International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Development status and breadboard results of a laser communication terminal for large LEO constellations

S. Müncheberg

C. Gal

J. Horwath

H. Kinter

et al.

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118034 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536031

Development Status and Breadboard Results of a Laser Communication Terminal for Large LEO Constellations

S. Müncheberg[a], C. Gal[a], J. Horwath[a], H. Kinter[a], L. Martin Navajas[a], M. Soutullo[b]
[a]Mynaric Lasercom GmbH, Friedrichshafener Str. 1, 82205 Gilching, Germany; [b]Mynaric USA Inc., 2905 Westcorp Blvd. Suite 214, Huntsville, AL 35805, USA

ABSTRACT

Several operators plan to launch mega-constellations of several hundred or even thousands of satellites over the next years to provide global, high-speed and secure backbone communications. Most of these constellations will use a hybrid approach, with radio links for communications with the ground and free-space optical communications for inter-satellite links. First demonstration satellites were successfully launched in 2018.

Since 2009 Mynaric has successfully demonstrated high-speed laser communications in air-to-air, air-to-ground and ground-to-ground applications. Data rates up to 10 Gbps were achieved and altitudes up to 20 km were reached. First airborne terminals and ground stations for airborne and space applications were delivered to commercial customers. Building on the heritage from operations in the harsh environment of the stratosphere, Mynaric started two years ago with the development of a low-earth orbit (LEO) optical terminal for inter-satellite links.

The LEO terminal will provide a data rate of 10 Gbps full duplex over distances of up to 4500 km and a compact design with simple mechanical and thermal interfaces to the satellite bus. The Critical Design Review (CDR) shall be held in autumn 2018 and completion of the qualification is planned for 2019. A demonstration mission in LEO using two satellites is planned in 2019/2020.

Breadboard testing is in progress for several key components such as the coarse pointing assembly (elevation and azimuth axes), the fine pointing assembly and the communication subsystem. Radiation tests were successfully performed to verify the EEE parts approach using COTS and automotive components. RFI/RFP processes are being done to select key subcontractors/suppliers and to gather costing information for the recurring, high-volume serial production of the terminals.

The paper presents the design overview of the terminal and reports on the current development status. The CDR status and results of the breadboard tests are presented and an outlook towards the first demonstration in space is given.

Keywords: Free space optical communications, constellations, LEO

1. OPPORTUNITIES FOR LASER COMMUNICATIONS

The future approaches with an unprecedented surge in demand for bandwidth to cope with the Internet of Things era. High-resolution Earth Observation missions, space-based cloud storage, or internet from skies and space extend the need for bandwidth significantly, beyond the capabilities of terrestrial infrastructure, usually fiber-based. Hence, traditional ground-based telecommunications networks and geostationary satellites will soon be operating alongside constellations of LEO satellites and high-altitude platforms to deliver global network coverage.

It is therefore expected that broadband in the sky will become a huge market in the coming years. The main applications and players are:

- High-altitude communication networks: e.g. Facebook Aquila, Google Loon, …
- Satellite communication constellations in LEO: e.g. Telesat, Globalstar, OneWeb, Leosat, KLEO, SpaceX …
- Inflight broadband: e.g. Gee, Sitaonair, Airborne Wireless Networks, gogo, Thales, …
- Global satellite ground station networks: BridgeSat, KSAT, SSC, RBC, …

As bandwidth demands rise, RF spectrum becomes increasingly difficult to obtain due to large demand and the lengthy application processes. Therefore, opportunities arise for free-space optical (FSO) laser communication, a technology that can meet the growing bandwidth needs of airborne and space applications. Laser communication can deliver very high data rates over long link distance and will be capable of delivering multiple terabits of data per second in the near future.

FSO technology is enabling all the aforementioned applications. It is not subject to spectrum limitations, very difficult to jam or to eavesdrop due to the narrow divergence of the laser beam and less susceptible to interference.

Several operators of upcoming LEO satellite constellations have publicly stated that they are considering employing laser communications for inter-satellite links. These are:

- Leosat: up to 108 satellites in six orbital planes in 1400 km polar orbit [1]
- KLEO: 300 satellites in twelve orbital planes in 1100 km near-polar orbit [2]
- SpaceX Ku/Ka-Band: 4425 satellites in various orbital planes at 1110 to 1325 km [1]
- SpaceX V-Band: 7518 satellites in various orbital planes at 335 to 345 km [1]
- Telesat LEO: minimum of 117 satellites in 6 polar planes at 1000 km and 5 inclined planes at 1248 km. [1]

2. MYNARIC'S HERITAGE AND ROADMAP

Mynaric was founded in 2009 as a spin-off of the DLR Institute of Navigation and Communication (IKN). DLR IKN is active in the development of laser communication terminals reaching back more than 20 years. They have licensed portions of their technology for commercial exploitation by Mynaric.

