Digital Motion Imagery, Interoperability Challenges for Space Operations

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With advances in available bandwidth from spacecraft and between terrestrial control centers, digital motion imagery and video is becoming more practical as a data gathering tool for science and engineering, as well as for sharing missions with the public. The digital motion imagery and video industry has done a good job of creating standards for compression, distribution, and physical interfaces. Compressed data streams can easily be transmitted or distributed over radio frequency, internet protocol, and other data networks. All of these standards, however, can make sharing video between spacecraft and terrestrial control centers a frustrating and complicated task when different standards and protocols are used by different agencies. This paper will explore the challenges presented by the abundance of motion imagery and video standards, interfaces and protocols with suggestions for common formats that could simplify interoperability between spacecraft and ground support systems. Real-world examples from the International Space Station will be examined. The paper will also discuss recent trends in the development of new video compression algorithms, as well likely expanded use of Delay (or Disruption) Tolerant Networking nodes.

I. Introduction

Imagery has been a part of space flight from the very beginning. Imagery was one way of proving to the world the endeavors were real and sparked the imagination of the public. Imagery also became a key tool for science and engineering as missions became more numerous and complex. After the safe return of the crew of Apollo 13, engineers were anxious to see the pictures taken of the stricken Service Module. Those images helped engineers on the ground confirm what caused the near fatal accident. Likewise, a puff of smoke from one of STS-51L's solid rocket boosters, seen from an engineering motion picture camera, pointed investigators to the eventual conclusion that one of the booster's seals led to the destruction of *Challenger*. A few key frames of high-speed film alerted engineers of a foam strike during the launch of STS-107. When *Columbia* disintegrated during entry, that foam strike became a likely cause of the accident. Accidents and near-misses in spaceflight utilize imagery, often video and motion imagery, as a tool to give clues into root causes of failures. What was once seen as a "nice to have" is now seen as a critical tool for engineers and spacecraft designers.

In the modern era, even un-manned missions feature video or motion imagery capabilities. Advances in compression and modulation make the addition of imagery capabilities possible. Often times, the application is something other than conventional video and is referred to as motion imagery instead. Conventional video refers to standard television system compatible applications that can be routed, monitored and recorded with readily available television equipment. Motion Imagery can include conventional video, but also refers to applications other than standard video, often having unique frame rates, resolutions and algorithms and can be viewed with computer screens and traditional television monitors.

As we look to future missions, manned and unmanned, to the Moon, Lagrange points, Mars, and beyond, it is logical to expect some type of motion imagery system will be a feature of the spacecraft. Back on Earth, multiple space operations centers will want to monitor, record, archive and redistribute the imagery. It is likely many future missions will be multi-Agency International projects, with space operations centers across the globe monitoring activities at the same time.

Technology advancements in a broad variety of fields related to motion imagery are enabling future missions to utilize commercial equipment, along with emerging standards, to make motion imagery a practical part of space operations. Commercial advancements in cameras and sensors, compression, and modulation are key contributors. Meanwhile, the Consultative Committee for Space Data Standards (CCSDS) has working groups publishing standards for Internet Protocol over CCSDS packet protocols, Delay (or Disruption) Tolerant Networking, and digital motion imagery for space applications. The era of full motion imagery as part of space communications and operations is upon us.

II. Motion Imagery Operations Concepts

Motion imagery capabilities on spacecraft suffer from the constraints of bandwidth, power consumption and mass. Without these constraints, it is likely that launch control rooms and space operations centers would resemble security monitoring centers at casinos with multiple monitors and views of rockets, payloads, rendezvous maneuvers, and astronaut activities.

Rocket-based motion imagery is particularly constrained. High Definition Television (HDTV) cameras output nearly 1.5 Gigabits per second uncompressed. Converting that output to a compressed, packetized transport stream capable of live distribution to a ground station can be a daunting challenge. Fortunately, commercially available encoders are getting more efficient and smaller. The most bandwidth efficient encoding utilizes h.264 (or MPEG-4 Part 10). The trade-off is the h.264 algorithm compresses not only frames, but also pixel blocks within and between multiple frames. Inter-frame algorithms that compress groups of pictures are very efficient, but imagery analysts prefer encoding algorithms that utilize intra-frame encoding, where each frame is maintained. Intra-frame encoding algorithms, such as Motion JPEG-2000, require considerably more bandwidth for live streaming motion imagery. If analysis quality imagery is needed from a rocket based imagery system, it is likely the imagery will need to be recorded and retrieved later. One possible solution might be to design a recording device that could be ejected and retrieved later. The infamous “ring” shot from the staging on the Saturn V rockets was retrieved this way. A small 16MM film camera was placed on the second stage. It was ejected shortly after second stage ignition and retrieved from the ocean. Another option is to record the imagery on a drive in the spacecraft. Spacecraft usually have more communications bandwidth than rockets in flight. When a higher bitrate communication link is established, the imagery stored from the rocket-based imagery system can be downloaded to ground systems. However, the spacecraft communication link must have a high bit-rate to get all that data to the ground, and will likely be interrupted with communications outages before a large file can be downlinked. Applications for interrupted file transfers that can resume the transfer at the point of interruption are necessary to make this practical.

