air-LUSI

airborne LUnar Spectral Irradiance Mission

Presented by Kevin Turpie

Earth Science Technology Forum
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Goddard Space Flight Centere
Greenbelt, MD

air-LUSI Team

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In Memoriam

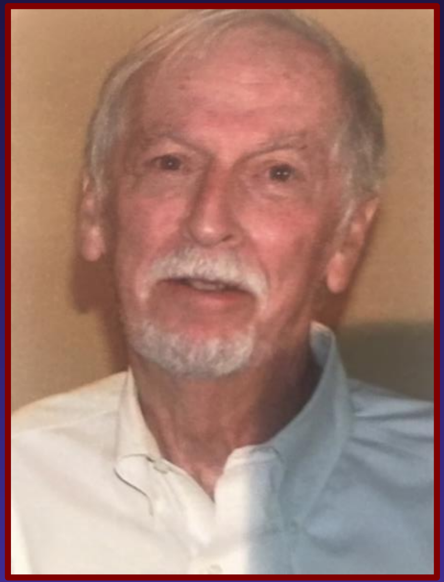
Keith Lykke

1956 - 2016

Bob Barnes

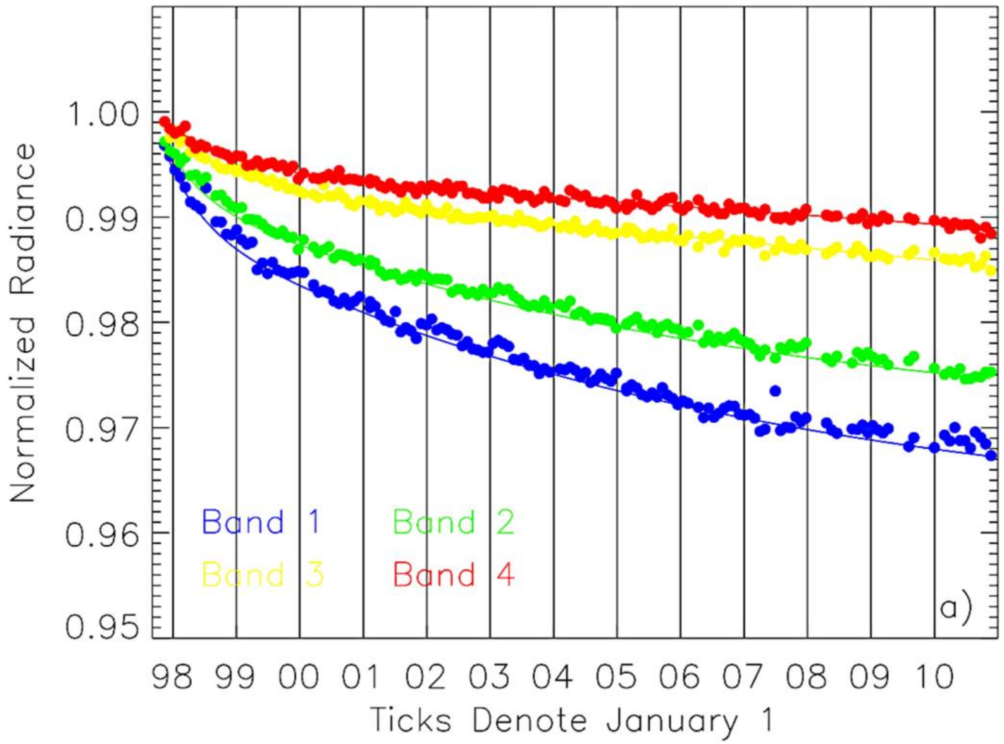
1947 - 2015

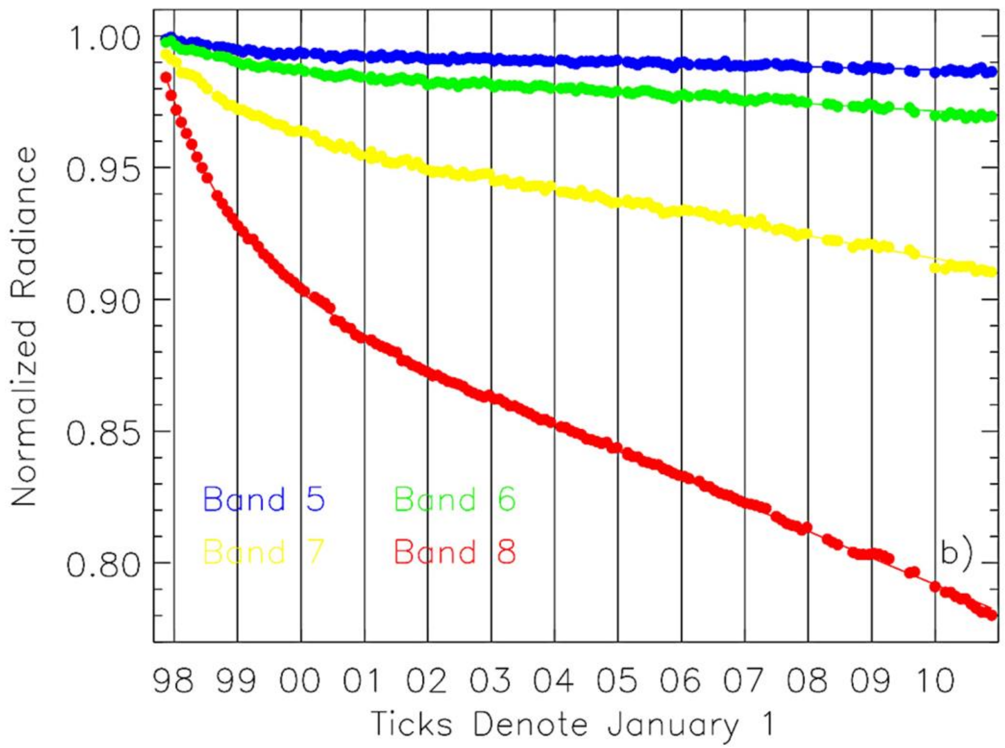
Dennis McCarthy



1940 - 2018

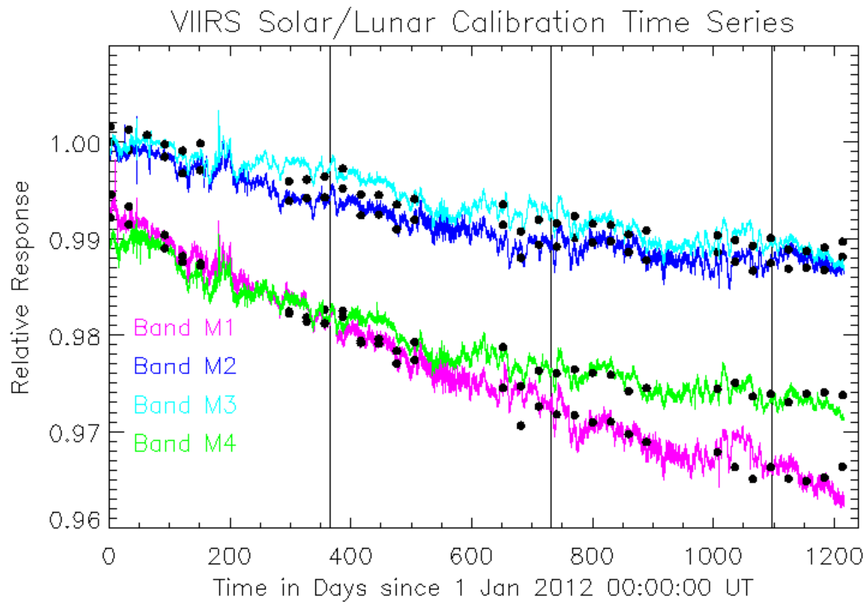
From Eplee et al. (unpublished)

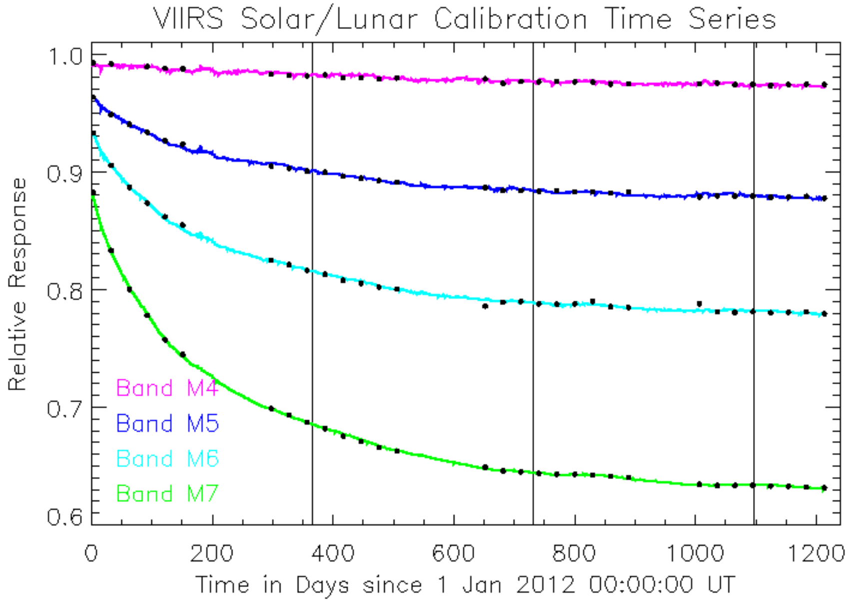


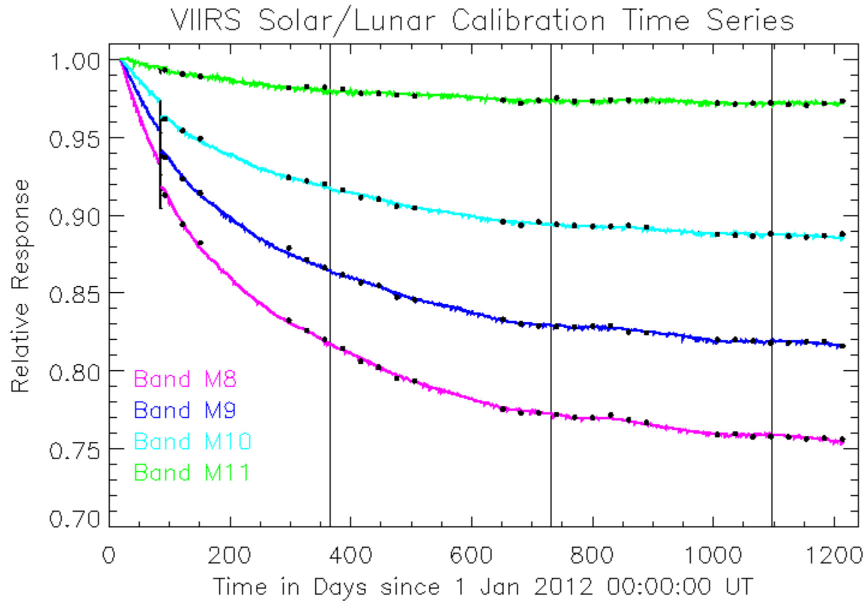


- **LUNAR CALIBRATION -** The Moon has proven invaluable in providing a time-dependent calibration for Earth observing satellites, especially for ocean color missions (e.g., SeaWiFS, VIIRS, and PACE).
- **ROLO MODEL** - Knowledge of the Moon's total spectral irradiance given any viewing and illumination geometry is provided by USGS's RObotic Lunar Observatory (ROLO) model.
- **ROLO IMPROVEMENT** - Very accurate measurements of lunar irradiance could expand the use of ROLO to a broader range of applications of the Moon as a reference for ocean color missions.

