Contract No 4000128359/19/NL/AR

Feeder-Link Demonstration Using Technology Demonstration Payload on Alphasat

Final Presentation

ESTEC / Teams
March 22nd, 2023

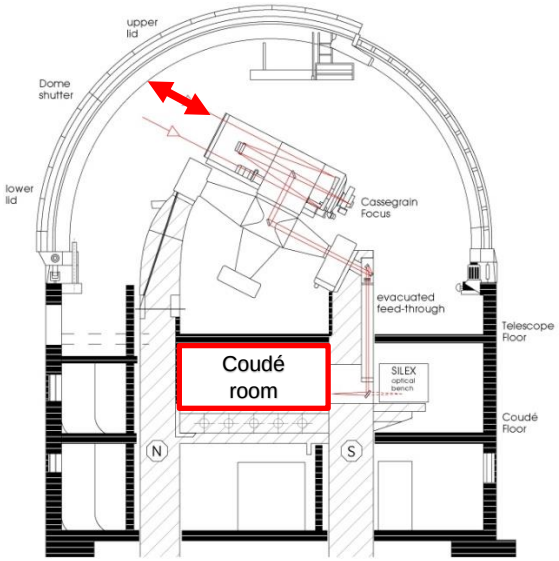
GENERAL ATOMICS SYNOPTA

Content

- Project Overview
- Breadboard Design & Development
- On-Site Test Campaign
- Link Data Analysis
- Summary & Conclusion

Project Overview

- **Feeder-Link Demonstration Using Technology Demonstration Payload on Alphasat ("Alpha-Up")**
- **Duration:** October 2019 – March 2023
- **Objectives**
  - Development of an optical feeder-link breadboard
    - Uplink wave front pre-compensation (tip/tilt)
    - CCN: With adaptive optics (AO)
  - Demonstration of optical feeder-link technology between Alphasat TDP1 and ESA OGS (Tenerife)



ESA OGS

Alphasat

Breadboard Design & Development

- Background
- Preliminary Measurements
- Design Overview
- Link Budget Analysis
- Factory Testing

Background

- **Goal:**
  - Bi-directional link, with transmission and reception in a common aperture on ground
  - Make use of the downlink wavefront measurement, to pre-compensate the uplink beam

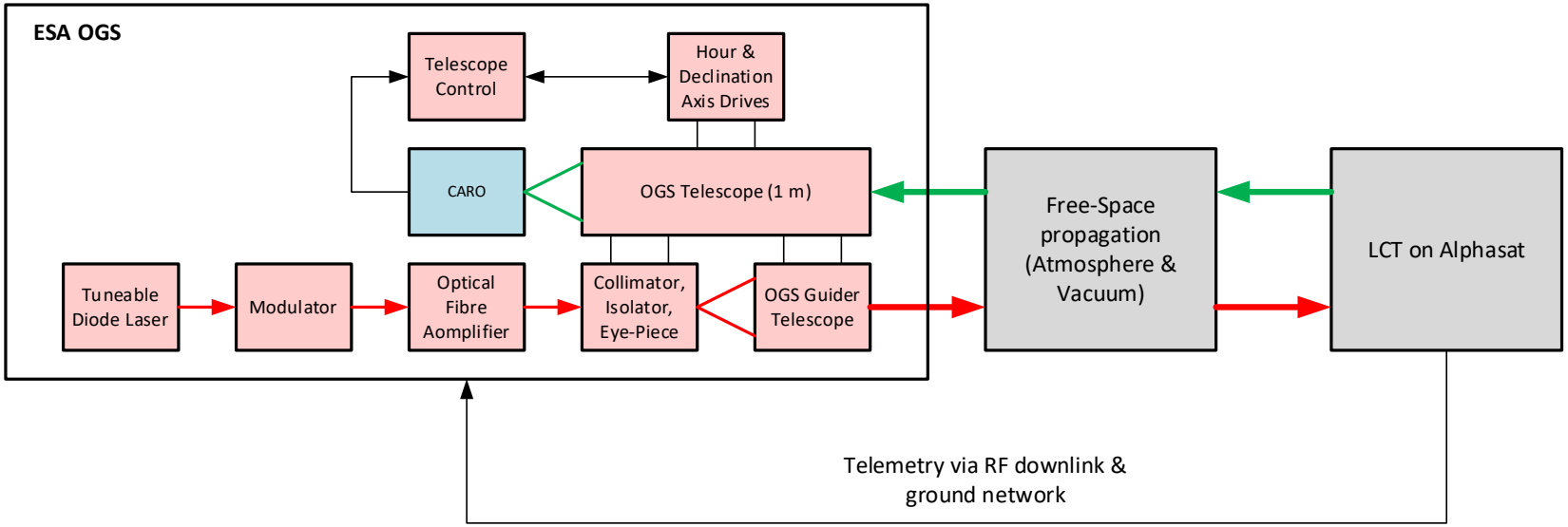
- **Boundary conditions:**
  - LCT was originally designed for bi-directional coherent communication with Nd:YAG lasers (Tx & Rx only separated by 30 GHz / 0.1 nm)
  - Ground transceiver (adaptive optics) has incoherent wavefront sensor

Background

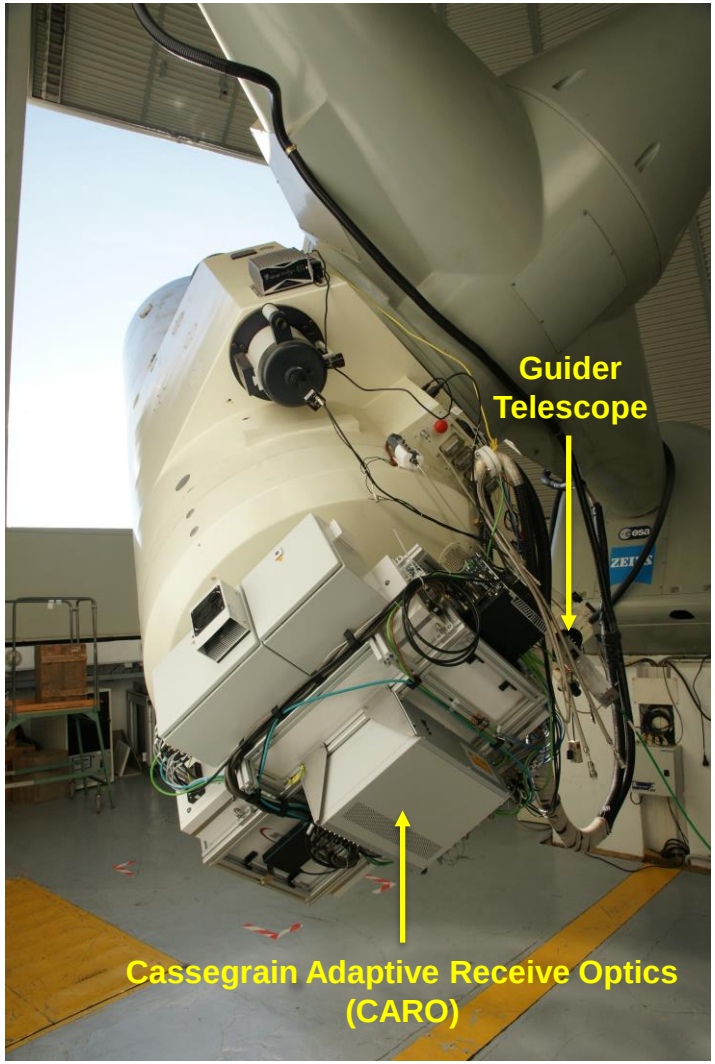
- **To avoid self-blinding due to back-reflection on ground, de-tune the uplink to the extent possible**
- **LCT features an incoherent Fine Acquisition Sensor (FAS), with tracking & recording capability → make use of it**
- **Methodology:**
  - Start with preliminary measurements, to explore the detuning capability
  - Decide on the spectral filtering, to avoid self-blinding

