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Receiver Performance of ESA Ground Terminal During Lunar Laser Communication Demonstration (LLCD)

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NASA's Lunar Laser Communication Demonstration (LLCD) has proved the capabilities of optical communication between the LADEE space craft orbiting the Moon and three complementary ground stations (NASA/MIT, JPL and ESA) on Earth. For ESA's optical ground station on Tenerife, an innovative fibre coupled receiver unit has been developed. It comprises highly sensitive optical detectors, synchronisation electronics (for clock recovery and frame synchronisation), a fast decoder (able to decode data at the same speed as it is received) and a large data buffer with a high speed data interface. For modulation and coding, Pulse Position Modulation (PPM) in combination with the Serially Concatenated PPM (SC-PPM) error correction scheme is used.

This paper focuses on the experiment's results and field experience. At ESA's optical ground station, the optical downlink beam at a wavelength of 1550nm was received with a 1m telescope and coupled into a multi-mode fibre. Via this fibre, the receiver unit has successfully detected and decoded a vast amount of data from the LLCD experiment during different passages and at different times of the day. The performance results are analysed and presented. Atmospheric conditions and the fibre coupled approach are discussed and lessons learned are presented. The experiment provides valuable input for both, the further advancement of deep space laser communication as well as for the discussion of optical links through the atmosphere. Both topics have been pursued by RUAG for years.

Keywords— Optical communication, LADEE, LLCD, PPM, SCPPM, Multimode, Photo Multiplier Tubes, APD.

I. Introduction

The European Space Agency (ESA) has upgraded its Optical Ground Station (OGS) on Tenerife to serve as a complementary ground station for NASA's Lunar Laser Communication Demonstration (LLCD). In October and November 2013 the OGS successfully participated in optical downlink experiments from NASA's LADEE spacecraft orbiting the moon to the ground. RUAG has developed a fiber-coupled receiver unit for these experiments [1]. At the OGS on Tenerife the 1m-Ritchey-Chretien telescope couples the received optical downlink signal into a multimode optical fiber which routes the signal to the receiver unit one floor below (see Fig. 1). An overall block diagram of the complete receiver chain is depicted in 0. The ground receiver unit has the following objectives:

- Detect the optical signal provided by the LLCD space terminal
- Digitize and synchronize the signal (clock and frame synchronization)
- Decode the data
- Store the data on a large data buffer

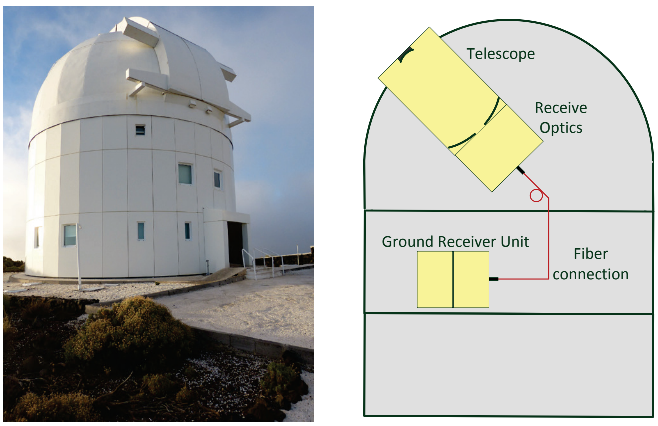

Fig. 1. ESA Optical Ground Station on Tenerife

The LADEE spacecraft uses a 16ary-PPM signal (Pulse Position Modulation) where one pulse within 16 time slots is transmitted (see Fig. 2). Thus, one optical pulse encodes 4 message bits. The payload data are packed into frames of 7560bits. Combined with the PPM modulation a Forward Error Correction (FEC) scheme called Serially Concatenated

PPM (SCPPM) [4] is applied. A frame alingment sequence of 16 PPM symbols is preceeding each encoded and modulated frame. The spacecraft supports five different downlink modes with the user data rate ranging from 39Mbps (slot width 3.2ns) to 622Mbps (slot width 0.2ns). Its laser transmits at a wavelength of 1550nm and the estimated power level on the detector at OGS is ~350pW [1].

