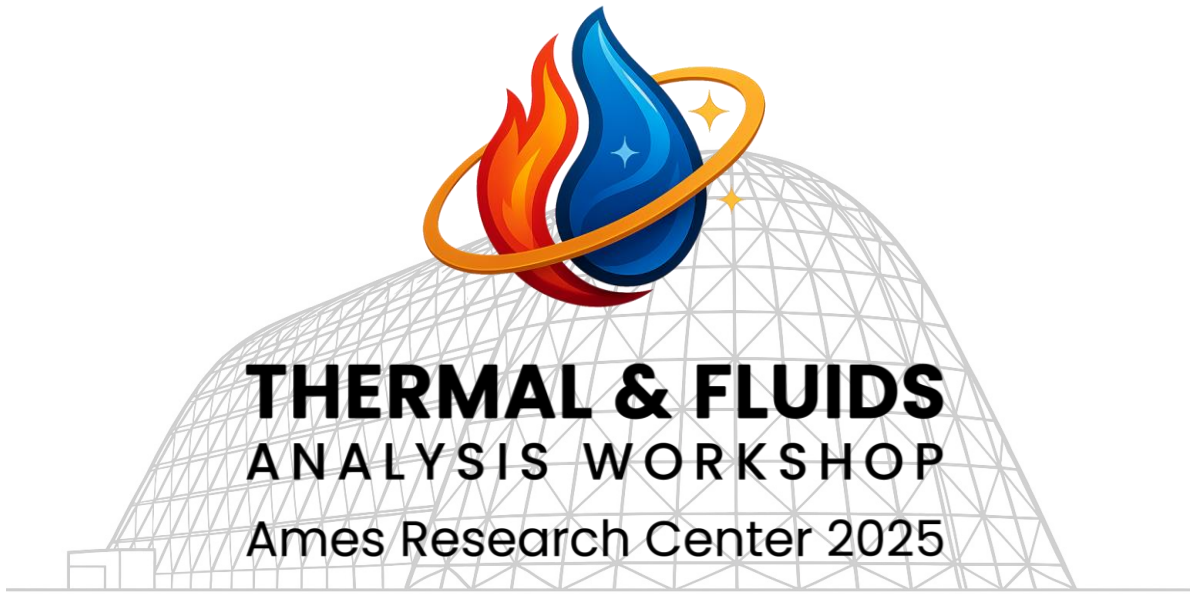
[Approximate Method for Comparing NEQAIR Visible Spectral Emission Predictions Against Onboard Footage]

Presented by: Heston Briant



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NASA Launch Servies Program

Thermal & Fluids Analysis Workshop 2025
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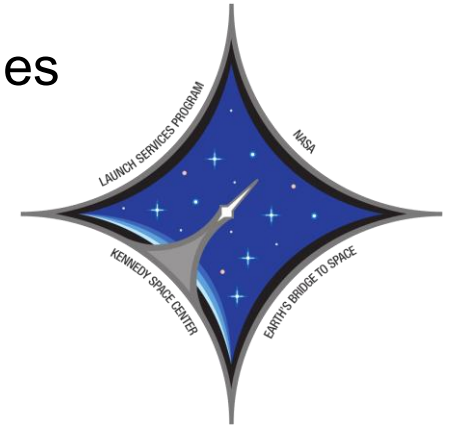
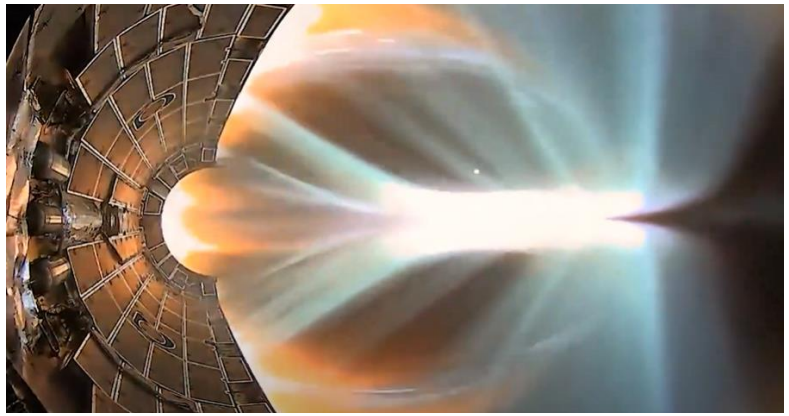
Motivation

- NASA's Launch Services Program (LSP) is beginning to encounter reused hardware that has flown in the hypersonic reentry regimes.
  - Industry is trending towards recovering hardware from increasing altitudes
  - Falcon Heavy Fairings
  - Starship
- Capabilities building exercise & proof of concept
  - Gain experience running hypersonic CFD cases
    - Launch vehicle concerns are predominantly supersonic
  - Gain experience with radiative heating tools
  - Proof of concept for a qualitative assessment of NEQAIR





