Demonstration of a Ka-Band communication path for On-Orbit Servicing

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ABSTRACT

The objectives of on-orbit servicing (OOS) missions include manipulation, proximity operations and inspection of target satellites. Therefore the servicer satellite often has to be teleoperated at low latency for several minutes to fulfill these tasks. That means communication plays a crucial role for OOS missions because real time teleoperation including high data rates has to be realized. So the communication path from front end sensors on the servicer spacecraft to the operator on ground has to be optimized and the latency time has to be minimized.
Furthermore a long access time from the ground station is required because continuous communication with the satellite is mandatory for most of the OOS tasks. This can be realized by an inter-satellite link via a geostationary relay satellite, which has the advantage that a satellite in Low Earth Orbit (LEO) can be accessed from one ground station for about half an orbit.

To evaluate both, the requirement of a long access time from the ground station as well as the need of a short latency time, an end to end communication scenario was implemented at the Institute of Astronautics (LRT) at the Technische Universität München (TUM). This scenario includes different spacecraft sensors (e.g. stereo cameras, LIDAR systems), a Ka-Band ground station and man machine interfaces.

This paper describes the setup of a realistic simulation of a communication path from a data source to an operator via space-link. Furthermore the method of latency measuring depending on the data source is described. The communication architecture is embedded in a spacecraft simulator to simulate On-Orbit Servicing scenarios like Space Debris removal and target inspection.

1. INTRODUCTION

The idea of on-orbit servicing is to assemble, repair and maintain satellites in space [1]. This has the advantage that satellites which are basically in good condition but have a minor malfunction do not have to be replaced entirely. Only the critical component will be changed. Other scenarios could be refueling or lifetime extension. Those OOS missions can be performed autonomic, telepresent by humans or be a mixture of both, meaning supervised. The Institute of Astronautics focuses its research on real time teleoperation (RTTO) to enable telepresent and supervised operations with a human operator. In reality such a telepresent OOS mission could look like the scenario pictured in Fig.1. A servicer satellite in low earth orbit shall manipulate a target satellite. Data produced by sensors on board of the servicer satellite is transmitted over the return link to the ground station where the human operator receives and processes the data. After that the operator is able to control the servicer satellite via the forward link.

To enable RTTO three critical key aspects are required those are also necessary to perform successful telepresent servicing [2]: Long continuous contact time, low round-trip delay and a high data rate. A long continuous access time from Earth to the servicer satellite can be accomplished by an intersatellite link via a data relay satellite (DRS) in geostationary orbit (GEO) [3]. This is important for efficient work since a direct link from a ground station to a satellite in low earth orbit results in a continuous link time of only a few minutes. A low round-trip delay and thus also the elapsed time between recording data on board the spacecraft until reception at the ground station is critical in the field of telepresent operated spacecrafts because a large round-trip delay degrades the performance of the operator [4]. High data rates could be required during some mission phases (e.g. inspection, rendezvous and docking) where the operator has a demand for sensor and video data with high frame rates and high resolution [5]. This results in requirements for a high bandwidth link, typically realized in higher frequency bands as the Ka-band (20 to 30 GHz).

