Design and performance of a 40W uplink laser transmitter for NASA's O2O laser communications mission

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Free Space Laser Communications Conference; SPIE Photonics West 2025

Jan. 30, 2025

Outline

- Artemis II / O2O Mission Overview
- Uplink Transmitter Implementation
- Uplink Transmitter Results / Characterization
- Summary

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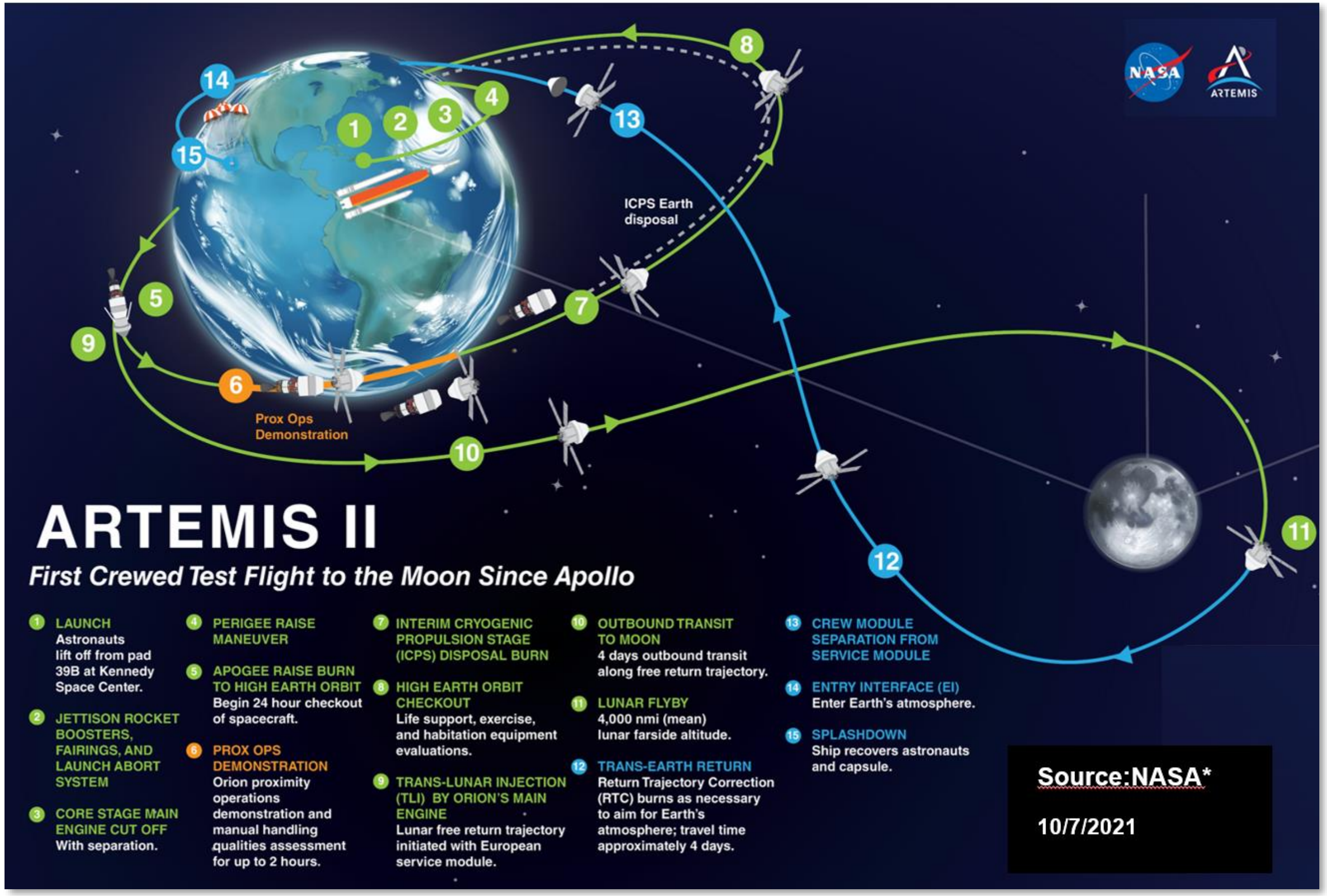
Artemis II Mission Overview

- **Artemis is NASA's program with the goal to return humans to the moon**
- **Artemis I (uncrewed) had a successful lunar flyby in 2022**
- **Artemis II is a crewed mission, currently* scheduled to launch no earlier than April 2026**
  - **11-day mission, includes lunar flyby**
  - **S-band phased array antenna at 6 Mbps from lunar ranges to NASA's Deep Space Network**
  - **Optical Comm Capability:**
    - **Up to 260 Mbps downlink**
    - **10/20 Mbps uplink**

Lasercom enables large volume mission data uploads / downloads, file transfers, real time video conferencing



https://www.nasa.gov/humans-in-space/nasas-first-flight-with-crew-important-step-on-long-term-return-to-the-moon-missions-to-mars/
https://en.wikipedia.org/wiki/Artemis_II

*as of January 2025

Optical Communications Architecture

O2O: Orion Artemis 2 Optical communications

O2O space terminal:

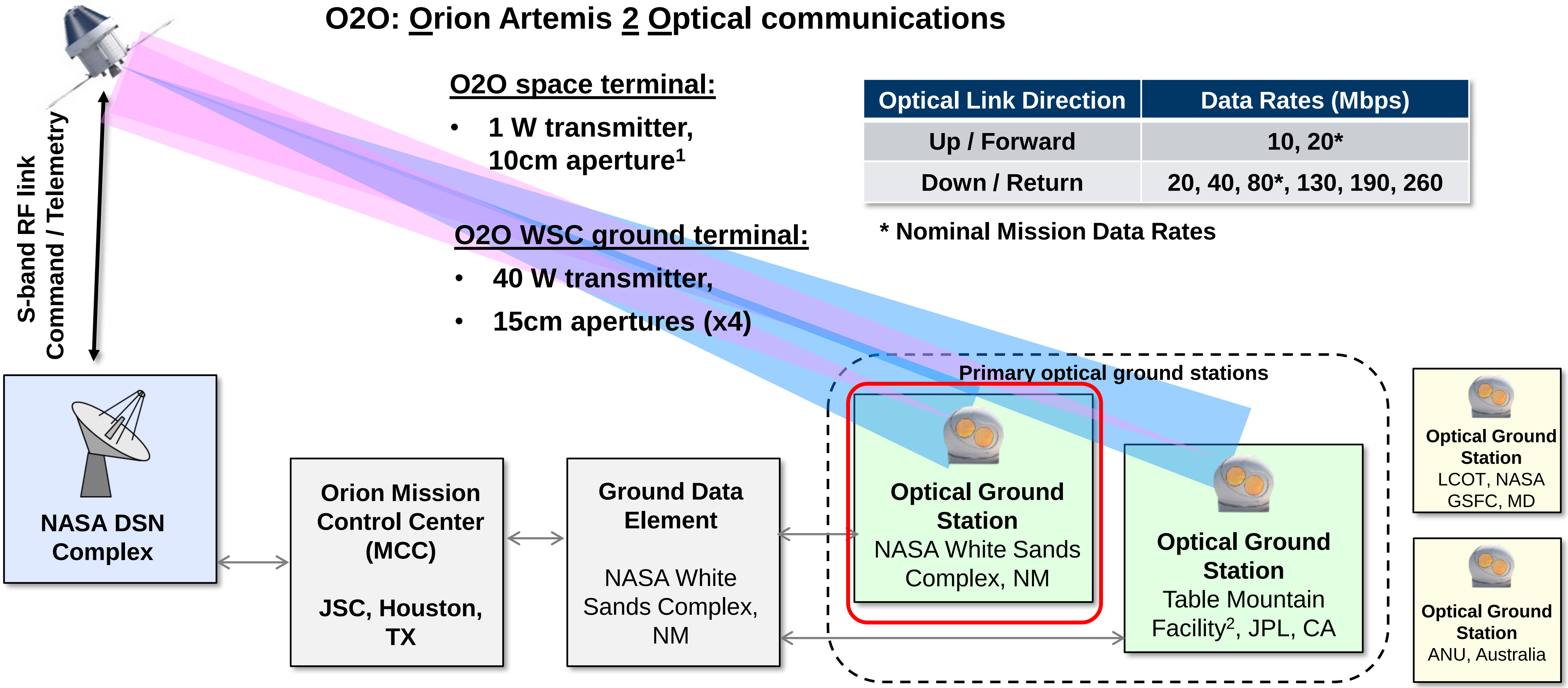
- **1 W transmitter, 10cm aperture[1]**

O2O WSC ground terminal:

- **40 W transmitter,**
- **15cm apertures (x4)**

Optical Link Direction	Data Rates (Mbps)
Up / Forward	10, 20*
Down / Return	20, 40, 80*, 130, 190, 260

*** Nominal Mission Data Rates**



[1] F. Khatri et al, “Optical communications operations concept for the Artemis II crewed mission to the Moon”, https://doi.org/10.1117/12.2649345
[2] A. Biswas et al, “Optical-to-Orion (O2O) ground terminal (GT) at Table Mountain Facility (TMF)”, https://doi.org/10.1117/12.2650574

WSC – White Sands Complex (NASA)
JSC – Johnson Space Center (NASA)
DSN – Deep Space Network