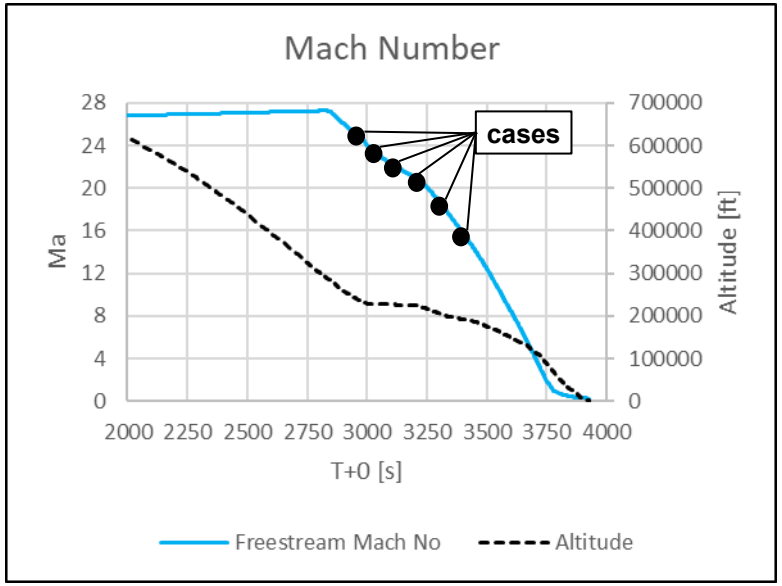
Falcon Heavy Fairing Reentry Footage

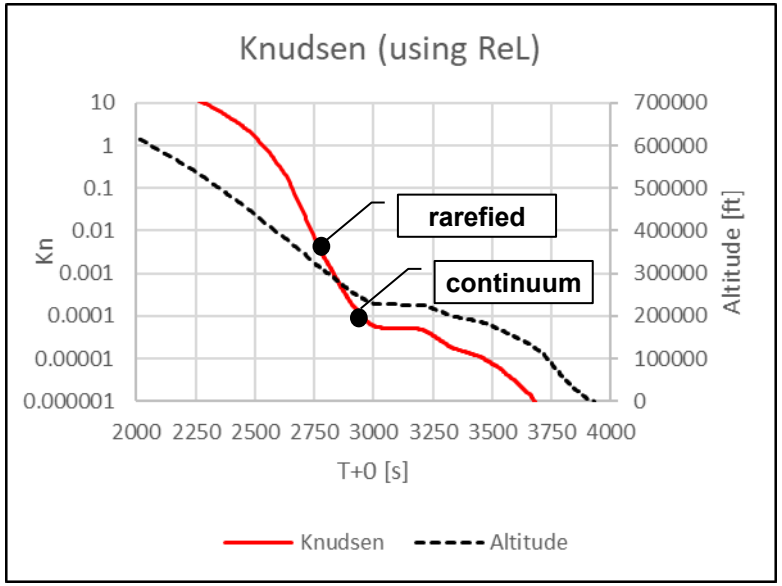
Qualitative NEQAIR Assessment

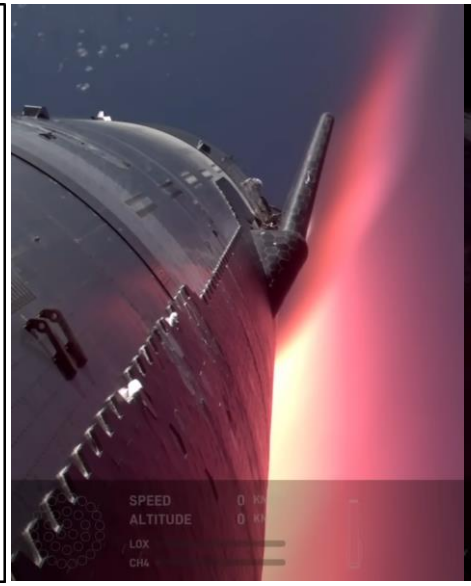
- Idea: Compare NEQAIR visible spectrum predictions to onboard footage
  - Make spectral emissions predictions for a Line of Sight (LOS) that corresponds to a camera view, apply a camera filter and covert to an RGB value, and compare resulting color to the observed color.
- Multi-component workflow
  - Trajectory: MINIVER-II (legacy aeroheating code)
  - Geometry: Spaceclaim CAD
  - Flow field: LAURA with HARA - radiatively coupled CFD
    - Grid generation: Pointwise
    - Post Processing: Paraview
  - Spectral Emissions: NEQAIR
  - Post Processing: Python
- Ultimately only a proof of concept, not an NEQAIR assessment
  - This work ultimately highlight the hurdles for this concept and can not comment on NEQAIR's accuracy.

Trajectory

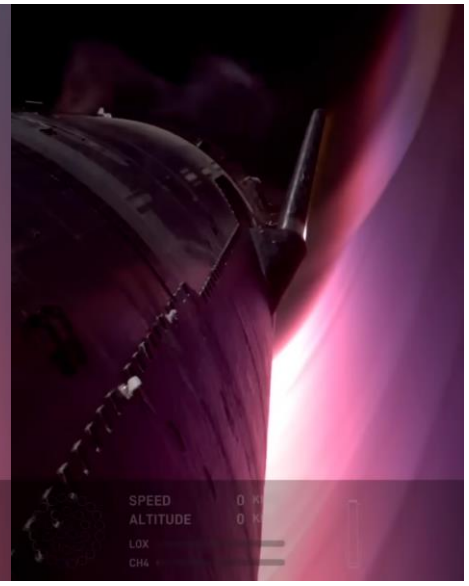
- Need a hypersonic flight with a camera view of the windward side
  - Starship test flight 5 live stream: provides Velocity, Altitude, and AOA
  - KSC's in-house aeroheating code (MINIVER-II) used to interpolate free stream air properties
    - U.S. Standard Atmosphere, 1976 is built in.
- Cases should be continuum and hypersonic
  - Not concerned with traditional CFD case criteria (q, alpha, Mach, heating, etc.)
  - Selected 6 timestamps based on interesting color changes.







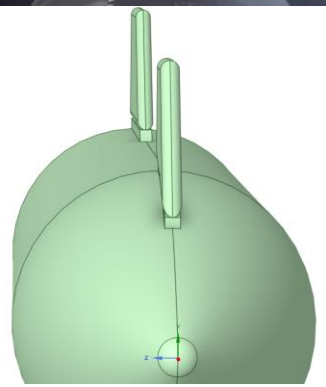
rarefied



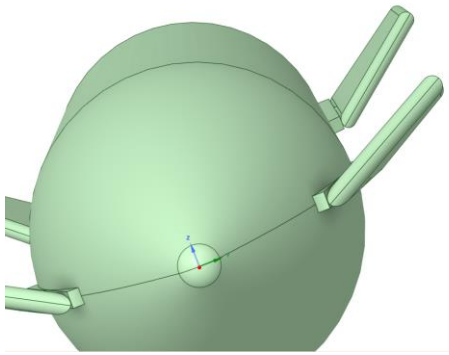
continuum

Geometry

- Starship estimation
  - Overall dimensions sourced from public enthusiast guesses.
    - ~ 9m diameter, 36m cylinder section, 50m total height
  - Camera is embedded in the foreword wing's tip
    - Flaps actuate in flight. Assumed ≈30° during entry <u>for camera LOS</u>

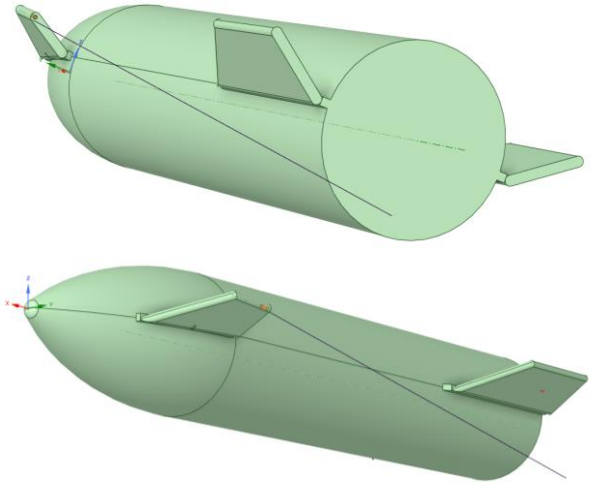


Starship With Wings Flat



Starship With Wings at ≈30°

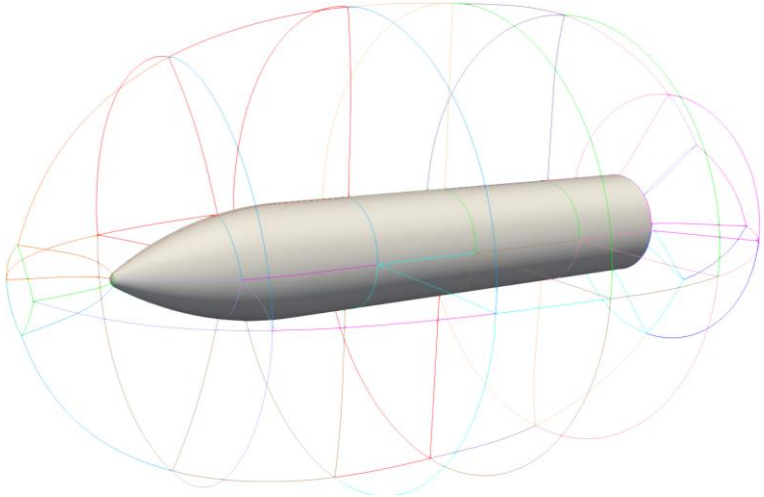
Starship Camera Location (reproduced with permission from RGV aerial Photography)



