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DEMONSTRATION OF COMMUNICATIONS SYSTEMS FOR FUTURE HUMAN EXPLORATION DURING THE OPSCOM-1 TEST USING THE ISS

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Abstract— Most exploration roadmaps are calling for demonstrating operational scenarios including robot/rover control from orbiters around other heavenly bodies. The Multi-Purpose End-To-End Robotic Operations Network METERON aims to demonstrate operations, communications and robotic concepts and technologies in preparation for future human exploration missions. OPSCOM-1, the first METERON experiment, was performed by ESA in October 2012 as a feasibility assessment of some communications aspects needed for future experiments. During OPSCOM-1, the ISS crew followed a procedure to send instructions through a Graphical User Interface (GUI) on a laptop on the ISS configured for METERON to a simple rover located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. Feedback for these instructions and the position of the rover were automatically gathered in files that were verified and transferred to the GUI on the ISS by manual ground commands of ground operators at the Belgian User Support Operations Centre, which was in charge of operations related to the ISS. Crew commands were sent to the rover using the Disruption Tolerant Network (DTN) protocol and feedback from the rover used the standard Telemetry and Telecommand path.

The communications concept was successfully demonstrated during OPSCOM-1. Thanks to the extensive preparation activities prior to the experiment and the dedication of the OPSCOM-1 team (ground and ISS) during the experiment itself, all objectives were achieved successfully. Time latency between commands sent by the crew through the GUI and the movement, position and picture feedback of the command to the crew was between 3 and 5 minutes. OPSCOM-1 demonstrated that the DTN protocol can be used in telerobotics activities and the operational aspects of moving a rover from the ISS have been validated. Limitations of the uplink channel to the ISS led to long waiting times for the crew to receive feedback to their actions. These limitations should not apply anymore for future tests. The next METERON experiment, OPSCOM-2, will demonstrate the full functionality of "packet custodiancy". This DTN feature should guarantee that no telemetry/telecommands are lost during transport.

I. EXECUTIVE SUMMARY

On October 23, 2012 the Multipurpose End-To-End Robot Operations Network (METERON) OPSCOM-1 experiment was successfully executed. It was the first time an astronaut in orbit successfully commanded a rover on the surface of a heavenly body (the Earth) by direct commanding. This is what caught the media's attention. However, the primary objective of OPSCOM-1 was to demonstrate communications concepts and technologies that may be used for future METERON experiments and ultimately future human exploration missions. In particular OPSCOM-1 aimed to in-flight validate the performance of elements of the Disruption Tolerant Network (DTN) protocol in a real operations scenario involving systems on the ground and on the ISS. This real operations scenario consisted of an astronaut (Sunita Williams) remote controlling a very simple rover using only information passed through the DTN communications chain.

OPSCOM-1 satisfied all its objectives. Preparations are now on-going for OPSCOM-2, a follow-on experiment that will in-flight validate DTN capabilities that were not possible to test during OPSCOM-1, controlling ESA's Eurobot Ground Protoype (EGP) rover with an end-to-end mission monitoring control system.

II. BACKGROUND

In the 60s and 70s the first human exploration steps were taken by repeated visits the Moon. Once the Apollo programme ended, all human exploration beyond Low Earth Orbit (LEO) was put on hold and has not been resumed since. Instead, the focus of human spaceflight was to establish a quasi-permanent presence in orbit around the Earth, allowing for research to be conducted in a microgravity environment. This has allowed for experiments targeted towards future human exploration to be carried out in a variety of fields, in particular regarding life sciences, transportation, and engineering required for sustainability of life in an orbiter. However, human exploration of other heavenly bodies has many challenges that go beyond what is applicable to human orbiters around the Earth, in particular due to the vastly increased distances involved. As a reminder – the distance from the Earth to the ISS ranges between 330 km and 435 km. The shortest distance between Mars and the Earth is 54 600 000 km.

It is very important to ensure that when discussing future human exploration scenarios we have as much experience as possible regarding how the challenges of long-distance human spaceflight can be met and flight-validated systems in place that are ready to do the job. It has been recognised that in order to safely send people to other heavenly bodies we need to gain experience in executing end-to-end scenarios using the assets currently available to us to allow us to make informed decisions today when defining future human exploration missions as well as demonstrate (on ground and in-flight) concepts and technologies that will be used for such missions.

Many, if not most, of the major space agencies have initiatives in place to prepare for future human exploration missions. Since it is not yet known where humans will travel next, most activities cover topics that are of relevance regardless of the destination. One such initiative is the ESA-led METERON project.

METERON

The Multipurpose End-To-End Robot Operations Network METERON addresses a subset of the challenges highlighted above by allowing for experiments to be carried out that pave the way for future concepts and technologies in the areas of communications, operations and robotics.

The primary objectives for each of the three pillars of METERON are:

Communications

Demonstrate communications concepts and technologies that are being considered for use in future human exploration missions. Issues such as disruption tolerance, delays caused by distance, hard real-time communications (video, haptic data, etc.) and multiple asset communications will be demonstrated.

