids may provide essential resources such as water and rocket fuel for exploration, colonization, and even terraforming of Mars.

On Mars, video should be useful in detecting and studying transient or dynamic phenomena such as dust storms, dust devils, and lightning in the atmosphere. Seeps of subsurface gases or liquids may occur on Mars. Mars contains substantial evidence of past volcanic activity including several apparently extinct volcanoes. Current volcanic or seismic activity may produce various releases of gases or liquids and other dynamic processes. Evidence of geologically recent seepage of groundwater has been reported[3]. If Mars possesses subsurface water or ice, surface seepage or eruptions of water or steam, even geysers or hot springs in volcanic regions, are possible. Geysers and hot springs have been proposed as possible sites for the origin of life on Earth.

The subsurface lithoautotrophic microbial ecosystem (SLiME) in the Columbia River Basalt Group is frequently suggested as a model of current subsurface life on Mars[4]. This ecosystem produces significant amounts of methane. Natural gas was produced commercially at the Columbia River Basalt Group early in the twentieth century. A subsurface ecosystem similar to the Columbia River Basalt Group is likely to produce seepage of methane at the surface. In general, the most likely signature of subsurface life at the Martian surface would be surface seeps of gases or possibly liquids.

Conventional theory holds that the largest, by mass and volume, identifiable trace of past life on Earth are subsurface deposits of oil, natural gas, and other hydrocarbons. Oil is attributed to simple single-celled organisms trapped in sediments and pressure cooked over several million years[5,6]. If Mars was once warm and wet, supporting lakes and oceans with primitive microorganisms, Mars may possess subsurface deposits of oil and natural gas. These would cause seepage of oil and gas, especially methane at the surface of Mars. While trace gas detectors probably offer the greatest chance of detecting seeps of subsurface gases, video can assist in detecting and studying these dynamic phenomena[7]. Many gases of interest such as methane are transparent to visible light and could only be detected indirectly in the visible spectrum. An infrared video camera may be able to detect and observe releases of gas or fluids that would be invisible to a visible light camera, especially since gases or liquids from deep within the planet are likely to be warmer than the surface of the planet.

Although current animal life on Mars seems extremely unlikely, video would be better able to detect and identify animals than still images, especially if the animals are well camouflaged or small. Similarly, video will be better suited for detecting a variety of unanticipated transient phenomena on Mars or other planets. These exotic possibilities include new physical phenomena and mobile probes from extraterrestrial civilizations.

Video technologies for Mars pose a challenge because of the limited power, volume, and total weight of systems that can be transported to Mars, especially for robotic missions, the possible vulnerability of video systems to the harsh space environment, the large bit rate requirements of digital video, and the high bit error rates of deep space communication links. Video systems in Earth orbit share many of these challenges.

Video technologies for Mars have been previously studied for a proposed mission to Mars to fly a small airplane down the Valles Marineris canyon. This study concluded that a video system based on the International Organization for Standardization (ISO)'s MPEG digital video compression standard could be built with a total weight of 2 Kg including heavy shielding, a size of about 800 cm^3, and a power dissipation of 20 Watts or less[8]. MPEG (Motion Pictures Experts Group) digital video at 352 pixels by 240 pixels, 30 frames per second, requires a bit rate of one megabit per second[9]. The bit error rate requirement is 10^{-6}. A video system of this type typically causes a peak signal to noise ratio (PSNR) of about 30 dB between the compressed image and the original uncompressed 352 by 240 pixel frame. The proposed video system consisted of a camera lens or lenses, a CCD or other imaging array, and a video processing system to compress the digital video for transmission back to Earth.

Table 1. Mars Video System Parameters

Parameter	Value
Size	800 cm^3
Weight	2 KG
Power	20 Watts
Bit Rate	1,000,000 bits per second
Bit Error Rate	10^{-6}
Compression	MPEG-1 or MPEG-2
Width	352 pixels
Height	240 pixels
Frame Rate	30 frames per second
Peak Signal to Noise Ratio	30 dB (approximate)
Subjective Video Quality	Comparable to VHS NTSC analog videotape

MPEG digital video at 352 by 240 pixels, 30 frames per second, with a bit rate of one megabit per second is about the lowest subjective video quality that viewers find acceptable. The 352 by 240 pixel, 30 frames per second, video format is known as SIF for Source Input Format. Video with dimensions of 176 by 120 is known as Quarter SIF or QSIF. MPEG-1 SIF digital video is sometimes referred to as "VCR quality" or "VHS quality". Properly encoded MPEG-1 SIF digital video is comparable to analog VHS videotape in subjective video quality.

