airborne Lunar Spectral Irradiance (air-LUSI) Mission Capability Demonstration

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UMBC / JCET / NASA / GSFC

CalCon - 21 September 2020

On-line Conference

cal con

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air-LUSI

NASA UMBC NIST USGS Guelph Hawk

air-LUSI Team

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air-LUSI Primary Objective

To make very accurate, SI-traceable lunar spectral irradiance measurements for the improvement of satellite lunar calibration.

- We estimate the uncertainty for the Engineering Flight Campaign to be <2% (k=1). Current error budget indicates an uncertainty ~0.8% (450 – 900 nm) for the Demonstration Flight Campaign.

- air-LUSI intends to improve its measurement accuracy with each campaign.

- We believe that we can potentially reach further below 1% by next campaign.

Why air-LUSI?

Current ground-based systems are all subject to their own set of issues of weather and with removing atmospheric effects, while future on-orbit measurements will be subject to many of the same risks that lunar calibration seeks to mitigate.

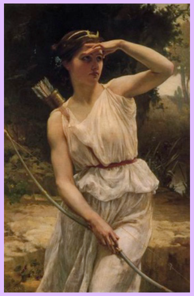
- **air-LUSI** is the only system in existence that has both a small atmospheric correction and an ability to check the calibration before and after use and to monitor it up to the point of data collection.

- **air-LUSI** is an essential part of the multi-dataset approach to building a new lunar reference, providing confidence to new datasets that nothing else can.

More importantly, we know that **air-LUSI** works.

Air-LUSI Subsystems

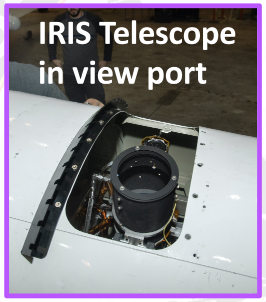
ARTEMIS – Autonomous, Robotic TElescope Mount Instrument Subsystem

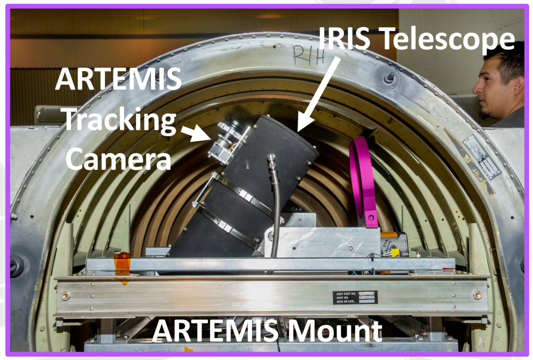


- Uses tracking camera on telescope and computer controlled PID loop.
- Keeps telescope fixed on the Moon to within 0.1°.

