air-LUSI

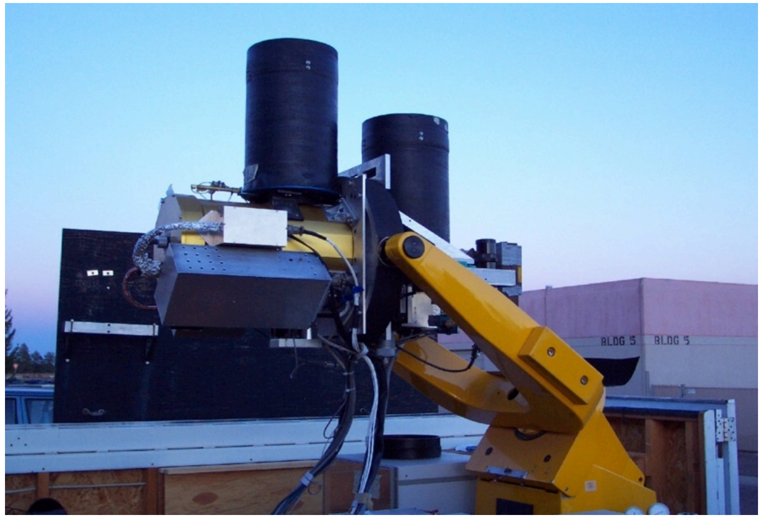
airborne LUnar Spectral Irradiance Mission

Presented by Kevin Turpie
18 October 2018
MODIS/VIIRS Science Team Meeting
Silver Spring, Maryland

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?



ROLO telescopes zenith-pointed at dusk

Uncertainty in the model absolute scale *may be* ~5-10%

- originates with the ROLO telescope empirical dataset
- the main source of error is the atmospheric correction

The current absolute accuracy limitation is <u>solely with the lunar model</u>.

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

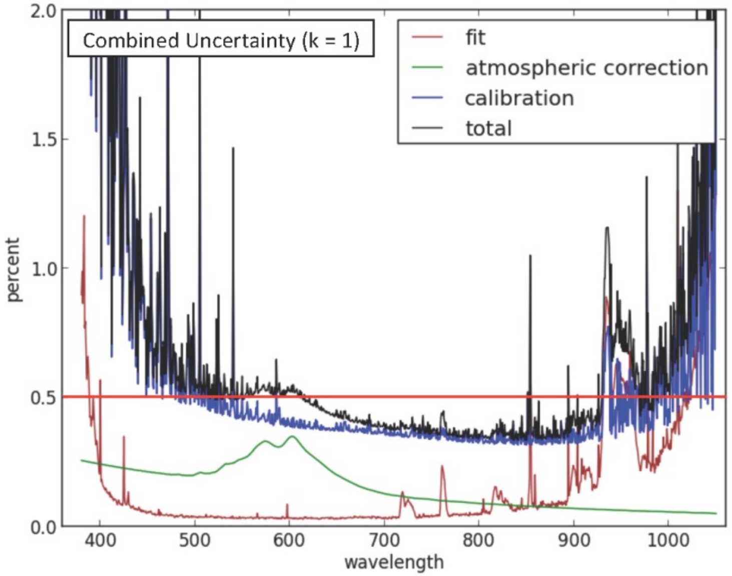
To achieve a high-accuracy, SI-traceable absolute lunar calibration reference requires acquisition of a new measurement database.

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

"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).



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

air-LUSI Objectives

- **Fly** the ground-based LUSI system above 90% of the Earth's atmosphere on an ER-2 aircraft to measure lunar spectral irradiance ultimately to an unprecedented level of accuracy (<0.3% k=1 uncertainty).

- **Provide a capability** to operationally acquire SI-traceable extraterrestrial lunar spectral irradiance over a broad range of viewing angles, lunar phases, and libration angles.

air-LUSI Team

Kevin Turpie, PI (UMBC/GSFC 616.2)
Steve Brown, Co-I (NIST)
John Woodward, Co-I (NIST)
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Clarence Zarobila (NIST)
Stephen Maxwell (NIST)
Dana Defibaugh (NIST)
Joe Rice (NIST)
Marc Mogavero (Hawk)
Ron Bettini (Hawk)
Gene Eplee (SAIC/GSFC 616.2)

Approach

- **IRIS** - **IR**radiance **I**nstrument **S**ubsystem: 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.

ER-2 Basic Configuration

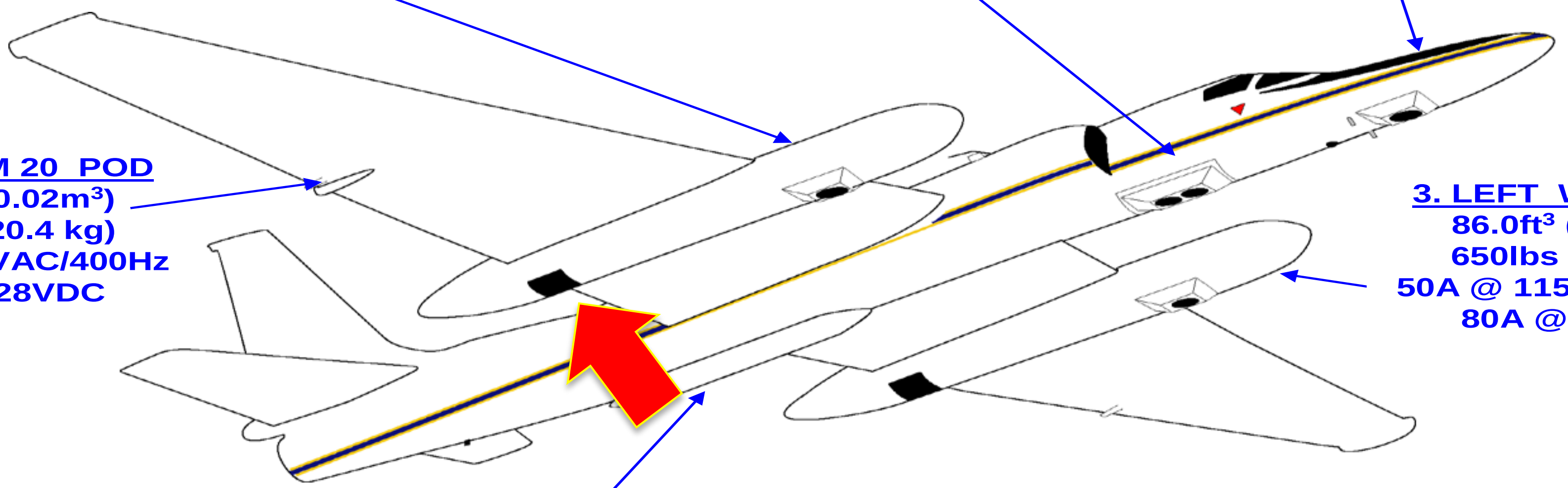
4. RIGHT WING POD
86.0ft^3 (2.43m^3)
650lbs (294 kg)
50A @ 115VAC/400Hz
80A @ 28VDC

2. Q-BAY
64.6ft^3 (1.83m^3)
1000lbs (454 kg)***
100A @ 115VAC/400Hz
140A @ 28VDC

1. NOSE
47.8ft^3 (1.35m^3)
700lbs (317 kg)***
50A @ 115VAC/400Hz
70A @ 28VDC

5. SYSTEM 20 POD
0.74ft^3 (0.02m^3)
45 lbs (20.4 kg)
30A @ 115VAC/400Hz
30A @ 28VDC

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



6. CENTERLINE POD
14.0ft^3 (0.40m^3)
350lbs (159 kg)
Electrical Shared with Q-Bay

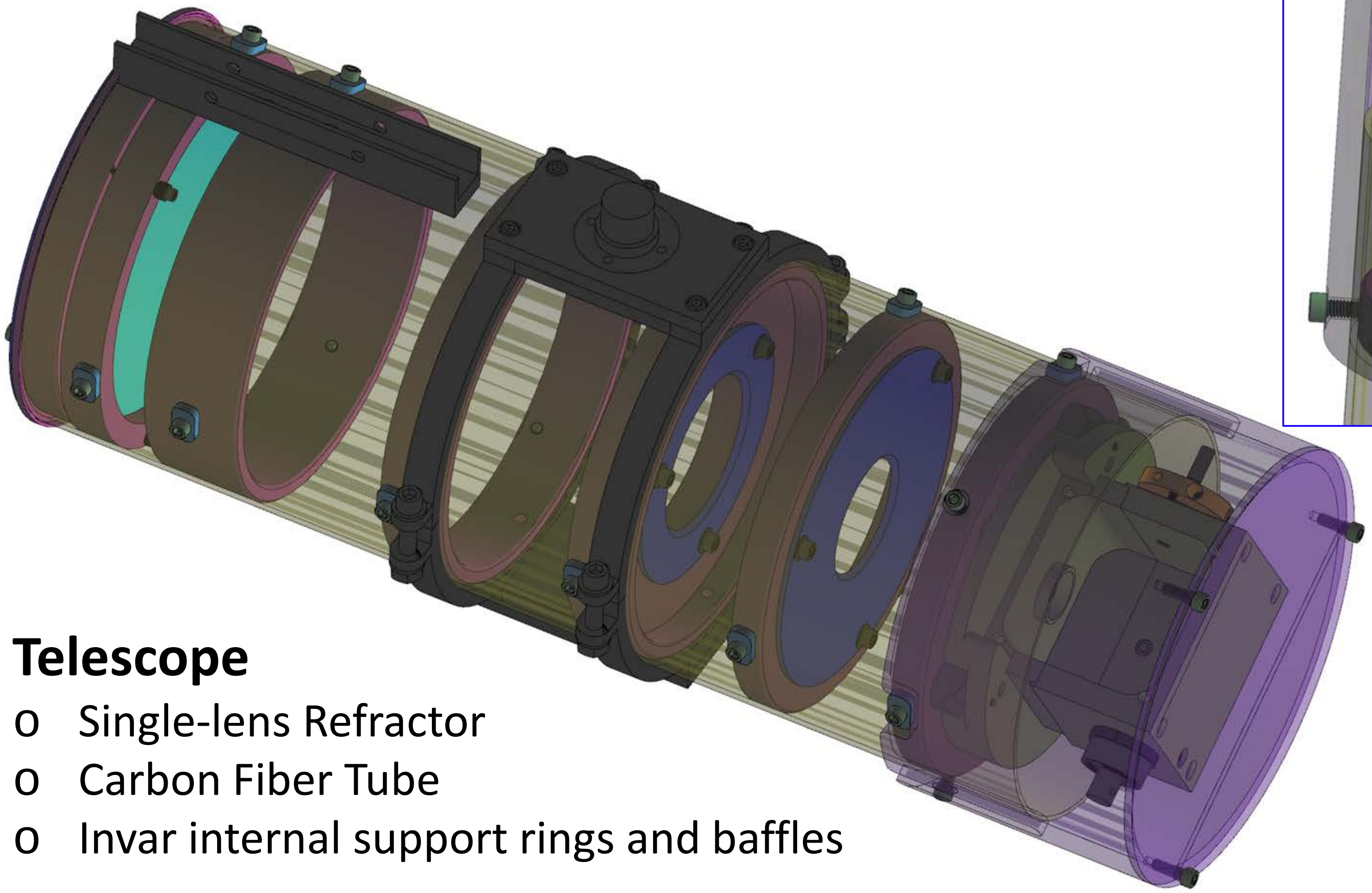
*** - Max combined Q-Bay and Nose payload cannot exceed 1300lbs