Over the past 10 years Mynaric has successfully developed airborne terminals and ground stations for air-to-air and air-to-ground links. In several projects, most of them with commercial customers, data rates of up to 10 Gbps and flight altitudes up to 20 km were achieved. In 2017 Mynaric cooperated with Facebook Connectivity Labs and successfully demonstrated a 10 Gbps downlink from an airplane. [3]

Following successful demonstrations, Mynaric delivered complete systems to customers including air-to-ground terminals and ground stations for air-to-ground and space-to-ground links.

Based on that heritage, Mynaric started to develop a terminal for large constellations in LEO. Mynaric's product development roadmap is shown in Figure 1.

Figure 1: Mynaric roadmap 2017-2020

3. LEO TERMINAL DEVELOPMENT PLAN

Building on Mynaric's success in airborne, stratospheric, and ground terminals, the LEO terminal is specifically designed for use in the low Earth orbit environment.

Since the stratospheric environment is subject to many of the same harsh conditions of the LEO environment (e.g. large temperature ranges, very low air pressure, solar radiation), much of the design heritage from the stratospheric terminals can be used. New factors to be considered are the radiation environment as well as the vibration and shock environments caused by the rocket launch.

The terminal development is based on requirements derived from discussions with providers of communication constellations in LEO. The terminal requirements are defined broad enough to support several constellations as well as launch vehicles. The interfaces to the satellite are kept as simple as possible e.g. by providing a single unit for external mounting on the satellite and by using standard power and data interfaces common to small satellites.

The System Requirements Review (SRR) for the LEO terminal was successfully held in April 2017 and the Preliminary Design (PDR) in December 2017. After PDR several key suppliers were selected to support the detailed design efforts, e.g. for the optical telescope and the electronics. Also, breadboards were built to verify the design of critical components such as the coarse pointing assembly. The Critical Design Review (CDR) shall be held in October 2018 and will release the manufacturing of the Qualification Model (QM). The qualification campaign is planned to be finished in 2019 and a demonstration mission in LEO shall be launched in 2019/2020.

The model philosophy shown in Figure 2 includes Breadboards (BB) and Engineering Models (EM) for functional and performance testing of critical components, a Qualification Model (QM) for qualification testing, and Flight Models (FM) which will be delivered for an in-orbit demonstration in 2019/2020.

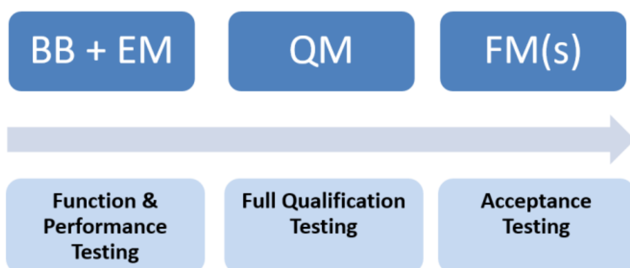

Figure 2: Model philosophy

4. LEO TERMINAL BLOCK DIAGRAM

In Figure 3 the block diagram of the laser terminal is presented. The optical system assembly performs the core functionalities required for operating a free space optical communication link. This system contains the optomechanical elements needed for incoming laser beam reception and stabilization as well as the accurate pointing and stabilization of the transmitted laser beam. The electronics system assembly incorporates all the electronics components needed for data preparation and evaluation, as well as the terminal control computer needed for system control functions. Besides the power and data bus system also the powerful software system plays a decisive role in the laser terminal that operates all elements of the unit and establishes the communication between the terminals.

