

Why Developing a Full-sun UV Spectrograph Sounding Rocket is Difficult but Necessary

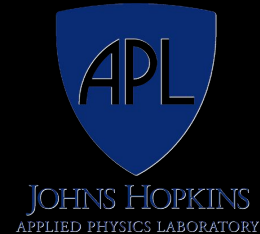
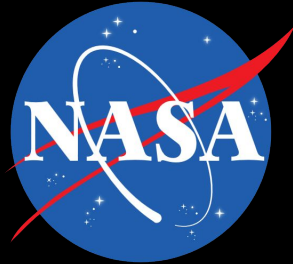
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Charles Kankelborg, Larry Paxton, Gary Zank*

20th AIAC, Santa Fe, NM
October 31 - November 4, 2022



CENTER FOR SPACE PLASMA AND
AERONOMIC RESEARCH AND THE
DEPARTMENT OF SPACE SCIENCE



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FURST:

Full-sun UV Rocket SpecTrograph

- Launch Date: Summer 2023
- Launch Location: WSMR, NM
- Altitudes: 110-260 km
- **Spectral Range: 120-181 nm**
- Resolution:
 - $R > 2 \times 10^4$
 - $\Delta\lambda < \sim 60\text{-}90 \text{ m\AA}$
 - $\Delta V < 15 \text{ km/s}$

Purpose:

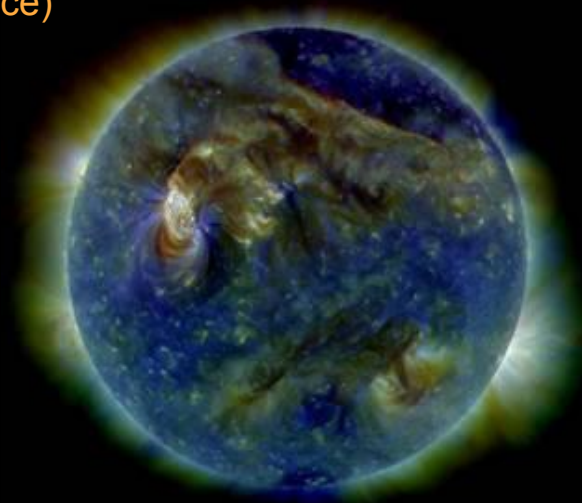
To gather the most complete high-resolution full disk UV spectra of our Sun.

Motivation > Brief History > Our Work > Future Work

Broad Scope > Narrow Scope > Future Scope

Why do we care?

- To obtain high-resolution UV spectra
 - UV spectra contains many lines used to measure plasma properties
- To directly compare our sun with HST data
 - We don't often think of the sun-as-a-star (point source)



(See Curdt+ 2001, Judge+ 2017)

Motivation > Brief History > Our Work > Future Work

Broad Scope > **Narrow Scope** > Future Scope

Why hasn't it been done yet?

- Instrument calibration is challenging
 - **UV Absorption** is high in air
 - Availability of diagnostic lamps

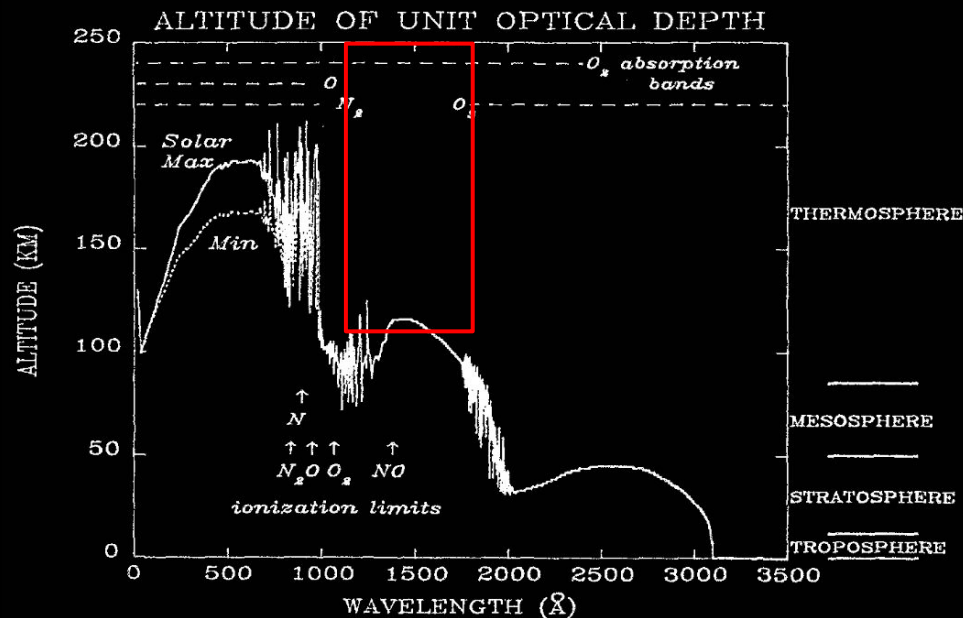


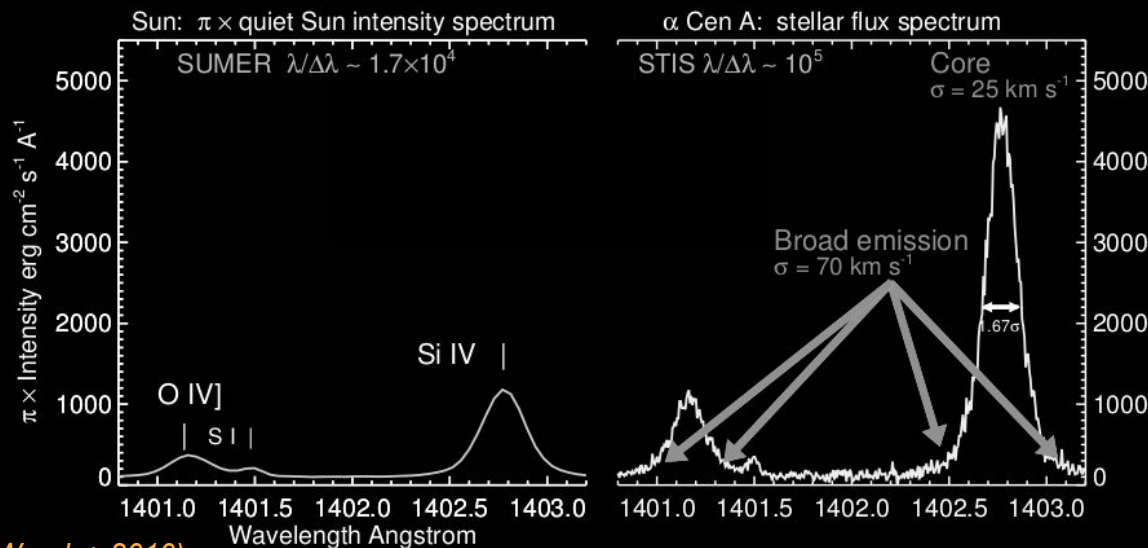
Figure 1 from Meier 1991, FURST range in box

Motivation > Brief History > Our Work > Future Work

Broad Scope > **Narrow Scope** > Future Scope

Why hasn't it been done yet?