Operations

Demonstrate operations concepts and technologies that will be required for future human exploration missions. Issues such as human-in-the-loop rover/robot operations, multi-rover operations, multi-operator interaction, and monitoring and control of systems-of-systems will be demonstrated.

Robotics

Demonstrate robotics technologies and operations that are being considered for use in future human exploration missions. Issues such as supervisory control, haptic tele-operation, need for force feedback and stereovision, where to put the robot operator, operations of multiple rovers / robots (at different locations or at the same site), and human/robot collaboration will be demonstrated.

METERON takes its requirements from a variety of exploration initiatives in Europe and worldwide. One important source of information/requirements regarding future human exploration is the International Space Exploration Coordination Group ISECG [6].

METERON provides a platform for execution of experiments covering the areas highlighted above. This platform contains several sites that are involved at levels suitable to a given experiments. A priority is to optimise the use of existing expertise and infrastructure as far as practical and possible. One of these sites is the ISS.

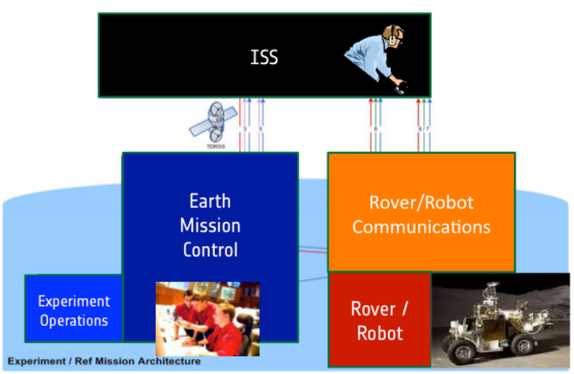

Figure 1 - METERON Reference Architecture

The high-level architecture of METERON is illustrated in Figure 1. The ISS represents a crewed orbiter around a heavenly body. Delays in communication caused by distance will be artificially injected. The Robot/Rover systems (the right hand side of the diagram) represent assets deployed on the heavenly body.

The proposed METERON experiments are listed in Figure 2. The initial experiments in this table are technology demonstration exercises that will, in addition to demonstrating concepts and technologies for future human exploration missions, validate elements of the system to be used for the end-to-end experiments including the ISS.

Experiment Name	Rationale & Benefits
OPSCOM-1	First DTN in-flight demonstration
OPSCOM-2	Validation of DTN; basic sequential operations of Eurobot, E2E Monitoring and Control
OPSCOM-3	DTN2 Validation; final E2E comms validation for METERON
HAPTICS-1	In-orbit calibration of Exoskeleton joints; body-grounded haptics tests
HAPTICS-2	Demonstration of first bilateral control over low latency link
COM4HAP-1	Demonstrate Ground to ISS Real time communications
COM4HAP-2	Demonstrate complete comms chain ISS to robot
SUPVIS-EUROBOT	Supervisory operations on lander mockup using Eurobot (with additional rover for visual support)
SUPVIS-JUSTIN	Demonstration using Justin at DLR of intuitive planning and operation software
EXO-1	Exo control of Light Weight Robot (LWR)
EXO-2	Exo control of Justin (DLR) including supervisory tasks
EXO-3	Exo control of ISS-based Robonaut (TBC)
ANALOGUE-1	E2E Mars exploration scenario with rover (Eurobot)

Figure 2 - Proposed METERON Experiments

From SUPVIS-1 onward the experiments are focused on demonstration of end-to-end operations concepts and technologies.

The first METERON experiment including the European Columbus Module of the ISS, OPSCOM-1, was successfully executed October 2012. This experiment is the topic of this paper.

III. OPSCOM-1 OBJECTIVES

The primary objective of OPSCOM-1 was to validate the Disruption/Delay Tolerant Network (DTN) architecture. It was agreed with NASA and CU Boulder to demonstrate its general suitability as a communications layer between ground and space in the METERON context. For this purpose, a DTN network was established between the ESA facilities in the European Space Operations Centre (ESOC - Darmstadt/Germany) and a METERON laptop on-board the ISS. The network performance and usability then was to be evaluated in the OPSCOM-1 experiment, by demonstrating simple robotic tele-control over the DTN network, where a crewmember on the ISS interacted with a simple rover on Earth.

The DTN architecture offers network access for space/ground transmissions similar to current earth-bound "internet" technologies, whilst hiding the complexity of the heterogeneous and disruptive space environment from the applications. DTN is designed to reliably transport data over unreliable links with possibly long delays and lack of continuous network connectivity [1].

DTN demonstration projects are being executed by both NASA and ESA. CCSDS standardization activities [2], transmission of space images to and from the NASA science spacecraft EPOXI located more than 32 million kilometres from Earth [3], or DTN ISS flight tests [4] exemplify that this protocol plays a valuable role in future space environments.