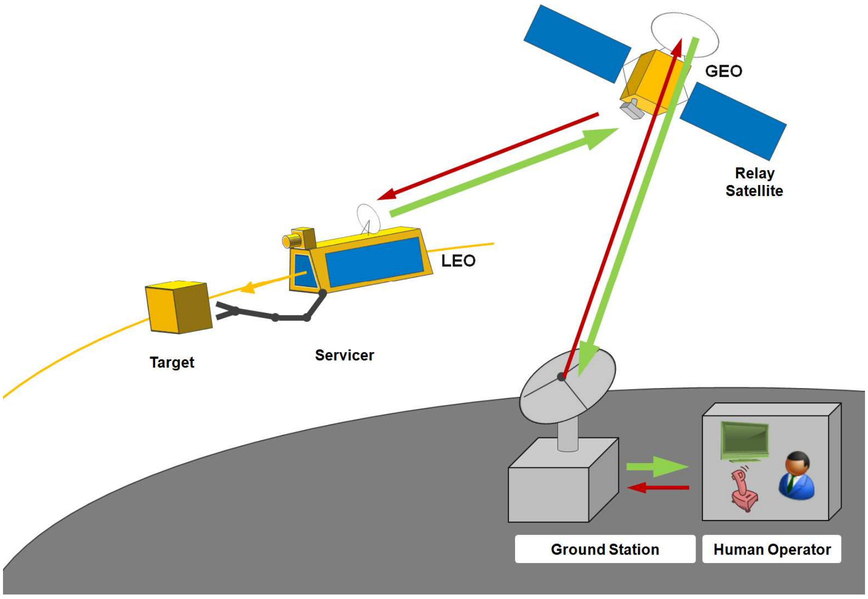

Figure 1: Typical real time teleoperation (RTTO) servicing scenario

To evaluate the general feasibility of telepresent real time operation for OOS missions there have been studies [6] at the Institute of Astronautics. The work focused on different concepts of telepresent control which included communication via a data relay satellite at low data rates in S-band (2 GHz). The feasibility of one of the above mentioned points, the use of a geostationary data relay satellite, was successfully demonstrated. The disadvantage of integrating a relay satellite into the communication loop is the increase of the round-trip delay. For a single hop the propagation delay caused by the speed of light is around 250 ms and for a relayed double hop it is even higher in the range of about 500ms. This is critical since for round-trip delays larger then 700ms humans lose the feeling of telepresence [7]. This limits the available time for data compression, packetizing and display to a minimum, which could be hard to reach as some parts of the processing had to be done on board of the servicer spacecraft and the processing power of space qualified hardware is limited. A demonstration that adequate round-trip delays required for telepresent real time teleoperation can be kept in a realistic communication scenario under high data rates in the Ka-Band has still to be done.

Therefore the big picture of the experiment presented in this paper is to find out, if the round-trip delay from generating data at the spacecraft including transmission via a DRS and displaying the data on ground can be kept below the requested time limits. Furthermore the quality of the data transmission shall be evaluated.

2. GENERAL EXPERIMENT IDEA

For the evaluation of a Ka-Band communication path its round-trip delays and the transmission quality a test environment needs to be implemented where measurements can be performed as close to reality as possible. To reach that goal two projects at the Institute of Astronautics will be brought together: Forrost (Forschungsverbund für Robotische On-Orbit Servicing Technologien) and Racoon-Lab (Real-time Attitude Control and On-Orbit Navigation Laboratory). Forrost is a project funded by the Bavarian Research Foundation and is focused, among other things, on the Ka-band communication link between the spacecraft and the ground station, while the idea of Racoon is to implement a realistic ground based simulator to demonstrate the capabilities of telepresent real time teleoperation for in space operations. In order to perform a realistic measurement of the communication path two important things are required. First the implementation of a realistic high bandwidth communication path with measurement points for the characterization of the transmission delay and second a source for realistic data similar to that of a telepresent servicing scenario.

The realistic communication path will be implemented as showed in Fig.2 and is described in chapter 3.1 in detail. In contrast to the real scenario of Fig.1 some simplification are introduced. The communication path demonstrated in this work is focused mainly on the downlink from the spacecraft to the ground station because in that direction the amount of data is much higher than for the uplink [8]. The high amount of data results from the video data created by the onboard cameras. That data needs to be compressed on the spacecraft which can be realized using a new space computer currently in development. Thereafter it is transmitted over a real space link. To prepare the data for transmission over the link channel coding and modulation is done with a standard Ka-Band satellite modem. Since only one Ka-Band modem is available for the experiment, the modem is used to demonstrate both sides of the return link from the spacecraft to the ground station. The transmission section of the modem corresponds to the high frequency system on the servicer satellite while the receiving section corresponds to modem used at the ground station. It is assumed that the space-qualified hardware used later at a servicer satellite for data transmission would have similar features as the transmission section of the ground-based satellite modem used here. The DRS that will mirror the signal will be most likely Hotbird 6. Visualization of the video data for the human operator at the ground station is performed in a simple console using OpenGL. The forward link from the ground station to the servicer satellite is closed over the local network with an artificial delay created by software.