ARTEMIS Control Assembly

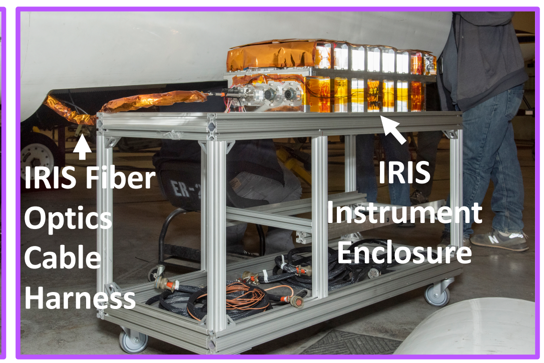
Pilot Switch Simulator

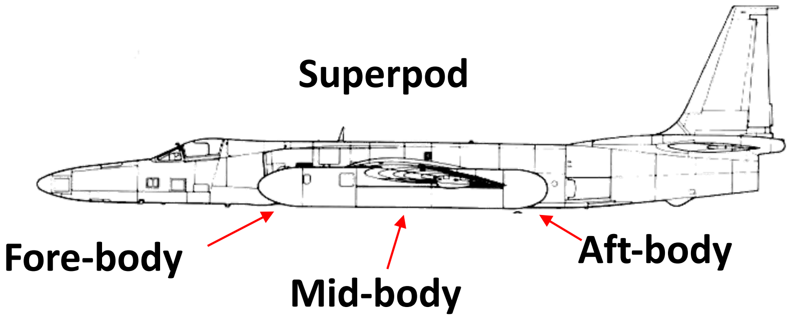




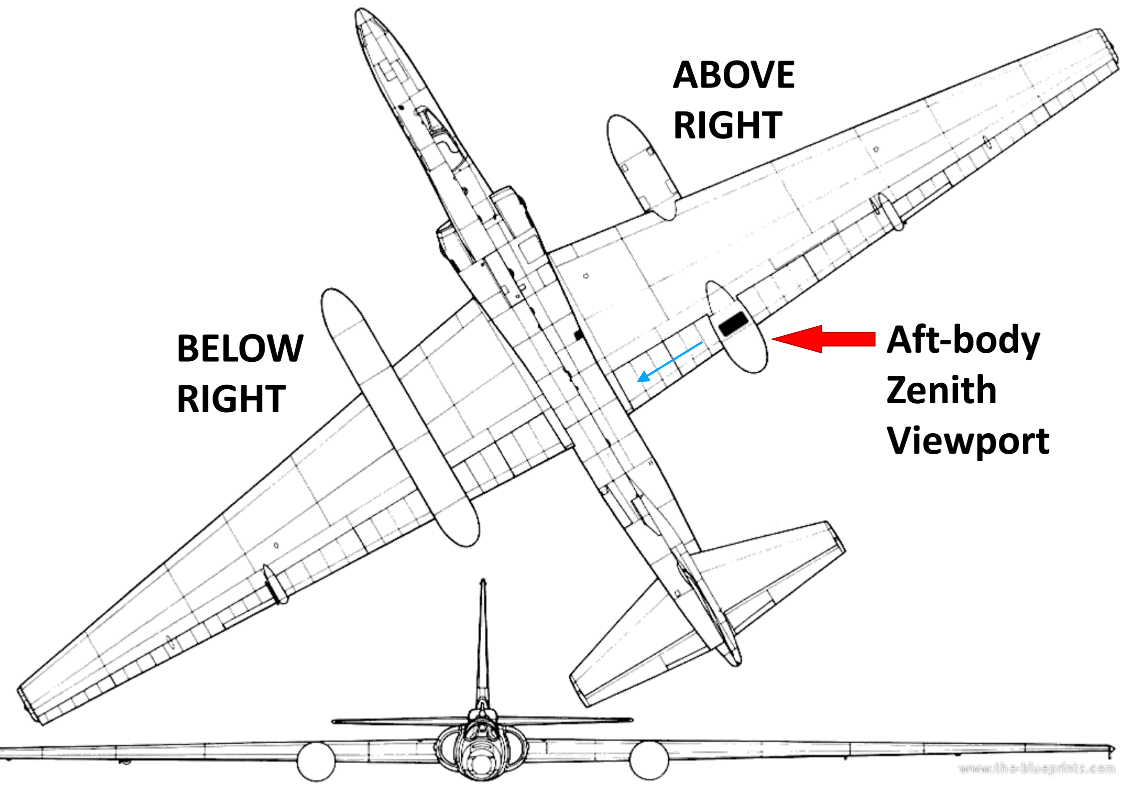
IRIS – IRradiance Instrument Subsystem

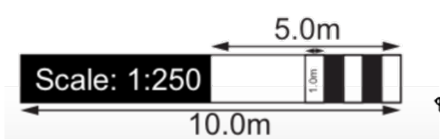
- A non-imaging telescope (integrating sphere at focal point).
- Light fed via a fiber optic cable to a spectrograph.
- On-board LED validation source.
- Instrument enclosure keeps the spectrograph and validation source at surface-level P & T during flight.





- The telescope and robotic mount are in Superpod Aft-body.
- The sensor enclosure and control computer are in Mid-body.
- IRIS telescope views to port through Aft-body Zenith Viewport.





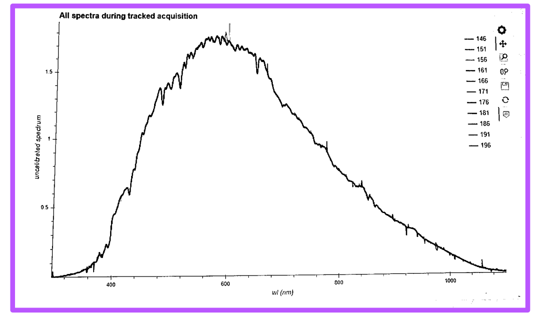
air-LUSI Flight Campaigns

Engineering Flight Campaign

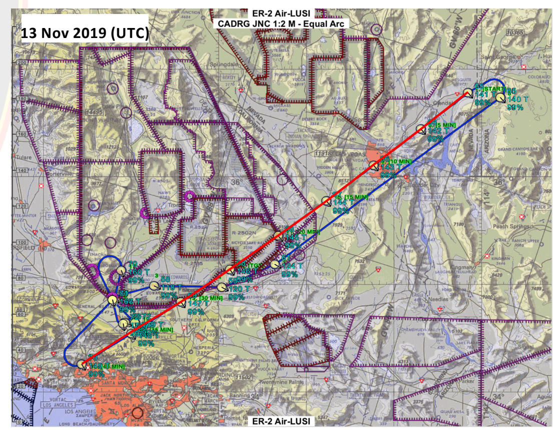
- air-LUSI executed two ~2-hour flights from 1-2 (UTC) August 2018.
- Subsystems were successfully tested during several flights.
- Moon was observed for 30-40 min. at ~21 km alt. for each flight.
- Data was recorded the 2nd night at a lunar phase angle of +53°.

Demonstration Flight Campaign

- air-LUSI executed five ~2-hour flights from 13-17 (UTC) Nov. 2019.
- Moon was observed for 30-40 min. at ~21 km alt. for each flight.
- Flights observed phase angles of +10°, +21°, +34°, +46° and +59°.
- Weather was fair for takeoff and landing. Last flight was shifted earlier to accommodate other aviation activities in the area.



Raw data view via telemetry during engineering test flights



Flight plan for first flight of the Demonstration Flight Campaign


Mobile Pilot Communication
Robotics
air-LUSI network and telemetry
Instrument Function
air-LUSI "Mission Control"



