Update on the Dependable Multiprocessor (DM7) ISS Flight Experiment

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Abstract—**The NREP (NanoRacks External Platform), host for the DM-related flight experiments, was deployed on the ISS in 2016. The DM7 ISS flight experiment was launched to the ISS in December 2016 as part of the NREP Mission 2 sortie. The NREP Mission 1/Mission 2 switch-over took place in late April 2017, at which time the DM7 flight experiment was deployed and activated shortly thereafter. During the initial on-orbit checkout, all three DM7 experiment missions were successfully demonstrated. Per the NREP mission schedule, DM7 flight experiment is scheduled to last 6 months. The paper provides an overview of DM technology, an overview of the DM7 ISS flight experiment, focusing on the integration and operation of the DM ISS flight experiment within the space/ground infrastructure for NREP-hosted experiments, a summary of on-orbit experiment results, and lessons learned.** [1, 2, 3]

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1. Introduction

Flying high performance, i.e., high throughput (MOPS, Million of mathematical Operations per Second, and high throughput density, e.g., MOPS/Watt, MOPS/kilogram, MOPS/Cubic Centimeter, and MOPS/$) COTS (Commercial-Off-The-Shelf) processing technology in Space is a long-held desire of NASA and the DoD. This desire goes back at least to the mid-90's and DARPA's (Defense Advanced Research Projects Agency) Space Touchstone program. Space Touchstone was DARPA's pioneering effort to fly an Intel Paragon super-computer in space. As part of the Space Touchstone effort, Honeywell and the Naval Research Laboratory (NRL) jointly developed a methodology for flying COTS in space [1], [2]. An overview of this methodology is provided in [1]. Since the Space Touchstone program, there have been several NASA and DoD efforts to accomplish this objective. Dependable Multiprocessor (DM), nee Environmentally Adaptive Fault Tolerant Computer (EAFTC)[3], were developed with this methodology in mind. To a large extent, DM can be considered the great grandson of Space Touchstone. The Gumstix™ ISS Flight Experiment and the DM ISS Flight Experiment (DM7) are key elements of this methodology leading to the TRL7 validation of DM/DM CubeSat technology which will be achieved through the CASIS-sponsored DM7 flight experiment. Consistent with this methodology, the NASA ST8 (Space Technology 8) DM project developed several models, the Radiation Effects/HW SEU Susceptibility Model, the Fault/Error Model, the Availability Model, the Reliability Model, and the Performance Model to support the prediction of DM system performance in different mission applications and environments. These predictive models will be validated by the DM7 flight experiment. More information about these ST8 DM models can be found in published literature [3], [4].

2. DM TECHNOLOGY OVERVIEW

DM and DM CubeSat technology development has been regularly documented in open literature [3] – [13]. A brief overview of DM and DM CubeSat technology is provided in this section to provide a basis for details of the DM7 flight experiment discussed in the remainder of the paper.

DM Technology

Flying high performance Commercial-Off-The-Shelf (COTS) technology in space to take advantage of the higher performance and lower cost of COTS-based onboard processing solutions is a long-held desire of NASA and the DoD. Funded by the NASA New Millennium Program (NMP) Space Technology 8 (ST8) project from 2004 through 2010, the development of Dependable Multiprocessor (DM) technology was, and still is, a major step toward flying high performance COTS processing in space. The objective of the

[1] 978-1-5386-2014-4/18/$31.00 ©2018 IEEE
[2] IEEEAC paper #2406, Version 8, February 5, 2018.

[3] The project formerly was known as the Environmentally-Adaptive Fault-Tolerant Computing (EAFTC) project.

ST8 DM technology advance was to demonstrate that a high-performance, COTS-based processing cluster can operate in a natural space environment. The goals of the ST8 project were to demonstrate a high-throughput, scalable, and easily-programmable processing solution capable of achieving high throughout density, high system availability (> 0.995), and high system computational correctness (> 0.995) in terms of the probability of delivering undetected erroneous or untimely data to the user.

As developed and demonstrated, DM is an architecture and software framework that enables COTS-based, high performance, scalable, cluster processing systems to operate in space by providing software-based SEE-tolerance enhancement in the form of a platform-, technology-, and application-independent Dependable Multiprocessor Middleware (DMM). The platform-, technology-, and application-independent DMM is DM technology. DM is not a specific hardware solution. DM technology was developed not to be a point solution, but to be able to incorporate new technologies, hardware and software, as they come on-line. DM software has been successfully ported to many platforms.

A DM system is a cluster of high performance COTS processors connected with a high-speed interconnect and operating under the control of a reliable, possibly radiation-hardened, system controller and platform, technology, and application-independent fault tolerant middleware. The system controller provides a highly-reliable and SEE-immune host to support recovery from radiation-induced events in the COTS hardware. The DM Middleware (DMM) manages jobs and missions executed on the cluster and, most importantly, enhances the fault tolerance of the system. The DMM controls applications, monitors the health and status of DM hardware and software components, enhances SEU tolerance, and manages the system and application recovery strategies. The features that distinguish DM from other COTS-based solutions are flexibility, scalability, and ease of use which are supported through user-friendly DM mission and job configuration files. Scalability comes in the form of a modular implementation and is limited by the scalability of the high-speed interconnect and the skill of the application developer. DM offers user-configurable fault tolerance with options spanning the mission level to the application level. Fault tolerant execution includes replication, i.e., temporal and spatial self-checking (SC) and triple modular redundancy (TMR), combined with more computationally-efficient Algorithm-Based Fault Tolerance (ABFT). DM can execute multiple missions sequentially or concurrently based on resource availability

A simple, non-redundant DM flight experiment system, e.g., consists of two node types, a System Controller node and a cluster of Data Processing (DP) nodes connected via a high-speed interconnect and a control "bus." Implementing a TCP/IP communication protocol, a DM system can be used with any high speed interconnect. Ethernet was the preferred choice of NASA for the initial ST8 flight experiment. In many applications, the DP nodes tend to be homogeneous, but the use of TCP/IP (Transmission Control Protocol/Internet Protocol) allows DM to support heterogeneous processing clusters as well. The control bus can be a specific mechanical instantiation, e.g., cPCI (compact Peripheral Control Interface, but in most implementations, the control bus is a virtual "bus" providing power to and discrete signal support for the cluster. Most DM systems include a Mass Data Storage node, which the DMM uses to implement some of its fault tolerance functions. A DM system can be used with any sensor that can interface with the cluster. For longer life and more critical missions, the DM system can be implemented with redundant system controllers and interconnects.

The NMP ST8 DM project did its TRL6 (Technology Readiness Level 6 – demonstration/validation in a relevant environment) technology validation in 2008 and 2009. The DM TRL6 technology validation demonstration included system-level radiation beam testing in which one (1) COTS DP board was exposed to a proton beam while executing the TRL6 application suite and operating in the context of a DM flight system including all DMM, experiment interface, and experiment data collection software. The system-level radiation testing validated the DM design and operation in a radiation environment. The DM TRL6 technology validation effort included the demonstration of low overhead and ease-of-use for MPI (Message Passing Interface)-based parallel applications. Summaries of the TRL6 technology validation effort can be found in [3], [4], [5], [6], and [7]. A comprehensive discussion of DM technology development from TRL4 through TRL6 is provided in [3].

Post-TRL6 DM technology development included increased data integrity protection for critical messages, support for OpenMP, the delivery of a DM TRL6 Testbed to JPL (Jet Propulsion Laboratory), and the porting of the ROCKSTER (Rock Segmentation Through Edge Regrouping) Mars rover application by Benjamin Bornstein (JPL) to the TRL6 Testbed. [8]

The main unique thing about a DM system is that it is a cluster of processors, which can be heterogeneous, network-wise and node wise. Most current COTS applications, even if they use SCP (Self Checking Pair) or TMR (Triple Modular Redundancy), are still "uniprocessor" applications. It is not that difficult to add a watchdog timer or a heartbeat to a uniprocessor application and reboot the entire system if necessary. DM was designed to support high throughput parallel multiprocessing applications. Running a DM multiprocessing application, if one of the nodes goes down, the application task can be quickly switched to a hot spare node. The application continues running with very little "off" time and, correspondingly, high Availability and Computational Correctness in terms of timely delivery of correctly processed data to the user, while the faulted node is rebooted and rejoins the cluster.

The "magic" of DM technology is not just SEE tolerance. The "magic" is in the combination of ease of use, low overhead, and SEE tolerance with rapid detection and recovery. Rapid detection and recovery is crucial for achieving high Availability and high Computational Correctness. Rapid detection and recovery is accomplished with an integrated application of HW and SW fault tolerance techniques. DM power management is provided not only to control power to the nodes, but also to detect and mitigate the effects of high current SEFIs/non-catastrophic SELs observed in COTS components.

The DMM is not a heavy-handed middleware. It makes sure the underlying platform is maximally available to the application. DMM is minimally invasive. Within the DM infrastructure, it lets the user do whatever he/she wants to do with the application. The user can employ the available DM Software Fault Tolerance (SW FT) techniques or not.

In terms of ease of use, DM takes care of fault tolerance and fault tolerance implementation issues totally transparent to the user. If the user wants to run an application TMR, spatial or temporal, all he/she has to do is tell DM that is what he/she wants to do. DM takes care of implementing it. DM will assign and schedule the TMR nodes and arrange for the "voting," which actually is done with files compares in protected memory rather than in a potentially "soft" voting element. As with other SW FT techniques, the user just accesses the desired DM service and DM takes care of it.

DM CubeSat Technology

Looking for a ride to space to achieve the all-important TRL7 (Technology Readiness Level 7 – technology validation in a real space environment), DM CubeSat technology, a smaller version of the original ST 8 DM flight experiment based on small, light-weight, low-power, and low cost Gumstix™ COM (Computer On Module) technology, proved to be the key to many potential flight opportunities. In 2010, DM CubeSat technology was sponsored by SMDC (Space and Missile Defense Command) as an Army SERB (Space Experiments Review Board) flight experiment, where it was combined with another Army SERB experiment, SMDC High Power Nanosatellite, to become the SMDC TechSat project. Since its formation in November of 2010, the SMDC TechSat project conducted successful PDR, Phase 1, and Phase 2 efforts. The Phase 1 effort culminated in a successful Flat-Sat Demo in September 2011. The Phase 2 effort culminated in a successful Phase 2 F-cubed Demo in September 2012.