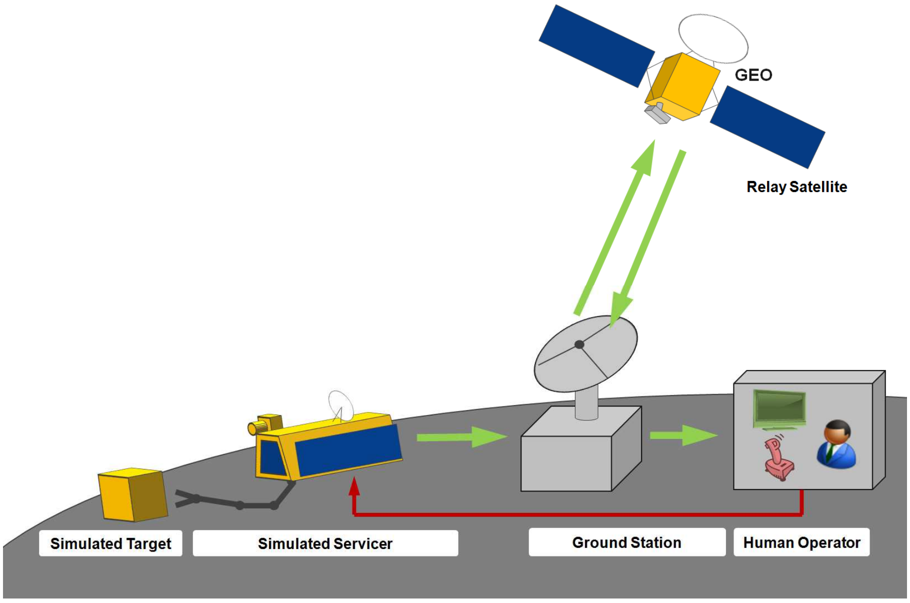

Figure 2: Simulation of the real time teleoperation (RTTO) communication path

Realistic data has to be generated and send over the communication path as it influences for example the image compression and data multiplexing performance and hence the entire round-trip time. This leads to the demand of a realistic orbital simulation environment where data generation can be done as close as possible to a real OOS mission. For this experiment the relative kinematic and environment conditions including lightning between the servicer satellite and the target satellite will be simulated in an OOS test bed on ground in part in software and in part in hardware as described in chapter 3.2.

Using the described setup of the communication path the feasibility and quality of the transmission for RTTO is characterized by measuring round trip delays, bit error rates, data rates and jitter depending on different sensor configurations. A detailed measurement description is given in chapter 4.