Preliminary Measurements

- **Bistatic configuration**
- **Downlink: Cassegrain Adaptive Receive Optics (CARO)**
- **Uplink: Guider Telescope**



Preliminary Measurements

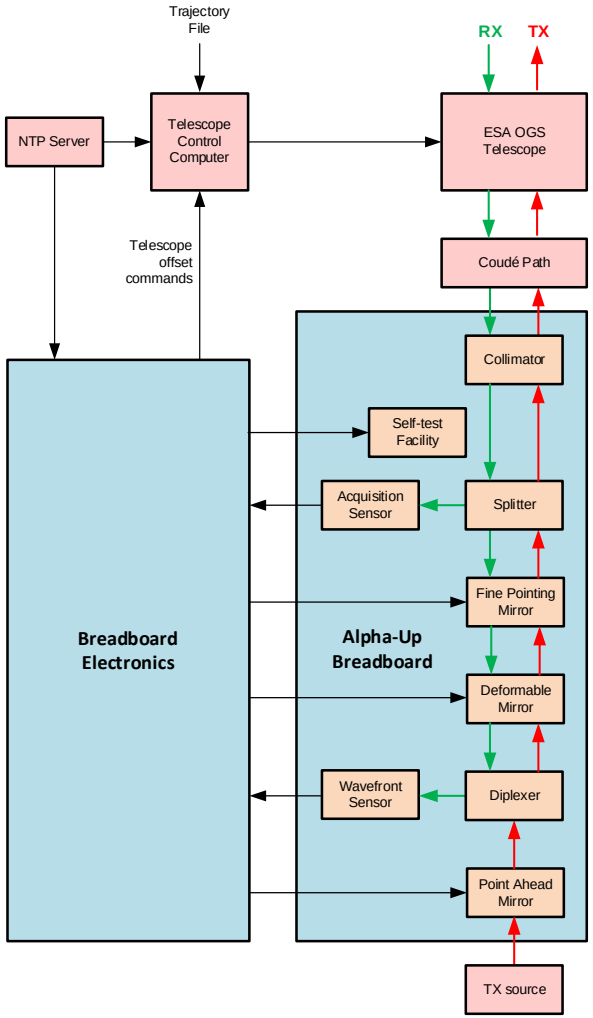


Tuneable Laser, Modulator, Amplifier

→ Detuning of ~10 nm possible

Alpha-Up Breadboard Design

- Acquisition sensor detects initial blips and corrects telescope pointing
- Uplink beam is injected via point ahead mirror and diplexer
- Both beams are corrected by fine steering mirror & deformable mirror
- Wavefront sensor equipped with ultra-narrow bandpass
- Additional filtering in the Tx path
- Self-test facility allows Tx/Rx alignment

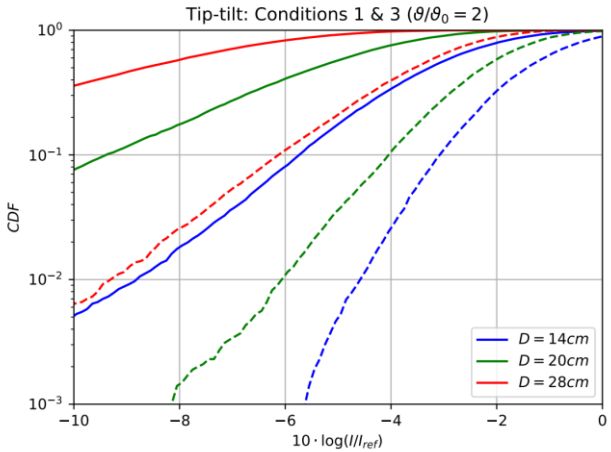


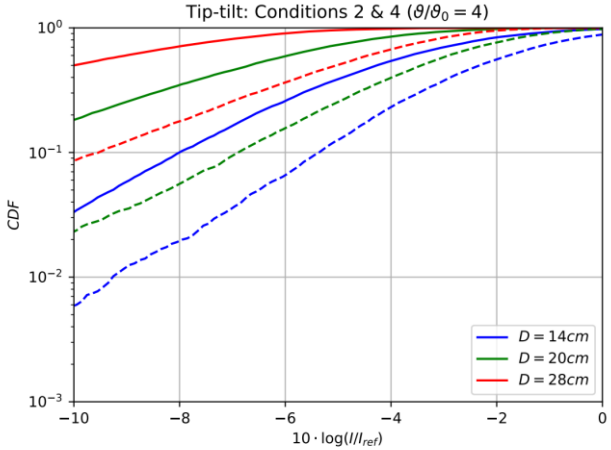
Link Budget Analysis

- **Multiple phase-screen propagation model was used to predict scintillation of uplink irradiance at the satellite**
  - Perfect phase conjugator on ground
  - 4 atmospheric conditions
  - 3 aperture diameters
- **Full pre-comp. is good at correcting boundary-layer turbulence**
- **At good seeing (r_0 ~ 10 cm), little difference between tip/tilt & full pre-comp.**
- **For the breadboard, 22 cm aperture diameter were chosen**
- **Less than 1 W (ex aperture) should be sufficient**

Link Budget Analysis

Normalized irradiance (tip/tilt pre-comp.)