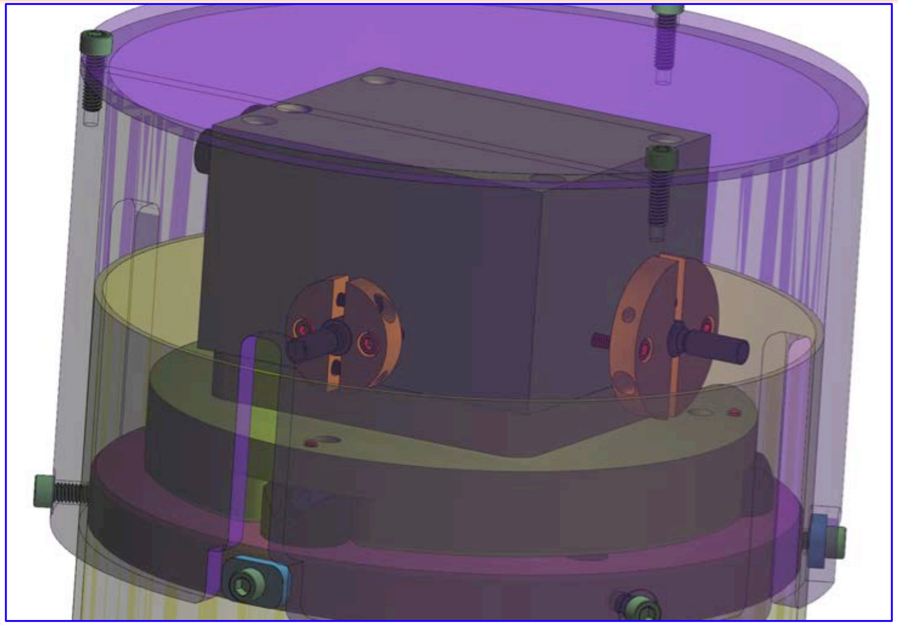
Specifications

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)

IRradiance Instrument Subsystem (IRIS)

Telescope Design





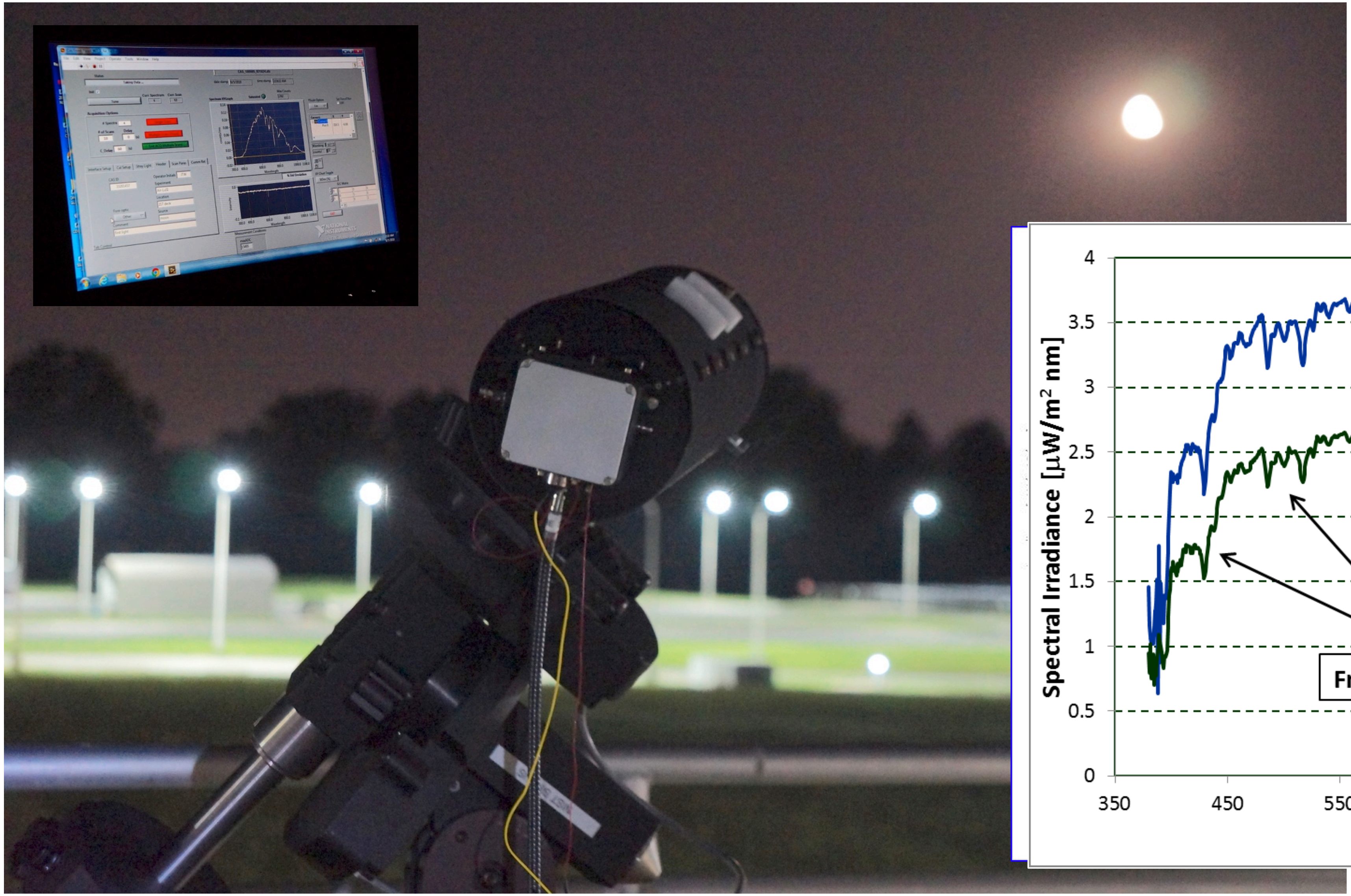
Telescope

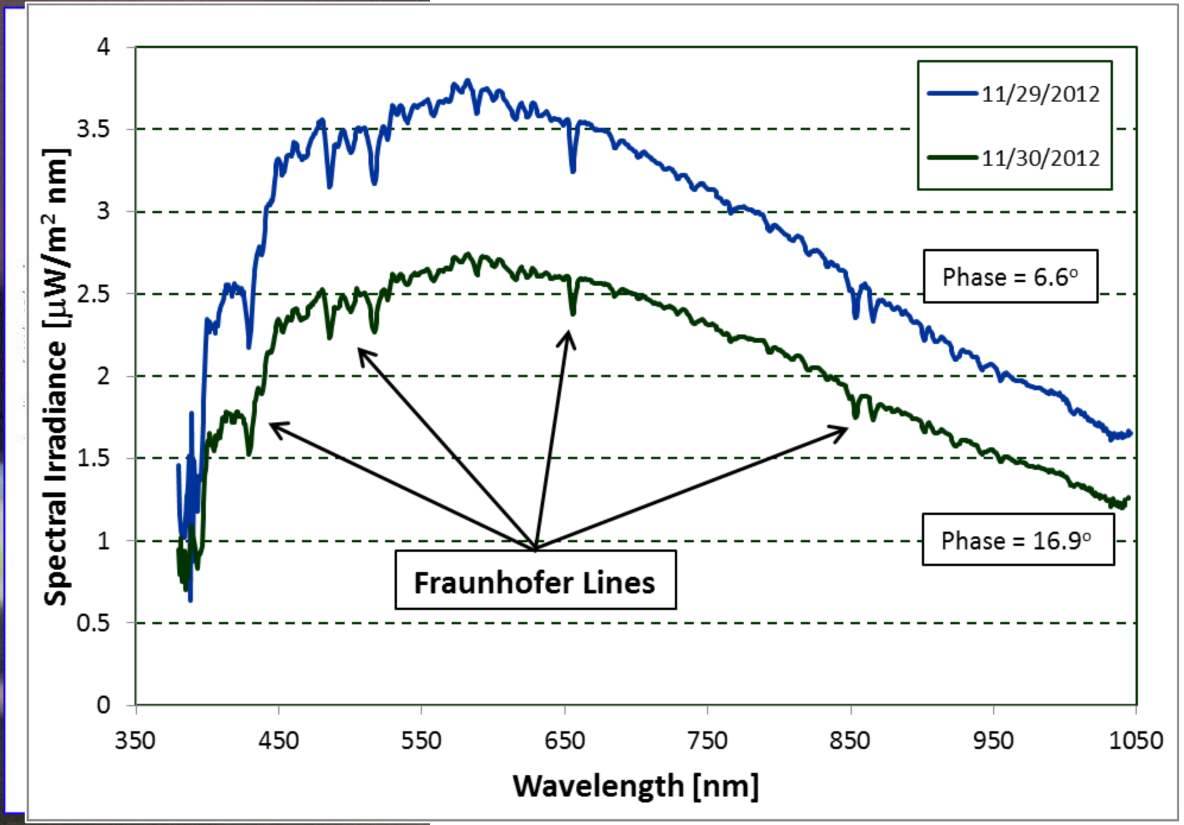
- Single-lens Refractor
- Carbon Fiber Tube
- Invar internal support rings and baffles

Integrating Sphere

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

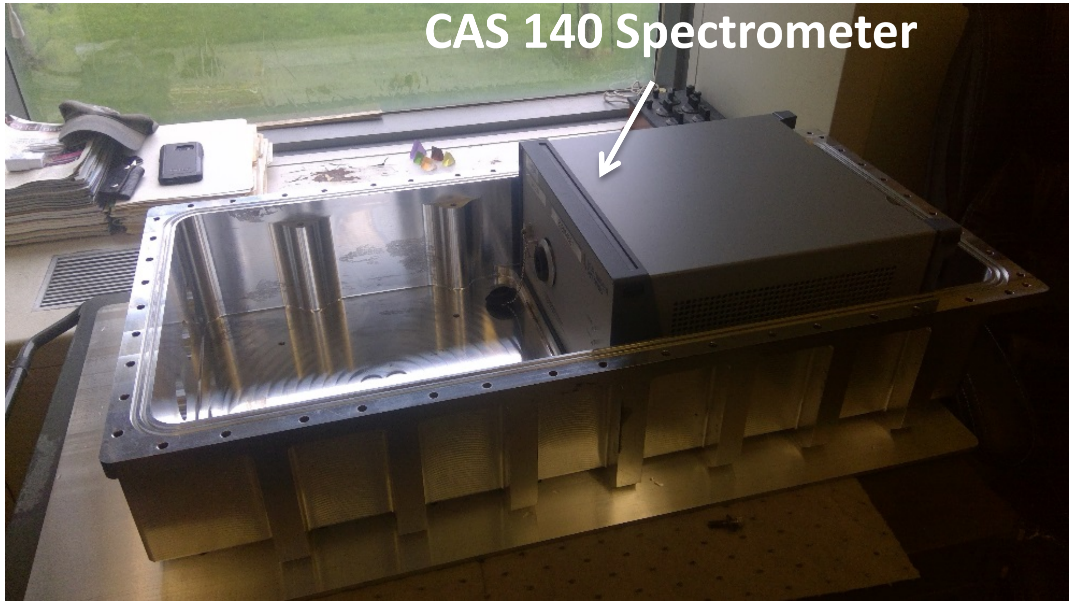
First Moonlight





IRIS Instrument Enclosure (NIST in a Box)

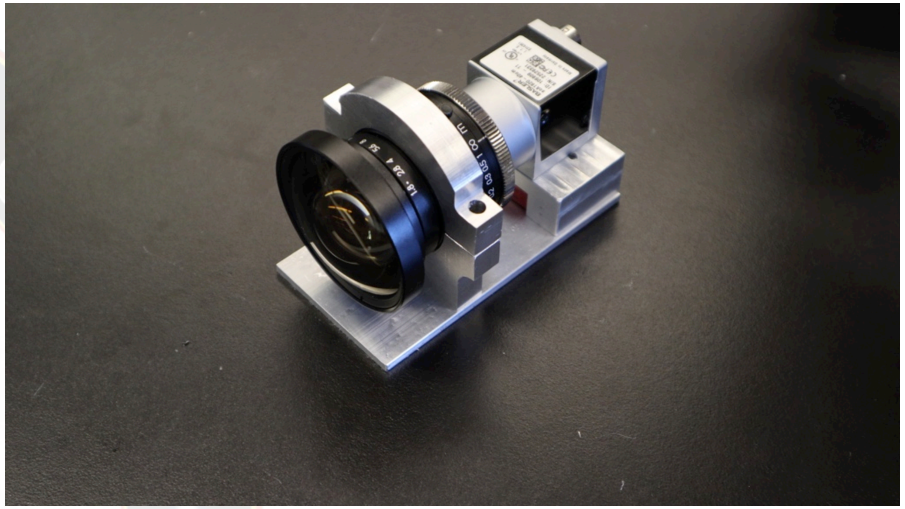
- Carved from a single block of high-grade aluminum.
- Holds spectrograph, validation source, DAQ and instrument computer.
- Temperature and pressure are maintained at sea-level.
- Formally pressure tested to 20 psig for 5 hours (18 hours in pre-check), with no measurable deformation.
- Pressure and temperature remain stable during engineering flights.

