Producing Exo-atmospheric Fiduciary Reference Measurements of Lunar Spectral Irradiance from the Airborne Lunar Spectral Irradiance (air-LUSI) March 2022 Flight Campaign

John Woodward, Stephen Maxwell, Thomas Larason, Steven Grantham – National Institute of Standards and Technology (NIST); Tom Stone – U.S. Geological Survey; Kevin Turpie – University of Maryland Baltimore County; S. Andrew Gadsden, Andrew Newton – McMaster University

CALCON

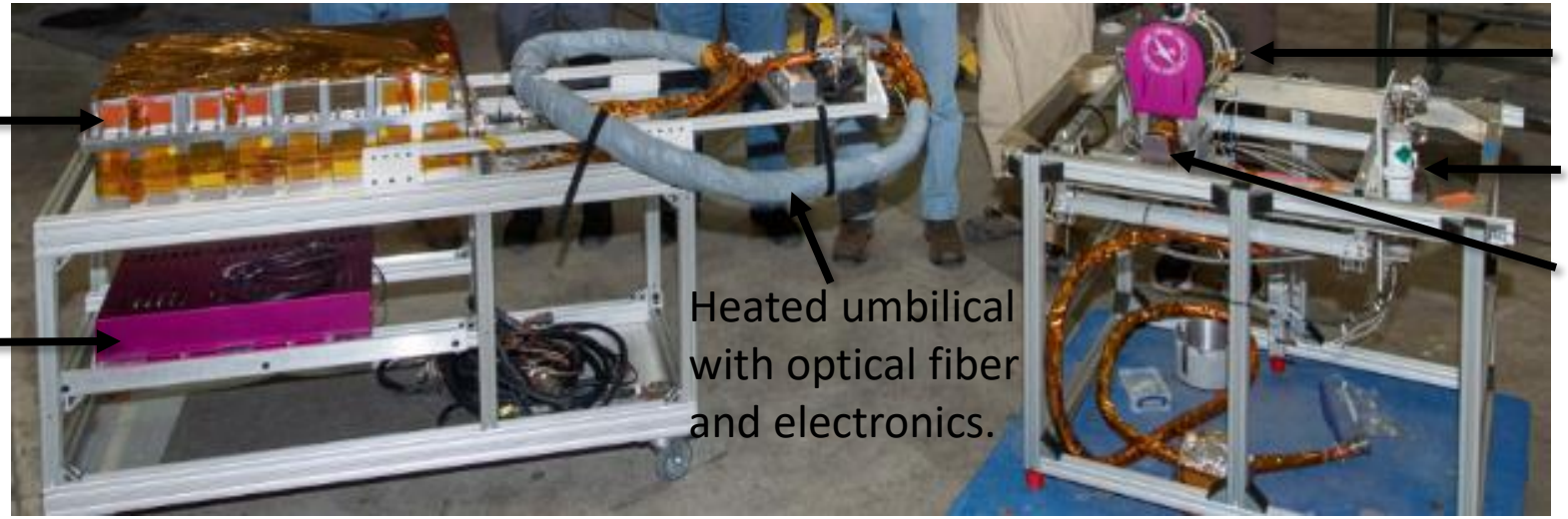
June 12, 2023

Air-LUSI Goals

- Make SI-traceable, top-of-atmosphere, spectral irradiance measurements of the Moon with sub-1% uncertainty.
- Create a transparent data reduction pipeline that is accessible to the lunar calibration community.

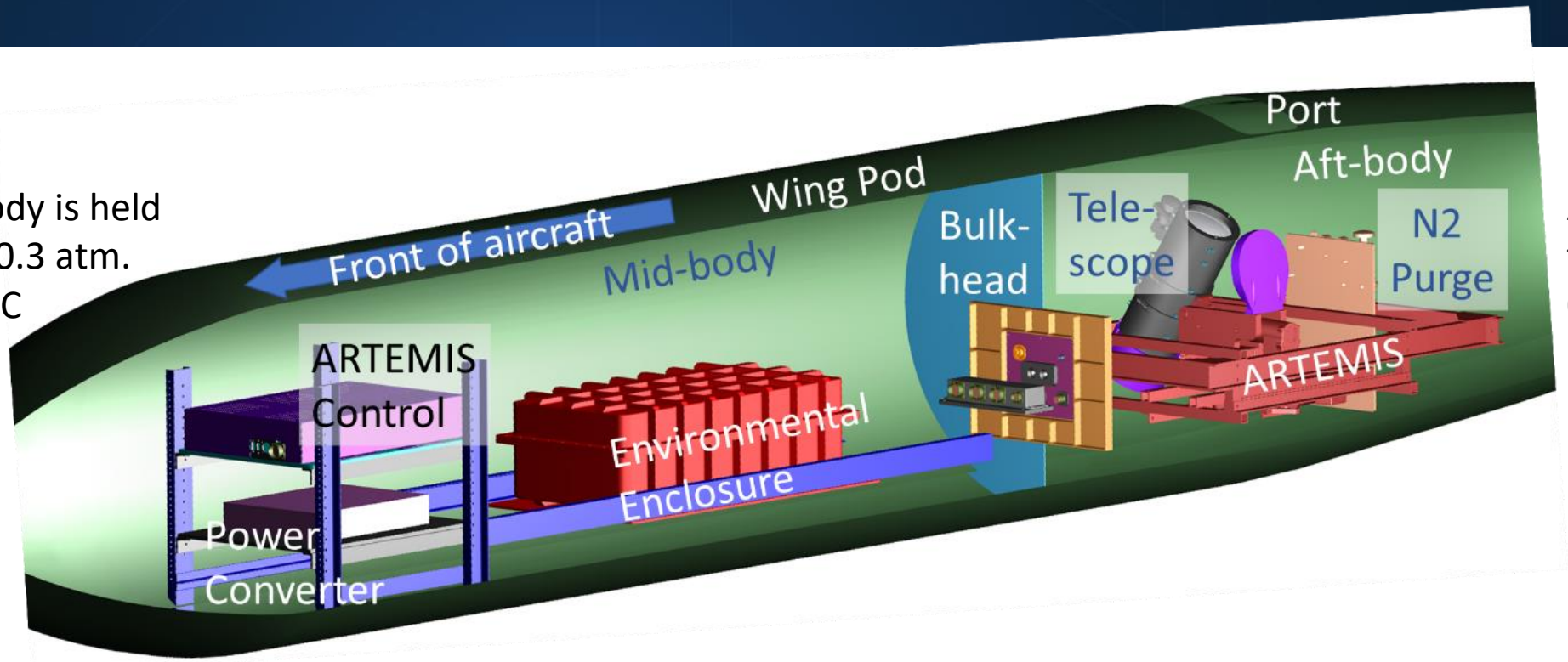
What is air-LUSI?

Air-LUSI is a telescope/spectrograph system designed to measure lunar spectral irradiance from a NASA ER-2 high-altitude aircraft.



Mounting in the aircraft

Mid-body is held above 0.3 atm. and 0 °C



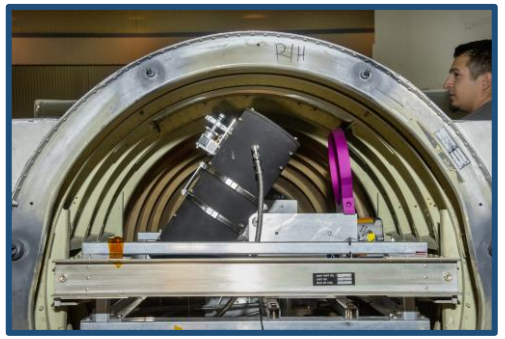
Aft-body is open to atmosphere – 0.05 atm., -60 °C

ARTEMIS control box

Upload

Umbilical cables

Aftbody



2022 Flight Planning

					Observational Windows				
					↑ Rising		↓ Setting		
	Date	Day	Lunar Phase	Max Elev	Transit Time	>46°	<72°	<72°	>46°	
	11-Mar-22	Fri - RDO	-71.6°	**81.2°**	7:20 PM			8:30 PM	10:40 PM	
TARGETS	12-Mar-22	Sat	-60.3°	**81.2°**	8:10 PM			9:30 PM	11:40 PM	
TARGETS	13-Mar-22	Sun	-48.8°	**79.0°**	10:00 PM	8:23 PM	8:50 PM	11:10 PM	1:10 AM	Daylight Savings Time Starts
TARGETS	14-Mar-22	Mon	-37.0°	**75.6°**	10:50 PM	8:24 PM	9:50 PM	11:40 PM	1:50 AM	
TARGETS	15-Mar-22	Tue	-25.0°	71.0°	11:30 PM	8:40 PM			2:30 AM	
TARGETS	16-Mar-22	Wed	-12.9°	65.7°	12:20 AM	9:40 PM			3:00 AM	
	17-Mar-22	Thu	3.8°	59.7°	1:10 AM	10:50 PM			3:20 AM	
	18-Mar-22	Fri	13.9°	53.3°	1:50 AM	12:10 AM			3:30 AM	

Blue = Next Day

Red = Astronomical Twilight Cutoff

Flight #2 cancelled due to high winds

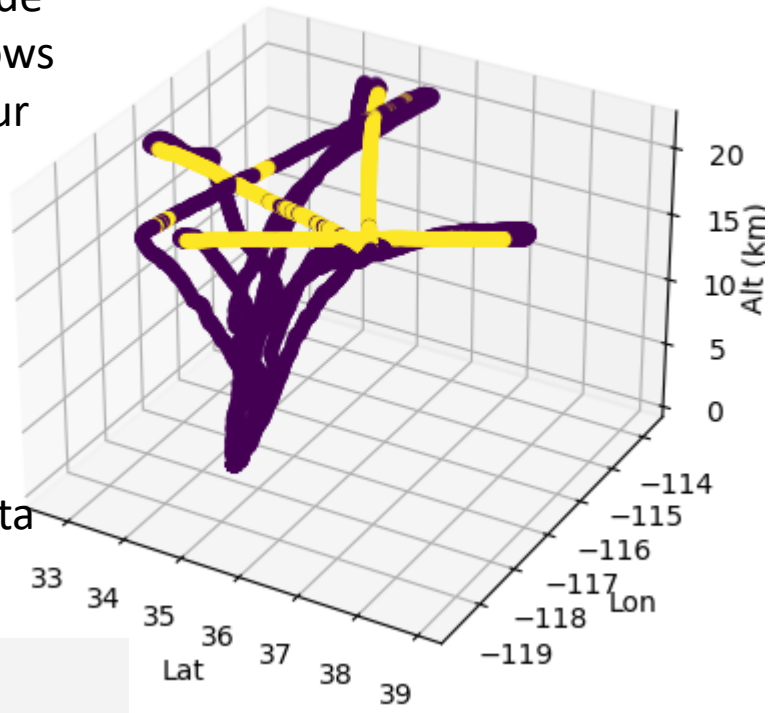
Flight #5 limited data collection due to turbulence