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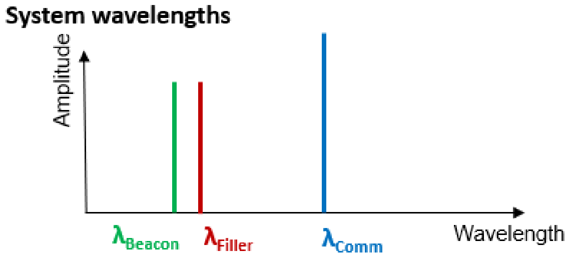
Ground Transmitter High Level Requirements

Signals / Output power

- Aggregate output power of 40 W
  - 10 W per channel, 4 channels
- Ability to vary output power in 3 dB steps
- Output single mode fiber length < 2.5m / channel
- Produce signals at
  - $\lambda_{UL\ COMM}$=154x.x nm, x4
  - λ_{Beacon}=153x.x nm, x4
  - λ_{Filler}=153x.x nm, x4



Acquisition

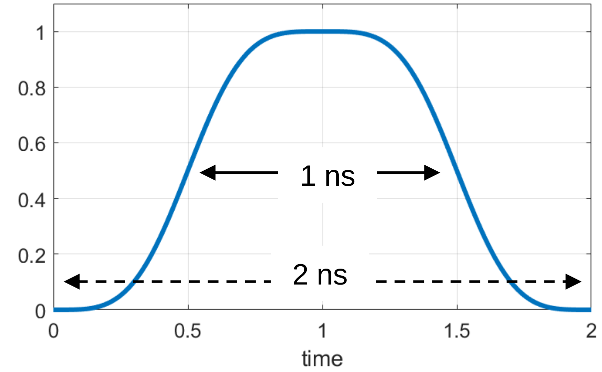
- One Acquisition and one Comm beam in each of the channels
- Beacon signal modulated at ~ 7 kHz[1]
- Vary power ratio between Comm and Acquisition signals in 3 dB steps in <2s; provide beacon-only signal[1]

Comm modes / waveform

- Support communication modes[1]:

Slot Rate	Slot Width	Pulse Width	Code Rate	Modulation format	Data Rate
250 MHz	2 ns	1 ns	1/3	PPM-32	~10 Mbps
500 MHz	4 ns	2 ns	1/3	PPM-32	~20 Mbps

- Pulse shape will be 50% RZ raised cosine[1]



- Relative time delay between 4 channels should be < 50 ps
- 25 dB Extinction ratio

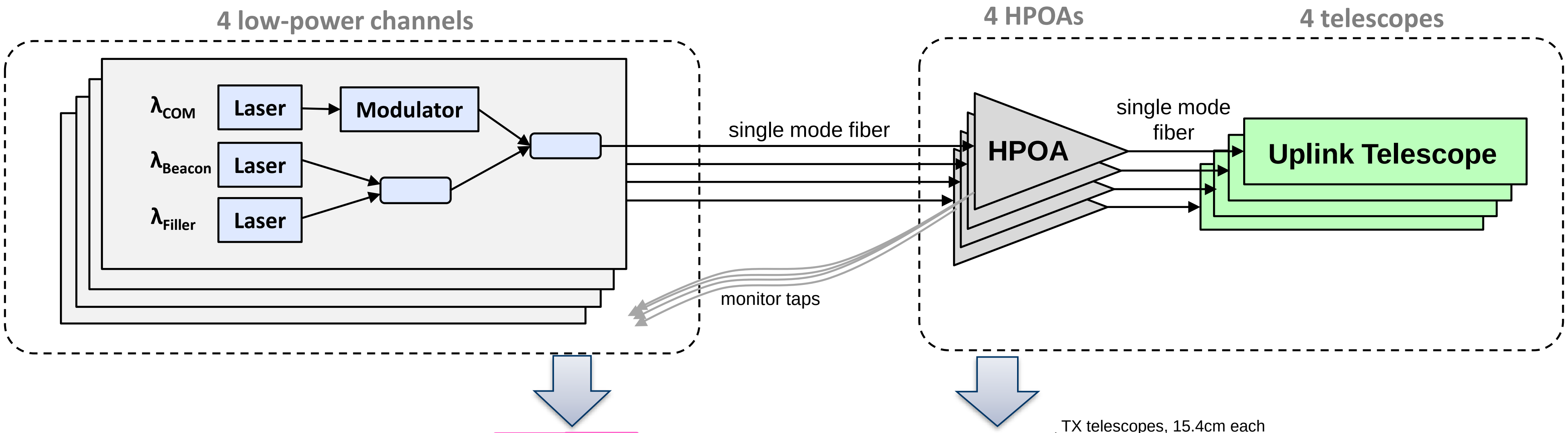
[1] O2O-ICD-1001 Stg_ICD

PPM – Pulse Position Modulation

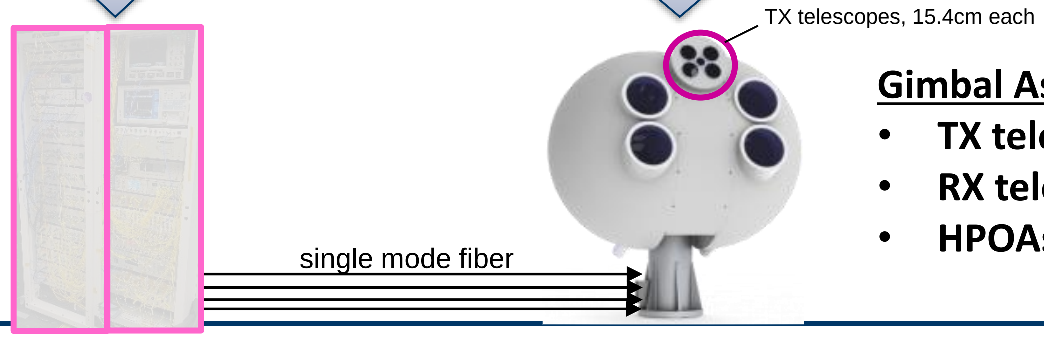
High-level Implementation

Four channels, each producing 10W of average power, 40W aggregate power

- Four low-power channels generate 32-PPM RZ50 signals and combine it with acquisition signals
- Four HPOAs amplify each low-power input signal to ~10W aggregate power each, deliver to telescopes
- Acquisition and transmission wavelengths go through the same HPOA



2 full-size racks contain:
- All low power hardware
- All diagnostic equipment needed
- 1% monitor taps diagnostics



Gimbal Assembly contains:
- TX telescopes (with tracking cameras)
- RX telescopes
- HPOAs (primaries + spares)

PPM – Pulse Position Modulation

HPOA – High Power Optical Amplifier

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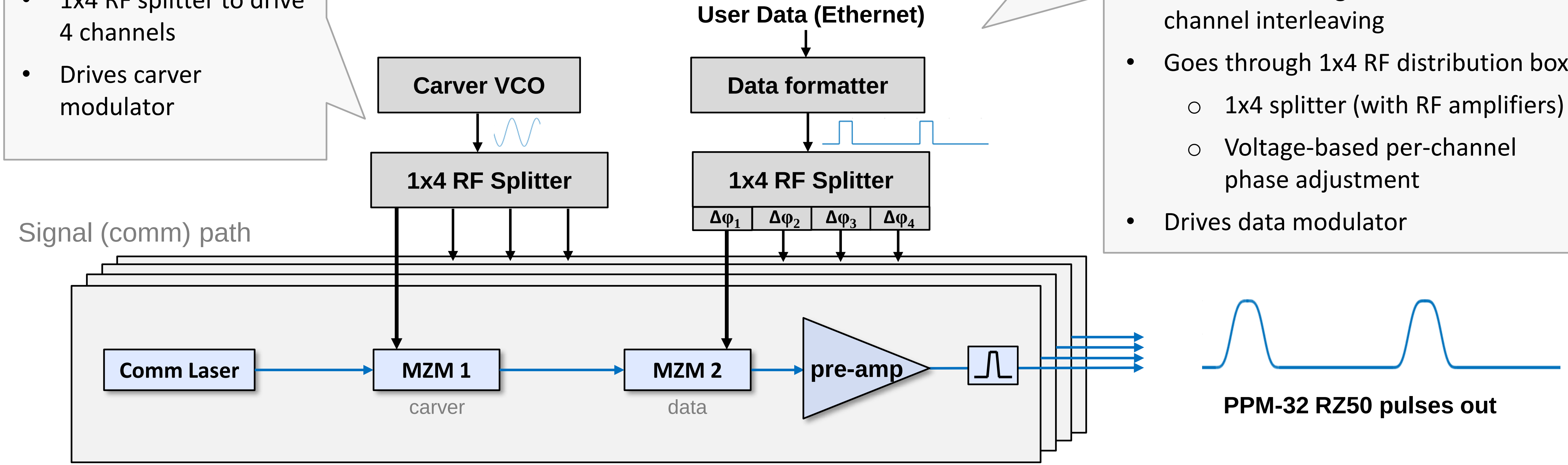
Transmitter Electro-Optics – Uplink Comm Signal

Carver:
- VCO set to 250 MHz / 500 MHz depending on the data / slot rate
- 1x4 RF splitter to drive 4 channels
- Drives carver modulator

Data formatter:
- FPGA-based data formatter
- Maps user data (ethernet frames) into CCSDS-compatible waveform
- SCPPM encoding + convolutional channel interleaving
- Goes through 1x4 RF distribution box
  - 1x4 splitter (with RF amplifiers)
  - Voltage-based per-channel phase adjustment
- Drives data modulator



CCSDS - Consultative Committee for Space Data Systems
SCPPM - Serially Concatenated Pulse Position Modulation