IV. METHODS

Communications configuration

For fast prototyping and to facilitate ISS and ground deployments, the METERON communication network between the METERON Operations Software (MOPS) for astronaut rover control, and the MOCUP rover on ground evolved in iterative steps. Since July 2009, the Colorado University at Boulder and the Huntsville Operations Centre (HOSC) have developed and implemented an experimental DTN capability between ISS and ground [5]. By configuring one of two Commercial Generic Bioprocessing Apparatus (CGBA) payloads onboard the ISS as DTN node (CGBA-5), they established DTN space to ground access to the Boulder Payload Operations Centre (POC) and the HOSC by encapsulating DTN bundles into traditional commanding and control protocols.

For the METERON experiments, this network was extended in space and on ground [10]. A laptop was installed in the ESA ISS research laboratory Columbus, an ESA pressurized ISS module supporting space research since its launch in February 2008. The METERON laptop was configured with the DTN software stack, monitoring and maintenance software as well as the specific experiment software, which communicates using the DTN. DTN traffic was routed via the CGBA DTN node over the existing link via HOSC to the Bioserve Payload Operations Control Centre (POCC). On ground, the Belgian User Support Operations Centre (B.USOC), responsible for METERON ISS operations was connected to HOSC and the POC. During crew activities B.USOC performed direct monitoring and control of the laptop via HOSC, and forwarded DTN traffic from the POCC to ESOC. The overall breakdown is illustrated below in Figure 3.

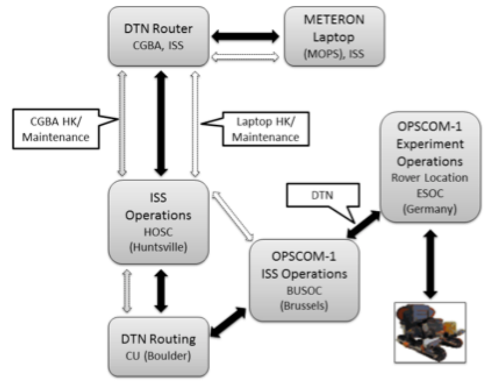

Figure 3 - OPSCOM-1 High-level breakdown

ISS configuration

The ISS on-orbit infrastructure used to allow the implementation of METERON OPSCOM-1 is represented in Figure 4 and Figure 5.

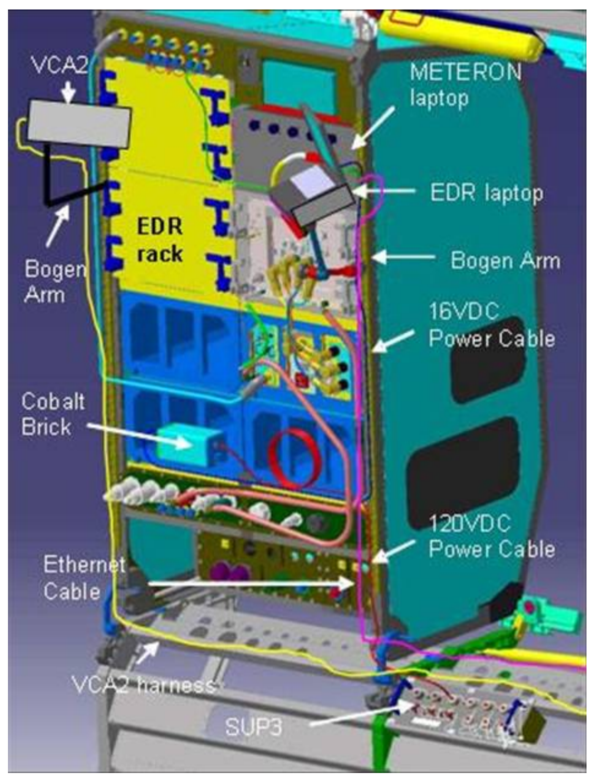

Figure 4 - Columbus Express Rack 2 Configuration for METERON OPSCOM-1

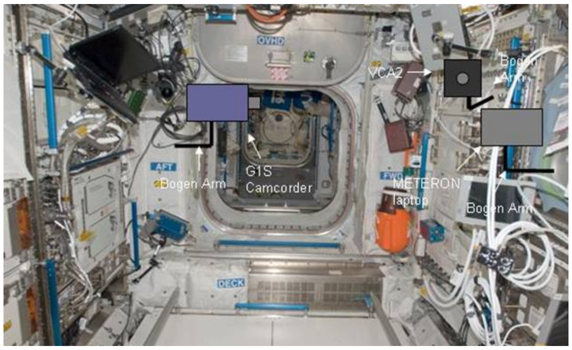

Figure 5 - Colombus Module congifuration during OPSCOM-1

As mentioned earlier, the payload hardware consists of a T61P laptop with a bootable DTN CD which is included inside the T61p laptop. Additional on-board equipment required for the OPSCOM-1 operations were:

- European Drawer Rack (EDR) laptop plate with bogen arm
- EDR Power Supply with 120-16 VDC power converter (Cobalt Brick) and power cable
- NASA Ethernet cable, for connection to US local area network for data communication
- ESA Columbus video camera for real-time video download of the T61p laptop screen
- NASA video camera for recording of public relation videos.