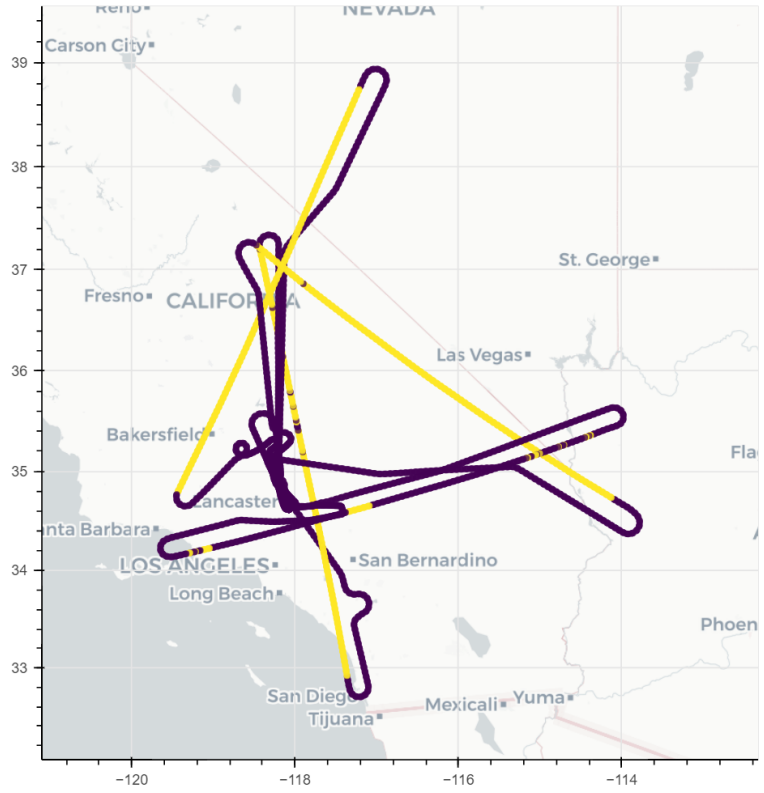
Flight Data

- 1368 files in flight data with 4104 spectra
- 37106 readings of monitor data (time, temperature, photodiodes, flight status . . .)
- 119 files from ARTEMIS with a total of 5856481 records
- navigation data from the ER-2
- all ancillary data are interpolated onto the midpoint times of each lunar spectrum and combined into an array that has 125 columns and 4104 rows
- written to "parquet" file that takes only 20 megabytes on disk and is then easily integrated with many open-source tools such as Pandas, Polars, DuckDB, and others
- The file format, Apache Parquet, ``is an open source, column-oriented data file format designed for efficient data storage and retrieval.'' https://parquet.apache.org/. Pandas, polars, [https://www.tadviewer.com/](Tad Viewer), DuckDB, etc can be used to view or manipulate these files

Example – Lunar Spectra Acquisition

Plot aircraft location and color code for valid lunar spectra. Yellow shows when rms tracking error meets our acquisition criteria.





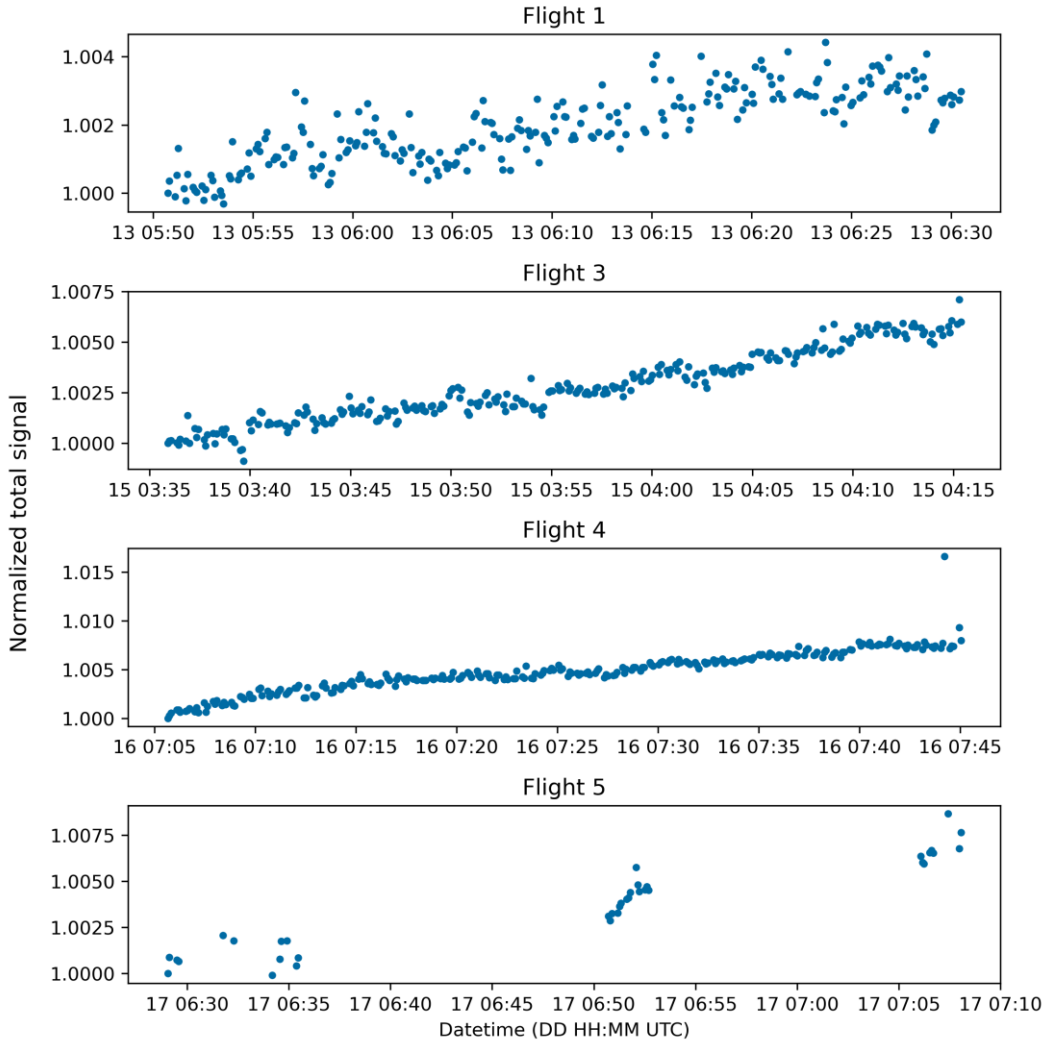
Relatively simple code allows interrogation of the combined data set:

```
ax.scatter3D(
    df_airlusi_extended.select("Lat"),
    df_airlusi_extended.select("Lon"),
    df_airlusi_extended.select("Press_Alt") * 12 * 0.0254 / 1000,
    c=df_airlusi_extended.select("Tracking_Quality_Flag"),
)
```

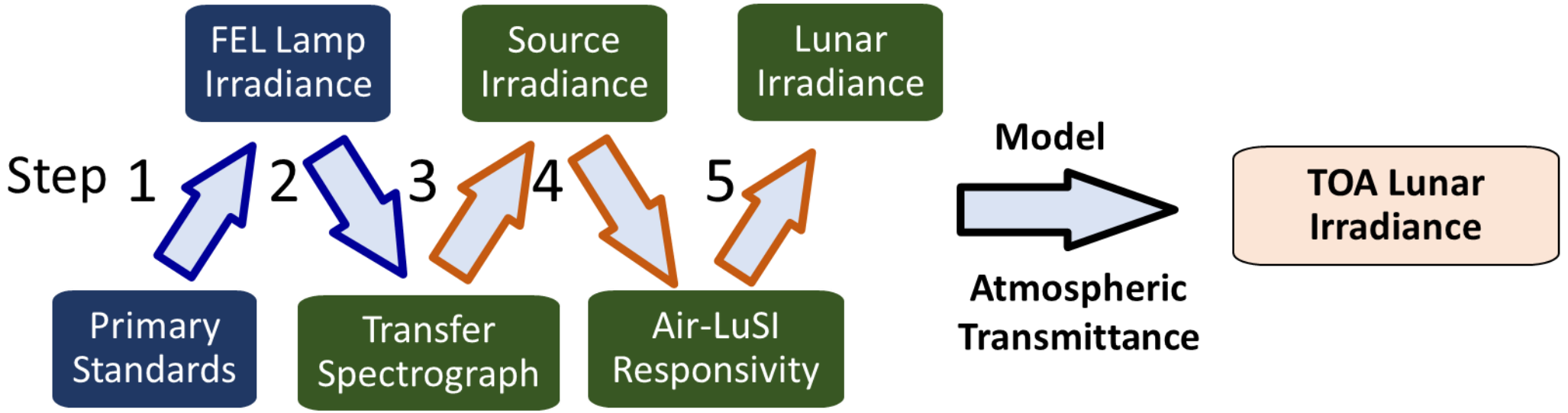
Example - Integrated Lunar Spectra

Plots of integrated counts from lunar spectra normalized to the initial spectrum. The slope is due to the brightening of the Moon throughout the flight. For each flight we provide a single calibrated spectra normalized to the midpoint time of the flight.

```
fig, ax = plt.subplots(4)
for n, (flight_num, df) in enumerate(
    df_airlusi_extended.filter(pl.col("Tracking_Quality_Flag") == True).groupby(
        "Flight_Number", maintain_order=True
    )
):
    y = df["Scan"].airlusi.to_numpy().sum(axis=1)
    y = y / y[0]
    x = df["CAS_Scan_Mean_Time"]
    ax[n].plot(x, y, ".")
    ax[n].set_title(f"Flight {flight_num}")
ax[-1].set_xlabel("Datetime (DD HH:MM UTC)")
fig.supylabel("Normalized total signal")
fig.set_dpi(300)
fig.set_size_inches(8, 8)
fig.tight_layout()
```