The development of DM CubeSat and SMDC TechSat leveraged $14M of NASA-funded DM technology development effort including the DMM (Dependable Multiprocessor Middleware), the ground command and telemetry processing and display software, and the spacecraft interface software. The spacecraft interface software included the generation of system time to time tag events and the generation of periodic polling messages to extract State of Health (SOH), telemetry, and experiment data.

The CubeSat-size DM payload processor was achieved and demonstrated through the use of COTS Gumstix technology shown in Figure 1. The Gumstix COMs are true COTS. In addition to providing power distribution and control to individual DP nodes, the DM Power Management Circuitry shown in the figure also provides circuitry needed to mitigate high current SEFIs exhibited by many COTS components.

The DM F-cubed flight prototype hardware including the prototype flight PWBs and the mechanical housing were developed by Morehead State University. In order to fit a reasonable amount of DM payload processing capability into the smallest possible package with good mechanical (structural and thermal) design properties, the DM F-cubed fight prototype hardware was developed as an integral unit as shown in Figure 1. The PWBs were designed with direct, board-to-board, interconnects which were part of the integrated mechanical design. Figure 1 also shows the complement of capability included in the DM payload processing flight prototype. Figure 2 illustrates the relative size of the DM CubeSat payload processing subsystem flight prototype – small enough to fit into the palm of your hand and light enough to be mailed across the country for the price of a few 1st class postage stamps. The outer dimensions of the actual DM flight prototype package are 75 mm x 75 mm x 35 mm, ~1/3 U. The total flight DM flight prototype package weighs ~ 120 grams. Power can be controlled with duty cycle and clock rate, but the peak power with all eight (8) Gumstix modules active would be ~12 - 18 Watts,

More details about DM CubeSat development including the DM CubeSat testbed and the F-cubed flight prototype can be found in [9], [10], [11], [12], and [13]. The DM7 fight experiment project heavily leverages the development of DM, DM CubeSat, and SMDC TechSat technologies. The DM CubeSat / SMDC TechSat payload processor flight prototype design is the basis for the DM ISS flight experiment discussed in the next sections.

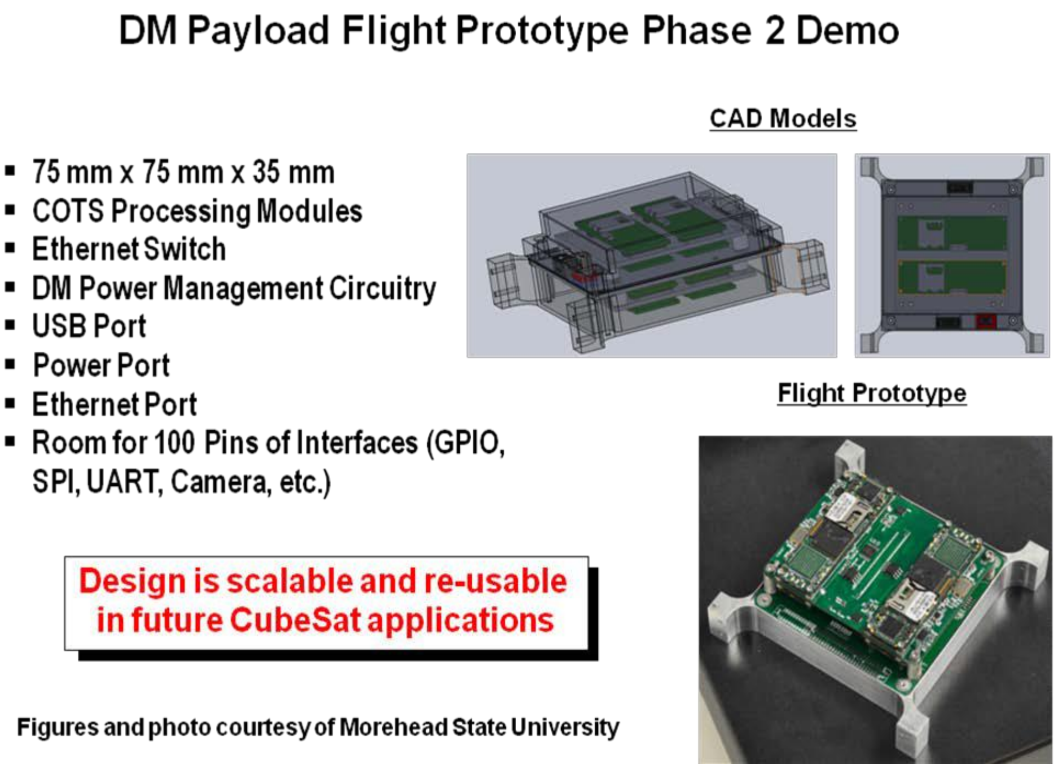


Figure 1 - DM CubeSat Payload Processor Flight Prototype Subsystem

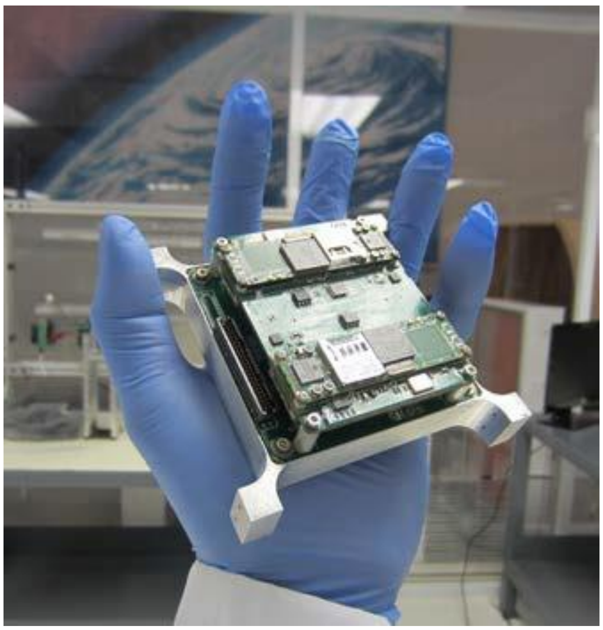


Figure 2 - DM Flight Prototype – Integrated Payload Processor Subsystem

(Photo Courtesy of Morehead State University)

3. DM7 FLIGHT EXPERIMENT–OVERVIEW

Overview

In September 2014, Honeywell and Morehead State University (MSU) were awarded a CASIS (Center for the Advancement of Science in Space) grant to fly a DM CubeSat payload processor as an ISS National Laboratory flight experiment. The plan was to leverage as much of the previous DM and DM CubeSat work as possible. This includes the flight and ground software from the original ST8 DM TRL7 flight system which has been ported to multiple DM CubeSat platforms, the DM CubeSat payload processor flight system prototype designed and built by MSU for SMDC TechSat, the C&DH subsystem and spacecraft interfaces designed and developed for SMDC TechSat, and the real-time, ground-commanded, programmable image compression application developed on the DM CubeSat testbed and demonstrated as part of the SMDC TechSat Phase 1 Flat-Sat Demo and the SMDC TechSat Phase 2 F-cubed Demo. The latter included a camera interfaced with a Gumstix COM.

A block diagram of the DM7 flight experiment configuration is shown in Figure 3. There are three (3) major elements in the on-orbit in the DM7 flight experiment configuration: 1) the DM CubeSat Payload Processor, 2) the NREP DHS (NanoRacks External Platform Data Handling System), and 3) the DM7 C&DH unit. The DM CubeSat Payload Processor is the primary focus of experiment, the NREP DHS is the host for the experiment, and the DM7 C&DH provides the interface between the NREP DHS and the DM7 flight experiment. The small four (4) node Gumstix-based DM cluster with the flight experiment camera is shown in the right-hand side of the figure. Also shown are two (2) additional Gumstix modules which serve as the DM System Controller and the DM Payload Processor interface with the DM7 C&DH unit.

The DM7 flight experiment needs a host platform to provide a mounting interface, communication and power for the DM CubeSat payload processor and associated hardware. The platform selected for the DM7 flight experiment is the NREP (NanoRacks External Platform) shown in Figure 4. The NREP was designed to accommodate standard 1U, 2U, and 3U CubeSat experiment chassis, but it can also accommodate custom experiment designs. The experiment chassis are mounted on the top and bottom of a removable palette. Passive experiments are mounted on the top of the palette. Active experiments are mounted on the bottom of the palette.

The NREP is designed to be a permanent ISS test platform which can support changeable experiments on a 6-month rotating basis; hence the planned 6-month duration of the DM7 flight experiment. The Japanese Robotic arm and the Japanese External Module (JEM) airlock are used to change out the experiments. The arm is used to retrieve and re-deploy the NREP. The arm brings the NREP into the JEM where the astronauts remove the current experiments for return to earth and replace them with the next cycle of experiments before the arm re-deploys the NREP. The timing and duration of the NREP ISS experiments are dictated by the JEM airlock cycles.

The DM ISS flight experiment hardware includes a DM7 flight version of the DM payload processor described in Section 2 [11], [12], [13], a camera, and the interfaces to the NREP DHS (Data Handling System). The DM ISS flight hardware is housed in a 1U chassis designed to meet NREP electrical and mechanical interface requirements.

As also shown in Figure 3, the DM ISS flight experiment is connected to the NREP via an umbilical cable which provides power to the payload and a serial link for command and telemetry to/from the experiment. Contact with the DM7 flight experiment is through the existing NREP/ISS communication infrastructure which includes the NREP DHS, the ISS communication capability, TDRSS (when needed), the NASA/MSFC ground facility, and the NREP ground facility as shown on the left hand said of Figure 3.

