5.625 Gbps Bidirectional Laser Communications Measurements Between the NFIRE Satellite and an Optical Ground Station

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Abstract—**5.625 Gbps bidirectional laser communication at 1064 nm has been demonstrated on a repeatable basis between a Tesat coherent laser communication terminal with a 6.5 cm diameter ground aperture mounted inside the European Space Agency Optical Ground Station dome at Izana, Tenerife and a similar space based terminal (12.4 cm diameter aperture) on the Near Field Infrared Experiment low earth orbiting spacecraft. Both night and day bidirectional links were demonstrated with the longest being 177 seconds in duration. Correlation with atmospheric models and preliminary atmospheric r_0 and scintillation measurements have been made for the conditions tested, suggesting that such coherent systems can be deployed successfully at still lower altitudes without resorting to the use of adaptive optics for compensation.**

Keywords-Nfire; Space to Ground Link; Laser Communication;

I. Introduction

In April 2007, the NFIRE (Near Field InfraRed Experiment) spacecraft was launched with a Tesat Spacecom LCT (laser communication terminal) aboard. The LCT sponsored by the DLR (German Space Agency) and developed by Tesat Spacecom utilized an international agreement between Germany and the United States to integrate the LCT to the MDA (Missile Defense Agency) built spacecraft, NFIRE. In February 2008, the NFIRE-LCT completed its first high data rate (5.625 Gbps) bidirectional link [1] between the NFIRE spacecraft and another DLR LEO (low earth orbit) spacecraft, TerraSAR-X. Since this original milestone, the reliability and performance of these inter-satellite laser links (ISL) has been reinforced by more than 100 successful experimental campaigns. In parallel to the in-orbit verification, it was decided by the international program team (consisting of The Aerospace Corporation (Aerospace), MDA, US-Air Force and Orbital Sciences Corporation on the US side, and Tesat, the DLR and the BWB [Federal Office of Defense Technology and Procurement] on the German side), to explore the capability of high data rate coherent laser communications through the atmosphere. A Tesat ground LCT was built and tested. After developing and maturing the ground LCT soft and hardware, repeated bidirectional 5.625 Gbps were recently achieved from an LCT on the NFIRE spacecraft to a Tesat ground terminal located at the ESA (European Space Agency) OGS (optical ground station) at an elevation of 2350 meters residing at Izana, Tenerife.

Laser links through the atmosphere can be challenging depending on the specific optical specifications, characteristics of the turbulence for the location/time and the elevation angle of the transmitted beam. For the case investigated here, a 1.06 micron coherent BPSK (binary phase shift-key) waveform was developed by Tesat Spacecom for inter satellite laser communication. By requirement, the near-diffraction limited beam was propagated up through a 6.5 cm aperture diameter from the ground LCT to a 12.4 cm counter transmit/receive LCT aperture at the NFIRE spacecraft. To preserve a coherent uniform beam, one should propagate through an atmosphere characterized by a prevailing Fried coherence parameter, r_0, greater than the transmit beam diameter. The mean r_0 based on a variety of data for the spring/summer Tenerife site is expected to be 16.9 cm at 1.06 microns and 20 degree elevation suggesting that the atmosphere in most instances is compatible from a coherence perspective with coherent communications. If one were to estimate the likelihood of achieving such a link at the OGS on Tenerife, based on the prevailing C_n^2 profile [2], one would predict rare closing of the link because even with expected variations the predicted r_0 for most elevation angles would be smaller than 6.5 cm. If the atmospheric conditions are in fact more like Haleakala, Maui, Hawaii whose night C_n^2 profile, Maui3 [3] has been repeatedly measured and verified, then one would expect to observe larger r_0's (16.8 cm at 1.064 microns and 20 degree elevation) consistent with long coherent transmissions. In addition, irradiance fluctuations as characterized by the SI (scintillation index) including beam wander for the uplink can also impact the link success. Recently, Yura and Fields [4] developed analytic expressions for the mean angular level crossing rate and duration of such crossings that result from atmospheric turbulence induced beam wander. If one were to assume a profile at Tenerife similar to the Maui3 profile, then the Yura and Fields predictions suggest single axis beam wander standard deviations of nearly 3 micro-radians at 20 degree elevation angle. The values could be almost 6 micro-radians if the Tenerife profile were represented by the HV-57 typically observed at a lower altitude desert-like land site such as Starfire Optical Range. Secondly, the estimated rate for the irradiance fluctuations can approach several hundred Hz thus impacting the control laws for spatial tracking algorithms of laser communication systems.