MZM – Mach Zehnder modulator
VCO – Voltage-Controlled Oscillator

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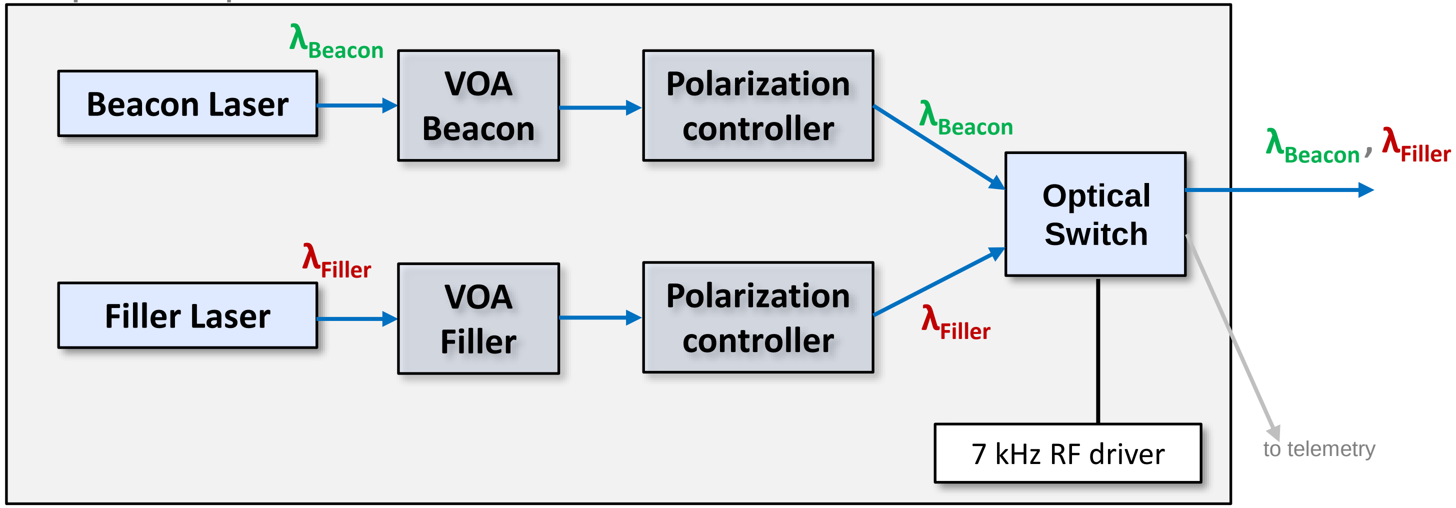
Transmitter Electro-Optics

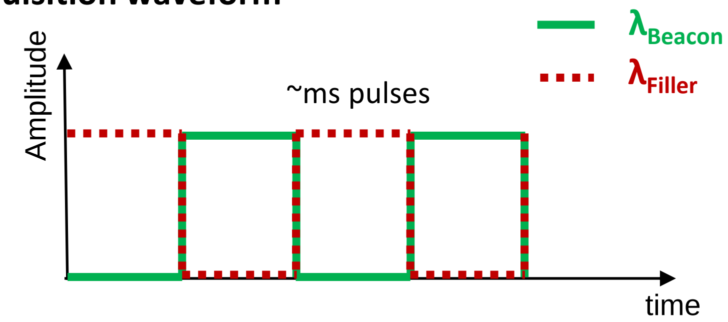
<u>Acquisition signals:</u>

- Primary acquisition wavelength (beacon) is modulated at 7 kHz level (square wave) required by space terminal acquisition sensor
- Filler wavelength is used to mitigate HPOA response to modulated beacon (cross-gain modulation etc)
- Filler is filtered out by the space terminal

Acquisition path

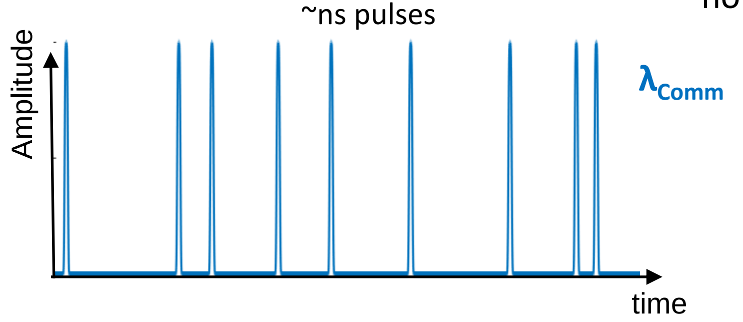


Acquisition waveform

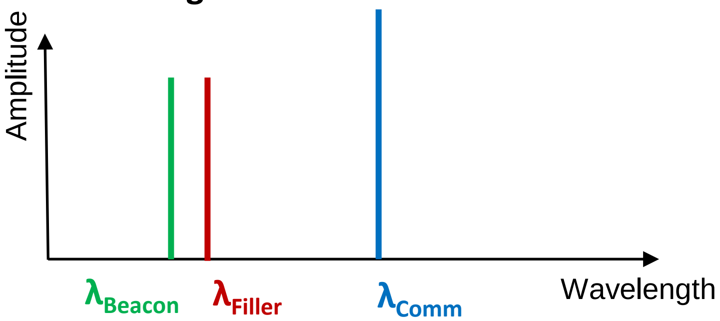


Comm waveform

*not to scale



System wavelengths



VOA – Variable Optical Attenuator
HPOA – High Power Optical Amplifier

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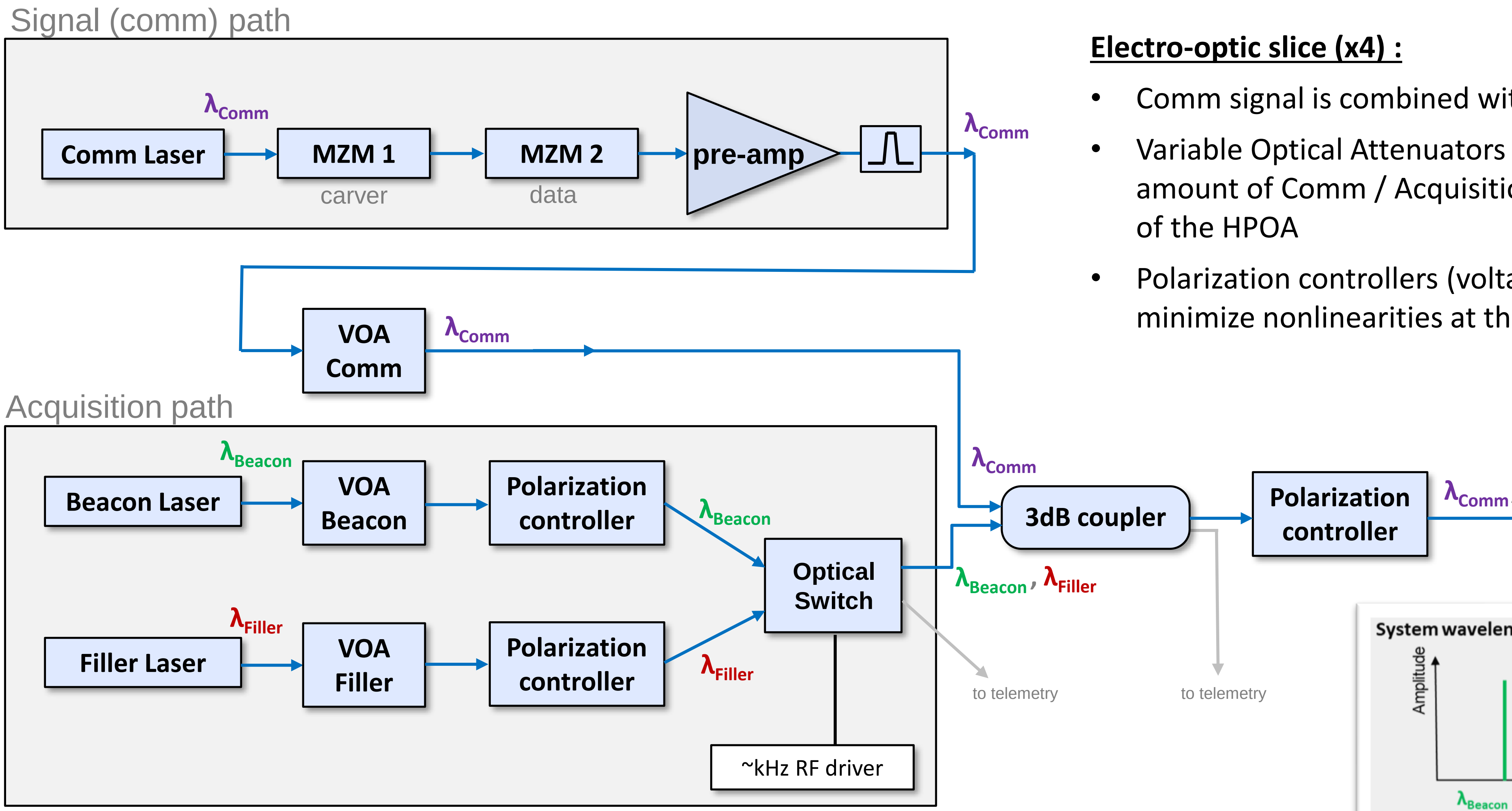
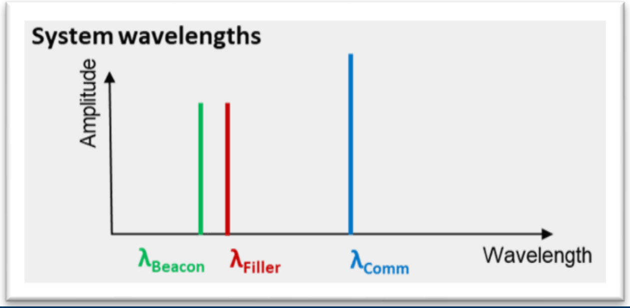
Transmitter Electro-Optics – Acquisition path