ARMSTRONG
FLIGHT RESEARCH CENTER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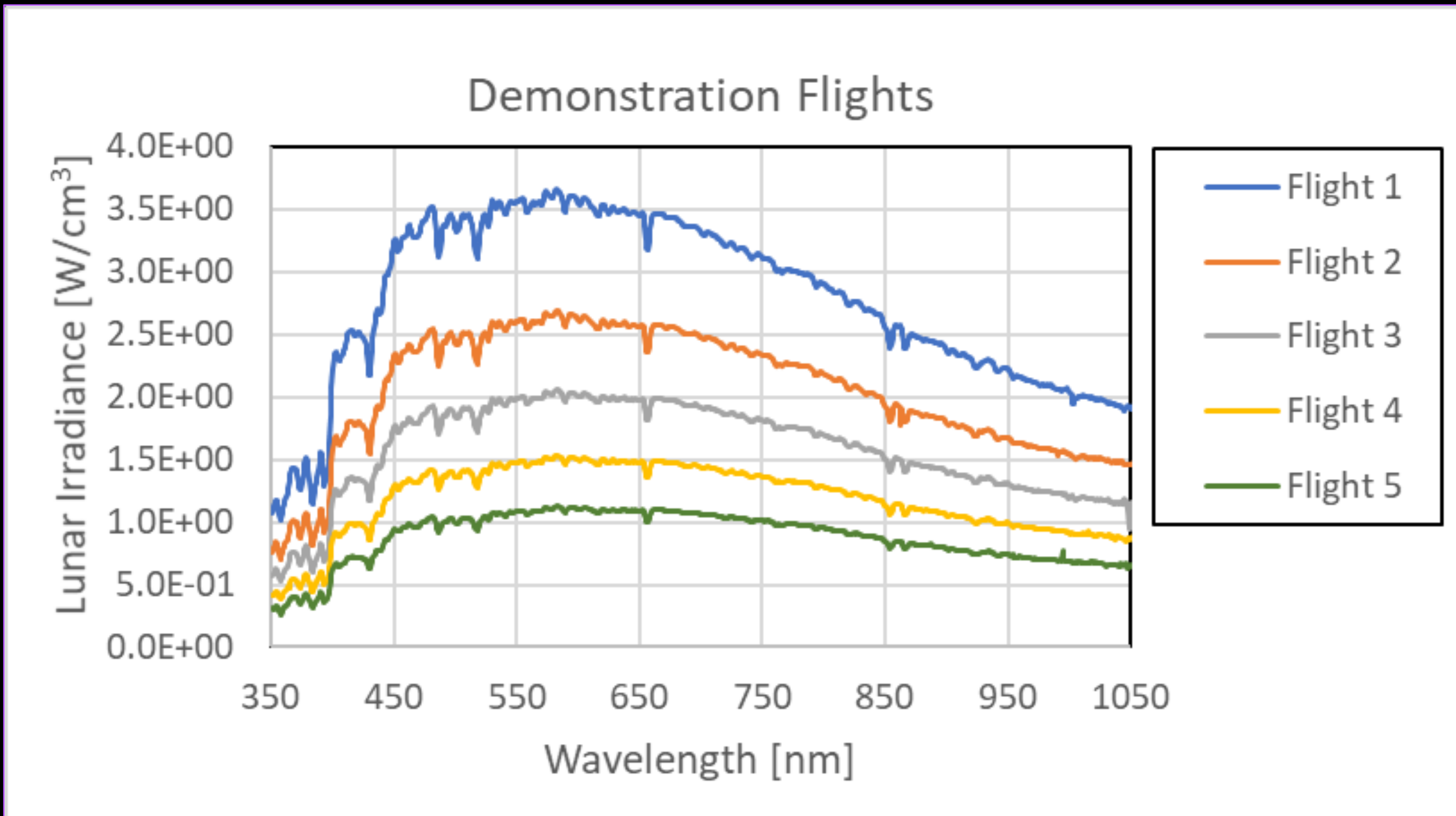