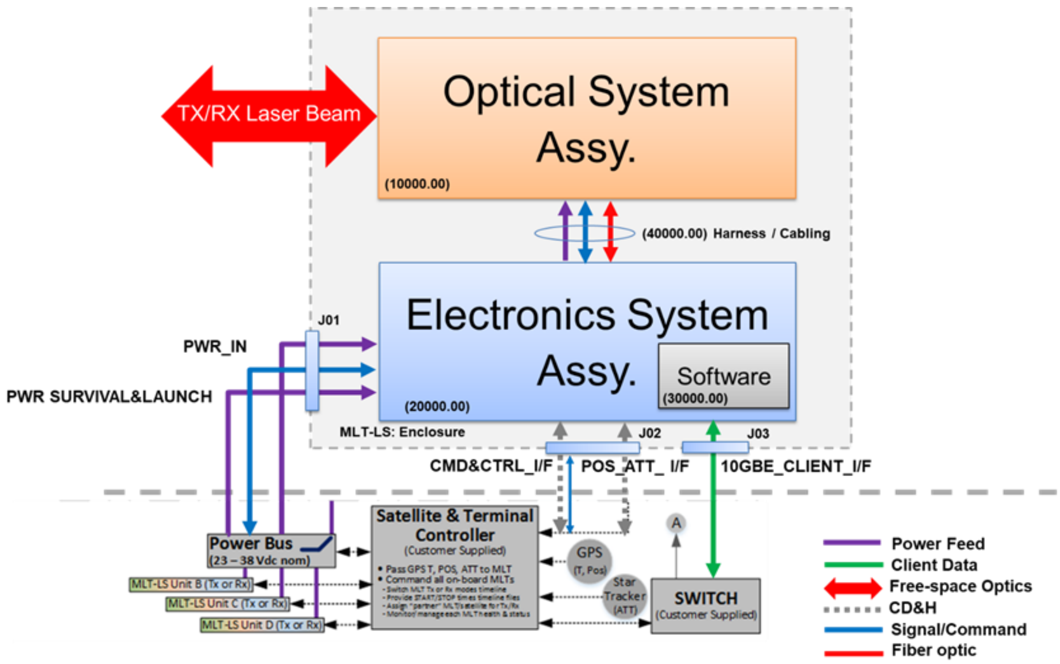

Figure 3: LEO terminal block diagram

The block diagram of the optical system assembly is shown in Figure 4. The optomechanical assembly of the CPA (Coarse Pointing Assembly) is responsible for a continuous data link. This movable mirror steers the received beam to the terminal optics and establishes a steady pointing toward the other satellite. For the further optical signal processing the telescope assembly (TLA) and the transmitting/receiving optics (TRO) are implemented into the laser terminal system.

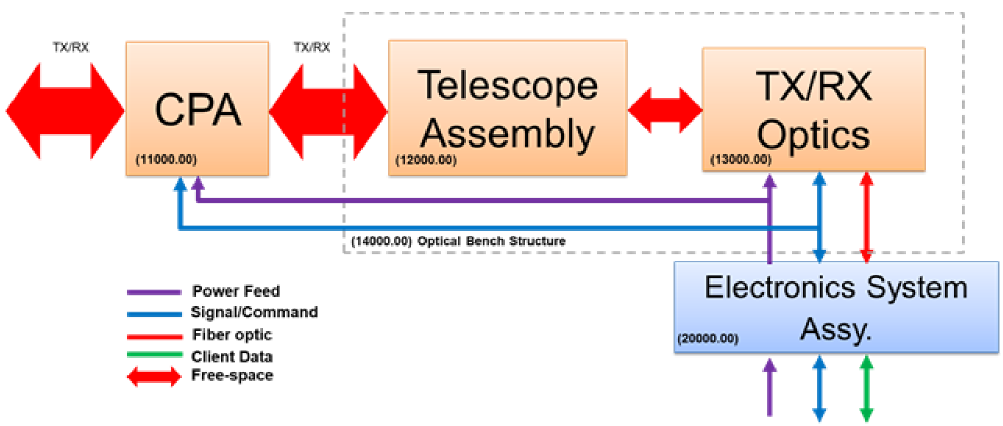

Figure 4: Optical System Assembly

The CPA provides the large angular motion needed for the communication, has a lower-bandwidth mechanism for initial open loop pointing and acquisition searching, and variable rate slewing. For the terminal design a gimbaled flat mirror configuration has been chosen. This configuration refers to an actuated mirror located in front of the telescope aperture to manipulate the transmit beam in azimuth and elevation directions. The main axis is equipped with a large bore angular encoder system for a precision drive mechanism. The various system assemblies are mounted on top of each other resulting the laser terminal.