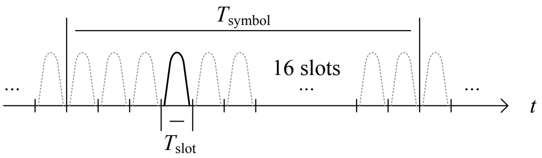

Fig. 2. Pulse position modulation

It was clear from the beginning that the faster modes cannot be supported in the given time and cost frame. Eventually, the receiver electronics was designed (and tested) up to 154Mbps. The baseline detector supports the slowest mode at a user data rate of 39Mbps (raw data rate 78Mbps). The back-up detector supports user data rates of 39Mbps and 77Mbps but requires higher power level.

The receiver unit was implemented with off-the-shelf electronics in a standard 19 inch rack. A Field Programmable Gate Array (FPGA) board was used for the receiver module as well as for the decoder module (0). The baseline detector unit comprises commercial photomultiplier tubes and was also integrated in a standard 19 inch rack. The backup detector was a custom made Mercury Cadmium Telluride (MerCadTel) APD. MerCadTel detectors achieve high quantum efficiencies (60-80%) and high internal gains at low noise figures ([6]). This experimental detector provided by CEA LETI was setup on an optical table at the OGS and operated with lab equipment. The data buffer is a commercial server system with several large storage disks in Redundant Array of Independent Disks (RAID) configuration.

The final setup as installed in the ESA ground station is depicted in Fig. 3. A picture of the back-up detector is given in Fig. 5. The fiber interface between telescope and receiver unit allowed independent development of the receiver optics at the telescope and the receiver unit. Furthermore, it allows swapping different detector or input types (test laser) by simply changing fiber connections.

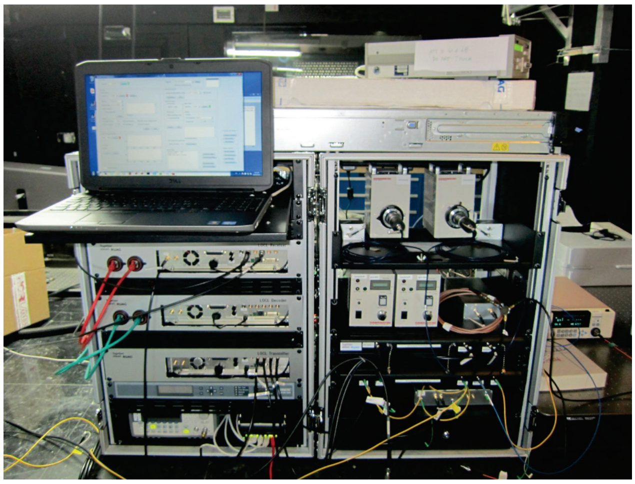

Fig. 3. Reciver Unit at ESA's optical ground station (left: electronics rack, right: detector rack)