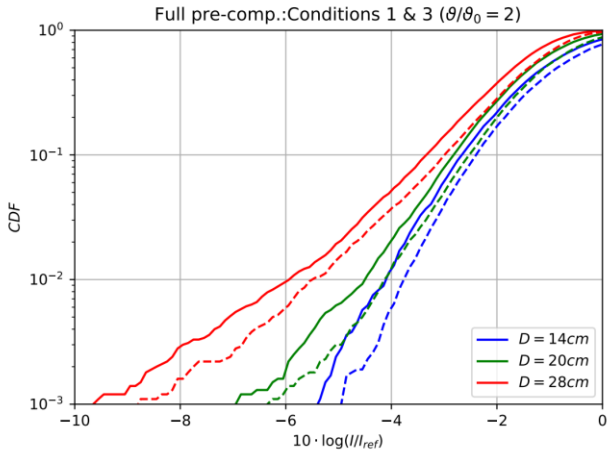


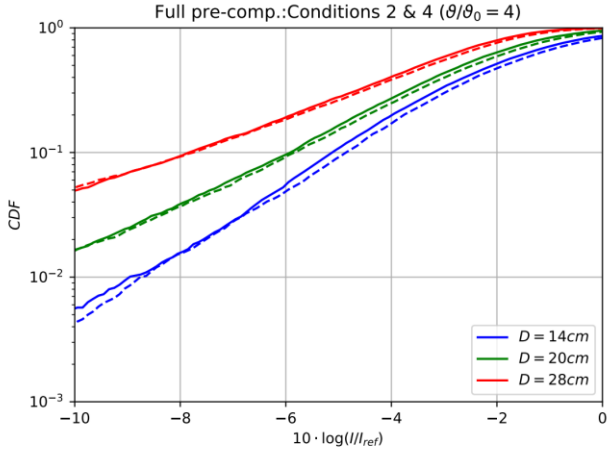


ϑ_0 ~ 2 arcsec

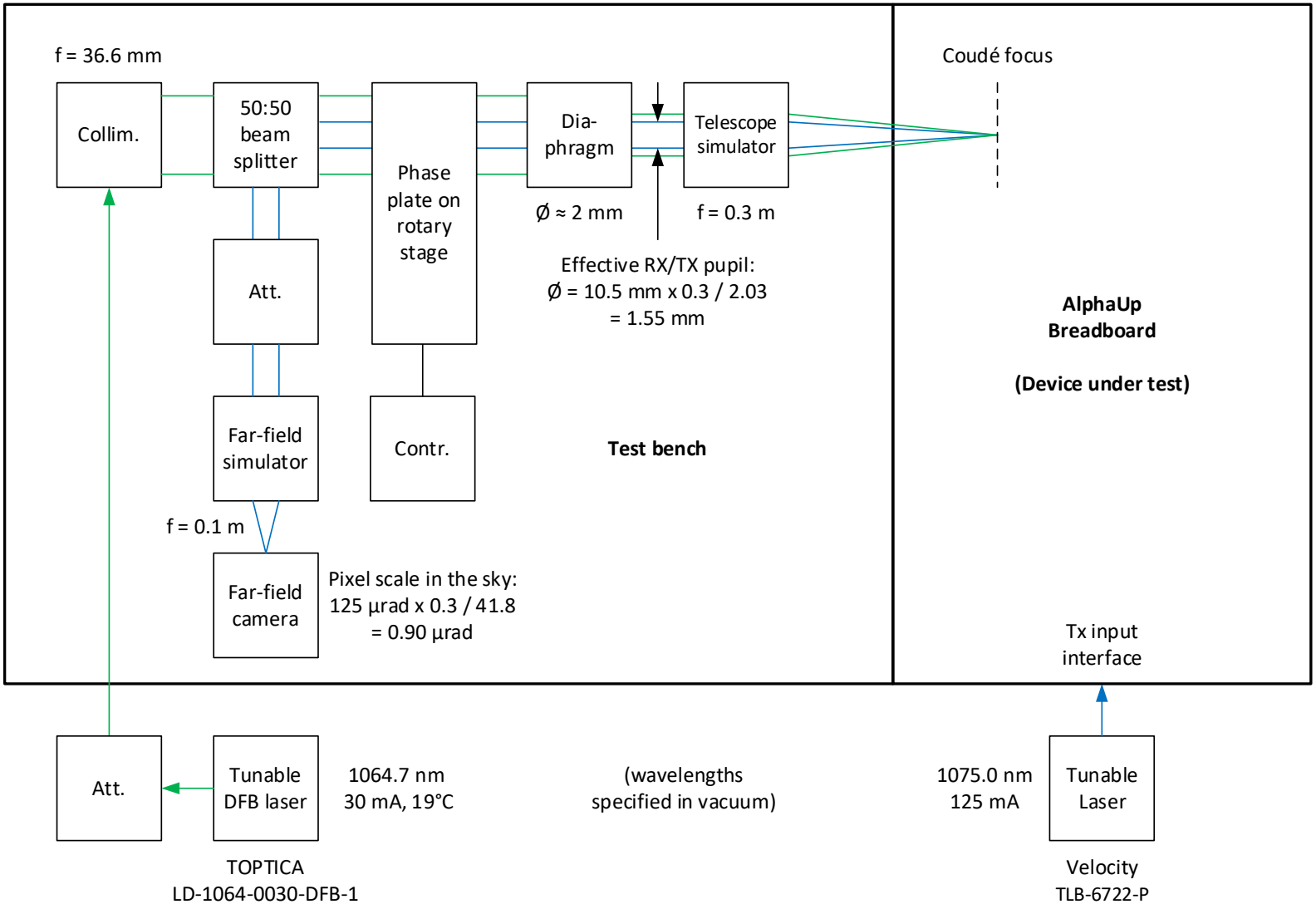
ϑ_0 ~ 1 arcsec

Normalized irradiance (full pre-comp.)