In addition to providing continuous downlink telemetry from the DM7 flight experiment, the NREP DHS provides a memory buffer to capture all of the output from the DM7 flight experiment. The buffer will store the DM experiment data until it can be down-linked to the ground. The down-linked experiment data will be forwarded from NASA/MSFC through the NREP ground facility to MSU and Honeywell for analysis.

The NREP memory buffer also provides temporary storage for the output from the DM7 flight experiment during occasional loss of signal (LOS) with the ISS. The buffer will store the DM experiment data until it can be down-linked to the ground.

The DM7 Flight Experiments

The DM7 flight experiment is designed to be an autonomous free-running experiment continuously collecting and reporting experiment data as long as the DM7 payload processor is powered up and active. As an autonomous free running experiment, the DM7 flight experiment does not entail or require a lot of commanding.

There are three (3) distinct parts to the DM7 flight experiment: 1) the DM radiation effects and response experiment, 2) the DM capabilities experiment, and 3) the DM camera experiment.

The first part of the DM7 flight experiment is the DM radiation effects and response experiment. The DM radiation effects and response experiment will run for approximately the first four months of the anticipated six-month active DM7 flight experiment duration.

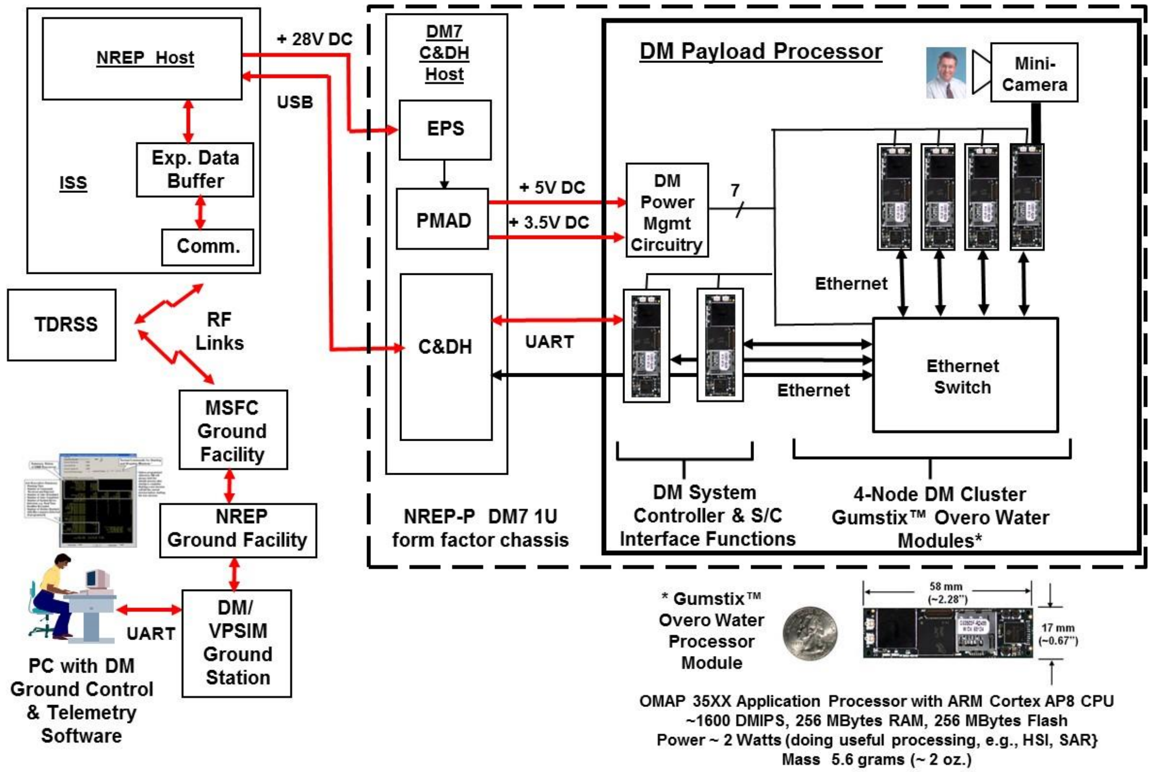


Figure 3 - DM7 Flight System Configuration

The second part of the DM7 flight experiment is the DM capabilities experiment. The DM capabilities experiment is the secondary DM7 experiment. After the initial DM7 primary experiment period has elapsed, the DM7 experiment will be commanded to switch to the DM capabilities experiment. The DM capabilities experiment will run for approximately 2 weeks of the anticipated six-month active DM7 flight experiment duration.

The third part of the DM7 flight experiment is the DM camera experiment. The DM camera experiment is the tertiary DM7 experiment. After the DM7 capabilities experiment period has elapsed, the DM7 experiment will be commanded to switch to the DM camera experiment. The DM camera experiment will run for approximately 2 weeks of the anticipated six-month active DM7 flight experiment duration.

After the DM7 camera experiment period has elapsed, the DM7 experiment will be commanded to switch back to the DM7 radiation effects and response experiment, which will run for the remainder of the anticipated six-month active DM7 flight experiment duration.

DM7 SOH and Experiment Data Telemetry

There are two types of DM7 SOH and Experiment Data Telemetry downlink messages: 1) DM Payload Processor SOH and Experiment Data Telemetry downlink messages, and 2) the DM7 SOH downlink messages.

The source of the DM Payload Processor SOH and Experiment Data Telemetry downlink messages is the DM payload processor. These messages are generated once every four (4) seconds.

The source of the DM7 SOH downlink messages is the DM7 C&DH. These messages are generated once every second as requested from the NREP DHS. The DM7 SOH downlinks include currents and temperatures, which are embedded in the responses to the periodic Status (S) requests from the NREP DHS.

DM7 Camera Images

When performing the camera experiment, the DM Payload Processor will capture and compress camera images for transmission to the ground. The nominal camera frame rate is 0.1 Hz, approximately one frame every 10 seconds.

There were two options for mounting the DM7 flight experiment camera, nadir-facing and aft-facing, Because most images from the ISS are taken nadir-facing, it was decided to have the DM7 camera face aft, i.e., in the ISS velocity wake direction, and take advantage of any events of opportunity. In the absence any specific events of opportunity, the nominal aft-facing view of the DM7 camera is depicted in Figure 7.

Normal Day Downlink Operation

During a normal day, the DM7 flight experiment will continuously generate experiment data to be sent to the ground. The type, the amount, and the data rate depends on the experiment being run. DM7 SOH and Experiment Data Telemetry are periodically transmitted the ground as determined by the polling rate programmed into the DM7 System Controller.

Because of the nature of the DM7 flight experiment, the downlink SOH and Experiment Data Telemetry messages must be sent to the ground and forwarded to the DM7 Payload Developers as quickly as possible for analysis and possible recovery action.

The DM7 flight experiment has a real-time requirement. The DM7 flight experiment measures Availability. The DM7 flight experiment can't afford to lose a whole day of operation because the payload operators didn't know the system had a problem: 1) because this affects the Availability calculation, and 2) the DM7 flight experiment needs the maximum up-time of the experiment to maximize the number of possible radiation-induce events experienced during the course of the active experiment period to have a "statistically-significant" experiment. The ISS radiation environment is very benign, i.e., there are not that many events that the DM7 flight experiment can afford to lose any active experiment time on orbit.

The DM7 camera experiment is expected to be of short duration, e.g., a week or two, compared to the 6-month duration of the entire DM7 flight experiment. Whenever the DM7 camera experiment is active, the NREP DHS will issue Put Commands (P-Commands) to the DM7 payload to downlink captured DM7 camera images. When the DM7 camera experiment is not active, there is no need for the NREP DHS to issue P-Commands to the DM7 Payload.

Activation of the DM7 camera experiment will be coordinated with the NanoRacks Payload Operations personnel. Coordination will involve advanced scheduling of the day(s), time(s), duration(s) of the DM7 camera experiment, and camera image downlink rates controlled by the automated execution of P-commands from the ground.

The DM7 payload has the capability to change the image compression ratio as commanded from the ground For normal operation of the DM7 camera experiment, a 100:1 image compression ratio will be used.

The DM7 C&DH will have the capability to buffer camera images to support the worst-case camera image generation and downlink rates.

When the DM7 camera experiment is not active, there is no need for Put Commands (P-Commands) to be sent to the DM7 Payload.

Other Normal Day Command Operation

The NREP-DHS automatically issue S-Commands to the DM7 Payload at a 1 Hz rate. The DM7 C&DH will respond to the S-Command by acknowledging receipt of the S-Command and by sending DM7 Payload SOH data including Payload currents and temperatures back to the NREP-DHS. The NREP-DHS transmits the DM7 Payload SOH to the ground.

Contingency Uplink Command Operation

Depending on analysis of the downlink SOH and Experiment Data Telemetry, if the telemetry data indicates the DM payload processor is in a state from which it can't recover on its own, it may be necessary to issue contingency commands to the DM7 flight experiment. These contingency commands include commands to the DM payload processor to reset a node or to restart an experiment, and commands to the DM7 C&DH to cycle power to a specific DM payload processor node or to cycle power to the entire DM payload processor.

This type of contingency recovery operation could involve short-term real-time interaction with the DM7 flight experiment system, e.g., issue a command and observe the ensuing downlink SOH and Experiment Data Telemetry to ensure the DM7 flight experiment system responded to the command correctly and the system is back on-line.

Relative to rapid recovery from on-orbit anomalies, for the original DM ST8 flight experiment, the ground system was instrumented to detect on-orbit anomalies in the SOH and Experiment Data Telemetry messages and to immediately contact the 24/7/365 on-call DM experiment operator to alert him/her to the existence of the anomaly. The on-call DM experiment operator would evaluate the data and initiate the appropriate immediate recovery action to get the DM system back on-line as quickly as possible.

Optional Uplink Command Operation

The 3rd DM7 experiment, the camera experiment, has no critical identified scientific objective. As such, it can run at almost any time during the 6-month DM7 flight experiment period. However, it may be desirable to have the DM7 flight experiment camera capture images of an unplanned "event of opportunity," e.g., an erupting volcano, an unusual oceanic event (a tsunami), ISS cargo vehicle docking, ISS CubeSat deployment, etc. If such an "event of opportunity" arises, it may be desirable to alter the nominal DM7 flight experiment schedule to take advantage of the opportunity by activating the DM7 camera experiment and/or changing the image compression ratio.