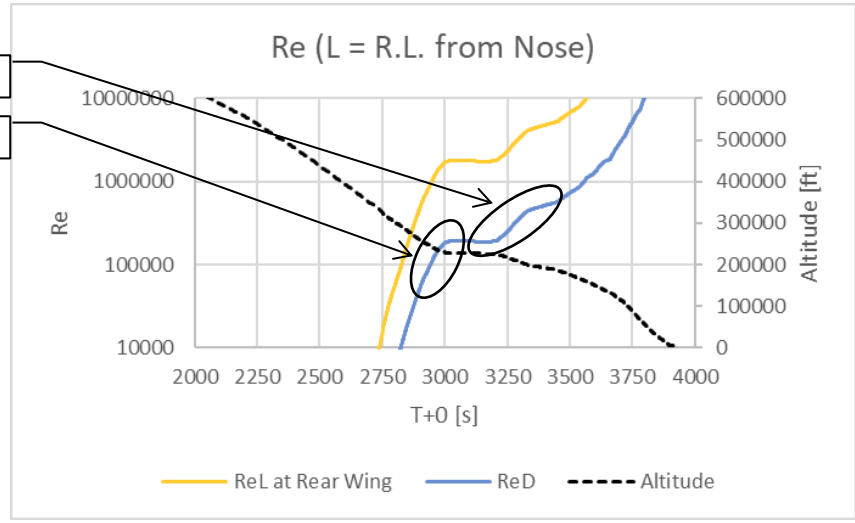
Starship Geometry With Line of Sight Shown

Flow Field

- LAURA 5.7: Langley Aerothermodynamic Upwind Relaxation Algorithm
  - Pointwise-generated 26 block structured grid
    - Extruded O- topology, no overset blocks (no wings)
    - 36,778,400 hex cells, Y+ = 1
    - MPI runs on KSC's kestrel cluster. Ranks = blocks = 26.
  - Cases grouped into laminar and turbulent, otherwise uniform settings.
    - Fully laminar for ReD ≈ 150,000 to reduce run times.
      - Ma 25, 22, 20 → laminar Ma 19, 17, 15 → kw-sst2003
      - Mostly focused on windward temperatures, not aero coefficients.
      - Run times improved once switched to line implicit and cfl reached 10
    - Chemical and thermal nonequilibrium enabled
      - 5 species (N2, O2, N, O, NO), two temperature (T_t, T_v)
      - Could not get 11 species with ions to run (NO+, N+, e-, etc.)
    - Zoby-RCG catalytic wall chemistry
      - Radiative equilibrium wall temperature
    - Radiation coupled with default HARA settings.
      - Stepped into HARA after >3000 iterations.
      - 3 HARA cycles with 250 flow field iterations between (run time limited).
  - L2 normalized residuals "converged"
    - Laminar cases dropped from ~ 6.8e+5 to 5.8e+1 over ~11,000 iter.
    - Turbulent cases dropped from ~ 5.1e+5 to 1.2e+3 over ~8,000 iter.