All hardware items were already on-board the ISS and the custodianship of T61p laptop with the needed DTN CD has been handed over from NASA to ESA before the start of the METERON OPSCOM-1 real-time execution.

In order to operate in this configuration, a deep engineering analysis of the Columbus configuration and usage of on-orbit hardware, resources and capabilities had been performed.

The analysis confirmed feasibility of the above represented configuration in terms of hardware compatibility and availability; mechanical, thermal, electrical, data and software interfaces as well as environmental conditions and required on-orbit resources like power consumption, data uplink and downlink capabilities, communication with crew infrastructure readiness, crew and ground personnel availability.

Robotic system

To generate more meaningful telemetry and telecommand streams, the MOCUP rover was added to the OPSCOM-1 DTN.

The MOPS rover control software allowed simple operations such as waypoint navigation, execution of command stacks, capturing, transmission and display of pictures as well as transmission of status telemetry.

The MOCUP rover framework is built on LEGO® bricks and the LEGO® NXT 2.0 Mindstorms kit. It is extended by an ARM Linux Beagleboard with 1Ghz CPU and 500Mb of RAM with a Debian Linux operating system. The USB Ports of the board are used to interface with the NXT brick to control the LEGO® motors for movement and the ultrasonic sensors for obstacle detection, a webcam for taking pictures and a wireless dongle for connection to the network. The rover control software is running on the Linux Beagleboard system and communicating via the DTN network with the MOPS user interface onboard the ISS.

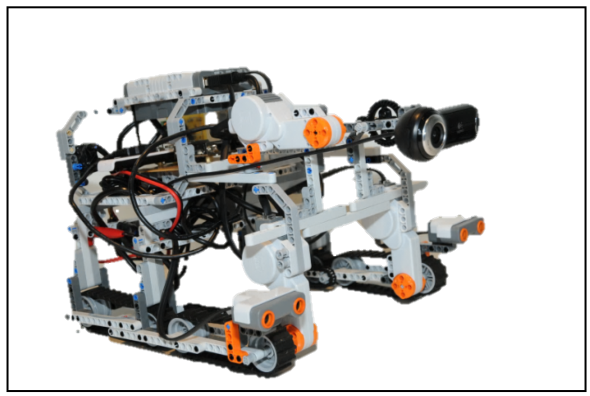

Figure 6. - The MOCUP Rover

The ultrasonic sensors of the Rover can detect obstacles in the front and rear, and can triangulate positions of objects in the front. If an obstacle is detected too close during movements, the rover is automatically stopped to prevent collisions, and an "interrupt" response is send back to the user interface.

Experiment Operations and Communications infrastructure

The OPSCOM-1 Operations and Communication infrastructure was hosted in the Special Mission Laboratory Environment (SMILE) at ESOC, a laboratory dedicated for experimental missions and concepts. This system is reusable for future METERON experiments. Virtual machine servers host the individual ground machines, facilitating development, deployment, backup and redundancy strategies for experiments. Missions such as

METERON utilize dedicated clients to access their virtual machines with their control systems during operations.

All machines in the METERON ground network are Linux-based virtual machines. Each machine acts as a DTN node with the ION DTN implementation installed. As much as possible of the software and configuration of the ground segment is managed in Debian [8][9] packages, such that updates of software as well as updates of configuration files on the individual machines are applied by installing a new, version controlled Debian package. The packages themselves are created in an automatic build environment upon check-in into the repository. The same concept is also applied for the METERON payload on-board the ISS, leaving any software and its configuration uniquely identifiable and traceable.

The ground segment contains an operational and a simulations chain, which can easily be realised through creating copies of the individual virtual machines. Also several MOCUP rovers have been built, such that simulations can be performed independently, as well as having a back-up rover to fail over in case of problems during operations.

DTN Development for METERON was in collaboration with the team at CU Boulder / Bioserve. Using their sophisticated simulators the specific CGBA ISS DTN network could be simulated to a degree that gave highly accurate estimations on timings and numbers of commands needed for transmissions between ground and ISS. This allowed the OPSCOM-1 team to exactly tailor software and experiment uplinks to available time windows and bandwidth restrictions.

During simulations, the network delays of the simulator were set to be representative of a realistic ISS scenario with around 6 seconds of round-trip time for each transmitted packet. As the DTN protocol was used in the communications chain, delays could be injected for various scenarios (e.g. Martian scenarios) without the danger of data packets timing out during transmission. In addition, the simulator allowed for pausing - hence delaying any data packet, as well as dropping packets to simulate data loss on the communications chain.