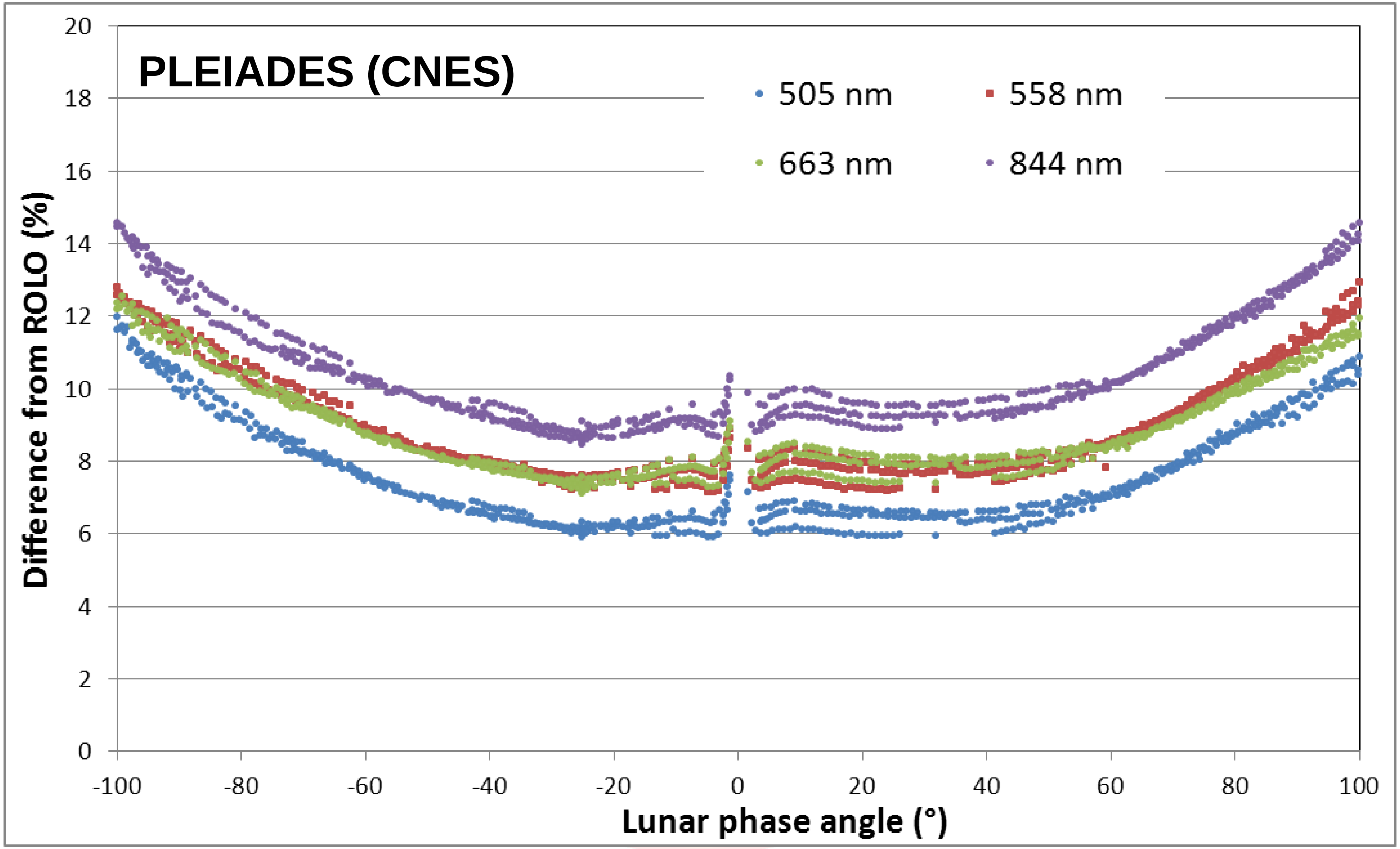
- Lunar calibration values, derived using ROLO were used for the time-dependent calibration of SeaWiFS.
- Lunar cal is now applied to Suomi NPP VIIRS to address small spurious trends in the solar calibration system.
- The PACE mission intends to use lunar observations for calibration.







Eplee, G., Turpie, K., Meister, G., Patt, F., Franz, B., Bailey, S., (2015). On-Orbit Calibration of the SNPP VIIRS for Ocean Color Applications, Applied Optics 54, 1984-2006

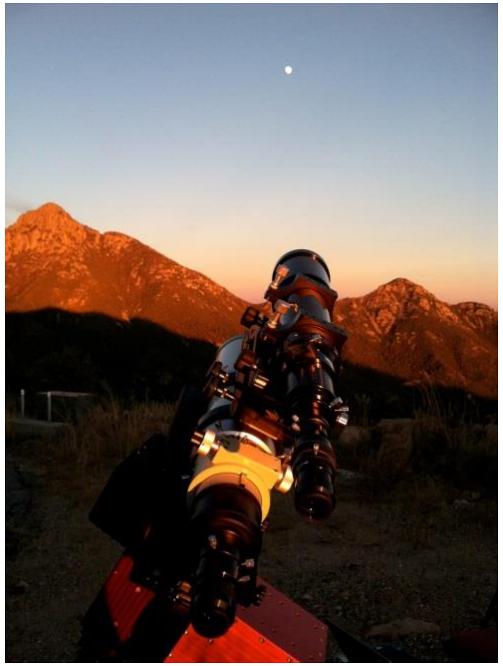


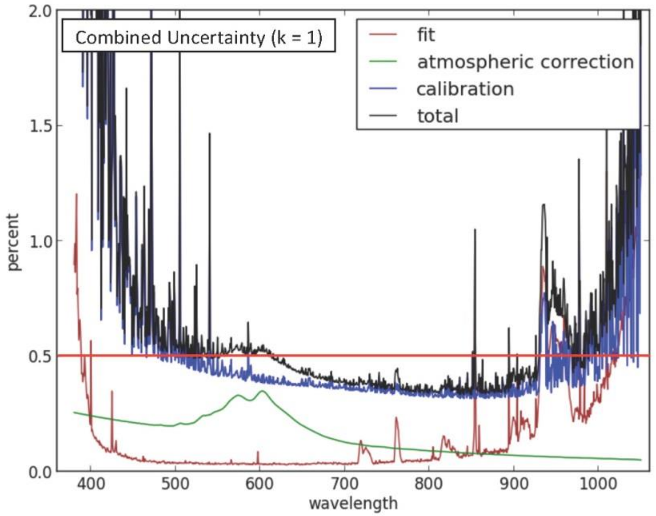
S. Lachérade — CNES

"ground" LUSI

NIST ground-based Lunar Spectral Irradiance (LUSI) project

- non-imaging optical system, COTS spectrometer: 390–1040 nm
- on-site calibration reference: 30 cm integrating sphere "artificial Moon"
- Mt. Hopkins, AZ: two nights in Nov. 2012 with good viewing conditions (out of three years).
  - atmospheric correction by Langley analysis of the lunar data
  - combined total uncertainty under 1% (*k*=1) from 400 nm to 1000 nm
- Current status: NIST staff is budgeted for setup at Mauna Loa, Hawaii (3397 m alt).





air-LUSI

Objective

- Advance the ground-based LUSI instrument system to fly on an ER-2 aircraft to measure lunar spectral irradiance ultimately to an unprecedented level of accuracy (<0.3% k=1 uncertainty) by flying above 90% of the Earth's atmosphere.
- Provide a capability to operationally acquire SI-traceable extraterrestrial lunar spectral irradiance over a broad range of viewing angles, lunar phases, and libration angles.

Impact: air-LUSI measurements can be used to enhance the Robotic Lunar Observatory (ROLO) model of exo-atmospheric lunar spectral irradiance, thus providing a highly accurate, stable calibration reference for Earth-observing satellite instruments over long time periods from the past into the future.

This is of particular value for space-based ocean color measurements, such as those from SeaWiFS, MODIS, VIIRS and PACE.

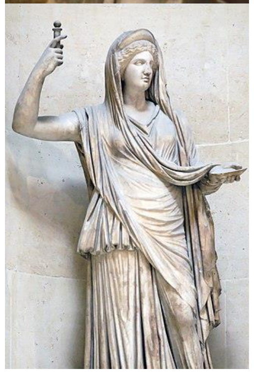
Approach

- **IRIS** - **IR**radiance **I**nstrument **S**ubsystem : a non-imaging telescope with integrating sphere feeding light via fiber optics to a spectrograph. An on-board validation source also sends light to the spectrograph via fiber optics.

- **ARTEMIS** - **A**utonomous, **R**obotic **TE**lescope **M**ount **I**nstument **S**ubsystem keeps telescope fixed on the Moon to within less than 0.1° .

- **HERA** - **H**igh-altitude **ER**-2 **A**daptation subsystem integrates subsystems and aircraft together. HERA team manages cables, interfaces and integration with the ER-2 aircraft and develops solutions to protect components from the extreme cold and low pressure during flight or high moisture from condensation during descent.

- Develop calibration protocol and detailed uncertainty budget. Perform pre-flight system-level tests, engineering flights, demonstration flights, and post-flight data analysis.