- High spectral resolution is required
 - **Plasma can have doppler velocities $\Delta V < 100$ km/s**



$$R = \frac{\lambda}{\Delta\lambda} = \frac{c}{\Delta v}$$

$$\Delta v_D = \frac{v_0}{c} \sqrt{\frac{2kT}{m} + v_{\text{turb}}^2}$$

Doppler Shift

Thermal Broadening

Turbulent (Non-thermal) Broadening

(See Woods+ 2010)

Motivation > Brief History > Our Work > Future Work

Broad Scope > Narrow Scope > Future Scope

Why are we doing this?

- To communicate new and improved methods:
 - **Radiometric Calibration:**
 - Error tracking and in-situ gain calibration
 - (Publications; Vigil+ 2021, 2022)
 - **Spectral Calibration:**
 - Simulated signal processing of noisy lab data
 - **Radiometric and Spectral calibration:**
 - Atmospheric absorption model
 - (Paper in progress)
- To show the value of long term characterization of the Solar UV variability

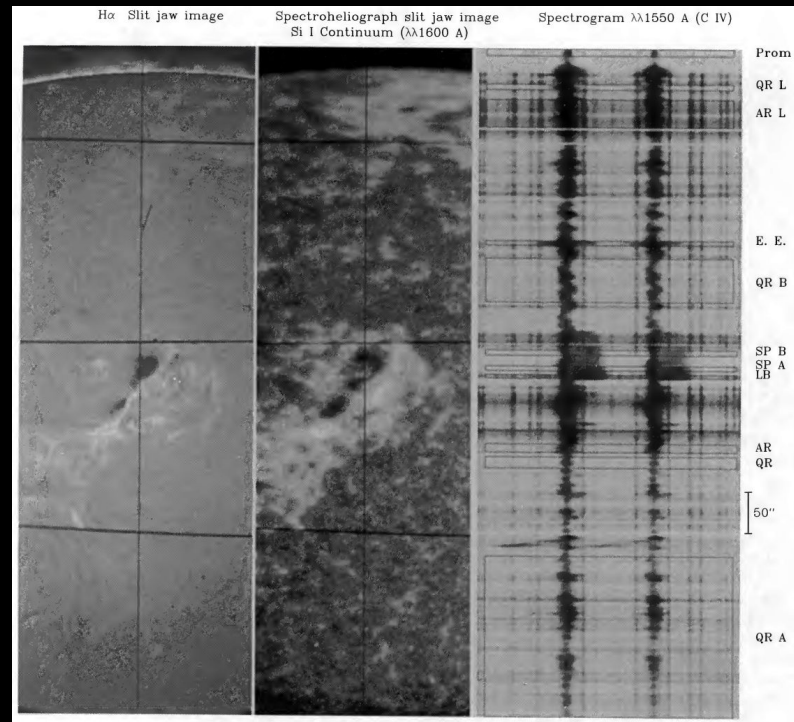


Late 1940s: Repurposed V2 rockets

- “NRL became the first to observe the ultraviolet radiation of the Sun with a spectrograph mounted on the tail fin of a A4 rocket.” (Curdtt+ 2001)

1978: HRTS

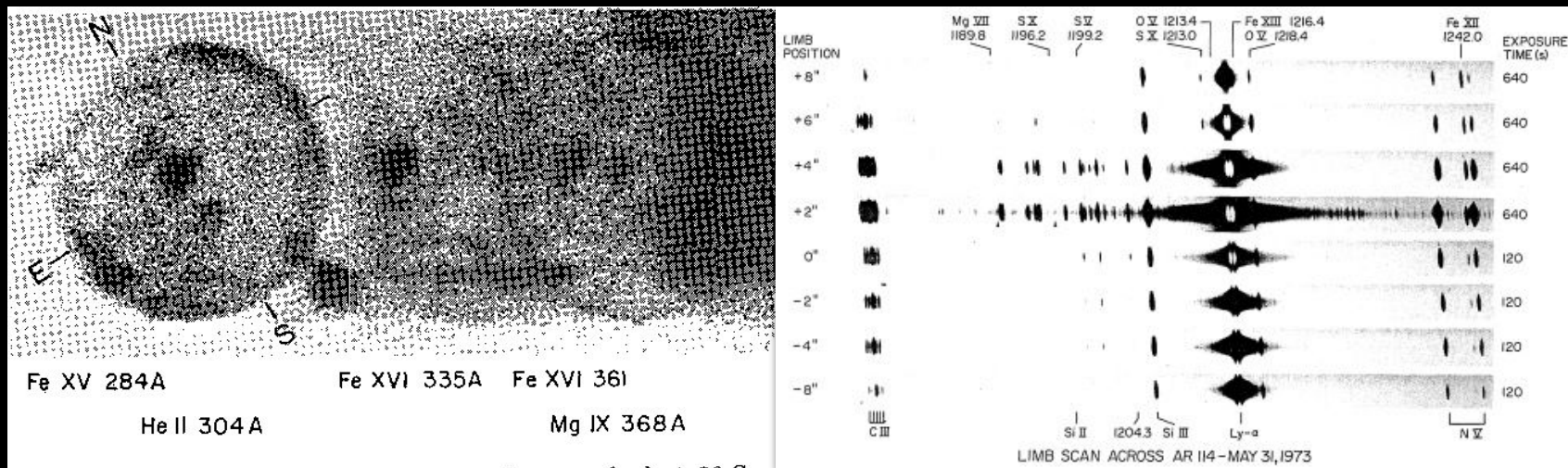
- High Resolution Telescope and Spectrograph
- Slit-based (0.5” wide)
- Large spectral range (1190-1730 Å)
- Good spectral resolution (~50 mÅ)
- High noise floor



Motivation > **Brief History** > Our Work > Future Work

First Solar Sounding Rockets > **First Solar Satellites** > Current Data

- 1973: Skylab (the first space-station)
 - Grazing-incidence, spectroheliograph, etc.
 - S-082B: Slit = 2" width, Range = 1100-1970 Å, Resolution = ~36.7-65.7 mÅ