Calibration Methodology



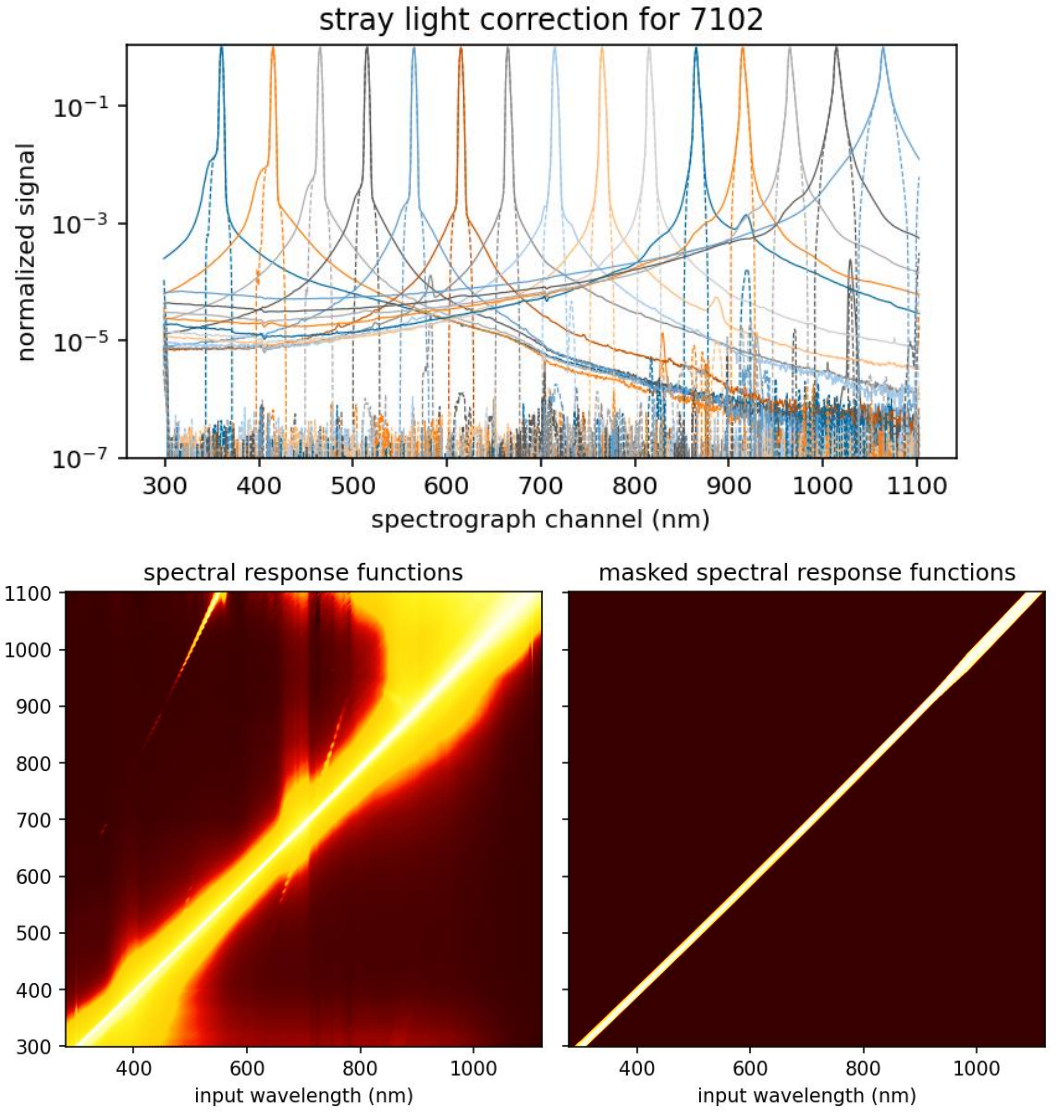
$$E_{Moon}^{TOA} = \frac{1}{\tau_{TOA}} \frac{S_{LUSI}^{Moon} T}{S_{LUSI}^{IS}} \left(\frac{D_1}{D_2}\right)^2 \frac{S_{TS}^{IS}}{S_{TS}^{FEL}} E_{FEL}$$

Characterization

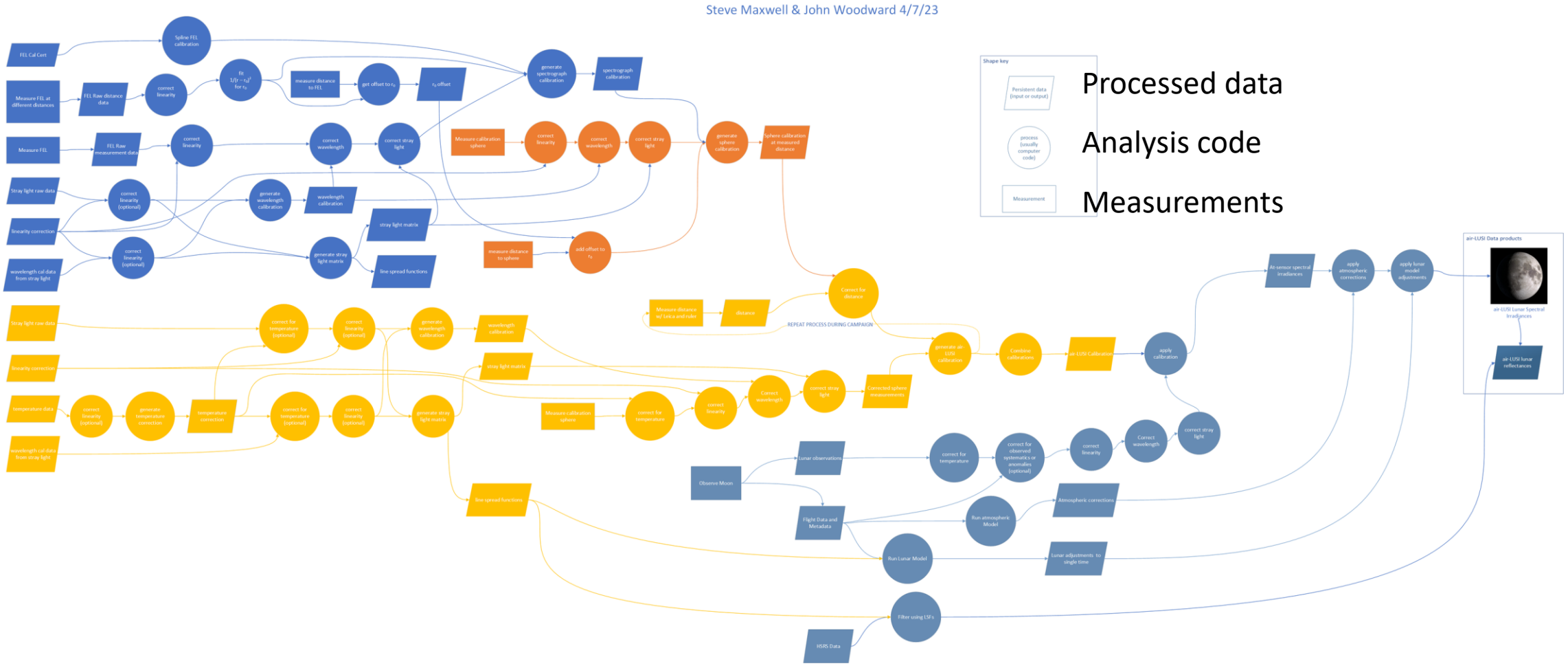
Spectrographs are characterized for linearity (beam conjoiner), stray light and wavelength (laser line inputs), and temperature.

Top figure shows spectrograph response to single wavelength inputs (solid lines) and the same inputs after stray light correction (dashed lines).

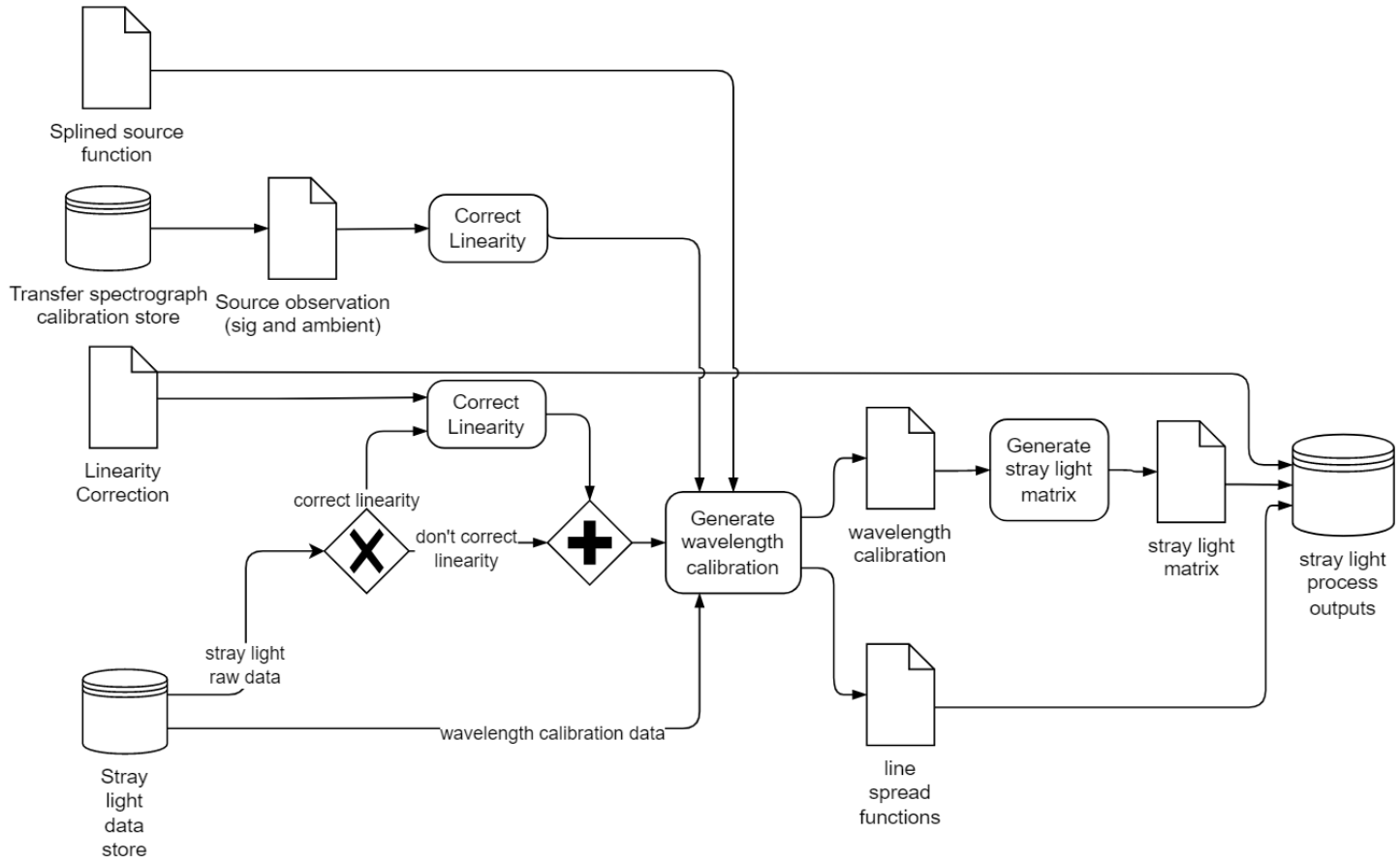
Bottom figure shows the spectral response functions generated from the single wavelength inputs. We allowed the in-band region to expand in the IR.