Motion imagery on spacecraft is often used to confirm staging operations and mission events such as solar array deployment, rendezvous and docking. These events often must be monitored live, with very low latency. The amount of data generated for live digital motion imagery will far exceed the combined requirements for other telemetry and voice data coming from the spacecraft. In effect, digital motion imagery will define the overall communication link specifications, including bandwidth and jitter specifications. Live streaming video using h.264 compression could require 6 – 8 Megabits per second of bandwidth for high quality, compared to all other telemetry which might total 2 Megabits per second. Compressed video streams, particularly when using h.264, are highly susceptible to packet loss and jitter. A decoder will freeze an image or produce no image at all if the data stream is interrupted or packets arrive out of order beyond the decoder buffer’s capacity to reorder. Streaming video from a spacecraft will require a communications link system with jitter (packet delay variation) not to exceed 10 ms, and bit error rates not to exceed 1×10^{-6} in order to ensure a live video data stream that can be received and decoded in real-time.

As cameras and compressors improve and available bandwidth to the ground increases, the quality of the motion imagery improves. The International Space Station (ISS) can now stream live HDTV to the ground, for example. Humans are exploring beyond low-Earth orbit. Live or recorded spacecraft-based motion imagery has been limited to low-Earth orbit and the fuzzy black and white television from the Moon landings. As we inevitably move human exploration beyond the Moon and continue to send sophisticated spacecraft into the solar system, motion imagery systems get more complex. The concept of “live” monitoring changes to perhaps mean “streaming” versus file-based transmission of motion imagery. Motion imagery systems for exploration beyond Earth orbit will need to be self-aware, capable of filtering through irrelevant content and storing what is considered to be important to be distributed later. Space operations centers back on Earth will retrieve files for playback later, or monitor recorded content as a stream in “real-time”.

The good news for designers of motion imagery systems for space applications is there are a variety of commercially available technologies to choose from, where little or no new development of these technologies is necessary. The bad news is these choices lead to different implementations across multiple spacecraft and space centers. One motion imaging system may utilize standard definition quality cameras with interlace scanning, 4:3 aspect ratio, a frame rate of 25 frames per second, and use MPEG-2 compression. Another might use high definition cameras with progressive scanning, 16:9 aspect ratio, a frame rate of 60 frames per second, and use h.264 compression. A number of format conversions were necessary, for example, for monitoring of the European Space

Agency's Automated Transfer Vehicle maneuvers and docking to the ISS. Space operations centers may require up-converters, down-converters, frame rate converters, and other translators in order to support motion imagery for multiple missions. Each conversion degrades and modifies the imagery. If analog sources are used somewhere in the signal path, the image degradation is even worse. Further, multiple format conversions can make trouble shooting very difficult if the final imagery has artifacts or is not what was expected. Narrowing down all these options to a set of common applications will make interoperability much easier. The Consultative Committee for Space Data Standards Motion Imagery & Applications Working Group http://cwe.ccsds.org/sis/default.aspx#_SIS-MIA is developing a set of standards to aid in the selection of these many commercial standards to meet a common set of applications.

III. Enabling Technologies and Strategies

A. Rocket-based Motion Imagery

Live, streaming rocket-based motion imagery is typically constrained by S-band telemetry links. The challenge for engineers and designers is how to trade the limited bandwidth, often limited to 10 Megabits per second, with the desire to have high temporal resolutions (high frame rates) while maintaining high spatial resolutions (lines and pixels), with multiple camera views. Strategies include taking advantage of knowledge about the mission events during ascent so cameras are switched on and off to provide motion imagery only when relevant events are occurring, such as ignition, lift-off, roll maneuvers and staging. The system automatically switches from one camera view to another during the mission time-line, using timing from a master clock on the rocket or motion sensors to trigger the switches. Another strategy is to "window" the motion imagery so that only the relevant information is encoded and transmitted (See Figure 1). For example, a High Definition camera has an aspect ratio of 16:9. A camera mounted on the side of a rocket, with a view looking down the side toward the engines, for example, might have a field-of-view that includes irrelevant information, such as sky or the sides of the rocket nearest the camera. If the engineers are mainly interested in the field-of-view near the bottom of the rocket, the system can be designed to "window" or ignore the irrelevant parts of the image, compress only the part of the image that is wanted, and route that slice of the image for distribution.