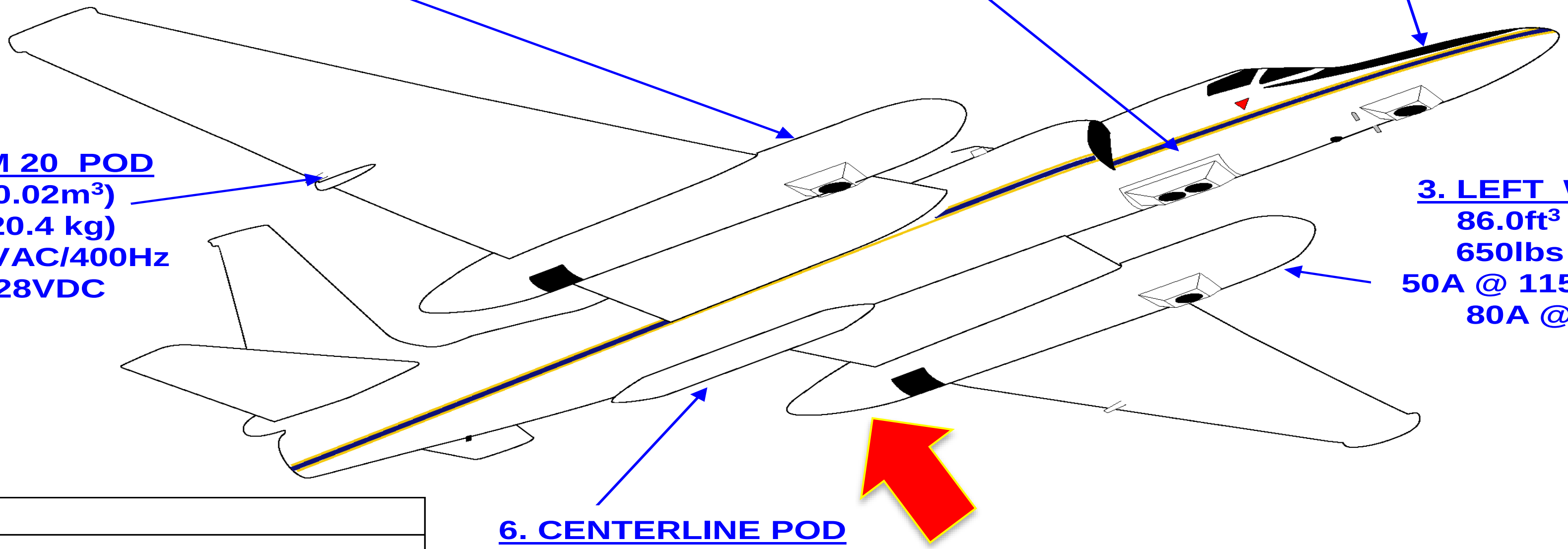
ER-2 Basic Configuration

4. RIGHT WING POD
86.0ft³ (2.43m³)
650lbs (294 kg)
50A @ 115VAC/400Hz
80A @ 28VDC

2. Q-BAY
64.6ft³ (1.83m³)
1000lbs (454 kg)***
100A @ 115VAC/400Hz
140A @ 28VDC

1. NOSE
47.8ft³ (1.35m³)
700lbs (317 kg)***
50A @ 115VAC/400Hz
70A @ 28VDC

5. SYSTEM 20 POD
0.74ft³ (0.02m³)
45 lbs (20.4 kg)
30A @ 115VAC/400Hz
30A @ 28VDC



3. LEFT WING POD
86.0ft³ (2.43m³)
650lbs (294 kg)
50A @ 115VAC/400Hz
80A @ 28VDC

6. CENTERLINE POD
14.0ft³ (0.40m³)
350lbs (159 kg)
Electrical Shared with Q-Bay

*** - Max combined Q-Bay and Nose payload cannot exceed 1300lbs

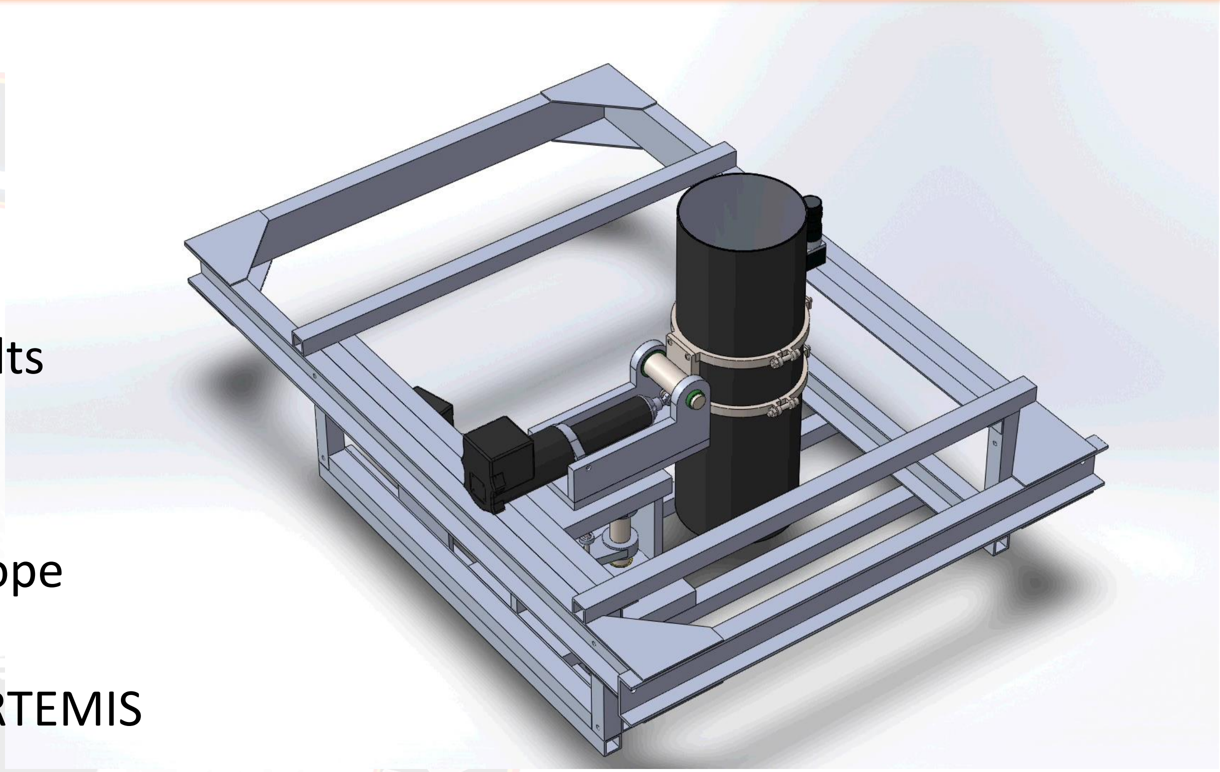
Specifications

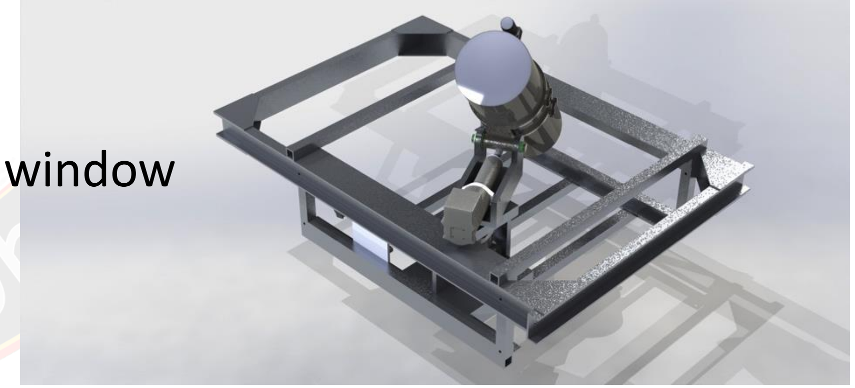
Crew:	One Pilot
Length:	62 feet, 1 inch
Wingspan:	103 feet, 4 inches
Engine:	One General Electric F-118-101 engine
Altitude:	Above 70,000 feet
Range:	Over 6000 nautical miles, subject to pilot duty time limitations
Duration:	Over 10 hours
Cruise Speed:	~400 knots above 65,000 feet altitude (~210 Meters/sec)

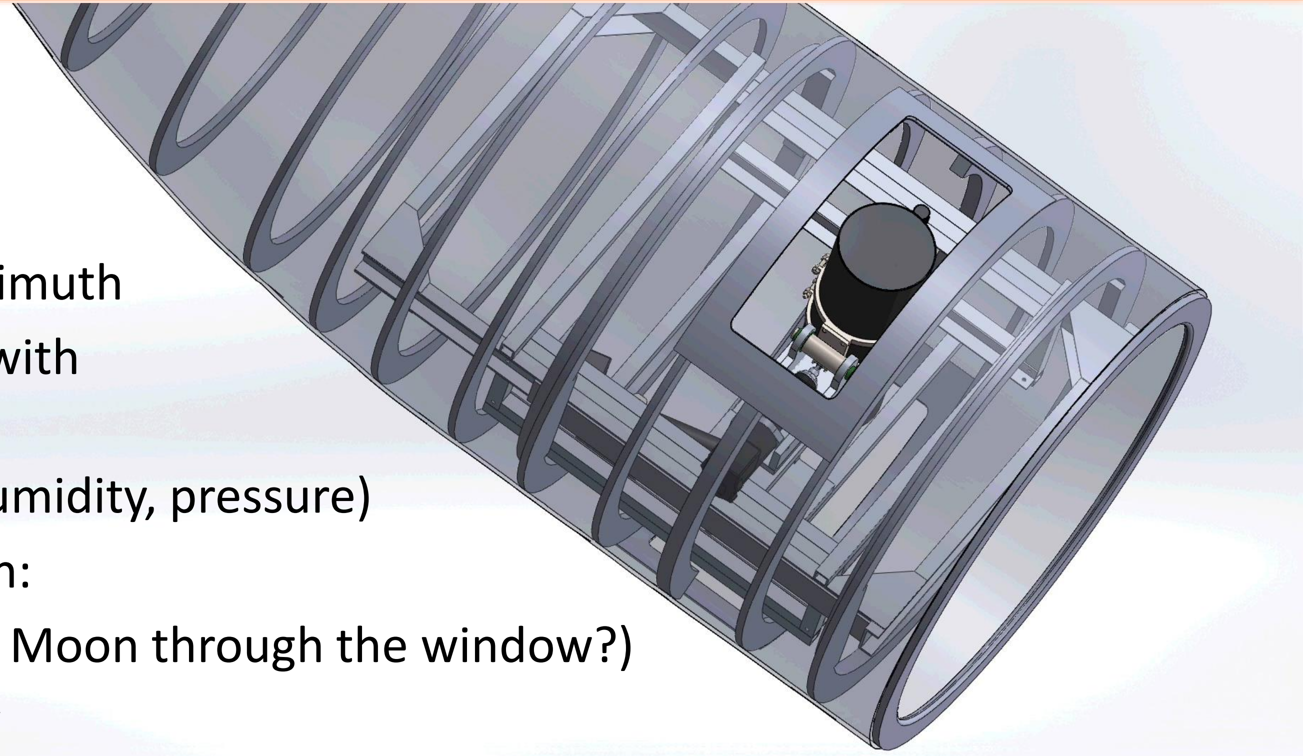
Autonomic Robotic TElescope Mount Instrument Subsystem (ARTEMIS)

ARTEMIS – Overall Design

- Frame is primarily composed of aerospace-grade square-tubing (Al 6061-T6)
  - Simpler fabrication and construction
  - No welds are used; only approved/certified bolts
    - Ease of installation and movement
- Telescope (designed and built by NIST) was designed in parallel with 'straps' that will securely hold telescope during desired movements
  - CAD models were shared between LUSI and ARTEMIS to minimize any integration issues
  - 'Internal rings' of telescope align with straps to minimize flexing or unwanted stresses on telescope
- ARTEMIS dimensions were constrained by telescope, pod, and window
  - Telescope dimensions were maximized in order to improve data collection





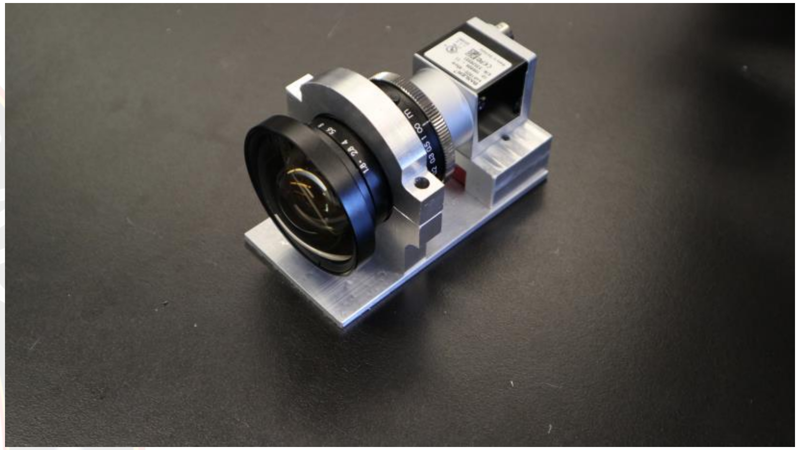


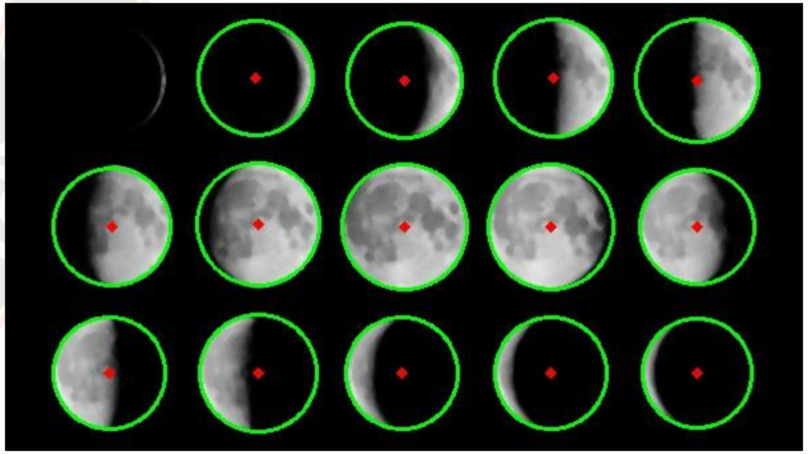
ARTEMIS – Overall Design

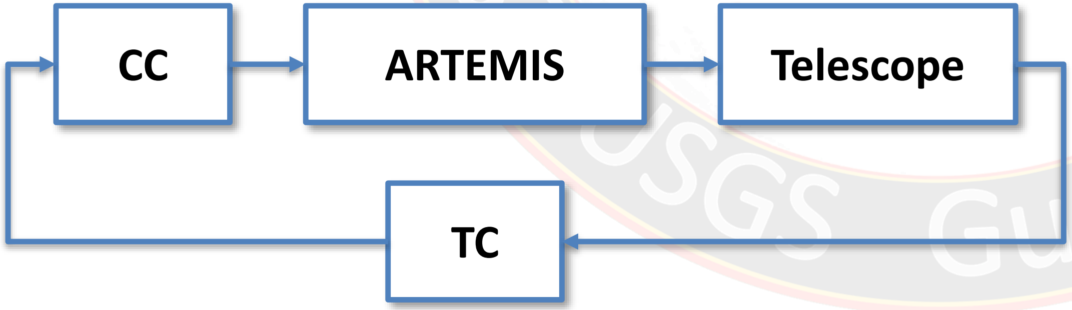
- Two linear aerospace-grade actuators were selected based on:
  - Two tracking movements: elevation and azimuth
  - Force required to reliably move telescope with good precision and repeatability
  - Environmental conditions (temperature, humidity, pressure)
- Tracking camera and lens were selected based on:
  - Window Field of Regard (i.e., can it see the Moon through the window?)
  - Dimensions of enclosed space and window
  - Resolution of images, pixel size, and data output to control computer
- Cylindrical bearings are extremely low-friction and repeatable for harsh environments
- Inertial measurement unit (IMU) will provide additional data for offline analysis
- Control computer is sufficiently small, portable, and computationally powerful enough to perform required calculations and to send the appropriate control signals to the actuators

ARTEMIS – Expected Performance

- Expected range of motion:
  - Elevation of Moon: 47° to 90°
  - Azimuth: ±15°
    - Based on unrestricted field of regard
    - Restricted by window geometry and telescope dimensions
- Expected tracking accuracy
  - air-LUSI mission requirement is 0.5° or better
  - ARTEMIS personal target of 0.25° or better
    - Depends on flight path and pointing device
- How do we control the telescope and track the Moon?