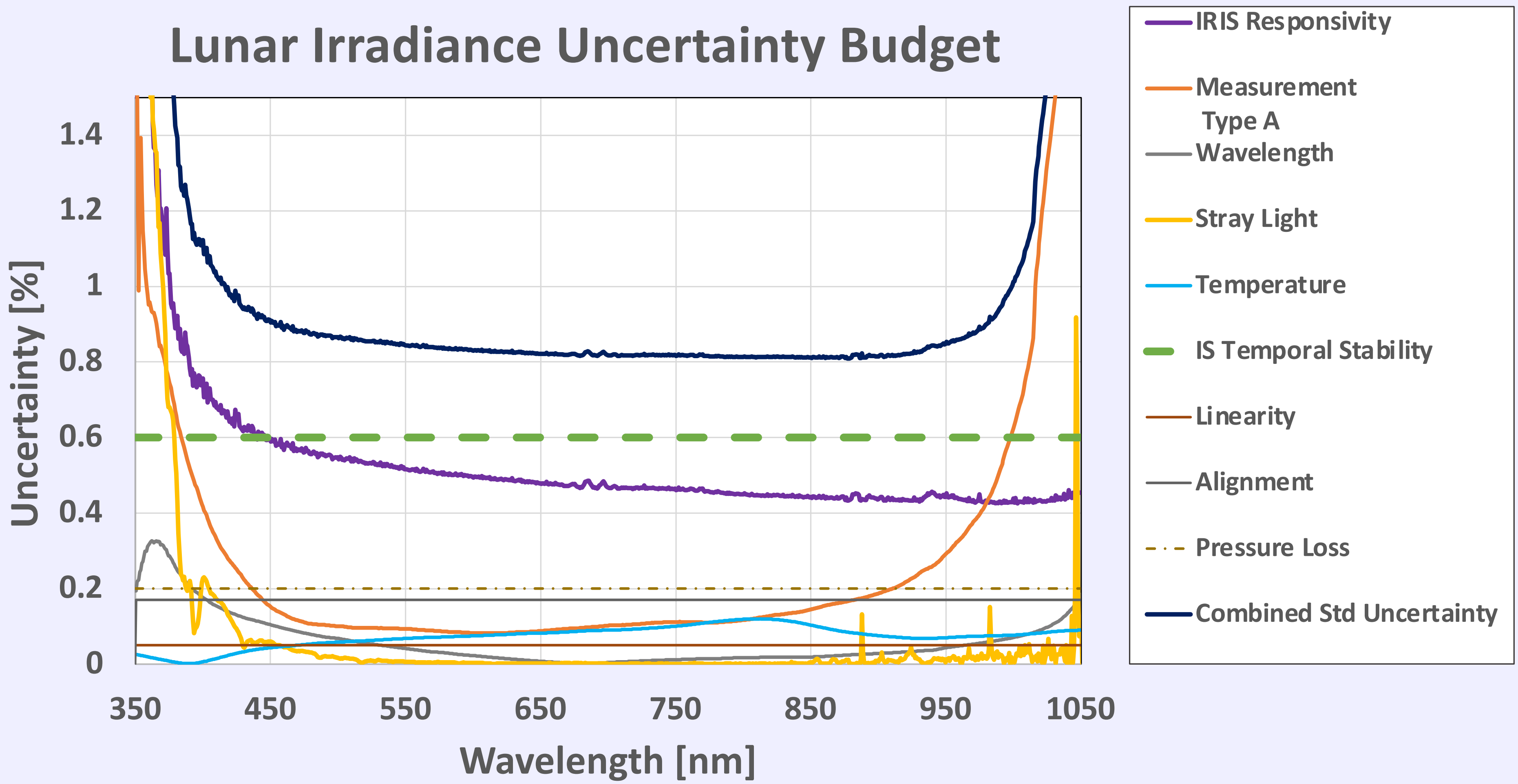
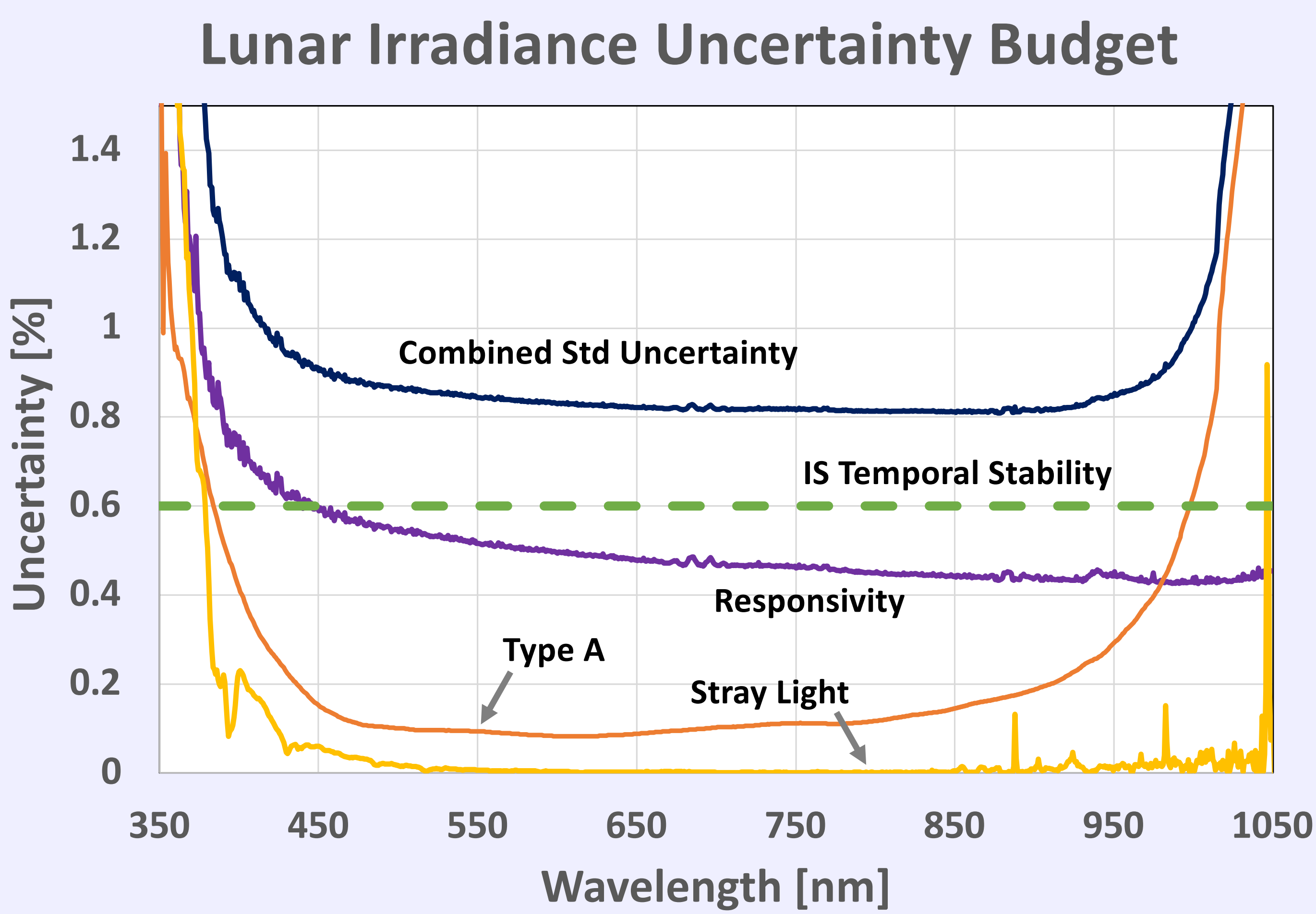
air-LUSI Results