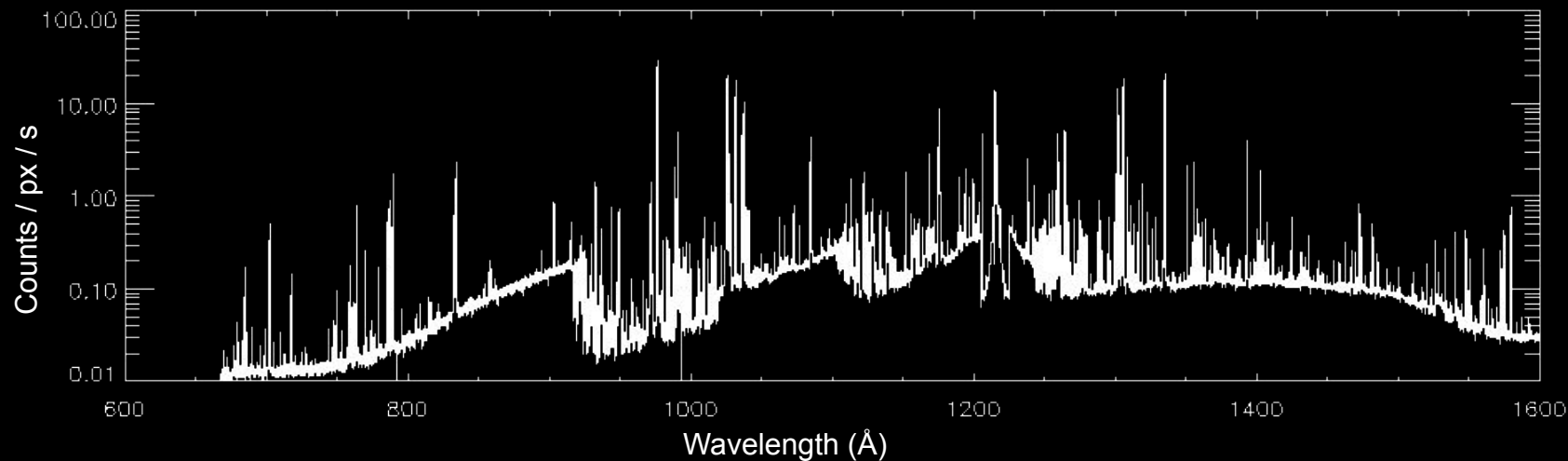
S-082A

S-082B

Motivation > **Brief History** > Our Work > Future Work

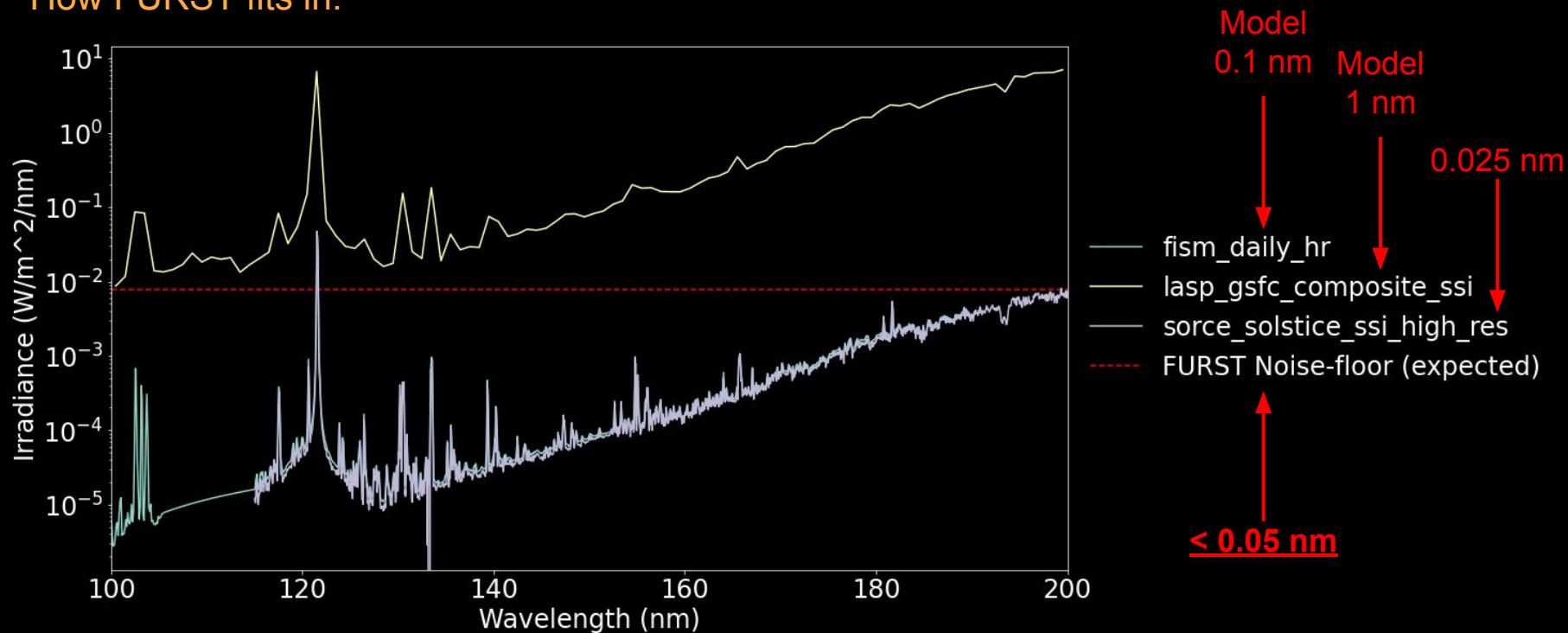
First Solar Sounding Rockets > **First Solar Satellites** > Current Data

- 1996-present: SUMER
 - Solar Ultraviolet Measurements of Emitted Radiation, onboard with SOHO
 - Slit = 1-4" width, Range = 660-1610 Å, Resolution = ~21-45 mÅ