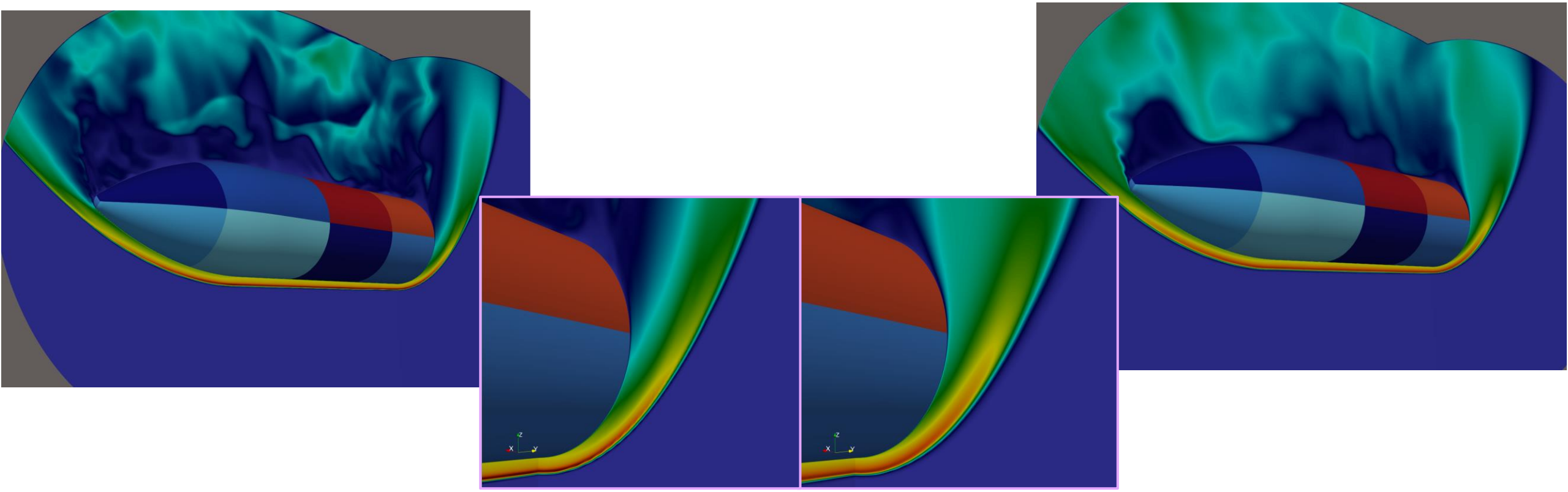


Pointwise Grid Blocks



Radiation Coupling

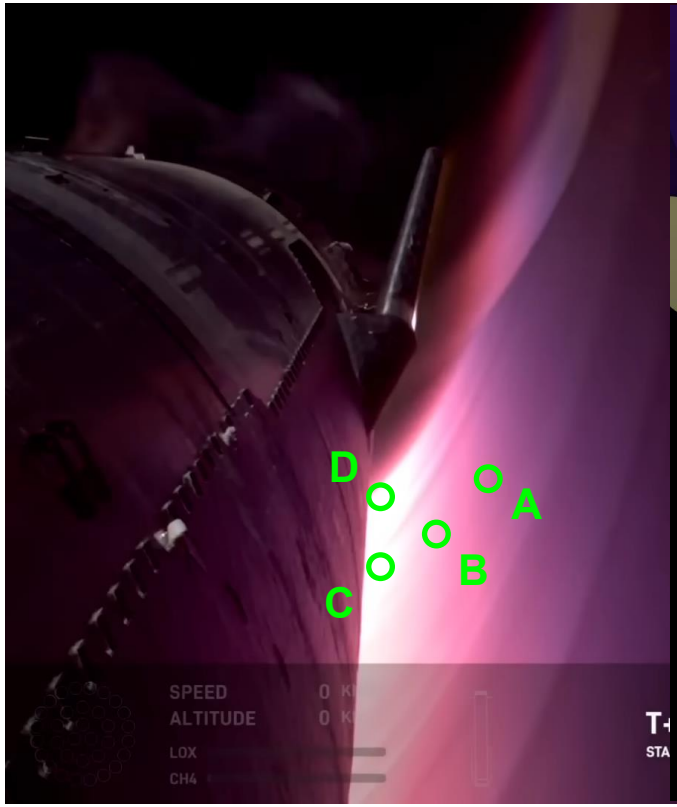
- Radiative energy transfer is accounted for in flow field via LAURA's HARA solver
  - Default HARA settings enable atomic lines and models molecular bands via Smeared Rotational Band approach—valid for optically thin regions.
    - CR park model populates electronic states for emissions and absorption of both atoms and molecules.
    - Absence of ions disables photoionization.



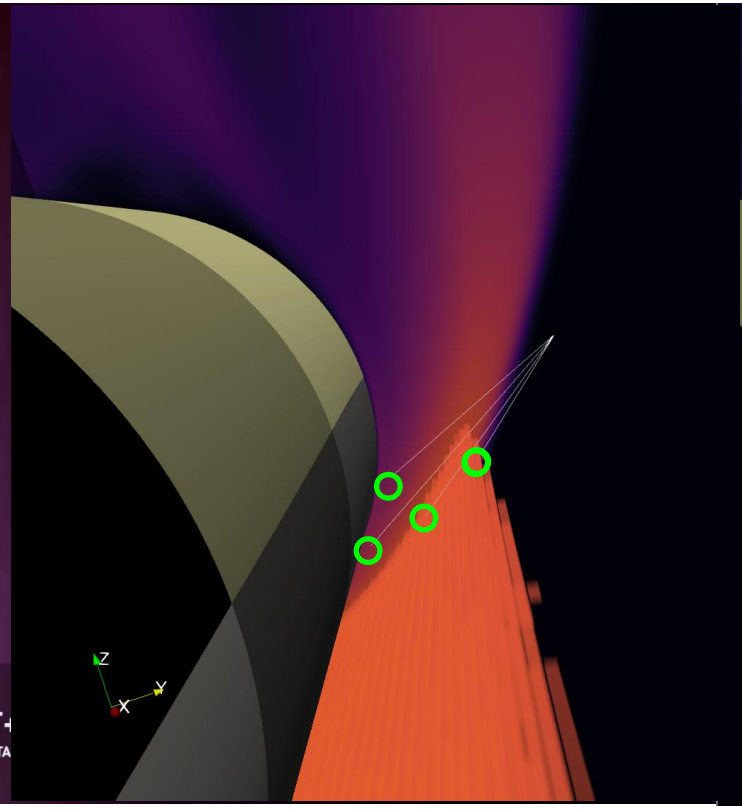
Before HARA cycle ***After HARA cycles***

Lines of Sight

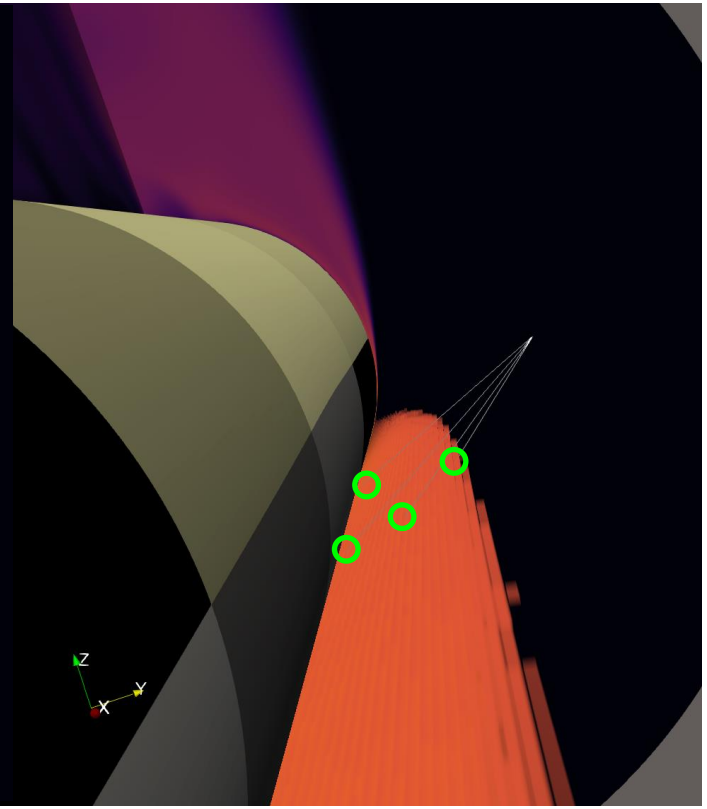
- NEQAIR needs temperatures and number densities along a line of sight (LOS)
  - Four LOSes are drawn to regions of varying color (A, B, C, D). Paraview's "Plot over line" filter used for data extraction.
  - Post processed flow field solution and CAD used to approximate camera position.
    - Rendering a T>6000K volume region was helpful to draw lines through.
    - Absence of wings considerably affects region near aft lip (D).