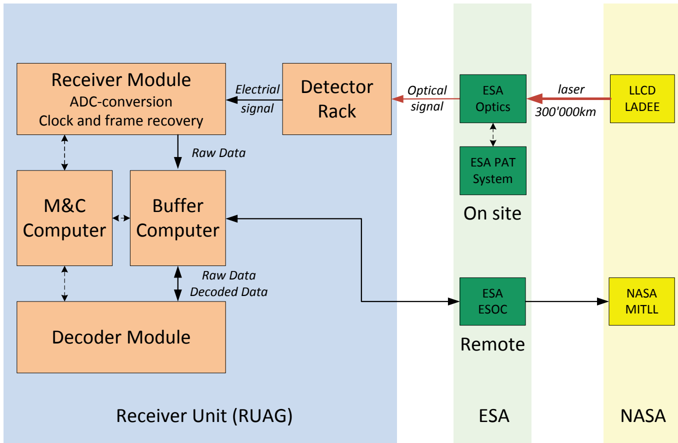

Fig. 4. Block diagram receiver chain

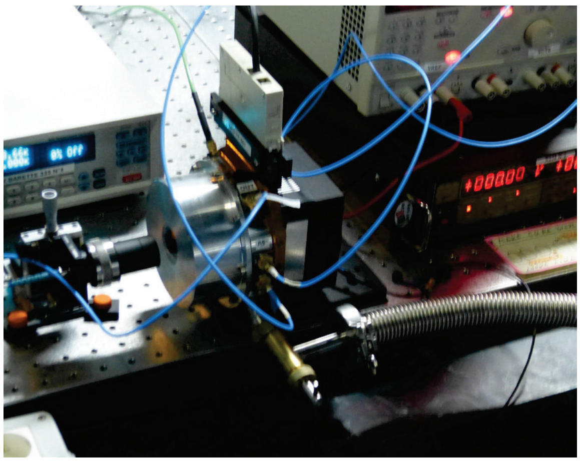

Fig. 5. Backup detector installed at ESA's optical ground station

II. Receiver Performance Standalone

To verify the receiver performance a dedicated optical transmitter module has been developed and delivered with the receiver unit. The transmitter module emulates the spacecraft terminal and provides a fibre coupled optical signal with the correct modulation and encoding.

The fibre interface between telescope and receiver unit (detector) provides the possibility to optically test the receiver unit with a test laser by simply switching fibre optic connectors. Thus, the receiver performance can be easily tested even after installation in the optical ground station. This was very useful, in particular when there was an issue with the backup detector (see section III.F).

Fig. 6 and Fig. 7 show the sensitivity of the receiver unit with baseline and backup detector respectively (tested before delivery). The symbol error rate (pulse detection) and the frame error rate of the decoded data are depicted. With the delivered transmitter module the on-site performance (at the OGS) has been verified to match the measurements in the lab.

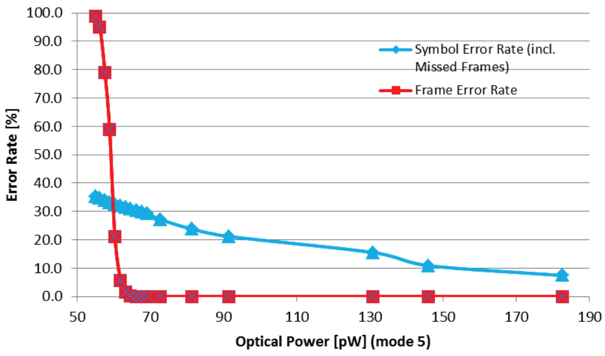

Fig. 6. Sensitivity photo-multiplier tube

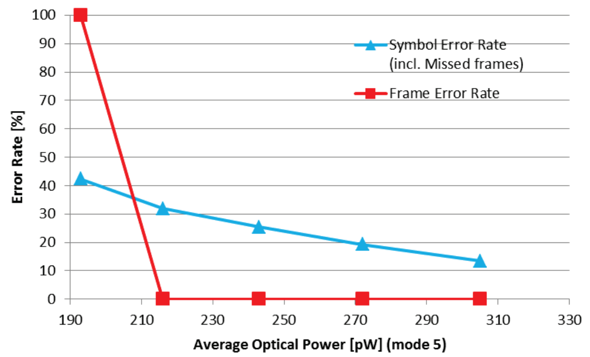

Fig. 7. Sensitivity APD

It is worth mentioning that the setup as installed at the OGS is almost identical to the setup used in the receiver verification before delivery (I).

Other important properties were tested before delivery and were not repeated at the OGS:

- Input collimator: Beam size and stability after the fibre cable were tested and optimised.
- Clock range and drift: The receiver chain was tested over a clock range of nominal value ± 300 ppm (parts per million) and with drifts up to ± 0.21ppm/sec
- Compatibility: NASA/MIT representatives have visited RUAG with their verified EGSE and performed a series of compatibility tests (wavelength, modulation and encoding, interleaver etc.).
- Power fluctuation (scintillations): Power fluctuations (up to 1kHz) were simulated with a acousto-optical modulator in the input chain. The receiver operated steadily.
- Passage test (long duration run): Downlink passes were run for up to 30 minutes. While short tests of only a few seconds normally produce enough data to measure the performance, the passage test should ensure the systems remains stable also in longer runs.
- Operation at high altitude: As the OGS is located at 2400m, the correct operation of the detector (air cooled Peltier-modules) in its rack was tested at comparable altitude in the Swiss mountains before delivery (Fig. 8).