As mentioned previously, the DM7 camera experiment is expected to be of short duration compared to the 6-month duration of the entire DM7 flight experiment. Whenever the DM7 camera experiment is active, P-Commands will be sent to the DM7 payload to downlink captured DM7 camera images. The P-commands will be sent to the DM7 Payload from the NanoRacks Ground Facility.

The rate at which P-commands will be sent to the DM7 Payload will be determined by the activity in the camera FOV (Field of View).

If there is an event of interest, e.g., docking of a cargo re-supply vehicle, a CubeSat deployment, etc., the P-commands will be sent to capture the activity in nearer real time.

Because NanoRacks Payload Operations personnel are cognizant of significant ISS event schedules, e.g., cargo re-supply docking, activation of the DM7 camera experiment will be coordinated with them. Coordination will involve advanced scheduling of the day(s), time(s), duration(s) of the DM7 camera experiment, and camera image downlink rates controlled by the automated execution of P-commands from the NanoRacks Ground Facility

The ISS infrastructure will store all data and images generated by the DM7 flight experiment. All of the DM7 flight experiment data will be downloadable to the ground at the end the active flight experiment.

The download of all of the DM7 flight experiment data stored on the ISS is commanded and controlled by the NanoRacks Payload Operators.

Partial DM7 flight experiment data can be commanded to be downloaded to the ground by the NanoRacks Payload Operators at any time.

With coordination between the Honeywell/MSU Payload Developers and the NanoRacks Payload Operators, the latter capability can be exercised to fill in gaps in the received downlink data due to temporary LOS between the ISS and the MSFC Ground Facility if necessary.

As mentioned previously, the DM7 experiment payload is hosted on the NREP. The NREP, depicted in Figure 4, is designed to be able to handle multiple standard 1U, 2U, and 3U chassis, but it can also accommodate custom experiment designs. The NREP provides power and telemetry links for the hosted experiments. The experiment chassis are mounted on the top and bottom of a removable palette. Passive experiments are mounted on the top. Active experiments, such as DM7, are mounted on the bottom side of the NREP palette as shown in the figure bottom. The DM7 flight experiment hardware includes a flight version of the DM payload processor flight prototype described in Section 2 [11], [12], [13], a camera, and the interfaces to the NREP/DHS. The DM ISS flight hardware is housed in a 1U chassis and mounted as shown in Figure 4.

Figure 5 is a photo of the actual DM7 experiment payload 1U chassis fabricated by MSU.to meet NREP requirements hardware is housed in a 1U chassis and mounted as shown in Figure 4.

As shown in Figure 5, an umbilical cable connects the DM7 flight experiment to the NREP. The umbilical cable provides the power and the command and telemetry to/from the experiment. The latter is a simple serial link.

The deployed NREP is mounted on the ISS in the location shown in Figure 6. The DM7 experiment payload is mounted on the NREP with the camera facing aft, providing a unique field of view (FOV), depicted in Figure 7.

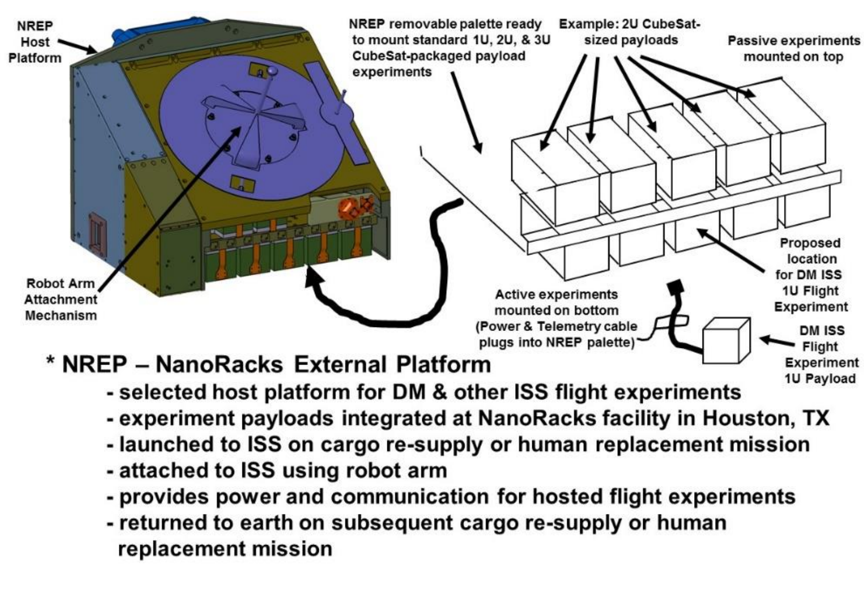


Figure 4 - NREP (NanoRacks External Platform) - Host for the DM7 Flight Experiment

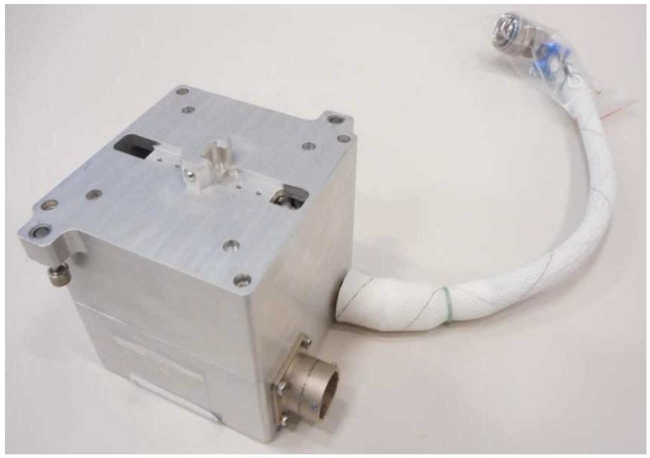
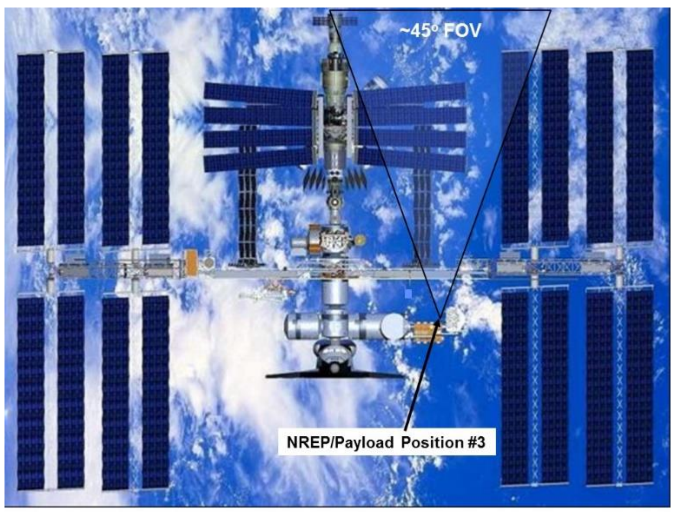


Photo Courtesy of Morehead State University

Figure 5 - DM7 Flight Experiment 1U Chassis



From NASA ISS Web Site

Figure 6 - Location of NREP with DM7 Flight Experiment on the ISS

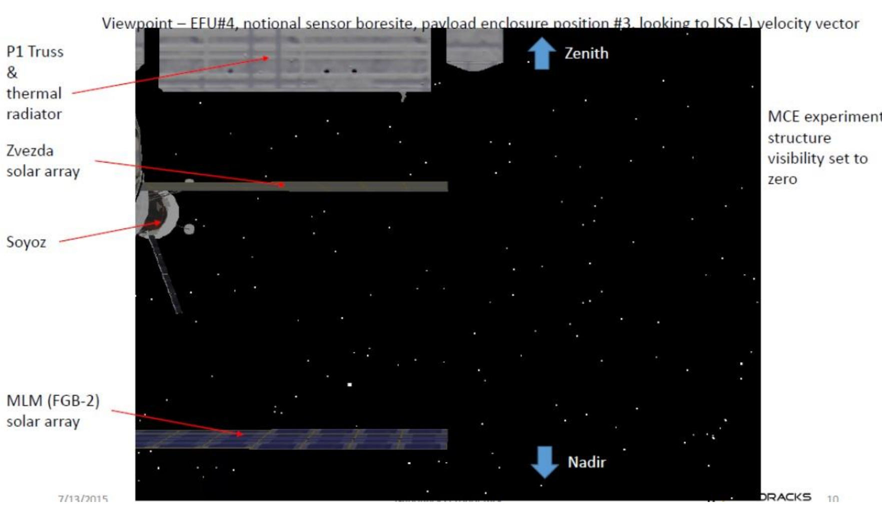


Figure 7 - Nominal Aft-Facing FOV for the DM7 Camera

DM7 FLIGHT EXPERIMENT COMMANDS

To minimize changes to the DM system, the existing DM command structure was retained. However, doing this required incorporating the DM command structure had to be incorporated in the existing NREP DHS/ISS space/ground infrastructure.

The NREP DHS offers a comprehensive set of commands to support a wide variety of experiments. Only four (4) NREP DHS commands were used for the DM7 experiment. These are: the ./S command, the ./D command, the ./P command, the ./X command.

The ./S command is a periodic (1 Hz) NREP DHS status command to which the payload responds with an <OK> response and the appropriate response fields filled with payload ID and other payload data. The DM7 system uses the time in the S command to tag DM7 telemetry and camera images.

The ./D command is an NREP DHS command to set up the ports for the downlink connection to the NREP DHS. The DM7 system responds to a ./D with an <OK> response and sets up the ports.

The ./P command is an NREP DHS "put" command used to transfer data from the payload to the NRE*P* DHS. The DM7 system responds to the ./P command with an <OK> response and initiates an sftp transfer of camera images to the NREP DHS.