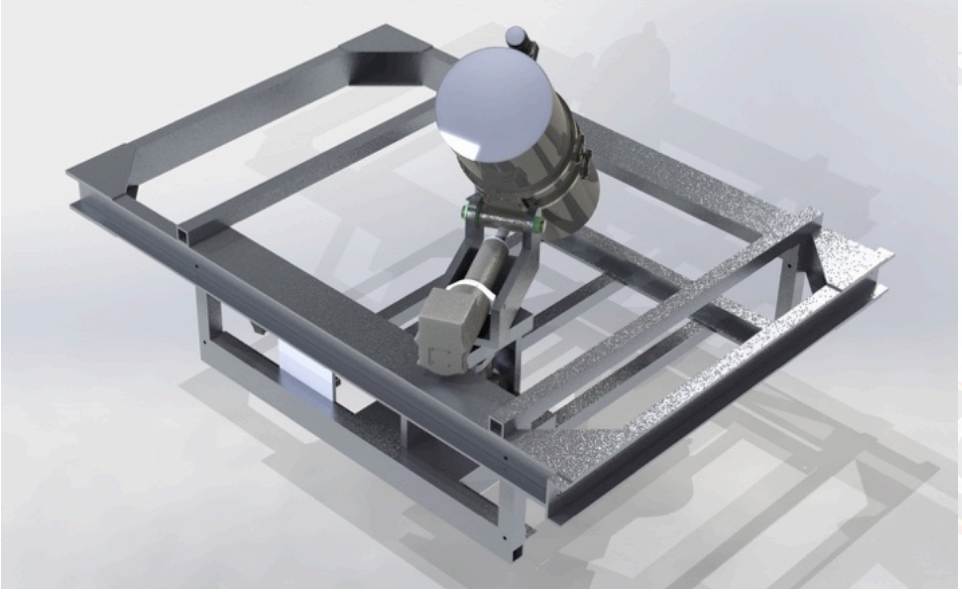


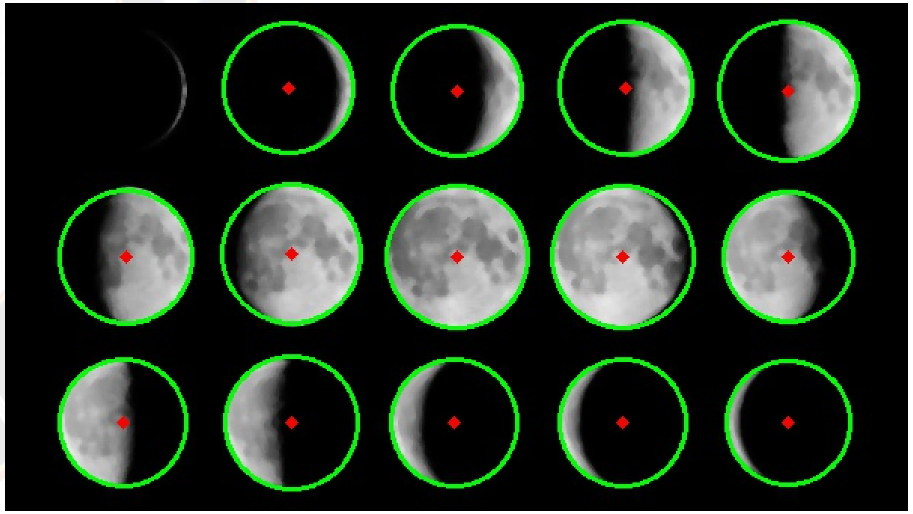
Autonomic Robotic TElescope Mount Instrument Subsystem (ARTEMIS)

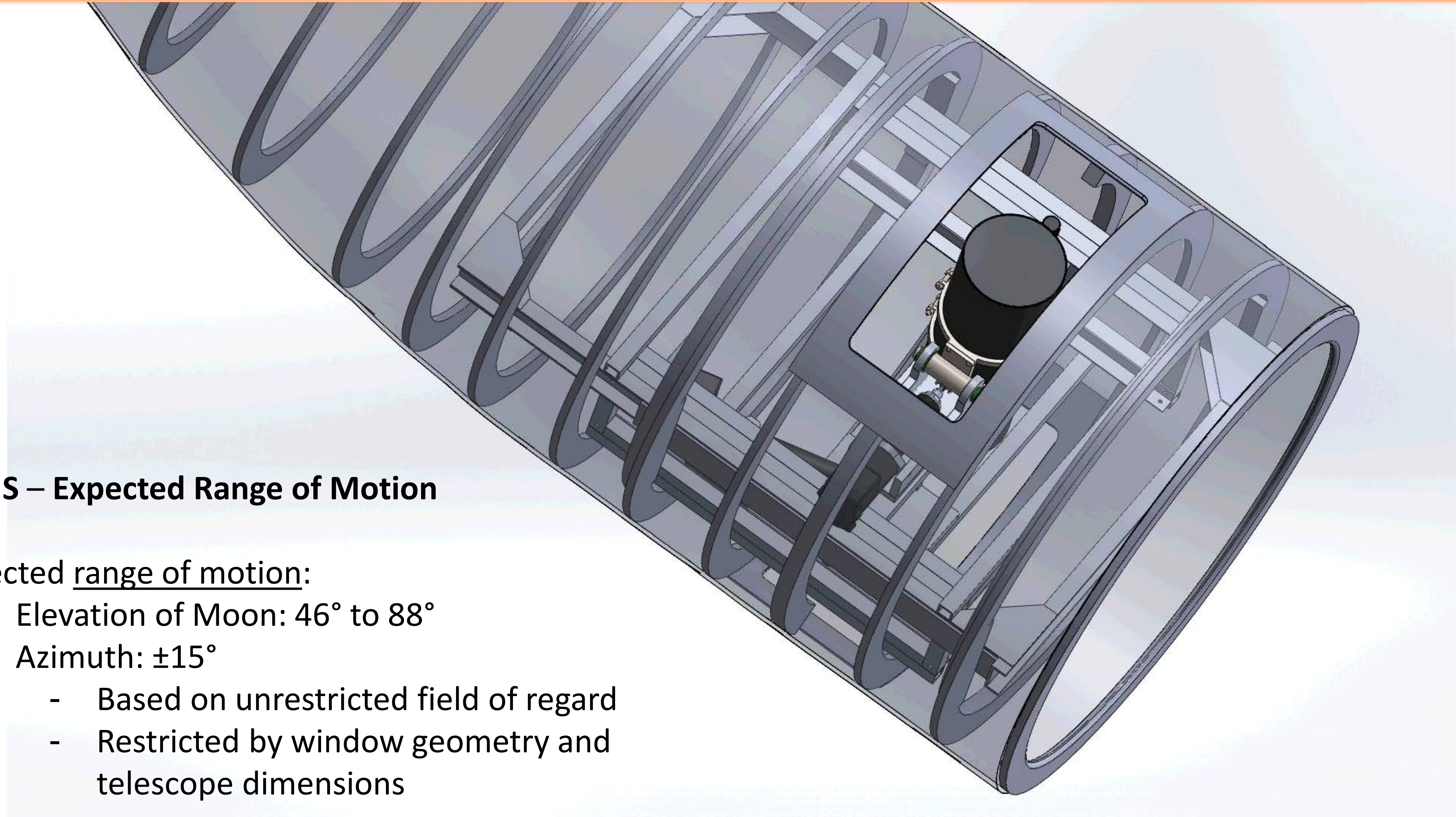
ARTEMIS – How do we control the telescope and track the Moon?

CC → Actuators → Telescope → TC → CC



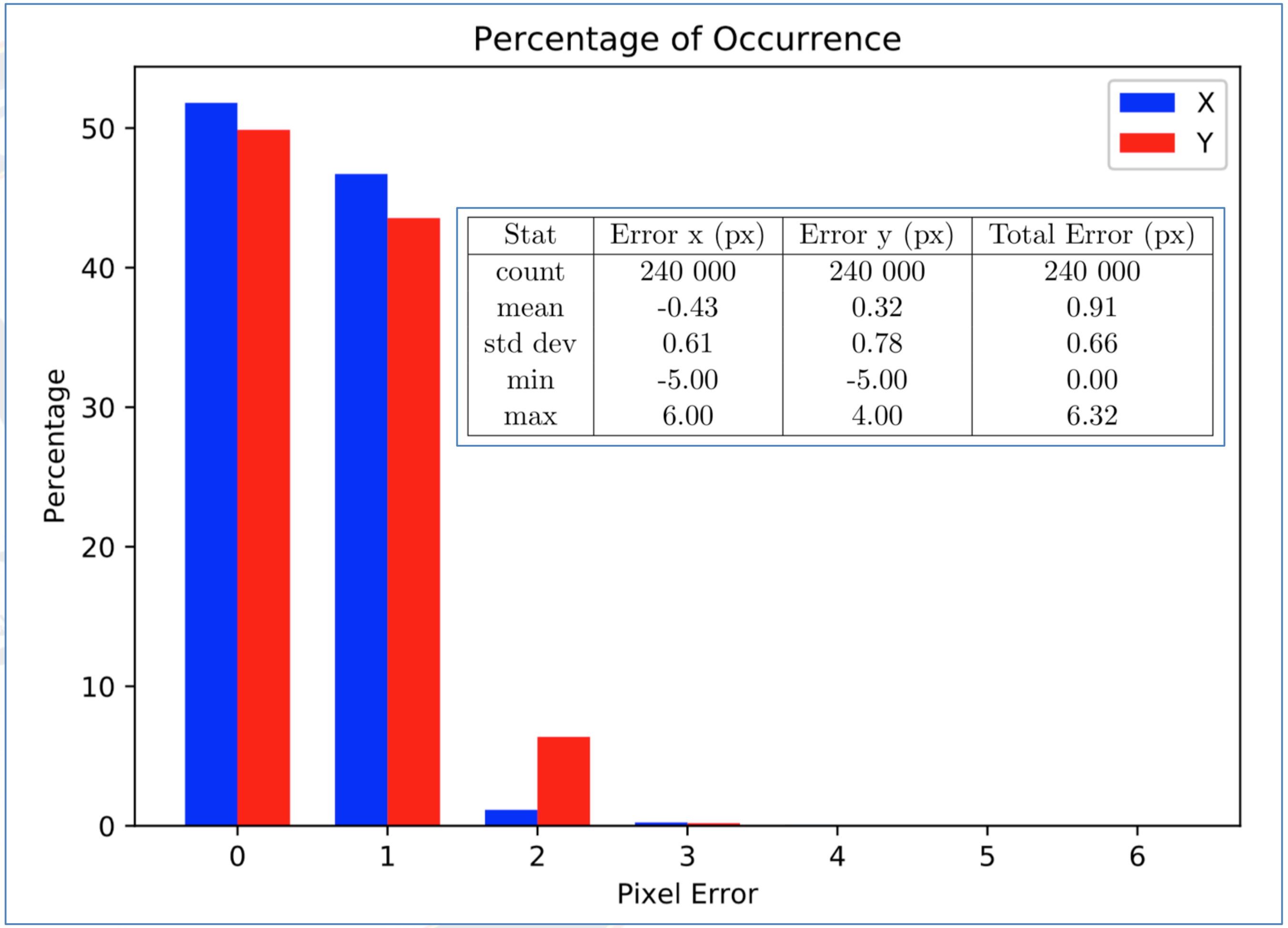






ARTEMIS – Expected Range of Motion

- Expected range of motion:
  - Elevation of Moon: 46° to 88°
  - Azimuth: ±15°
    - Based on unrestricted field of regard
    - Restricted by window geometry and telescope dimensions



Stat	Error x (px)	Error y (px)	Total Error (px)
count	240 000	240 000	240 000
mean	-0.43	0.32	0.91
std dev	0.61	0.78	0.66
min	-5.00	-5.00	0.00
max	6.00	4.00	6.32