This paper will report results of the recent campaign during the Spring and Summer of 2010 at Tenerife where nearly 50%

of the links from April through July resulted in bi or mono-directional communication using the 1.06 micron coherent Tesat lasercom waveform. In recognition of the limited detailed a priori understanding of the atmosphere, this study used a combination of telemetry from the various links combined with a parallel but separate atmospheric measurement capability to yield an unprecedented abundance of atmospheric measurement characteristics to correlate with the variable laser link performance observed during the campaign. To our knowledge, this is the first LEO-to-ground high data rate bidirectional link where slew rates typically average 10 mrad/sec and thus sample highly varying atmospheres. This also represents one of the first times that very high data rate signals obtained at both ends of the link allow one to measure the integrated column effects on both the up and down link simultaneously (except for the small difference in the lead ahead angle). Based on preliminary results reported below, the atmosphere at the Tenerife site appears to display a profile closer to the Maui3 [3] profile which was developed through experiments performed during the night at the 3,000 meter site on Mt. Haleakala, Maui, Hawaii. We will report r_0 and scintillation index values for a representative ensemble of the links at the OGS in Tenerife to afford a better understanding of what atmospheric behavior best determines the likelihood of link success. We will also attempt to correlate consistency of the link with the measured time dependent values of SI and r_0 and ascertain if Yura's and Field's [4] beam wander model accurately characterizes the link behavior within the available measurable link properties.

Finally, this and other data will be compared and evaluated to derive additional understanding of the open loop pointing performance of the terminal as compared to earlier data reported for the same hardware in space-to-space encounters [5].

II. Space-To-Ground Laser Communication Experiments

A. Maui

The ground LCT was air freighted inside a shipping container from Backnang, Germany to the island of Oahu in Hawaii, USA, late February 2009. It was then transported to the University of Hawaii site on Haleakala adjacent to the AMOS (US Air Force Maui Optical Station) facility for checkout and calibration during the months of March and April 2009. The US/German teams collaborated on a series of space-to-ground links between the NFIRE satellite and the LCT mounted in the small container depicted in Figure 1 between the 7th of May and the 17th of August 2009. At an altitude of 3058 meters it was hypothesized that the r_0 would be consistently large compared to the ground LCT aperture diameter of 6.5 cm. As measured at minute intervals and tabulated in figure 2, the mean r_0 over the campaign was 9.8 cm with a large standard deviation of 6.1 cms for the campaign engagements. The r_0 peak at 12 cm in figure 2 is

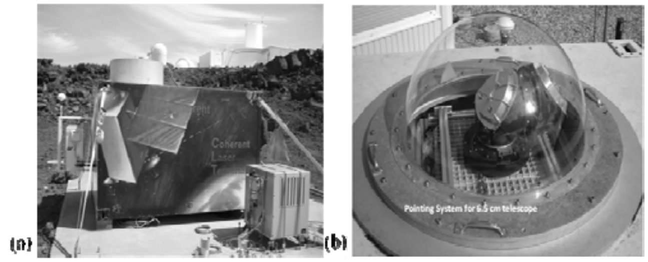

Figure 1. (a) Container on Haleakala with metal protective cover over the ground LCT. (b) Engagement ready LCT on AMOS except for removal of plexi-glass cover.

consistent with the Maui3 [3] night profile but clearly over the campaign of the links, there were many significant excursions from the Maui3-like conditions which in part may explain the low success rate.

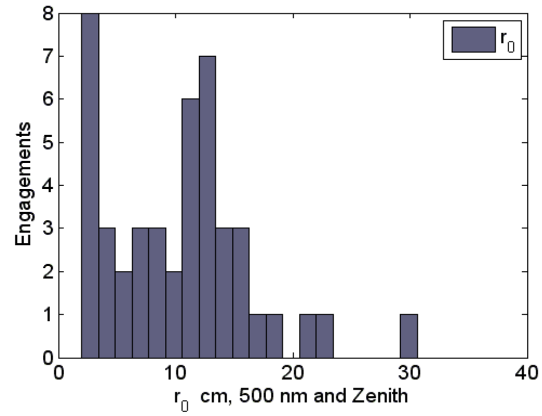

Figure 2. Number of link engagements with a mean Fried Coherence length (r_0) for the engagement plotted as a function of the Fried Coherence lengths. The means are averaged over the engagement length from the University of Hawaii, Haleakala monitor which measures and reports at zenith, 500 nm and 1 minute intervals.

Despite nearly 40% of the engagements occurring during optimum Fried coherence length (r_0) conditions, very few links resulted in continuous tracking or communications. After examining high resolution (1-5 kHz) tracking telemetry for many of the links from both the space and ground terminals, it was felt that several issues should be resolved. Many of the tracking interrupts coincided with high ground wind velocity (much greater than 20 km/hr), algorithm responses needed adjustment, and some ground hardware electronics still required optimization. As can be seen in figure 1b, after the plexi-glass cover is removed, the terminal is exposed directly to surface winds, heat gradients between the container and the outside and was subject to vibrations from the wind hitting the small overall container shown in figure 1a. For these and other reasons, the ground hardware was returned to the factory for cleaning and refurbishment and plans were made to install the LCT within the large ESA-OGS dome at Tenerife for commencement of a campaign in January of 2010. By removing the ground instrument from the small container and mounting it to the observatory pillar within the large ESA-OGS dome (shown in figure 3), it would not be subjected to vibrations and drag from the wind impinging on the gimbal directly or secondary vibrations from the dome container to the terminal. The ground gimbal design was not designed for open atmospheric operation.