The Telescope Assembly (TLA) receives the signal from a remote terminal and transmits the outgoing laser beam to a remote terminal. For the space terminal, the telescope configuration has been chosen as a single aperture device to perform both TX and RX functions. Optically seen, the TLA is an afocal telescope that reduces the received beam diameter or magnifies the outgoing light to the required dimension that fits the further imaging optics needs. For large distance laser communication, it is essential to have a high optical quality of the laser beam, hence the system must fulfill challenging wavefront requirements in a harsh environment.

The Transmission / Receiving Optics (TRO) assembly is directly attached to the telescope and constitutes the inner optical subsystem which performs the following functionalities:

- Collimation of TX laser Beam
- TX and RX beam stabilization by means of the Fine Pointing Assembly (FPA)
- Separation between TX/RX beams
- Point-ahead angle actuation on the TX beam by means of the Point-Ahead Assembly (PAA)
- Splitting and focusing of the RX beam on the different receiving detectors
- Photodetection on the communication signal
- Tracking error feedback measurement
- Self-calibration: measurement of TX/RX angular coalignment

The electronics system assembly is the central control element of the laser terminal. Its main tasks are the control of the beam pointing actuators as well as the control and supervision of the peripherals that are not directly involved in the laser tracking operation. Furthermore, it handles the communication with the satellite bus and the execution of the main commands. Some of these main tasks are:

- Peripheral management and internal power switching
- Laser terminal operational modes management
- Real-time data acquisition from the sensors
- Calculation of open-loop pointing angles using position and attitude information from the satellite
- Command the Coarse Pointing Assembly controller
- Calculation of the point-ahead angles and command the Point-Ahead Assembly
- Feedback Control of pointing actuators

The Laser Ethernet Transceiver (LET) encapsulates the user data stream into a packet format specially designed for the FSO channel. It modulates the outgoing laser beam and detects the pre-amplified received signal using front-end electronics.

The Electronics Power System (EPS) & System Supervisor converts the satellite power bus voltage into different DC voltages as demanded by the different modules and peripherals. It also performs activation / de-activation of different power output lines, monitoring of voltage and current of the different power lines.

5. LEO TERMINAL DESIGN

The MLT-LS is based on the existing series of stratospheric terminals. The design heritage of pre-existing flight models reduces the overall development risk while also minimizing development efforts and costs. The laser terminal follows the modular approach such that the subsystems can be manufactured and integrated at a common site allowing the required systems-level assembly, integration, and test operations to be carried out. The physical assembly of the MLT-LS and mounting interfaces to the satellite are shown in Figure 5.