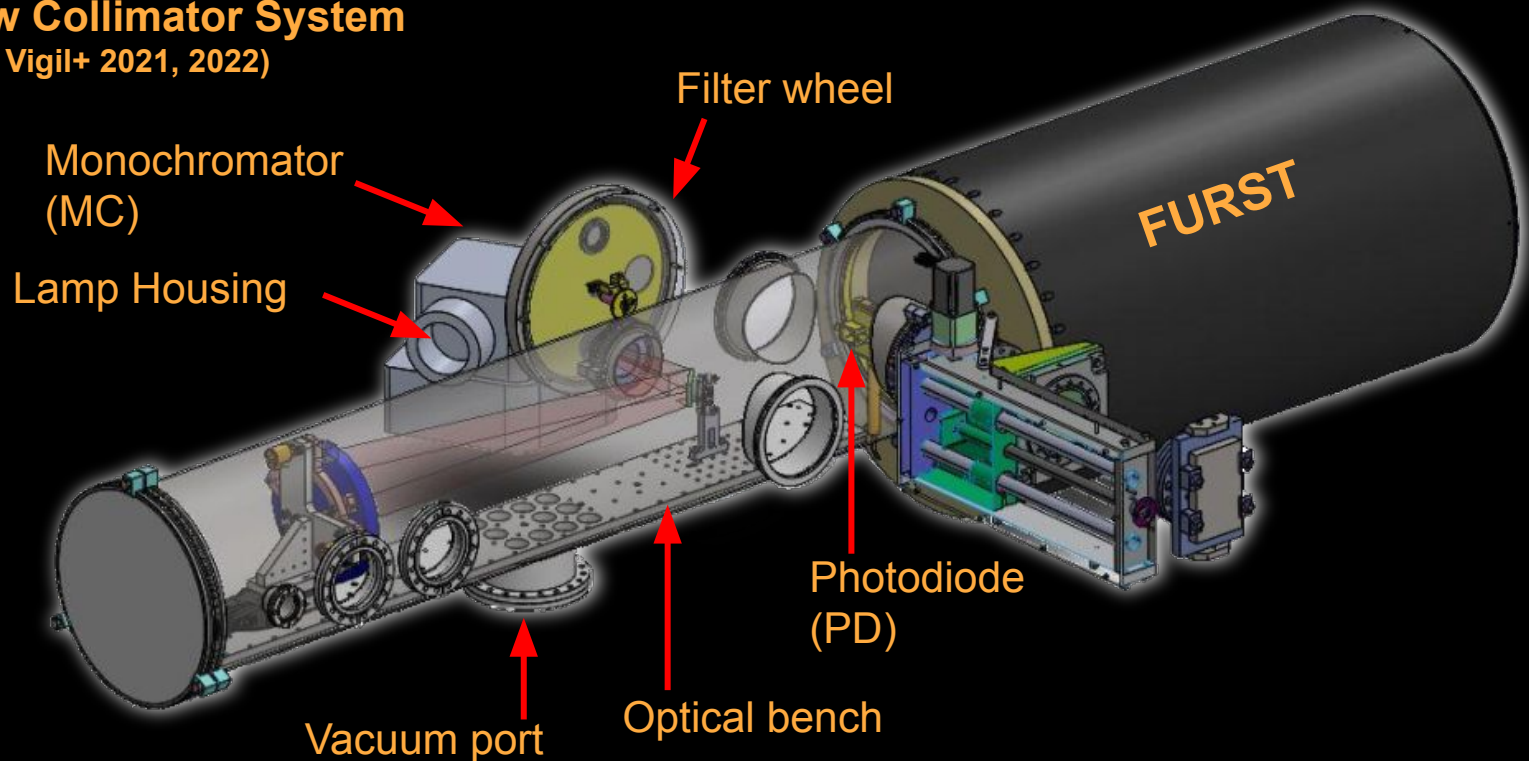
(See work by Paal Brekke)

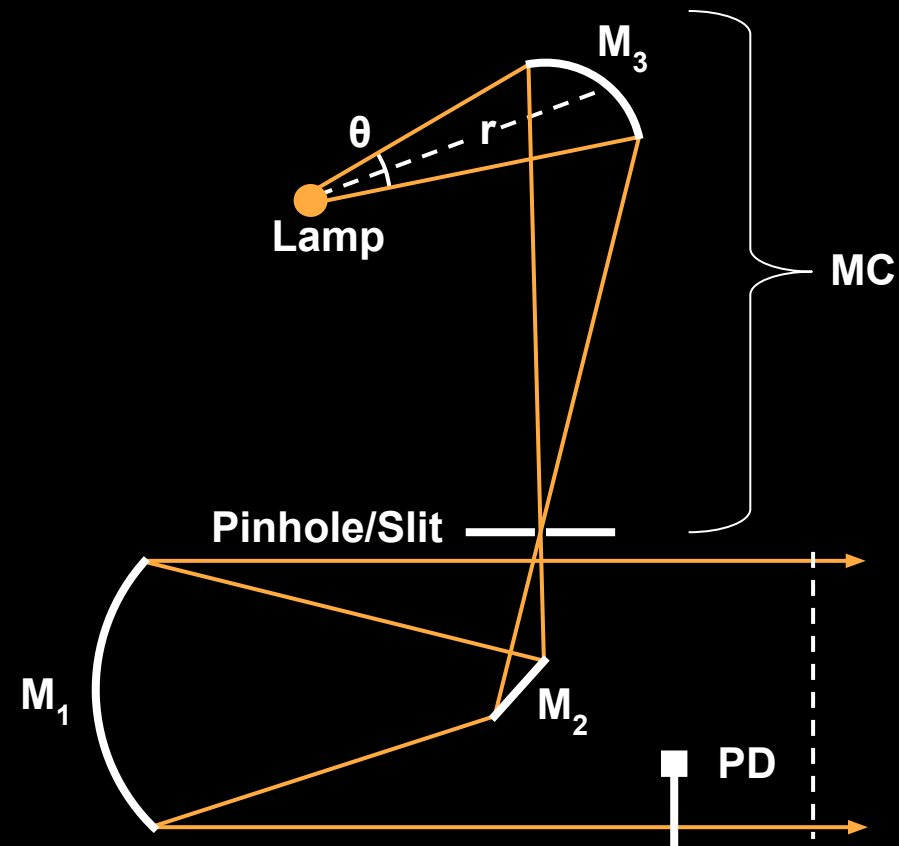
How FURST fits in:



New Collimator System

(see Vigil+ 2021, 2022)





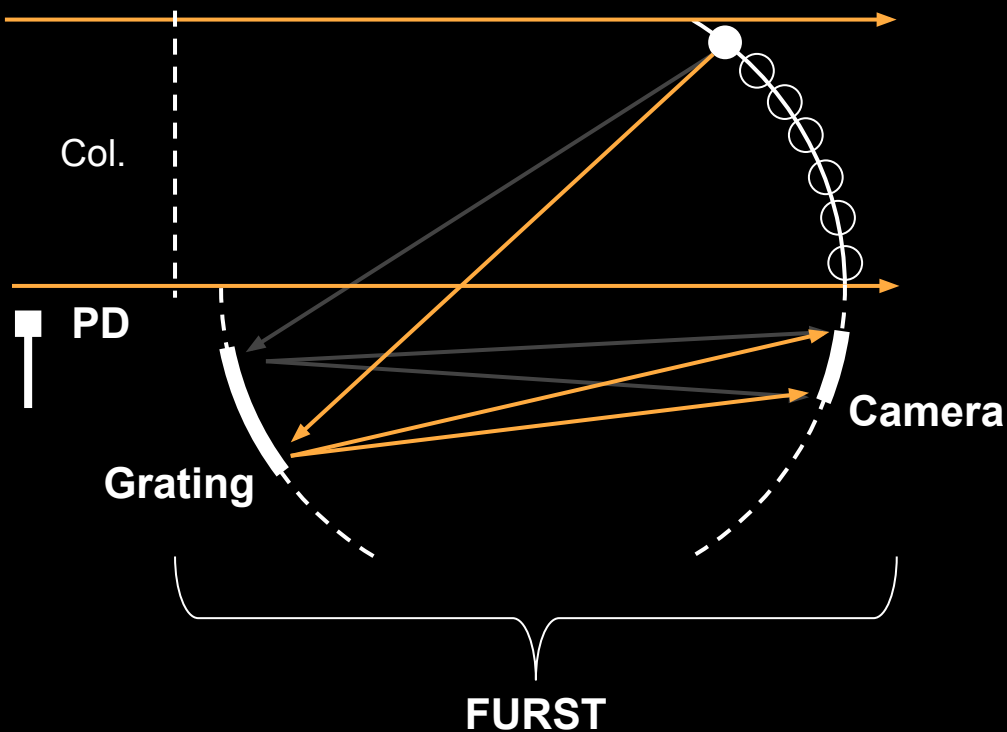
Radiometric:

- Collimator
 - Account for optics, vacuum absorption, etc.
- Photodiode Signal

$$S_{pd}(\lambda) = I_c(\lambda) A_{pd} R_{pd}(\lambda) \frac{hc}{\lambda}$$

$$I_c(\lambda) = \frac{I_{Pt}(\lambda) \gamma_c(\lambda) \Omega d A T_{abs,c}(\lambda)}{A_{beam}}$$

(see Vigil+ 2021, 2022)



Radiometric:

- FURST
 - Account for optics, vacuum absorption, camera, etc.
- Camera Signal

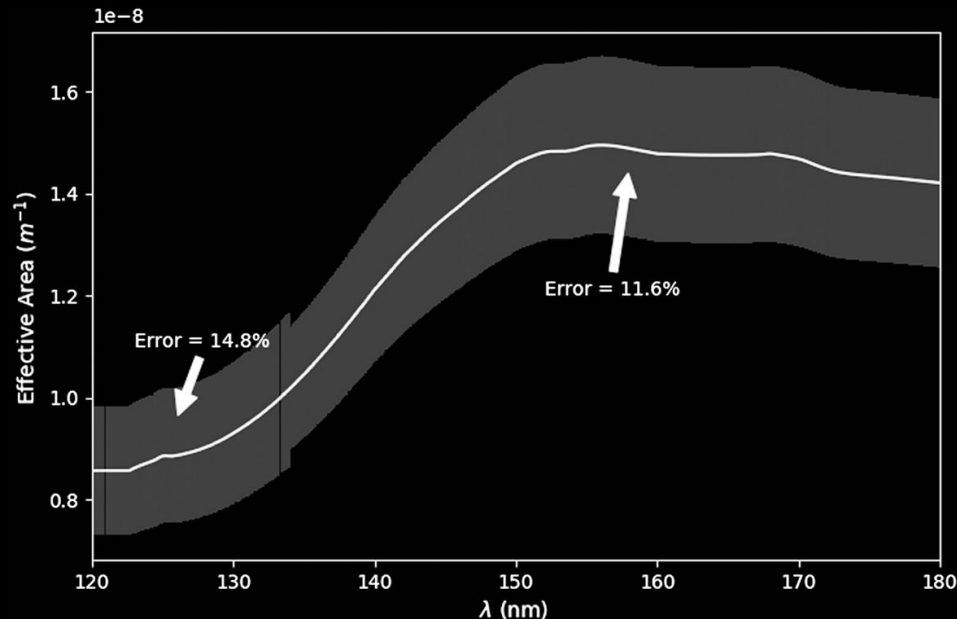
$$S_i(\lambda) = \frac{I_c(\lambda) A_{\text{eff}} Q E \eta G t T_i}{N_{px}}$$

Radiometric:

- Solve for Effective Area

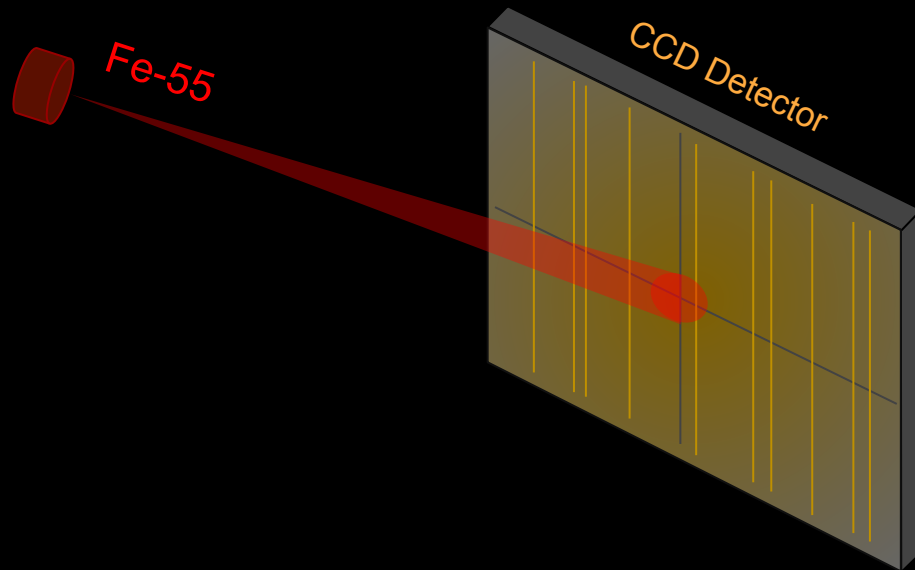
$$A_{\text{eff}}QE = \frac{S_i N_{px} A_{pd} R_{pd} \frac{hc}{\lambda}}{S_{pd} T_i G t \eta}$$

- Gain fluctuation ($G+\sigma_G$) is the least characterized variable!