Electro-optic slice (x4) :

- Comm signal is combined with acquisition signals
- Variable Optical Attenuators (VOAs) adjust the amount of Comm / Acquisition signals at the output of the HPOA
- Polarization controllers (voltage-controlled) minimize nonlinearities at the HPOA



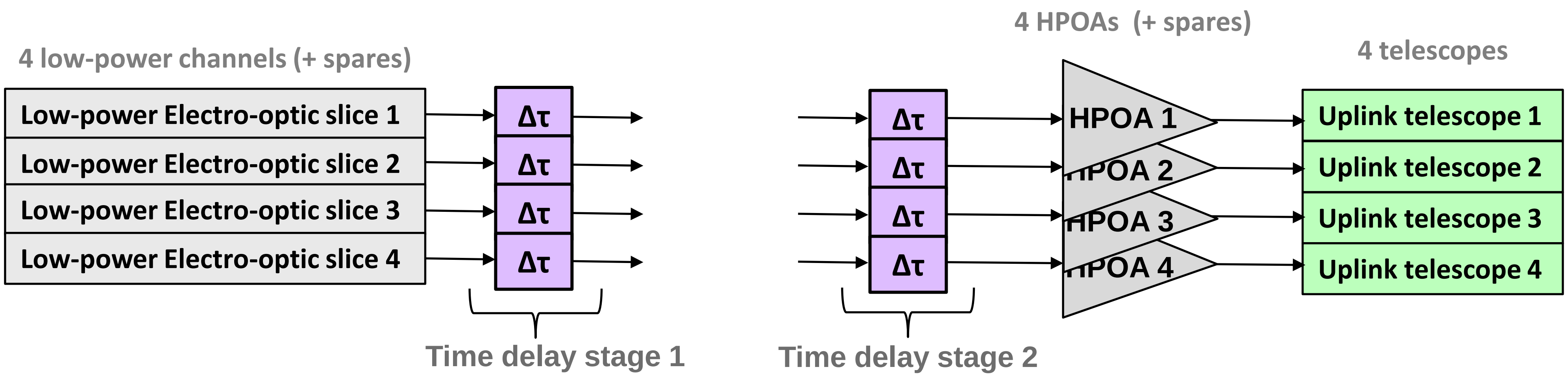
VOA – Variable Optical Attenuator
HPOA – High Power Optical Amplifier

Transmitter Electro-Optics – Time Alignment

<u>All TX channels are time-aligned at the output</u>

- **Low-power channels have different optical path lengths**
- **Individual HPOAs have different optical path lengths**

Spec: 1 and 2 ns optical pulses,
overlap by <50ps (~1cm in fiber)

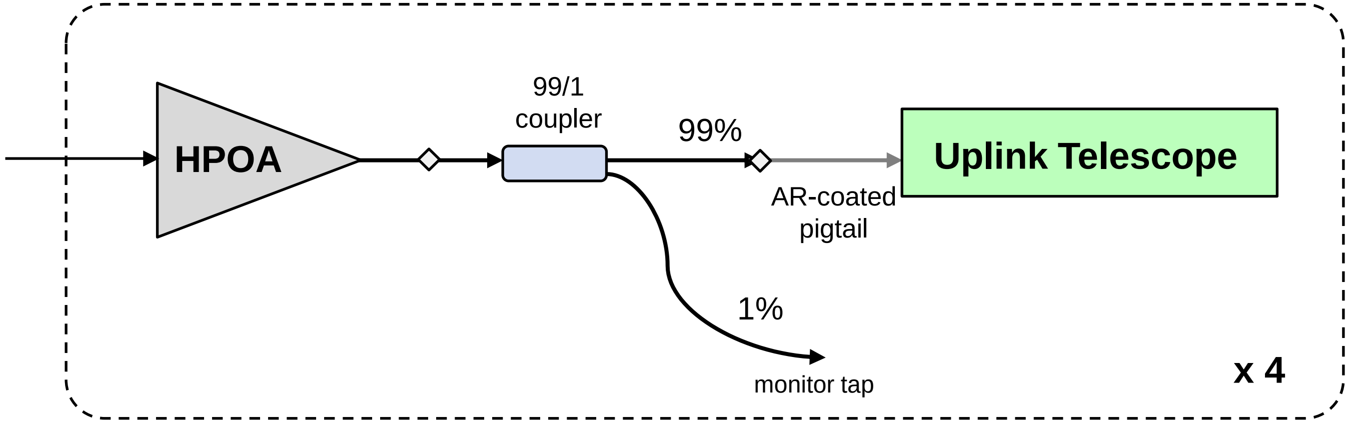


- **Outputs of all low-power channels are time-aligned to each other**
- **Inputs of all HPOAs are time-aligned to the telescope inputs**

Allows using any low-power channel with any HPOA

HPOA – High Power Optical Amplifier

High Power Optical Amplifiers



Commercial Off-the-shelf EDFA

- ~40 dB gain, up to 11W output
- OEM unit, not polarization maintaining
- Forced air cooling
- 99/1 coupler externally spliced to the output
- AR-coated pigtail connector to the uplink telescope
- 2.5 m total fiber length between the amplifier output and uplink telescope input

Uplink Telescope

- 15.4 cm afocal reflector
- Back-end optical assembly
  - Pointing / Acquisition / Tracking hardware
    - Fast steering mirror
    - Tracking camera for downlink signal
    - Alignment / other optics
- Separate telescopes for RX downlink signal

HPOA – High Power Optical Amplifier

Uplink Transmitter Hardware / Signal Monitoring

Two 42U size racks include all the modem / monitoring / diagnostic equipment

Time delay stage 1

System clocks / RF signals

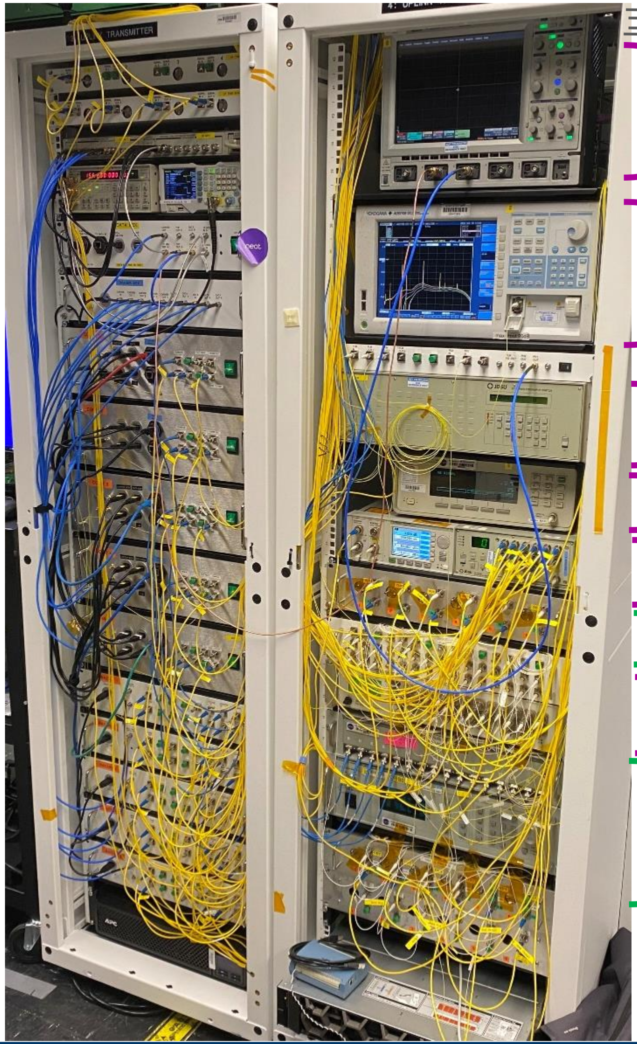
FPGA / Data Processor

RF 1x4 distribution

Uplink Comm path [MZMs, pre-amps etc] x5

Acquisition Signal path [Beacon / Filler mod, VOAs, pol control etc] x5

System PC



Scope

Optical spectrum analyzer

Optical switch

Wavemeter

Power Meter / VOA

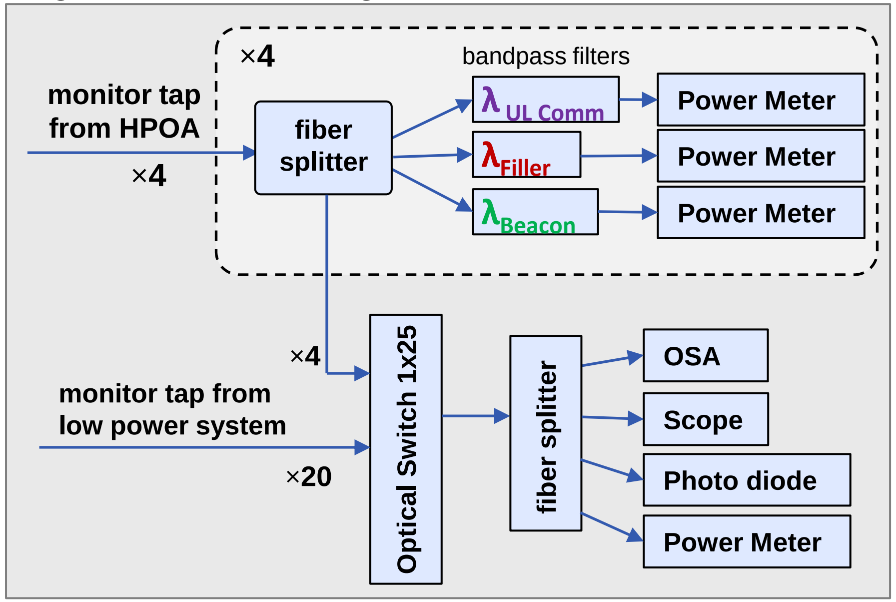
Time delay stage 2

Monitoring EO

All source DFB lasers / DFB Current & Temp Controller

Monitoring EO

Diagnostics / monitoring



- **Real-time power stabilization**
- **Real-time Comm/Acquisition ratio control**
- **Real-time wavelength monitoring / control**