air-LUSI Results



air-LUSI Results



- At-sensor uncertainties are <1% (k=1) from 420 nm to 1000 nm.
- Uncertainty is dominated by the **IS Temporal Stability** component and we are working to reduce this effect.
- **Responsivity uncertainty** stems from the FEL lamp irradiance calibration (which might be cut in half by using SIRCUS before future campaigns).
- **Type A uncertainty** from low counts in the UV (flux) and NIR (responsivity) is also a significant contributor.
- **Stray light** in the spectrometer similarly affects mostly the UV and NIR regions.

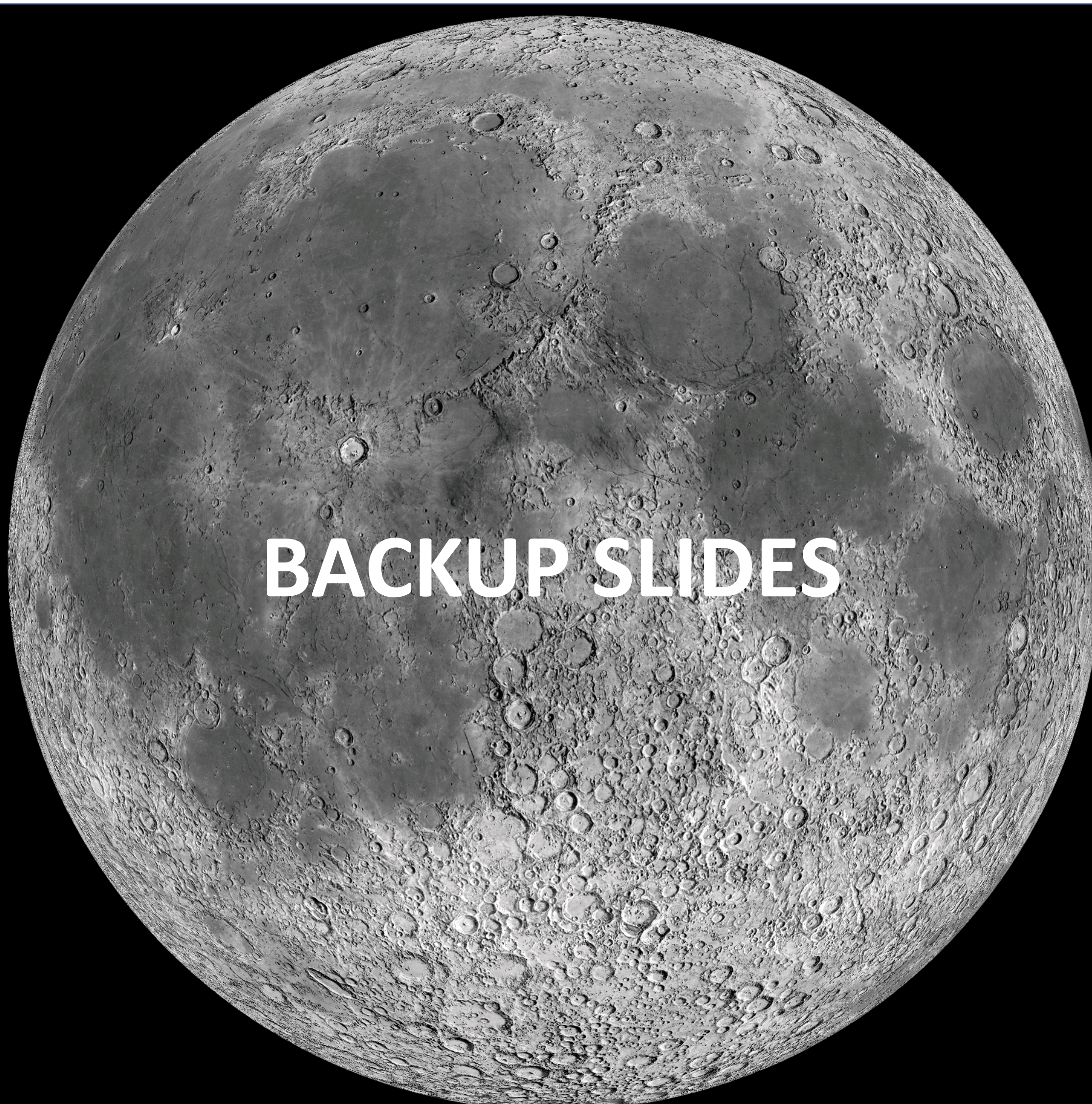
Summary

- air-LUSI is critical for development of an accurate absolute lunar calibration
  - Not affected by issues of orbiting systems or atmospheric correction issues of ground systems.
  - It will be critical to lay the groundwork for current and future efforts.
  - We know that it works now.
- Demonstration Flight Campaign successfully yielded:
  - Lunar Spectral Irradiance for five nights at phases: 10°, 21°, 34°, 46° and 59°.
  - Error budget gives an uncertainty of ~0.8 % (k=1), which can be improved.
  - We are currently verifying that this uncertainty estimate is accurate.
- Future tasks:
  - Comparing air-LUSI to ESA data, LIME, ROLO, and PLEIADES (and maybe Terra MODIS).
  - Doing initial work on repairs and maintenance.
  - Several tasks dependent on lab access have delayed efforts because of COVID-19.
- Future flights also depend on funding sources, aircraft availability and lunar observational windows.

Thank You!