The ./X command is an NREP DHS "execute" command to the payload. The payload command to be executed is embedded as a command character string in the NREP DHS .X command. The DM7 system responds to the .X command with an <OK> response, interprets the command character string, and takes the appropriate action. The DM7 experiment operational concept was based on a limited set of high-level commands including cycling power to the DM7 payload, controlling power to individual nodes, toggling individual nodes, and changing the experiment mission and applications being run.

The ./S, ./D., ./X, and ./P commands are the only NREP DHS commands used by the DM7 flight experiment. For robustness, the DM7 system was designed to accept and respond to all NREP DHS commands. For NREP DHS commands not used by the DM7 flight experiment, the DM7 system responds with <NOK> response and an "Unsupported command" message back to the NREP DHS.

PRE-FLIGHT TESTING

MSU fabricated two (2) flight DM7 units. One DM7 flight unit (shown in Figure 5 and the prototype flight unit, which was sent to Honeywell for software development, integration, and testing. The actual DM7 flight unit was kept in the clean room at MSU. When the final flight software was ready for testing flight system using TeamViewer, a secure Remote Desktop Access capability, which allowed remote loading of the DM7 with the flight hardware, Honeywell remotely accessed the DM7 flight software and remote monitoring, and command and control of the DM7 flight including VPSIM. A block diagram of the remote access setup is shown in Figure X. This configuration supported the transmission of DM7 commands in NREP format, the monitoring and display of DM7 status using VPSIM, and the display of captured camera images, in essence allowing "test like you fly" testing of the DM7 system.

Following integration and testing of the DM7 flight software with the DM7 flight hardware, MSU completed the final fabrication of the DM7 flight unit which included final mechanical stabilization of the components, i.e., screwing and epoxying, adding thermal compound, and closing and sealing the 1U chassis. With the packaging of the DM7 flight unit complete, MSU performed EMI/EMC testing and environmental testing of the DM7 flight system. The DM7 system was tested to the EMI/EMC and vibration profiles provided by NanoRacks. Following the successful EMI/EMC and environmental testing at MSU, the DM7 flight system was shipped to NanoRacks in Houston, TX for final fit check and pre-flight functional testing with the NREP DHS Engineering Model.

Final fit check and pre-flight functional testing with the NREP DHS Engineering Model was performed by NanoRacks. NanoRacks provided the same remote access setup using TeamView which allowed a few minor tweaks to the DM7/NREP DHS interface software and additional "test like you fly" testing. After testing all of the NREP-compatible DM7 commands and overall DM7 operation, and performing complete end-to-end testing of the DM7/NREP DHS/ISS space/ground link, NanoRacks deemed the DM7 flight experiment ready to fly. NanoRacks delivered the DM7 flight experiment to the NASA Cargo Mission Center for launch.

4. THE DM7 FLIGHT EXPERIMENT

The DM7 payload was launched to the ISS on HTV6 on December 9, 2016. The NREP Mission 1 / Mission 2 switch-over took place on April 27, 2017. The NREP was re-deployed and activated on April 28, 2017. A photograph of the DM7 payload mounted to the NREP at the end of the Japanese robotic arm during NREP redeployment is shown in Figure 8. During redeployment, it was requested that the astronaut controlling the robotic arm rotate the arm to show the two (2) NREP Mission 2 payloads. Figure 9 is a photo of the NREP re-mounted on the outside of the ISS ready for activation of NREP Mission 2. (The NREP payloads are on the nadir-facing side of the NREP.)

The DM7 payload was activated on April 28, 2017. As designed, as soon as it was powered on, NASA and NanoRacks reported the DM7 payload went on-line and started streaming downlink telemetry data. NanoRacks accommodated the DM7 payload developers' request for real-

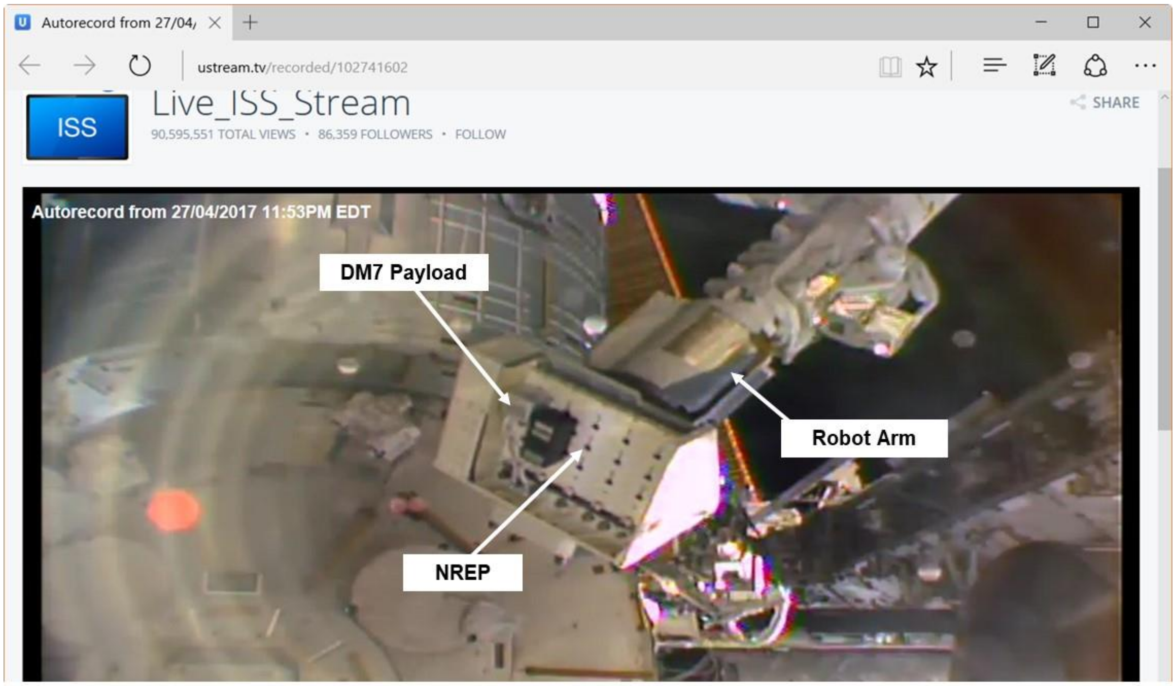


Image courtesy of NASA

Figure 8 - NREP with Mission 2 Payloads Attached to the Japanese Robotic Arm During Redeployment

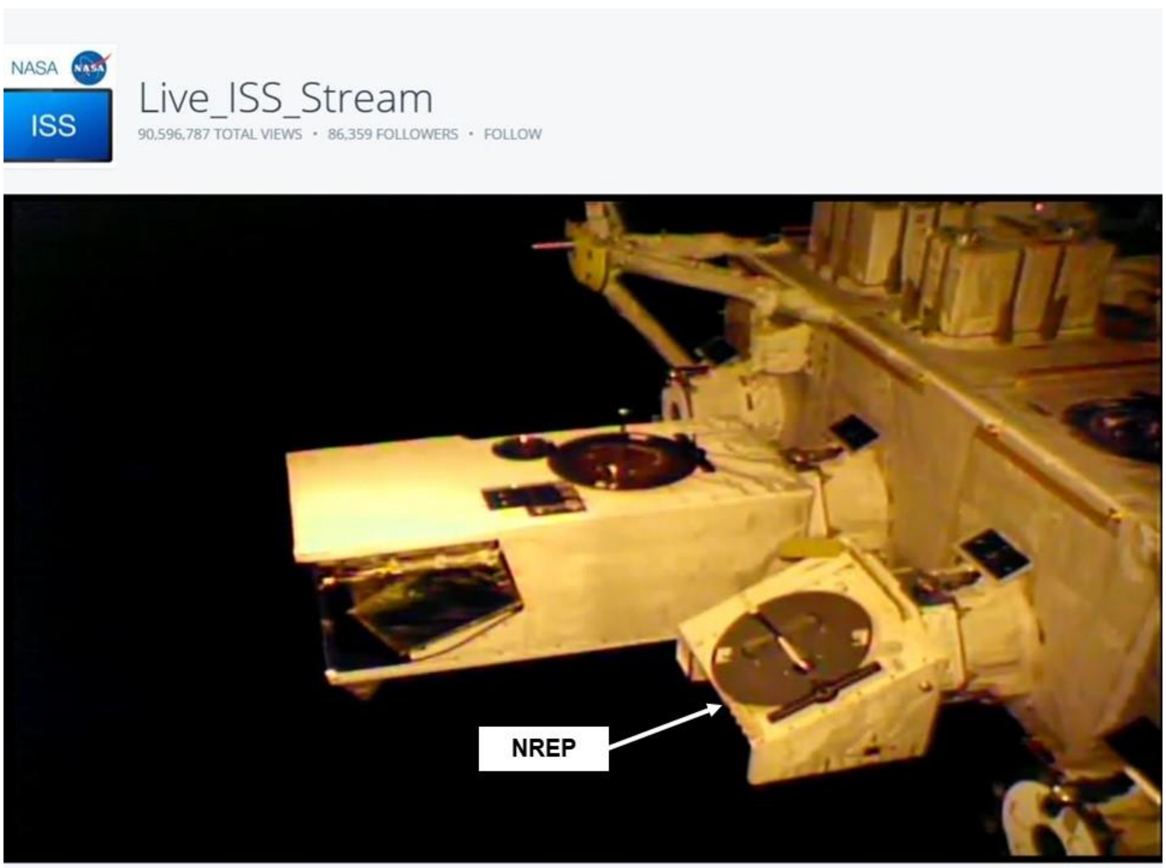


Image courtesy of NASA

Figure 9 - NREP Mounted on the ISS

time telemetry from the DM7 experiment by providing streaming telemetry data to Morehead State University. Since this was the first time streaming capability was provided for an NREP experiment, some effort was anticipated to get the "kinks" out of the link. There were a few kinks, but the kinks were minor and were quickly and sequentially resolved. At first, the NREP ground facility not forwarding streaming telemetry to MSU. NanoRacks made some software changes and telemetry data started being transferred to MSU. The next issue was the host computer at MSU had an inadvertent firewall and incorrect port ID. Once these two issues were corrected, MSU started to receive data from the NREP ground station, but the data was not being accepted by the DM7 ground software. This was because the received downlink messages had 11 bytes prepended to DM telemetry messages. With the 11 bytes removed, the DM7 ground software started to receive the messages and update the DM VPSIM SOH (State-of-Health) and EDT (Experiment Data) displays, which allowed DM personnel on the ground to monitor DM7 performance and operation in real time. Once the downlink link issues were resolved, the DM7 downlink telemetry streams continued through normal LOS outages and link switch-overs through different TDRSS spacecraft when ISS was not in direct contact with MSFC ground facility. Telemetry data was buffered during outages and streamed on the downlink as soon as the link connection was restored with continuous updating of the DM SOH and EDT displays.

