Optical Modem Enabling Broadband Datacom Links for Crewed Cis-Lunar Missions

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ABSTRACT

We report on the design, development, and testing of our high-power broadband optical modem supporting NASA's crewed Artemis-2 mission. The O2O modem will be mounted in the crewed Orion module and provide a broadband 505,000 km bi-directional optical link back to earth while *en route* to the moon.

The full-duplex modem consists of a high-power optical transmitter and receiver optimized for serially-concatenated pulse-position modulation (SCPPM). The transmitter is a master-oscillator power-amplifier optical architecture using efficient cladding-pumped amplification in erbium-ytterbium co-doped fiber. The transmitter outputs up to 1 W at ≈1550 nm (limited for eye safety) and supports 6 different user-rates ranging from 20.39 Mb/s to 260.95 Mb/s using PPM16 and PPM32 modulation formats. The optical receiver supports two user-rates: 10.19 Mb/s and 20.39 Mb/s with both rates employing PPM32. The narrowband receiver filtering is optimized to simultaneously accept four separate wavelength channels to mitigate atmospherics through spatial diversity. A configurable interleaver provides additional protection against atmospherics-based signal fading and a powerful soft-decision error correction scheme enables highly sensitive detection. The measured sensitivities at the two bit-rates are -73.8 and -71.8 dBm, respectively.

The architecture was designed for reliable operation in space, featuring automatic hardware interlocks, pump sparing for the amplifiers, and autonomous operation of all internal hardware and software control loops. The protoflight unit (PFU) was put through rigorous environmental testing which included pyroshock, vibration, electromagnetic interference/compatibility, and thermal-vacuum testing. The modem successfully passed all the environmental screening and has been declared at Technology Readiness Level (TRL) 6.

Keywords: laser communication; space qualification; fiber laser; pulse position modulation; erbium/ytterbium; deep-space communications; optical modem; free-space optical communications

1. INTRODUCTION

NASA's Artemis-2 mission is currently scheduled to launch in 2024 and will carry a human crew through a cis-lunar orbit. The Orion module will have the Optical-to-Orion (O2O) payload[1] which will include an optical modem designed, built, and tested by CACI capable of supporting broadband full-duplex optical communications to lunar distances on the order of 505,000 km. The CACI Modem Module (MM) design leverages other recent flight acquisition programs including DSOC[2]. The MM supports power, telemetry, and data interfaces to the external Controller Electronics (CE) module on the spacecraft, as well as optical fiber interfaces to the Optical Module (OM). The MM operates in the 1.5 µm near-infrared optical band, enabling the use of relatively mature Telcordia-qualified fiber-based optical components. The multi-rate Tx/Rx data paths employ optical pulse-position modulation (PPM) to maximize link sensitivity. The MM data rates can be adjusted to optimize link sensitivity and are commanded by the CE and adjusted through PPM order, pulse width, and code rate. The Tx user-rates range from 20.39 to 260.95 Mb/s and the Rx supports 10.19 and 20.39 Mb/s user-rates. The MM is designed as a fully autonomous sub-system in that it maintains all its own control loops. The mechanical, electrical, and optical systems are all designed to withstand challenging environmental requirements which include stresses due to launch (e.g. pyroshock and vibration) and operation in space (e.g. temperature and radiation). The MM has been fully environmentally tested and is at Technology Readiness Level (TRL) 6.