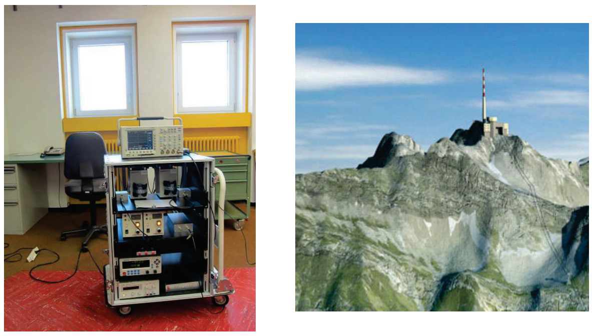

Fig. 8. Detector rack operation in Swiss mountains (2500m above sea level)

All tests were finally passed, although some improvements were necessary :

- The optimum input beam for the PMT was found to be slightly de-collimated (even though the datasheet states 'collimated input beam'). RUAG suspects that the perfectly collimated input beam leads to very small spots on the photocathode causing local over-exposure.
- In long duration runs a network driver bug was discovered and could only be fixed after lengthy error investigation.

The throughput of the different receiver modules and processing software are listed in TABLE I. In principle, recording of the PPM slot values and the firmware decoder reach real-time throughput, while the software processes much slower. Hence, it takes a couple of hours to de-interleave one batch of 1 min before it can be further processed in case that channel interleaving is applied. Note that the software decoder is only a backup solution as it is extremely slow compared to the firmware implementation which in contrast profits from parallel processing.

TABLE I. THROUGHPUT OVERVIEW FOR A 1 MINUTE RECORDING

Component	Run Time	Output Throughput	Output Data Type
Receiver module	1 min	1.875Gbps	Raw data
Software channel deinterleaver	~5 hours	~6.25Mbps	
Decoder module (Firmware SCPPM decoder)	1 min	39Mbps	Decoded user data
Software SCPPM decoder	~30 days	<1kbps	

TABLE II. LADEE DOWNLINKS TO ESA GROUNDSTATION

Date	Downlink attempts/success	
26.10.2013	1	1
27.10.2013	2	2
28.10.2013	1	1
29.10.2013	3	3
02.11.2013	2	2
18.11.2013	1	0

III. PERFORMANCE IN ESA GROUND STATION

A. Installation

Thanks to the modular design with a simple fiber connector as main interface, the complete receiver unit could be installed and verified in one day. As the overall experiment is very complex this is considered a major achievement.

B. Operation

In October and November NASA have made various downlinks to ESA's OGS on Tenerife (see TABLE II. Further downlinks in spring 2014 are in discussion.)

Once sufficient power was available on the detector, the receiver unit operated reliably and stable. The one failed downlink was an attempt to operate the backup detector. As it turned out a distorted thermal shield in the detector's vacuum enclosure had been blocking part of the signal. With the test laser the root cause could soon be identified and the issue was fixed soon thereafter, but no more downlinks could be attempted due to local weather conditions.

The downloaded data (~20GByte) were mainly pseudo-random sequences and some telemetry data. The downloads were made at a user data rate of 39Mbps and with different interleaver depths employed. The main focus of the experiment were not 'the data', but the demonstration of optical communication. Thus different configurations were tested rather than running a link over long duration. On a typical day the OGS could use 2-3 passes of about 20 minutes. A couple of possible downloads could not be attempted because of bad weather (October/November being the bad weather season at the observatory) or because the spacecraft was too close to the sun (telescope limitations). These days are not included in TABLE II.