Use of the DM SOH and EDT displays was important for two reasons: 1) most experiments tend to generate more data than can realistically be analyzed (The DM7 experiment was no exception.), and 2) real-time monitoring allowed the DM7 payload developers to observe, respond, and control the DM7 payload in real time. The former was anticipated. The DM7 SOH and EDT displays shown in Figures 10 and 11 were set up to allow direct high-level monitoring of DM7 availability, computational correctness, most recent node and application recovery times, cumulative node and application recovery times, and DM7 software status including the start and completion of applications, node assignments and utilization, and DMM fault tolerant middleware activity.

Commanding of the DM7 payload had to be coordinated through NASA and NanoRacks. and only NanoRacks personnel could issue commands to the DM7 on-orbit. The DM7 experiment was designed to be autonomous with minimal commanding during the course the experiment. As it turned out, a lot more commanding was done to test on-orbit functionality and to diagnose on-orbit anomalies. As result, the ability to do real-time monitoring and control of the DM7 was paramount. Jerry Mathew (NanoRacks) was instrumental in monitoring and controlling the DM7 experiment, and in aiding the understanding and debugging the on-orbit anomalies encountered. The DM7 experiment operational concept was based on a limited set of high-level commands including cycling power to the DM7 payload, controlling power to individual nodes, toggling individual nodes, and changing the experiment mission and applications being run. NanoRacks also supported "ssh" access to the DM7 hardware to help understand and debug on-orbit anomalies.

NanoRacks supported testing and diagnosis of anomalies by providing real-time remote viewing of their NREP status display which including monitoring of the power drawn by the DM7 payload and the status of DM7 telemetry generation (see Figure 44). NanoRacks also obtained permission from NASA to let us view the ISS AOS/LOS Acquisition of Signal/Loss of Signal display. The former aided diagnosing some node anomalies. The latter allowed the scheduling of DM7 payload testing around known ISS link outages and eliminated the DM7 payload and NREP as sources of temporary telemetry dropouts.

Successful On-Orbit Checkout

Initial on-orbit functional testing successfully demonstrated all three (3) DM7 experiment missions. Based on observation of the high-level DM SOH and EDT displays, executing the Radiation Effects Mission, no SEU induced node failures or computational errors were detected. Similarly, executing the Fault Tolerant Capabilities Mission, no SEU induced node failures or computational errors were detected. This was not unexpected because the ISS orbit is a relatively benign radiation environment. Intentionally induced node failures, e.g., by issuing a command to cycle power to node, demonstrated DM system recovery with nominal node and application recovery times. Executing the Ground-Commanded Programmable Image Compression Mission, "stunning" 100x and 1000x compressed images were captured as shown in Figure 12. The aft-pointing DM7 payload camera provided a unique view from the ISS. With currently available capability, there wasn't sufficient bandwidth for real-time video transmission, but the DM7 payload captured a series of 100x compression snapshot images, which Dr. Charles Conner (Morehead State University) turned into a video montage which showed changing cloud patterns as the ISS transits in its orbit, shadows moving across the ISS structure, and articulating Russian solar panels. The video montage can be viewed at: https://drive.google.com/file/d/0BxRGaTELkYoubmNBOHBQWnV2eURVUUdSd2V2Y21KREZIRkFj/view?ts=5a0b50a2 [14]

On Orbit Anomalies

The DM7 payload successfully completed environmental testing at Morehead State University and final pre-flight testing, including simulated on-orbit operational testing, at Nano Racks prior to being delivered to the NASA Cargo Mission Center for launch to the ISS. To the best of our knowledge a fully functional DM7 payload was delivered to NASA.

As soon as the DM7 payload was powered on on-orbit, it started executing the default mission as it was designed to do. Although the DM7 downlink telemetry link wasn't fully