2. MODEM MODULE DESIGN

2.1 System Engineering

The tables below summarize some of the key technical and environmental requirements flowed to CACI for the MM. As noted in Table 1 the MM is designed to operate in the optical telecom C band and is a full-duplex modem (i.e. transmit and receive paths are simultaneously active). The optical Tx waveform is delivered on polarization maintaining (PM) fiber to the external optical module (OM) with a polarization extinction ratio (PER) of at least 14 dB and at up to 1 W of power. The MM can be commanded to reduce the output power to several lower setpoints. The Rx is designed to be polarization insensitive (PI) with minimal performance variation across orthogonal polarization state inputs. The receive sensitivity is defined as the mean optical input signal power where the CCSDS-compliant output frame error rate (post error correction) drops below 10^{-5}. Both Tx and Rx operate with serially-concatenated pulse-position modulation (SCPPM) compliant 16-PPM and 32-PPM formats. In order to mitigate atmospheric channel fading, the MM supports a convolutional interleaver with ~2 ms depth. The MM also provides multiple loop-back testing modes. Finally, the MM provides a spacewire interface to the CE for telemetry and command, and data is exchanged over an ethernet interface. These requirements, and more, were tested comprehensively before delivery.

Table 1. Summary of key Modem Module optical requirements

Parameter	Requirement
Optical Wavelength Band	C-band
Modem Configuration	Full-duplex
Polarization	PM Tx, PI Rx
Optical Output Power	1 Watt
Polarization Extinction Ratio (PER)	> 14 dB
Tx Rates	20.39 – 260.95 Mb/s (6 modes)
Rx Rates	10.19, 20.39 Mb/s
Rx Sensitivity	-73, -70 dBm
Modulation Formats	16-PPM, 32-PPM
Coding/FEC	SCPPM
Channel Interleaver	Convolutional, 2 ms
Loopback Testing	Optical, Shallow/Deep Datapath
Size, Weight, and Power	10.75x13.5x8 in^3; <11 kg; <62 W
Electrical Interfaces	Spacewire (T&C), 1G Ethernet (Data)

Table 2. Summary of key Modem Module environmental requirements

Parameter	Requirement
Temperature Range	-24 – 61°C (Survival) -10 – 54°C (Boot) -5 – 54°C (Operational)
Radiation TID, LET Threshold	120 Rad(Si), ≥ 37 MeV-cm^2/mg
Shock	315g
Vibe	7.97 grms
EMI/EMC	RS, RE, CS, CE

The environmental requirements are summarized in Table 2. The MM is designed to survive over the temperature range -24 to 61°C and operate from -5 to 45°C. There is an additional requirement that the MM should be able to enter the boot state at -10°C where the FPGA can power up, load its image, and start reporting telemetry through the software interfaces. The radiation requirements are relatively mild, as shown below, which reflect the nature of this crewed mission. The shock and vibration requirements are up to 315g and 7.97 grms, respectively. Finally, the MM is designed to pass MIL-STD-461 electromagnetic interference (EMI) and electromagnetic compatibility (EMC) testing, including radiation susceptibility (RS), radiated emissions (RE), conducted susceptibility (CS), and conducted emissions (CE). All of these requirements were rigorously assessed during environmental testing which included thermal vacuum (TVAC), shock and vibe, and EMI/EMC.

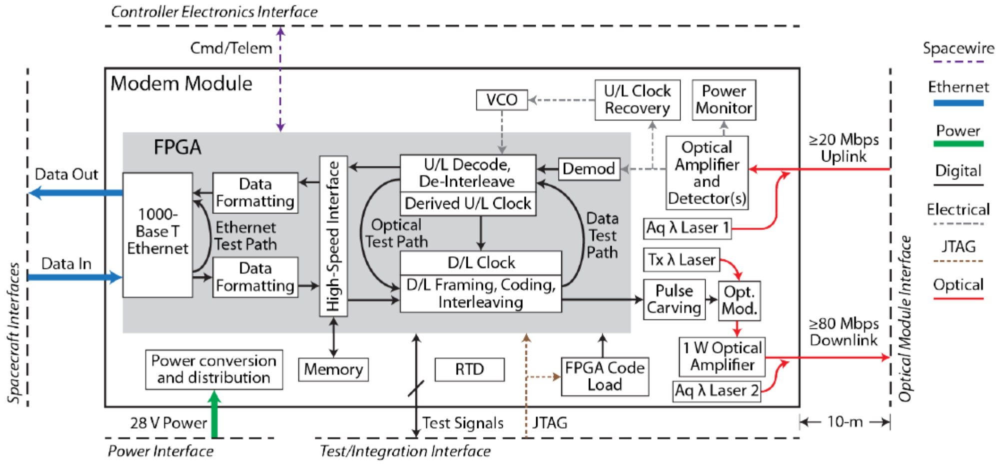

Figure 1. High-level system diagram of optical modem module.