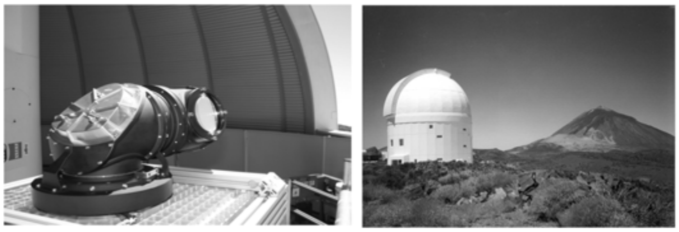

Figure 3. The ground LCT mounted in the ESA-OGS dome in Izana, Observatori del Teide. The left image shows the LCT resident in the dome of the ESA-OGS. The dome slit is in the upper right of the left image and was programmed to move with the azimuth movement of the LCT.

During January to early April, many opportunities were cancelled at Tenerife because of gale-force winds that posed potential damage to the dome. Many links recorded as failed attempts in Maui took place in similar or worse wind conditions as those cancelled in Tenerife, but the experiments took place anyway, because of the team's learning curve for understanding weather impact to the links/hardware and the Maui site did not prohibit such links.

B. *Tenerife results*

As one will quickly discern from the link statistics in Tables 1 and 2, Tenerife was considerably more successful compared

TABLE I. OVERALL CAMPAIGN STATISTICS FOR MAUI AND TENERIFE

Statistic	Number for Maui 2009	Number for Tenerife 2010
Total number of planned SGL	50	126
Total number performed	40	79
Total number of SGLs NOT performed because of Weather, Scheduling, Dome issues, Hardware, NFIRE LCT issue	10	47
Tracking	31, 62 %	79.0%
Uplink communication only	0	8
Downlink communication only	5	1
Bi-directional communication	0	9

to Maui, especially after the consistently bad weather from January to April 2010 improved in late April. Much of January to April had gale force winds and cloud cover that prevented the execution of many planned links. In addition, many executed links in the same period also did not lead to link closure due to weather.

Though qualitative to date, the improved link statistics compared to Maui can be largely attributed to repackaging the terminal on a stable mount within the dome. Improvements to the locking circuitry and excellent weather from late April forward also contributed to the better results. Unfortunately, the team only obtained r_0 measurements at night and primarily for the links within the last month so we will not be able to unequivocally attribute link success or failure to r_0 values except in a few isolated cases as will be noted. Links must be planned weeks in advance for satellite protocols and one can't perfectly plan the best elevation profile and be sure that it coincides with weather and all other execution logistics. The Tenerife results demonstrate the difficulty in trying to get all elements working together, but they also clearly demonstrate the growth of the capability. In comparison to the ISLs, the team is still on the learning curve because the LEO high data rate SGL has many elements to understand and optimize and is much more subject to random weather.

III. SGL 14TH JULY 2010

A. *Scintilation index Results and Analysis*

To date the space to ground link (SGL), on the 14th of July 2010 was the longest duration of continuous LEO tracking to the ground (225 s) and bi-directional communication (177 s). This SGL had a large range of elevation angle excursion greater than +/- 40 degrees. This SGL serves as an excellent example for illustrating characteristics of the atmosphere during an SGL. For this particular night, metrological readings from a weather station located about 100 meters from the OGS were: humidity 30 %, wind speed 1 m/s and a temperature of 16 deg C. Astronomical seeing conditions were noted to be better than normal during this SGL. As with all the SGLs, the range varied over the engagement, however a propagator range dependent power adjustment routine on both LCTs was active (as always) to ensure constant power at each terminal. Therefore, any power fluctuations are due solely to atmospheric effects. Figure 5 shows the range and elevation during the encounter on the 14th of July 2010. The range varied from 1350 km to 450 km and the elevation angle between 10 and 58 degrees.