Another strategy might be to vary frame rates during different stages of rocket ascent. During early ascent phases, for example, the frame rate from one camera might be set to 60 frames-per-second, then reduce the frame rate to 15 frames-per-second for a later phase to allow another camera to utilize bandwidth to distribute motion imagery at the same time. Camera "A" might start the ascent phase at 60 frames-per-second until Launch + 30 seconds, then camera "B" begins operating. Camera "B" may begin at L + 30 seconds at 45 frames-per-second and camera "A" is reduced to 15 frames-per-second. In this way, two views are available using the same bandwidth.

The system could also buffer frames to be transmitted later in the ascent phase. Early in the rocket ascent the system could transmit 30 frames-per-second while buffering an additional 30 frames-per-second. Late in the ascent phase it could transmit the buffered frames. Using timing information encoded within the motion imagery, the full 60 frames-per-second could be reassembled. This strategy has the advantage of providing at least some motion imagery from cameras during ascent in case of catastrophic event, vs. having all motion imagery captured on board for full transmission later in flight. An accident might destroy the drive where the imagery was stored, meaning no video was ever received.

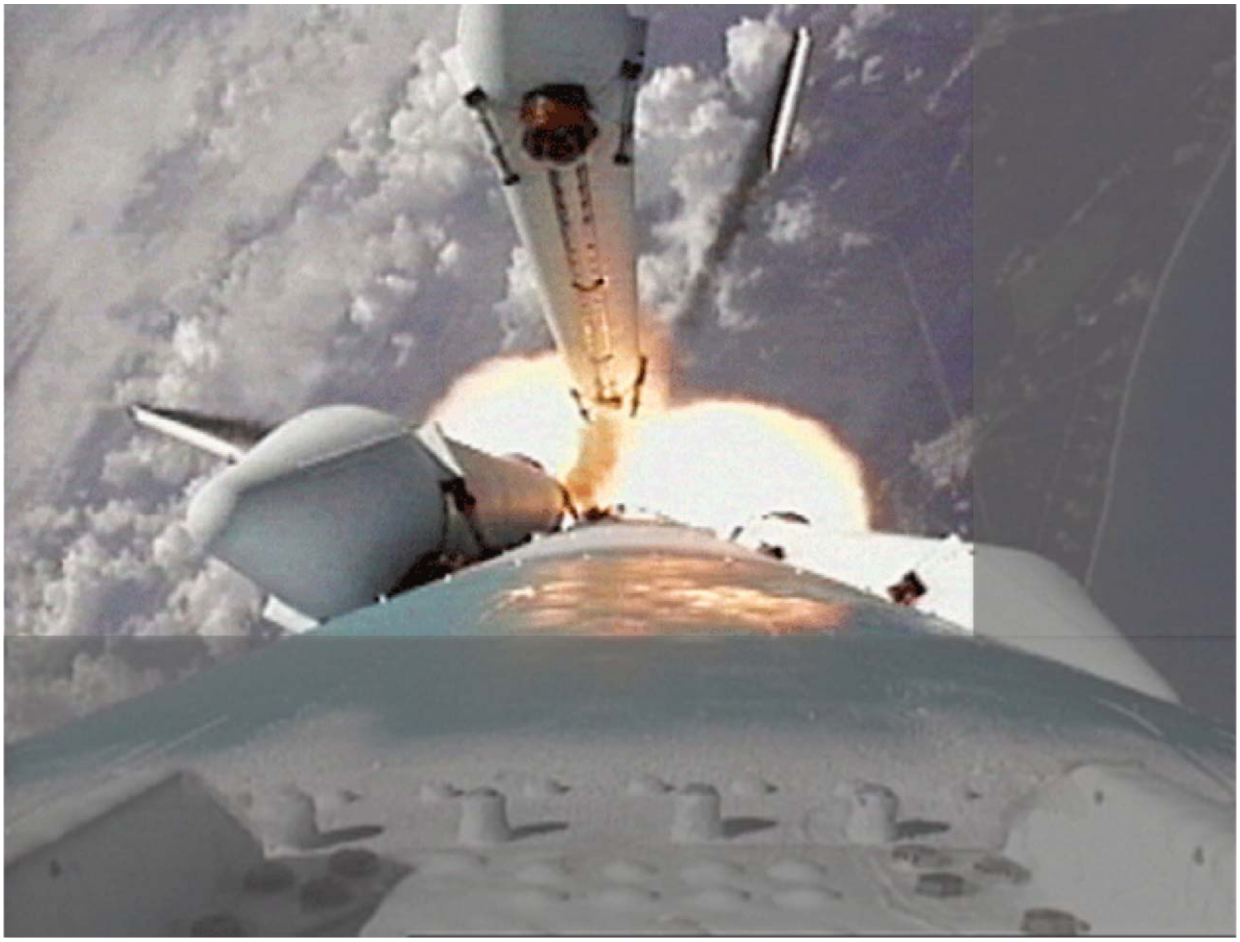

Figure 1. Still frame from rocket-based motion imagery with windowed content.

B. Spacecraft-based Motion Imagery

One of the more complex and expensive aspects of an external spacecraft camera system is controlling and aiming (if the camera isn't fixed). A camera is much more useful for space operations if it can tilt and pan and if the lens has a variable focal length. In that way controllers can change the field-of-view, which is very useful for more complex spacecraft like the ISS, but would also be helpful if monitoring space walking astronauts on an asteroid, Moon base, or on Mars. But such a system requires a command uplink from control systems on the ground to the spacecraft, or control systems in the spacecraft, or both. The mechanical