A high level system diagram of the various internal and external MM interfaces is shown in Figure 1. User data flows in and out of the MM over the 1000 Base-T Ethernet interface. Downlink data flows through the CCSDS-compliant datapath and is transformed into PPM symbols and carved into an optical waveform with a high bandwidth electro-optic modulator. A 1 W high-power optical amplifier boosts the signal to the required output power which is then transferred to the OM over a 10 meter single-mode polarization maintaining (PM) fiber. The optical uplink flows into the MM receiver over 10 meters of polarization insensitive (PI) fiber and is down-converted to baseband electrical signaling through a low-noise optical receive chain. A sensitive optical power meter reports the receive power over telemetry and a robust clock recovery sub-system works with margin below the lowest required receive power for data recovery. The uplink is processed back through the datapath and sent out to the ethernet interface. Various loopback paths on both the data and optical side enable datapath testing.

Power is supplied nominally at 28 V to an external port and telemetry & command is over spacewire. The MM also has separate Tx and Rx acquisition lasers. These lasers supply low-frequency amplitude-modulated light out of both the Tx and Rx fibers that the OM then uses for alignment purposes.

2.2 Optical Design

The MM Tx master oscillator power amplifier architecture is shown in Figure 2. A distributed feedback laser (DFB) provides a wavelength-stable, continuous wave (cw) signal to the electro-optic modulator that carves out the pulse-position modulated symbols with high extinction ratio. An optical tap provides power to a photodiode (PD) that is used to bias-control the modulator and monitor the output power from the master oscillator. If the power falls below a minimum value, an interlock is triggered based on this PD reading and the amplifier proceeds through a staged shutdown to prevent a dangerous lasing event.

The stage 1 pre-amplifier is based on core-pumped Er-doped fiber. A pair of single-mode 980 nm pumps are used in a hot-spare configuration, where if a single pump fails the other surviving pump can run at an increased output power to compensate and keep the MM Tx operational. A tap follows the amplification to monitor the forward-going signal power and maintain the amplifier in an automatic power-control mode, and the back-reflection port monitors for large reverse-going power levels.

The stage 2 power amplifier is built from a cladding-pumped ErYb co-doped fiber. Two strings of 940 nm multi-mode pumps are organized in a cold-spare configuration so that if the primary string fails, the Tx can be commanded into operation with the secondary string. A high-power optical isolator protects the 2-stage amplifier from large backreflections from the OM. A polarization beam combiner (PBC) is used to bring the acquisition laser (i.e. the DFB in the stage 2 amplifier) out to the OM on the fast axis of the PM fiber. The PD following this DFB is used to maintain the desired output power. The final tap has two PDs attached. One is for monitoring and stabilizing the output power from stage 2, and the reverse PD is for back-reflection monitoring. A large transient back-reflection can damage the isolator, and this power monitor also has an interlock for shutting down the amplifier if a large reflection is detected.