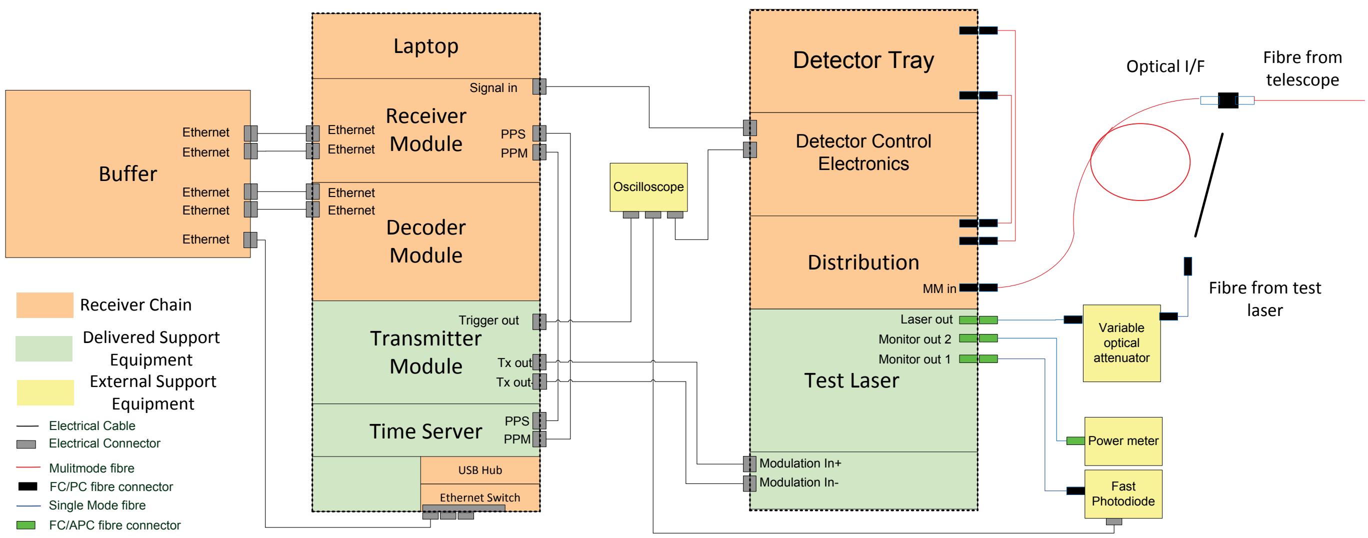

Fig. 9. Block diagram of the reciver unit with support equipment as installed at ESA OGS

C. *Sensitivity and Frame Error Rate*

Fig. 10 shows the average frame error rate versus the received power (on the detector) for two batches of 2 minutes each. For this analysis, all received frames have been checked whether they contain any errors (using the payloads checksum). Each frame is assigned to a power level bin by means of the measured power at the frame start. For each of these 2pW windows, the average frame error rate is calculated by dividing the number erroneous frames by the total number of frames.

For comparison, the frame error rate achieved during tests in the lab before delivery is shown in the same plot. Note that the power level do not match because the LLCD terminal laser has a higher extinction ratio than the test laser. Thus the field performance (sensitivity) is actually better than the lab performance. Furthermore, the curves of the recorded batches fall less steep than measured under laboratory conditions. This is caused by the observed power fluctuations. Hence, the power level can vary slightly over one frame duration.

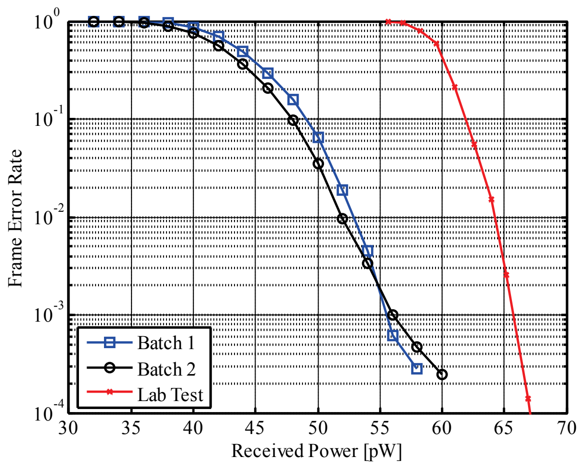

Fig. 10. Frame error rate averaged over received power windows of 2pW.