systems required for panning, tilting, and zooming are challenging. The external space environment requires special materials, coatings, and lubricants to enable a lens to change focal lengths, for example, without seizing or allowing the lubricants to leak onto the lens elements. A pan-tilt unit is also expensive and complicated to deploy externally in the space environment. The extreme temperatures, radiation, and, in the case of the Moon, regolith, can damage or destroy the mechanisms. A strategy to alleviate these concerns is a camera system that has no moving parts. As cameras get smaller, while at the same time have improved spatial resolution, it is possible to design and deploy a camera system that can have a 360º field-of-view by placing multiple cameras next to each

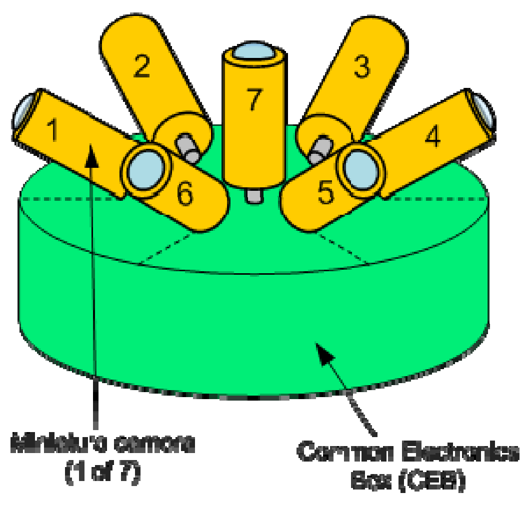

Figure 2. Multi-camera concept

other (see Figure 2) and electronically “stitching” the video together. By using cameras that over-sample the desired resolution, the zoom function can be provided by electronically zooming into the sensor. For example, if 1280 x 720 progressive @ 60 frames-per-second is the desired output, using cameras that have resolutions of 1920 x 1080 or greater would allow digital zooming into a 1280 x 720 image space without degrading the image quality. Further autonomy can be achieved by adding software that monitors the video from all the cameras and automatically switches the field of regard to whatever programmers or engineers decide is of most interest. For example, such a camera system on Mars could be designed to be sensitive to motion. Rather than storing or streaming irrelevant data, it could detect a brief event such as a “dust-devil”, track the event, tag, store and transmit it when the communications link was available. The rest of the time the imagery from all the cameras would be buffered temporarily using electronic storage within the camera system and eventually discarded until a relevant event occurred. Such a system would be more efficient for both the storage system as well as utilizing precious bandwidth, and would not require commanding from the ground or another spacecraft.