Labeled LOS Targets



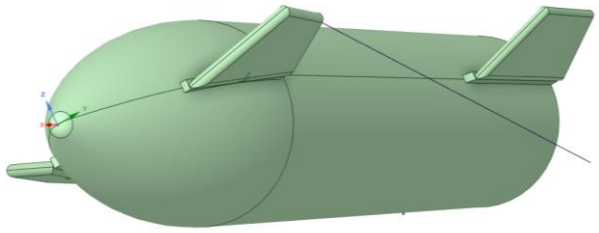
Contour Plane Shown at Start of Wing



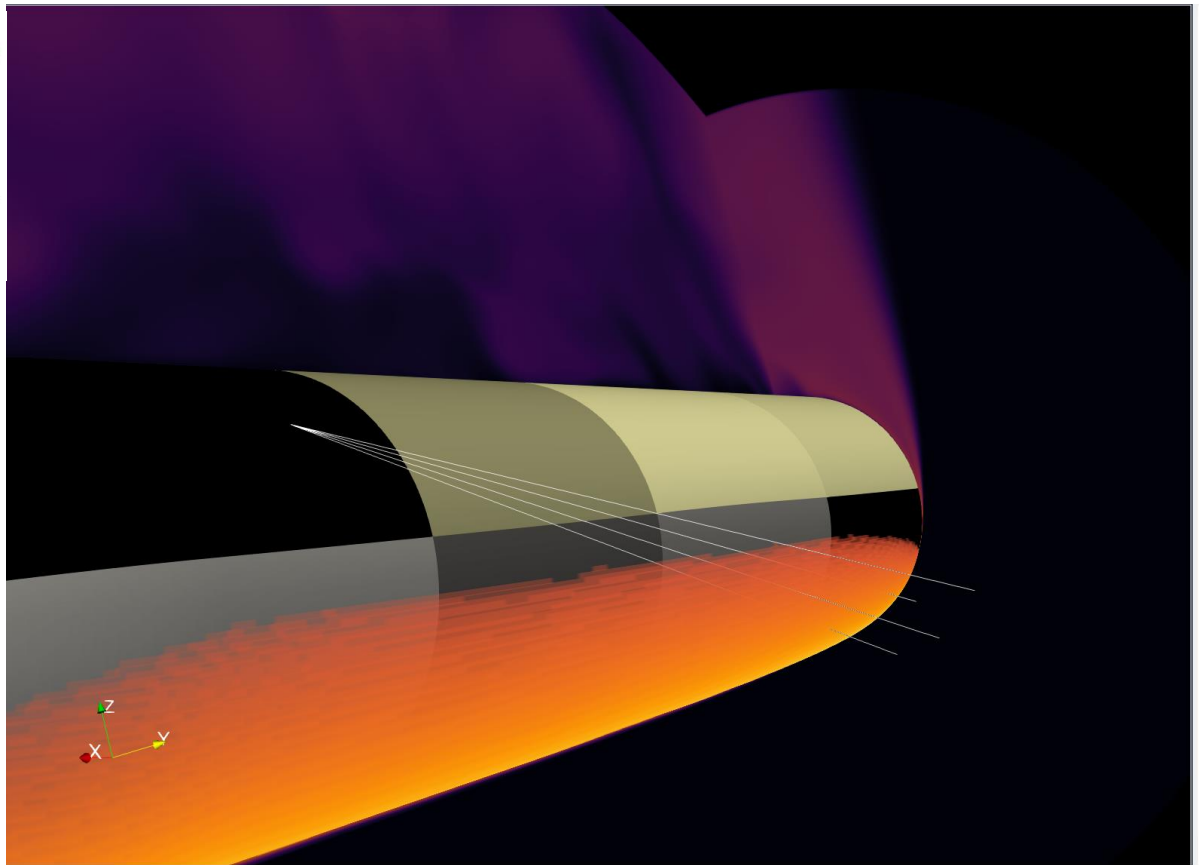
Contour Plane Shown at Aft Lip

Lines of Sight (cont.)

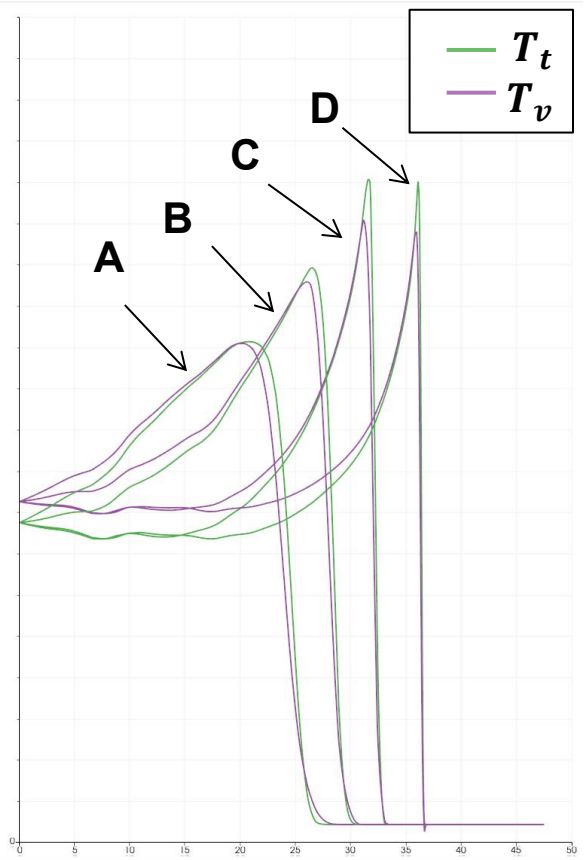
- Lesson learned: LOS definition includes lots of uncertainty
  - If onboard optics are to be used for this purpose, explicitly knowing the line of sight or camera field of view would be essential to quantify uncertainty.



Starship Geometry With Line of Sight Shown



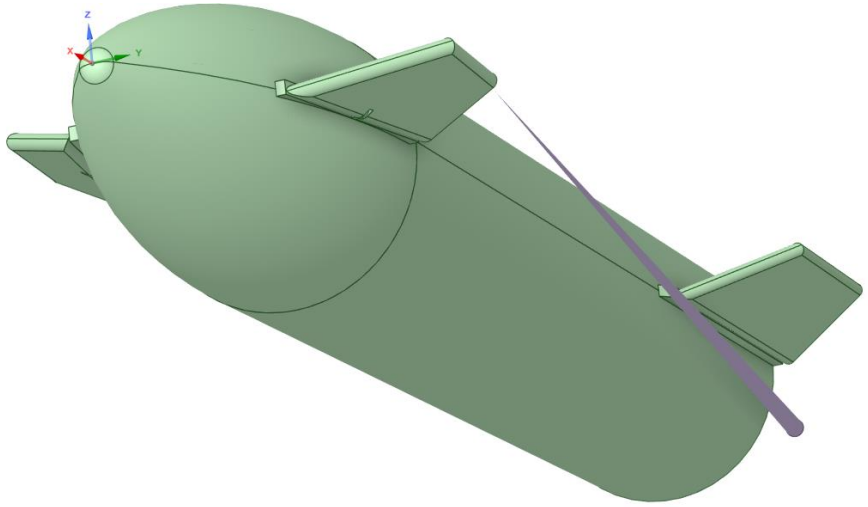
View of 4 LOS Through Emitting region



LOS temperature plot

NEQAIR settings

- NEQAIRv15.3 runs based on the included Afterbody Earth Entry test case.
  - Computes detailed spectral irradiance arriving at the camera's aperture for each LOS.
    - Intendent lines of sight is a working approximation.
    - Future work should improve with 3D view factor methods available in NEQAIRv15.3.
  - Used tangent slab geometry with 0.5° semi angle.
    - Approximates the circled regions in the field of view (FOV).
    - Pixel % coverage addressed in post processing – only looking a small region of the view.
  - Irradiance.out provides high resolution spectral irradiance for python post processing.
    - NEQAIR's accuracy is hindered by the 5 species 2 temperature CFD. Electrons and ions are not present in LOS.dat.
    - Future work should include 11 species and more temperature states.
- This work is focused on the visible spectrum
  - Heating concerns are usually from UV or VUV, not the visible wavelengths.