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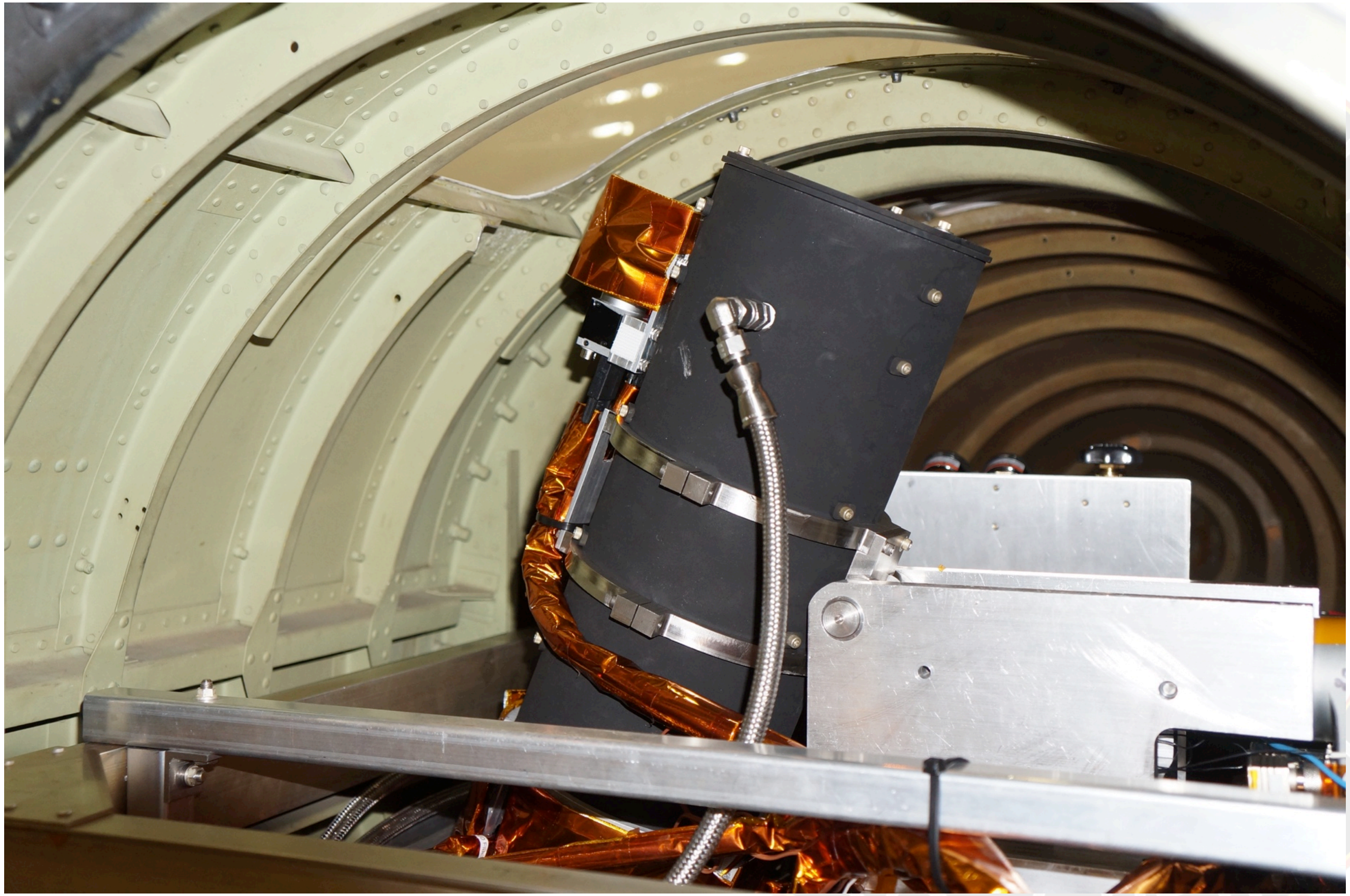
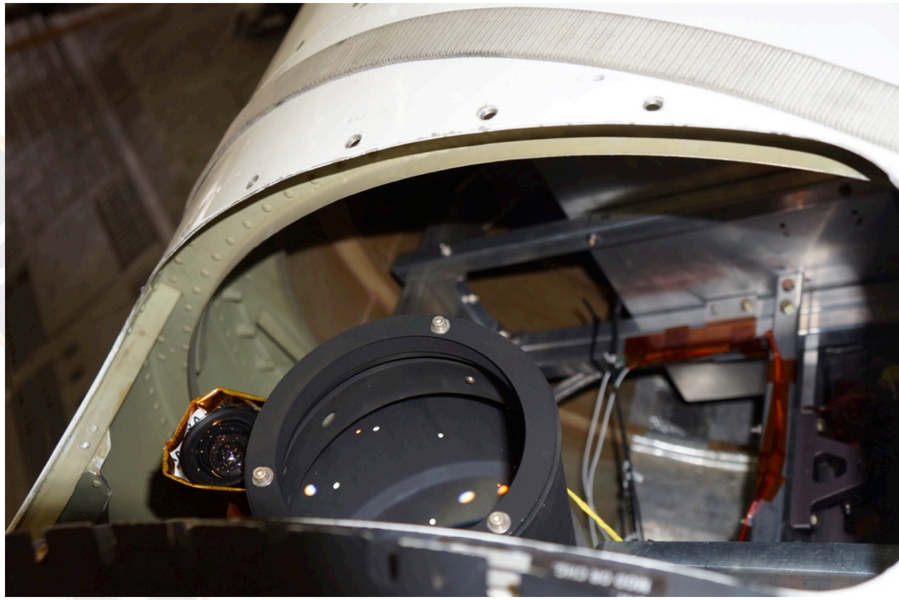
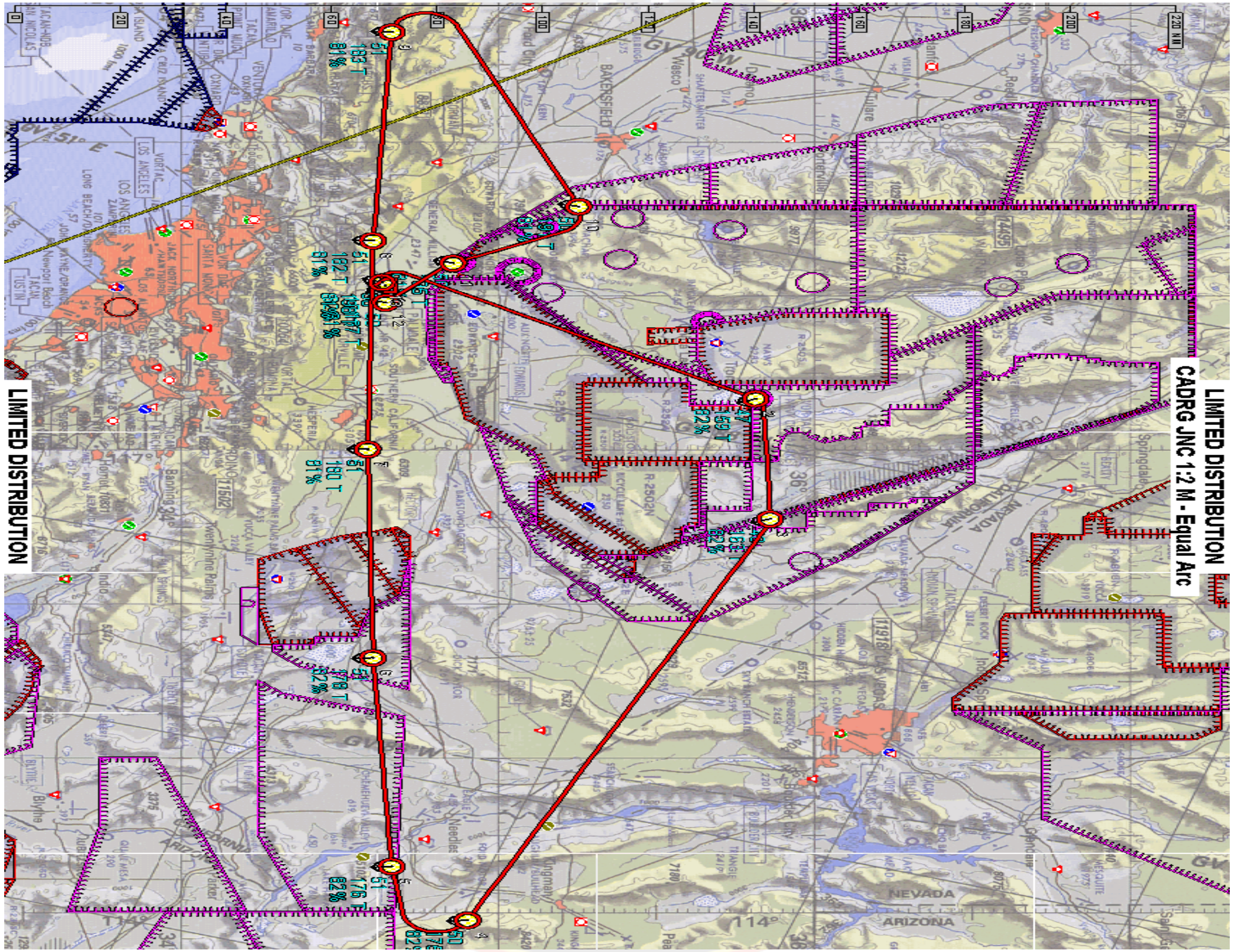


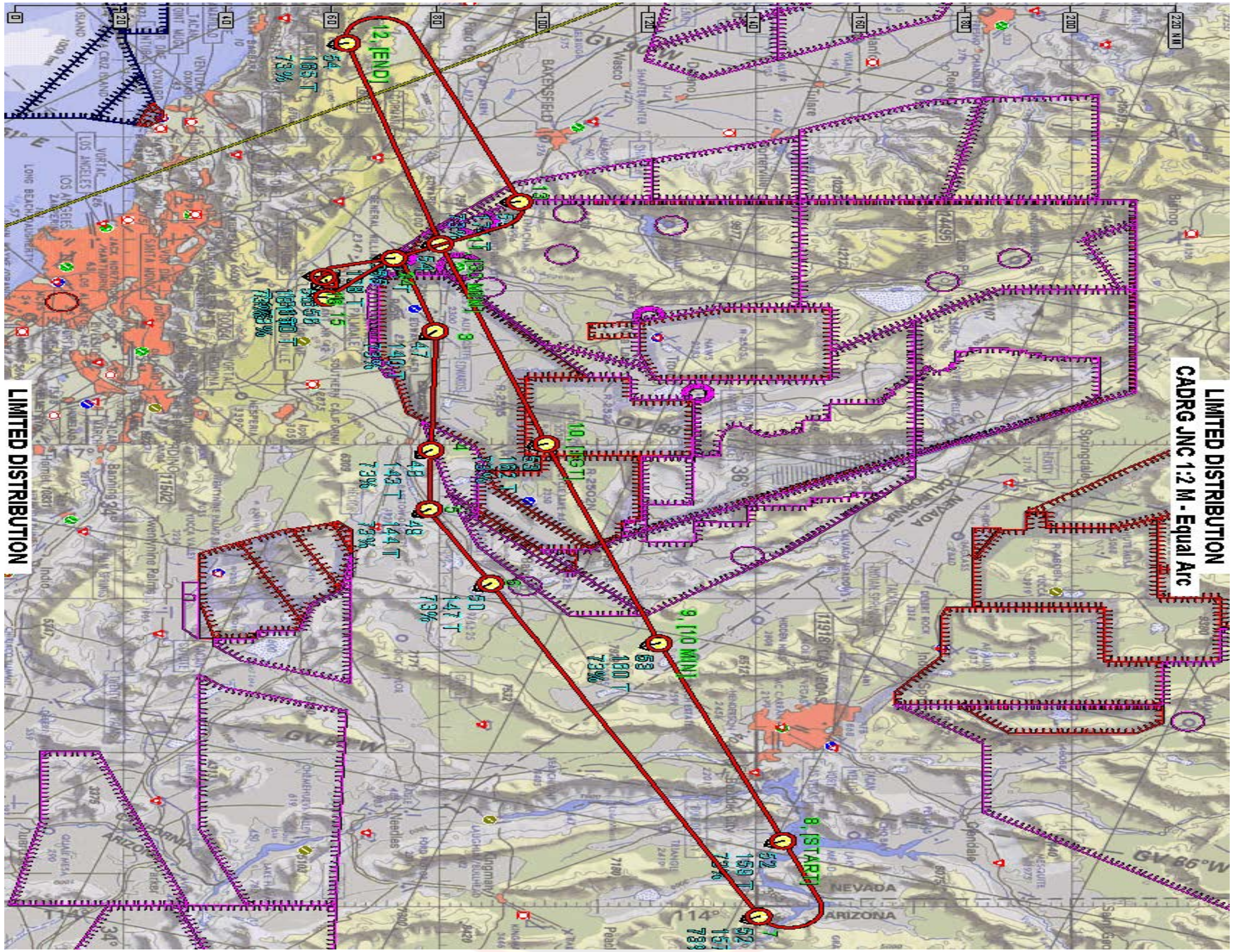


IRIS telescope view out the wing pod view port while situated on ARTEMIS.