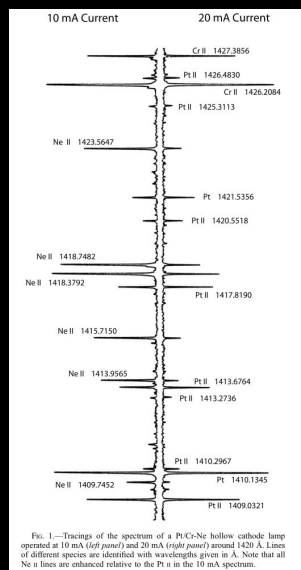


Radiometric:

- In-flight Gain calibration
 - Small radioactive source
 - Different energy (5.9 keV)
 - Confined location
 - Improve variability to 1%



Radiometric → Spectral: Diagnostic Lamp Simulation

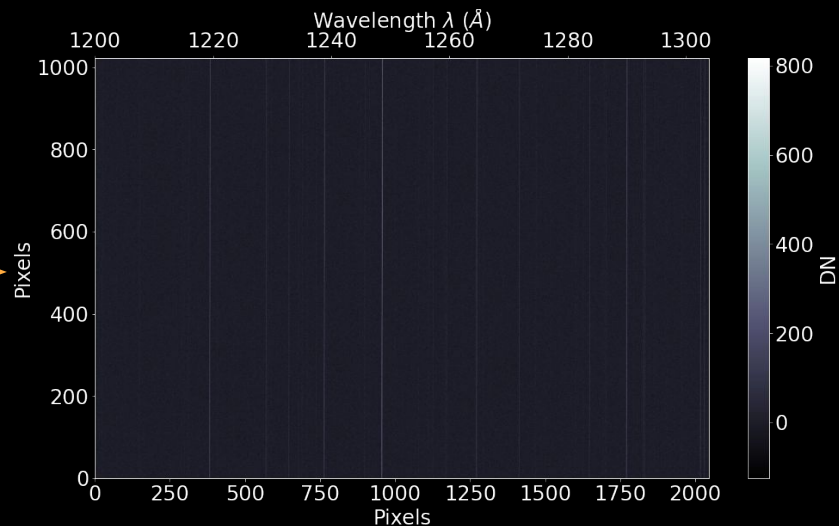


7 cylinders

Plate Scale
and Tilt

Instrument
Response

Camera Noise



DN conversion

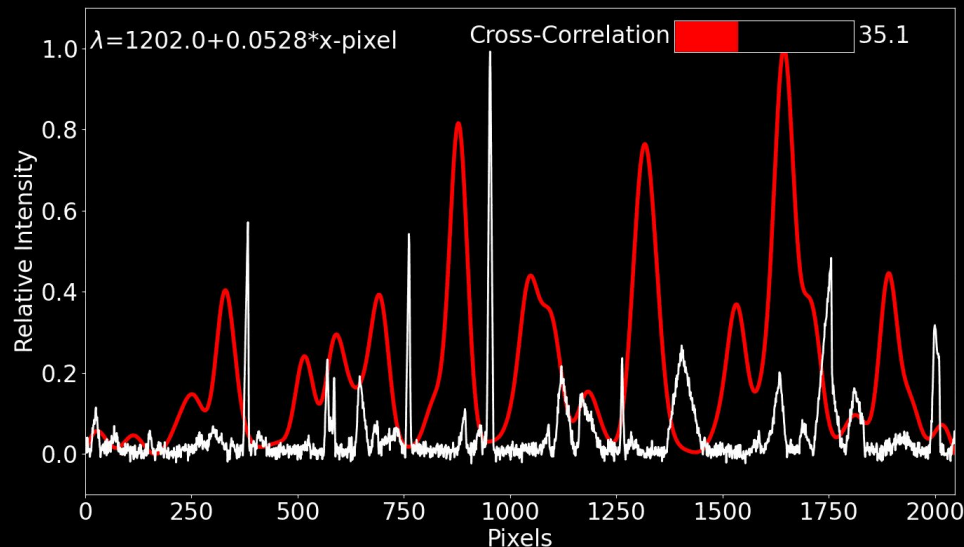
(ph → e →
DN)

controlled by
Camera Gain

Spectral:

- Compare spectral atlas and noisy measurement
- Optimize mapping parameters using Cross-Correlation
- Example in 1D:

$$\begin{aligned} \lambda &= \lambda_0 \\ &+ A \cdot p_x + B \cdot p_x^2 \\ &+ C \cdot p_y + D \cdot p_y^2 \\ &+ E \cdot p_x \cdot p_y \end{aligned}$$



Spectral:

- Solve for R and ΔV resolution

$$R = \frac{\lambda}{\Delta\lambda} = \frac{c}{\Delta v} \implies \Delta v = c \frac{\Delta\lambda}{\lambda}$$

For Lab Cal:

- Compare to original mapping function to get Delta Lambda

$$\Delta\lambda = \lambda_{\text{fit}} - \lambda_{\text{map}}$$

For Flight Cal:

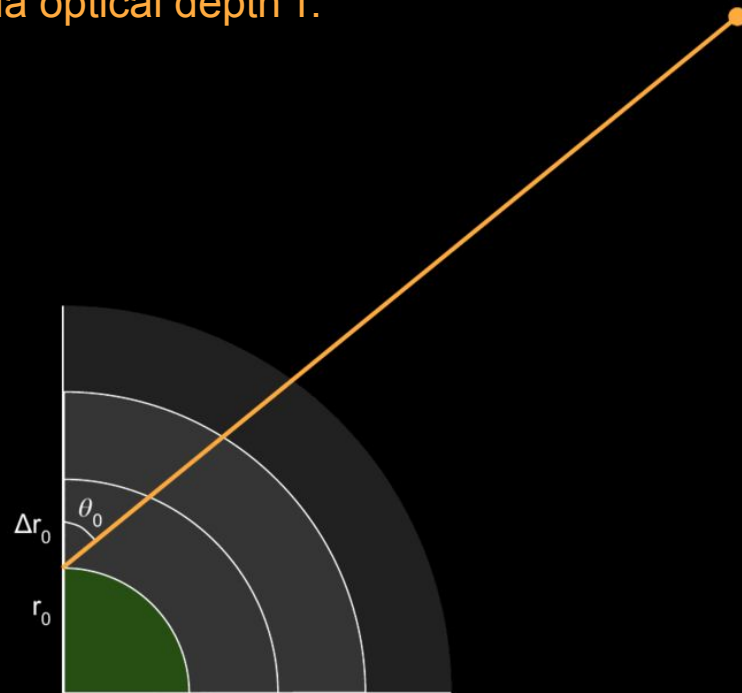
- Propagate error through mapping functions

$$\Delta\lambda = \Delta\lambda_0^2 + (p_x \Delta A)^2 + (p_x^2 \Delta B)^2 + \dots$$

Beer-Lambert's Law to estimate Transmission T via optical depth τ :

$$T = e^{-\tau}, \quad \tau_{i,j} = \sum_{i'=i}^{\infty} \sigma_{i',j} \eta_{i'} \Delta L_{i'}$$