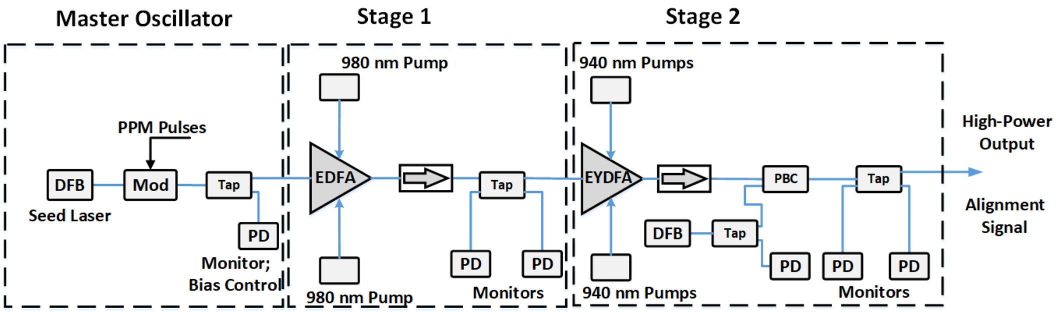

Figure 2. Optical Tx architecture

The MM Rx architecture is depicted in Figure 3. The front-end has a 2x2 optical tap for coupling the backwards propagating acquisition laser output and the incoming low-power uplink signal input. A bandpass filter provides isolation against the Tx and other undesired signal inputs and an isolator prevents ASE from the downstream optical amplifiers coupling back into the OM. Multi-stage low-noise amplifiers (LNA) boost the low input signal power to high enough levels to drive the high-speed photodiode (“Rx” in Figure 3). Inter-stage optical filters prevent ASE build-up and gain saturation in the LNAs. The first LNA stage is very linear by design, and an optical tap feeds a PD and a very narrow bandpass RF filter enables measurement of the signal input power. The last block in the low-amplification chain is a narrow optical bandpass filter which eliminates as much of the ASE as possible from the upstream LNAs to maximize receive sensitivity. The final portion of the optical receiver is a variable optical attenuator (VOA) and PD power monitor which stabilizes the optical power into the high-speed receive diode. The bandwidth of this power control is engineered to be slow enough that it integrates through atmospheric fading (i.e. does not mitigate fading), but does optimize against slow input power drifts (e.g. as spacecraft flies away from the ground-based uplink transmitter).

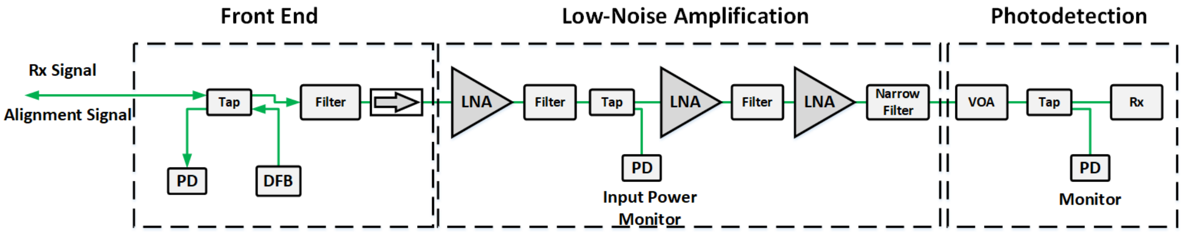

Figure 3. Optical Rx architecture

One of the key factors in optimizing receive sensitivity is to make the narrow optical filter after the last LNA stage as narrow as possible. This helps to reduce the dominant source of detection noise (signal-to-spontaneous beat noise) in the system. An athermal Fiber Bragg grating is an ideal choice for this filter and can be fabricated down to GHz bandwidths. Several system trades and considerations, however, require the filter bandwidth to be wider with an impact on receive sensitivity. These include Doppler accommodation, temperature shifts, and manufacturing tolerances on center frequency and bandwidth.

Another system trade, flowed to CACI, is the use of a multi-laser uplink signal to mitigate atmospherics[3]. The O2O uplink generates copies of the PPM data on each of four separate laser lines separated by ≈GHz and mutually incoherent (i.e. not frequency locked). Each line has its own transmit aperture, spatially separated, so that each line sees its own statistically independent fading channel through the atmosphere. The four laser lines are then incoherently summed in the receiver and the result is significantly reduced fading in both frequency and duration. A simulation of the resulting power fading is shown in Figure 4. The narrow-band optical filter must be wide enough to accommodate this wide-band multi-wavelength uplink signal, and the receive electronics are optimized to process signals with the bandwidth and dynamic range indicated in Figure 4. Part of the component engineering process for this optical filter was ensuring that once mounted, heated, and tested in vacuum it was able to maintain the correct center wavelength.