C. Distributing Motion Imagery

The most complex aspect to deploying robust motion imagery systems on future exploration missions will be routing and distributing the streams of data. Imagine a mission to an asteroid, the Moon, or Mars, where multiple spacewalking astronauts are deployed. Each astronaut might have a helmet-mounted camera. In addition, cameras mounted on the spacecraft or deployed on rovers or stands might serve as third person monitors of the activity. If the mission is international, space operations centers around the globe will be monitoring the video feeds (See figure 3). If the mission is near-Earth, the feeds will be monitored in real-time, with very low latency from actual time of events. If the mission is at an asteroid or on Mars, the video may be arriving tens of minutes behind actual time.

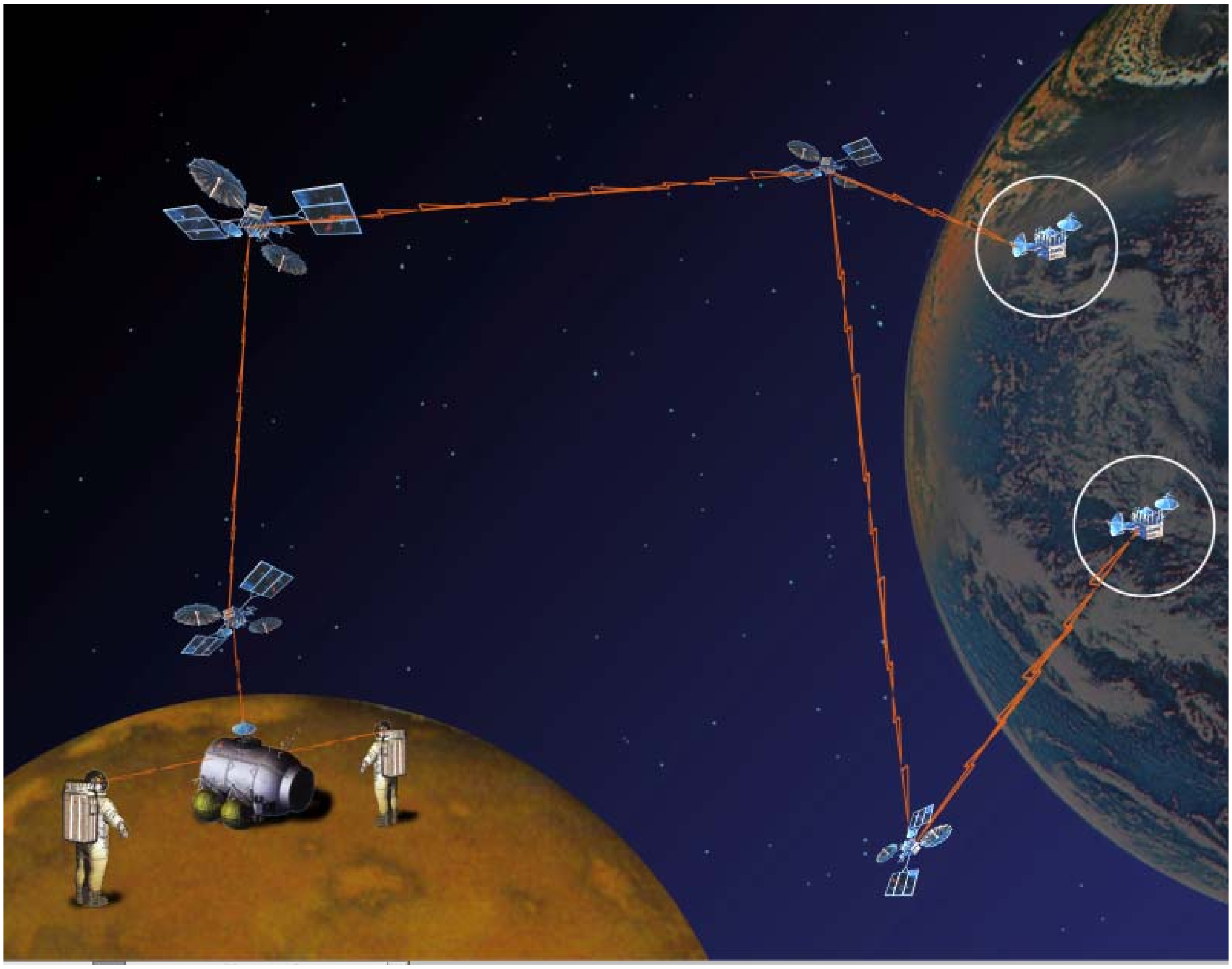

Figure 3. Multiple sources of video distributed across multiple satellites or “nodes”, with high potential for disruption.