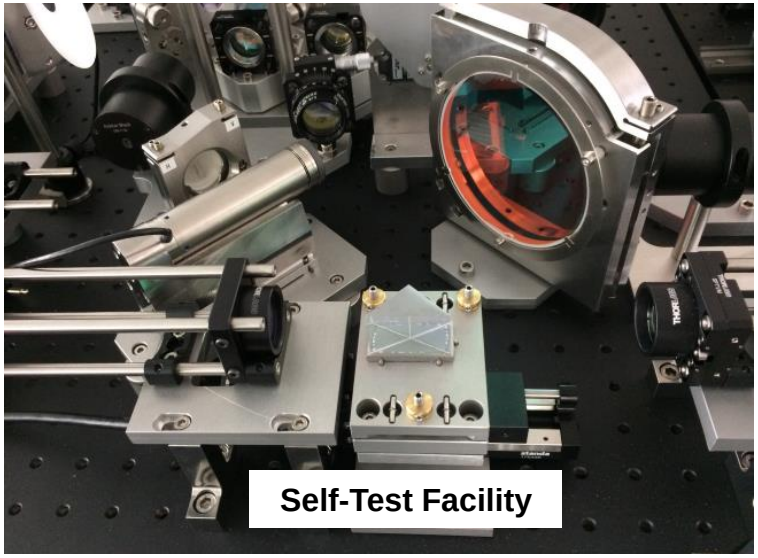


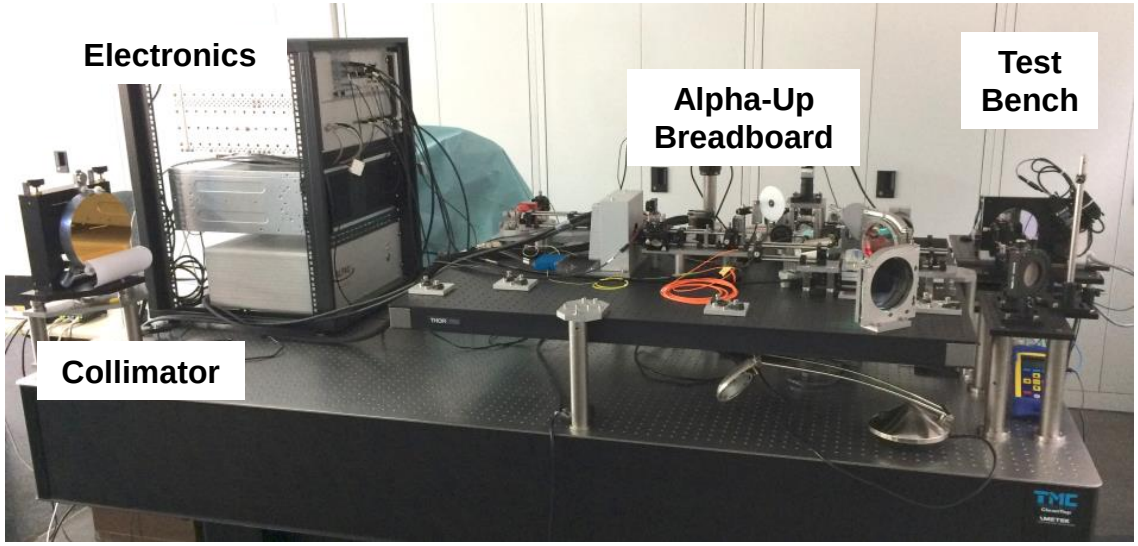


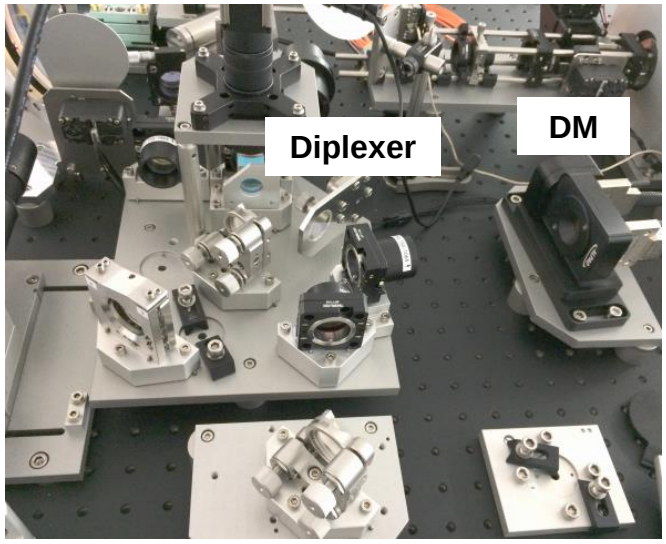
Factory Testing



Alpha-Up Breadboard at the Factory







GENERAL ATOMICS SYNOPTA

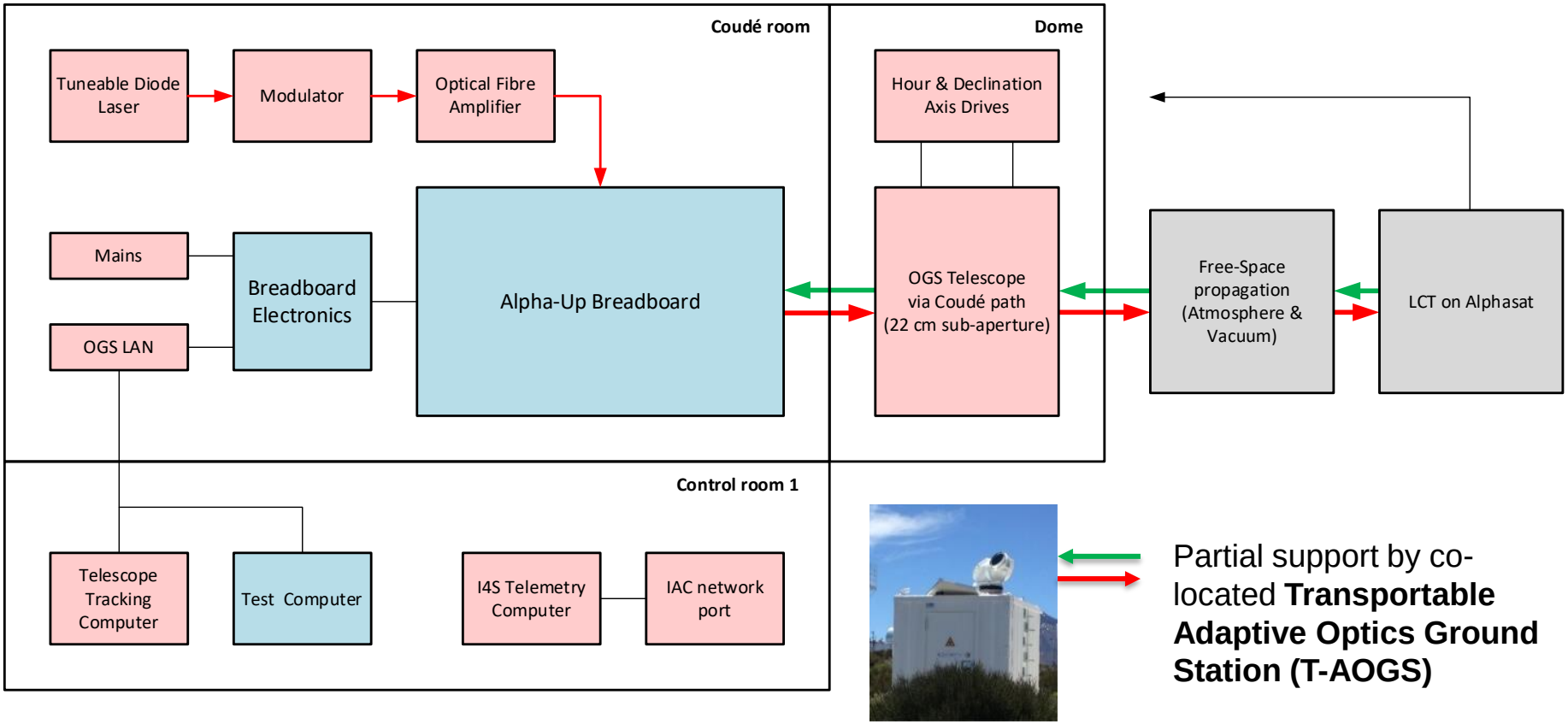
Factory Test Results

- **Adaptive Optics performance:**
  - Static Strehl ratio (far-field irradiance) ~ 88%
  - Closed-loop rejection cut-off frequency ~ 200 Hz
  - Dynamic Strehl ratio (full pre-comp.) ~ 57% … 93%
    - Worst case: r_0 = 5.6 cm, v = 15 m/s

- **Tx/Rx alignment stability ~ ±2 µrad in 3 hours**

- **Internal back-reflection: Ok**
  - Tested at low power, with spectral filtering removed
  - Extrapolated to the final setup → System can handle tens of Watts

On-Site Test Campaign

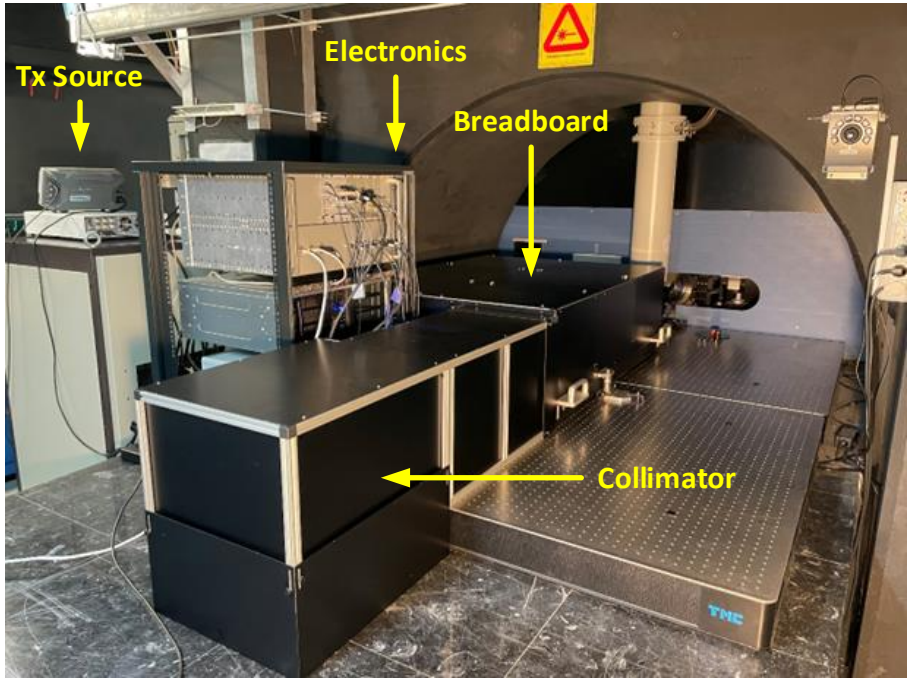


Partial support by co-located **Transportable Adaptive Optics Ground Station (T-AOGS)**

- **"Live" telemetry: Max. of individual FAS quadrants**
- **After 2 days: Sum of 4 quadrants @ 1 kHz → irradiance**