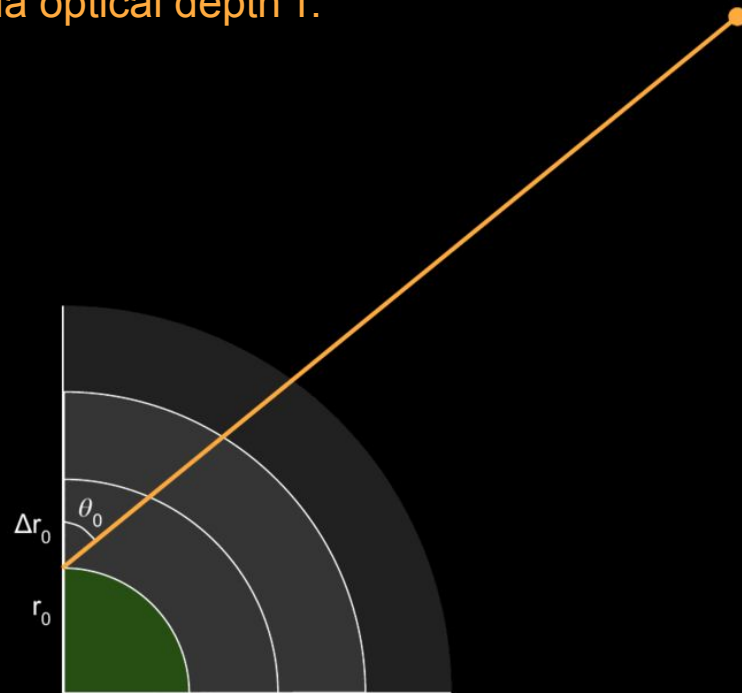

- Spherical-shells model solves for the **differential path length ΔL**
 - Zenith Angle θ_0 : NOAA Solar Position Calculator
 - GPS location of launch gives r_0
 - Integrated Python packages



Beer-Lambert's Law to estimate Transmission T via optical depth τ :

$$T = e^{-\tau}, \quad \tau_{i,j} = \sum_{i'=i}^{\infty} \sigma_{i',j} \eta_{i'} \Delta L_{i'}$$

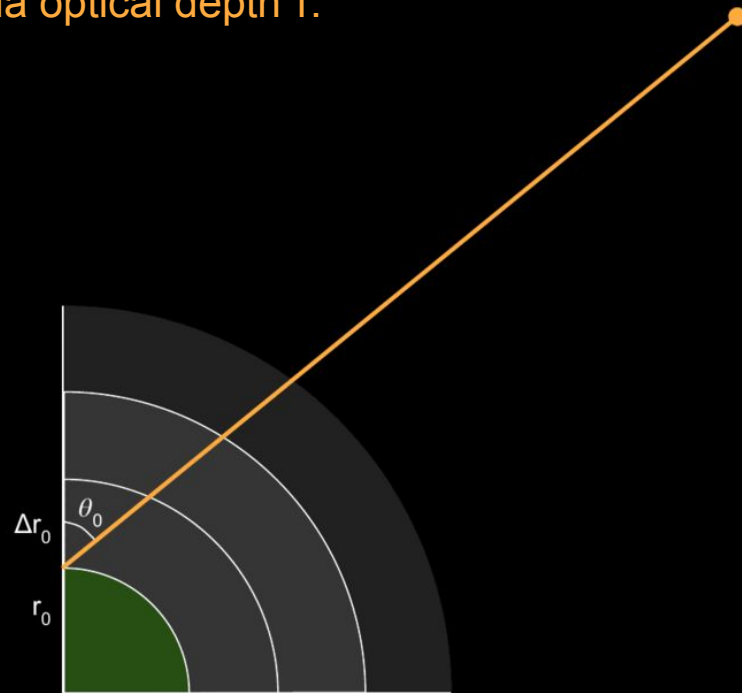

- NRL-MSISE Atmospheric Model gives **density η**
 - Also gives temperature variation
 - Integrated Python packages



Beer-Lambert's Law to estimate Transmission T via optical depth τ :

$$T = e^{-\tau}, \quad \tau_{i,j} = \sum_{i'=i}^{\infty} \sigma_{i',j} \eta_{i'} \Delta L_{i'}$$


- MPI-Mainz UV-VIS Database gives **absorption cross-section σ**
 - Varies with temp and wavelength
 - Incomplete database
 - Custom Python-based web-importer

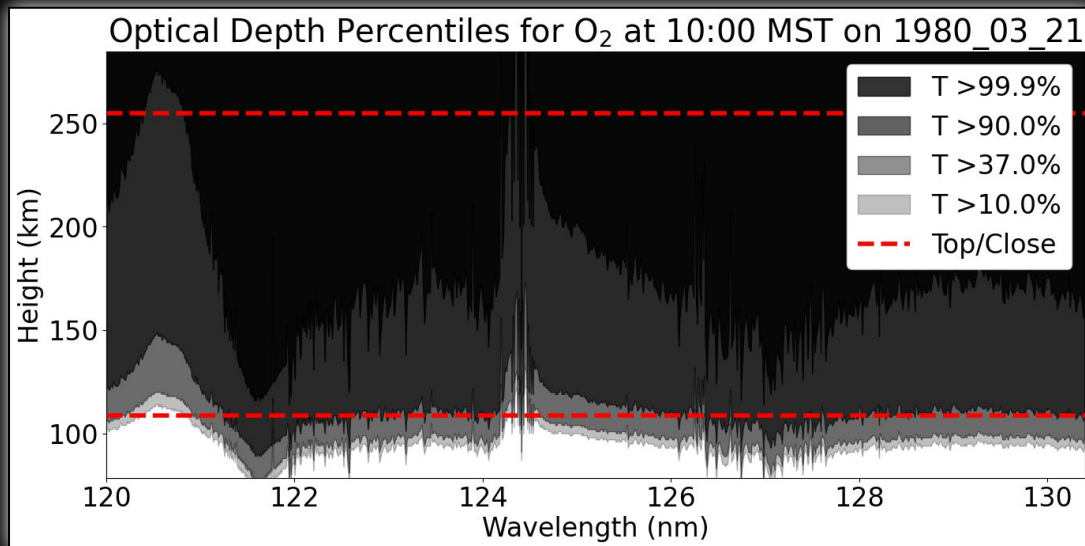


Motivation > Brief History > **Our Work** > Future Work

Radiometric and Spectral Calibration > **Atmospheric Absorption**

Estimate impact on FURST, or any Sounding Rocket:

- Results match Meier 1991
- **Implications on launch:**
 - Time window
 - Date range
 - Locations (Poker Flat)
- **Implications on Data:**
 - Signal-to-Noise Ratio (SNR)
 - **Calibration lines**