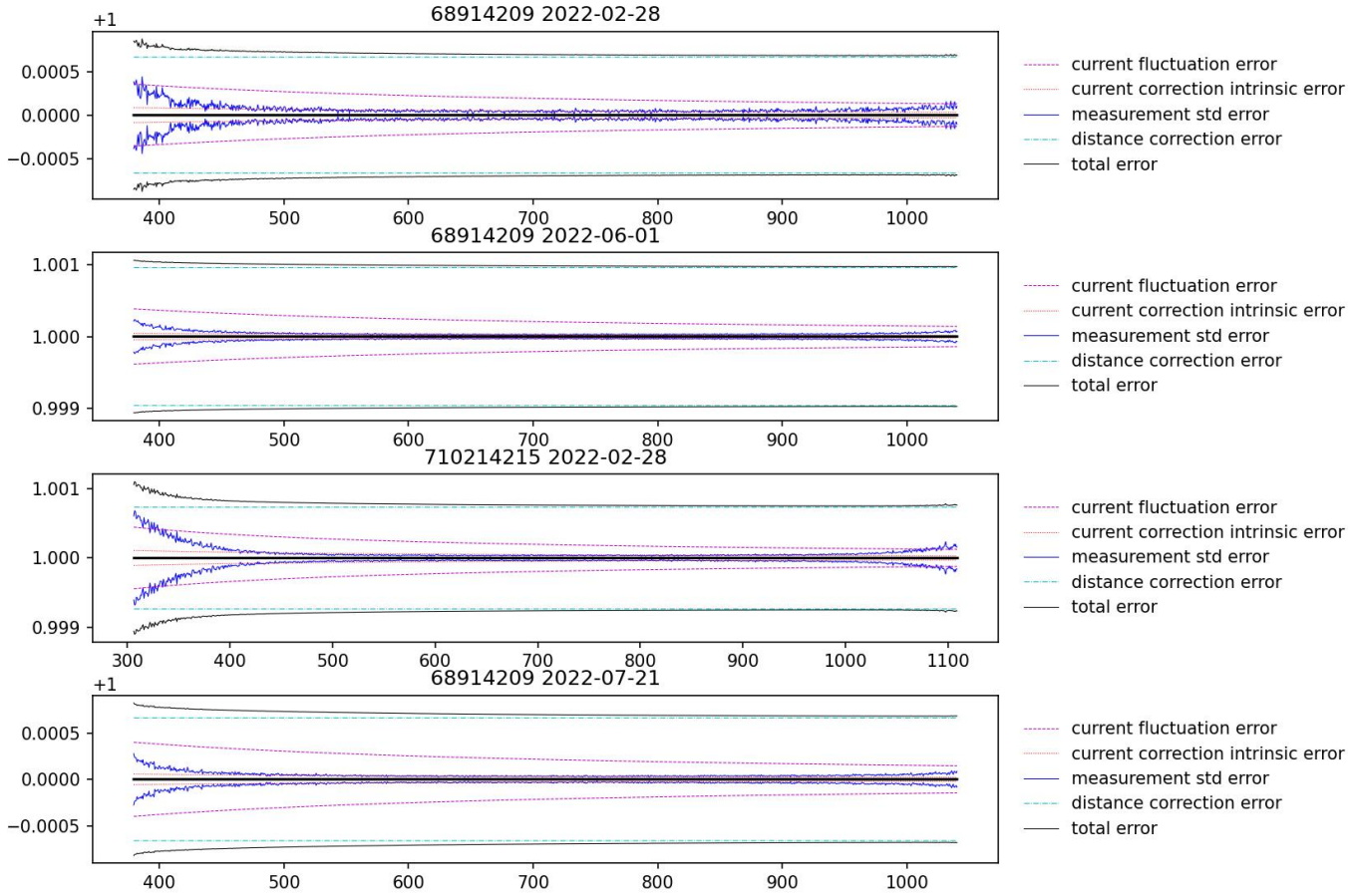
Draft Air-LUSI data processing pipeline



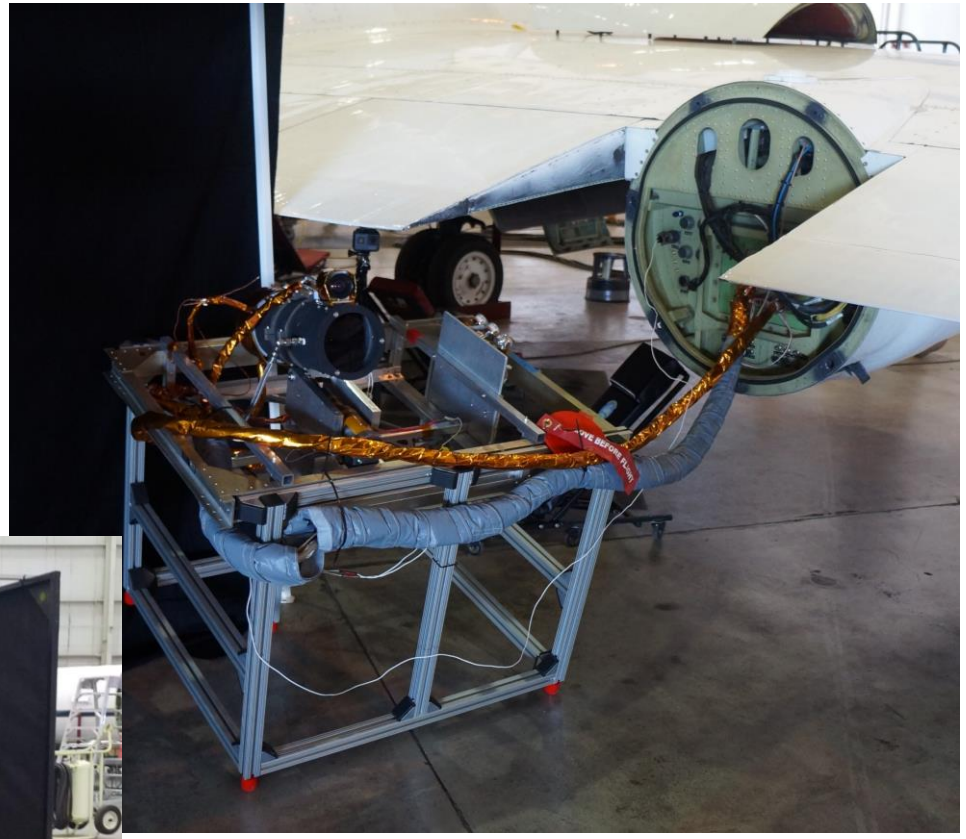
Data flow chart for stray light and wavelength characterization



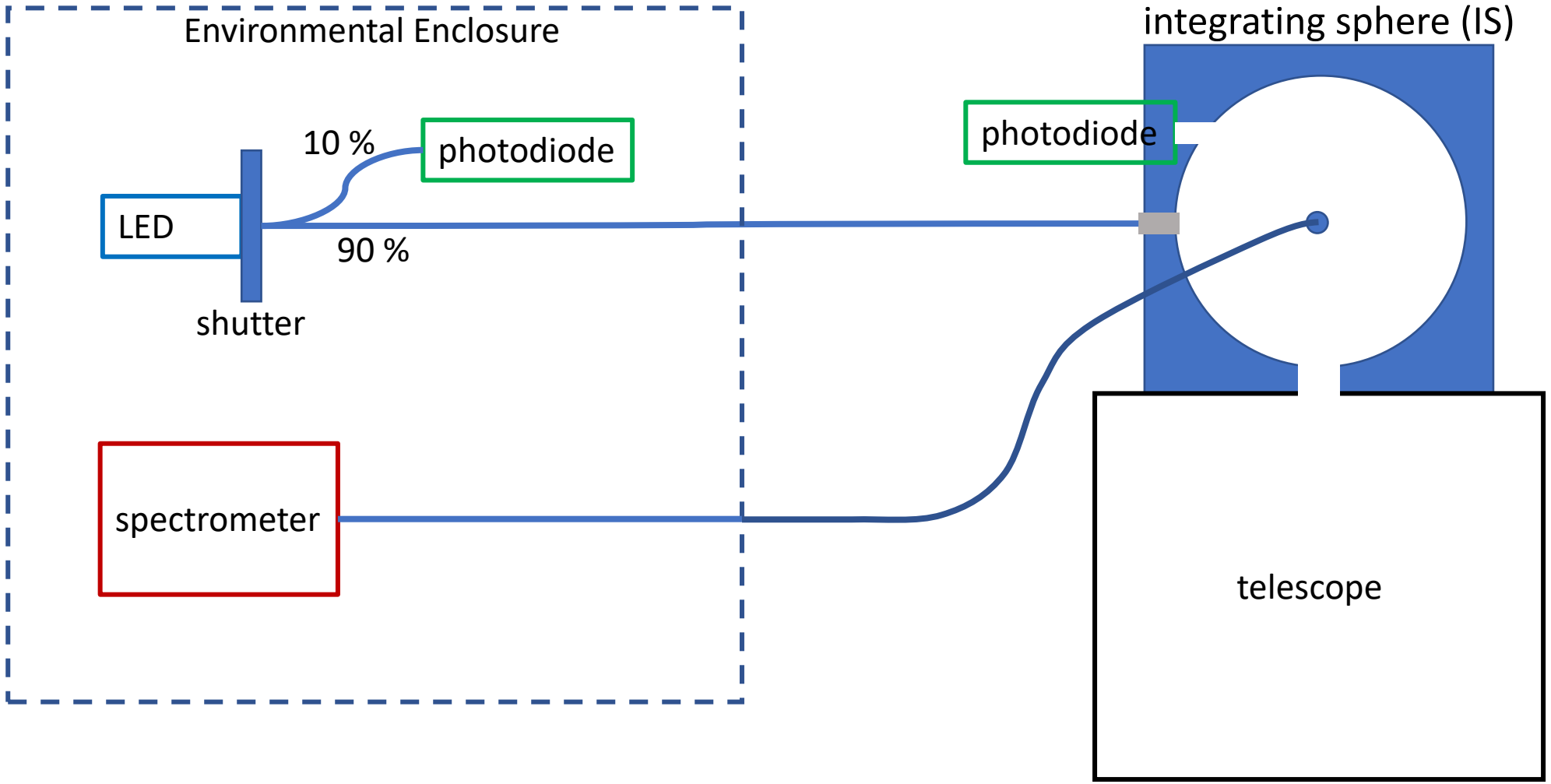
Measurement uncertainty for calibration of transfer spectrograph with FEL lamp