D. *Observed Power Flucutations*

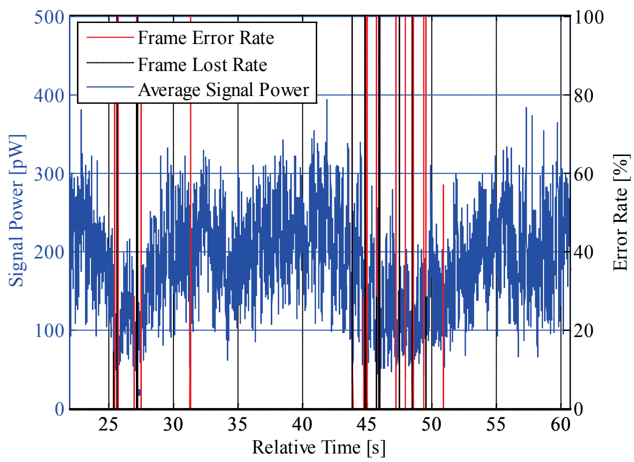

Fig. 11. Received power on the detector, frame error and lost rate.

The detector output signal can be used to determine the average optical input power. Calibration measurements for this purpose have been made in laboratory tests. The observed power fluctuations were heavier than anticipated. Fig. 11 shows the received power for a sample batch (left axis) and the corresponding frame error rate (right axis). Clearly, the occurrence of frame errors corresponds to low received power.

However, it could be shown that such a batch as depicted in Fig. 11 could be received error free when using interleaved modes [1].

The theoretically expected lognormal distribution for the fluctuation of received power due to atmospheric scintillations was only occasionally observed. Most downlinks show a rather Gaussian distribution (Fig. 12 and Fig. 13 respectively).

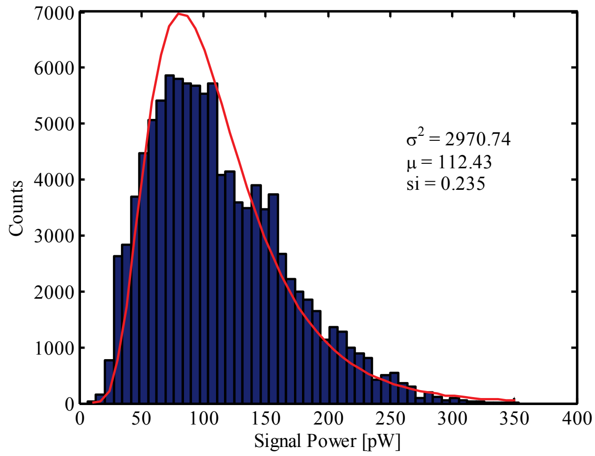

Fig. 12. Histogram of received power

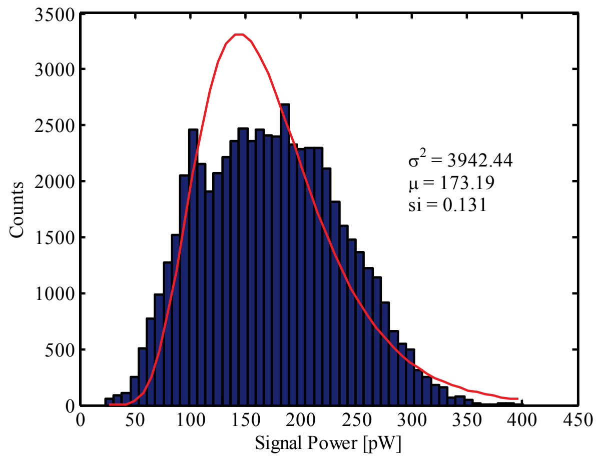

Fig. 13. Histogram of received power

The power spectrum of the observed power fluctuations shows a steep roll off around 10Hz. A typical spectrum is depicted in Fig. 15.