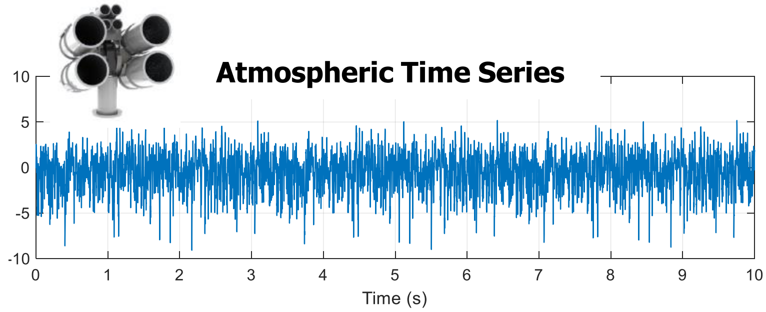

Figure 4. Simulated time series of the fading receive optical power

2.3 Electrical Design

The high-level electrical architecture of the MM is illustrated in Figure 5. The electrical sub-systems are organized onto four boards: Power, Control, Transmit, and Receive. The Power Board accepts the nominal 28 Vdc bus power input and provides clean, filtered DC power at multiple voltage levels to the rest of the MM. The Control Board contains the Xilinx Zynq FPGA, ARM9 hard core central processing unit (CPU), and double data rate (DDR) memory. The Control Board hosts the Test Port (capped for flight), spacewire, and ethernet interfaces. The electro-optic components are mounted in the Transmit and Receive Boards. Components which are sensitive to temperature variations, or generate significant heat on their own, are mounted directly to the cold plate to ensure a good thermal path. Most of the EEE parts meet NASA Level 3 requirements.

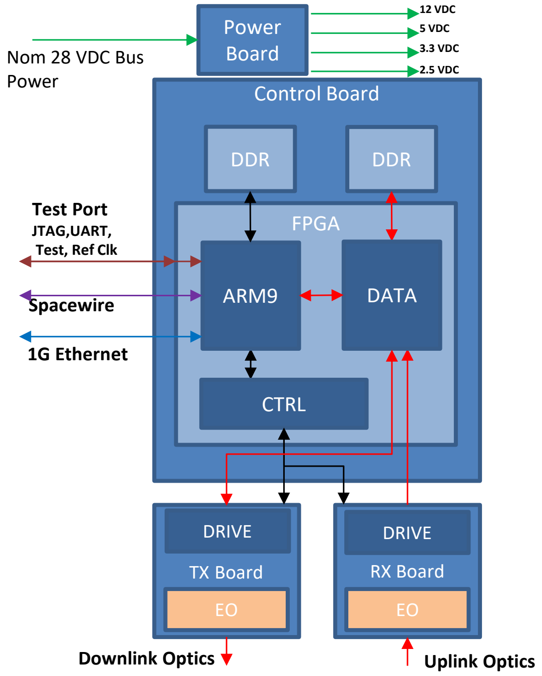

Figure 5. Electrical architecture.

Autonomous operation of the MM is handled through coordination between software (CPU-based) and firmware (FPGA-based) controls. The MM software interfaces with electronics directly over the serial peripheral interface (SPI) bus as well as indirectly using control interfaces in the FPGA fabric. The transmit data path includes a large Ethernet ingress data buffer and HDLC encapsulation which is then passed to a dedicated SCPPM encoder. The receive data path consists of a high-speed sampling analog-to-digital converter (ADC) followed by a soft decision SCPPM decoder that implements a log-MAP iterative decoder algorithm. The coded modulation scheme is compliant to CCSDS 142.0-B-1.