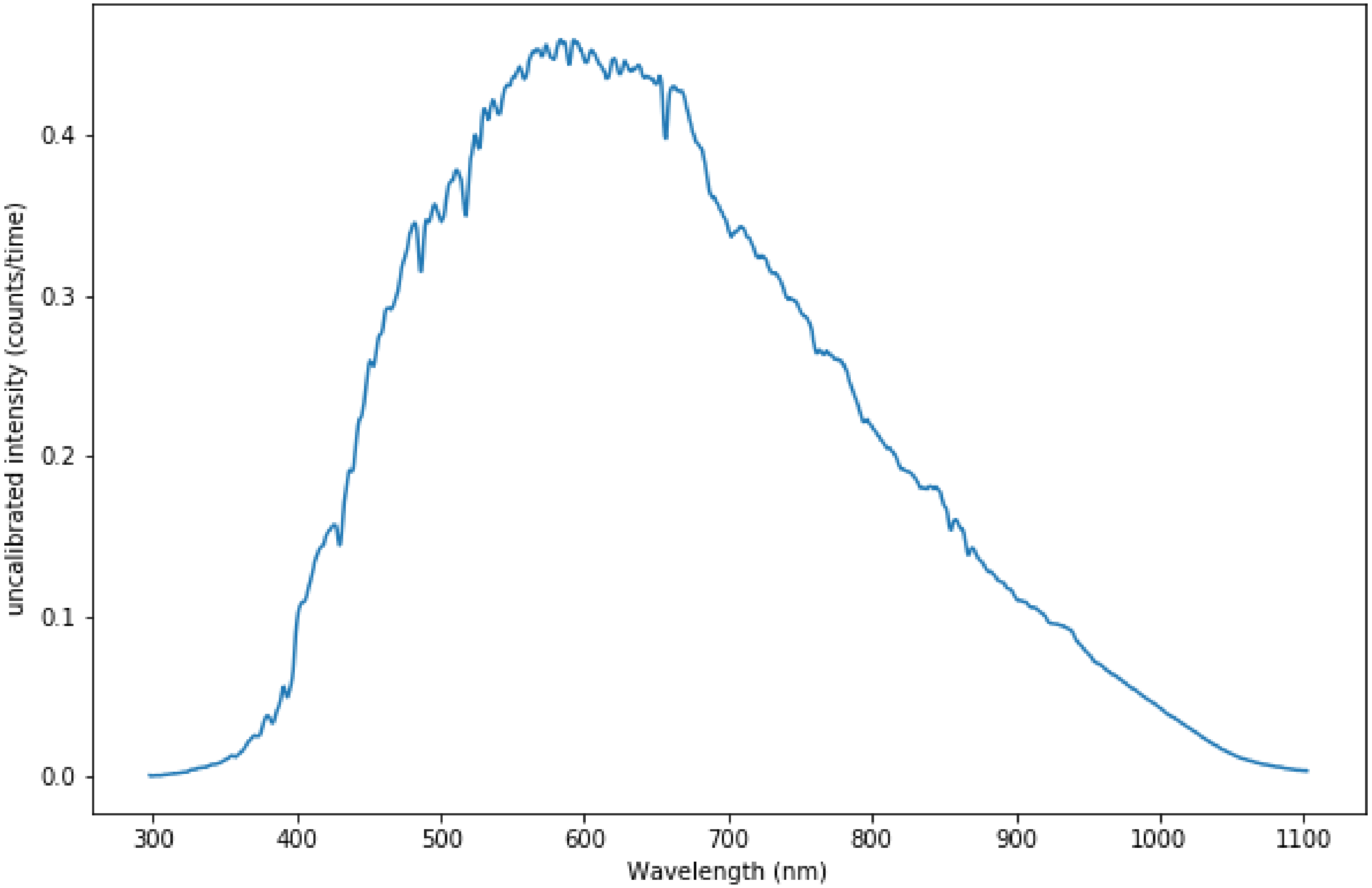
Aug 1 flight lines



Aug 2 flight lines



The air-LUSI situation room.



uncalibrated intensity (counts/time)
0.0
0.1
0.2
0.3
0.4
300
400
500
600
700
800
900
1000
1100
Wavelength (nm)

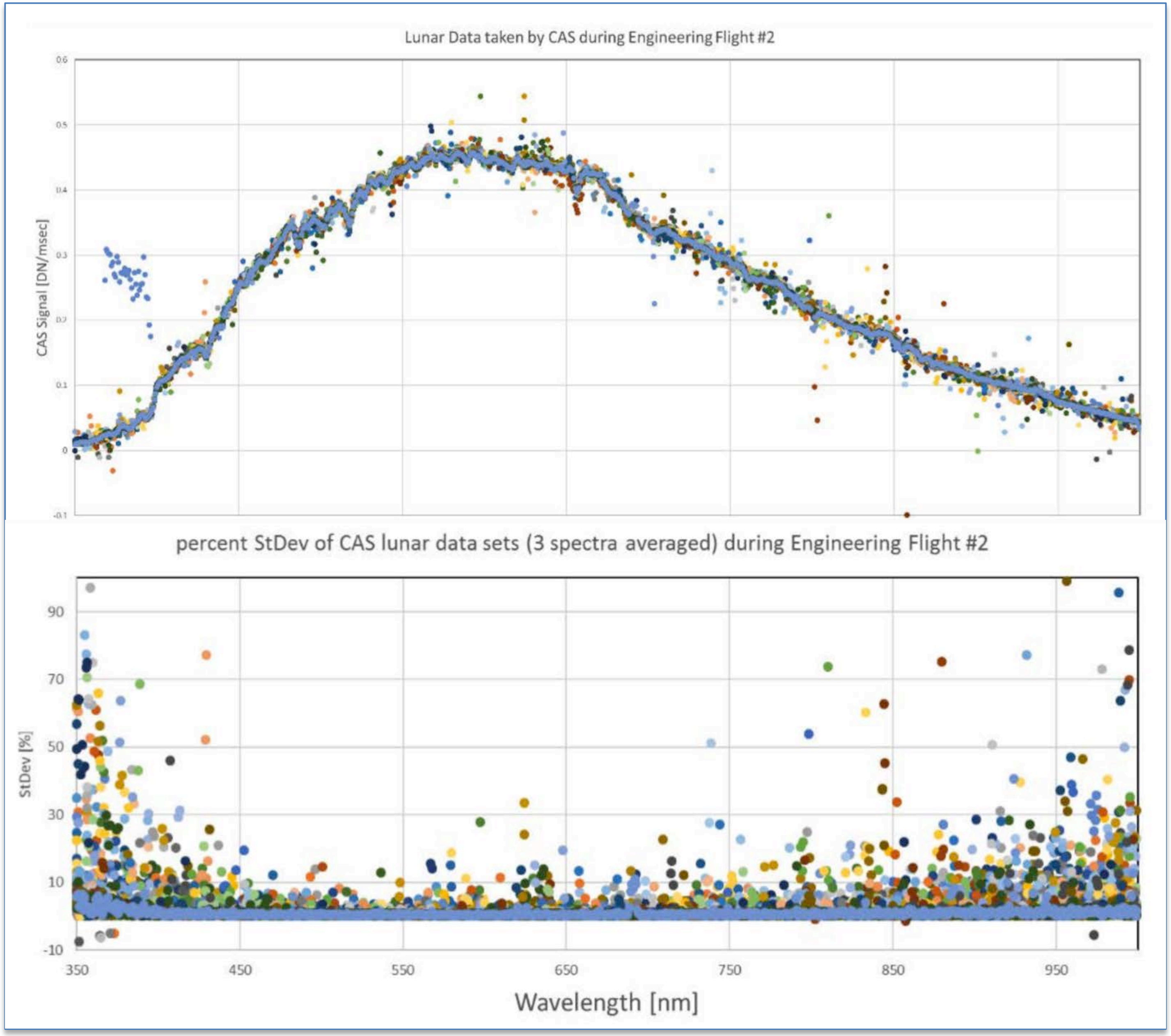
SUMMARY

- Integration and testing of IRIS, ARTEMIS, and HERA were successful.
- Integration of the air-LUSI system onto the ER-2 aircraft was successful.
- HERA heaters performed as designed.
- ARTEMIS locked onto and tracked the Moon to within about 0.1°.
- IRIS instrument enclosure held pressure and temperature steady.
- IRIS telescope and instrument collected lunar irradiance with high SNR and sensitivity to the lunar spectrum.
- Calibration processing must be done to get geophysical values and uncertainties.
- Engineering data will be analyzed to check out systems and identify possible improvements.
- Planning and preparations will begin for next flight in the November / December time frame.

THANK YOU

BACKUP SLIDES

Entire data set for Engineering Flight 2 (Aug 2)



Initial Top-Level Calibration Error Budget

	Relative Uncertainty [%]			
Component	450 nm	550 nm	650 nm	750 nm
Transfer Spectrograph (R)	0.159	0.159	0.159	0.159
Calibration Source (E)	0.313	0.241	0.213	0.213
Telescope Calibration (R)	0.462	0.365	0.329	0.330
Lunar measurement (E)	0.597	0.486	0.445	0.446

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

LUNAR OBSERVATIONS FROM SPACE

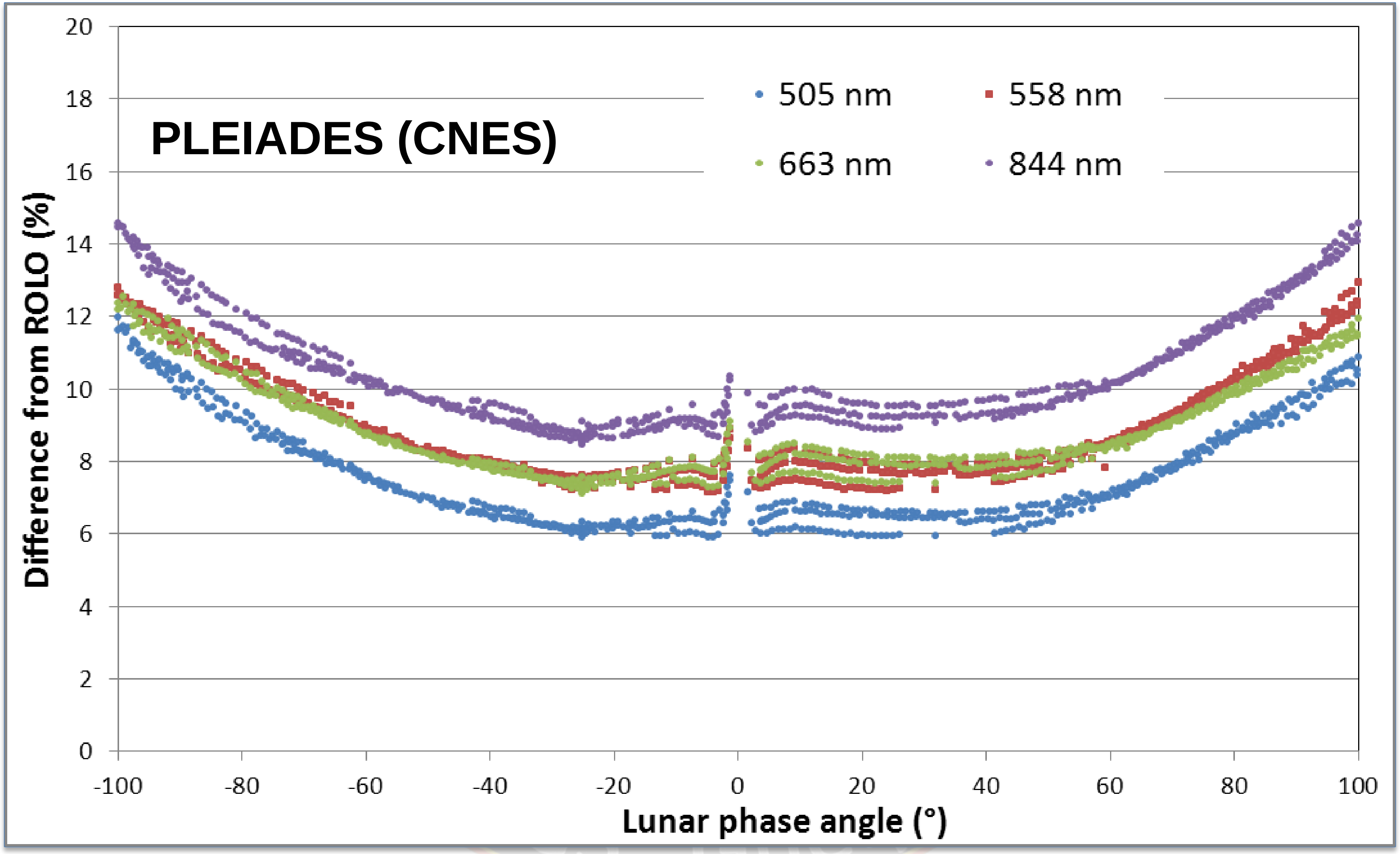
- 58 Moon obs by SNPP VIIRS
- 6 by J1/N20 VIIRS
- 522 by Terra MODIS (inc. serendipitous obs)
- 377 by Aqua MODIS
- 64 by Landsat 8 OLI
- 26 Hyperion spectral images of the Moon have been processed to irradiance.
- Several thousand from geostationary imagers
- 1.7 million by the Planet Labs fleet.
- Others: EPIC, CERES, SCIAMACHY, PROBA-V, OCO-2, GOSAT, and PLIEADES
- HiRISE did lunar cal obs from orbit around Mars.