Operations Preparation

During OPSCOM-1 preparation (training and validation) focus was on the interaction of the geographically distributed teams to maintain the nominal timeline and resolve problems within the scheduled ninety minutes of crew time, using the METERON infrastructure available at the time [7]. Over eighteen simulations, each increasing in functionality and complexity, each METERON site practiced operations with only the telemetry available as expected in OPSCOM-1, with an engineer taking the place of the astronaut crew member operating the rover. A series of undisclosed communication and robotic failures were then deliberately injected into various systems for the teams to identify, diagnose and resolve in order to re-join the nominal timeline. In other words, the simulations also trained the operations teams and helped to optimise the procedures. The ISS crewmembers considered for the experiment were trained prior to launch at the European Astronaut Centre (EAC) by driving MOCUP using the MOPS GUI and the ISS Operational Procedures.

ISS Operations

A precise process had to be followed to integrate OPSCOM-1 as an ESA payload into the ISS schedule. At first detailed requirements identification and agreements with international partners were worked out. At B.USOC, all systems, laptop engineering model and links to ESOC were installed to allow for stand alone and inter-centre simulations and later for the flight operations through HOSC and Col-CC. The teams developed crew and ground procedures covering both the nominal and contingency activities for OPSCOM-1 and were used in extensive training and simulations. The OPSCOM-1 activities were inserted in the ISS planning process and maintained at planning reviews. An Experiment Sequence Test (EST) was performed as a general rehearsal validating the ground segment and operational products. Certification of Flight Readiness with HOSC and Col-CC was obtained successfully and on time for the OPSCOM-1 related activities, including telecommand, telemetry and voice link capabilities.

After installation of the laptop in Columbus under NASA responsibility together with CU Boulder, the rest of the activities leading to OPSCOM-1 and the OPSCOM-1 activities were performed under ESA responsibility. The laptop and its connectivity and commandability from ground were first checked out, then the MOPS software was uplinked, installed and checked out while continuously monitoring the laptop health and status.

The OPSCOM-1 test itself was supported by monitoring the voice loops and the over-the-shoulder video from Columbus and the crew procedure included voice interaction with the ground team in a cascading way through the interface of the flight control team at Col-CC and more particularly the EUROCOM talking directly to the crew. Ground procedures including file uplink and downlink were supported by ESOC and B.USOC via the HOSC telecommand and telemetry channel. The DTN channel was enabled and maintained by CU Boulder.

Operations Execution

October 19 2012 the OPSCOM-1 team declared readiness to go ahead with the experiment, following a successful dress-rehearsal. OPSCOM-1 ISS activities took place October 23, 2012. All actions scheduled prior to crew activities we successfully executed. The go-ahead to initiate crew activities was given following a roll call confirming all teams and associated systems were ready to proceed.

The OPSCOM-1 operations team at ESOC was communicating directly with the METERON ISS Operations team at B.USOC for ISS matters and BioServe for DTN matters. The ESOC OPSCOM-1 team communicated with Sunita Williams, the astronaut designated for the OPSCOM-1 experiment, via B-USOC. The Columbus Control Centre in Oberpfaffenhofen, the HOSC and of course the ISS were all on the voice loop. Video monitoring of crew activities and the laptop screen were also available during the experiment.

During OPSCOM-1 there were periods of no payload data traffic. This was governed by the status of the links between the ISS and ground stations. The coverage pattern is illustrated in Figure 7.. The gaps are periods of no signal. During these gaps the astronaut could not command the rover.

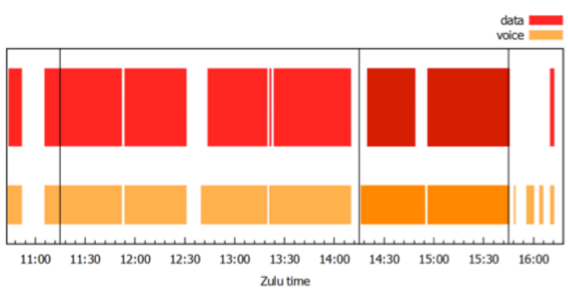

Figure 7 - The ISS coverage pattern during OPSCOM-1

MOCUP successfully responded to astronaut commanding from the METERON laptop for the sequence execution, moving it in three stages separated by snapshot execution. MOCUP moved as planned in a straight line towards the first target, which was successfully described by Sunita Williams. The waypoint driving procedure was then executed, and MOCUP correctly drove from target 1 to target 2. Another picture was taken and described.

During driving to target 3 the rover did not reach the planned position. Analysis revealed that a command had been "lost" between space and ground. The recovery procedure for such a contingency was activated and operations could continue.

Once the 90 minutes slot allocated for OPSCOM-1 crew time had elapsed (due to the anomaly and coverage pattern during the experiment) the closeout procedures were executed to retrieve all experiment data. The communications objectives foreseen for OPSCOM-1 were met.

During the debriefing the astronaut offered to use one hour of her spare time to complete optional operations objectives. The ground segment had 2 hours to prepare for the new time slot and 40 minutes of commanding were identified in that slot.