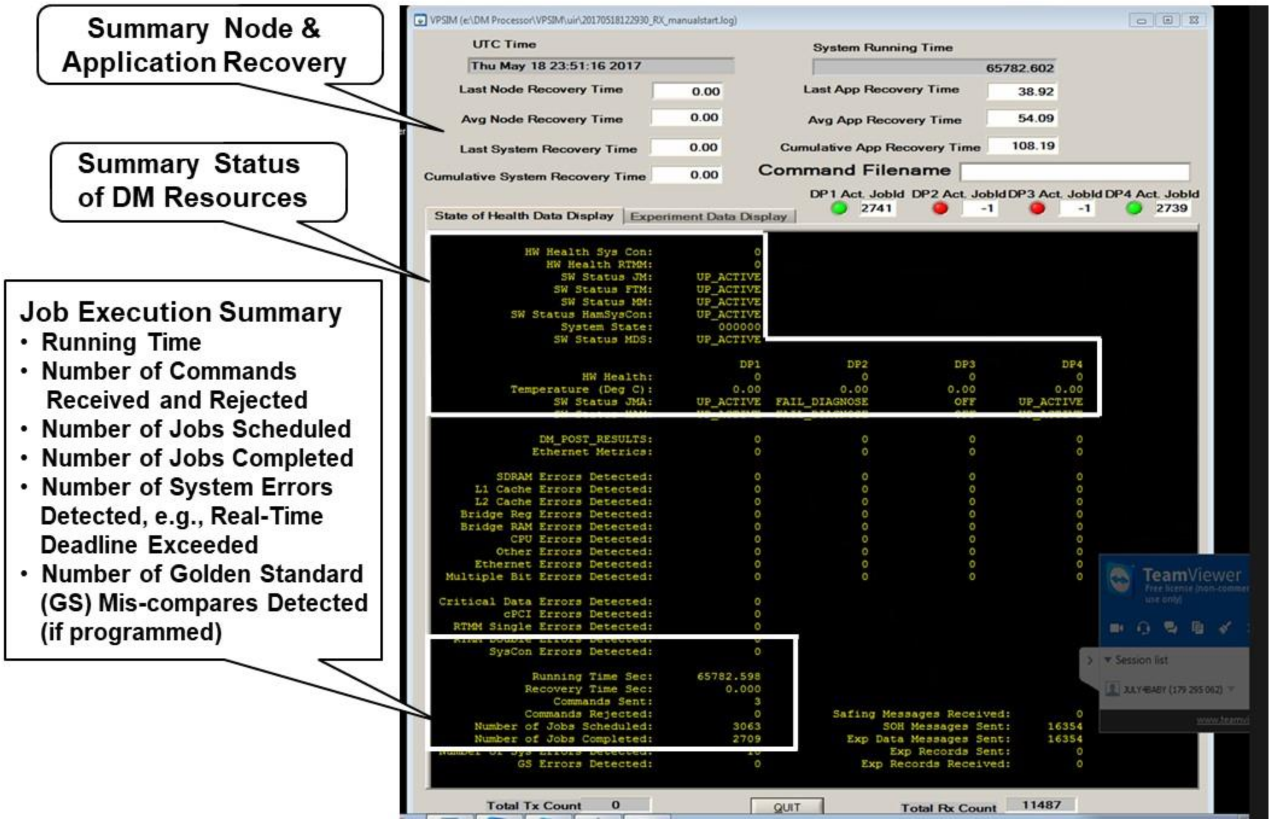


Figure 10 - DM VPSIM SOH Display

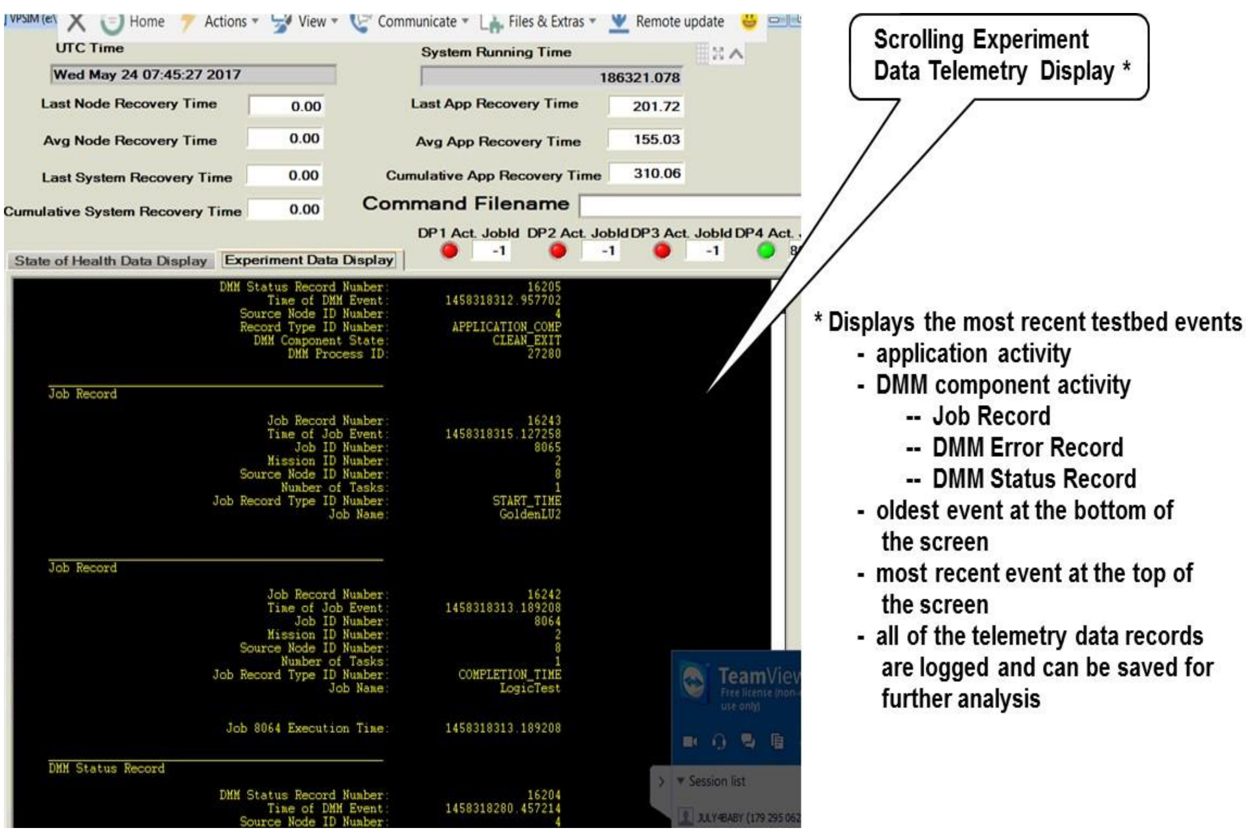


Figure 11 - DM Experiment Data Telemetry Display

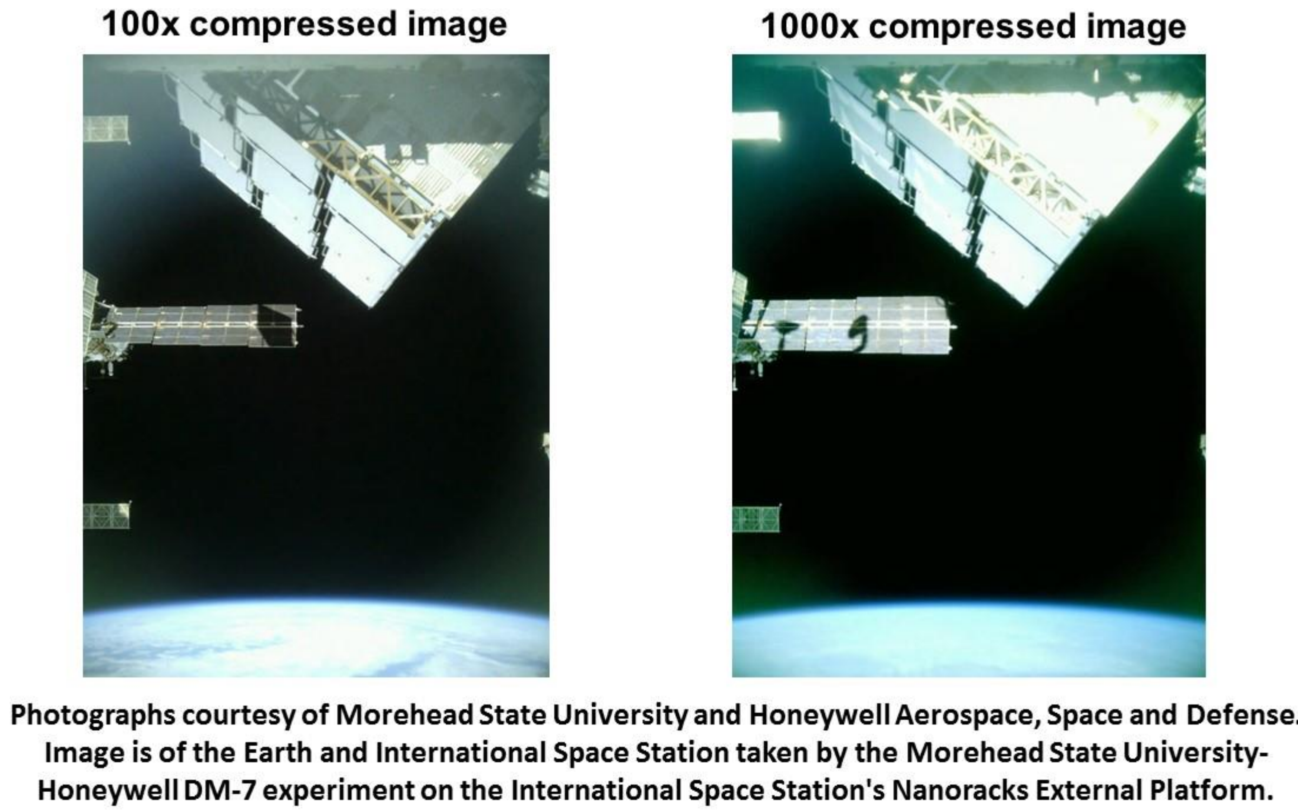
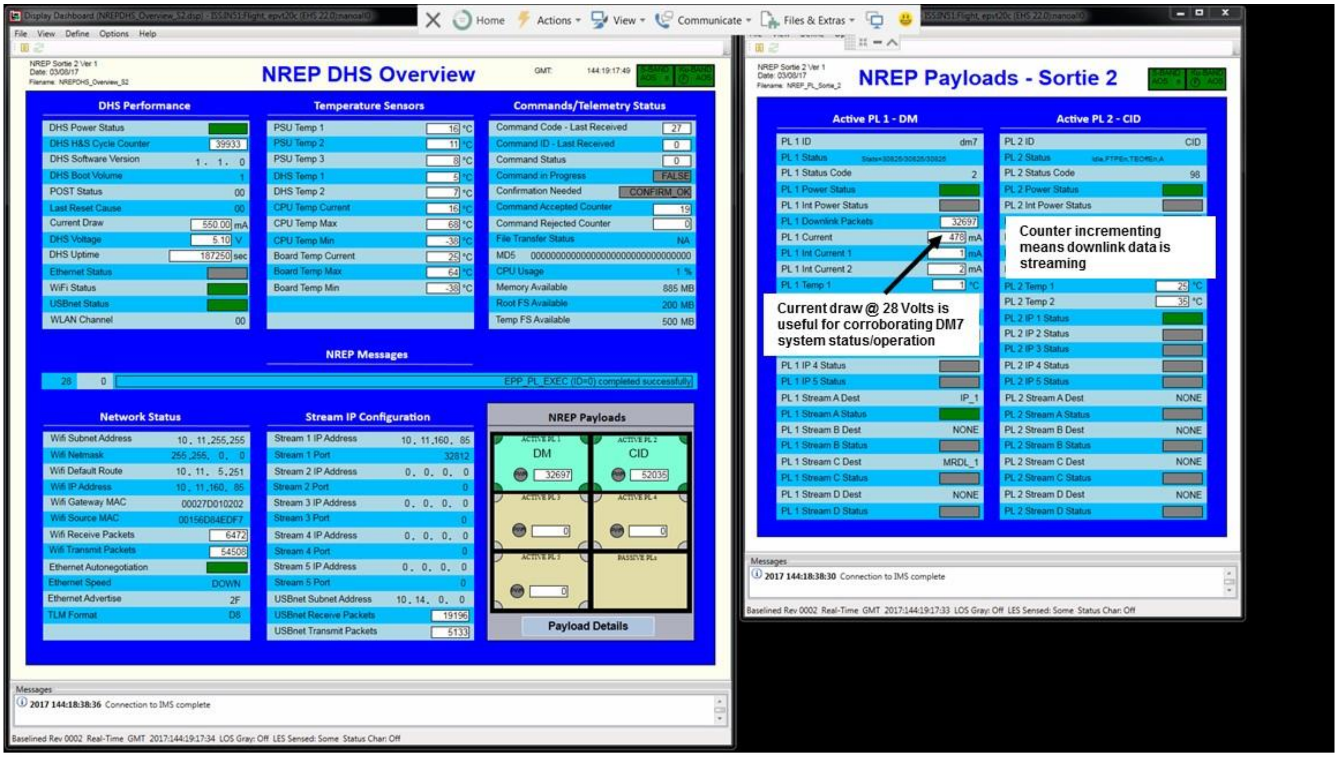


Figure 12 - Examples: DM7 Payload Compressed Images

operational yet, NASA and NanoRacks reported that the DM7 payload was generating telemetry data. The DM7 payload continued to generate telemetry for the first day and a half of operation. After the first day and a half of operation, the first on-orbit anomaly encountered was the stoppage of the generation of telemetry data. A command to cycle power to the DM7 payload restored the generation of telemetry, which continued for several more hours, after which telemetry generation ceased. Another command to cycle power to the DM 7 payload was issued and the telemetry generation resumed but for a shorter period of time. This hinted at the possibility of a thermal issue but, with no thermal instrumentation in the DM7 payload or on the NREP, there was no way to confirm or discount the possibility of a thermal issue affecting the DM7 payload.

The second on-orbit anomaly encountered was the inability of the DM7 payload to boot up consistently with a full complement of four (4) DP nodes. By this time, the DM7 real-time telemetry data link was operational and we were able to use the DM VPSIM SOH display to monitor the performance of the DM payload and the status of the individual DP nodes in real time. Monitoring the SOH display showed DP# 3 was not coming up ACTIVE and becoming part of the DM7 cluster. Operating with three (3) DP nodes was not a major problem because the DM7 experiment was designed to operate with fewer than four (4) DP nodes. loss of DP3 is not catastrophic. Loss of one node only reduces the effective system SEU rate by ~16.7%. The DM7 payload can demonstrate all functionality, including Spatial TMR, with three (3) active DP nodes. Initially it was concluded that DP#3 suffered a physical failure during launch. However, during subsequent functional testing that included multiple re-boots of the DM7 payload, the SOH display showed that DP#3 occasionally would go ACTIVE, sometimes with DP#4 ACTIVE and sometimes with DP$4 INACTIVE.