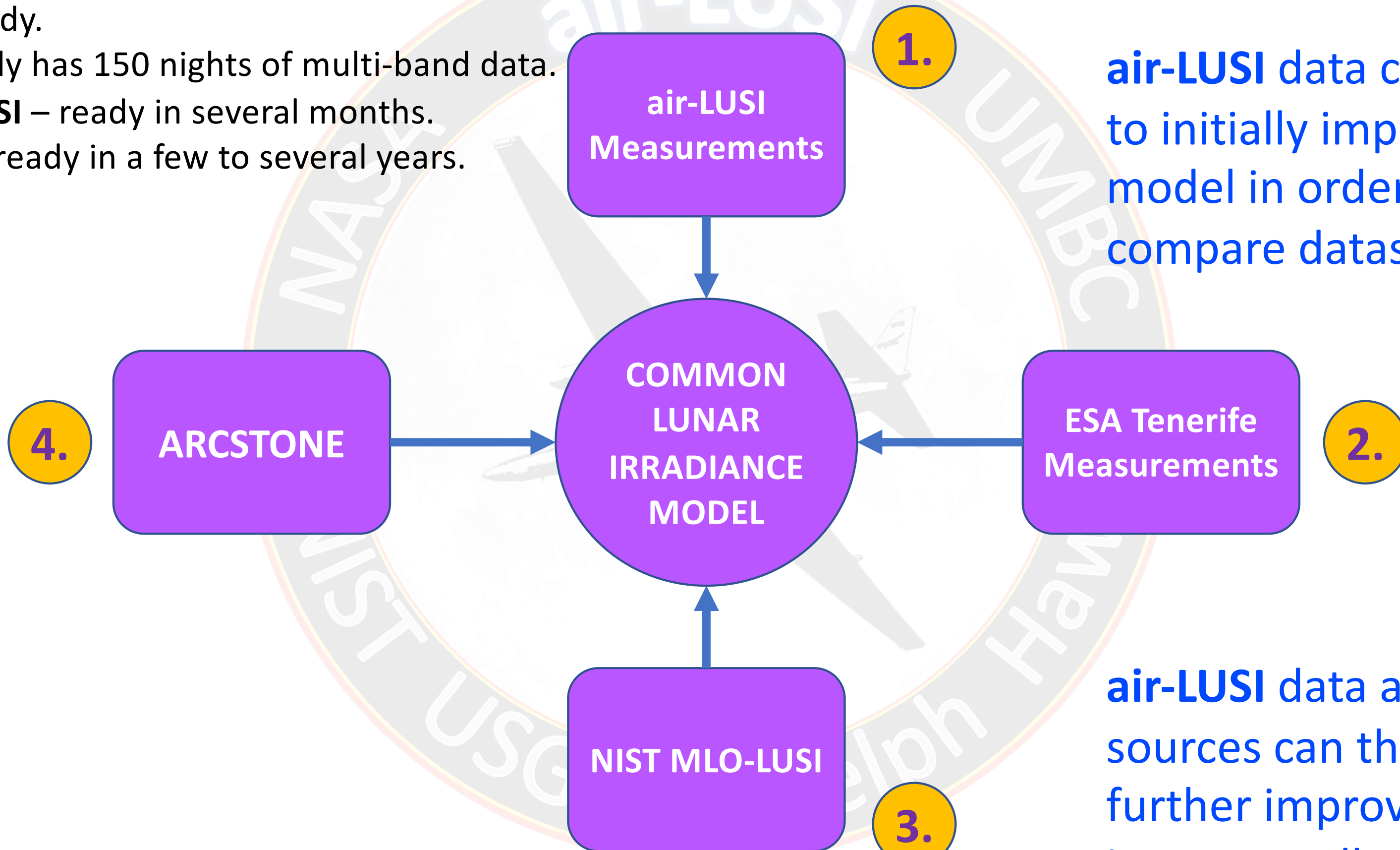
air-LUSI Team (Left to Right) – Steven Grantham, Andrew Newton, Kevin Turpie, John Woodward, Tom Larason, Stephen Maxwell (not shown: Steve Brown, Andrew Gadsden, Andrew Cataford, and Tom Stone)

BACKUP SLIDES



air-LUSI Data Future Application

1. **air-LUSI** is ready.
2. **ESA –** currently has 150 nights of multi-band data.
3. **NIST MLO-LUSI** – ready in several months.
4. **ARCSTONE** – ready in a few to several years.

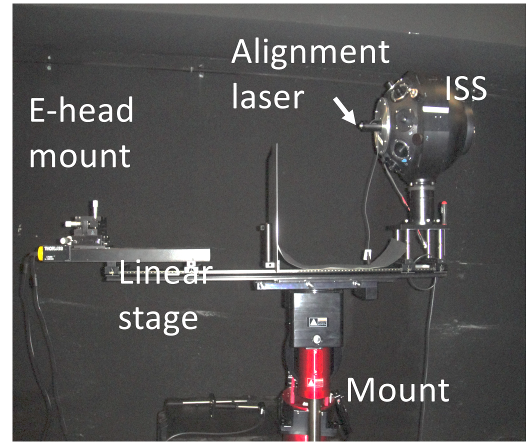


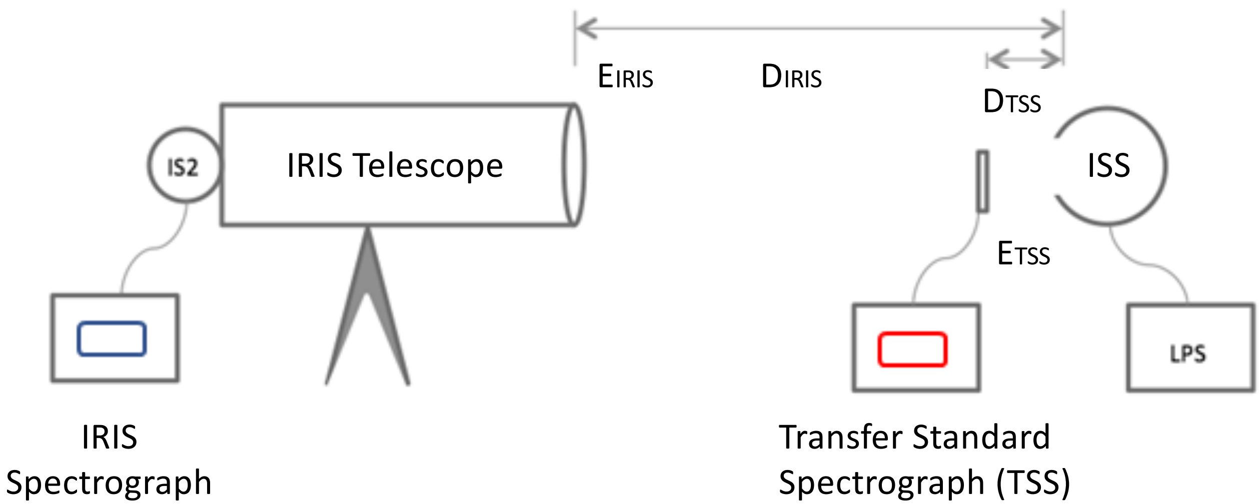
air-LUSI data can be used to initially improve the model in order to inter compare datasets.

air-LUSI data and other data sources can then be used to further improve model incrementally.