Alpha-Up Breadboard at the OGS

Coudé room

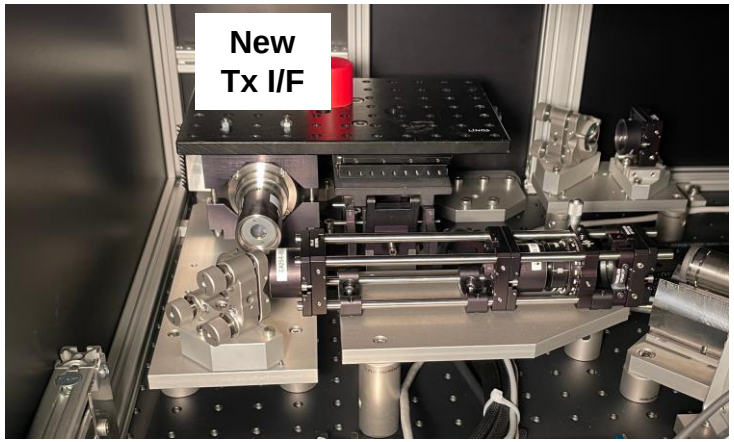


Telescope pointing to Alphasat

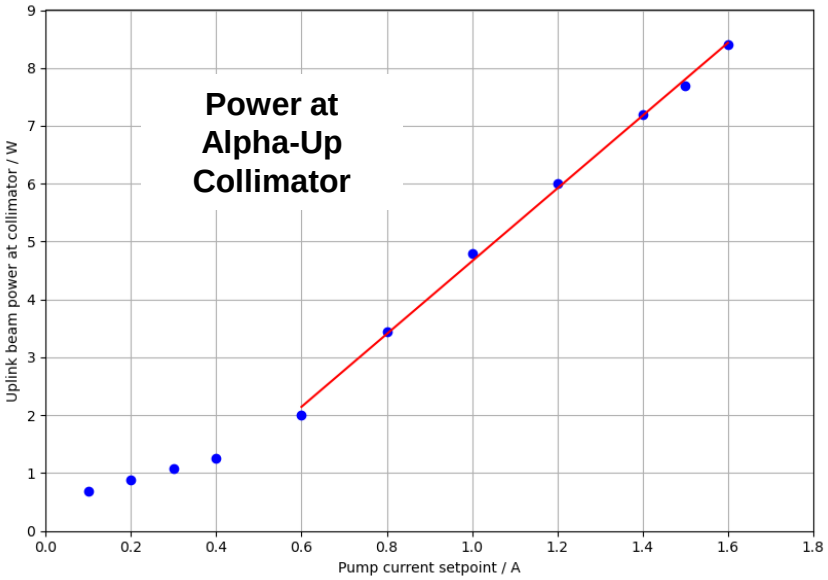
On-Site Test Campaign: History

- Nov. 23-27: Setup, alignment
- 92 links scheduled (8-10 per day)
- Nov. 28/29: First light, OPA failure at the 2nd uplink trial, LCT FDIR
- Nov. 30/Dec. 1: OPA replacement, LCT investigations
- Dec. 2: Four uplinks, but weak signal at LCT
- Dec. 3: LCT malfunction, correction of polarization / pilot tone frequency
- Dec. 5: Six successful uplinks (bad seeing)
- Dec. 6-9: ~2 successful links per day, otherwise bad weather

Optical Power Amplifier Replacement

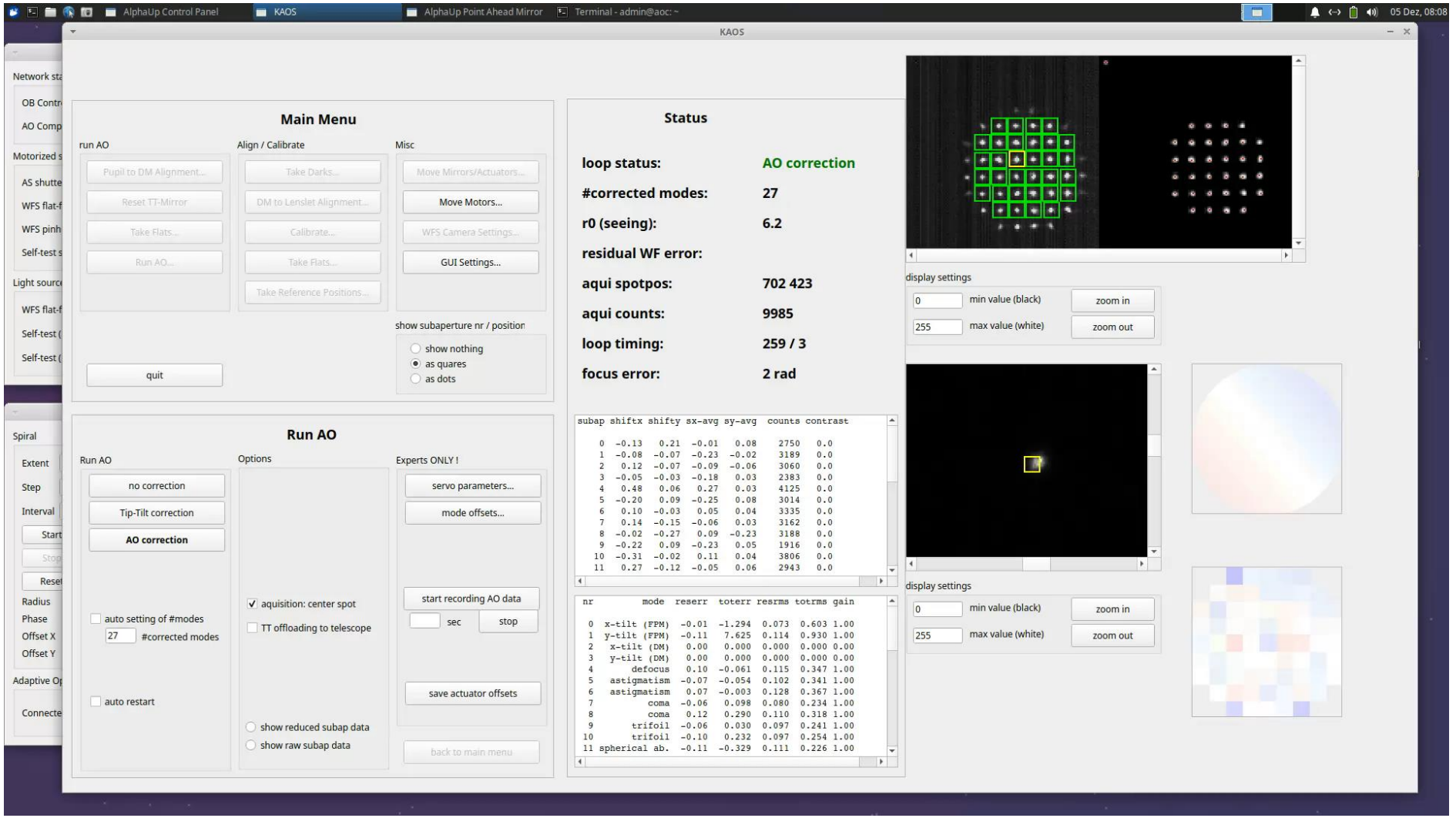


Amplifier specified up to 1070 nm, but operated at ~1075 nm



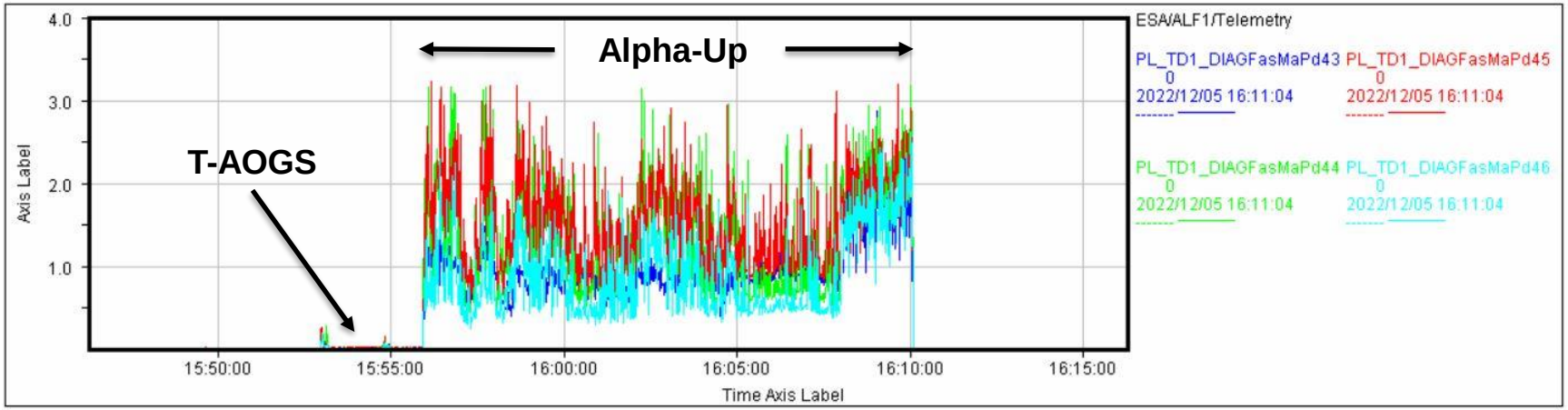
Coudé Path Transmission ~50%

Adaptive Optics Example (Dec. 5th, 8:00)