There is no generally accepted metric for video quality, although the Peak Signal to Noise Ratio (PSNR) is frequently used as a proxy for video quality. No other objective video quality metric (several have been proposed) consistently outperforms PSNR in reproducing subjective ratings of video quality by human observers. PSNR sometimes disagrees with subjective ratings by human observers. Loosely, VHS or VCR quality means that the video appears the same or similar in quality to a VHS NTSC analog videotape viewed on a television set under normal viewing conditions, typically with the viewer seated 5−7 picture heights from the television. Video with different spatial resolutions, e.g. 352 pixels by 240 pixels and 720 pixels by 480 pixels, can have the same subjective video quality.

MPEG-2 digital video at 720 by 480 pixels and 30 frames per second requires about 6-8 megabits per second[10]. This is good digital video quality and is used routinely in DVD's (Digital Versatile Discs) and other consumer digital video products. This is sometimes referred to as "Studio" or "Broadcast" quality. An MPEG-2 digital video system for

Mars would have the same size, weight, and power requirements as the MPEG-1 system if commercial off the shelf (COTS) components can be used. The bit rate requirement would be 6-8 megabits per second.

The principal obstacle to video for Mars missions appears to be the low bit rates currently possible over communications links between Mars and Earth. These have been less than 100 kilobits per second when the satellites have line of sight from Mars to Earth. The establishment of communications relay satellites in Mars orbit may resolve this. The NASA Jet Propulsion Laboratory is considering a variety of communication relay satellite networks in Mars orbits with projected bit rates of 1-10 megabits per second[11,12].

Although essential for thorough exploration of Mars, communication relays are infrastructure and do not provide an immediate tangible return on investment. Thus, generating support for funding communication relay systems can be difficult. It is much easier to justify a relay if it performs some other function such as planetary exploration. Indeed, to date all relays sent to Mars have been part of planetary exploration probes with still image cameras such as the Mars Global Surveyor. A high bandwidth relay satellite may carry the first video system to Mars to observe the Martian dust storms and seek other transient phenomena. In addition to entertainment value, this may be useful for formulating Global Circulation Models (GCM) of the Martian atmosphere.

Digital video on robotic missions to Mars may be significantly affected by the mechanical stability of the platforms. Digital video compression technologies such as MPEG digital video use compression methods such as motion estimation and frame differencing that may be degraded by jitter in the camera from frame to frame. An airplane or balloon may experience jitter due to turbulence in the Martian atmosphere and limitations of the aerobot's guidance and control systems. A rover will be traversing a rocky surface. Mobile probes must provide sufficient mechanical stability for digital video compression to work efficiently.

Missions to the Valles Marineris canyon on Mars, a popular proposed destination for Mars missions, may suffer from multipath interference effects. Signals sent by the probe back to a relay or directly to Earth will also bounce off the canyon walls or floor, interfering with the primary signal. This can cause serious problems for communications, especially compressed digital video signals, which are highly susceptible to lost data.

The radiation issues for Mars missions including Mars orbiters are much less severe than Earth orbit. Mars lacks a significant magnetic field and has no radiation belts, unlike Earth. Typical total ionizing dose for Mars missions is 10-20 Krads. It is likely that shielding such as an aluminum case can protect against Total Ionizing Dose (TID) effects during Mars missions. The primary concern is single event effects from high energy Galactic Cosmic Rays (GCR) that can penetrate any shielding. Single event upsets (SEU) could be detected using embedded monitoring hardware or software that could reset the video encoder or other hardware as needed. Single event latchup, however, can permanently damage a video processing chip. This seems to be the largest radiation concern and could force the use of radiation hardened Complimentary Metal Oxide Semiconductor (CMOS) even for a Mars mission.

Commercial applications including the Internet, computing, entertainment, surveillance, and medical video are steadily driving video technologies toward lower power, lighter weight, and higher levels of integration on a single chip, higher quality, and higher compression ratios for the same perceived video quality. Mobile and other wireless applications must address many of the same noisy channel and mechanical robustness issues as space missions. However, radiation is not a significant issue on Earth. Radiation hardening and some other space-hardening issues such as extreme temperatures may require custom development of video encoders or cameras.