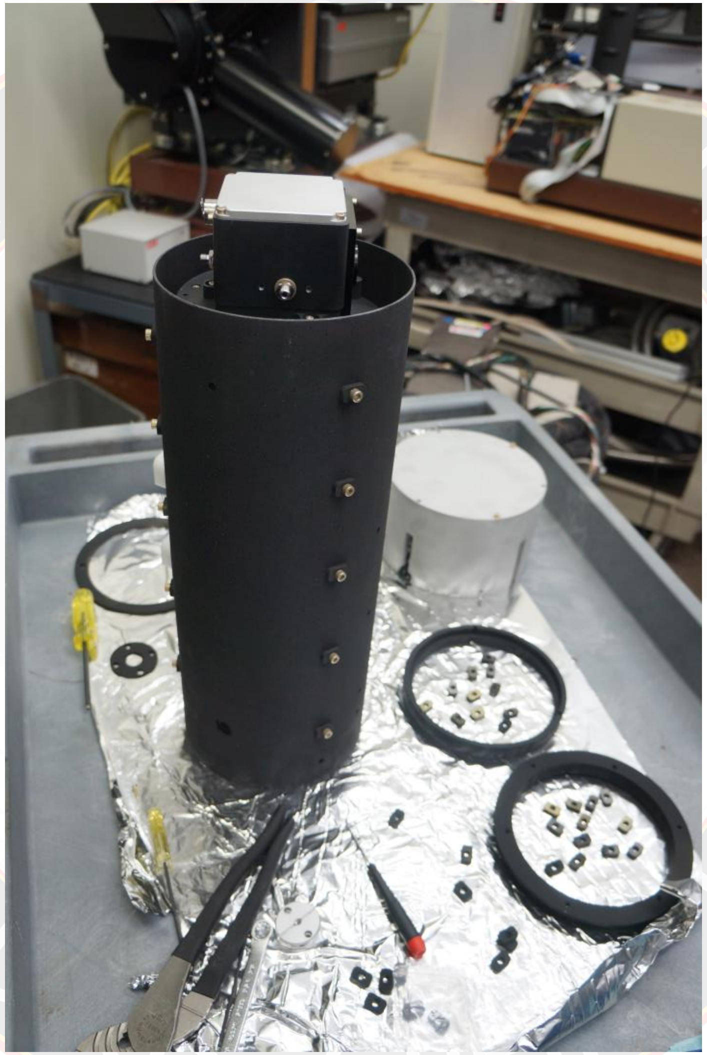


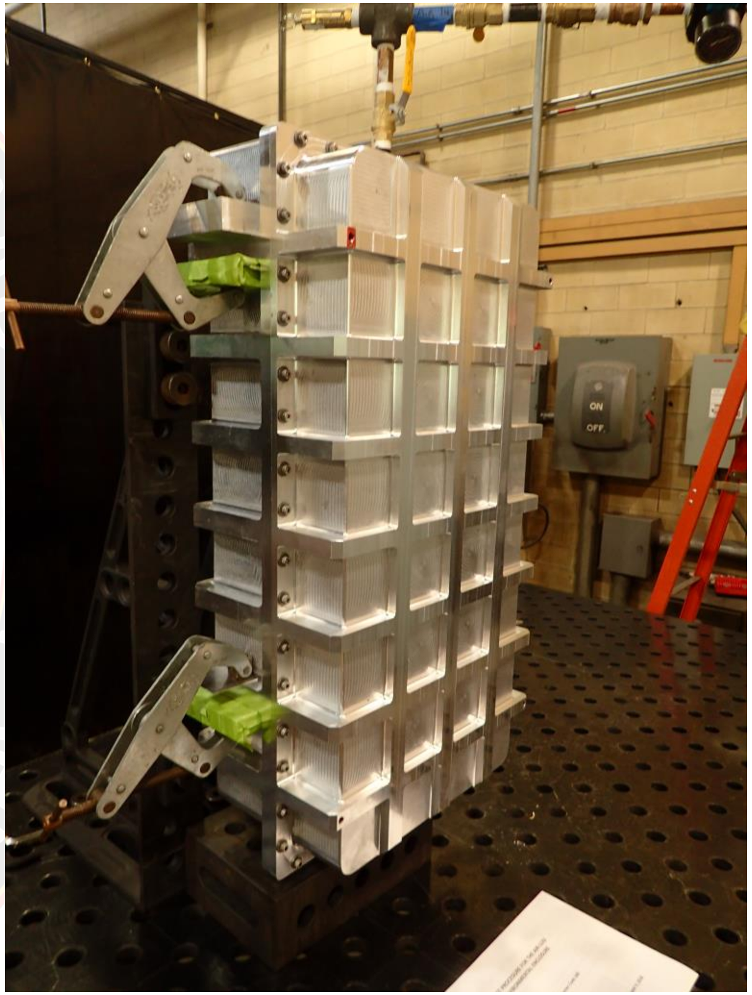
IRradiance Instrument Subsystem (IRIS)

IRIS Subsystem

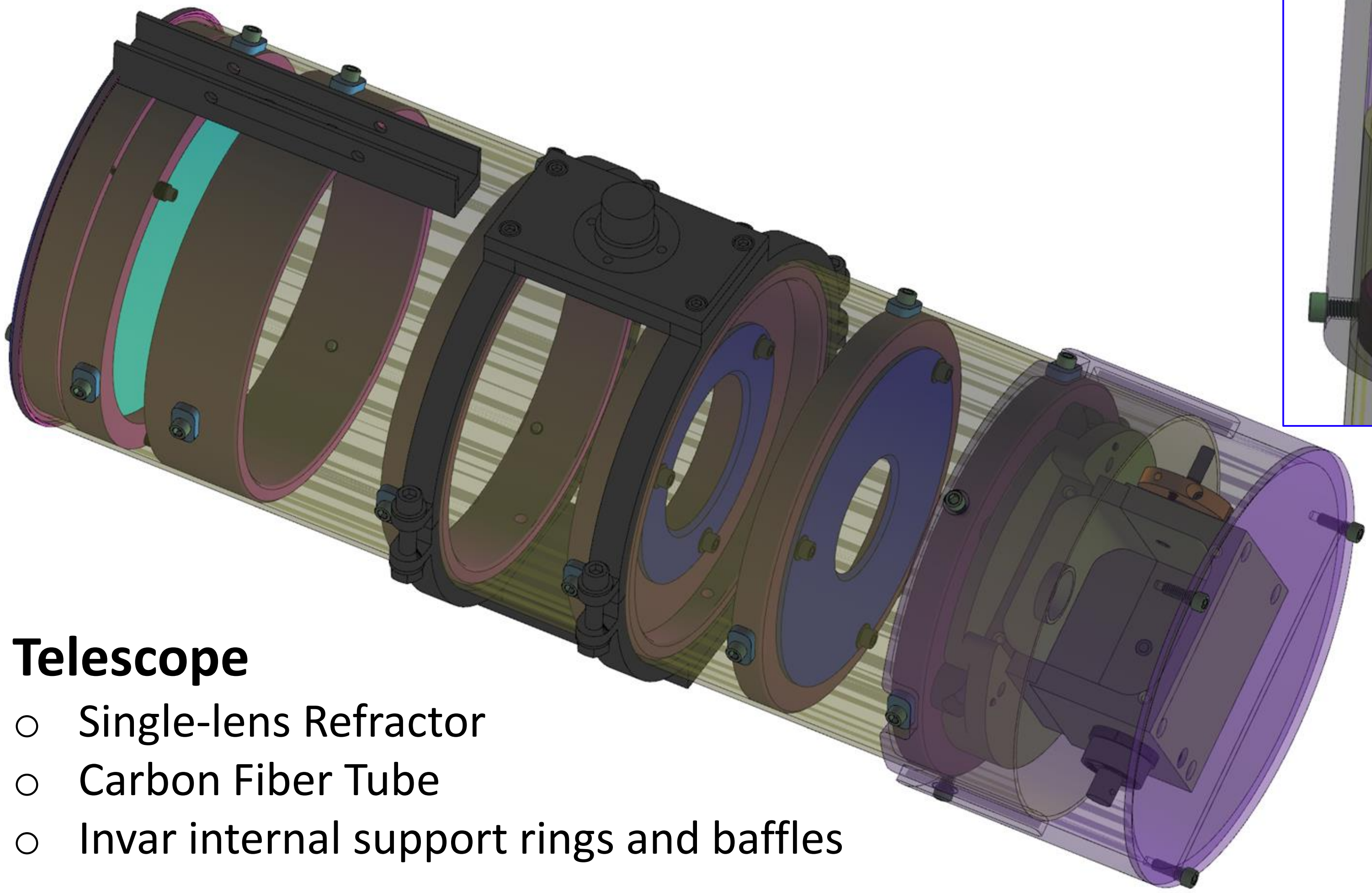
Major Components

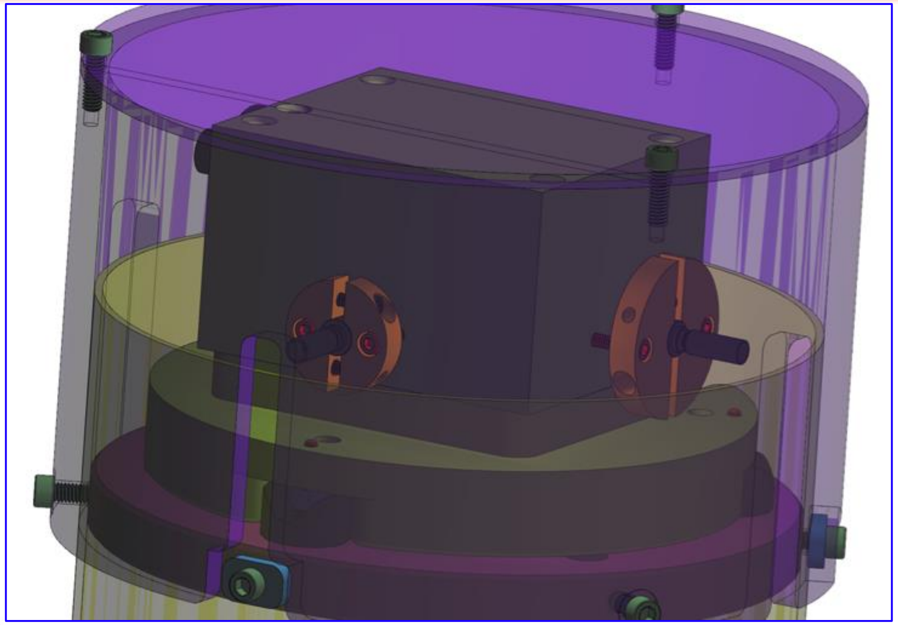
- Instrument Enclosure
- Telescope
- Integrating sphere
- Spectrograph
- Fiber Bundle
- Validation source
  - LEDs
- Data Logger
- Instrument Computer