Hanger Cal Setup during Flight Operations

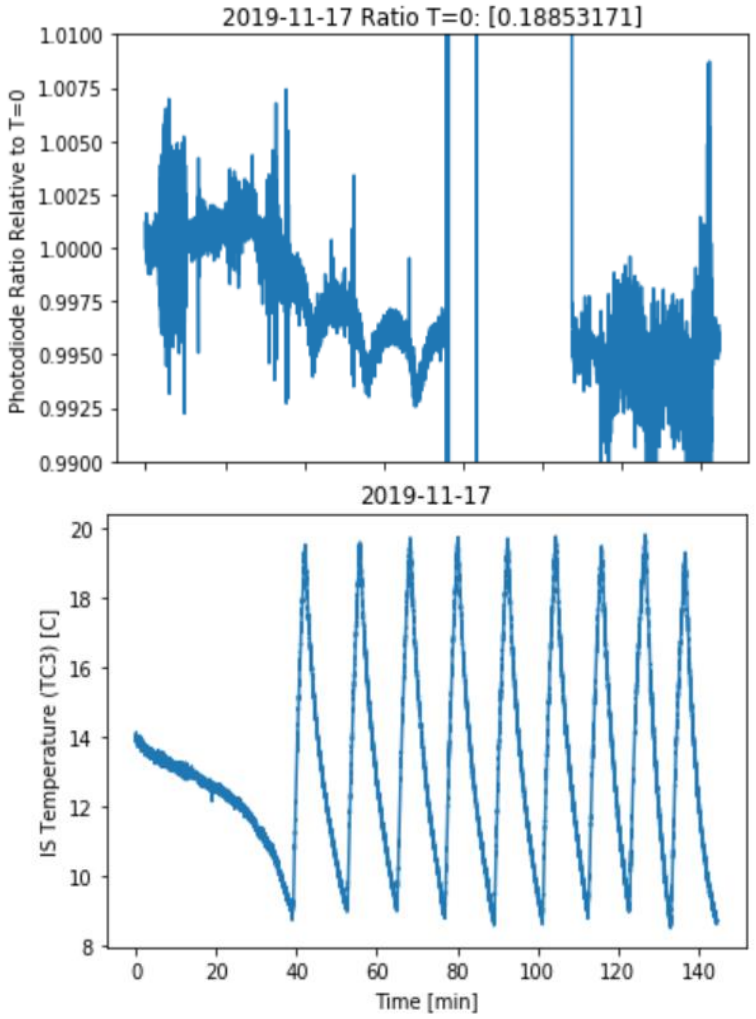


LED validation system



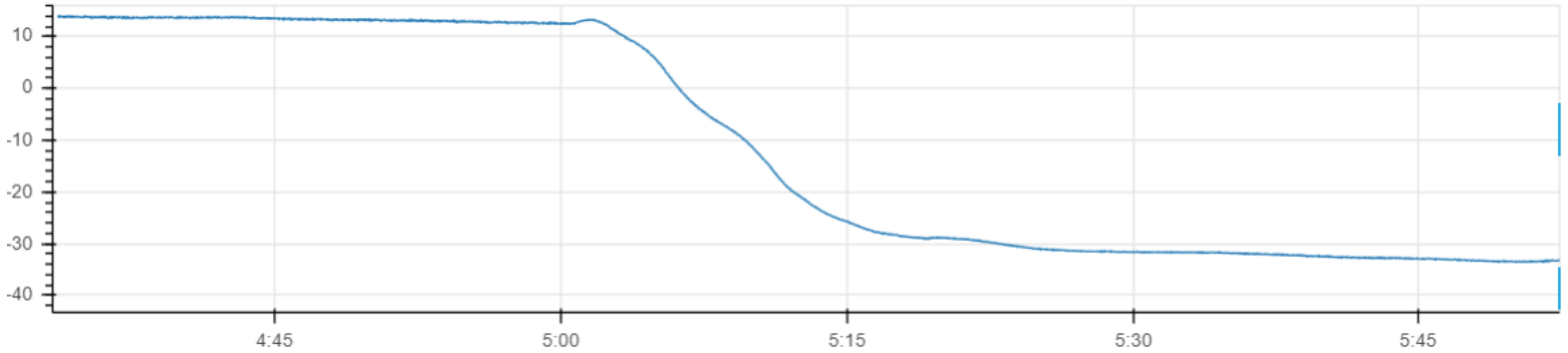
LED Validation – Demonstration Flight #5

On the demonstration flights the LED validation source shutter failed, so we changed the software and only used it on the last flight. It showed both an 0.6% drop in the IS throughput and an 0.2% oscillation with the same period as the heater on the IS. Better temperature control was required.