E. *Comparison with Tracking Camera*

With the kind support of ESA, RUAG was allowed to have a closer look at the image data of the tracking camera. Fig. 14

illustrates the power fluctuations which were observed during operation in the OGS. During the experiment suboptimal coupling between the telescope and the multimode fiber leading to the detector has been observed. The camera images on the bottom show how the spot is moving around the tracking center marked with the yellow cross. Considering the fiber diameter of 200µm and the pixel pitch of 20µm, the 9x9 pixel window (marked in green) has been taken to find a position where the corresponding pixel sum correlated with the recorded power signal. The curve is scaled according to the receiver chain's power estimation. A significant correlation has been found with an offset of -3 and 2 pixels in x- and y-direction, respectively. Investigation in other time instances have shown similar offsets but in other directions. The OGS telescope has a focal length of 13300 mm. One pixel of the infrared camera corresponds to about 1.5 µrad full angle. Even if possible image blurring is taken into account, it seems that the spot was spread and often larger than the fiber core of 200µm diameter. At the same time the spot showed significant movement, possibly due to tracking errors (tip tilt correction was not implemented in the first downlink sessions in October/November 2013). Thus it is suspected that a significant contribution to the observed power fluctuations is stemming from instable coupling conditions. With this is mind it seems unrealistic to have a reliable measurement of atmospheric conditions (i.e. scintillation index at different day times or elevation angles). Luckily ESA together with the German Aerospace Center have made a measurement of power fluctuations in parallel [7]. Therefore, a small co-aligned telescope was used to measure the optical power separately.