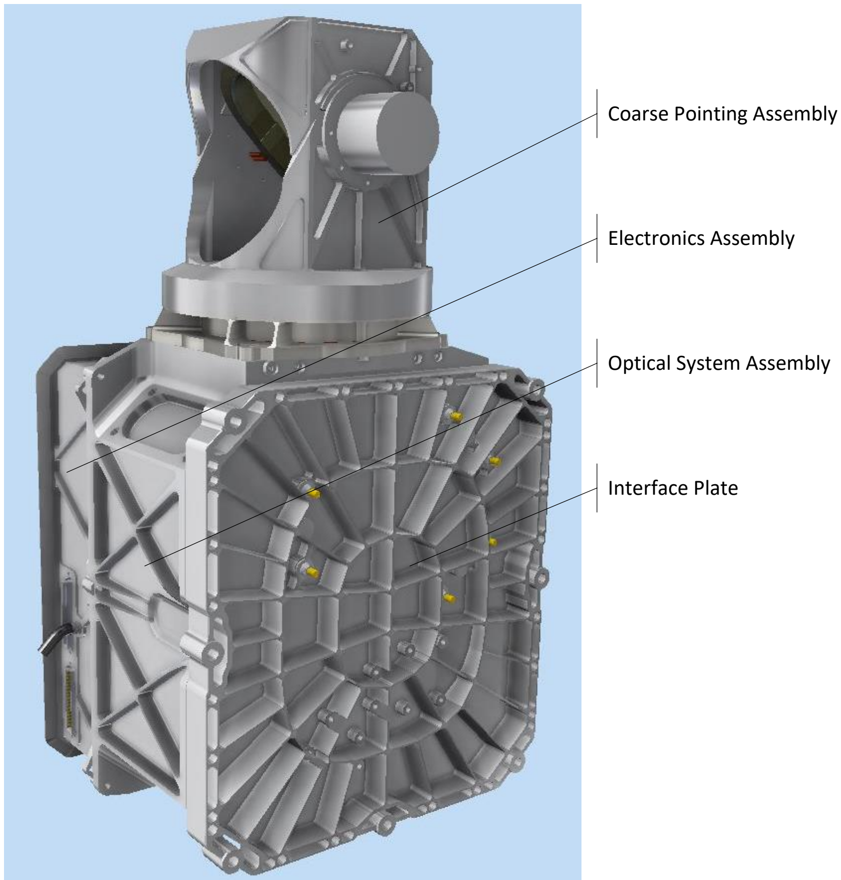

Figure 5: LEO terminal overview

Typically, the satellite platform will carry multiple laser terminals, resulting in a satellite constellation that provides multi-direction communication links. The main interfaces to the satellites are:

- Mechanical: the mounting interface, mounting holes, and required screws are going to be defined in agreement with the specific satellite provider. Detailed mounting provisions remain flexible while satellite integration decisions are being developed.
- Thermal: for the operation mode the thermal interface is designed to maintain the temperature range of -40°C to +60°C.
- Electrical: using a standard 28 VDC power input.

6. LEO TERMINAL PERFORMANCE

6.1 Key specifications

The key performance parameters of the terminal are shown in Table 1. Please note that this technical data is based on current available information and is subject to change as the design activities are progressing.

Table 1: Key performance parameters

Parameter	Value	Comment
Link Distance	Up to 4500 km	
Aperture Diameter	80 mm	TX/RX aperture
Operational Wavelength	1550 nm band	Uses two bands for TX and RX
Optical TX Power	1 W (max. average)	Per channel, add extra power for more channels
Data Rates	10 Gbps (full duplex)	Data rate on one channel/color, extendable to multiples of 10Gbps in future.
Dimensions	630 x 430 x 250 mm	Includes CPA and electronics
Target Mass	< 20 kg	
Power Consumption	< 60 W	
Input Voltage	28 V DC	
Field of Regard	Az.: ±175° El.: +5/-25°	
Angular Velocity	Az.: > 5.0°/s El.: > 0.2°/s	In-plane and cross-plane communication
Acquisition Time	< 30s	Initial acquisition
Data Interface	Gigabit Ethernet	Full compliance with the 803.3 IEEE standard
Link Margin	> 3dB (EOL)	
Vibration	7g RMS	
Operating Temperature	-40°C to +60°C	
Radiation environment	500 krad TID/year	
Lifetime	5-7 years	Depending on orbit altitude
Optical Links within Network	In-Plane Cross Plane	In-plane require 2 terminals (baseline). Cross-plane links require additional terminals.

6.2 Link budget

The link budget ensures that reliable communications can take place at the specified distances, data rates, and bit error rates by imposing constrains on critical systems parameters such as transmission power or receiver aperture. For the case of inter-satellite operations at LEO orbit, some general aspects are considered for the design. Due to the absence of atmosphere at typical orbit heights (above 500 km), the impact of atmospheric turbulences and absorption on the FSO channels can be disregarded. The link budget, therefore, to effect communication between two LEO satellites in motion, may be broken down into two distinct parts:

- Static link budget: considers the elements of the communication link that are not directly affected by the overall motion of the system – e.g. TX power, TX gain, optical transmission losses, etc. - or are affected by slow-changing parameters - e.g. free-space loss (loss associated with the distance between the two communicating terminals), background light loss.
- Dynamic link budget: models the imperfections of the transmitter and receiver tracking systems, leading to pointing losses. This part considers parameters such as Tx pointing losses and Rx tracking losses.

For the LEO to LEO link the modulation scheme for encoding and decoding the information to a channel symbol is Intensity Modulation with Direct Detection (IMDD) with a data rate of 10 Gbps.

The receiver configuration for the satellite terminal considers a conservative estimate for the expected sensitivity compared to the current state-of-the art. For the TX beam, diffraction limited beam divergence is assumed together with 1W of output power at standard telecom NIR wavelength. For the calculation the used telescope aperture diameter is considered for both transmission and reception cases. Losses at the optical elements in the TX and RX paths due to imperfect coatings and absorptions in optical elements, are assumed to be -1.55 dB.

Since the TX and RX terminals are assumed to be identical, the same loss shows up in both paths. For the application scenario, diffraction limited beam divergence is considered together with a pointing error of factor 10 lower than the beam divergence. These assumptions lead to a pointing loss of -1.18 dB for the IMDD configuration at a target bit error rate of 10^{-12}. The result of the link budget assessment is presented in Figure 6.