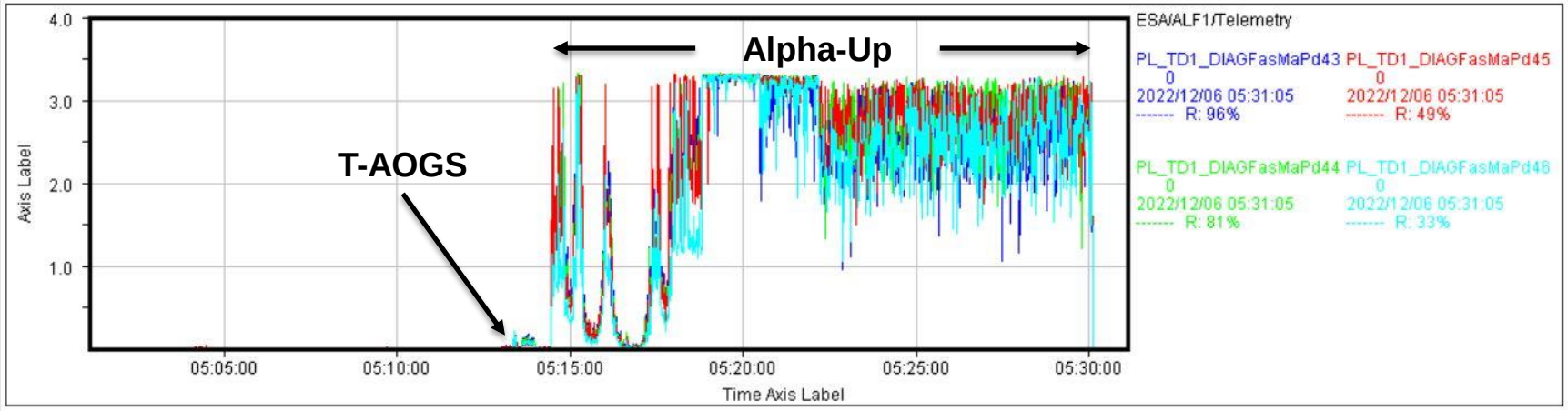


“Live” Telemetry Examples (I4S, ~15s delay)