HPOA – High Power Optical Amplifier
VOA – Variable Optical Attenuator

EO – Electro-Optics
OSA – Optical Spectrum Analyzer

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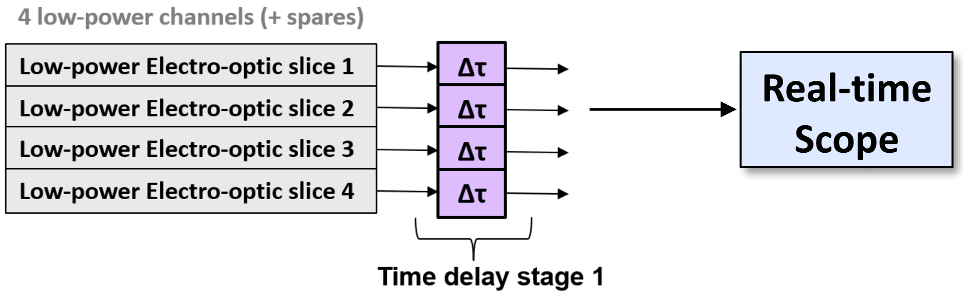
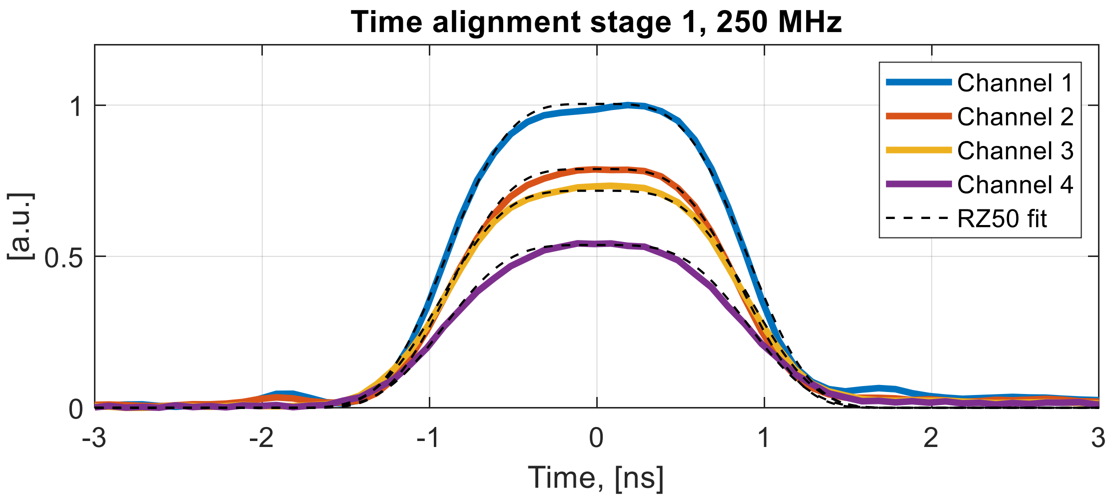
Results: Pulses / Time Alignment

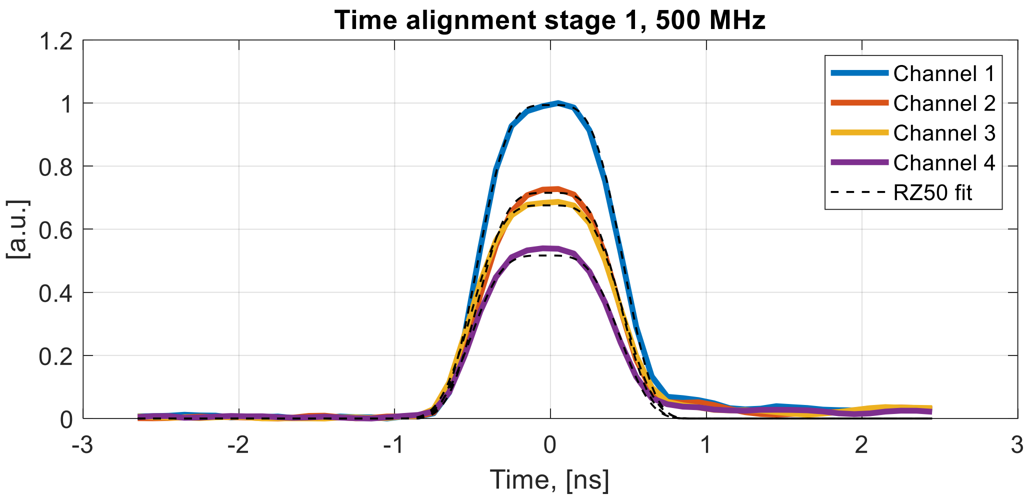
- **Time-align 4 channels to 50 ps (spec)**
  - **250 MHz ~1 ns RZ50 pulses**
  - **500 MHz ~2 ns RZ50 pulses**