MPEG digital video is highly sensitive to uncorrected errors. MPEG makes heavy use of variable length codes to achieve high compression. A single-bit error can cause loss of synchronization between the encoder and the bitstream or the bitstream and the decoder. In the worst case, a single bit error can cause the loss of a half-second of MPEG digital video. This happens when a single bit error causes loss of synchronization early in the MPEG I frame, the key frame used by the motion estimation and compensation. All the frames until the next key frame are encoded or decoded improperly.

The synchronization problem due to the variable length codes is one of the main reasons that MPEG hardware encoder and decoder design is especially sensitive to timing errors such as clock skew. There is very limited tolerance for errors since the effects of errors are not localized spatially or temporally if synchronization is lost. Thus, porting a working commercial bulk CMOS MPEG chip design to radiation hardened CMOS, where the signal timing will be different, may be difficult.

The problems with variable length codes over noisy communications channels have been extensively studied for mobile and wireless video applications on Earth. Several methods exist to modify the variable length codes without adding significant overhead to avoid the loss of synchronization and reduce the impact of uncorrected errors. These methods are not incorporated in the MPEG-1 or MPEG-2 standards. One method, reversible variable length codes (RVLC), has been incorporated in the ISO MPEG-4 and ITU-T (International Telecommunications Union – Radio Sector) H.263+ digital video standards.

Thus, video technologies for Mars and other space missions may encounter some special conditions not reproduced in commercial applications on Earth. The most worrisome is that missions to Mars or other space missions may require a radiation hardened video encoder. Fortunately, it is technically feasible to fabricate a single-chip or few chip MPEG digital video encoder using radiation hardened CMOS semiconductor processes[13]. An MPEG digital video encoder chip requires about 3−5 million transistors (about one million logic gates) and a system clock speed no greater than 54 MHz. This can be achieved in one or a few chips using state of the art radiation hardened CMOS semiconductor processes such as Honeywell RICMOS-V. Thus, there is no fundamental obstacle to creating compact, lightweight, low power video systems for missions to Mars or other space missions. No advances in radiation hardened CMOS semiconductor process technologies are required.

VERY LOW BITRATE VIDEO

The biggest obstacle to televising missions to Mars is the limited bandwidth possible between Mars and Earth. A complementary approach to building a Mars communication network is to develop video compression algorithms superior to the industry standard MPEG video compression which can achieve a bit rate of about 1 Megabit/second for VHS quality video. For example, a very low bitrate video compression algorithm able to achieve VHS quality at 56 Kilobits/second could transmit video in real-time using the existing Mars to Earth communication links. There are two reasons for developing very low bitrate video compression. First, the cost and schedule of a Mars communication network such as the one envisioned by the NASA Jet Propulsion Laboratory are quite expensive and quite long. A real-time, continuous twenty-four hours per day, seven days per week Mars communications network will probably cost billions of US dollars (Table 2) and take decades to construct. As a result, the network may never be built. In the case of a privately funded mission to Mars, the cost of a Mars network appears prohibitive. A private mission would rely on at most a few relays. Secondly, even if a Mars network is built, bandwidth will still be at a premium. A single channel of high quality video may consume the entire network.

Table 2 Rough Estimate of Cost of a 24/7 Mars Communication Network (1-10 Megabits/second)

Mars Network Element	Cost Per Element	Number of Elements	Total Cost
Geosynchronous Mars Orbit Relay Satellites	$500 Million	3	$ 1.5 Billion
Low Mars Orbit Constellation Relay Satellites	$200 Million	10	$ 2.0 Billion
Earth Support (Deep Space Network)	$100 Million	1	$ 0.1 Billion
Mars Network Total			$ 3.6 Billion

While there is significant schedule risk, a custom video encoder fabricated in one or a few radiation hardened CMOS chips will probably cost in the range of 5–10 million US dollars to design and fabricate once a superior video compression algorithm is developed. Historically, video compression algorithm development is done with software prototypes implemented using the C or C++ programming languages[14,15], or sometimes symbolic or numerical manipulation languages such as Mathematica[16], MATLAB, or Maple[17]. VLSI hardware designers use the software prototype also known as a behavioral model, usually coupled with a written specification provided by the algorithm developer, to develop a chip design in the Verilog or VHDL hardware description languages. The cost to develop a chip once a superior video compression algorithm is developed is small compared to the several hundred million US dollar cost of even a single Mars communication satellite.