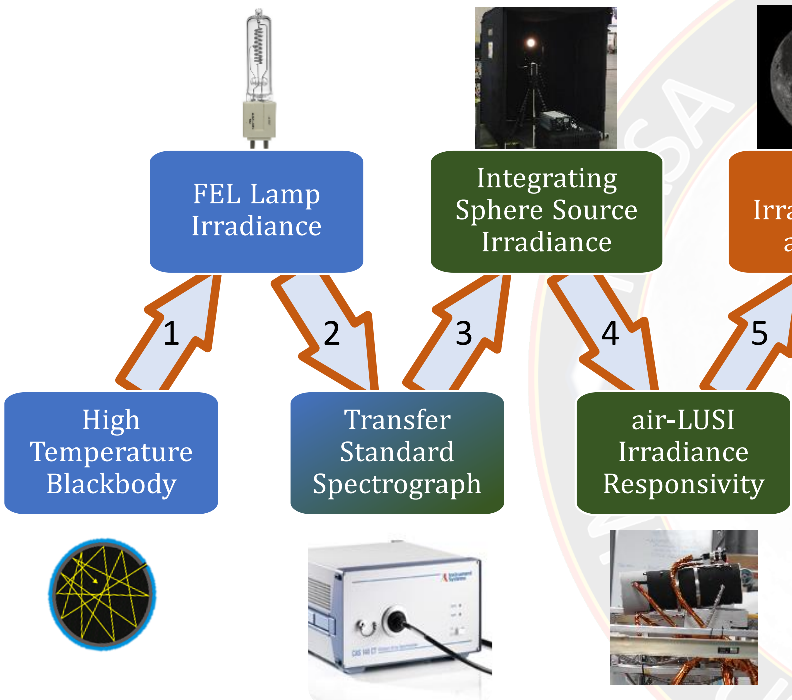
Calibration Scheme

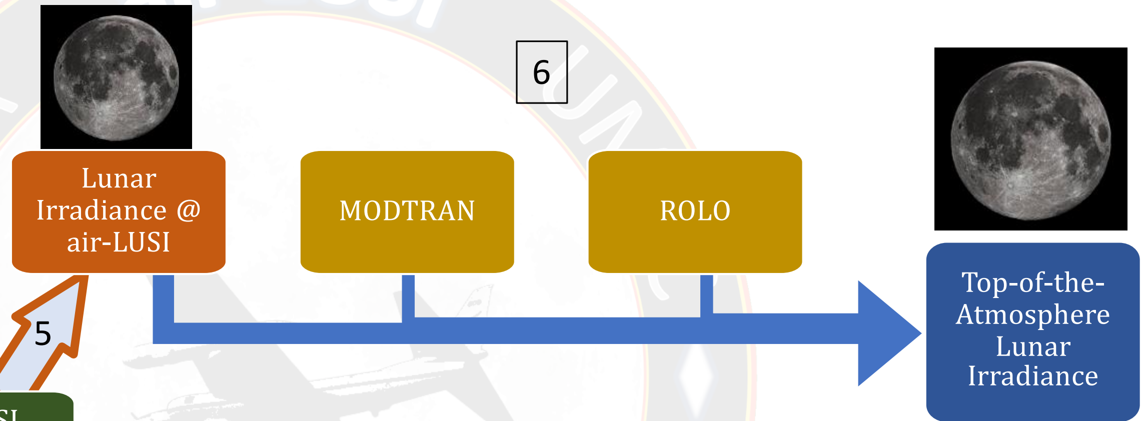
Air-LUSI is calibrated by observing a lamp-illuminated integrating sphere source (ISS) with the approximate angular subtense of the full moon. The output of the ISS is measured by a transfer standard spectrograph (TSS) that holds an SI-traceable scale form NIST.
The inverse square law and measurements of the distance between the integrating sphere and the transfer standard and IRIS are used to transfer the scale to IRIS.





air-LUSI Calibration/Lunar Measurement Chain





Measurement Equation (w/o Atmospheric Correction)