Relative pulse delay for 250 MHz

Ch 1	Ch 2	Ch 3	Ch 4
0 ps	8 ps	8 ps	8 ps

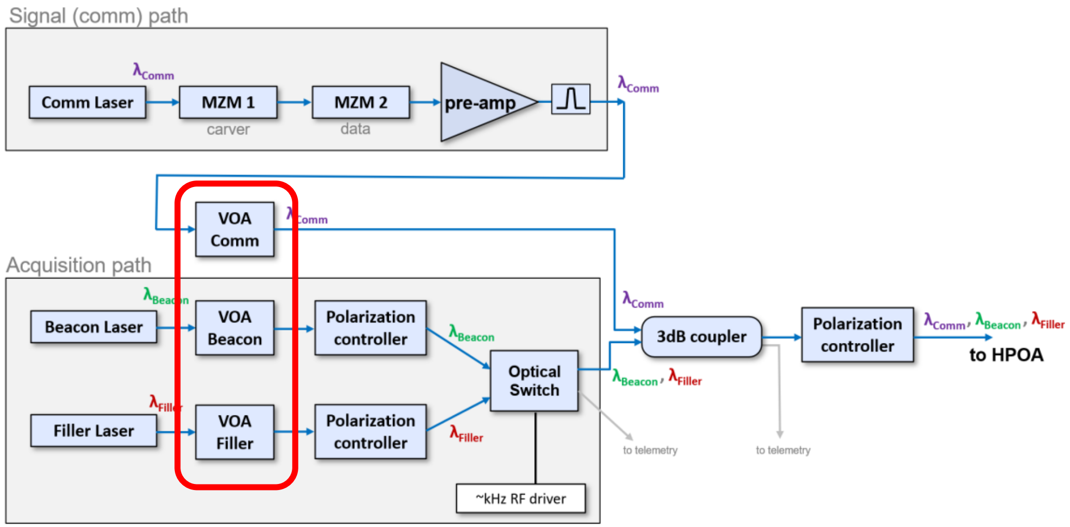


Relative pulse delay for 500 MHz

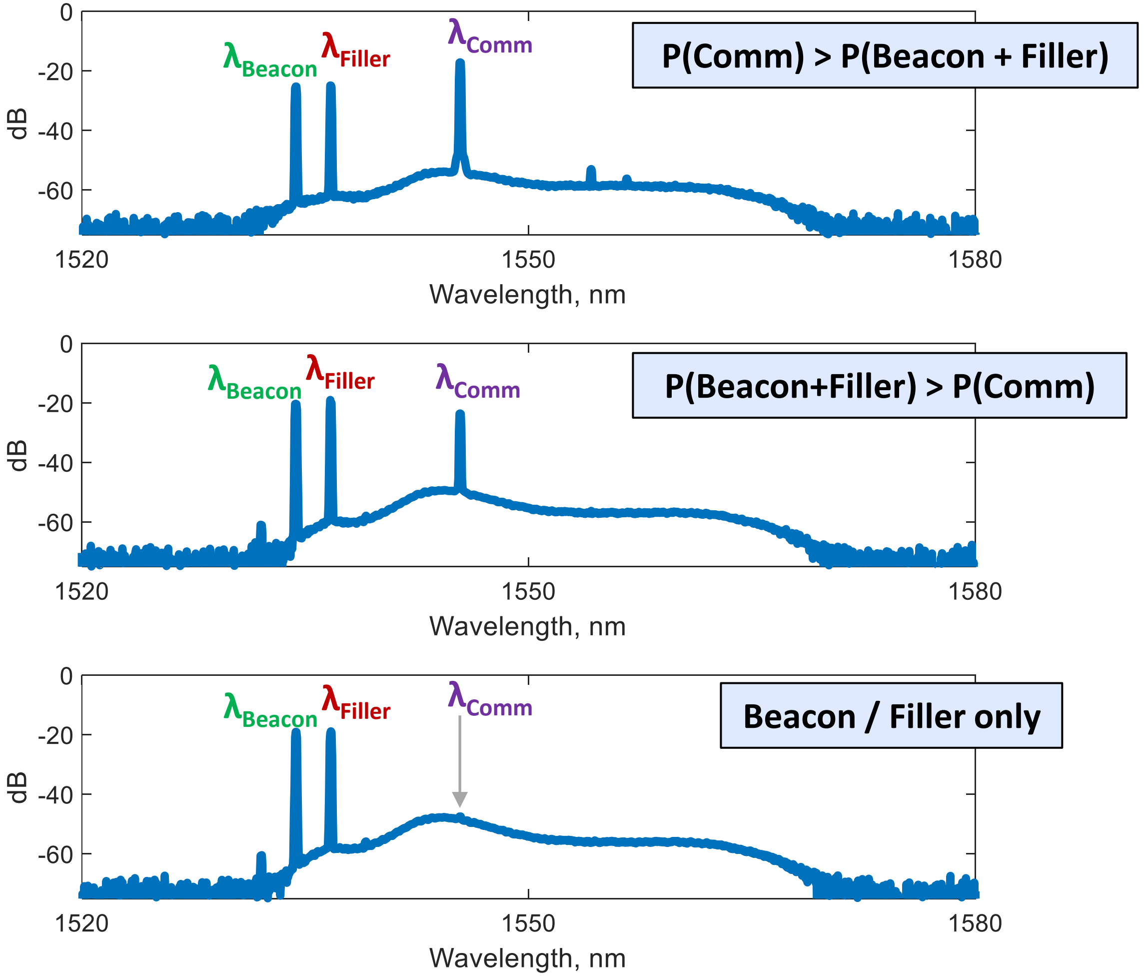
Ch 1	Ch 2	Ch 3	Ch 4
0 ps	10 ps	20 ps	32 ps

Results: Comm/Beacon Ratio Control

- **Diverged beacon is used for spatial acquisition**
- **Need the ability to rapidly (<2s) change the amount of comm / acquisitions signal powers at the output of the transmitter**
  - ➢ Acquisition → Beacon / Filler only
  - ➢ Comm / tracking → P(Com) >> P (Beacon + Filler)
- **All 3 wavelengths (λ_{Comm}, λ_{Beacon}, λ_{Filler}) go through the same HPOA**
- **Implemented via Variable Optical Attenuators (VOAs)**
- **Automatic control loop maintains constant ratio on operation**



Output Signal Spectra (measured after HPOA 1% tap)



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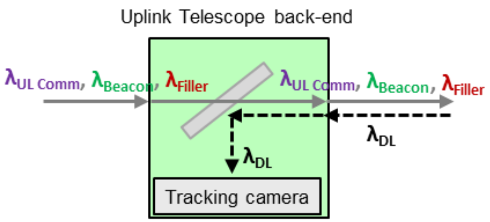
Results: Polarization Control

High peak power causes parasitic nonlinear effects

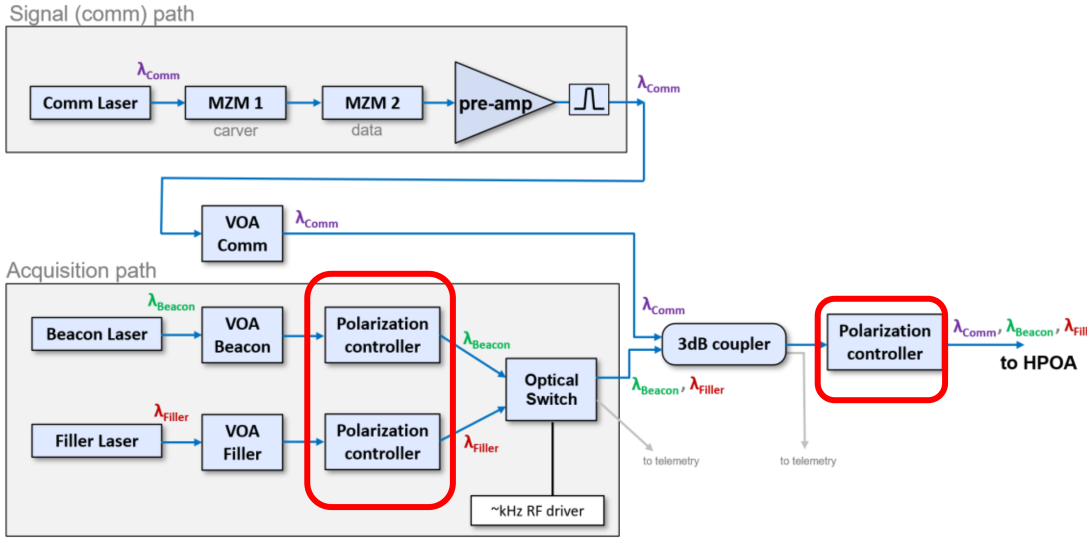
- PPM-32 + guard slots + RZ50 pulses → $P_{peak}=80\times P_{aver}$ → $P_{peak}=800W$

- **Takes power away from signal beams**
- **Interferes with the tracking camera (looking at downlink signal)**

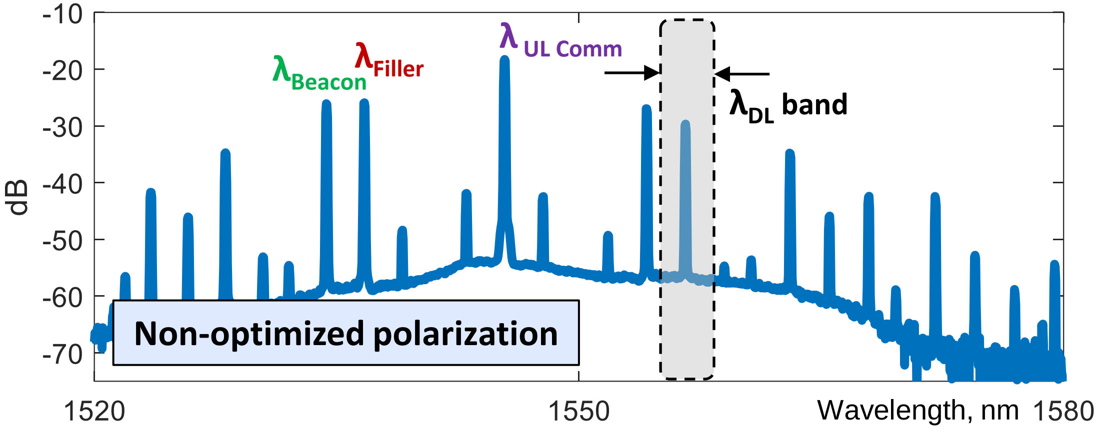


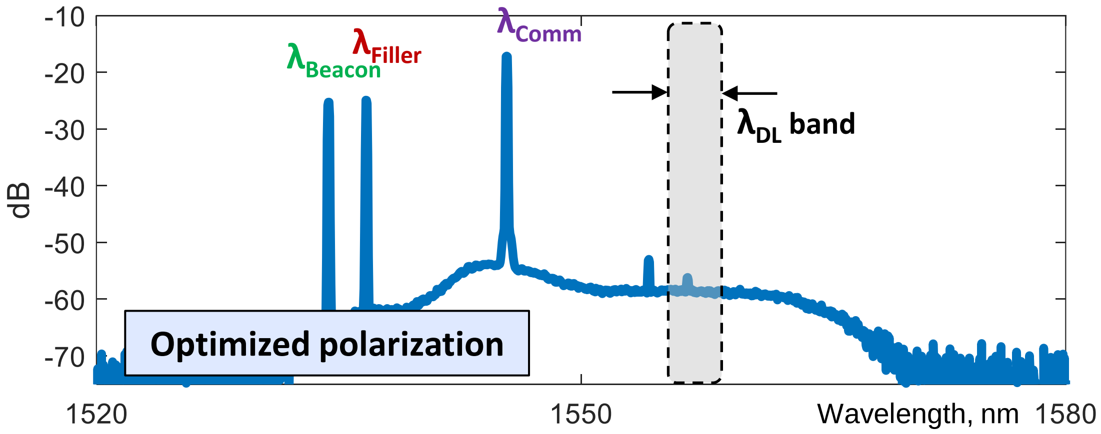
Mitigated by:

- **Minimizing the length of fiber post-HPOA (~2m)**
  - HPOAs are mounted at the gimbal next to the telescopes
- **Polarization control (voltage-controlled polarization rotators)**