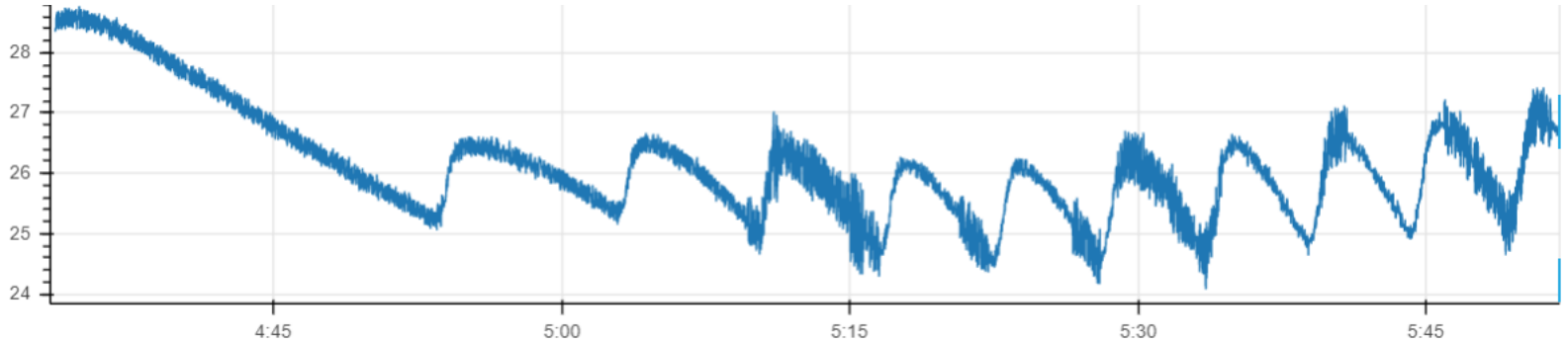


LED Validation – Operational Flight #4

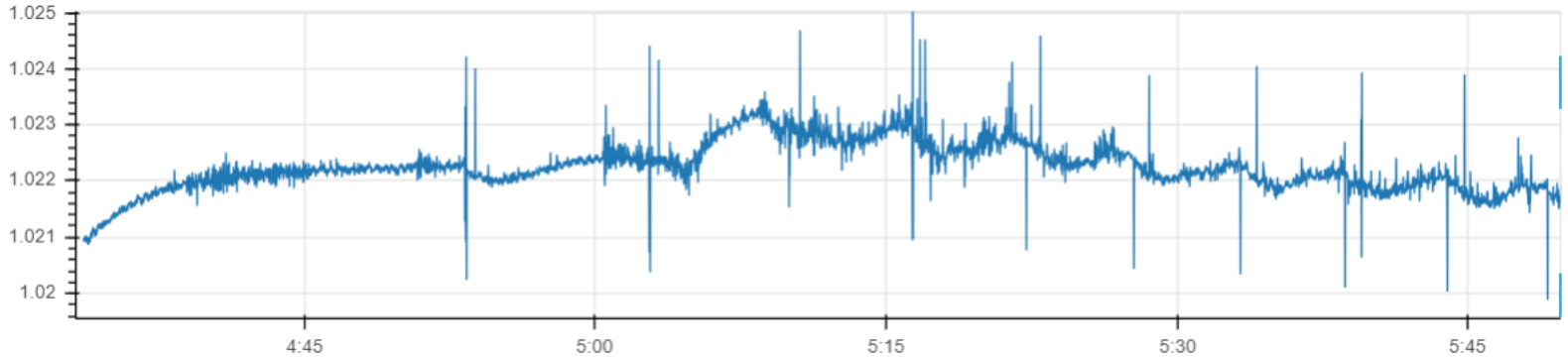
Aft pod ambient temperature, C



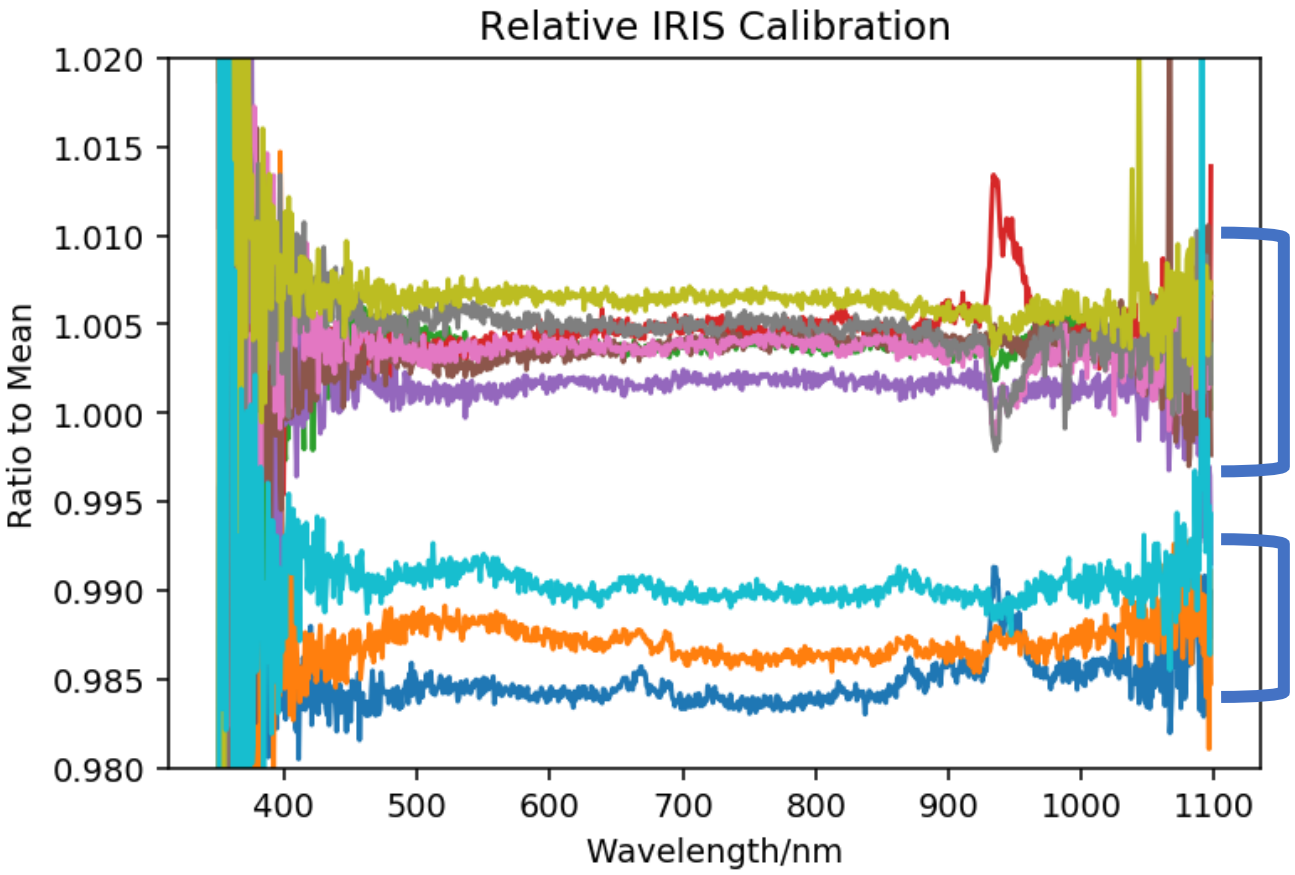
Int. sphere core temperature, C



Photodiode ratio



IRIS Irradiance Responsivity Calibration



On Aircraft

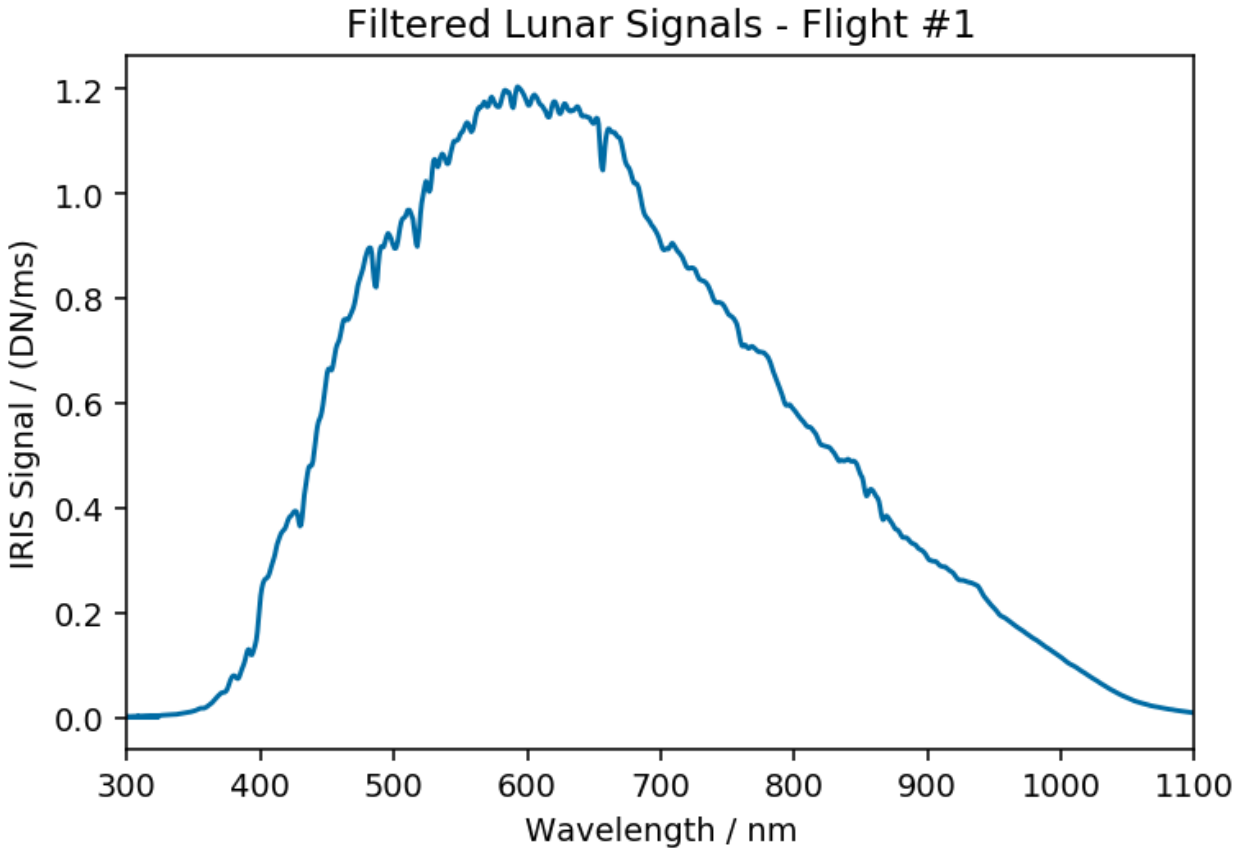
Off Aircraft

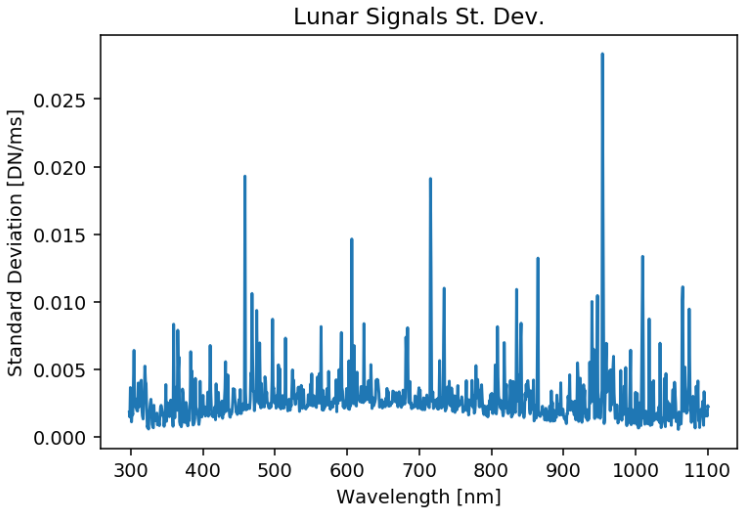
Lunar Measurements

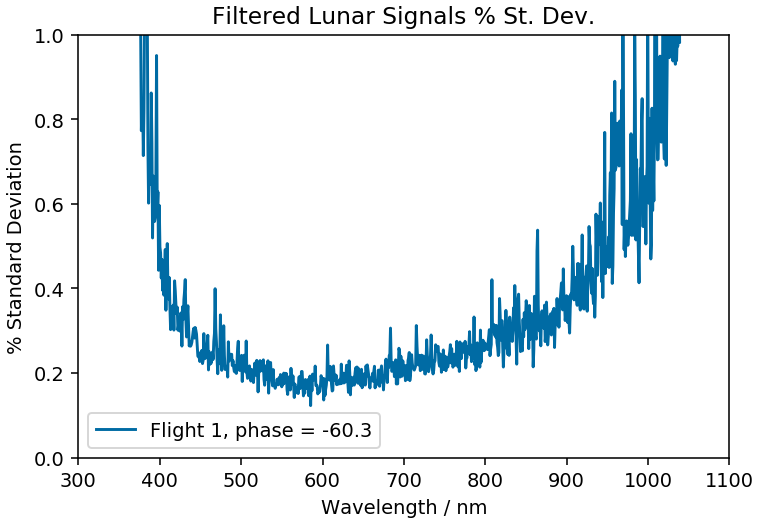
We were scheduled to fly on five consecutive nights on March 13 to 17 (local time). Flight #2 was cancelled shortly before take-off due to high winds. During Flight #5 we experienced turbulence that exceeded the ability of the ARTEMIS tracking system for much of the flight, but with the high lunar irradiance at low phase angle we did collect enough spectra for a viable data set. Note that the flights retain their original numbering, so we have data from Flights 1, 3, 4 and 5.

Each IRIS data file consists of a 5 s dark spectrum and three 5 s light spectra. Data are recorded in DN/ms. These files are taken continuously during the flight. The LED validation source illuminates the telescope integrating sphere while the telescope is stowed for ascent and descent. The LED is shuttered while the telescope tracks the Moon.