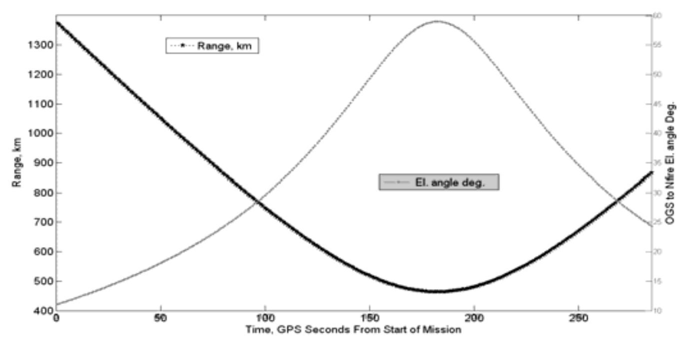

Figure 4. OGS to Nfire Range and Elevation engagement characteristics for the 14th of July 2010, starting at 23:27:00 UT.

During all SGLs, 5 kilo-samples/s of high resolution data is routinely recorded at the ground LCT for both the fine acquisition sensor (FAS) and the track sensor (TS). Both detectors are quadrant detectors (PIN-type) the FAS being a direct-detection and the TS a coherent device respectively. For the purposes of analyzing and illustrating the atmospheric effects of an SGL, the direct detection method is better suited, however, the same atmospheric effects are observed from adjusted TS data. The FAS signal reported here is the sum of the four quadrants, but each individual quadrant shows the same time dependent response.

Figure 5 is the raw FAS signal plotted versus time. The envelope of the intensity fluctuations due to atmospheric scintillation follows an hour glass shape which is indicative of an elevation trajectory from low-maxima-low. Pockets of increased SI can also be seen. The drop-out in the middle is due to an obscuration in the dome at the apex of the elevation angle progression.

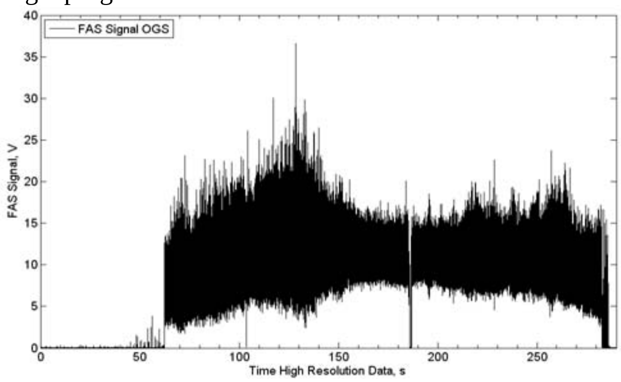

Figure.5. High resolution data for the OGS received FAS signal plotted against mission time. The dropout at 186 seconds is due to a physical obscuration inside the dome. Note that both NFIRE and the ground LCT remained locked through this fade.

The FAS data can be used to calculate the Scintillation Index by averaging over 1 degree intervals. Figure 6 shows the FAS SI and the predicted SI plotted against elevation angle.

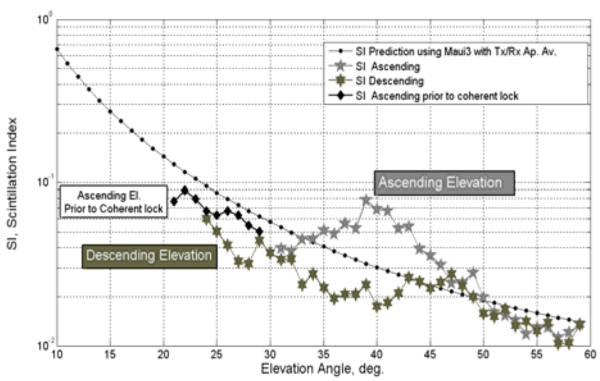

Figure 6. Measured FAS SI and predicted SI plotted against elevation angle. The predicted SI uses the Maui 3 model and takes into account receiver and transmitter aperture averaging. Three regions highlighted in this plot; 1st ascending elevation prior to coherent lock, 2nd ascending elevation during bidirectional communication and 3rd descending elevation also during bidirectional communication.

The predicted SI is derived from the Maui3 model where r_0 is 13 cm (500 nm and Zenith) and the effect of transmit and receive aperture averaging has been included. The plot shows three different regions: the first is ascending elevation during frequency acquisition but prior to coherent lock and occurs between 21 and 29 degrees, the second is ascending elevation after coherent lock and the third is descending elevation. Regions two and three were coincident with bi-directional communication between the OGS and NFIRE. Generally, the SI is below the predicted SI value; however, there are two pockets of increased SI in which one is on the ascending and the other on the descending elevation. These pockets have also been observed by Shelton [6] who described bursts in SI for stars on time scales of 20-100 seconds where it was noted that different parts of the atmosphere sampled had different parameter values for the turbulence.

IV. Conclusions and Future Work

To our knowledge the results reported here constitute the first repeated high data rate (5.6 Gbps) low earth orbit bidirectional laser communication. During the late spring and summer of 2010, the atmospheric conditions during both day and night at Tenerife were statistically well represented by the Maui3 profile. Consistent high data rate scintillation index was provided during a high percentage of the links.

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