Remote Sensing Activities: Spaceborne Imaging Spectrometers

ISS Orbital Pattern

Sensor	Orbit	Global?	>1µm?	Status
HICO	ISS	No	No	Off
CHRIS/Proba	Polar	No	No	Working
Hyperion	Polar	No	Yes	Off
EnMap	Polar	No	No	2020
DESIS	ISS	No	No	2018?
HISUI	ISS	No	No	2019?
PRISMA	Polar	No	No	2019?
COCI	Polar	Yes	No	-
PACE+	Polar	Yes	Yes	2022
GeoCAPE	GEO	No	No	-
HyspIRI/**SBG**	Polar	Yes	Yes	-
Landsat 10	Polar	Yes	Yes	-

ROLO biases are predominantly phase dependent.



S. Lachérade — CNES

Remote Sensing Activities:
Airborne Campaigns and Feasibility Studies

Sensor	Activity	Sensors	Subject of Study
ABC LOBO	Study	AVIRIS, PRISM	S. FL Watershed
CORAL	Campaign	PRISM	Coral Reefs
HyperMAQ	Study	?	Coastal/Inland Waters
HyspIRI APC: CA	Campaigns	AVIRIS-C	Coastal/Inland Waters
HyspIRI APC: HI	Campaigns	AVIRIS-C (+PRISM?)	Coral Reefs (MOBY)
C-HARRIER	Instrument	2 Line Spectrometers	Coastal/Inland Waters
AirShrimp	Instrument	Line Spectrometer	Coastal Waters
Great Lakes AC	Campaigns	Imaging Spectrometer	Inland Water Quality
GLiHT	Campaigns	Imaging Spectrometer	S. FL Mangroves
air-LUSI	Instrument	Spectrograph	Moon (Reference)

Lunar Calibration

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

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

ER-2

The air-LUSI system just prior to upload onto the ER-2.