2.4 Mechanical Design

The MM is built with an aluminum chassis with walls at least 0.10 in. thick. Bolts are used to assemble the unit and all joints and seams are EMI-gasketed. The final mass of the unit is 11.36 kg (including the fiber conduit) and the volume is 10.8 x 13.5 x 8 in^3. The Transmit, Receive, Power, and Control boards were integrated onto individual cold plates and built as sub-assemblies. Optical components not integrated onto an electrical board were mounted on the opposite side of the cold plates. Each of these four "slices" are then integrated into the Al chassis. Building as slices allowed for convenient sub-assembly testing and simplified the build process. Comprehensive thermal, vibration, and shock modeling/analysis was used to inform the mechanical design.

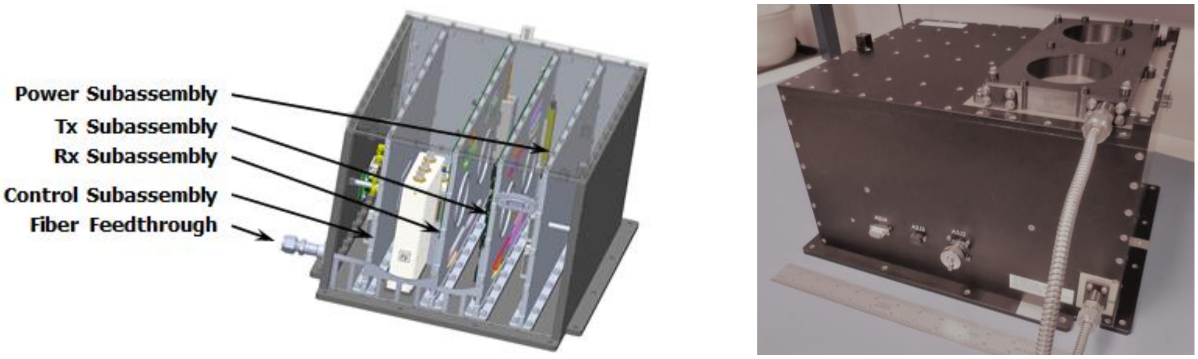

Figure 6. (Left) MM cut-away showing orientation of the four electrical boards. (Right) Exterior view of the assembled MM.

Figure 6 (left) shows a cutaway of the internal construction of the MM. The four slices can be seen with their electrical boards and optics. Figure 6 (right) shows an exterior view of the completed MM. The front-facing panel contains the spacewire, test, and ethernet ports. The fiber feedthrough conduit reaches to a splice box mounted on top of the MM.

3. MODEM MODULE TESTING

3.1 Performance Testing

We summarize here some results from a few of the key optical performance tests on the MM. Figure 7 (left) shows outputs from our measurement of Tx polarization extinction ratio (PER). PER is measured while the MM is in the vacuum chamber mounted to a cold plate. The Tx is run into a polarimeter which monitors the output polarization state while the cold plate is ramped across the entire operational temperature range. Temperature ramping the system in this way highly samples the overall phase space created by the combination of all component temperature-induced fast and slow fiber axes phase shifts[45]. These phase shifts cause the output polarization vector to trace out a finite region on the Poincare sphere which increases in area as PER decreases. The area traced out on the Poincare sphere by the rotating polarization vector can be projected onto a plane, and such is shown as the inset in Figure 7 (left). The smallest circle containing all measured points bounds the measured PER as ≈19 dB. The histogram plot in Figure 7 displays the PER data in a different way, and the steep edge near 19 dB is consistent with the inset.