The worst-case link budget calculations result in link margins of 4.44 dB for 10 Gbps at a typical link distance of 4000 km.

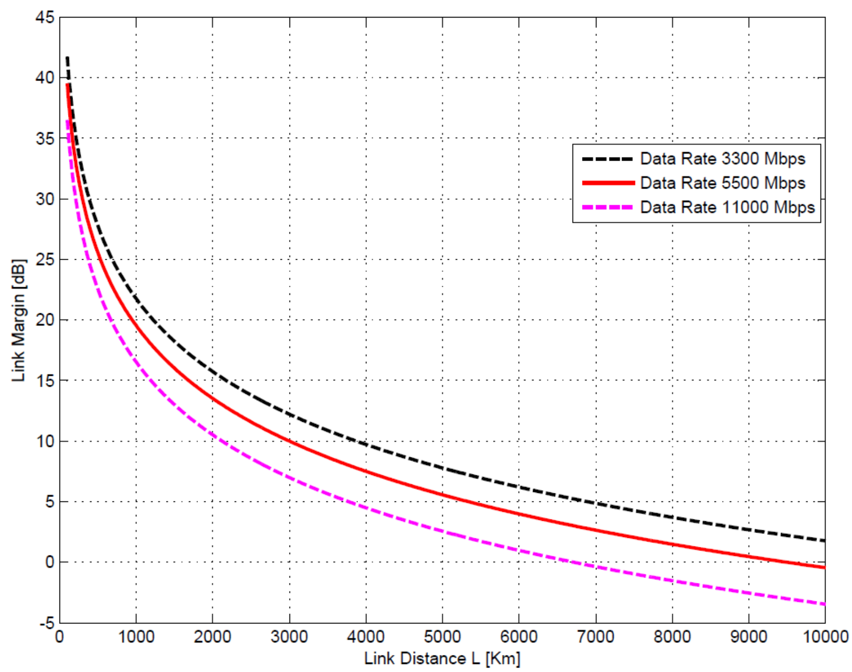

Figure 6: Link budget results

7. BREADBOARD ACTIVITIES

To support and to verify the detailed design, Mynaric is developing several breadboard models (BB) for key subsystems and components:

- Coarse Pointing Assembly azimuth axis
- Coarse Pointing Assembly elevation axis
- Fine Pointing Assembly/Point Ahead Assembly
- Receiver Coupling Assembly
- Filter Wheel
- Communication Subsystem

These BBs are in various stages of completion and some details on the key subsystems are presented below.

7.1 Coarse Pointing Assembly Azimuth Breadboard

The CPA Azimuth BB is shown in Figure 7. Angular Contact Bearings (ACB) were selected for the test setup and different pairs of ACB were tested for its performance. A high-resolution encoder was used to measure the accuracy of the bearing.

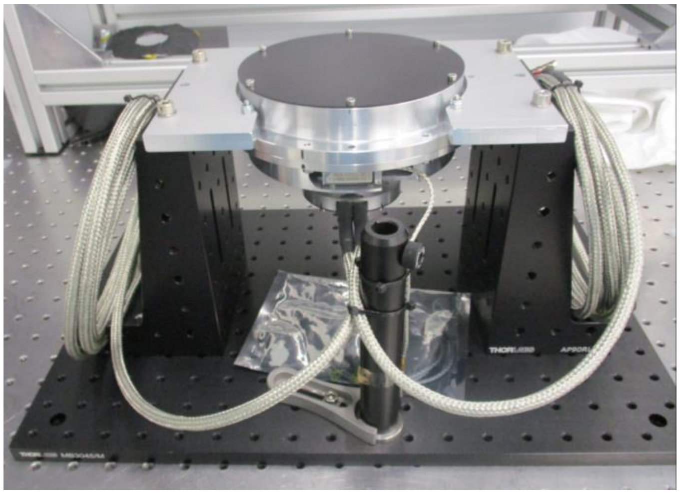

Figure 7: CPA azimuth BB

The block diagram of the test setup is shown in Figure 8.