Output spectrum at 10W output power

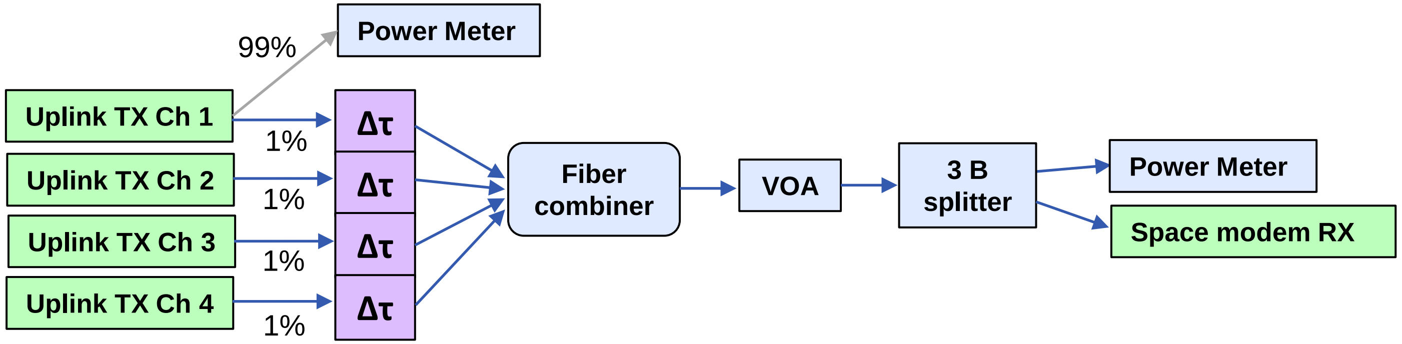




Results: CWER / Extinction Ratio

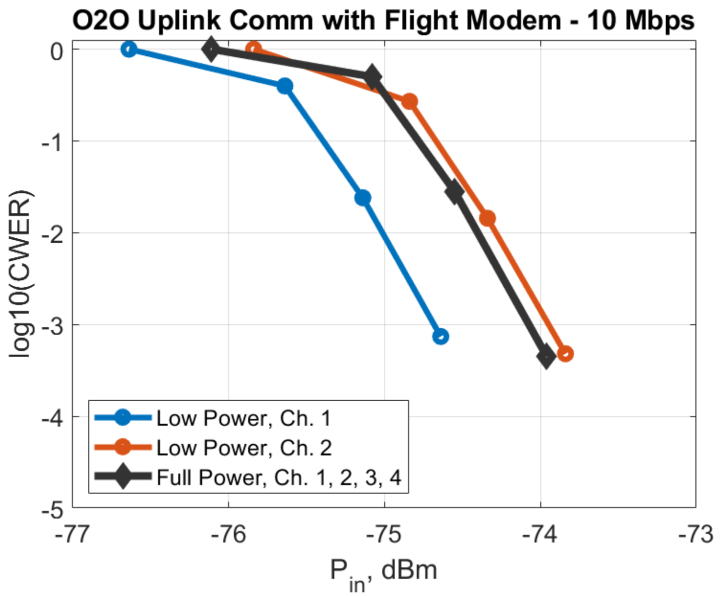
Codeword Error Rate (CWER) measurement setup:

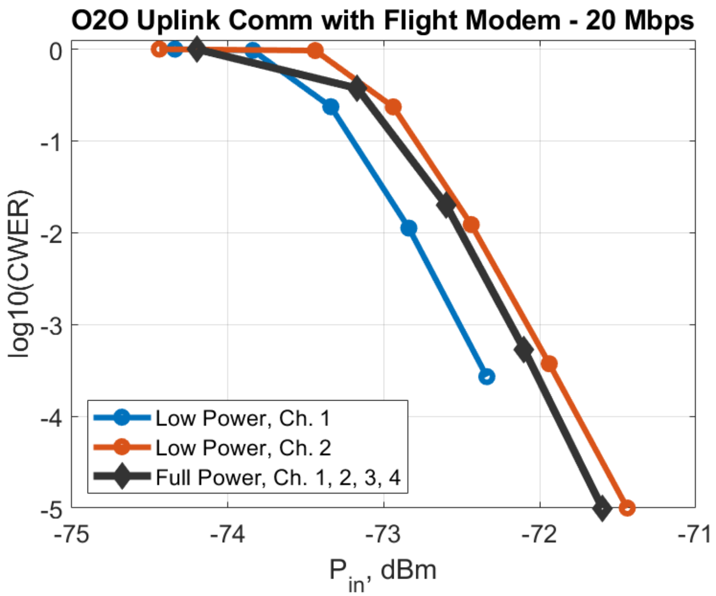
- Uplink TX vs flight modem RX



Extinction Ratio[1]

Channel	Low Power (pre-HPOA)	High power (10W)
1	32.2 dB	26.7 dB
2	30.1 dB	26.8 dB
3	26.8 dB	24.7 dB
4	30.0 dB	25.8 dB





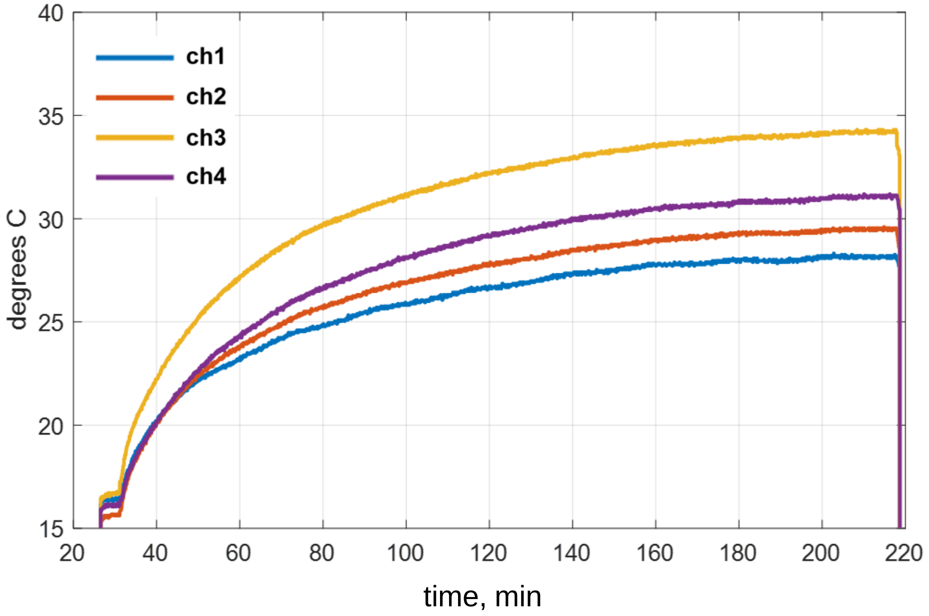
[1] Caplan, D. Laser communication transmitter and receiver design. *J Optic Comm Rep* **4**, 225–362 (2007). https://doi.org/10.1007/s10297-006-0079-z

CWER – Codeword Error Rate

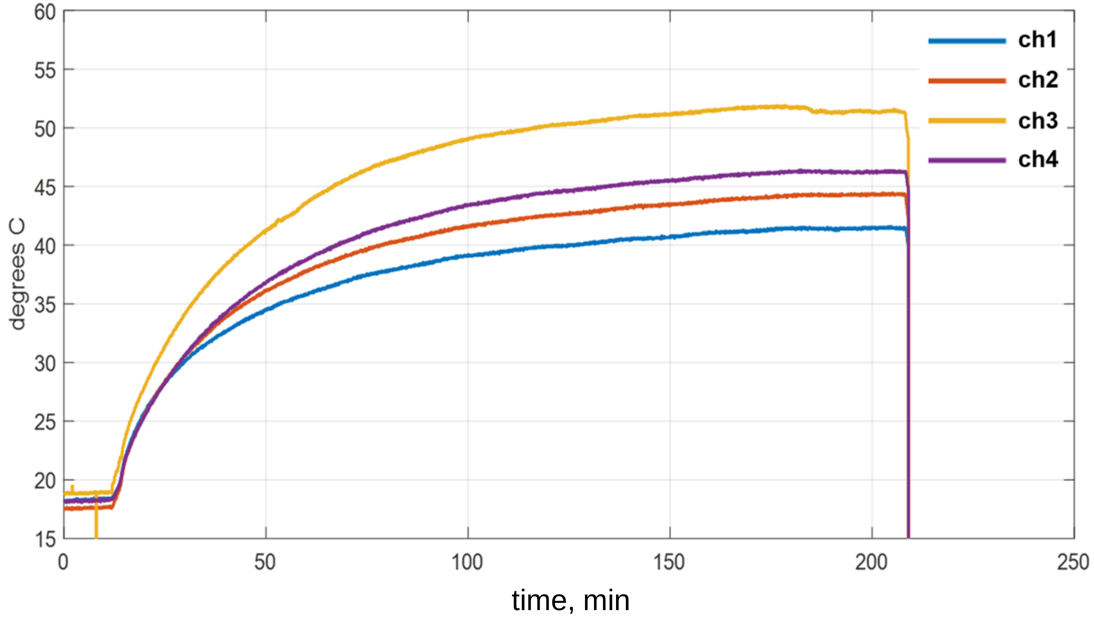
Results: Long-duration temperature tests

- **Four HPOAs are mounted inside the gimbal, close to each other**
- **Forced air cooling + heat sinks mitigate heating**
- **HPOAs can safely operate to 60C**