The MPEG and H.26X (H.261, H.263, H.263+, and H.26L) video compression standards from the International Organization for Standardization (ISO) and the International Telecommunications Union (ITU) are based on the Discrete Cosine Transform and Motion Estimation/Compensation. While a number of research prototypes and commercial products exist based on the Discrete Wavelet Transform (DWT), the wavelet video compression algorithms have similar difficulties encoding edges in images to DCT video compression. Consequently, wavelet video compression does not enormously outperform DCT video compression.

Very low bitrate video for Mars missions would probably require developing algorithms or mathematical methods for contour based image coding that can outperform current Discrete Cosine Transform (DCT) and Discrete Wavelet Transform (DWT) compression methods. Contour based image coding consists of representing an image or image sequence as contours and textures filling regions delimited by the contours. The contours correspond to the edges and lines perceived by the human visual system. They should closely correspond to the lines in a line drawing. Linear transforms such as the DCT and DWT have considerable difficulty efficiently compressing contours. The contours can be coded as vertices of polygons, control points of splines or other polynomials, or a number of other known methods. The textures can be encoded as transform coefficients from the DCT, DWT, or other transforms. Further compression can be achieved by scalar or vector quantization of the control points and the transform coefficients followed by entropy coding. In image sequences motion estimation and compensation can be applied to the control points of the contours to enhance the compression.

Table 3 computes the bitrates for video with one-hundred (100) contours and one-hundred (100) textured regions delimited by the contours in each video frame. Sophisticated entropy coding and scalar or vector quantization is not used in this simple calculation. One can expect at least a factor of two improvement in compression with these methods. Video with only one-hundred contours in a frame is relatively low complexity video, such as videoconferencing, e.g. an astronaut reporting to mission control or transmitting a message to family members on Earth. VHS quality video can have substantially more than one-hundred contours in a video frame. Most VHS tapes probably fall in the range 100 to 1000 contours giving a bitrate of 80 to 800 Kilobits/second using crude contour-based video coding. With sophisticated compression methods such as entropy coding and scalar or vector quantization of the control points for the contours, the video bit rates will probably run in the range from 40 to 400 Kilobits/second, depending on the complexity of the images (defined as the number of distinct contours or objects in the image).

Table 3 Bitrate for Contour-based Video
(Low Complexity Source Material) at VHS Quality

Parameter	**Value**
Video Frame Spatial Resolution	720 (H) by 480 (V)
Number of Contours in Video Frame	100

Number of Textures in Video Frame (Distinct Regions Delimited by Contours)	100
Number of Bits for a Control Point	20 (Two 10-bit integers for the horizontal and vertical location of the control points in the frame)
Number of Control Points Per Contour	5
Bits Per Contour	100 (5 × 20)
Bits Per Texture	10
Bits in Contours Per Video Frame	10,000 (100 × 100)
Bits in Textures Per Video Frame	1,000 (100 × 10)
Total Bits Per Video Frame (Key Frame)	11,000
Bits Per Second (All Key Frames/No Motion Compensation)	330,000 (30 × 11,000)
Bits Per Motion Vector	20 (2 × 10)
Motion Vectors in a Frame	100 (1 for each contour)
Bits Per Motion Difference Frame	2000 (20 × 100)
Bits Per Second (Key Frame every 15 frames)	78,000 (2 × 11,000 + 28 × 2,000)
Bits Per Second (Key Frame every 30 frames)	69,000 (11,000 + 29 × 2,000)
Bits Per Second (Key Frame every 60 frames)	64,500 (11,000 + 59 × 2,000)/2

Contour based video coding and the closely related object-based video coding has been studied for several years. For example, the Signal Processing Laboratory at the Swiss Federal Institute of Technology – EPFL in Lausanne, Switzerland has done extensive work on object-based video coding using concepts similar to those outlined above. These formed the basis of EPFL's contribution to the competition for the ISO MPEG-4 multimedia and video standard. A start-up company in the Silicon Valley, Pulsent, is developing a video codec (compressor/decompressor) that may be a kind of contour or object-based video coding.