The test proceeded to the manual commanding stage, where individual commands to rotate the rover and to take pictures were selected from a menu by the astronaut and executed. The sequence was - rotate left, take picture, rotate left, take picture, drive forward, take picture, drive forward, take picture. The sequence was successfully completed. During the free driving the second image generated by the rover was partially corrupted but this did not affect the test.

V. RESULTS

Experiment Results

The DTN protocol was the enabler for the direct, near real time communication in METERON from the ISS/MOPS to ESOC/MOCUP. Due to its Convergence Layer adapters for various network protocols ("Channel" for BioServe space to ground system, TCP and UDP for internet connections), a full end-to-end chain could be established between ESOC and ISS.

Specifically this allowed to:

- "bping" (similar to IP ping but via DTN bundle protocol) each individual node in the network, e.g. from ESOC to ISS. Although 3 different network protocols served the connection in between rover and control software, the DTN connection appeared as a continuous link between the two endpoints.
- Send data between DTN nodes: using the C libraries of the ion DTN implementation, it was easily possible to transmit binary data (in this case rover commanding Strings) between the nodes. The Python applications of MOPS and

MOCUP used a wrapper around this library to communicate over DTN.

The network proved to be highly scalable, allowing addition of further DTN nodes in any direction of the chain.

The data between ground and the ISS payload was encapsulated within Rack Interface commands to the payload. The command link was shared with all payloads and achieved around one command per second, carrying 80 bytes of usable data per command up to the payload. The downlink rate to send commands from the astronaut to the rover achieved a maximum of 400kbit/second of streamed data. Hence in METERON, the larger amounts of data such as rover telemetry and pictures needed to be uplinked via the minor link while the large ISS downlink capability was only used for small-sized commands and payload housekeeping.

During OPSCOM-1, higher commanding rates than 1 command/second had been observed with around 1.5 commands/second. As they were not guaranteed, simulations had been (and are still) executed with 1 command/second.

The normal average DTN ping time from BioServe ground to the ISS/CBGA was 5.5sec RTT. The extended network including the METERON laptop routing via the Internet to ESOC/Germany did not add significant delay, achieving a RTT of 6.8sec on average (including hops over four more DTN nodes, firewalls and secured VPNs). Transmission of DTN over IP as compared to direct IP transmissions as well did not show significant increase of delays as we observed a ground RTT of 0.5sec between ESA/Germany to Boulder/USA via Brussels USOC (including all DTN hops, firewalls and secured VPNs).

Space to ground data from MOPS to MOCUP Rover as well as bundle pings and bundle acknowledgments from ground to space had been transmitted via DTN. Any payload results from the rover (position updates, sensor readings, pictures) had to be manually transferred via ESOC-B.USOC file uplinks (not DTN) to the T61p for processing on the laptop. This was due to policies for early DTN experiments, that no direct DTN uplink traffic from external entities was allowed to the ISS. As expected during OPSCOM-1 preparation, file uplink worked well. Usage of automated scripts and well-trained personnel in B.USOC allowed to transmit the rover responses quickly enough to the ISS to limit wait times for the astronaut. The most important observations for file transmissions were:

- Although very automated, the time of the manual operator actions for upload and processing of files still amounted to 28-56% of the total time of each uplink to an average of one to two minutes. This time will not be necessary when full two-way DTN communication is used.
- The play/pause mechanism of the uplink system was very useful. It was used to pause and resume file uplinks during loss of signal periods of the ISS, where no commands could be sent to the payload.
- The status/position updates of the rover uplinked in the position files were in a human readable but not data efficient form. Therefore, these files were "large" compared to the information transmitted within. Tests showed that compressing this data for transmission could have saved 50% in the position file sizes. In general a more efficient protocol could be used in the future.

As mentioned earlier, it was observed that one rover command was lost during transmission from space to ground. As DTN was used without custody transfer, the command was not automatically resent. In future tests we will analyse whether custody transfer solves the issue. Investigation of the anomaly was complicated by the fact that there had been no means of identifying where in the chain the command was lost. No command verification stages on the downlink space-to-ground were available. This is one of the areas of improvement in the upcoming OPSCOM-2 experiment.

The static routing of ION DTN applied was sufficient for OPSCOM-1, but enhancements will be implemented for future experiments. Every DTN node in the chain had to be configured individually and manually for proper routing of traffic to other DTN nodes. Static direct neighbours and groups of nodes behind that neighbour had to be defined at each node with their IPN numbers. As long as ranges in this experimental setup had been cleanly identified the routing was maintainable on the individual nodes. "Gateway nodes" had been defined connecting the ESA and NASA nodes with specific group rules defined for any nodes behind them.

This configuration is not easily extendable: During the project, one DTN node was moved from BioServe to Europe, hence the clean separation of this routing could not be maintained and an explicit rule for the number not within the ranges had to be defined. In future setups with increasing DTN nodes and partners, either DTN node numbers need to be strictly changed in case of moves to be kept within the predefined ranges of gateway nodes, or more dynamic routings such as in the "IP-world" need to be found.