If the motion imagery is being streamed, it will be subject to communication link integrity. Compressed video streams are highly susceptible to jitter and packet loss. Decoders will freeze the image or stop outputting usable imagery if the data stream is incomplete or interrupted. If the imagery being streamed is from stored files on the spacecraft, it could be resent. If, however, the motion imagery is being streamed in real-time from the spacecraft, with no spacecraft recording system, then it is critical that the data stream is robust and protected as much as possible. Disruption or Delay Tolerant Networking (DTN) systems would dramatically improve the ability to distribute motion imagery data streams.

DTN should enable a practical solar system internetworking capability. Typical Internet Protocol networking utilizes a packet structure that assumes a continuous network link. DTN is designed for networks that are subject to disruptions or breaks in the network link. There are three classes of video transmission under DTN: 1) File transfer of recorded video; 2) Real-time delivery, best effort; 3) Real-time delivery, no packet drop.

With DTN, in the case of an imagery file download from Mars, for example, the file will be bundled into larger packets and distributed across the various links. If there is a disruption in the link, the file would not have to be retrieved again from the source, but rather the missing parts of the file would automatically be forwarded when the communications link was restored. The Licklider Transmission Protocol[1] will note loss of DTN bundles (which would contain 1-*n* video frames) and request retransmission of missing bundles.

If motion imagery is being streamed across a DTN enabled network, space operations centers could monitor the stream being received in real-time with assurance that parts of the stream that may be missing due to disruptions can be retrieved or reconstructed later. In some instances, it is likely a space operations center will want an interrupted stream to resume "in progress", resuming in real-time with the latest video to arrive. In that case, the prioritization will need to be for real-time packets that arrive to be processed first (best effort). Packets that arrive late or out of order would be stored and used to reconstruct the entire sequence after the fact. The data would be forwarded using DTN Bundle Protocol[2] without custody transfer and would be available to the receiver/decoder on a best effort basis.

In other instances, a space operations center will want to resume where the stream left off, so that no video or motion imagery is missed or incomplete. In that case, prioritization would be for continuity of packets (no packet drop). Packets received out of order or later would be buffered until the sequence could be properly reconstructed.

In either case, the video acquisition system should include timing data within the compressed video data stream as an aid to reconstructing the correct sequence order. The Consultative Committee for Space Data Systems has standards documents under review that address both DTN and how DTN can be utilized for video applications. See http://cwe.ccsds.org/default.aspx for the latest versions of these documents.

IV. Conclusion

Video and motion imagery is ubiquitous in modern life here on Earth. It is difficult to go anywhere without seeing a television monitor. Modern mobile devices are capable of playing movies and streaming live video. In the early days of spaceflight, video and motion imagery was rarely practical. Today, even routine unmanned rocket launches feature live streaming video from camera systems attached to the side of the rocket. As bandwidth increases, modulation systems evolve, and camera systems and compression all improve, video and motion imagery are likely to become requirements for future spacecraft and exploration missions. Engineers and systems designers for these future spacecraft will be able to take advantage of smart systems that can isolate relevant information from the irrelevant, stitch together motion imagery from a suite of cameras into a single video stream, and distribute those streams across a Delay Tolerant Network system to enable robust monitoring and recording of motion imagery at multiple space operations centers across the globe.

Appendix A
Acronym List

CCSDS	Consultative Committee for Space Data Standards
DTN	Delay (or Disruption) Tolerant Networking
HDTV	High Definition Television
ISS	International Space Station
MPEG	Moving Pictures Expert Group

Appendix B
Glossary

Consultative Committee for Space Data Systems	Founded in 1982 by the major space agencies of the world. A multi-national forum for the development of communications and data systems standards for spaceflight.
Delay Tolerant Networking	An approach to computer network architecture that addresses technical issues in networks that lack continuous network connectivity.
Motion Imagery	Refers to specialized imaging systems that generate continuous or sequential streaming images. Covers applications not considered traditional video.
Video	Traditional applications of worldwide standardized television applications such as NTSC, ATSC, PAL and SECAM.

Acknowledgments

The author thanks Jack Hood from Marshall Space Flight Center for creating the art for Figure 3, and Marc Walch from the Jet Propulsion Laboratory for permission to utilize the illustration for Figure 2.

References

[1]CCSDS, Delay Tolerant Networking Working Group, Draft Recommended Standard, “Licklider Transmission Protocol for CCSDS”, CCSDS 734.1-R-2.

[2]CCSDS, Delay Tolerant Networking Working Group, Draft Recommended Standard, “CCSDS Bundle Protocol Specification”, http://cwe.ccsds.org/sis/default.aspx#