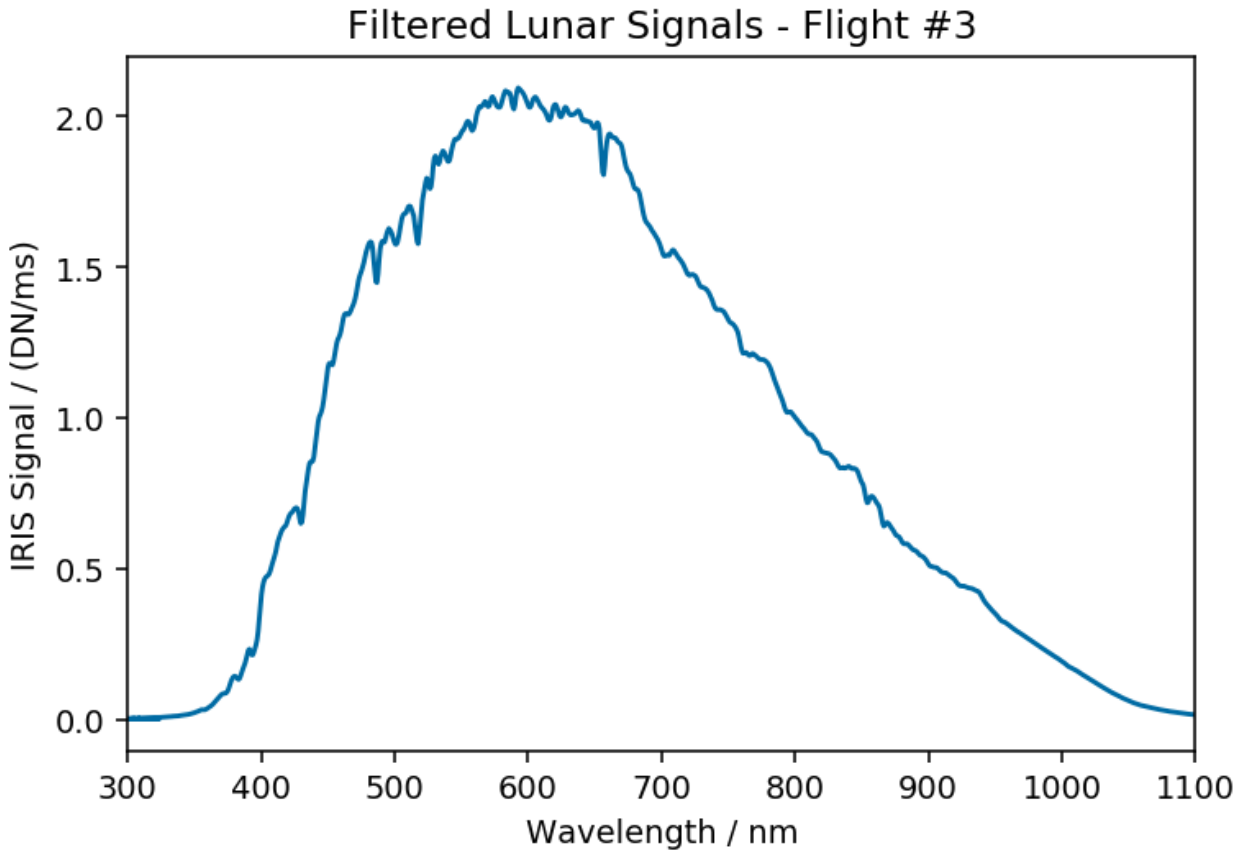
Lunar Measurements-Flight #1

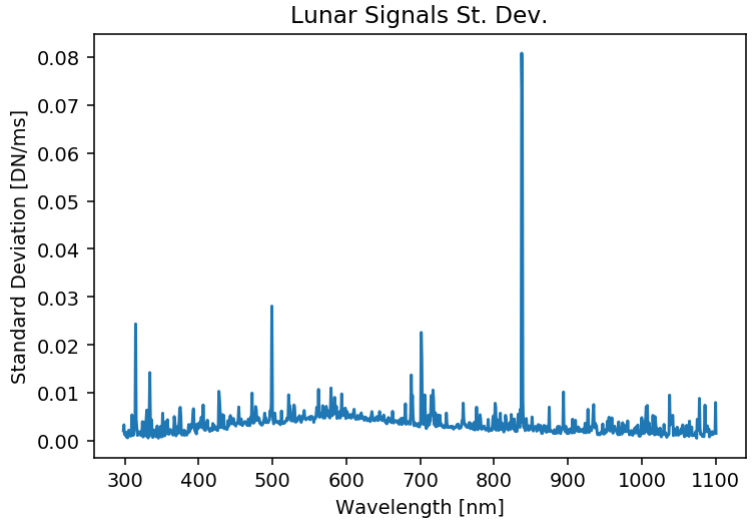


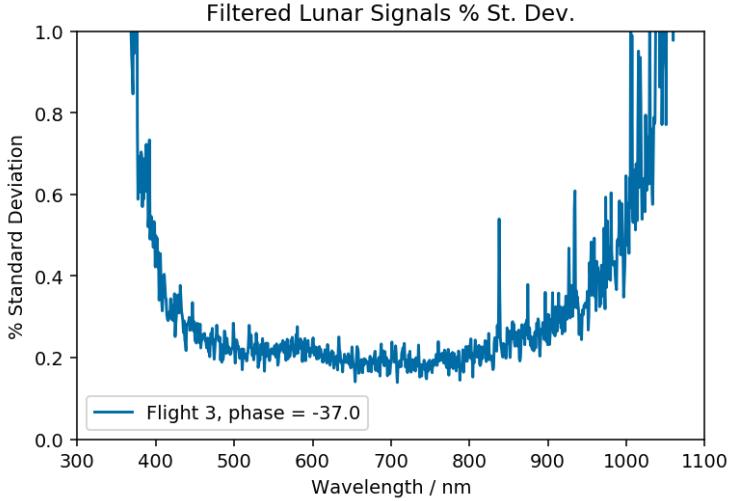




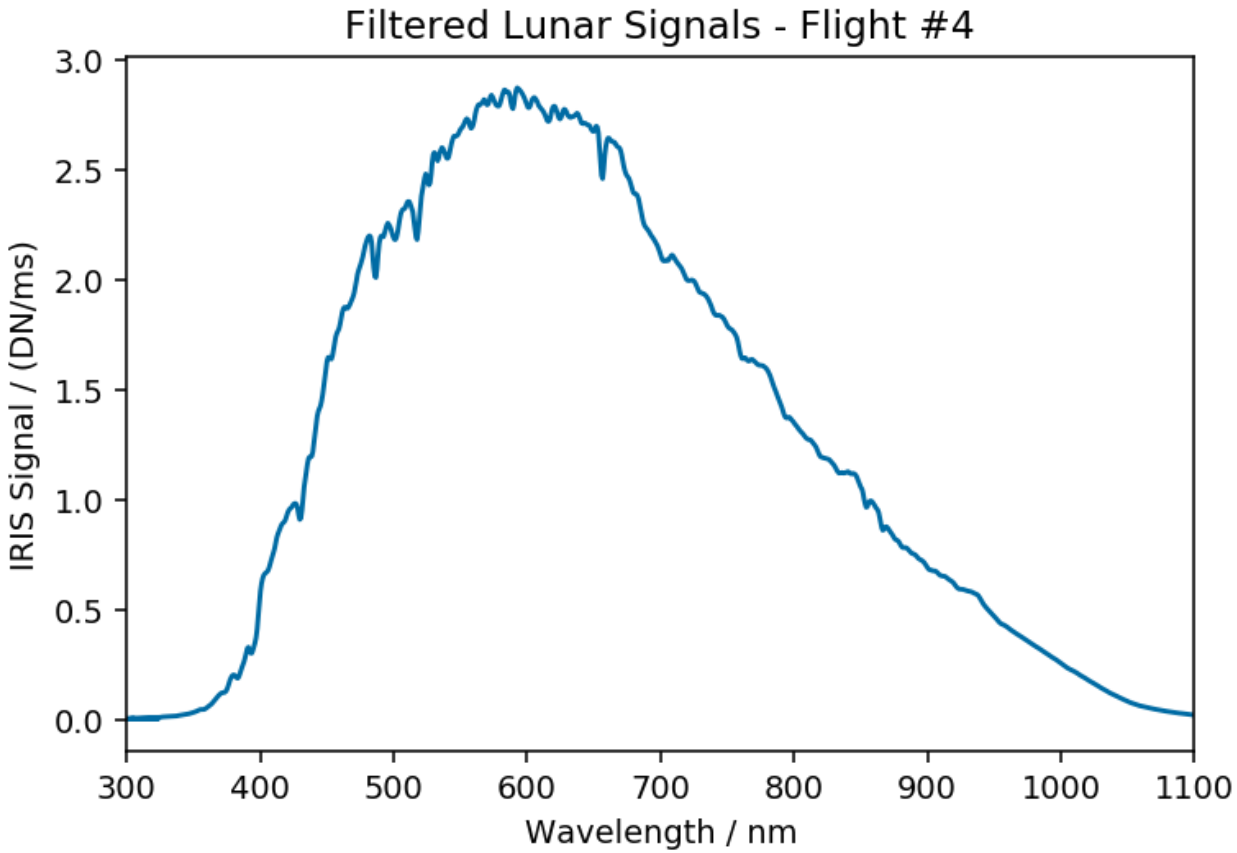
Lunar Measurements-Flight #3

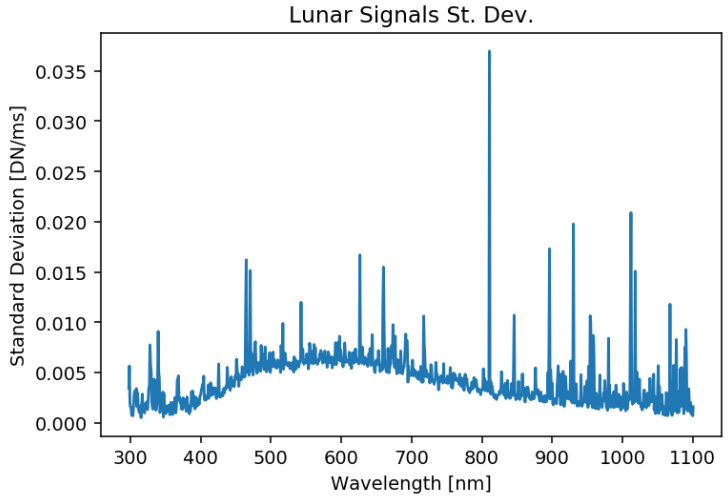


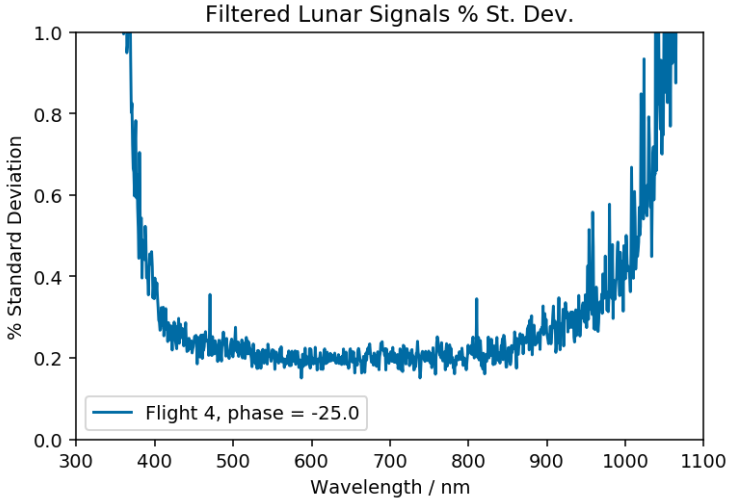




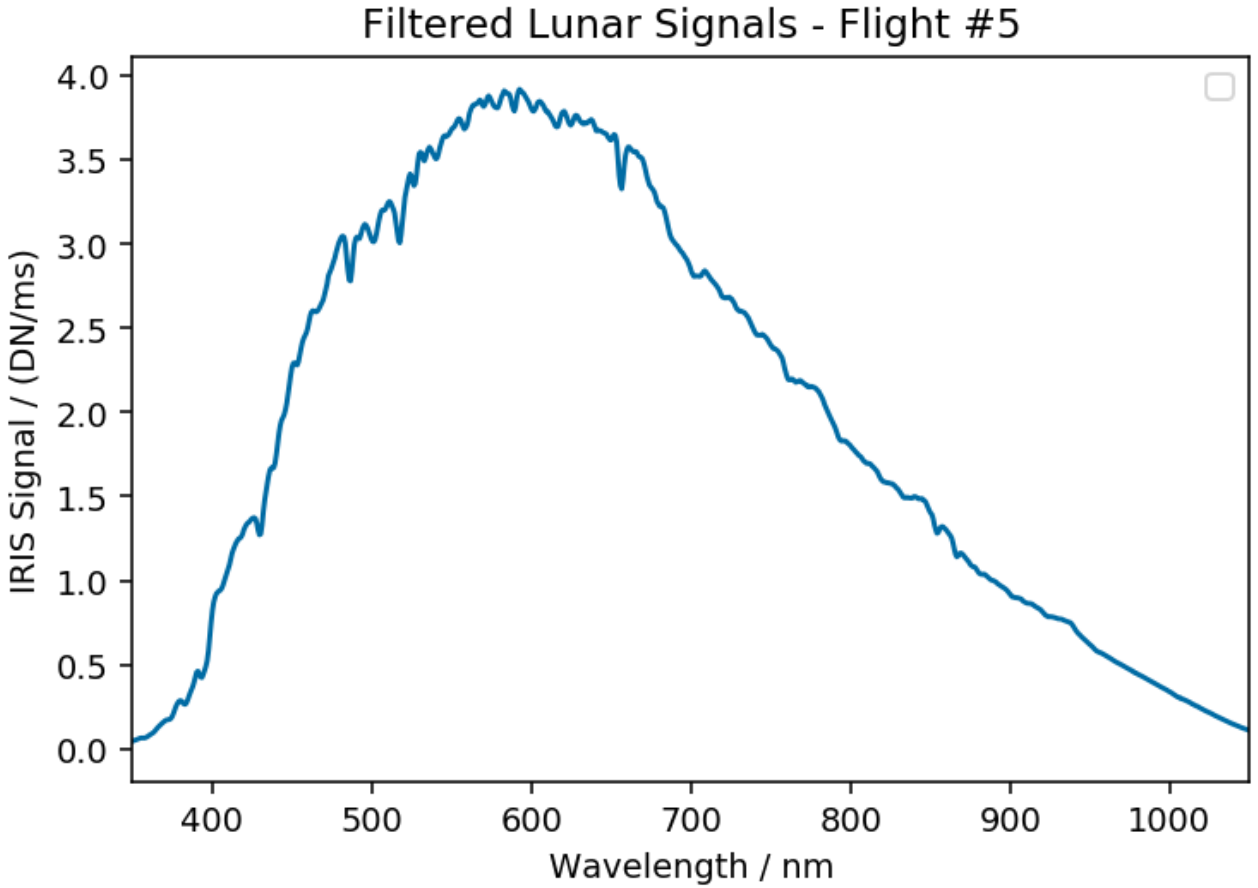
Lunar Measurements-Flight #4

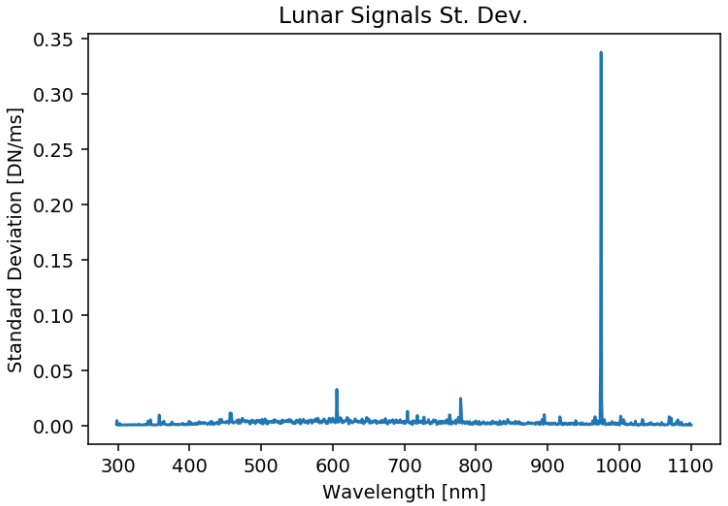


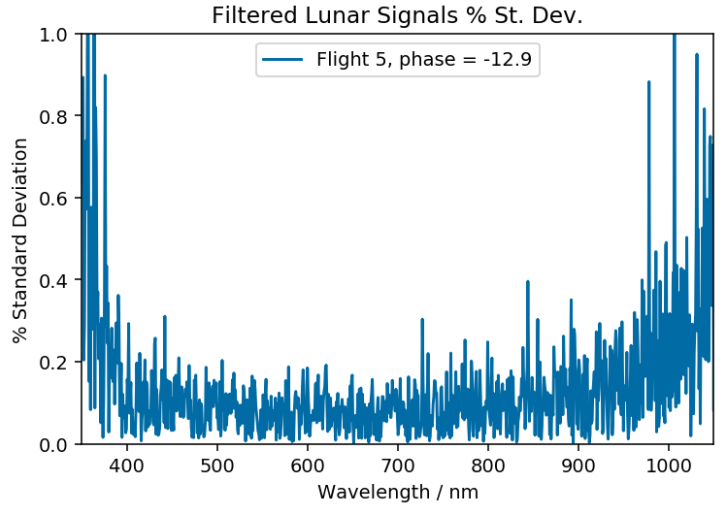




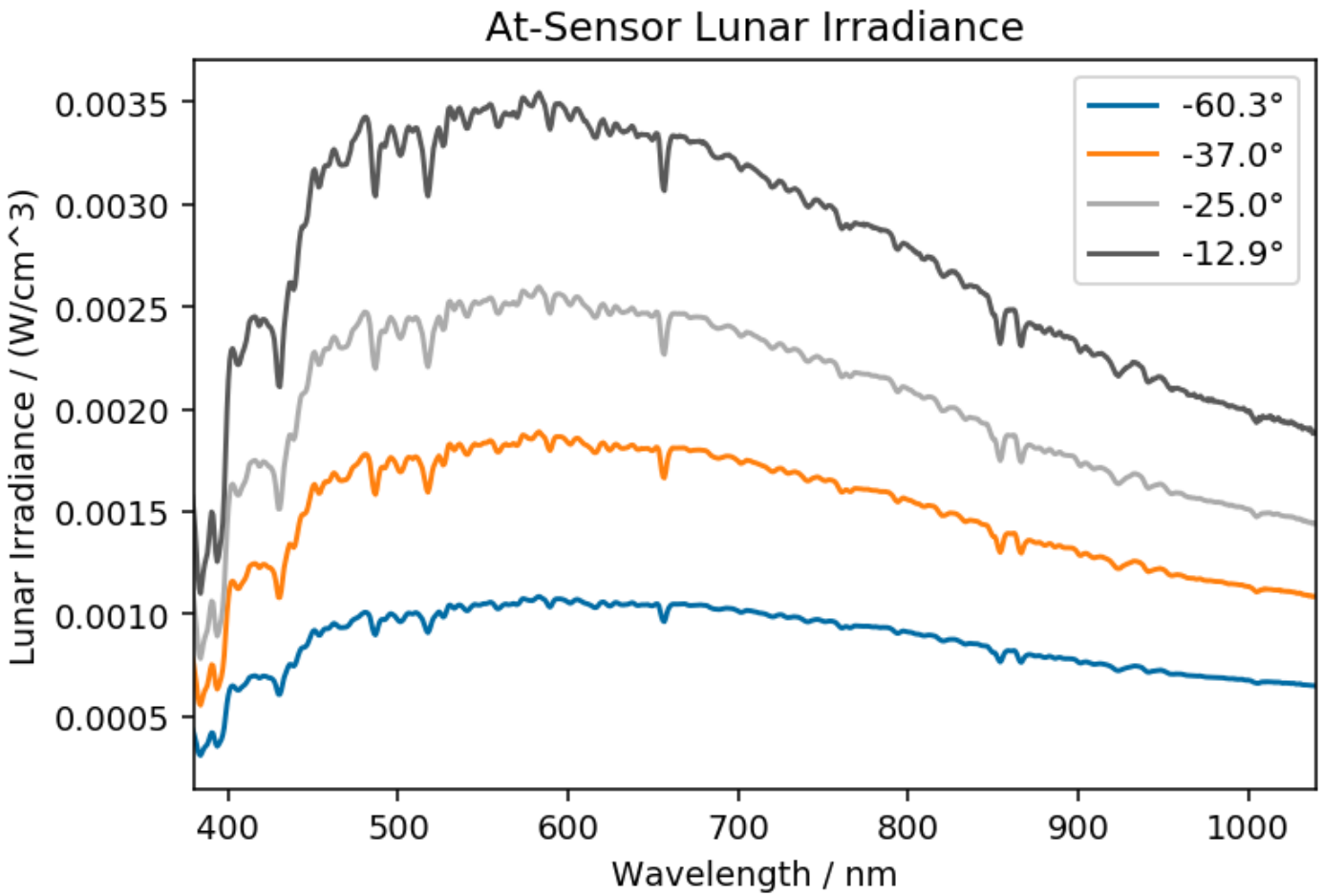
Lunar Measurements-Flight #5





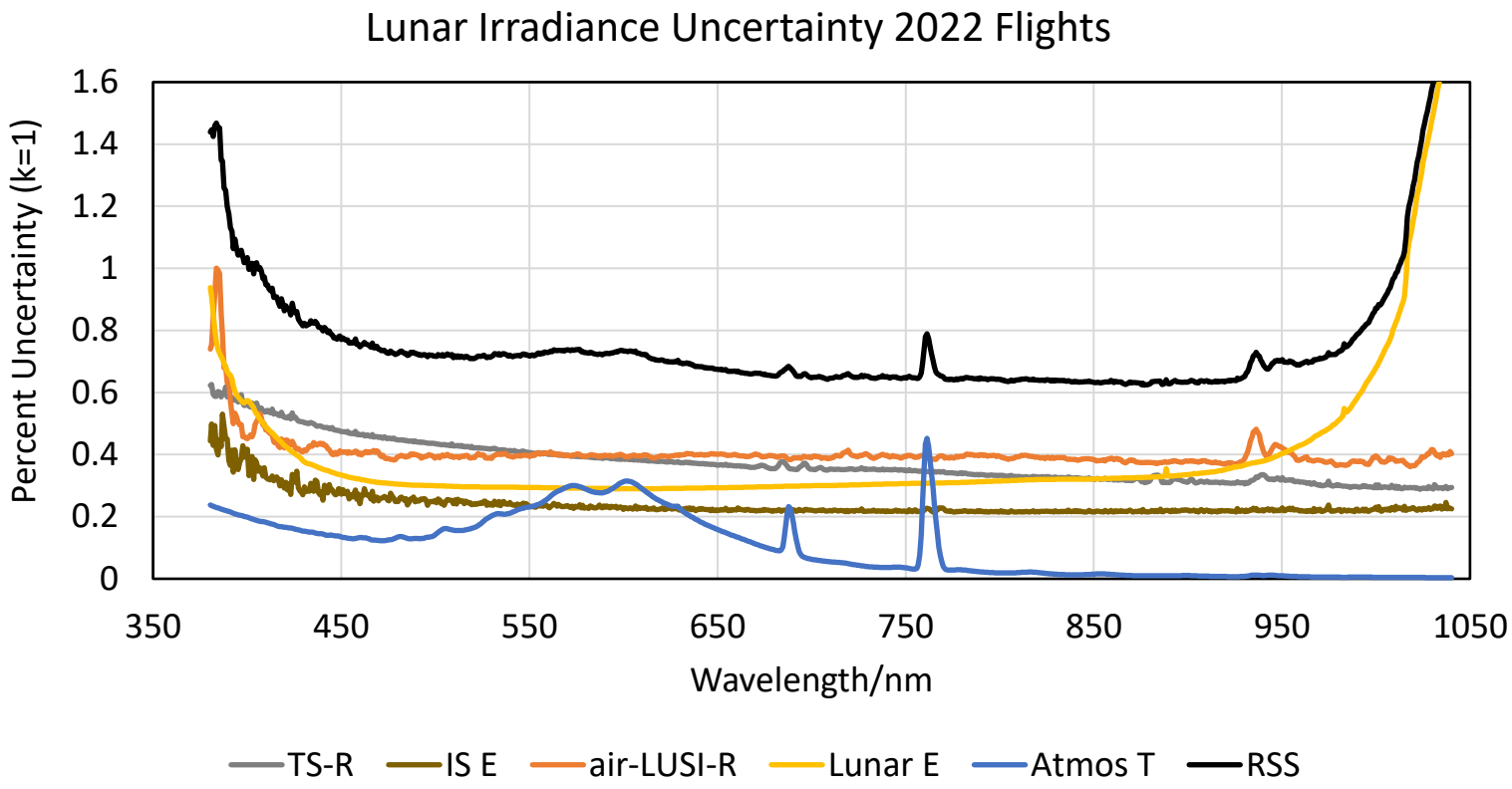


Preliminary Lunar Measurements - At-Sensor Flux



Preliminary Uncertainty Budget

Fixing the issues identified in the Demonstration Flights eliminates the uncertainty components shown with the dashed lines and reduces our projected uncertainty to less than 0.7% from 450 nm to 900 nm.



Conclusions