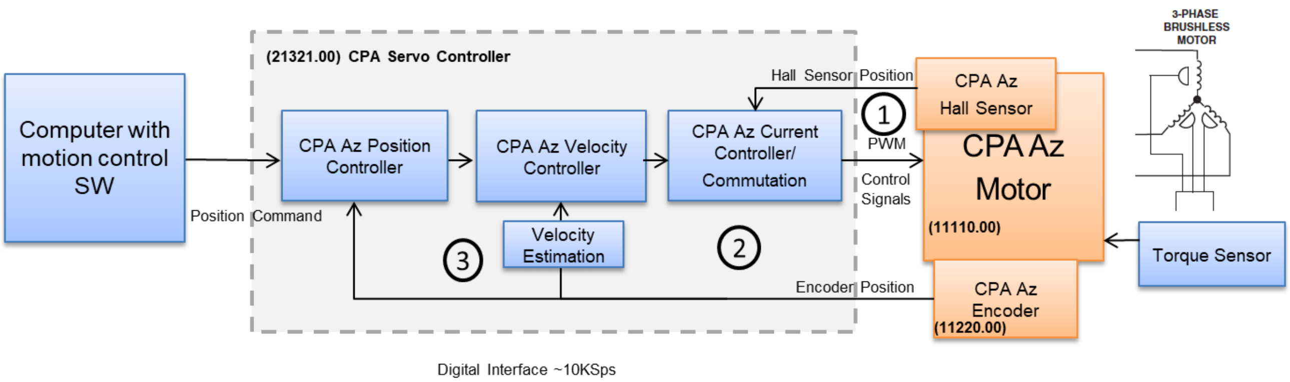

Figure 8: CPA Azimuth BB test setup

The following tests and measurements were performed:

- Functional & characterization tests with and without mass dummy: Torque of bearings, encoder accuracy (resolution, jitter measurement)
- Bearings: Monitor torque ripples and friction with encoder, position accuracy (iterative test with +/-0.1° around 0 Position) with acceleration of 0.03°/s², Performance of bearing after 1000 cycles (+/-180°)
- Temperature tests with functional tests during operation (-40°C to +70°C) and after storage at -60°C to +120°C
- Mechanical tests with mass dummy: Sine Vibration, Functional tests, 20 g RMS Vibration, 800-1000 g Shock tests
- Lifetime test: Performance of bearings after more than 10000 revolutions

7.2 Coarse Pointing Assembly Elevation Breadboard

The CPA elevation BB is shown Figure 9.

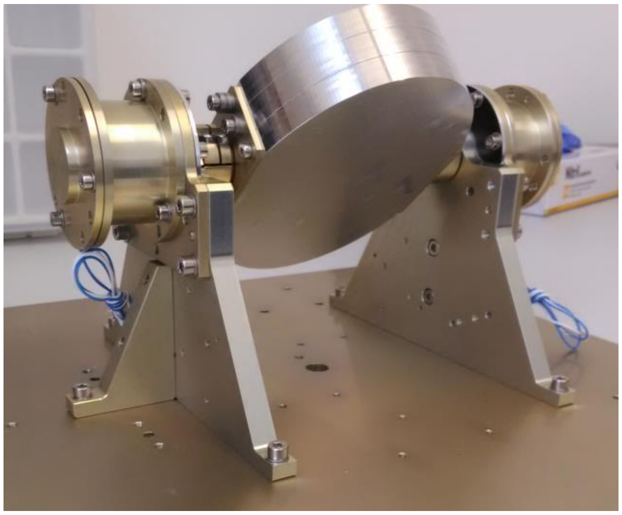

Figure 9: CPA elevation breadboard

The block diagram of the test setup is shown in Figure 10.

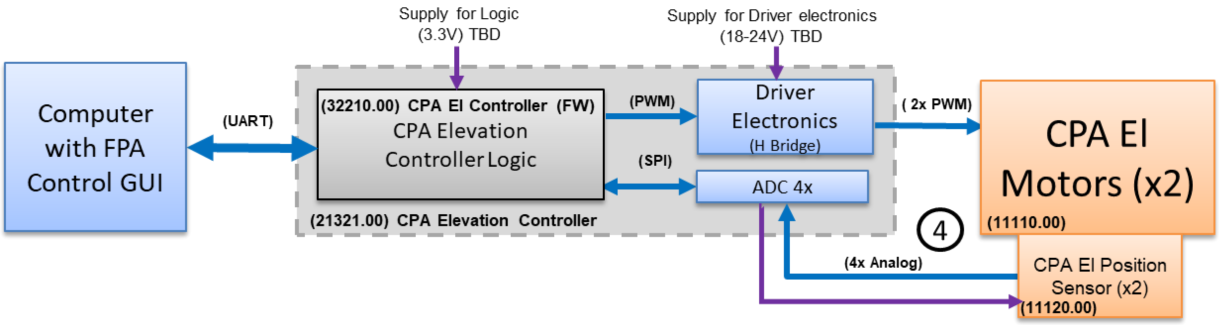

Figure 10: CPA Elevation BB test setup

The following tests were performed:

- Functional & characterization tests
  - Sensor System accuracy: Position Measurement Resolution, Linearity Measurement, Jitter measurement at rest position
  - Controller Design & Characterization: Controller Design, Control Performance Tests, Position Control accuracy (iterative test with +-0.1° around 0 Position) with acceleration of 1.4E-3°/s²
  - Temperature tests with functional tests during operation (-40°C to +70°C) and after storage at -60°C to +120°C
  - Mechanical tests: Sine Vibration, Functional tests, 20 g RMS Vibration, 800-1000 g Shock tests
  - Lifetime test: +-7.5° with acceleration of 1.4E-3°/s² for calculated lifetime

7.3 Fine Pointing Assembly/Point Ahead Assembly Breadboard

The FPA/PAA BB is shown in Figure 11.

Figure 11: FPA/PAA BB

The block diagram of the test setup is shown in Figure 12.

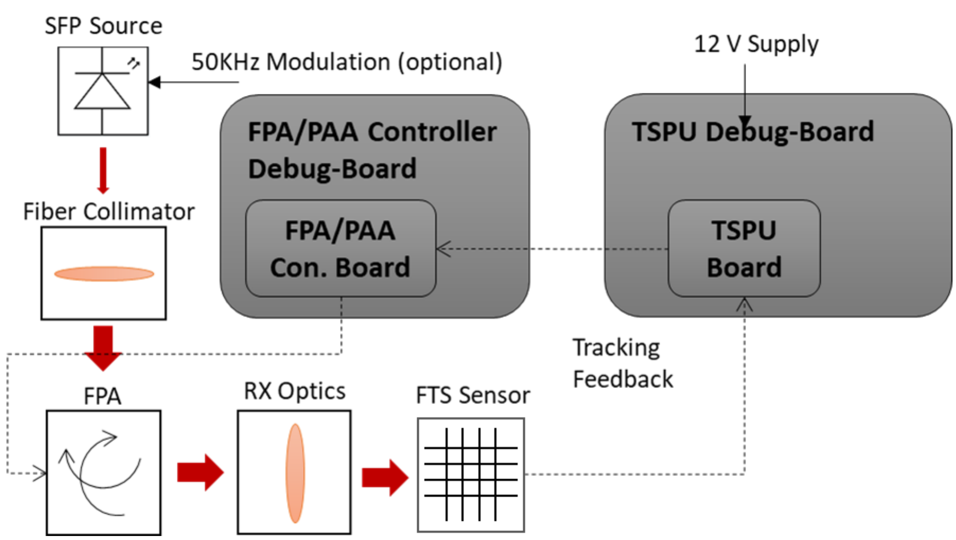

Figure 12: FPA/PAA BB test setup

The following tests were performed:

- Functional & characterization tests
  - Sensor System Characterization: Position Measurement Resolution, Linearity Measurement, Jitter measurement at rest position
  - Controller Design & Characterization: Controller Design, Position Control Performance Tests, Optical tracking performance
- Temperature tests with functional tests during operation (-40°C to +70°C) and after storage at -60°C to +120°C

REFERENCES

[1] FCC license filings LeoSat, Telesat LEO, SpaceX, www.fcc.gov
[2] KLEO Connect webpage https://kleo-connect.com/constellation
[3] Joachim Horwath, Dionisio Diaz Gonzalez, Luis Martin Navajas, Alberto Lozano Souto, Vardan Semerjyan, Gokul Raju, Jan Grabowsky, Charles Garcia, Yi Lai, Torsten Bähr, Chien-Chung Chen, Farhana Haque, Andrew Grier, Harvard Harding, Matthew Hunwardsen, Eric Booen, Hamid Hemmati, "Test results of error-free bidirectional 10 Gbps link for air-to-ground optical communications", Proc. SPIE 10524, Free-Space Laser Communication and Atmospheric Propagation XXX, 105241F (15 February 2018)