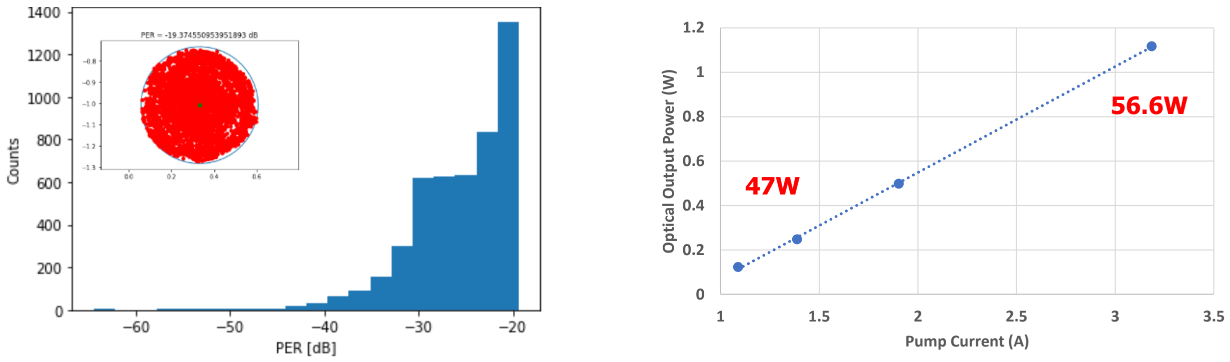

Figure 7. (Left) Polarization extinction ratio measurements. (Right) Tx optical output power as function of multi-mode pump current. Red numbers indicate total bus power draw at max and min optical power measurements.

The Tx output optical power can be set to 4 different values, and these are shown in Figure 7 (right). Here, the output power is plotted as a function of the multi-mode pump current. The numbers in red also indicate the bus electrical power draw at the min and max pump current settings.

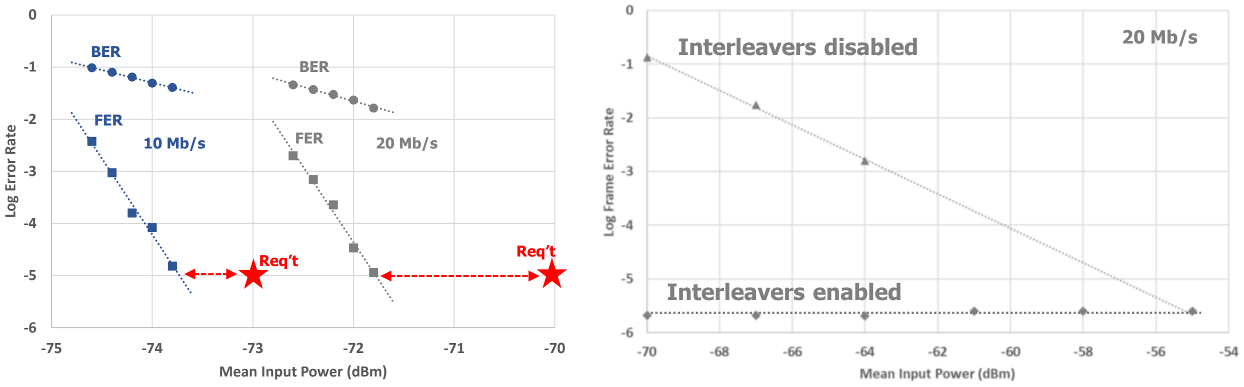

Figure 8. (Left) Measured BER/FER performance for both uplink modes. (Right) Comparison of measured FER in presence of atmospheric fading with and without interleavers activated for uplink mode 2.

MM Rx sensitivity is assessed by measuring bit and frame error rates. In order to generate a CCSDS-compliant uplink signal, a spare set of MM boards was integrated into a test emulator setup. The emulator contained a fast variable optical attenuator (VOA) digitally programmed with the sequence shown in Figure 4 to simulate atmospherics. The Rx decodes header bits as hard-decisions and these reported values (prior to error correction) are used to estimate the receive bit error rate (BER). The frame error rate (FER) is the number of errored CCSDS frames at the FEC output, and the sensitivity is evaluated at the input power where the FER $\leq 10^{-5}$. Figure 8 (left) summarizes these sensitivity measurements for both uplink modes with fading disabled. The 10 and 20 Mb/s sensitivities were measured as ≈ -73.8 and -71.8 dBm, respectively, corresponding to sensitivities as low as ≈ 8 photons/bit. The required FER is observed when the BER is well above 10^{-2}, demonstrating the power of the SCPPM error correction.