Telescope Design





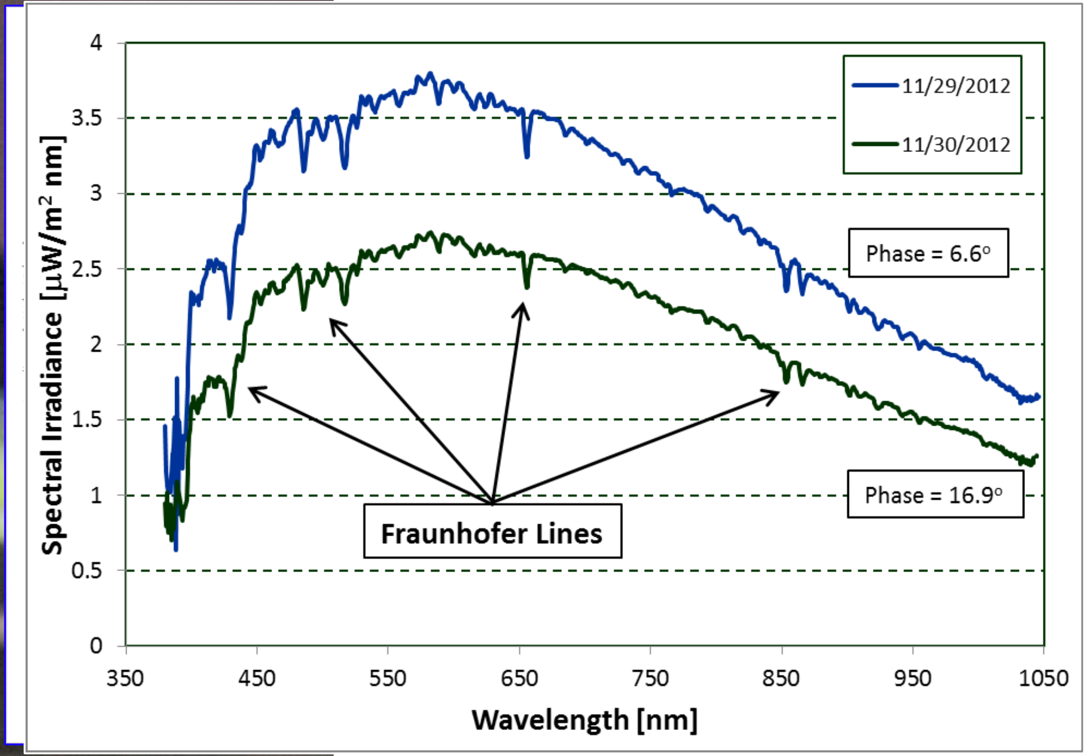
Telescope

- Single-lens Refractor
- Carbon Fiber Tube
- Invar internal support rings and baffles

Integrating Sphere

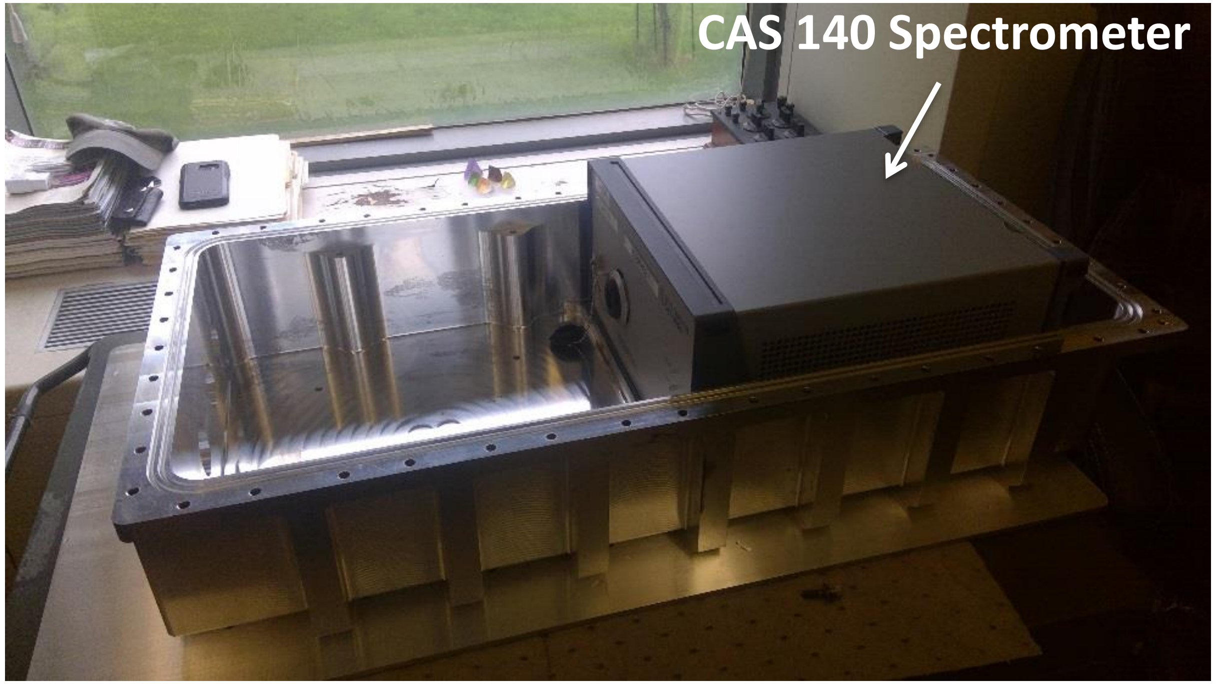
- Used for collecting light
- Removable
- Improves accuracy
- Scrambles polarization
- Fiber optic ports for
- Spectrometer
- LED Validation Source

First Moonlight



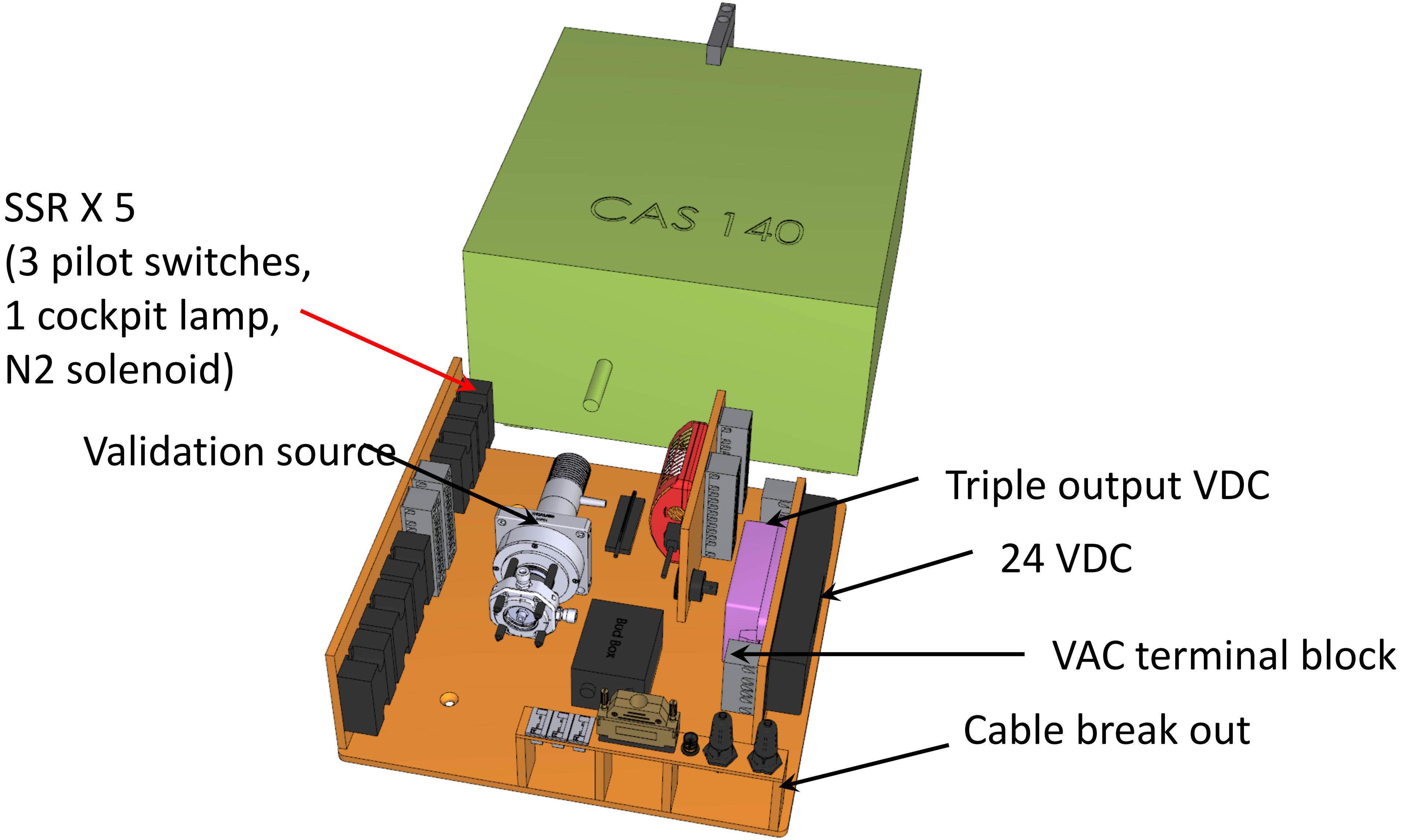
IRIS Instrument Enclosure – NIST in a Box

- Holds spectrograph, validation source, and instrument computer.
- Temperature and pressure are maintained at sea-level
- Formally pressure tested to 20 psig for 5 hours (18 hours in pre-check), with no measurable deformation.