Dec. 5th FAS signals



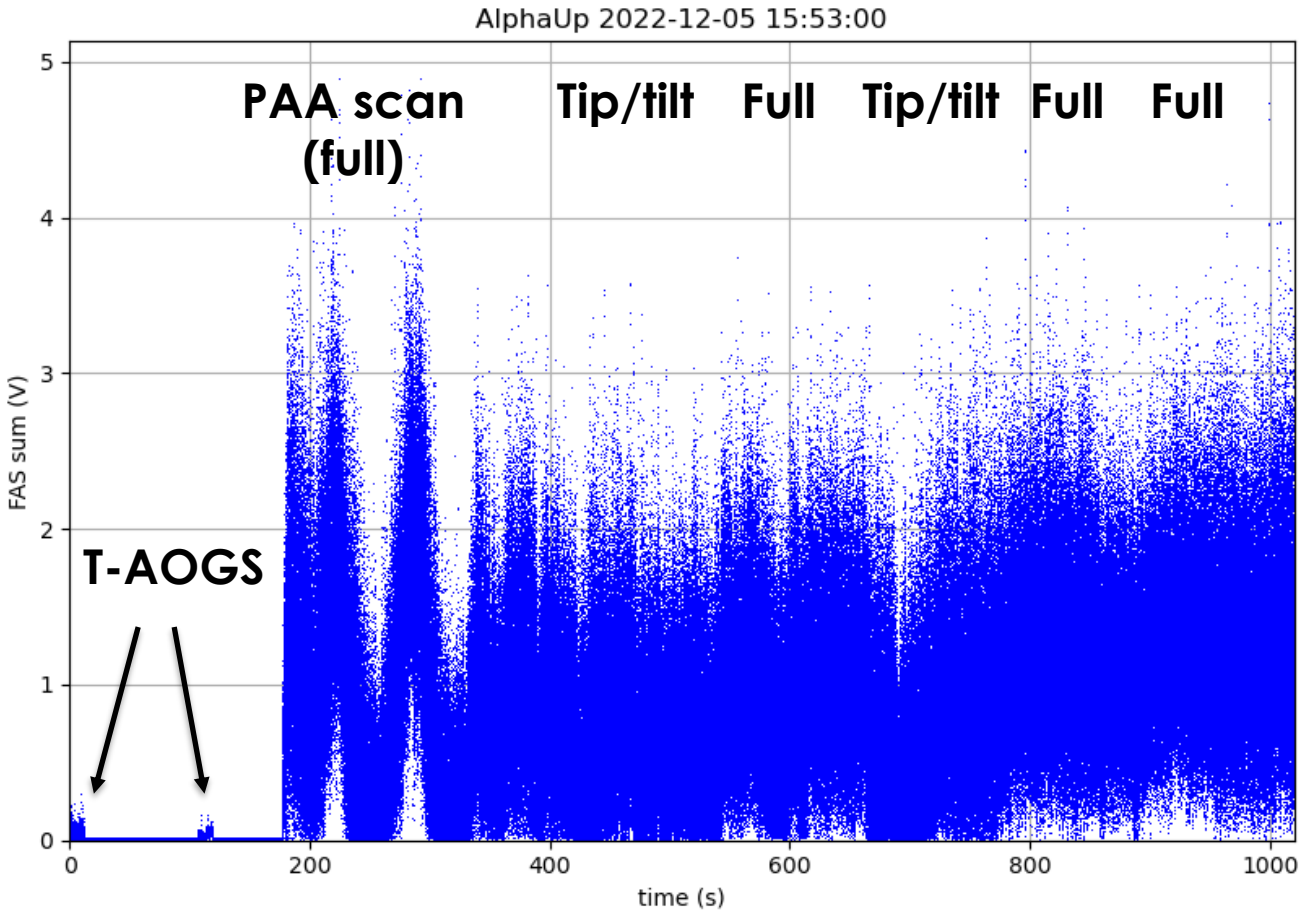
Dec. 6th FAS signals



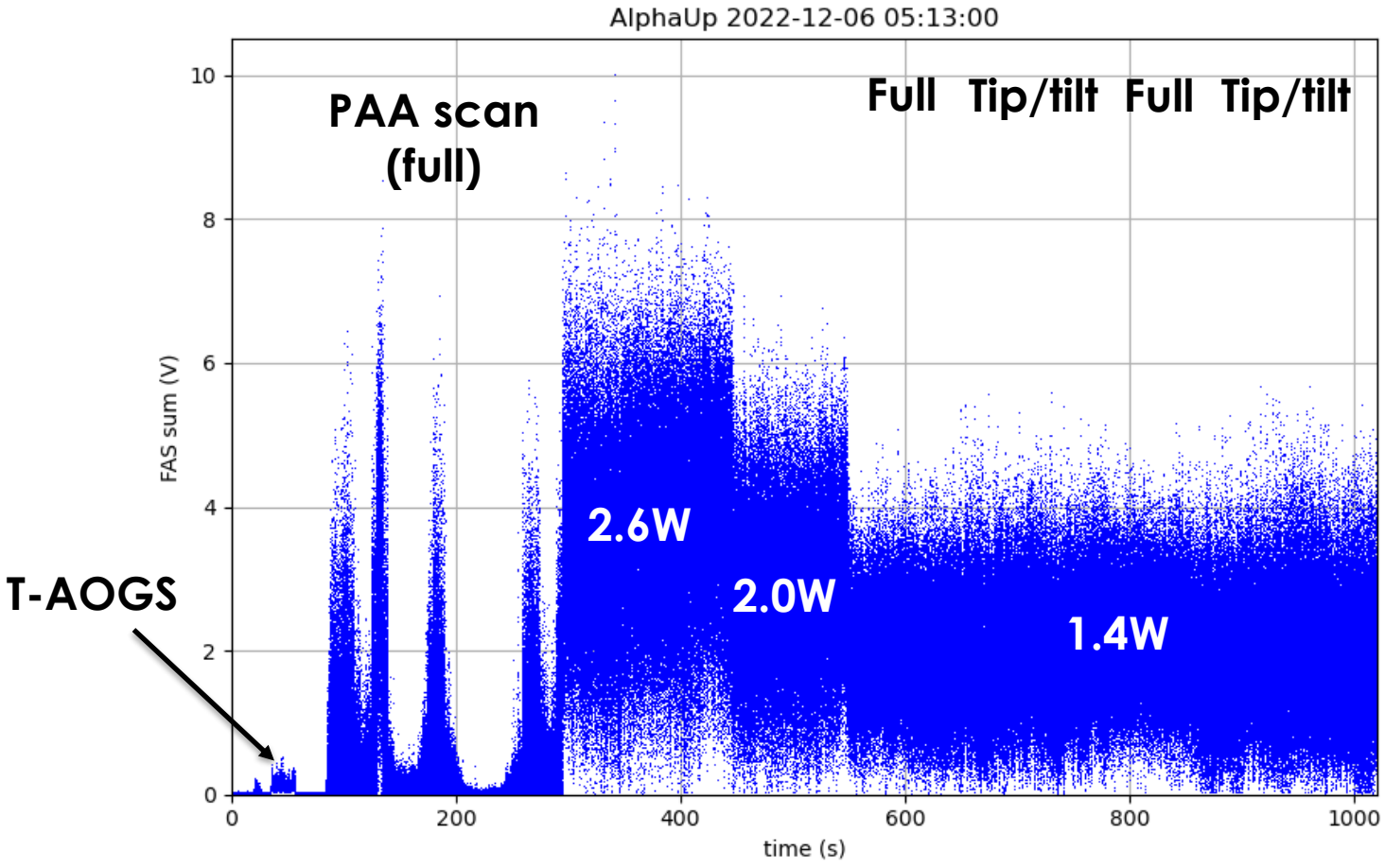
Link Data Analysis

- **Uplink Irradiance Examples**
- **Overview of Analysed Links**
- **Channel Transmission**
  - Mean, Variance
  - Fading Statistics
  - Temporal Spectra
- **Analysis Summary**

Dec. 5th: ~3W ex telescope, circular PAA scan



Dec. 6th (good seeing): Spiral scan, var. power

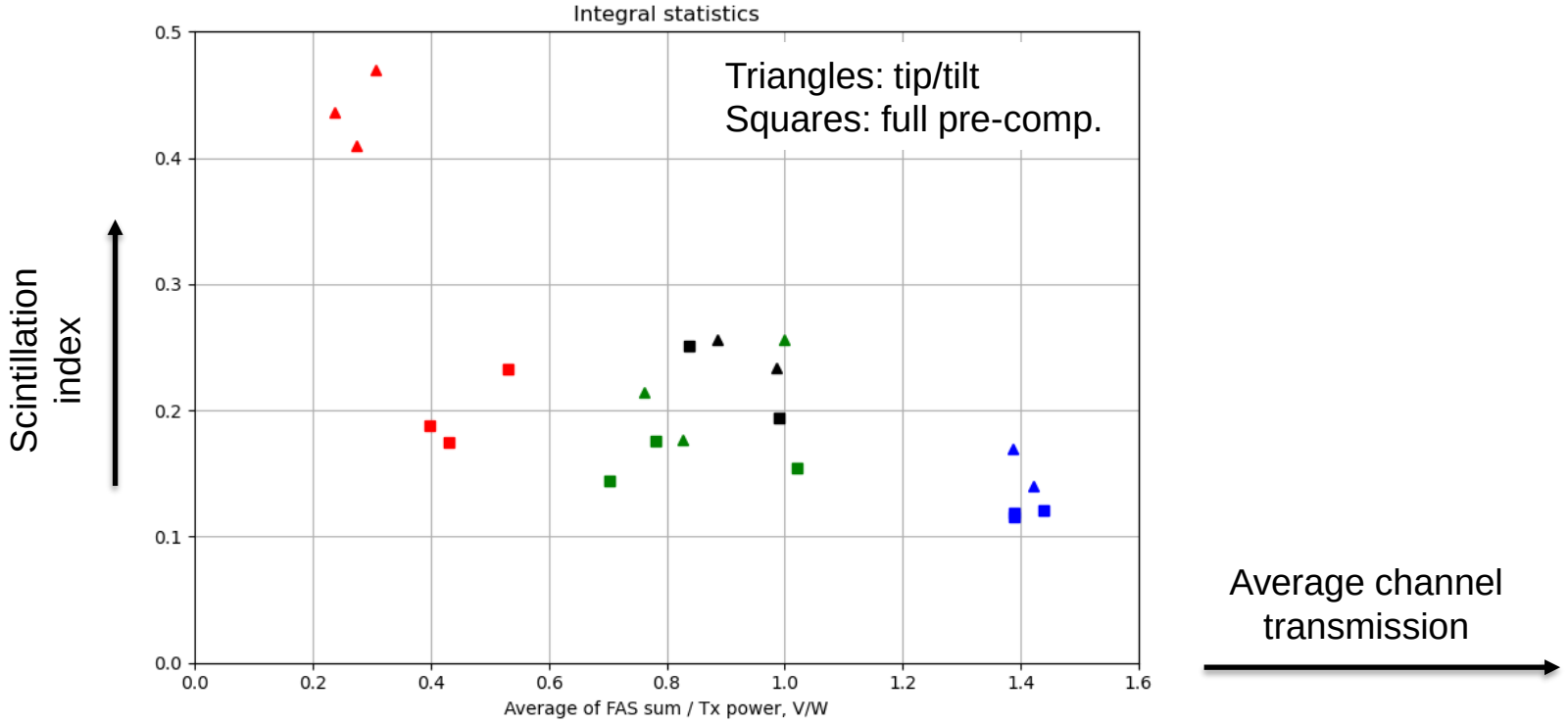


Overview of Analysed Links

- **In total, FAS data from 13 links was analysed**
- **6 links: plausible FAS data**
- **7 links: Point-ahead angle chosen incorrectly**
  - Significant decrease of average power / increase of scintillation index, w.r.t. optimum setting during PAM scan
  - Optimisation with "live" telemetry was difficult
  - Possible reasons for variable PAM optimum:
    - OPA pointing stability, especially after "high-power enable"
    - Residual error in the Tx/Rx alignment procedure / thermal drift

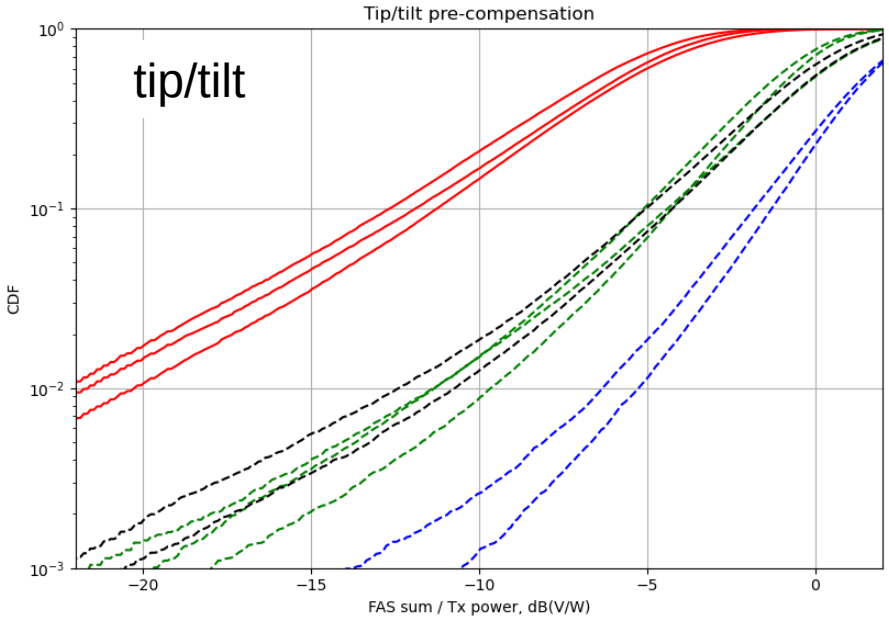
Channel Transmission: Mean, Variance

Date	Start	Link ID	Est. r_0	T-AOGS	Measurements	Est. Tx power	Colour in figures
Dec. 5th	14:53	#50	<5 cm	Y	2 measurements	3.0 W	red
Dec. 5th	15:53	#51	<5 cm	Y/N	4 measurements	3.0 W	red
Dec. 6th	05:13	#56	7-14 cm	Y/N	5 measurements	2.6 … 1.4 W	blue
Dec. 7th	05:13	#65	6-14 cm	N	4 measurements	4.2 … 2.3 W	green
Dec. 7th	20:33	#73	6-14 cm	N	2 measurements	4.2 … 1.7 W	green
Dec. 9th	18:23	#91	6-12 cm	N	4 measurements	3.0 W	black