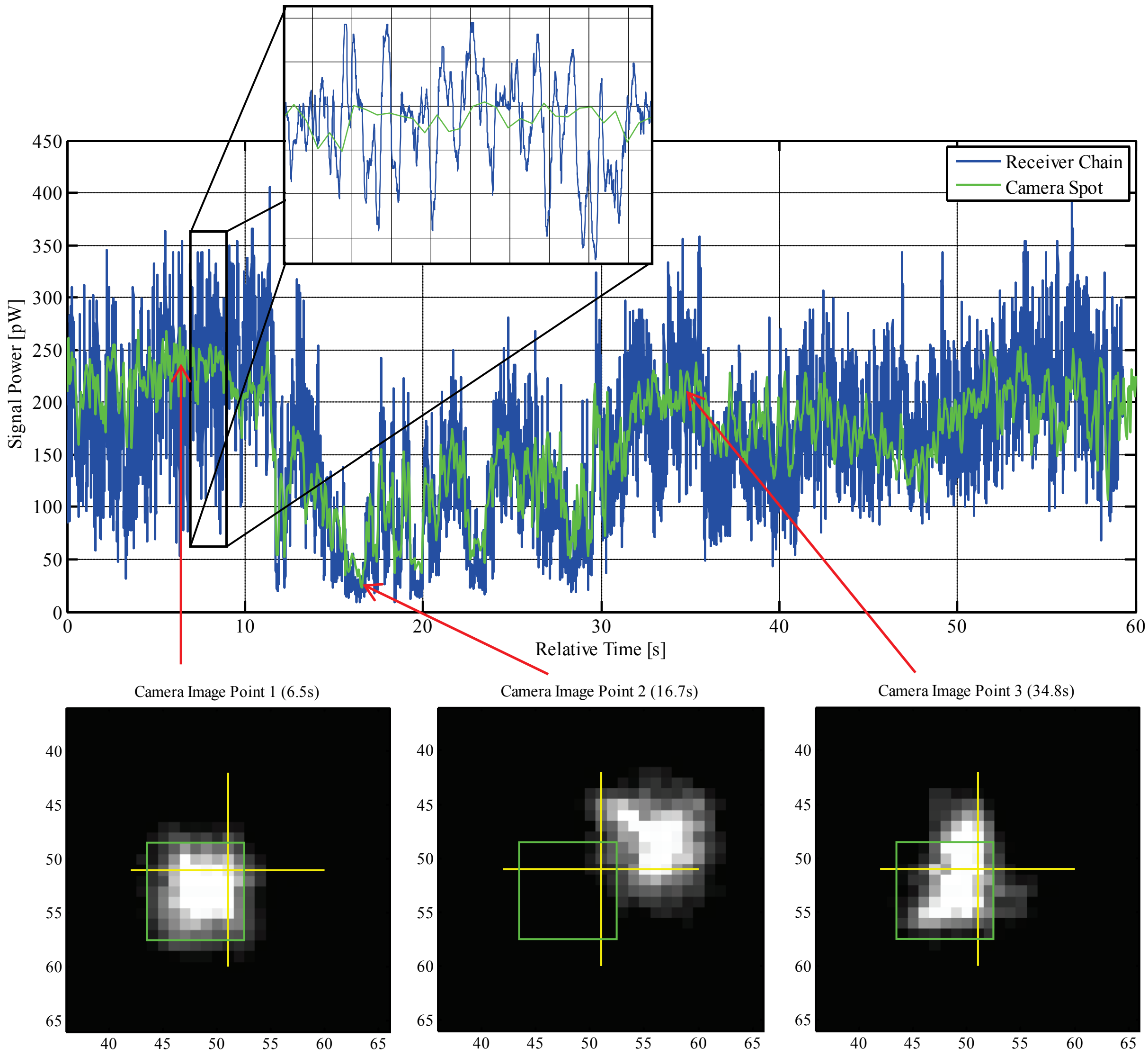

Fig. 14. Signal power comparison between the receiver chain and data based on the tracking camera images.

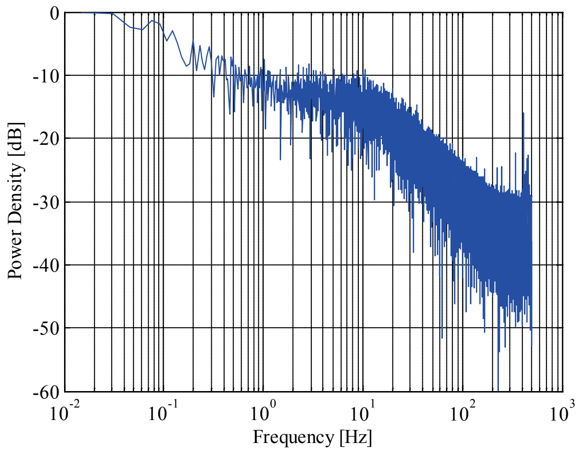

Fig. 15. Typical spectrum of received power

F. Discussion Fiber Interface

The modular design with a simple fiber interface allowed independent development and testing of the receiver unit and the receive optics (telescope). The possibility to optically test the receiver unit with a test laser even after installation at the OGS proved to be very valuable. In one of the last downlinks the back-up detector did not show any signal. Within a day the root cause could be found (see section B).

Also installation and functional check of the receiver unit could be made in one day only. In its basic configuration the receiver unit only has a fiber connector, a network cable and a power plug as interface.

The drawback of this solution seems the delicate fiber coupling. However, it seems feasible with proper tip-tilt correction to achieve a more stable coupling. For most communication detectors the size of the detector is not larger than the 200µm fiber core. The observed additional losses of the fiber interface are negligible.

IV. Conclusion

RUAG has developed a fully functional ground receiver unit for the Lunar Laser Communication Demonstration and installed it in ESA's optical ground station. A custom made large core fiber is used to route the optical signal from the telescope to the receiver unit. The receiver unit itself comprises two types of detectors - a commercial PMT and a customized MerCadTel-APD. From the optical signal the receiver unit recovers the data frames and decodes the data.

During various downlinks in October and November 2013 the unit has successfully received and decoded data from NASA's LADEE spacecraft orbiting the moon. In these downlinks with a user data rate of 39 Mbps the unit achieved the target frame error rate of 1e-4 at power levels as low as 60pW (Fig. 10). The high sensitivity and the stable operation of clock recovery and frame synchronization enabled the receiver unit to worked reliably under severe power fluctuations.

The observed power fluctuations (at the receiver unit) were more severe than anticipated - probably mostly due to image motion and according efficiency drops when coupling the light into the fiber. Power fluctuations could be overcome by the use of interleaved modes and error free downloads had been achieved.

Further downlinks in spring 2014 are in discussion.

Acknowledgements

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