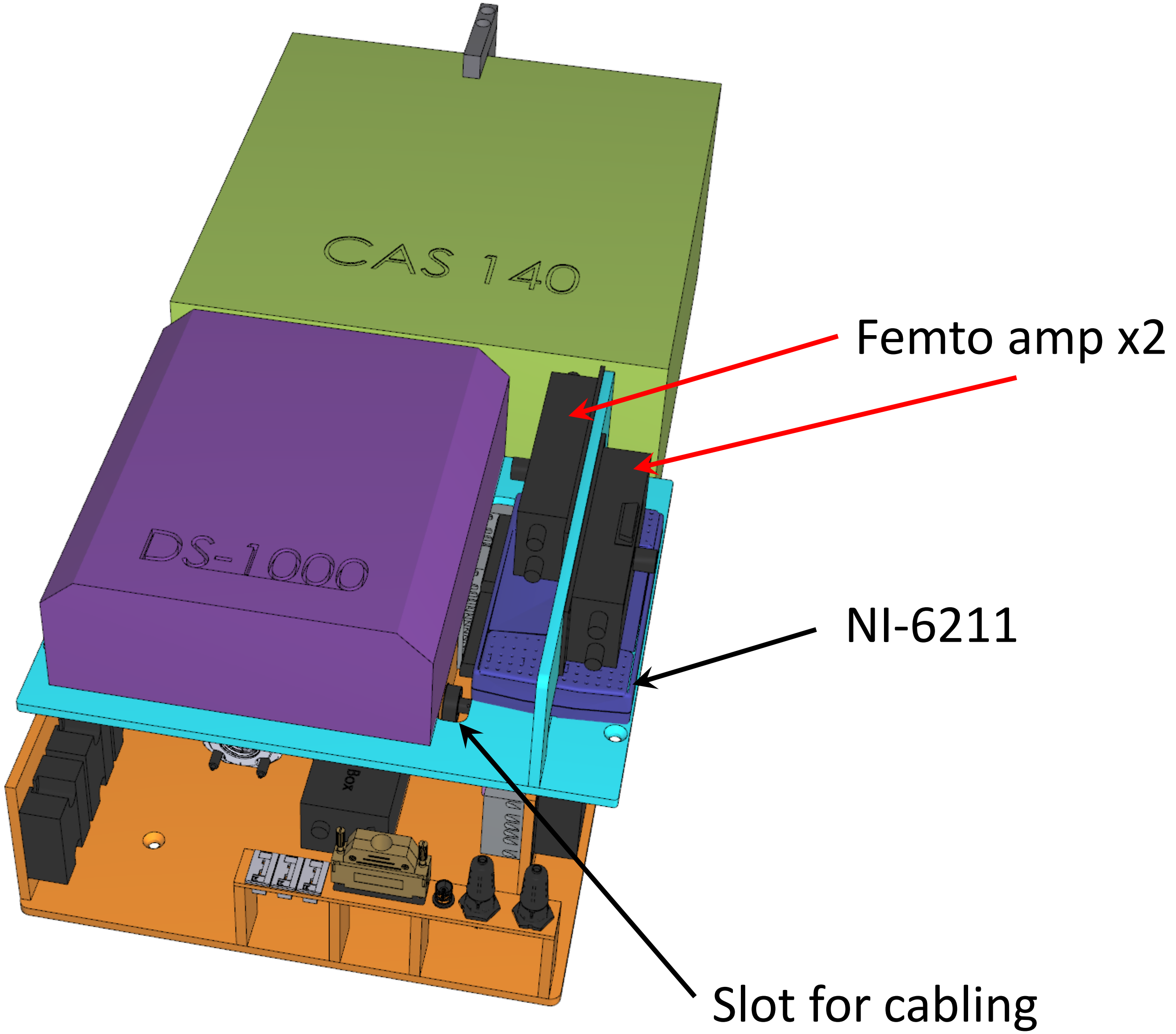


3D-Printed, 2-level interior rack

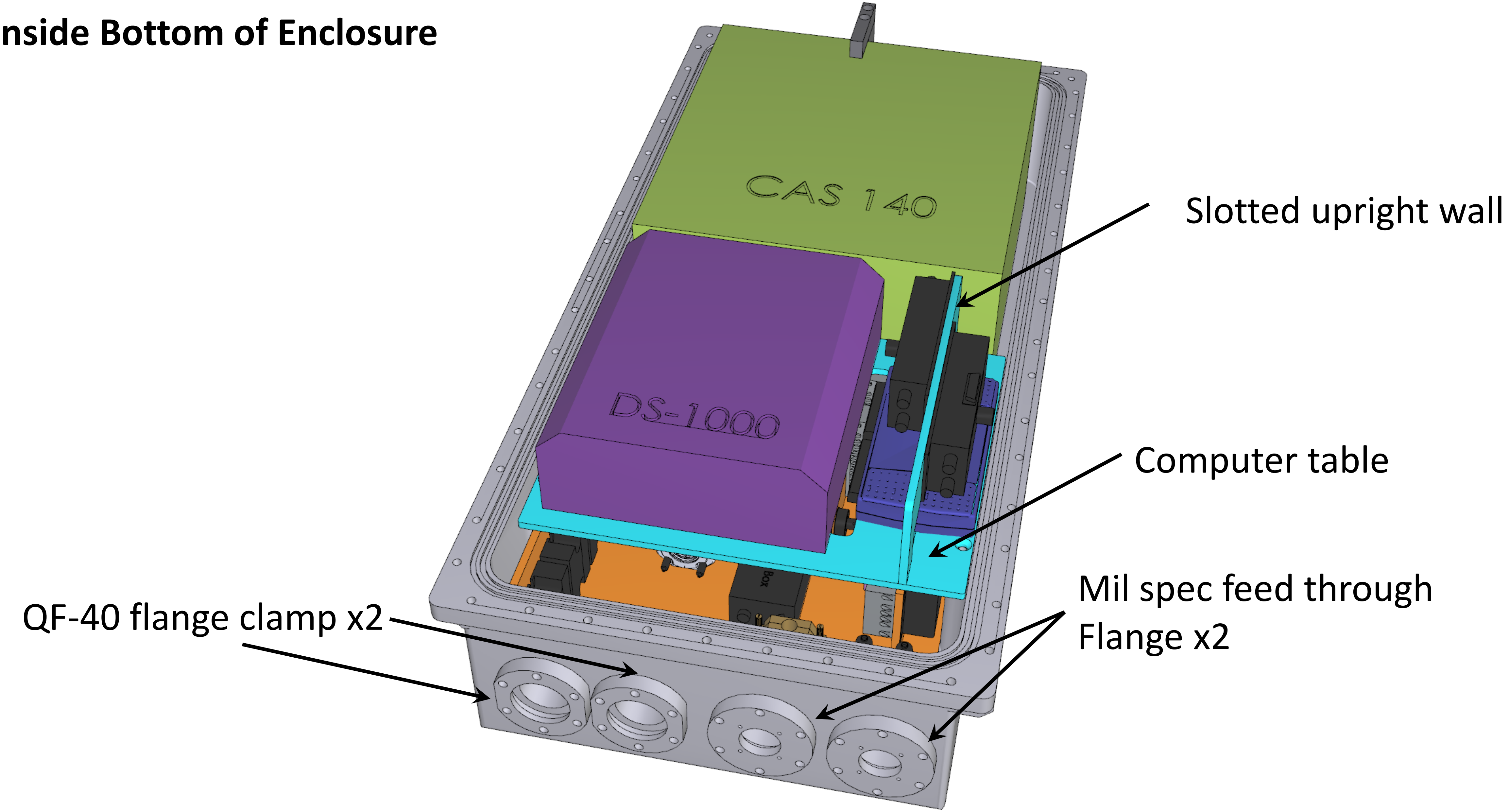
Bottom Level



Top Level



Inside Bottom of Enclosure

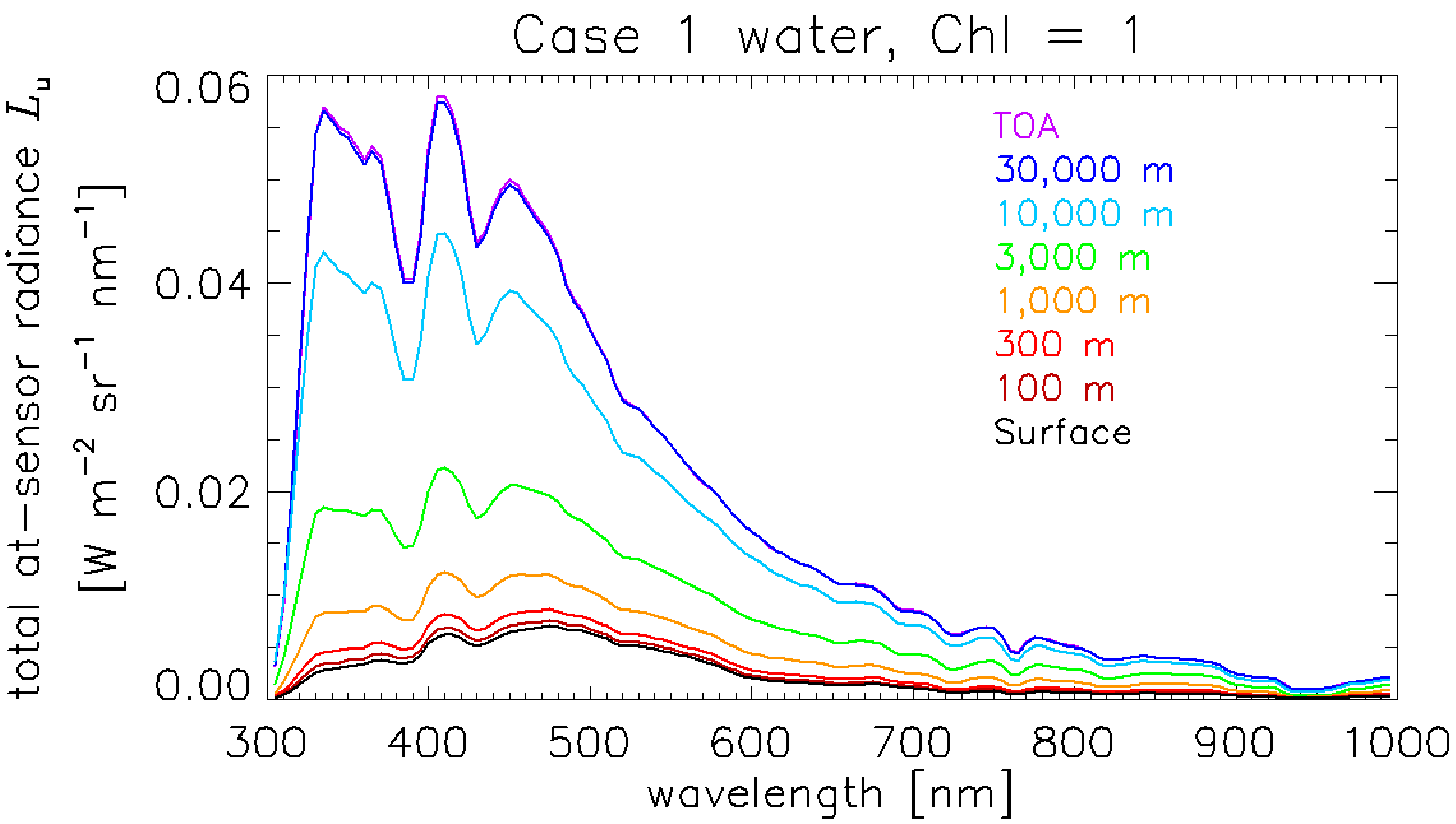


PREPARATION BEFORE MAIDEN FLIGHTS

- Engineering flights are scheduled for data collects at 0400 Aug 1 & 2.
- ARTEMIS is being moved from U of Guelph to NIST today and integration begins.
- Parts for Thermal Management System (HERA) are already at NIST.
- Cables are being prepared for integration (HERA).
- IRIS Enclosure will be populated in the next week.
- Several tests are planned for subsystems and systems before shipping to AFRC.
    - Thermal Tests (T/VAC & Environmental Chamber)
    - Alignment Calibration for ARTEMIS
    - "Pick-Up" test – Full system mobile, tracking the Moon (late June).
- Shipping is schedule for 13 July 2018, with arrival on 16 July 2018
- Team mobilizes and arrives at AFRC on 16 July to begin aircraft integration work.
- Current Priorities: Thermal Management System functionality, Cable development, and meeting all airworthiness targets.

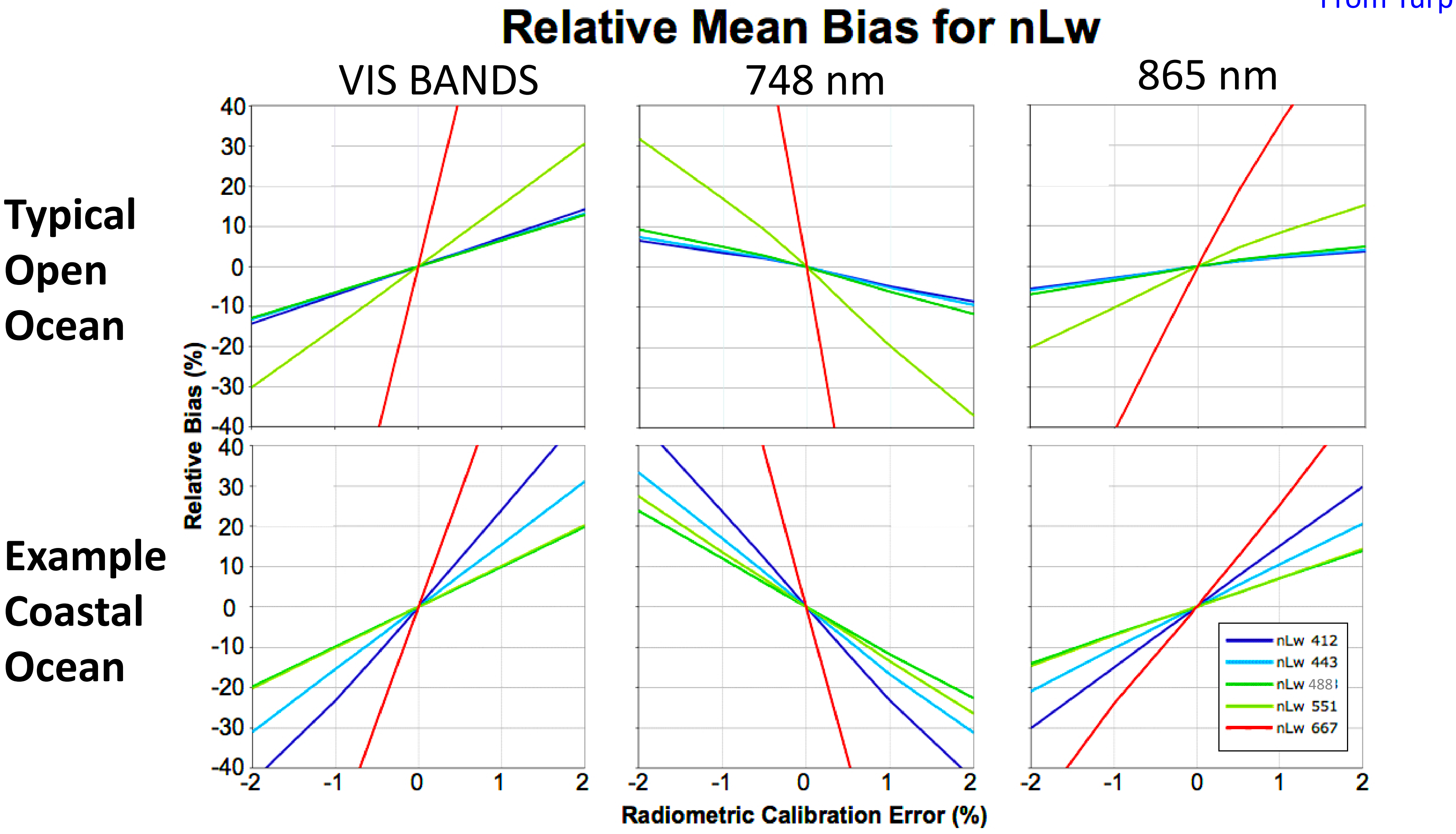
THANK YOU

BACKUP SLIDES



Mobley, C.D., 2013. The Atmospheric Correction Problem," in Ocean Optics Web Book, http://www.oceanopticsbook.info/view/remote_sensing/the_atmospheric_correction_problem, accessed 18 March 2013.