3. DETAILED EXPERIMENT SETUP

3.1 Communication path (Forrost)

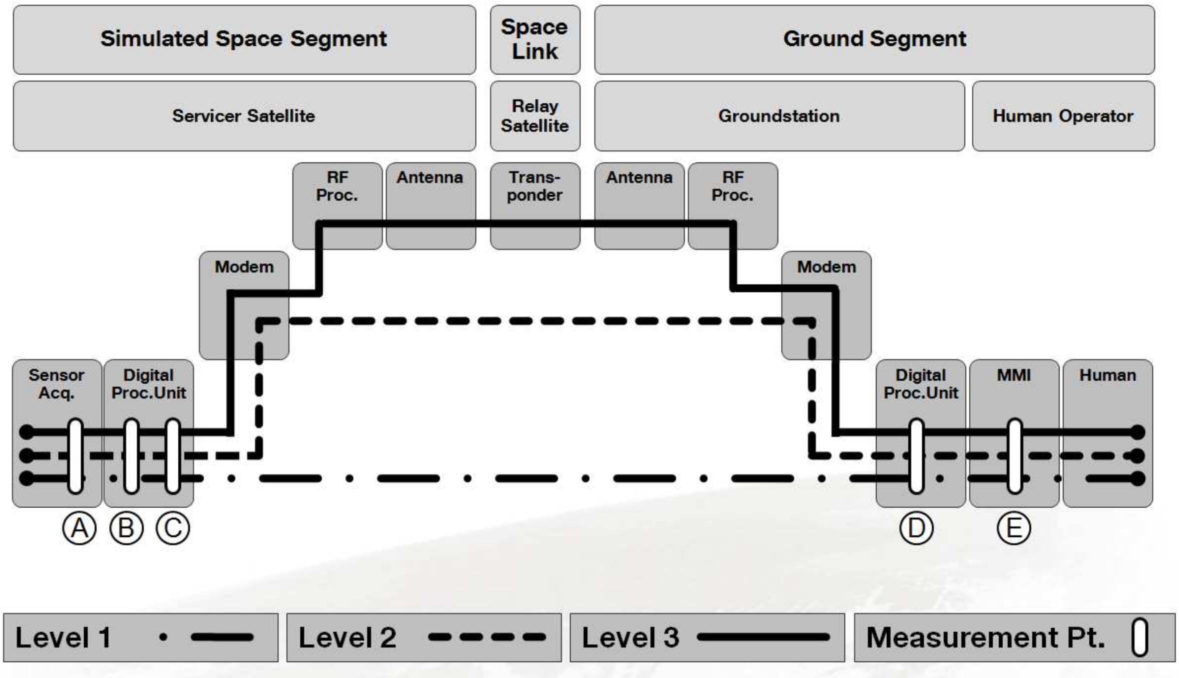

Figure 3: Depiction of measurement setup and measurement points

Data Acquisition and Processing on the Servicer Satellite

For data acquisition and processing, among other sensors, the ERViS computer [9] is used which is being developed at the moment. Based on work by *Diehl GmbH* three universities (*Universität Erlangen, Hochschule Hof, Technische Universität München*) are about to upgrade the computer. The goal is to design a real-time data and video processor which is composed of “Commercial-of-the-shelf” (COTS) components. At the end of its development ERViS will contain three independent working CPUs which can be run in redundant operation with high reliability or independent from each other with high performance. In the first case the three CPUs do the same processing and using a voting mechanism to evaluate the quality of the data and in the second case each CPU can process its own data to increase the processing speed (Fig. 4).

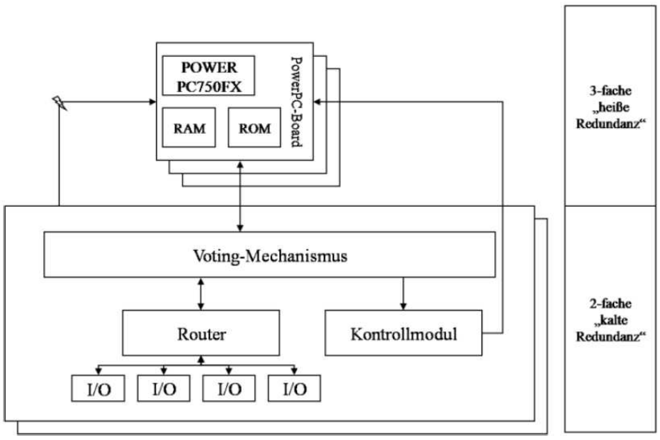

Figure 4: ERViS Computer Design

At the moment three ERViS computers exist which are at Technical Readiness Level 3 (TRL). They were tested successful concerning functionality, stability and interfaces. But nevertheless more redesign is required to reach smaller dimensions of the computer and assure radiation hardness. In the OOS Scenario ERViS will be used to process the video data taken by the onboard cameras. The camera will have a resolution of at least 640x480 pixels, a grey scale of 8bit/pixel and a frame rate of 15 Hz. This leads to an uncompressed data rate of about 40 Mbit/sec which can be reduced by onboard compression to about 5 Mbit/sec. In the future additional data processing tasks such as data multiplexing shall also be added to ERViSs task areas.

Modem, RF Processing and Space Link

The downlink path starts with the recording of the data (Fig. 5) from sensors (e.g. camera, haptic sensors, housekeeping data sensors). These data is transmitted to onboard data handler which collects the data from the different sensors and forward these data to the protocol packetizer. After that the data is multiplexed by the data multiplexer into one continuous data stream. Then forward error correction coding is applied by the channel coder to the data stream. The next steps are to modulate, up-convert and transmit the data stream via a data relay satellite. After receiving the data from the DRS the stream runs through the communication path in the other direction until it arrives at the man-machine interface for further processing by the human operator.