A compressed image or image sequence data format and a decoder that converts the compressed data to an uncompressed bitmap image can be designed with current knowledge. For example, the ISO MPEG-4 video compression standard incorporates concepts from contour and object-based video coding through the MPEG-4 video objects and the Shape Adaptive Discrete Cosine Transform (SA-DCT). In MPEG-4 digital video, the frames can be segmented into disjoint regions or video objects. The Shape Adaptive Discrete Cosine Transform adapts the transform so that the DCT does not cross the edge of the object, which would yield inefficient coding. The DCT applied across an edge yields many large non-zero transform coefficients that cannot be substantially compressed using the quantization, run-length encoding, and entropy coding used by MPEG and H.26X video encoding.

The principal obstacle to contour based video coding is the encoder that converts uncompressed bitmap images or image sequences to compressed data. Current edge detection and image segmentation algorithms are inadequate to properly identify and extract contours from natural images. While some edges are found correctly, these algorithms find spurious edges and fail to find other edges. Very low bit rate video compression probably requires developing methods for image segmentation, edge detection, or object detection comparable to the human visual system in accuracy.

A research and development program to develop very low bitrate video compression for Mars missions would probably need to investigate mathematical methods for edge detection substantially different from the local gradient and derivative based methods such as the Sobel, Kirsch, Marr-Hildreth, Canny, and Shen-Castan algorithms. Edge detection appears to be a non-local process and non-local mathematics appears necessary to solve the edge detection problem. Non-local edge detection means that whether a pixel in an image is classified as an edge depends not only on the immediate neighborhood of the pixel but in some instances may depend sensitively on distant parts of the image or even the entire image. The research program would:

1. Review the mathematics, applied mathematics, and science literature for mathematical methods that can be applied to edge detection.

2. Investigate the formal mathematical definition of an edge.

3. Review the vision science literature for experimental data that may elucidate edge detection methods.

4. Conduct psychophysical experiments on edge detection as suggested by theoretical considerations where such experiments do not exist in the literature or where replication of reported experiments may provide insight.

5. Derive a mathematical method or methods for edge detection.

6. Develop a prototype using Mathematica, Maple, MATLAB, C/C++ or some other prototyping tool that takes images as input and generates an edge map comparable to a line drawing by a skilled artist.

7. Integrate the algorithm into very low bit rate video coders such as the MPEG-4 encoders and various research prototypes. It may be possible to use the ISO MPEG-4 digital video standard. If this is not possible, develop a very low bit rate video encoder and decoder prototype.

It is likely that a very low bitrate video compression algorithm for Mars missions could not be implemented as software, although this would be preferred. Consequently, the very low bit rate video encoder prototype would be used as a behavioral model for a VLSI video encoder chip design.

CONCLUSION

It is technically feasible to fabricate a single-chip or few chip MPEG digital video encoder using radiation hardened CMOS semiconductor processes. Thus, there is no fundamental obstacle to creating compact, lightweight, low power video systems for missions to Mars or other space missions. Televising Mars missions with MPEG digital video compression probably requires the establishment of a Mars communication network, a network of communication relay satellites in orbit around the planet. Contour based video coding can probably achieve bit rates of 40 to 400 Kilobits/second with subjective quality comparable to a brand new VHS videotape. Development of very low bitrate video compression using contour or object-based video coding may eliminate the need for a Mars network, reduce the required size and scope of the Mars network, or greatly increase the number of channels or the quality of the video relayed by the Mars network.

ACKNOWLEDGEMENTS

This work was supported in part by GFT Group Incorporated. Some preliminary work related to this paper was supported in part by the Applied Information Technology Division, NASA Ames Research Center and the NASA Research and Education Network (NREN). NASA Ames Research Center assembled a large team to prepare the Mars Airplane proposal that inspired this work. The author thanks all members of this team, especially Julie Pollitt, Julie Schonfeld, Ruben Ramos, and Hiroyuki Kumagai. The author thanks Andrew B. Watson of the Vision Science and Technology Group at NASA Ames Research Center. The author also thanks his colleagues at the Desktop Video Expert Center – Steve Kyramarios, Mark Allard, Mike Fitzjarrell, Kathy Charland, Steve Sipes, and Joe Flores.

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