From Turpie et al. 2009



A small relative error in the at-sensor measurement leads to a relative error in the surface measurement that is an order of magnitude larger.

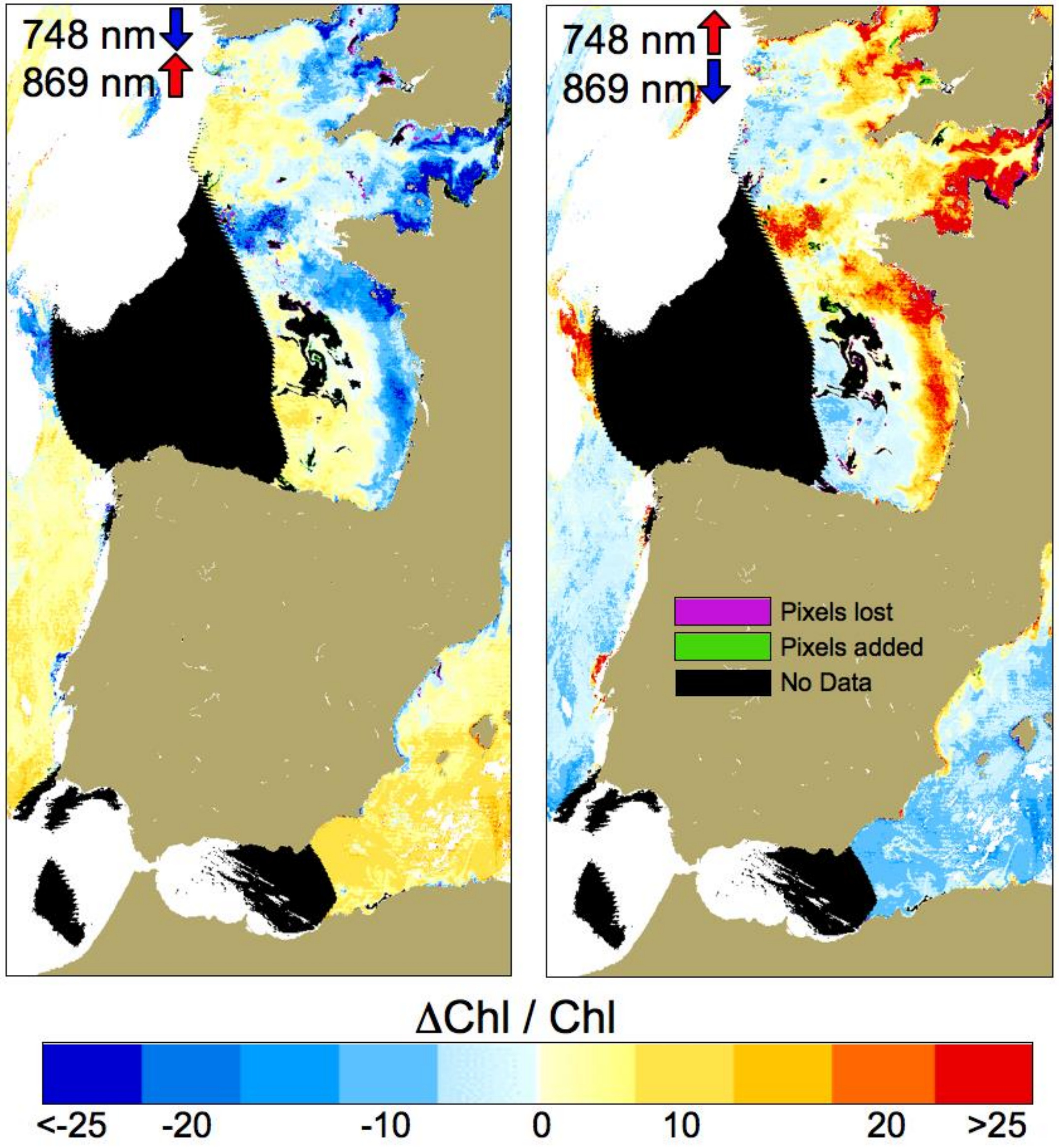
Individually or in combination these errors can affect estimates of biogeophysical parameters.

For instance, changes in opposite directions in the NIR channel can cause coastal and open ocean chlorophyll *a* to change in opposite directions.

Small drifts in calibration over time can lead to misinterpretation of geophysical observations.

Hence, we need an accurate, stable time-dependent calibration of ocean color sensors.

From Turpie et al. 2009



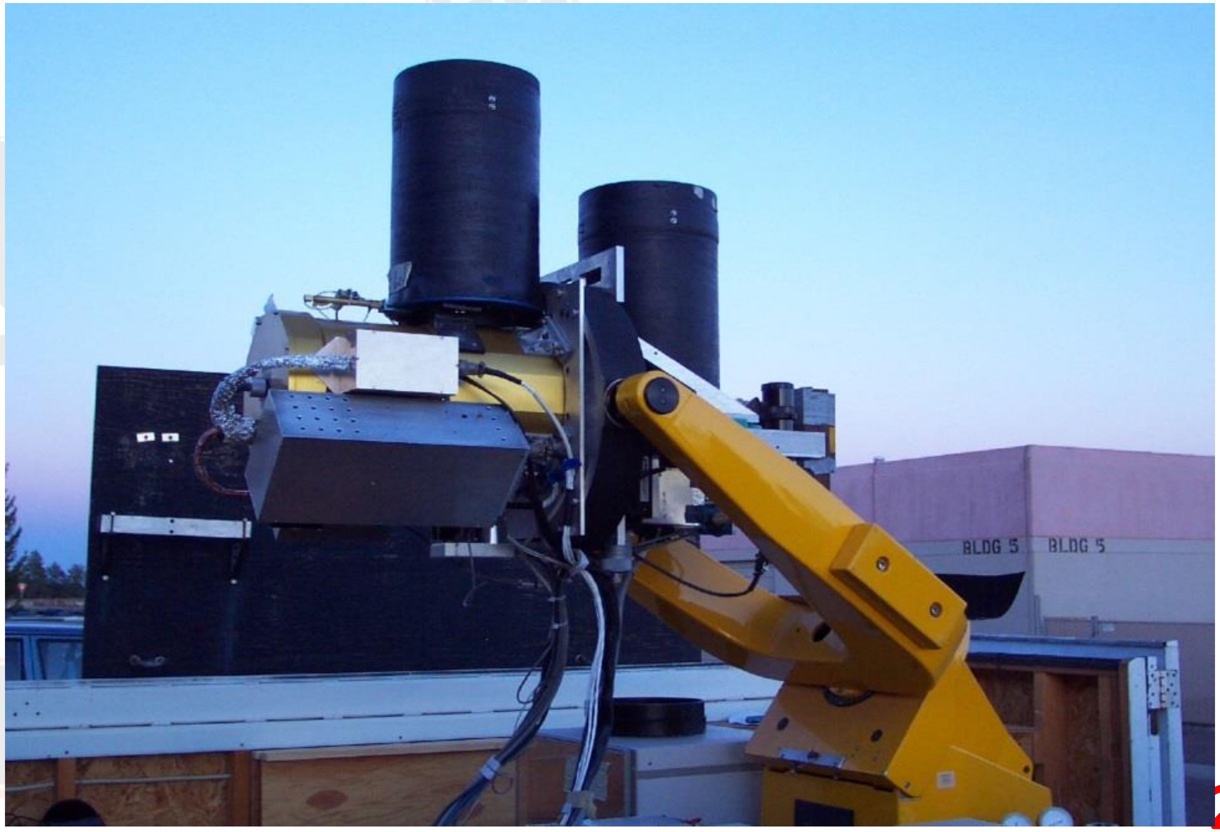
DEVELOPMENT OF THE ROBOTIC LUNAR OBSERVATORY MODEL (ROLO)

Extensive characterization of the Moon using ground-based measurements acquired by a dedicated facility —

the Robotic Lunar Observatory (ROLO):

- Located on USGS Flagstaff campus, 2143m altitude
- Twin telescopes, 20 cm dia.
  - 23 VNIR bands, 350−950 nm
  - 9 SWIR bands, 950−2450 nm
- Imaging systems — radiance
- > 110,000 Moon images
  - phases from eclipse to 90°
- > 900,000 star images
  - used for atmospheric transmission corrections

ROLO telescopes zenith-pointed at dusk



Limitations of the Current System

Although the ROLO model is the most precise and reliable lunar radiometric reference available, it typically is not used for absolute calibration.

Why not?

Uncertainty in the model absolute scale is ~5-10%

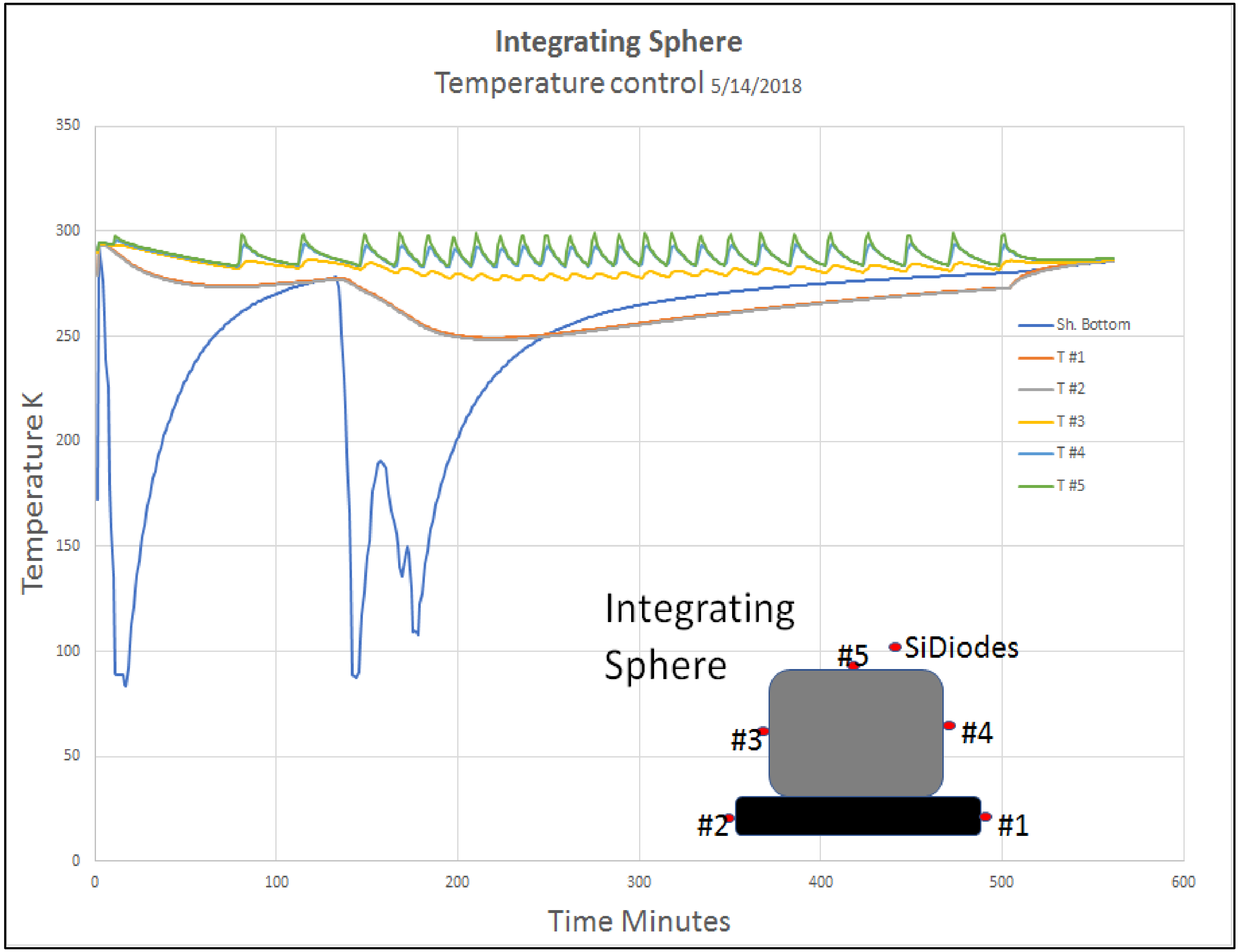
- originates with the ROLO telescope dataset
- the main source of error is the atmospheric correction
  - derived nightly from star observations, but airmass range is limited to ≤2
  - applies also to Vega, which is the calibration reference for ROLO

The current absolute accuracy limitation is solely with the lunar model.