2.5 W output power from each HPOA



10 W output power from each HPOA

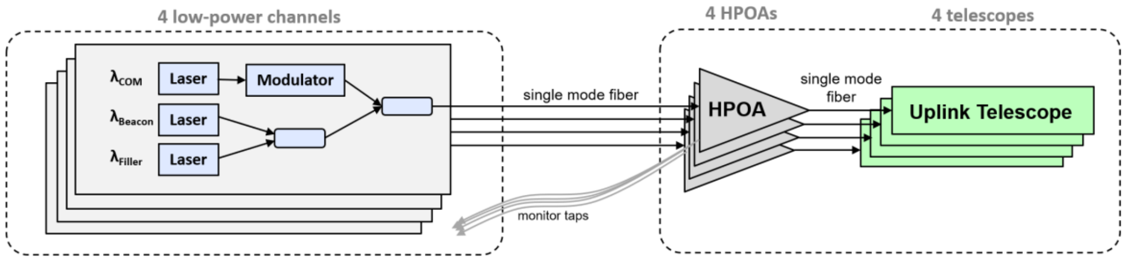


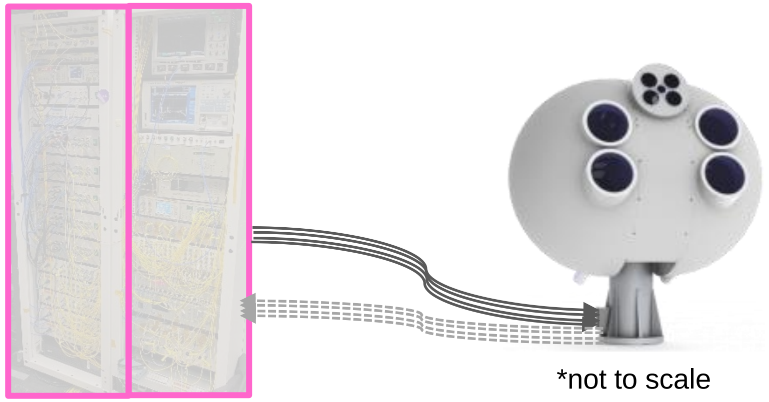
HPOA – High Power Optical Amplifier

Summary

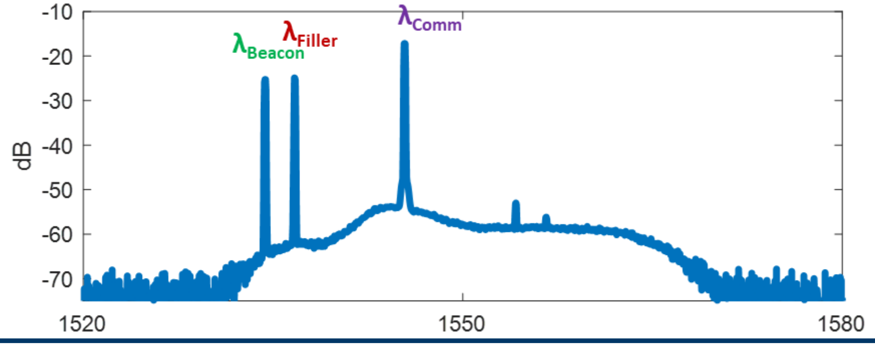
Demonstrated a 40W ground-based optical transmitter

- **Fiber-based system (SMF) up to the telescope input**
- **Four communication channels → four amplifiers**
  - **Channels time aligned to <50 ps**
- **PPM-32, RZ50 pulses**
  - 250 MHz slot rate @1/3 code → 10 Mbps
  - 500 MHz slot rate @1/3 code → 20 Mbps
- **Tested with up to 10 hours of continuous operation at 10W**
- **Fast (<2 s) switching of acquisition / comm signal ratio**
- **Monitoring:**
  - **Real time telemetry on low and high power signals**
  - **Automatic real-time power stabilization**
  - **Automatic real-time Comm/Acquisition ratio control**
  - **Automatic real-time wavelength monitoring / control**





*not to scale



PPM – Pulse Position Modulation

HPOA – High Power Optical Amplifier
SMF – Single Mode Fiber

Backups

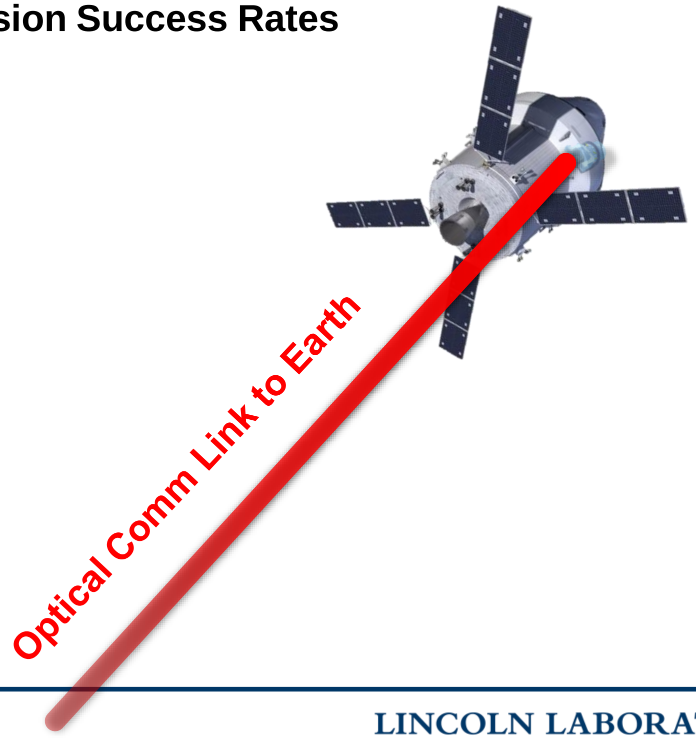
O2O Mission Objectives

- **Artemis I used radio frequency comm link, S-band downlink of ~ 6 Mbps at lunar ranges**
- **Artemis II adds <u>optical communications capability</u> which provides up to 260 Mbps return link and 20 Mbps forward link from/to Lunar vicinity**

Optical Link Direction	Data Rates (Mbps)
Up / Forward	10, 20*
Down / Return	20, 40, 80*, 130, 190, 260

*** Mission Success Rates**

O2O: <u>O</u>rion Artemis <u>2</u> <u>O</u>ptical communications



<u>Development Test Objective (DTO):</u>

Implement a laser communications capability for the Orion series of spacecraft, starting with Artemis II, in order to enhance its operational utility by

1. **Transferring files from Mission Control Center (MCC) in Houston to/from Orion**
2. **Transferring real-time video downlinks from Orion to MCC**
3. **Utilizing operational performance envelope by demonstrating optical comm during various conditions**

[1] https://esc.gsfc.nasa.gov/projects/LEMNOS

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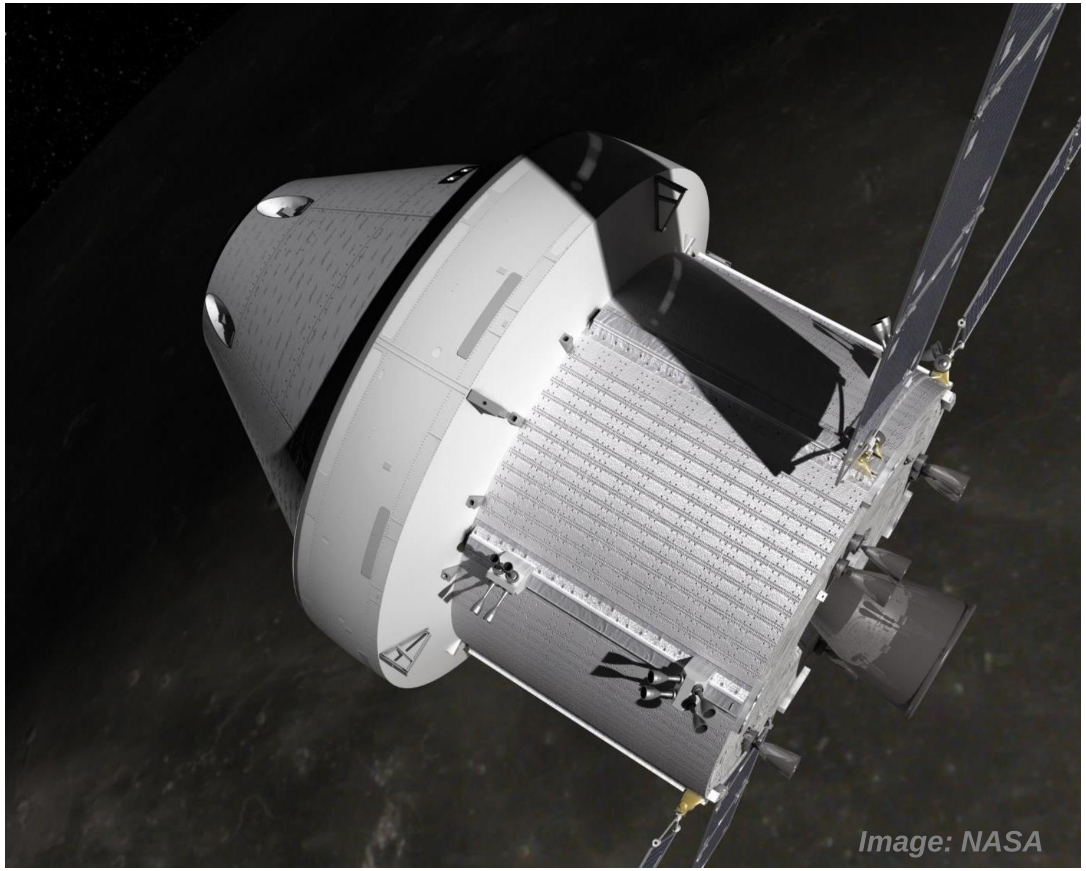
O2O* Overview

- **Launch planned for 2024**
- **Artemis RF comm capability:**
  - **S-band phased array transmitters**
  - **Up to ~6 Mb/s from lunar ranges to NASA Deep Space Network**
- **O2O lasercom system to operate on Artemis II Orion service module**
- **O2O Optical comm capability:**
  - **1 W transmitter, 10 cm aperture**
  - **Up to 260 Mbps downlink**
    - **80 Mbps nominal downlink**
  - **20 Mbps uplink**
  - **Real time mission video**
  - **Real time scientific data transfer**



***Orion Artemis-2 Optical Comm**