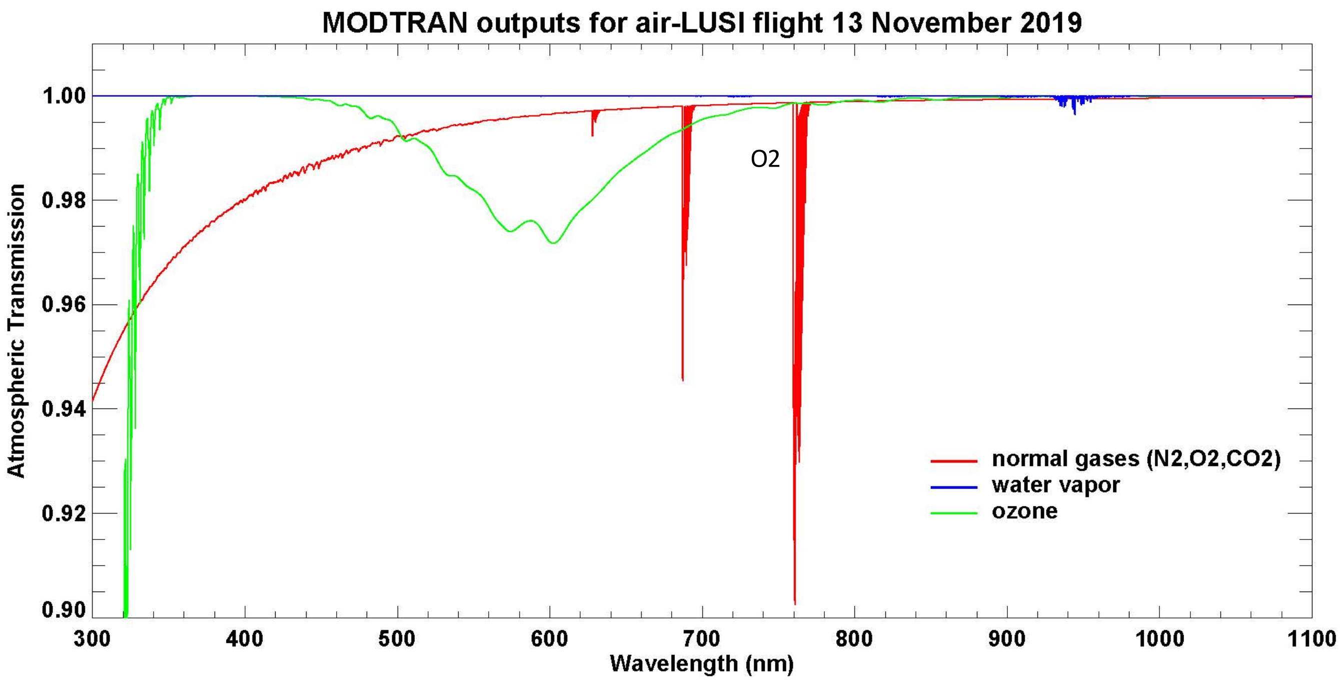
$$E_{IRIS}^{Moon}(\lambda) = E^{FEL}(\lambda)\frac{S_{IRIS}^{Moon}(\lambda)}{S_{IRIS}^{ISS}(\lambda)}\frac{S_{TSS}^{ISS}(\lambda)}{S_{TSS}^{FEL}(\lambda)}\left(\frac{D_{TSS}}{D_{IRIS}}\right)^2$$

E – Irradiance, S – Signal, D – Distance, λ – wavelength.
Subscripts are the measuring instrument: Transfer Standard Spectrograph (TSS) or IRIS.
Superscripts are light source: FEL, Integrating Sphere Source (ISS), or Moon.

MODTRAN atmospheric transmission for air-LUSI flight 1

MODTRAN setup:

- slant path to space from 21.215 km altitude, zenith angle = 22.047°
- 1976 US Standard Atmosphere, 380 ppmv CO_2



Error propagation for atmospheric correction:

The exo-atmospheric lunar spectral irradiance E_{LUSI} is computed by dividing the at-sensor lunar spectral irradiance by the transmission T_s as a function of λ. The relative uncertainty is RSS with the at-sensor uncertainty of the transmittance.

$$E_{LUSI}(\lambda) = \frac{E_{IRIS}^{\mathrm{Moon}}(\lambda)}{T_s(\lambda)} \qquad \left(\frac{\sigma_{E_{LUSI}}}{E_{LUSI}}\right)^2 = \left(\frac{\sigma_{E_{IRIS}^{\mathrm{Moon}}}}{E_{IRIS}^{\mathrm{Moon}}}\right)^2 + \left(\frac{\sigma_{T_s}}{T_s}\right)^2$$

Assuming a conservative 10% error in the model, maxima are given at the following wavelengths, which has a nearly insignificant impact on the at-sensor uncertainty.

$$\left(\frac{\sigma_{T_S}}{T_S}\right)^2 \approx 0.20\% \quad @\lambda = 400\text{ nm}$$

$$\left(\frac{\sigma_{T_S}}{T_S}\right)^2 \approx 0.32\% \quad @\lambda = 620\text{ nm}$$

2022 Avg Lunar Phase (deg)

Month

Day	1	2	3	4	5	6	7	8	9	10	11	12
1											-79	-71
2										-89	-67	-60
3									-86	-76	-56	-48
4									-72	-63	-44	-37
5								-82	-60	-51	-32	-26
6							-90	-69	-47	-39	-19	-15
7						-84	-78	-56	-35	-27	-7	-3
8		-85		-91	-89	-74	-66	-44	-23	-15	4	8
9	-86	-74	-92	-83	-79	-61	-53	-31	-11	-2	16	18
10	-76	-64	-84	-72	-68	-49	-40	-19	3	11	27	29
11	-65	-54	-73	-61	-56	-36	-27	-4	17	22	38	39
12	-55	-43	-63	-49	-44	-23	-15	10	29	34	48	50
13	-44	-32	-52	-38	-31	-11	-2	22	41	45	59	60
14	-34	-22	-42	-26	-19	1	13	35	53	56	69	71
15	-23	-11	-30	-13	-6	16	26	47	64	67	80	81
16	-13	1	-19	-1	7	29	39	59	75	78	90	91
17	-1	14	-8	12	20	42	52	71	86	88		
18	10	25	7	24	33	56	65	83				
19	21	36	18	37	46	70	77	92				
20	32	48	29	50	60	83	89					
21	43	60	41	64	74							
22	54	72	54	77	87							
23	66	85	67	91								
24	77		81									
25	90											
29												-90
30											-84	-78
31										-91		-69

Considerations for finding a Flight Window

- Getting the 1st or 2nd Quarter Moon can be problematic (time and elevation during night).
- Phases before the Full Moon are best observed Dec/Jan – Mar/Apr.
- Phases after the Full Moon are best observed Sept/Oct – Dec/Jan.
- Sometime both before and after can be seen around Dec/Jan.
- Moon is not fixed to calendar months, so these ranges shift slightly from year to year.
- Month around the Winter Solstice are preferable because the Moon is higher (less atmosphere) and the nights are longer (larger window of opportunity).
- Moon also successively reaches max elevation at later and later times each night.