The large improvement in sensitivity when using interleavers during atmospheric fading is demonstrated in Figure 8 (right). Without the Tx-interleaver and Rx-deinterleaver running, the estimated sensitivity for uplink mode 2 is ≈ -55 dBm (based on extrapolation). When the interleavers are enabled no frame errors are recorded in the measured input power range (the FER shown with the interleavers running corresponds to zero errors over the measurement time interval).

3.2 Environmental Testing

The MM has undergone comprehensive environmental testing to verify it can meet the O2O mission requirements. For thermal vacuum (TVAC) testing, the MM was mounted inside the CACI vacuum chamber shown in Figure 9 (left) on a chiller plate. Electrical feedthroughs enabled power, telemetry and command, data, and test signals to be routed to and from the MM. Optical feedthroughs enabled the measurement of Tx downlink waveforms and input Rx uplink signals to the MM for complete testing of the datapath. The TVAC test flow included 2 survival cycles (-24 to 61°C) followed by 12 operational cycles (-5 to 54°C). The operational cycles included multiple cold and hot starts of the MM, several rounds of comprehensive verification testing, and continual functional operation during ramps and dwells. The MM successfully completed TVAC testing.

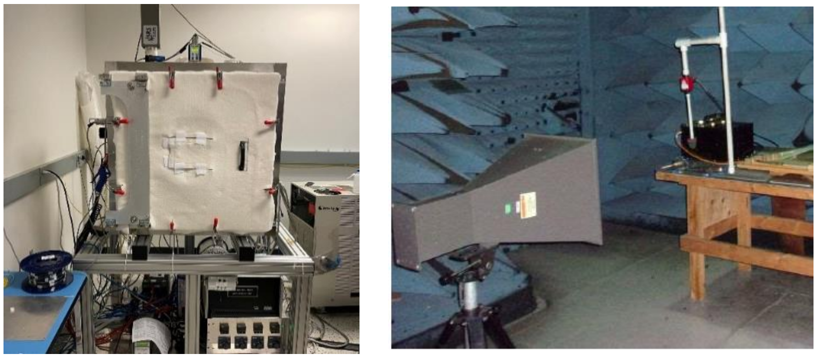

Figure 9. (Left) CACI vacuum chamber. (Right) Off-site testing setup for EMI/EMC.

The MM also underwent electromagnetic interference (EMI) and electromagnetic compatibility (EMC) testing offsite. Conducted emissions/susceptibility and radiated emissions/susceptibility testing were carried out in accordance with MIL-STD-461. An example test setup is shown in Figure 9 (right) where the modem is mounted to a chiller plate inside an RF anechoic chamber. The MM also successfully passed all these tests.

Finally, mechanical verification of the MM included unit-level vibrational and pyroshock tests. Limit load testing and random vibration were carried out in accordance with GEVS GSFC-STD-7000. Pyroshock testing was done up to 315g on 3 axes. The MM was continually assessed throughout the mechanical testing to ensure there was no degradation in performance. The MM passed all mechanical testing.

4. SUMMARY

CACI has successfully designed, built, tested, and delivered a pair of O2O broadband modem modules (MM) in support of NASA’s crewed Artemis-2 mission to cis-lunar orbit. The O2O modem will be mounted in the crewed Orion module and provide a broadband bi-directional 505,000 km optical link back to earth while *en route* to the moon. The full-duplex modem consists of an optical transmitter and receiver optimized for pulse-position modulation. The transmitter outputs up to 1 W and supports bitrates up to 260.95 Mb/s. The optical receiver supports bitrates up to 20.39 Mb/s. The MM has passed extensive environmental testing and is declared at TRL 6.

5. ACKNOWLEDGEMENT

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