The Moon potentially can provide an absolute calibration reference with total uncertainty under 1% (*k*=2)

To achieve a high-accuracy, SI-traceable absolute lunar calibration reference requires acquisition of a new measurement database.

From Tom Stone, CEOS WGCV IVOS-29 Meeting 15 Mar 2017



TVAC Test

- Demonstrated survivability of telescope, i.e., repeatability of measurements.
- Test showed that heating system on the integrating sphere work well to stabilize its temperature.

The system consists of a refracting telescope that focuses the lunar light into an integrating sphere which is fiber coupled to a spectrograph. Advantages include a low sensitivity to lunar shape and polarization and a relatively simple in-field calibration protocol. The spectrograph is extensively characterized using NIST's SIRCUS facility.

LUSI Ground-based lunar telescope system

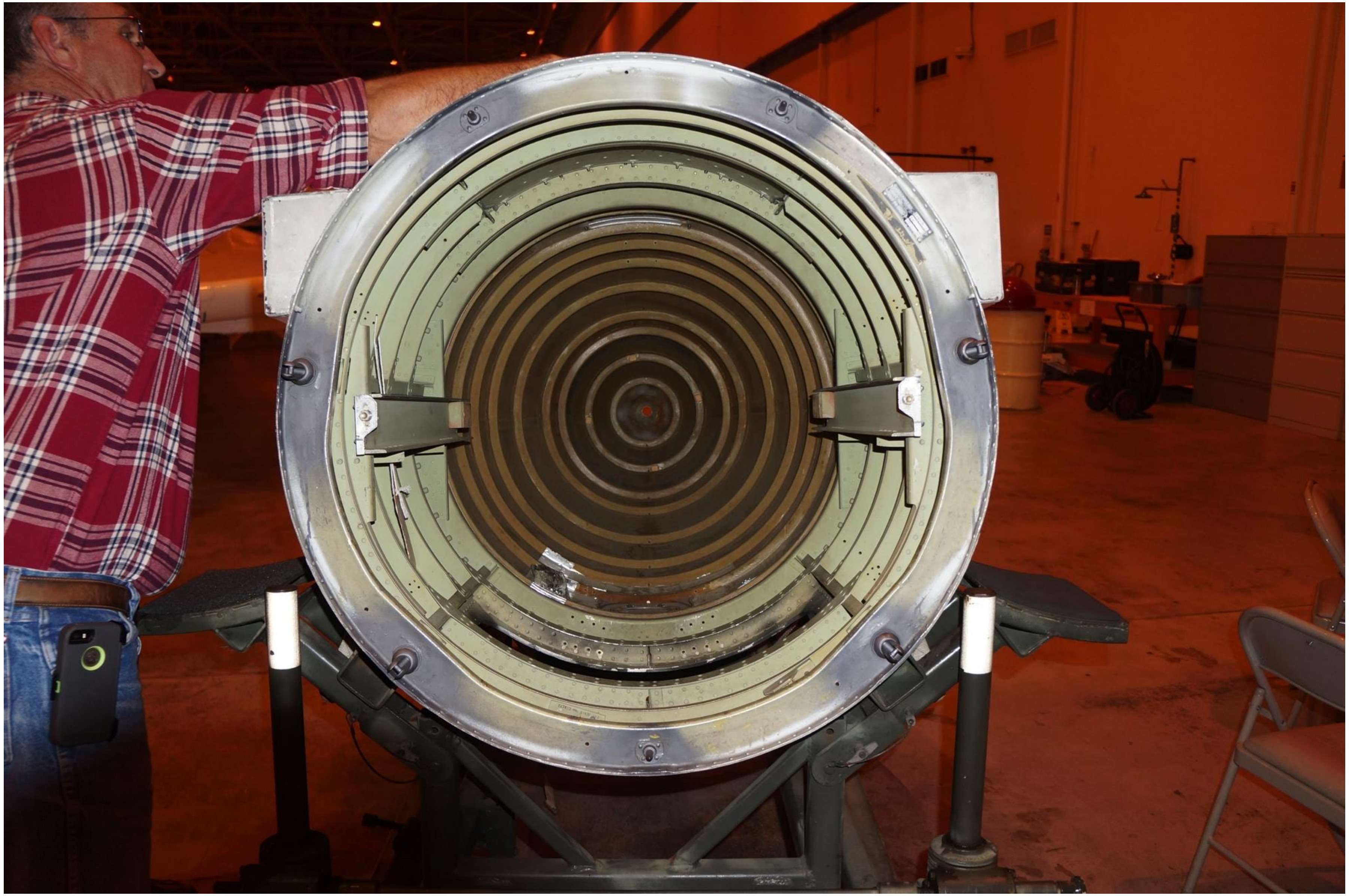
CAS spectrograph

ER-2 SuperPod Midbody Payload Area

Forward Midbody looking Aft

Lower Midbody looking Up and Aft

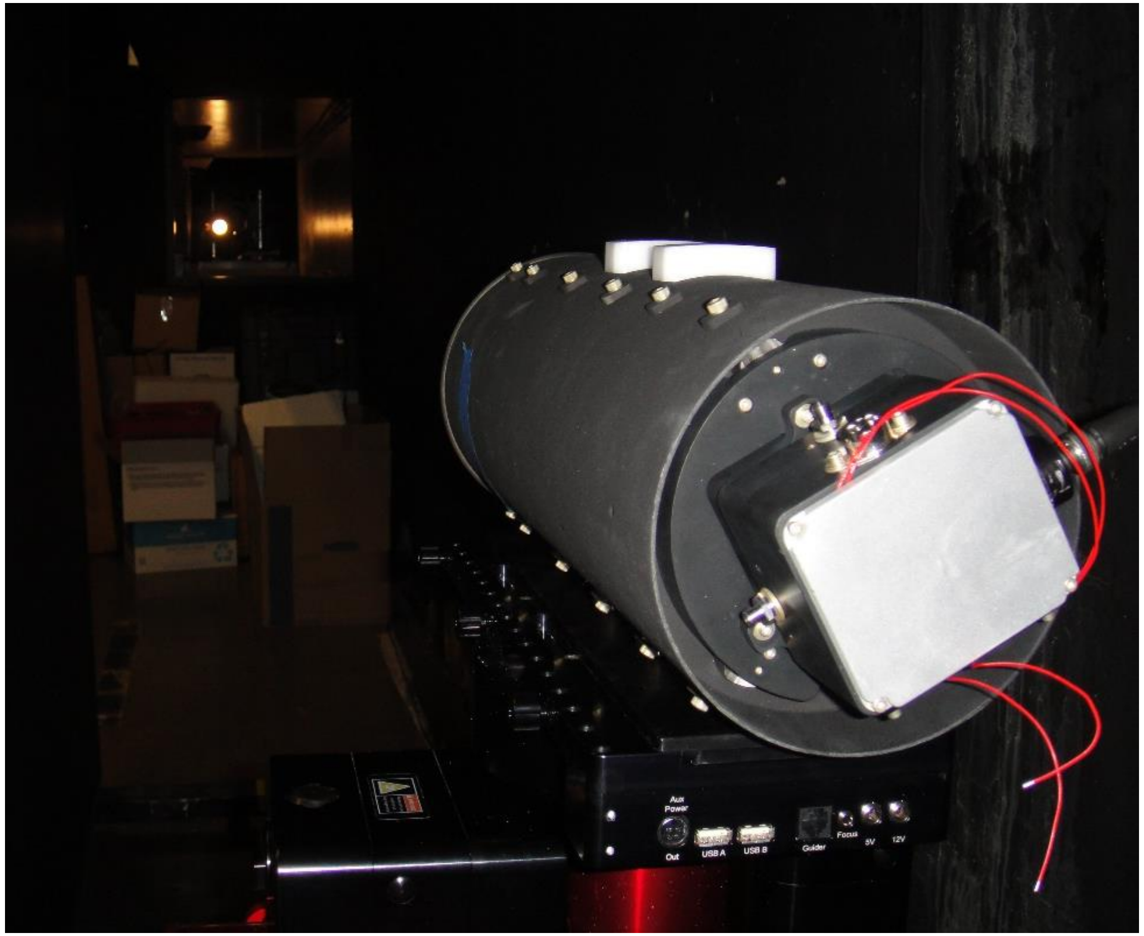
ER-2 Aft-Body Payload Area



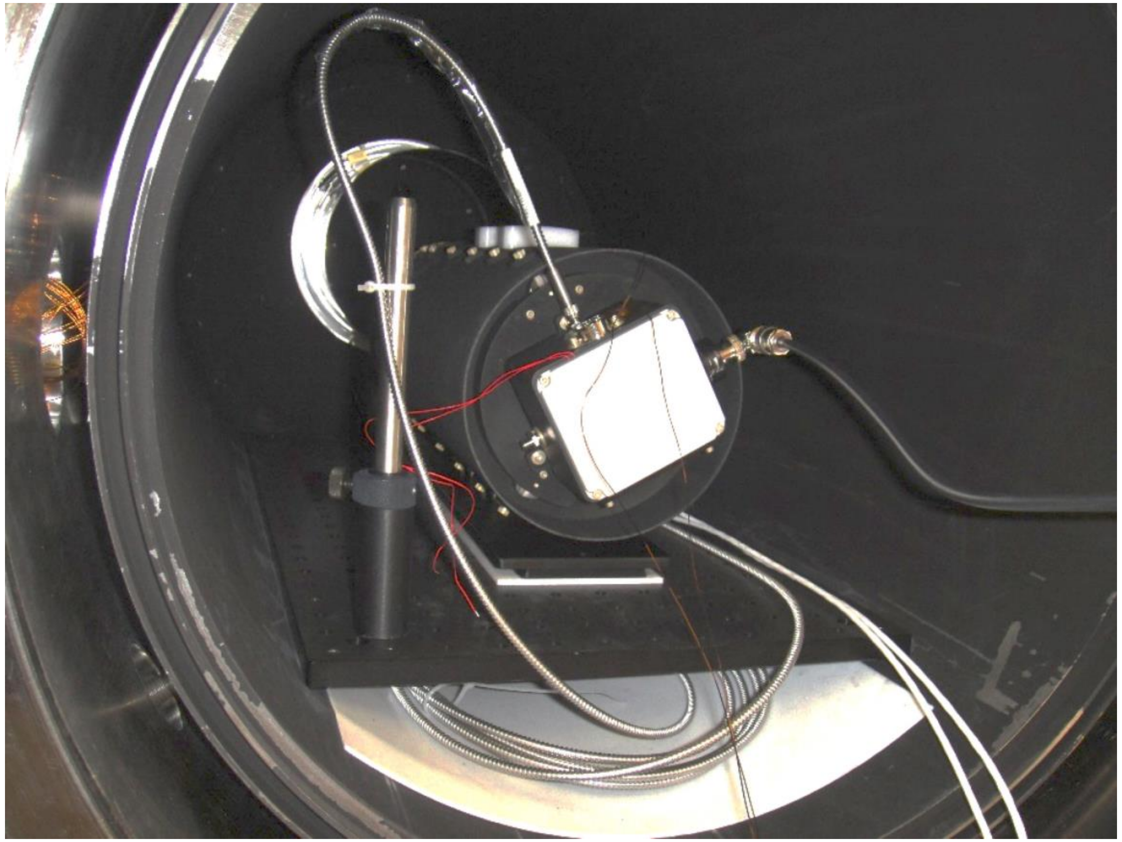
Removable Alignment Camera

- Use for test telescope alignment
- Stray light testing
- Aligning ARTEMIS tracking camera

Tunnel Test



Tunnel Test 1: Back view of the telescope on a Mount looking toward a source, white circle in the background. The white oblong 'disks' on the top of the telescope body are Teflon. They and are used during TVAC testing.



TVAC Test: View of the telescope installed in the TVAC chamber from the back. Toward the front end of the picture is the integrating sphere detector. The Teflon on the bottom of the chamber is to protect the fiber from getting too cold.