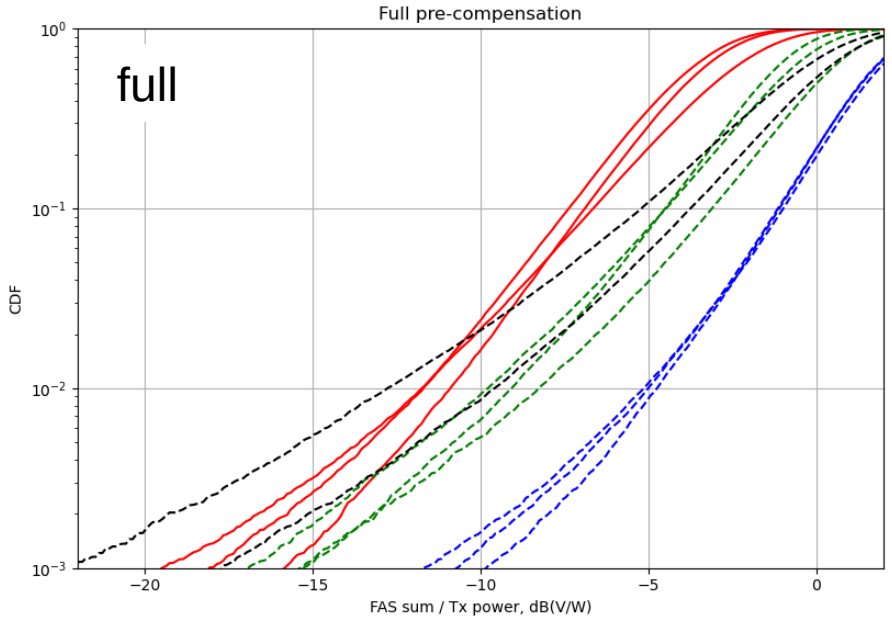


Channel Transmission: Fading Statistics

- **Solid lines: Strong boundary layer (Dec. 5th)**
- **Dashed lines: Weak boundary layer (Dec. 6th-9th)**



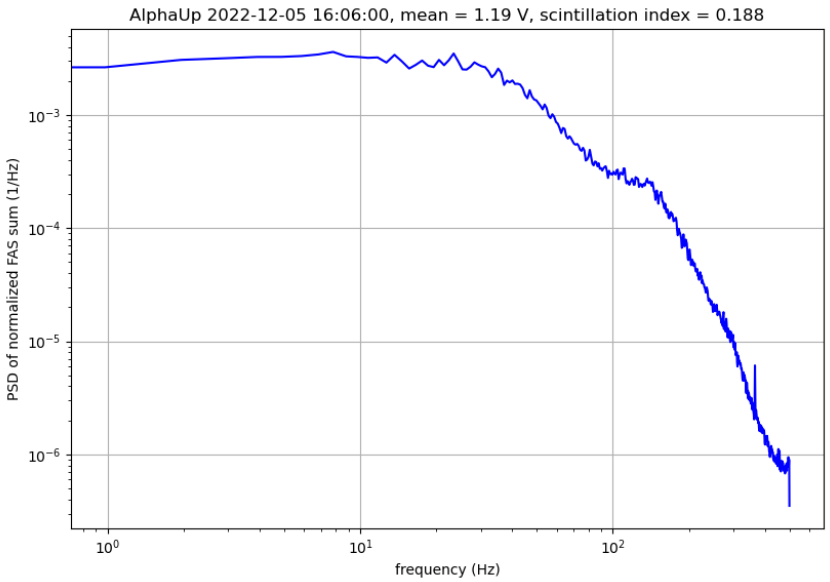
Channel transmission →



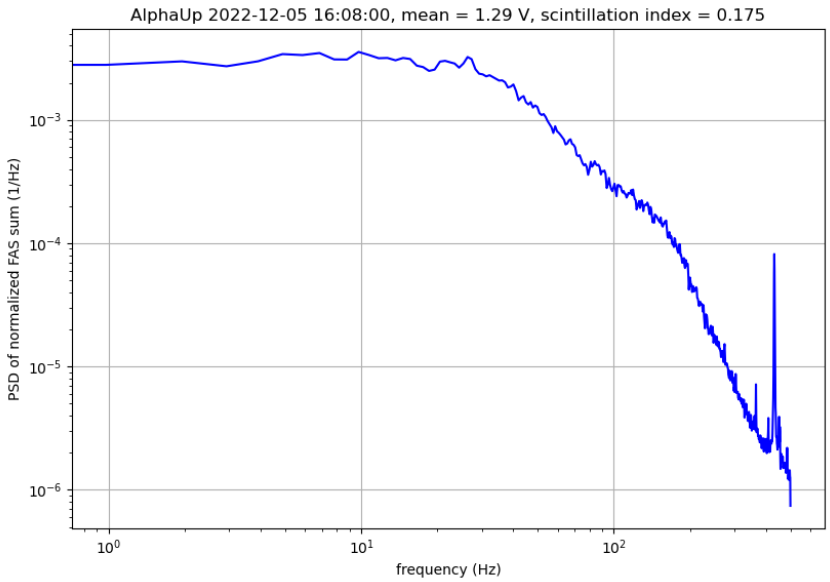
Channel transmission →

Channel Transmission: Temporal Spectra

with T-AOGS support
(LCT: coherent tracking)



without T-AOGS support
(LCT: tracking on FAS)



Analysis Summary

- **Full pre-comp., strong turbulence (Dec. 5th)**
  - Average power increased (factor 1.4…1.7), scintillation index decreased (factor 2); at 99% confidence: +10 dB
- **Weak turbulence (Dec. 6th-9th)**
  - Good uplink performance in both modes (as expected)
- **Alpha-Up can be used stand-alone (without T-AOGS support) in future campaigns**
  - Temporal modulation of the sum signal, caused by TDP1 tracking on the FAS, can be safely neglected
- **Down-sampling to 1kHz is a valid operation**
  - Relevant frequency range of uplink scintillation: up to 300Hz

Summary & Conclusion

- **Optical feeder-link technology has been successfully demonstrated between Alphasat TDP1 and ESA OGS**
  - Common 22-cm receive/transmit aperture
  - Tip/tilt pre-compensation
  - Full pre-compensation
- **Full pre-compensation, using adaptive optics, allows larger Tx aperture (antenna gain), and can compensate for strong boundary-layer turbulence**
  - Tx aperture size is limited by an-isoplanatism / point ahead
  - The system is more sensitive to residual pointing error / drift
- **Alpha-Up & Alphasat TDP1 are well suited as testbed for further investigations**

Acknowledgements

- **Thanks to ESA**
  - for funding the activity
  - for providing access to / support for the ESA OGS and its equipment

- **Thanks to Tesat-Spacecom GmbH**
  - for operating the Alphasat Laser Communication Terminal and the Transportable Adaptive Optics Ground Station
  - for providing the pre-processed sensor data

Thank You!