↑
a

**Look for
these in
signal**

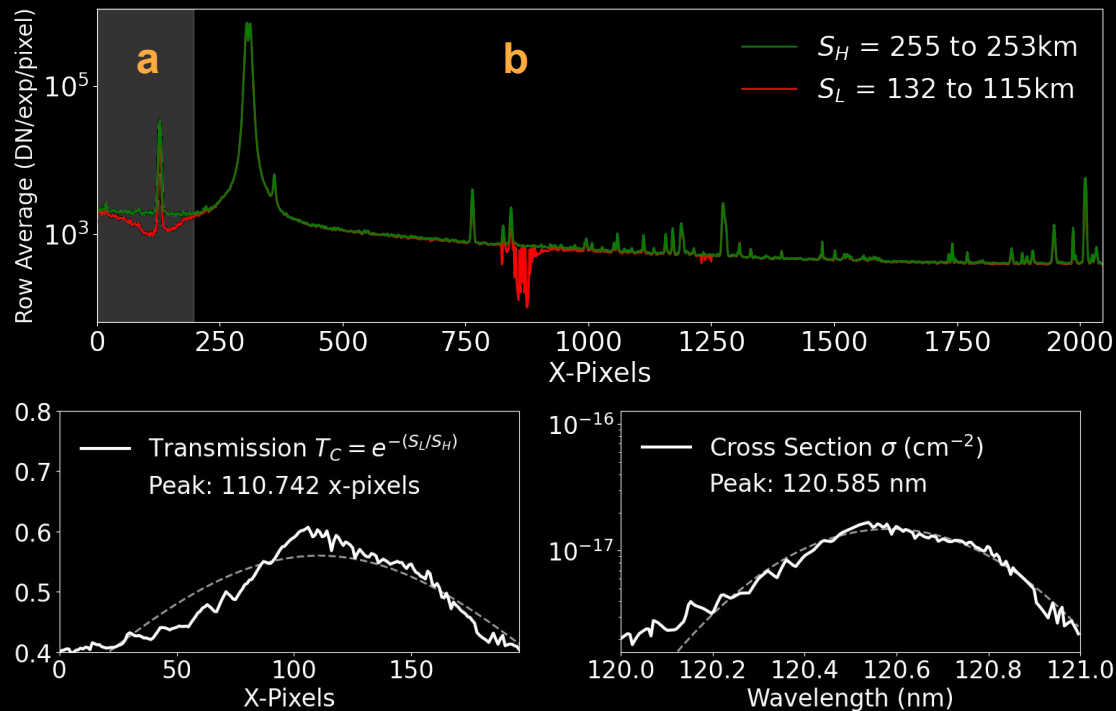
↑
b

Simulating Noisy Signal:

- Used HRTS Quiet Sun
- Folded into FURST optics
 - *Note: FURST noise floor will be significantly lower*
- Example between 120-130.4 nm

Use for Calibration:

- Select 2 pairs of pixels/wavelengths.
- Plate scale estimated to an error of ~0.5%.
- Paper in Progress

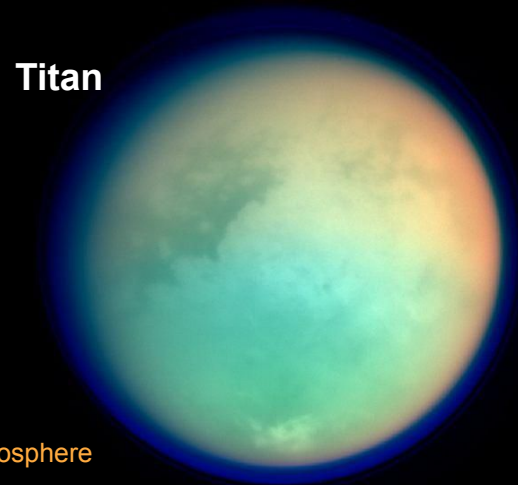
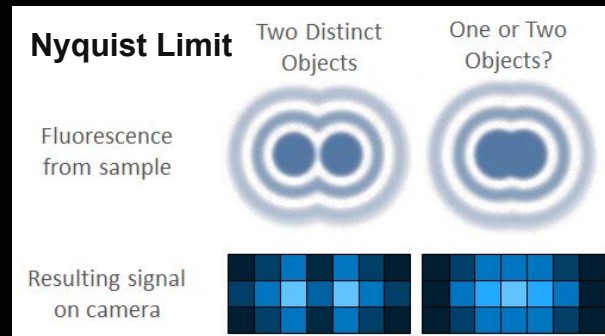


Applications of Calibration Techniques

- We may beat our initial resolution goals
 - **Preliminary results show $\Delta V < 3$ km/s**
 - Intentional clocking of the CCD to overcome Nyquist limit

Broader Applications:

- May be useful for measuring planetary atmospheres or winds
 - Jupiter, Saturn, Titan, etc.
- **Compare with HST data**
 - Potentially some correlations with JWST



(See He 2019; Sun 2018, 2019, 2022)

Nyquist image: <https://www.photometrics.com/learn/camera-basics/camera-resolution>

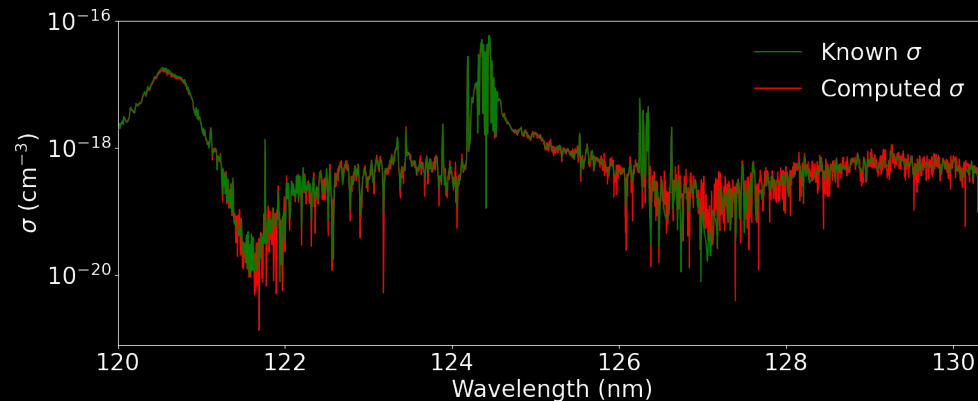
Titan image: <https://astronomycommunity.nature.com/posts/47562-supersonic-winds-in-titan-s-upper-atmosphere>

Applications of Atmospheric Absorption model:

- To understand the impact on **future** missions
 - Broadening launch parameters such as time, date, location
 - Estimate effect on data and correct for it
- To understand the impact on **past** missions
 - Correct past data
 - **Uncover atmospheric properties**

Broader Application:

- Use 2 images from SR data to factor out absorption cross-section
- Preliminary results: error of ~27%



Motivation > Brief History > Our Work > Future Work

Calibration > Atmospheric Model > Improvements

Future Calibration work:

- Transition from Pt lamp to **Dt lamp**
- Assemble and test new collimator and PD setup
- Validate in-situ Gain calibration

Future Atmospheric Model work:

- Calculate H & O self-absorption
- Improve absorption database
 - temperature dependency
- Improve refraction calculations



Thank you!

Feel free to contact me with suggestions and advice!

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