IRIS instrument enclosure loaded into the wing pod mid-body

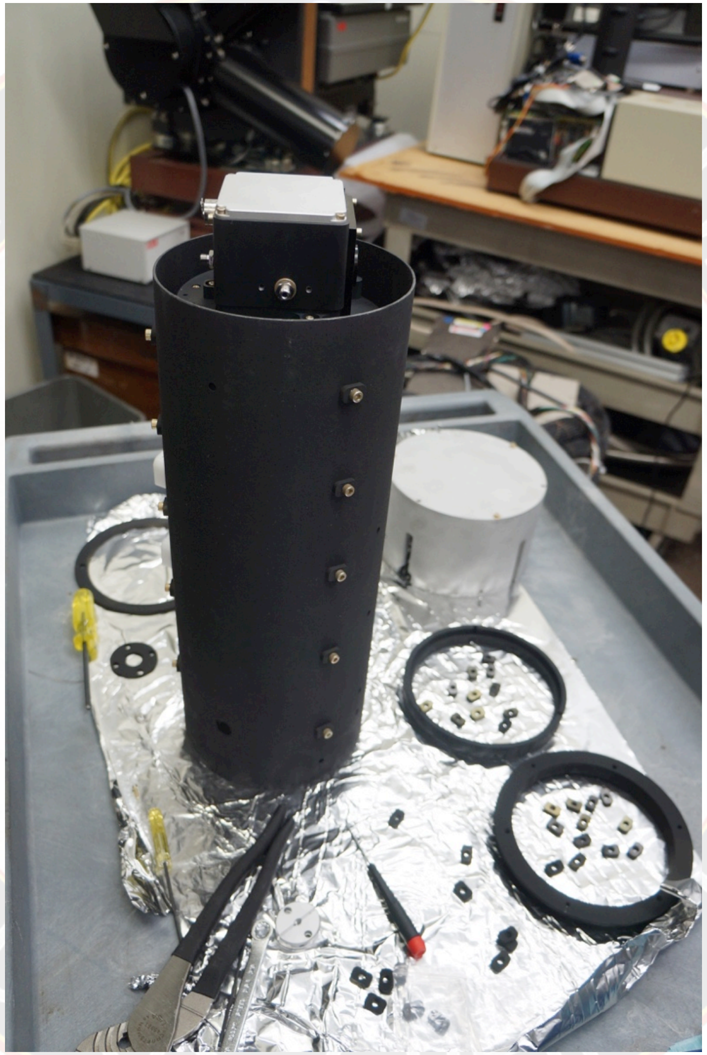
ER-2 SuperPod Midbody Payload Area

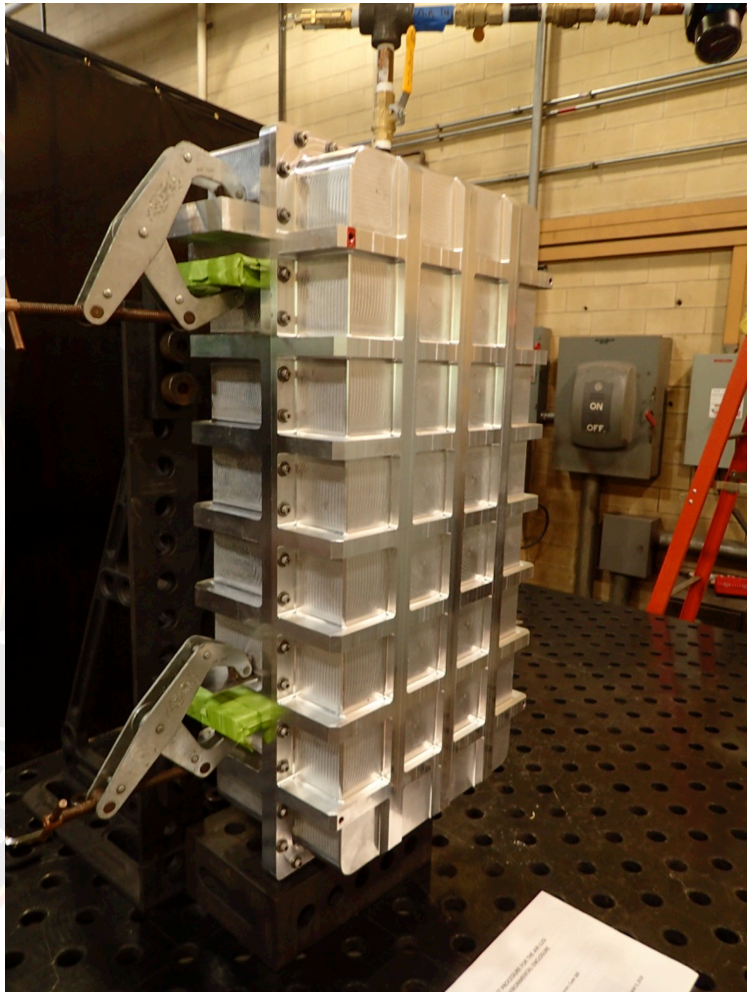
Forward Midbody looking Aft

Lower Midbody looking Up and Aft

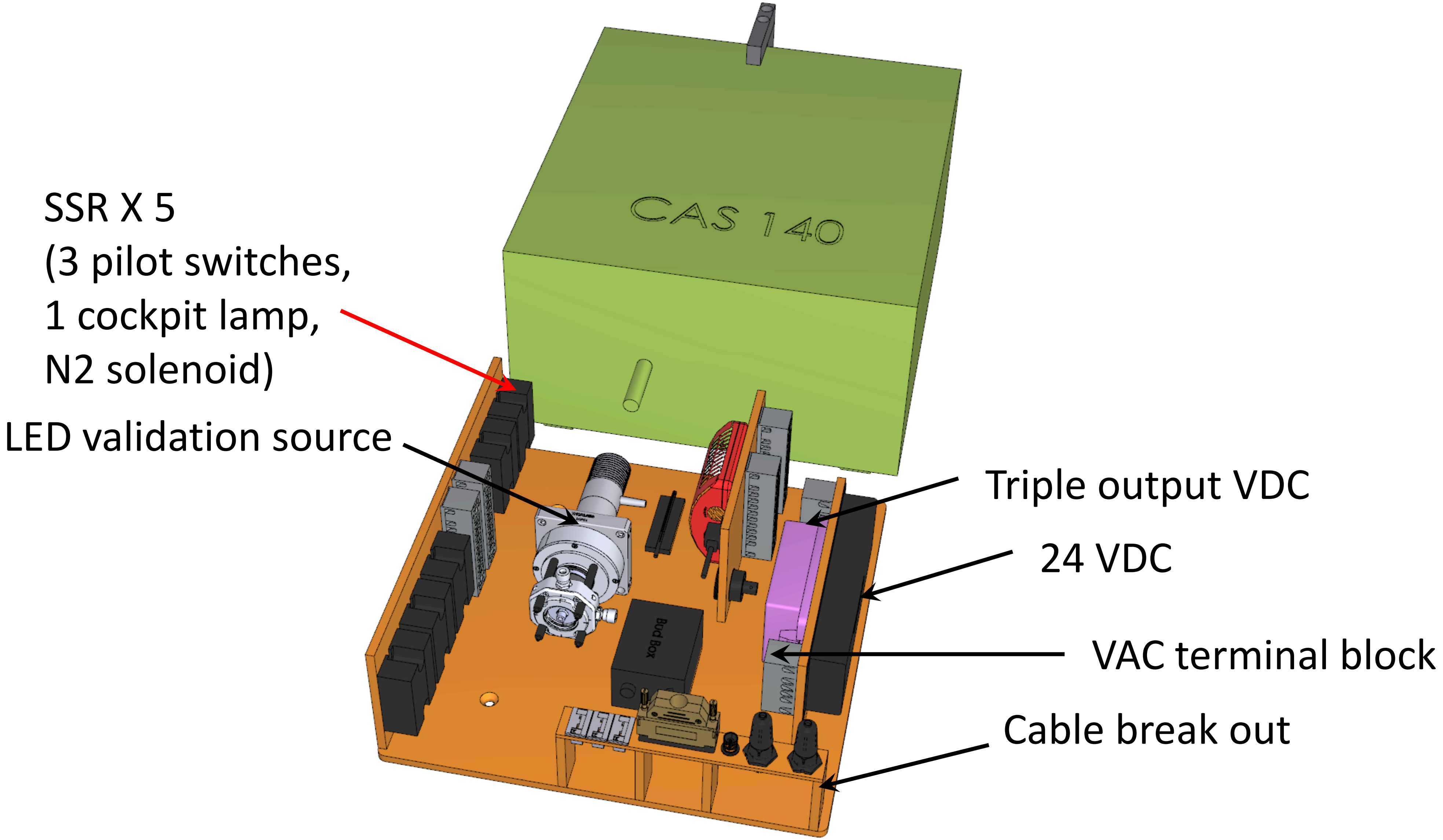
IRIS Subsystem

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

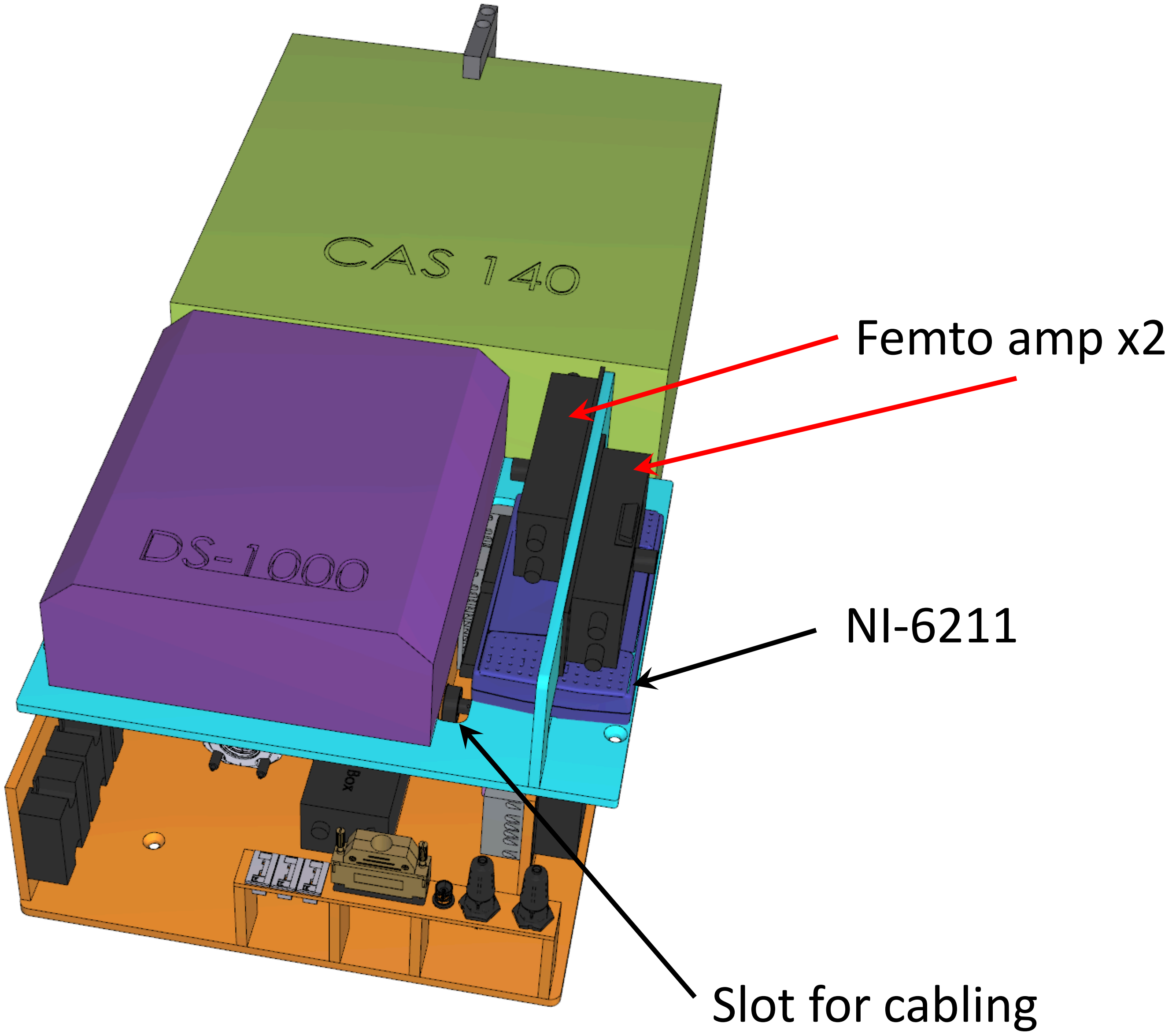




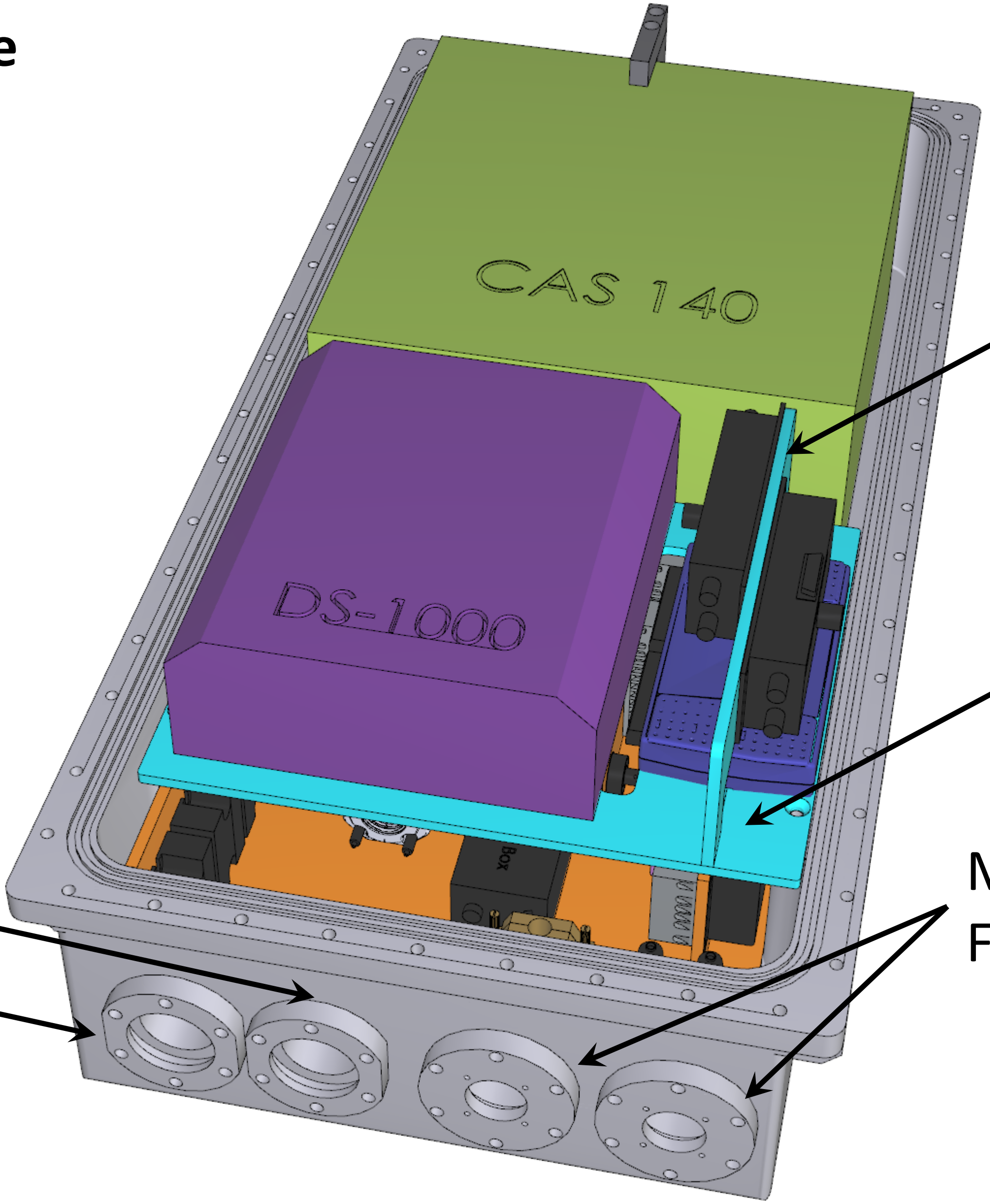
Bottom Level



Top Level



Inside Bottom of Enclosure



Slotted upright wall

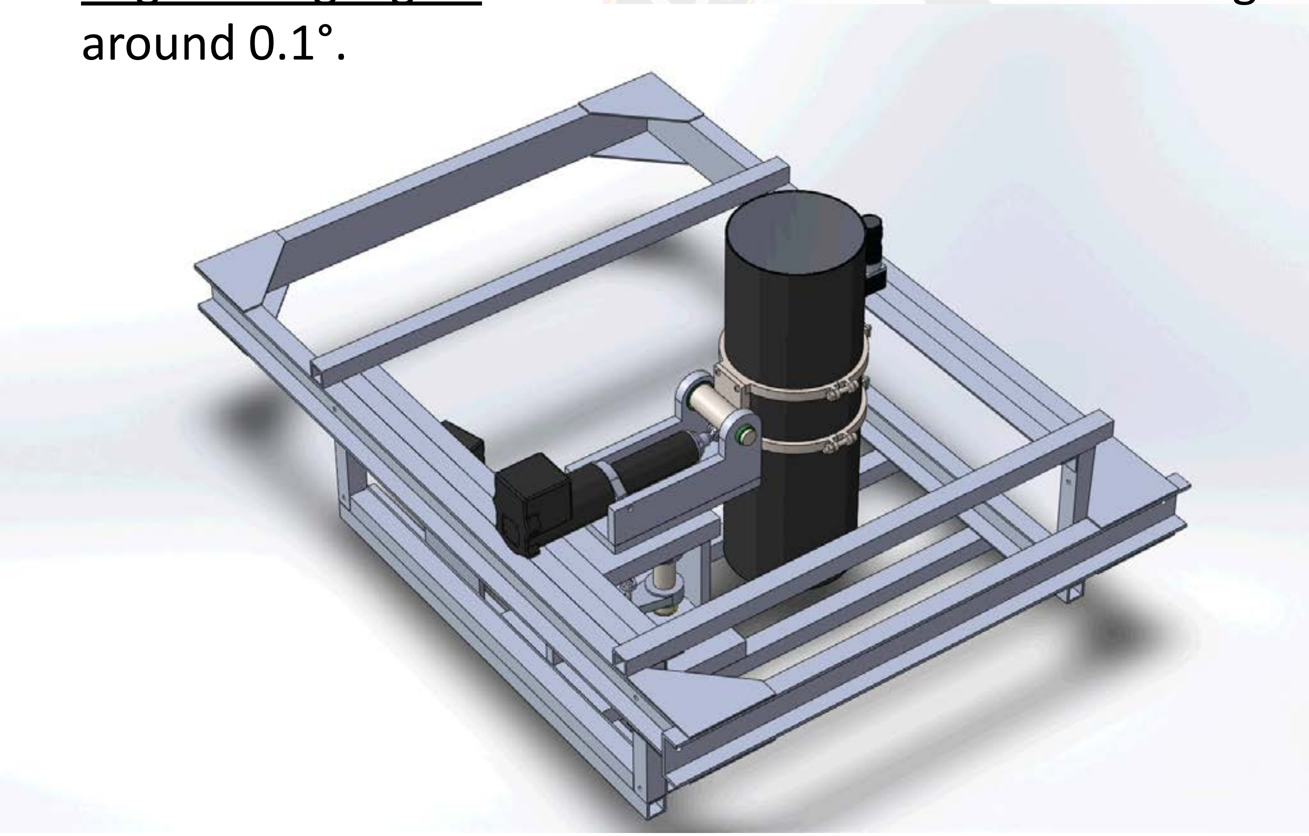
Computer table

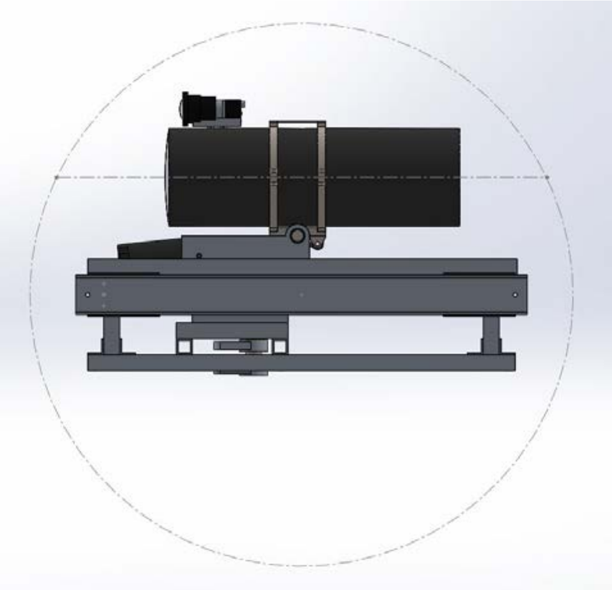
Mil spec feed through
Flange x2

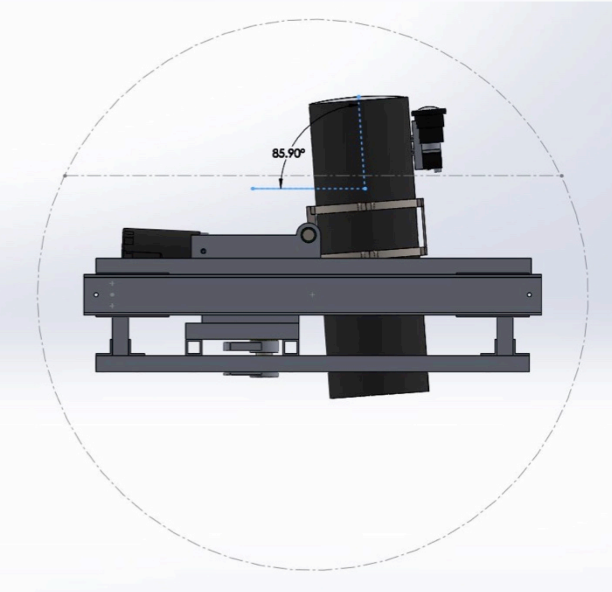
QF-40 flange clamp x2

ARTEMIS – Testing and Performance

- <u>Controlled Autonomous Tracking (CAT) Test</u> – testing in laboratory tracking a light spot on wall or ceiling.
- <u>“Pick-Up” Test</u> – Lunar tracking from bed of moving vehicle.
- <u>Engineering flights</u> – ARTEMIS tracked the Moon in flight to within around 0.1°.