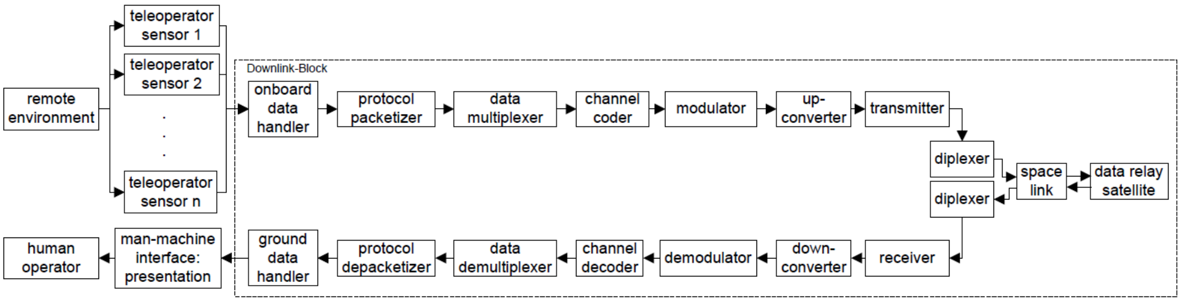

Figure 5: Modem Configuration for the Downlink

3.2 OOS Simulation Environment (Racoon)

As depicted in chapter 2, the type of data sent over the link is important as it influences the link performance and must therefore be considered within the link characterization. In order to produce realistic sensor data (foremost video data but also other telemetry) the simulated space environment of Racoon-Lab is used. The Racoon-Lab itself is a ground based on-orbit servicing and space debris removal simulator that is currently in development and will be capable of simulating near-realism on-orbit servicing scenarios in the future. Its design is based on the system architecture of a real space mission and is therefore suitable to simulate scenarios as illustrated in Fig. 1. On the top level it consists of four major parts. First a simulated space segment contains all relevant parts that are exposed to the space environment. These parts are assembled to a simulated spacecraft that combines computer simulated and real space hardware to return realistic responses and sensor information to the human operator. Sensor and actuator stimuli of the simulated spacecraft interact with a simulated space environment. The simulated environment is itself part software and part hardware as needed for the simulated spacecraft. Second a link segment enables realistic communication between the simulated spacecraft and the ground station and is the critical bottleneck limiting data rates and access times. Third a ground segment contains data processing facilities as well as the operator environment where humans can test and evaluate new control concepts for the servicer robot operating in the proximity of the target. Finally a simulation control segment offers many simulation control and analysis tools to identify possible hazards for real missions and reveal new targets for future optimizations. Racoon-Lab is a long time strategy of LRT. Thus results of the Forrost project will later enhance many components within the simulated spacecraft, the link and ground segment.

The hardware part of the simulated space environment used for this experiment consists of a dark room to simulate the black space background for cameras and includes in the current configuration two mechanisms to perform planar proximity operations in the orbital plane of the servicer. The mechanisms are a 2D motion table and three degrees of freedom rotation device (Fig.6). The table has a travel distance of 4m by 5m so that close range proximity operations can be simulated. The loading capacity is 100kg which allows even large experiment setups to be carried. The maximum travelling speed is 0.25m/s and above the normal relative velocities reached during proximity operations but could be required in some axis mapping configurations where additional virtual velocities are added. The configuration of the rotation device is suited to simulate the movement of a nutation free spinning target. It will carry a lightweight mockup of the uncooperative target satellite, covered with realistic surfaces. Additional degrees of freedom will be included later, if required for the experiments. All axes are coordinated and driven by a real-time motion controller, so that inputs from the simulated spacecraft or the operator can be mapped immediately to the motion hardware. A 2000W electrical power light source is used to simulate lightning conditions.

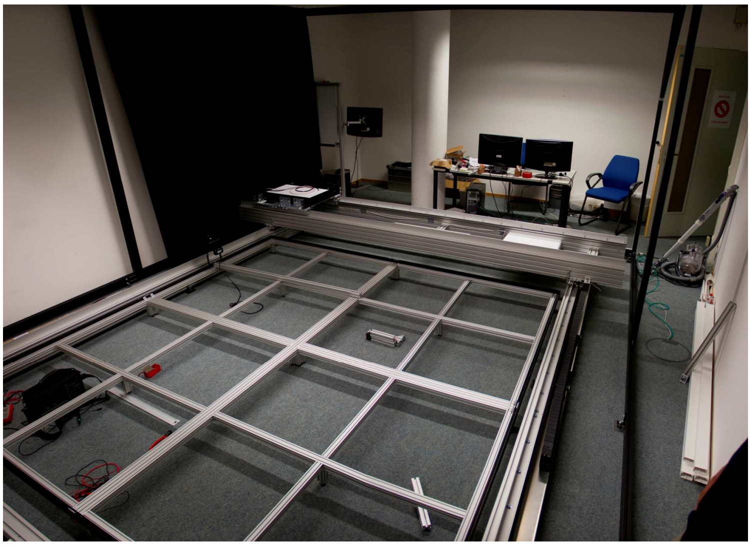

Figure 6: Work in Progress on the Hardware Part for Simulating the Space Environment

4. MEASUREMENT OF LINK PERFORMANCE

As stated in chapter 2 the link performance in the given scenario is defined by the four parameters data rate, round trip delay, jitter and bit error rate. To obtain values for these parameters, timestamps, transferred packet sizes and packet checksums are logged at different positions in the communication path according to Fig.3. The measurement points are all located in the digital data processing domain (sensor acquisition, digital data processing unit or man-machine interface). Fig.3 also depicts the 3-Level Approach for the measurements. Level 1 measurements only involve the digital processing units which either simulate the On-Board or On-Ground hardware. Communication is established via applicable protocols (e.g. UDP). In Level 2 the satellite modem of the ground station is added to the test setup which includes multiplexing and modulation/demodulation into the communication path. The RF-output channel of the modem is directly fed back into the RF-input channel so that the complete data processing can be tested without using a real space link. Finally in Level 3 all parts of the communication path are considered which will include a real-world satellite link via a geostationary communication satellite (e.g Artemis or Hotbird 6) in the measurements.