Lessons Learned

OPSCOM-1 was limited to approximately two hours of operations, so operations lessons learned are based on some issues known prior to experiment execution and some minor issues that were actually resolved during the experiment. The first issue was the lack of data packet logging at various sites, inhibiting problem identification and recovery. Secondly, having to verbally instruct or confirm GUI interaction with the astronaut involved five voice loop hops, again inhibiting the speed of operations increasing the execution time of instruction execution. A system overview environment (the METERON Operations Environment) has been developed for use in ground tests and OPSCOM-2 that collects and makes available to each METERON site the status of links, certain telemetry parameters, telecommand verification stages etc. and allows the ground controllers to maintain the experiment with minimal verbal communication necessary with the ISS. A simple messaging system was proposed between space and ground to also minimise verbal crew to ground interaction. As the data was routed to a second MOCUP rover, the problem of dropped packets or unexpected response of the rover (HW or SW failure? Comms error? User error?) could be resolved within minutes. The use of a very basic rover receiving duplicate instructions proved of benefit during the OPSCOM-1 experiment.

Due to the complexity of the project involving many ground teams, such as B.USOC POIC, Col-CC, JSC, ESOC, ESA HSO ICP, IOT and CU Boulder, the preparation required close and transparent cooperation between the teams. The challenge in the project also lay in the integration of these novel techniques within the ISS constraints, sometimes resulting in necessary workarounds in the operations concept, but still within the objectives. An example of this, are the manual file transfers that had to be implemented. To avoid such late work around implementation it is essential to have all the correct teams identified and involved at the early stage of such a complex activity.

Stand-alone and joint simulations proved to be very valuable. Preparing for OPSCOM-1 involved very different segments: the operators had to learn how to work with the new DTN technology, they had to guide the astronaut through the procedure, and prepare for possible malfunctions. The simulations strengthened the bonds between B.USOC and ESOC, identifying the fields of expertise, and learning how to communicate most efficiently with each other. It also allowed testing the MOPS software extensively, and every simulation meant another review of the procedure written for the astronaut.

VI. OPSCOM-2

ESA, its international partners, as well as the Industrial Operator Team (IOT) managed by Astrium and responsible for the implementation of the ESA objectives on board the ISS, and B.USOC are currently preparing for the second METERON experiment – OPSCOM-2. The framework for the experiment is the same as for OPSCOM-1 – to demonstrate communications technologies for METERON and future human exploration missions. As has been highlighted above, it was not possible to test all elements of DTN during OPSCOM-1. Some of these will be covered by OPSCOM-2. The ESA Eurobot Ground Prototype (EGP) will replace the MOCUP rover. In addition, the METERON Operations Environment (MOE), will be used for Monitoring and Control (M&C) of the end-to-end system.

Objectives

The primary objectives of the OPSCOM-2 experiment are as follows:

- Implementation of a full DTN uplink, without the file transfer constraints applicable to OPSCOM-1 (i.e. allowing non-administrative DTN bundles on the uplink). Most importantly demonstration of bi-directional streaming without manual intervention.
- Custody transfer (store and forward, an important functionality of DTN), which was not enabled for OPSCOM-1.
- Testing of a communications "routing" that is closer to the final non/near real time communications chain that will be used for METERON. To test different "routes" through the ground segment, hence demonstrating using DTN as for a future "space internet".
- Tests involving introducing deliberate disruptions (on the ground network side) to demonstrate DTN's benefit of being disruption tolerant.
- Demonstrate the control of the EGP from the ISS. EGP is the same size as the Curiosity rover.

- Validate a new control interface for the EGP, a system upgrade which has been developed and is undergoing integration testing.
- Test the METERON Operations Environment (MOE) as an end-to-end monitoring and control system.

The OPSCOM-2 team is using 2nd or 3rd quarter 2014 as a target for experiment execution. In addition to its communications objectives it will be the first experiment where the full operational chain will be present, paving the way for the more complex end-to-end operations and robotics experiments.

DTN

The OPSCOM-1 experiment successfully validated the DTN implementation with Bundle Protocol over various Convergence Layers as protocol for METERON experiments. Providing a homogenous access between ground and space assets over long, delayed, heterogeneous networks in fashion of the normal “internet” proofed to facilitate immensely implementation and deployment of the experiment, which will be continued for future tests. Due to previous policy restrictions and limitations, not the full set of DTN capabilities was validated yet and will need to be addressed in the following OPSCOM-2 experiment. For this, a proper two way DTN communication will be established, removing all manual file transfers for direct rover commanding and telemetry reception in any direction. Furthermore, Custody Transfer (CT) will be enabled and examined in detail for the next phases, to study and refine how DTN traffic is resend and applications will need to treat long delayed or lost packets. As third major goal, various or multiple communication paths will be established for a communications routing that is closer to the final Non/near real time communications chain that will be used for METERON, which will allow to test different and multipath routes.