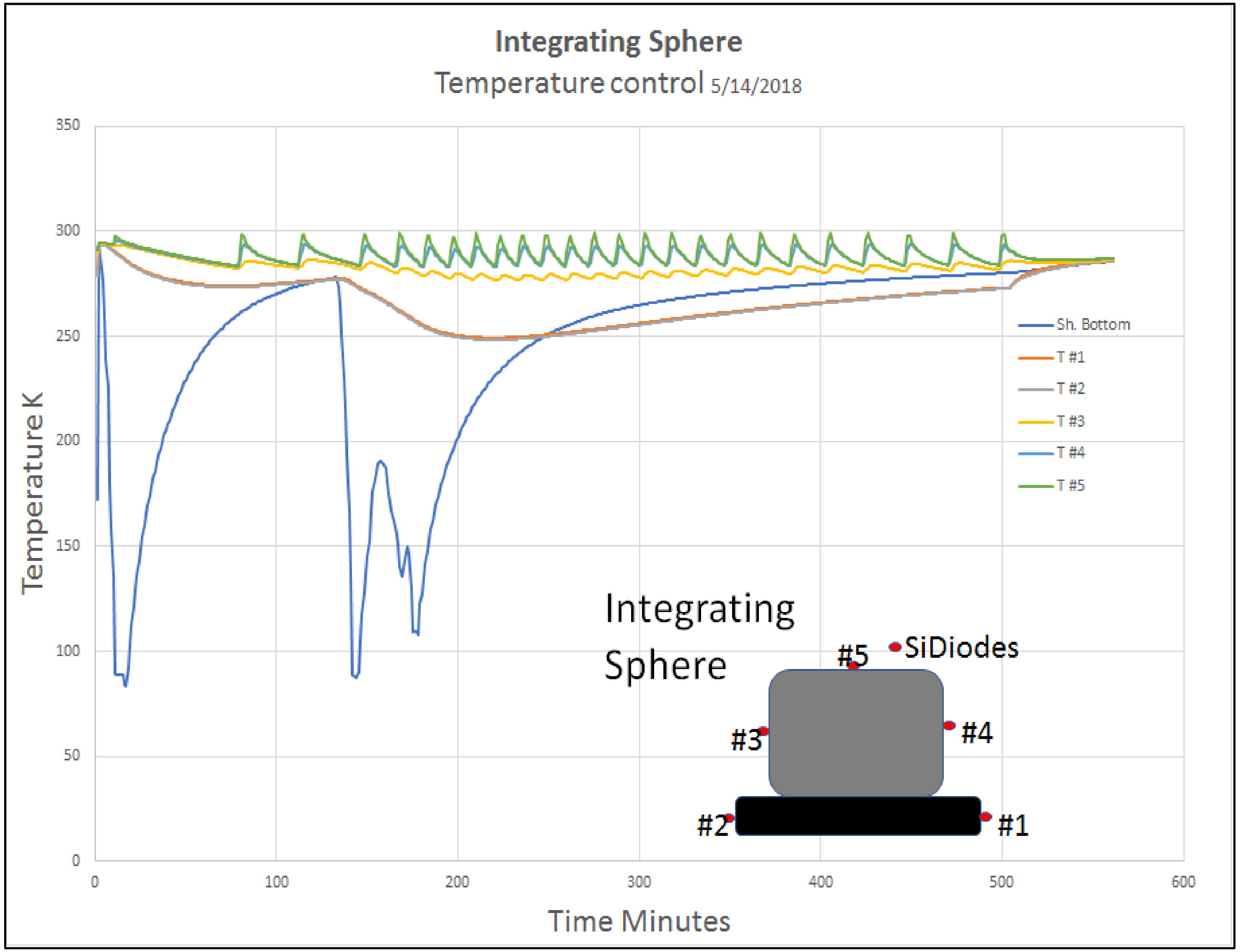




ER-2 Aft-Body Payload Area

Removable Alignment Camera

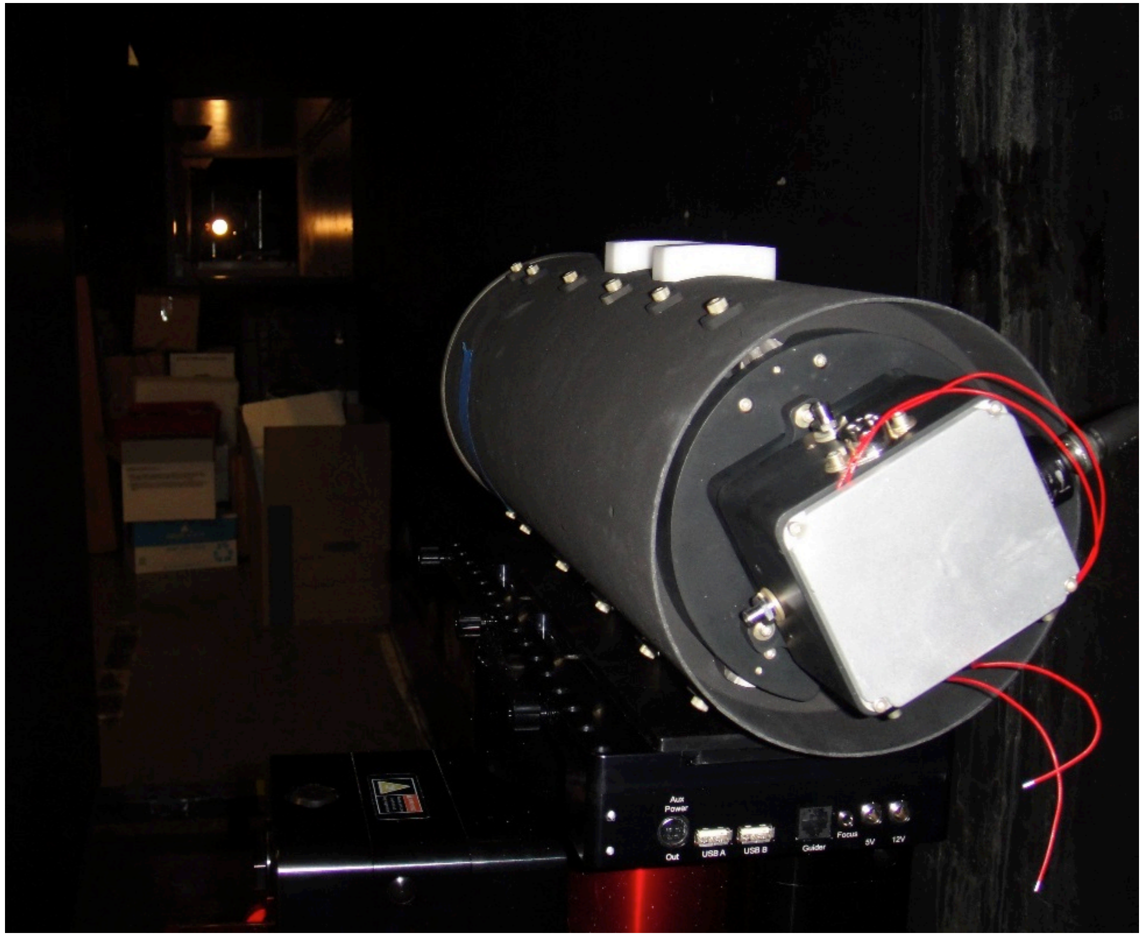
- Use for test telescope alignment
- Stray light testing
- Aligning ARTEMIS tracking camera



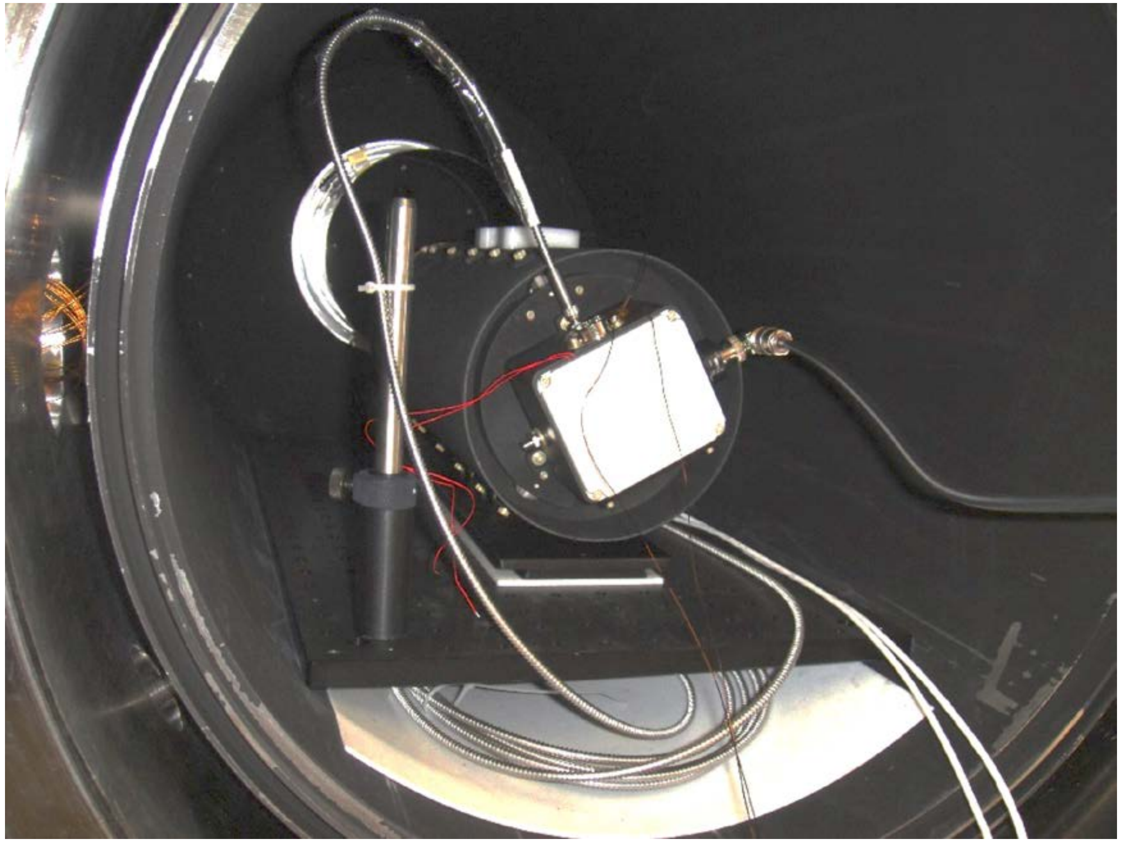
TVAC Test

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

Tunnel and T/VAC Tests



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 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.