As the communication path includes a bidirectional link data is transferred in both directions and the exact design of the single measurement points differ between the multiple data streams (video data, tele-command inputs, etc.). As the video transmission was the first data stream to be implemented it should be presented in this paper as leading example. The measurement points for this video data transmission are briefly characterized in table 1.

Table 1: Measurement Point description; e.g. Video Data Stream

Measurement Point	Software	Time of Measurement	Acquired Data
A	On-Board Video Processing	Sensor readout completed	• Timestamp
B	On-Board Video Processing	Image compression completed	• Timestamp
C	On-Board Video Processing Network Traffic Analyser	Image sending completed	• Timestamp • Image Size • Packet Checksum • Overall Packet Size
D	On-Ground Man-Machine Interface Network Traffic Analyser	Image receiving completed	• Timestamp • Image Size • Packet Checksum • Overall Packet Size
E	On-Ground Man-Machine Interface	Image drawn on screen	• Timestamp

Round Trip Delay & Jitter: To obtain the overall round trip delay the downlink and uplink one-way delay is combined. For the downlink one-way delay the time difference between sensor data acquisition and visualization for the human operator is measured. Therefore the software responsible for capturing, packetizing and transmitting the data in the On-Board Digital Processing Unit (DPU) is logging timestamps for each transferred frame. To gain more insight in the different data processing steps timestamps are acquired after sensor readout, compression and sending of each picture. On the receiver side the software of the man-machine interface (MMI) is logging timestamps after the complete reception of one image and drawing it on the screen. These timestamps allow measuring the total time needed for the downlink. For the uplink one-way delay the same approach is used logging timestamps at the Control Interface and the arrival at the On-Board system. As all logged timestamps are available for further analysis after the completion of the tests the jitter is calculated by post-processing of the logged data.

To get useful and accurate timestamps over distributed systems time synchronization becomes a vital task. One established method is using the network time protocol (NTP) proposed by [10]. It uses elaborate synchronization methods to obtain a local clock offset to an accurate Stratum 0 time server in the order of less than one millisecond, which is sufficient for the intended measurements. As a second synchronization method the software code uses a dedicated Synchronization Ping which is generated at the On-Board DPU and transmitted via a separated network connection to the On-Ground DPU. At the On-Ground DPU a local timestamp is created and transmitted back to the sender where it is used to calculate the clock offset. As the needed packet size is comparatively small the transmission and processing time is sufficiently small for the intended offset calculation. This method is used as a secondary check of the clock offset and for the real-time calculation of the offset needed for the display of the current delay in the MMI.

Data Rate: For the measurement of the data rate two measurements are conducted. The video transmitting software not only logs the timestamps but also the packet size of the sensor data packets (e.g. image size). In combination with the timestamps this allows the calculation of a payload data rate in bps. For obtaining the real world data rate that has to be transmitted via the satellite RF-channel the protocol overhead has to be added. To obtain this separate measurement a software for network analysis tracks the traffic of all involved network controllers and logs the transmitted packets including protocol overhead. As this measurement is conducted at both the On-Board DPU and the On-Ground DPU overall data rate can be determined.

Bit Error Rate: The measurement of the BER can be achieved by creating packet checksums or by 1:1 bit comparison of transmitted and received data packets. As the implementation is still ongoing a decision has not been made.

5. OUTLOOK

This paper described the work of the last two years to implement a Ka-Band communication path embedded in a realistic on-orbit servicing scenario. With the support of Racoon a test environment was designed to produce realistic sensor data for the measurement of the link performance which is part of the Forrost project. But this is only the beginning of the mission. In the next years the test environment will be developed further to get a more and more realistic test bed. Therefore more sensors are planned to be integrated. For example stereo cameras, distance meter or a LIDAR system.

For the measurement of the link performance a high data rate modem, a Ka-band antenna and a DRS will be integrated in the communication path. This will help to improve the estimation how much time passes from the generation of data onboard a spacecraft until the display on the computer of the human operator. The latency time and the quality of the transmitted data are key parameters for missions which are operated telepresent. So the work presented in this paper is one step towards the final goal of telepresent operated satellites which will be able to assemble, repair and maintain other spacecraft.

6. ACKNOWLEDGEMENT

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