Eurobot Ground Prototype (EGP)

The EGP is, as the name suggests, a prototype rover approximately the same size as the Curiosity rover, weighing 1,200 kilogrammes, and incorporating two seven-degrees-of-freedom robotic arms (Figure 8).

Figure 8 - The Eurobot Ground Prototype (EGP)

EGP will replace the MOCUP rover on the ground. A major feature of the experiment is that the EGP will be controlled using the same MOPS GUI by the crew on-board the ISS. This approach demonstrates an important unique capability of METERON: the ability of the network to monitor and control a wide range of rovers/robots, differing in size, functionality and complexity, using a common system connected by standard interfaces.

This satisfies one of the aims of METERON, namely to derive standards for interoperability of different systems to enable a simplified “plug-and-play” approach. This will significantly improve the capability to perform planetary surface exploration activities involving humans and robots, and multiple surface assets and operations centres.

Meteron Operations Environment

The METERON Operational Environment (MOE) is the generic term used for referring to a number of METERON software systems, deployed on the ground and on-board the ISS, which shall together provide a unified, system level monitoring and control solution for configuration and successful execution of the METERON experiments. MOE elements must accordingly interface with dedicated software systems involved at each node of the end-to-end METERON experiment chain, including the Robotic Control Systems of each participating robot.

The development of the MOE has started in the context of an industrial activity in 2012, following an agile development lifecycle based on the Scrum [11] methodology. The adoption of the Scrum methodology has led to an incremental development of the required functionality in close collaboration with the operational users and to the delivery of new features every four weeks.

The implementation of the MOE is based on the reuse of the existing ESA Ground Segment Test and Validation Infrastructure (GSTVI) and selected elements of the EGOS infrastructure such as the Parameter Archive, DARC. The GSTVI infrastructure is itself based on the generic ESA simulation environment SIMULUS. The GSTVI includes also a basic monitoring and control (M&C) element, which has been customised to address the needs of the METERON project.

In an attempt to harmonise the interface of the MOE to the diverse Robotic Control Systems of future METERON experiments, an initial set of METERON Robotic Services have been devised in compliance to the CCSDS MO Services specifications. These services shall isolate the proprietary interfaces exposed by each robotic system and expose a harmonised robotic API to the rest of the MOE software. The specification and implementation of these METERON Robotic Services are based on the CCSDS MO services framework. In fact the services for commanding, monitoring and command verification have been specified as a set of web-services in full compliance to the CCSDS MO Activity, Action and Parameter service specifications.

The envisaged end-to-end integration chain of the MOE→ METERON Robotic Services → Proprietary Robotic Control System → Robotic Element has been successfully validated in a number of simulation sessions, using to the current METERON validation rover MOCUP and its specific Robotic Control System MOPS and shall be used operationally in OPSCOM-2.

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REFERENCES

[1] [RFC 4838] Cerf, V., Burleigh, S., Hooke, A., Torgerson, L., Durst, R., Scott, K., Fall, K., Weiss, H., "Delay-Tolerant Networking Architecture", RFC 4838, April 2007.

[2] CCSDS SIS-DTN, SPACE INTERNETWORKING SERVICES AREA (SIS) - DELAY TOLERANT NETWORKING WORKING GROUP, http://cwe.ccsds.org/sis/default.aspx, (19/08/2013).

[3] EPOXY, http://epoxi.umd.edu

[4] Jenkins, A., Kuzminsky, S., Gifford, K., Pitts, R., Nichols, K., "Delay/Disruption-Tolerant Networking: Flight Test Results from the International Space Station". 2010 IEEE Aerospace Conference AIAA

[5] Nichols, K., Holbrook, M., Pitts, R., Gifford, K., Jenkins, A., Kuzminsky, S., "DTN Options and Utilization Options on the International Space Station". In Proceedings of SpaceOps 2010 Conference, 25 - 30 April 2010, Huntsville, Alabama, USA

[6] International Space Exploration Coordination Group (ISECG) – www.globalspaceexploration.org

[7] P. Steele, "Operations Toolset for Future Integrated Human, Robot and Automated Missions" , AIAA Space 2013, San Diego, paper ID 1664357

[8] Introduction to debian - About debian, http://www.debian.org/intro/about.en.html, 1997-2013 SPI and others, (02/09/2013)

[9] Debian New Maintainer's Guide, http://www.debian.org/doc/manuals/maint-guide/index.en.html, Copyright © 2010 Raphaël Hertzog, (02/09/2013)

[10] Bosquillon de Frescheville, F., Aiple, M., Martin, S., Patterson, D., "Set-up and Validation of METERON End-To-End Network for Robotic Experiments.", 11th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2011, ESTEC, Nordwiijk, Netherlands

[11] Scrum http://en.wikipedia.org/wiki/Scrum_(software_development)