NanoRacks supported further testing and diagnosis of this anomaly by providing 1) real-time remote viewing of their NREP status display which including monitoring of the power drawn by the DM7 payload and the status of DM7 telemetry generation (see Figure 13), and 2) support for real-time interactive control, testing, and monitoring of the DM7 payload. The DM7 payload was designed to power up the DP nodes sequentially to avoid any power surge issues. Knowing the power up sequence and the amount of current drawn by an operational node, and having the DM SOH and NREP status displays to monitor the system in real time, we were able to correlate DP node ACTIVE/INACTIVE status with the step increases in current drawn. It was observed that sometimes a node would only partially boot up. This was correlated with a lower current draw. A node that didn't boot up fully, would not go ACTIVE and become part of the DM7



* Image courtesy of NanoRacks

Figure 13 - NREP Status Display

payload cluster. There was no obvious explanation for this behavior, but the results were consistent with the observations. After about 2 months of functional testing and operation, we felt we had a pretty good understanding of how the DM7 was operating and performing on-orbit. After a full week of successful, continuous, autonomous operation, we were ready to start the long-term radiation experiment. After a command to cycle power to the DM7 payload was issued, the third on-orbit anomaly was encountered, the loss of the Ethernet connectivity of the DM7 payload network. Again, NanoRacks supported real-time interactive testing of the DM7 payload. Ultimately, the results of testing showed the DM7 interface processor could no longer find the Ethernet 0 device. The DM7 flight prototype at Morehead State University was activated in the hopes of being able to duplicate what was happening on-orbit and developing a fix that could be implemented remotely using the available capabilities.

To date, none of these anomalies have been fully explained or resolved with the on-orbit DM7 payload. One advantage of an NREP ISS experiment is that the experiment payloads are eventually returned to earth where they can be further examined and analyzed. There is a significant delay in the return to earth that includes waiting for the NREP Mission 2 /Mission 3 switch-over and a subsequent cargo de-supply mission. It is planned to test the DM7 flight payload once it is back in the laboratory. Hopefully these tests will be able to shed some light on what happened on-orbit.

Despite the loss of the Ethernet connectivity which prematurely curtailed the long-term radiation experiment, NanaRacks reported that the DM7 payload continued to, and is continuing to, generate telemetry indicating it is healthy. The Gumstix processor in the DM7/NREP interface continued to operate until the DM7 payload was powered down on December 20, 2017.

Other Anomaly Considerations

As indicated previously, the plan was, assuming everything worked perfectly, to issue only three commands during the entire course of the DM7 experiment, i.e., commands to switch between the three (3) experiment missions. However, due to the anomalies experienced, all of the contingency commands were exercised in attempts to isolate and, if possible, to correct the anomalies. When the high-level contingency commands failed to isolate the anomalies, NanoRacks supported lower level debugging capabilities, e.g., more detailed examination of internal DM7 files, which were outside of the basic experiment plan. In some cases this was very helpful, for example in isolating a potential issue with the MSP430 microcontroller used in the C&DH interface as described in the next paragraph.

At one point during early on-orbit check-out, it appeared that the MSP430 microcontroller failed to issue an initial heartbeat required to start the DM cluster. This was surprising because the MSP430 has a pedigree for successful operation in space on many experiments and missions and because of the simplicity of the timing circuit which generates the heartbeats. Cycling power to the DM7 payload rectified this apparent anomaly which never happened again.

Contrary to the recommended methodology for successfully flying COTS in space [1], [2], [15], due to limited funding, not all of the components in the DM7 flight system were subjected to pre-flight ground-based radiation testing. The major components, the Gumstix COM modules, were radiation tested as components by Honeywell and by Yosemite Space [16] and were shown to be suitable for flying in space, i.e., no catastrophic latch-ups and low SEE rates, but the DM7 payload was not radiation tested in a system context. The impact of not radiation testing all of the components in the DM7 flight system is uncertain.

Lessons Learned

As with all experiments, there are lessons to be learned. A few of the major lessons learned from the DM7 flight experiment are identified below:

1) Ensure adequate thermal sensing

Since there was no thermal instrumentation in the DM7 payload or on the NREP, there was no way to confirm or discount the suspicion of a thermal issue on orbit. The DM7 payload was designed, developed, and tested assuming a given /guaranteed NREP baseplate temperature. If the baseplate temperature was higher than assumed, all of the other temperatures in the thermal model would increase accordingly. There were opportunities to add thermal sensors to the DM7 payload, but this was not done. In retrospect, it would have been wise to do so to address the possibility of a thermal issue.

2) Check and check again

When the DM7 payload was buttoned up and delivered to the NASA Cargo Mission Center, all ground debugging capability was disabled, or so it was thought. In the course of working with NanoRacks personnel to resolve some of the on-orbit anomalies, the debug files requested for one of the nodes was larger than expected. Further investigation showed the reason for the large file size was that the ground debugging capability was still enabled on that node. While this wouldn't affect normal operation, it could affect long-term operation of the node

3) Remote debugging

NanoRacks did an excellent job providing the DM7 payload development team with the requested real-time telemetry. With this capability driving the DM SOH and Experiment Data Telemetry, it was possible to observe and assess DM7 payload performance in real time. NanoRacks was able to stream the downlink telemetry to Morehead State University. DM7 payload developers not co-locate on the MSU campus were able to use TeamViewer™ to look at the SOH and Experiment Data Telemetry displays in real time.

Performing more detailed debugging in real time was more difficult. At some future time, NREP payload developers will have direct access to their experiment payloads. Unfortunately, this capability wasn't available in time to support the DM7 flight experiment. Access to the experiment payloads had to be coordinated with NASA and were subject to ISS workloads and occasional line-of-sight (LOS) communication outages with the ISS. Commands to the payloads could only be issued by NanoRacks personnel. For simple high-level commanding the DM7 payload, this worked fine. For debugging purposes, requests for files and data dumps had to be processed through NanoRacks personnel, who were extremely helpful. However, there were delays while the NanoRacks personnel issued the command to collect the data, fetch the data, and then transmit the data to the payload developer. The time available for commanding and testing the DM7 payload on-orbit was limited to a maximum of two (2) hours per day. This mode of operation was expected but, to payload developers who are used to continuous rapid-fire debugging, the delays and the daily time limitation debugging a little more arduous than they were used to. On the other hand, we didn't anticipating doing so much anomaly testing and resolution

4) Retain as much ground testing capability as possible on-orbit

While most of the ground testing capability was retained, one key element, access to the Gumstix processor console ports was not. The Gumstix console ports were used during ground testing to analyze processor issues but they were capped off for flight. To minimize cost, only the simplest and most basic interface between the existing DM7 payload interfaces and the NREP were employed. It probably would have been possible to integrate the console ports with the NREP, but this was not done. It has been suggested that having console port access could have helped debug and fix the Ethernet issue.

5) Keep the payload team together

Almost nine (9) months passed between the final pre-flight testing of the DM7 payload and the occurrence of the first significant on-orbit anomaly. Over the course of this period, all of the DM7 payload developers either had changed jobs, had new job assignments, and, accordingly, had new priorities. One problem was that everyone's knowledge and skills had gotten a little rusty over time. The second problem was that, given new job assignments and priorities, it was difficult to gather resources to focus on the problem as a team, e.g., limited time constraints, concurrent scheduling, competing priorities, etc. Large programs can afford to retain their teams. Small projects don't have this luxury…... This inhibited our capability to debug some of the anomalies in real-time.

5. FUTURE WORK

Analysis of the on-orbit anomalies will continue. In addition to whatever images and telemetry data was downlinked and stored on the ground, all of the telemetry data generated by the DM7 payload during the experiment period was captured and stored on the ISS. This full experiment record will be downlinked to the ground and will be available for analysis when the flight experiment is complete.

As mentioned previously, one advantage of the NREP ISS experiments is that the NREP payloads are returned to the ground when the experiments are complete. The NREP Mission 2/ Mission 3 switch-over occurred on January 4, 2018. The DM7 payload was removed from the NREP and placed in ISS storage awaiting transfer back to earth. When the DM7 payload is returned to the laboratory, it will be tested. Hopefully the tests will shed some light on the anomalies experienced on-orbit. As a minimum, the payload will be subjected to power and thermal testing. It will also be interesting to see if contact with the Ethernet_0 device can be re-established and, if so, if the problem could have been corrected on-orbit if we had the capability and the resources to do so. Because the entire payload assembly was "potted" for mechanical stability and thermal considerations, it will be difficult to examine the assembly for mechanical problems, e.g., a bad solder joint or a lifted PWB (Printed Wiring Board) pad, without damaging the system.

Now that DM technology has been demonstrated in a space environment, it is assumed that there will be some interest in follow-up activity.

6. SUMMARY AND CONCLUSION

Developed as a sub-Class D NASA flight experiment, despite the premature curtailment of the long-term radiation experiment, the DM7 ISS flight experiment was a success. Initial on-orbit functional testing successfully demonstrated all three (3) DM7 experiment missions. Based on observation of the high-level DM SOH and EDT displays, executing the Radiation Effects Mission, no SEU induced node failures or computational errors were detected. Similarly, executing the Fault Tolerant Capabilities Mission, no SEU induced node failures or computational errors were detected. This was not unexpected because the ISS orbit is a relatively benign radiation environment. Intentionally induced node failures, e.g., by issuing a command to cycle power to node, demonstrated DM system recovery with nominal node and application recovery times. Executing the Ground-Commanded Programmable Image Compression Mission, "stunning" 100x and 1000x compressed images were captured. A video montage of 100x compression snapshot images showed changing cloud patterns as the ISS transits in its orbit, shadows moving across the ISS structure, and articulating Russian solar panels.

DM technology has been demonstrated in a space environment, for all intents and purposes, achieving TRL7. What DM7 has demonstrated is unique, a flexible, multi-function, multi-mission, fault tolerance capability in single, unified architecture that can operate in a space environment. It is expected that DM7 success will open up new opportunities for flying fault tolerant clusters of high performance COTS processors in space and correspondingly, will allow new missions and applications to be considered.

Finally, the results of the DM7 flight experiment showed Gumstix COM modules can operate in space, at least in a relatively benign space environment such as the ISS orbit.

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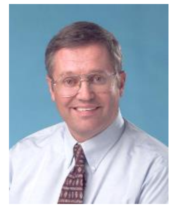
BIOGRAPHIES



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