- Air-LUSI successfully flew on four of five scheduled nights and made measurements of the lunar irradiance at -60.3°, -39.0°, -25.0° and -12.9° phases.
- Upgrades from the 2019 demonstration version of air-LUSI were successful, leading to improved data collection and lower uncertainties.
- A fully transparent data analysis pipeline and uncertainty analysis will be publicly available later this year.
- Air-LUSI is scheduled to fly in January 2024 and acquire spectra for positive lunar phases.

Air-LUSI Team and Collaborators

Kevin Turpie, PI (UMBC/GSFC)
John Woodward, Co-I (NIST)
Tom Stone, Co-I (USGS)
Andrew Gadsden, Co-I (McMaster)
Steve Grantham (NIST)
Tom Larason (NIST)
Stephen Maxwell (NIST)
Andrew Newton (McMaster)

Brian Hobbs (Armstrong)
Fran Becker (Armstrong)
Tyler Latsha (Armstrong)
Steve Brown, (NIST)
Clarence Zarobila (NIST)
Carol Johnson (NIST)
Howard Yoon (NIST)
Charles Gibson (NIST)
Yuqin Zong (NIST)
Toby Herman (NIST)
Andrew Cataford (U of Guelph)
Marc Mogavero (Hawk)
Ron Bettini (Hawk)