Starship geometry with 1° tangent slab FOV cone shown

Post Processing Irradiance

- Post processing the spectral irradiance requires camera details.
  - Assumed the camera is similar to a Go-Pro based on public mentions of Go-Pro use at SpaceX.
    - Use a comparable 12MP CMOS BSI for working specifics: Sony IMX304.
      - https://www.alliedvision.com/en/products/alvium-configurator/alvium-gm2/1236/
      - Provides Quantum Efficiency, full well saturation capacity, pixel size.
    - Go-Pro HERO4 specs provide aperture area = 0.85mm^2, and 1/30s estimate for exposure.
    - Camera is likely adjusting exposure and ISO. **All analysis is done with 1/30s exposure.**
  - Irradiance is converted to perceived color using the following process:
    1. Convert 1° FOV cone's spectral irradiance (E) to photon flux:

       $\phi_p(\lambda) = E(\lambda)/\frac{hc}{\lambda}$, where $c = 2.998 * 10^8$, and $h = 6.626 * 10^{-34}$
    2. Convert the photon flux to total photons through aperture in an exposure window:

       $\gamma_{tot}(\lambda) = \phi_p(\lambda) * A_{aperture} * t_{exposure}$
    3. Determine the number of pixels covered by the 1° FOV cone:

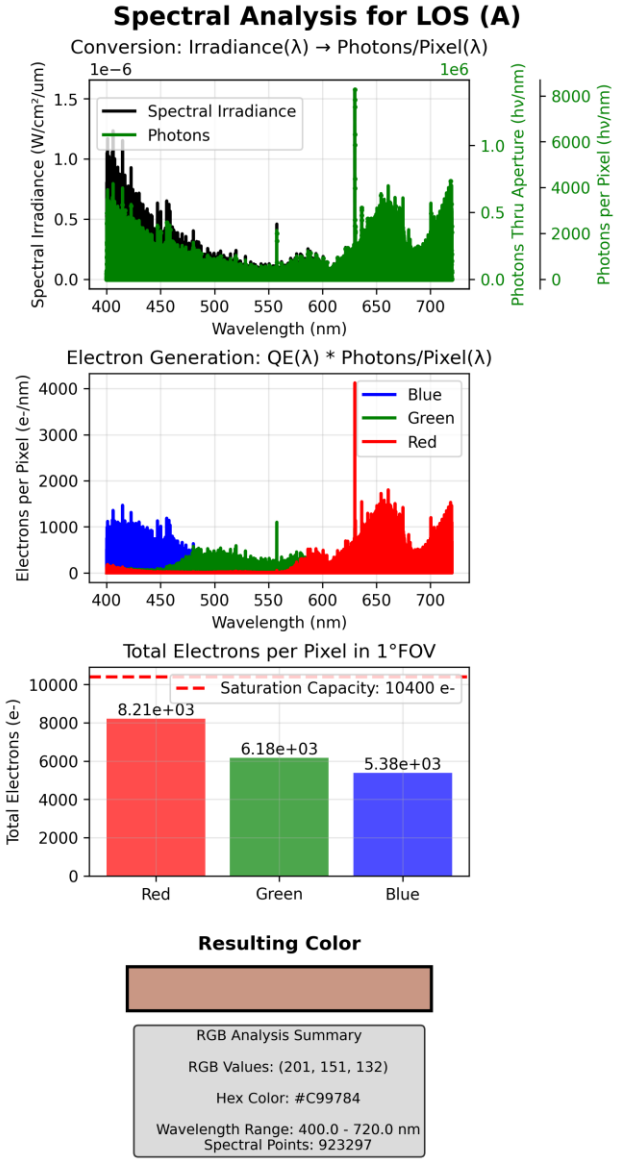
       $\theta_{pixel} = s/r$ where $s = focal\ length$ and $r = pixel\ length$ for a small angle

       $d_{pixels} = (FOV° * \frac{\pi}{180°})/\theta_{pixel}$ = the cone's diameter in units of pixels

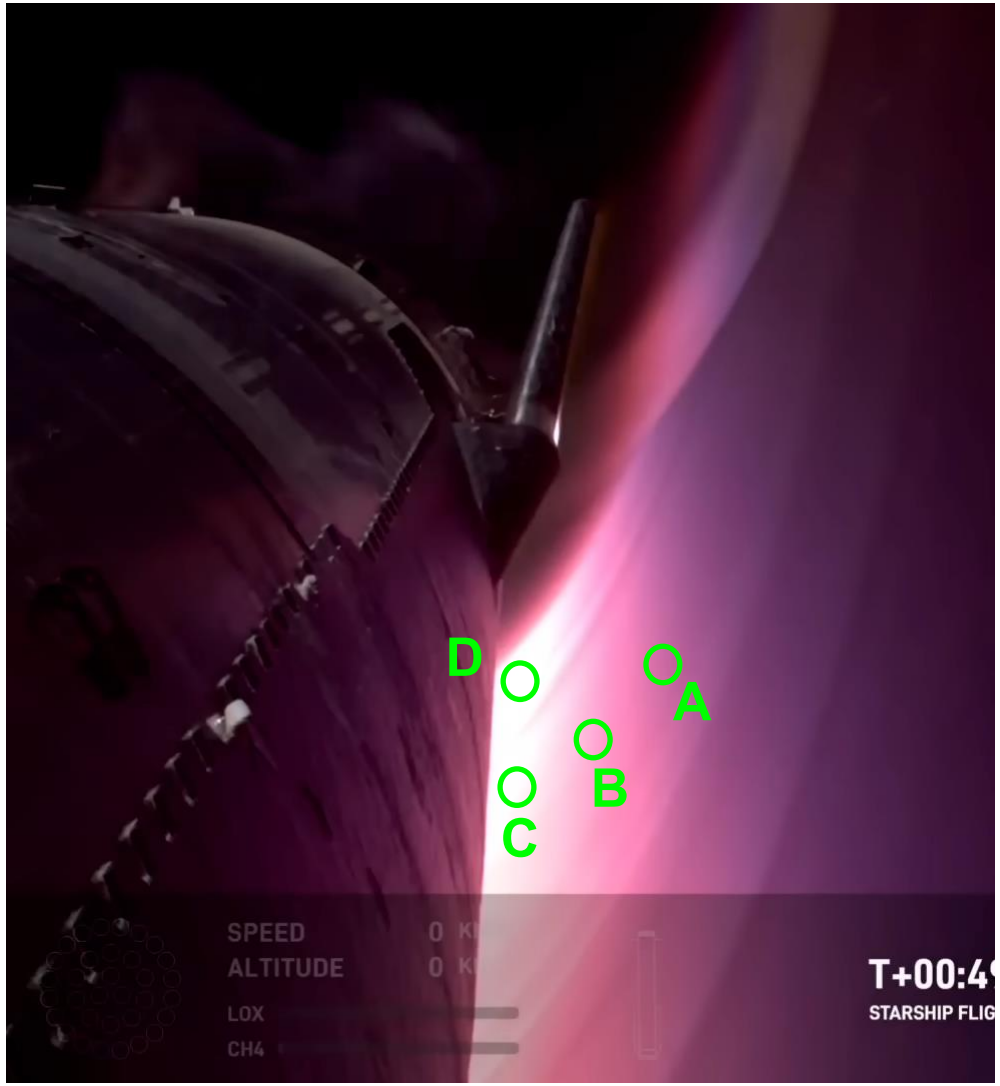
       $N_{pix} = \pi * (d_{pixels}/2)^2$ = the cone's area in units of pixels.
    4. Obtain the number of photons per pixel:

       $\gamma_{pixel}(\lambda) = \gamma_{tot}(\lambda) \ / \ N_{pix}$
    5. Convolve $\gamma_{pixel}(\lambda)$ with the assumed QE curves to obtain electrons per color:

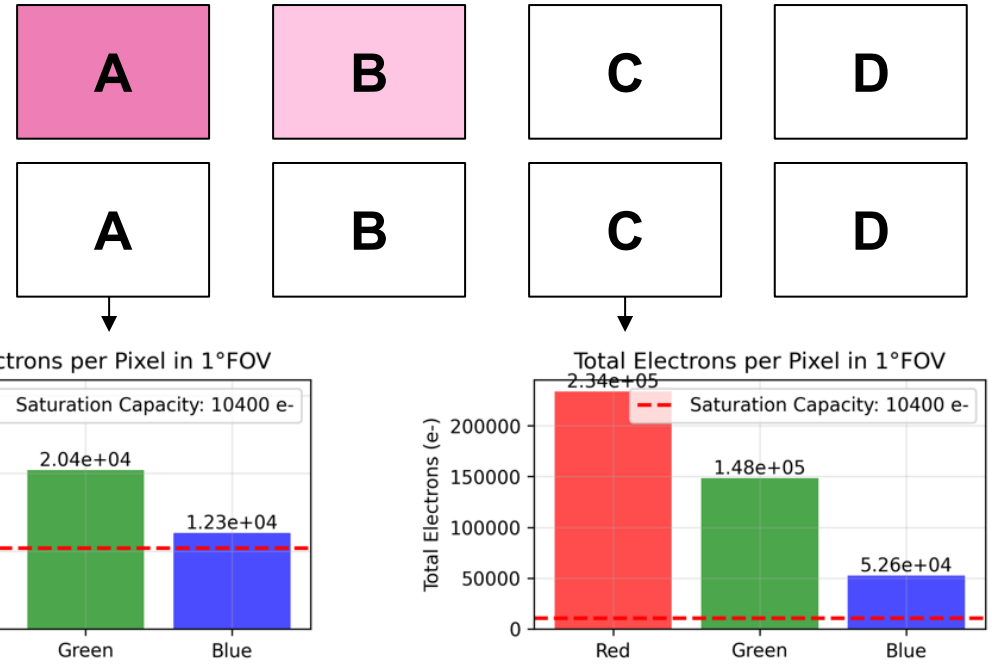
       $e^-_i = \int \gamma_{pixel}(\lambda) * QE_i(\lambda)\, d\lambda$ for $i = R, G, B$
    6. Normalize e^-_i against pixel saturation capacity and scale out of 255 to obtain RGB estimate.
  - All LOS Post Processing outputs are available in appendix.



NEQAIR RGB Results: Ma ≈ 25



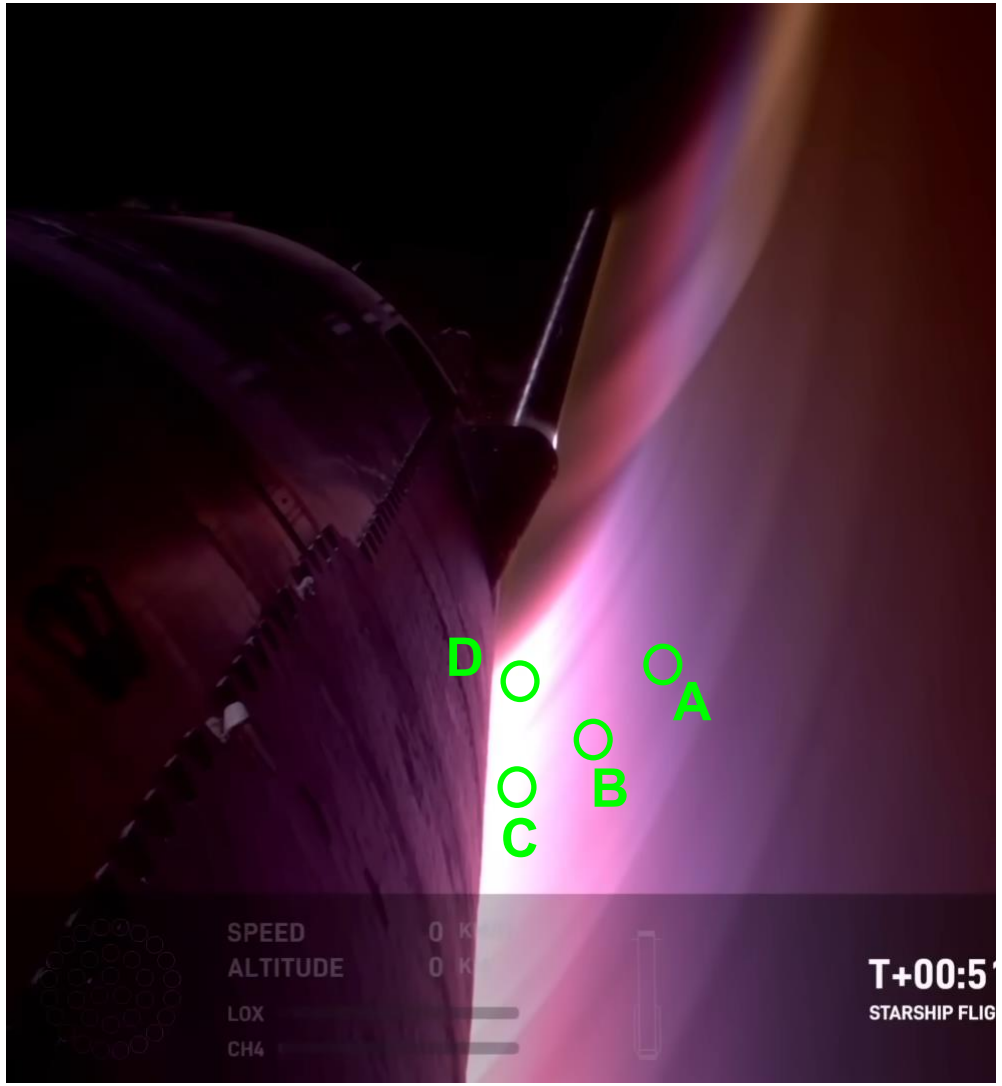
- Data:
- Model:



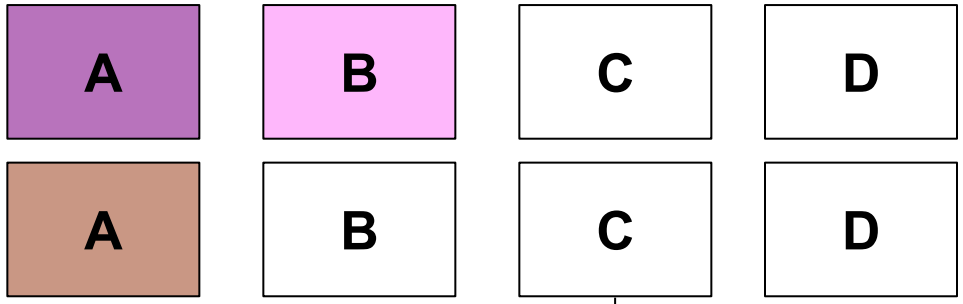
Total Electrons Per Pixel from LOS(A) and LOS (C)

- Observations:
  - LOS (C) and (D)'s pixels are extremely saturated. This could cause "spill over" into other pixels
  - The model predicts more visible radiation on LOS (A) and (B) than observed by camera. This may be attributable to the camera automatically reducing exposure time.

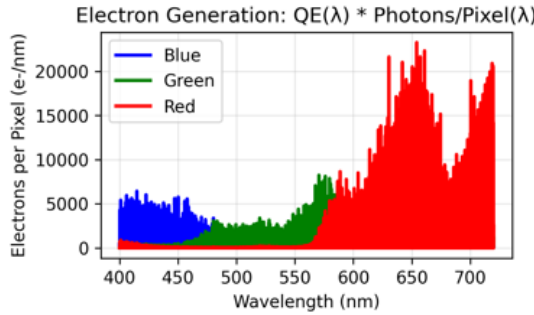
NEQAIR RGB Results: Ma ≈ 22



- Data:
- Model:



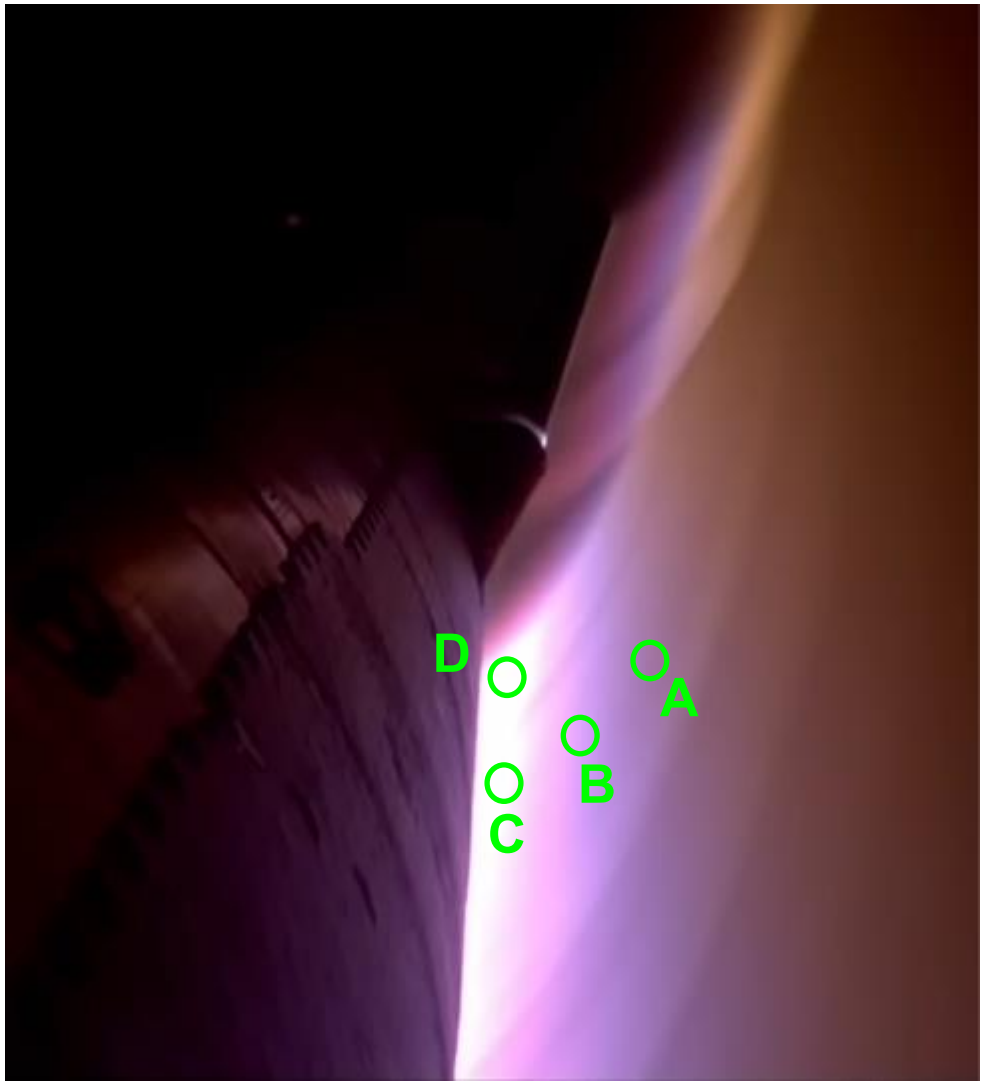
Rarefied Dim Shock Color



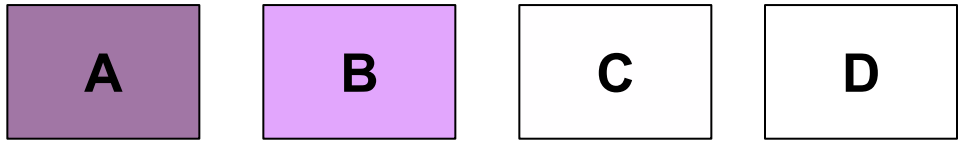
Red-dominated spectra

- Observations:
  - The brightness at LOS (A) and (B) is close to the data.
    - Averaged RGB values at are within 1% at LOS (A), 11% for (B)
    - In the model, LOS (B) is barely statured at this time.
  - The purple hue may be due to saturated pixel color distortion more than actual gas chemistry.
    - When the flow was dim and rarefied, it had a red hue, which somewhat agrees with Spectra

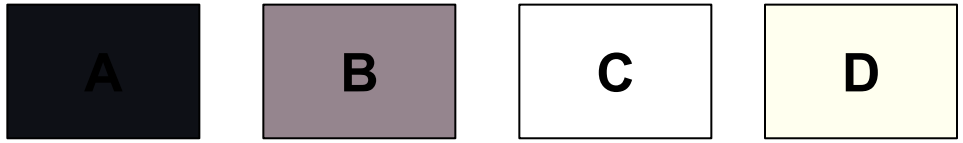
NEQAIR RGB Results: Ma ≈ 20

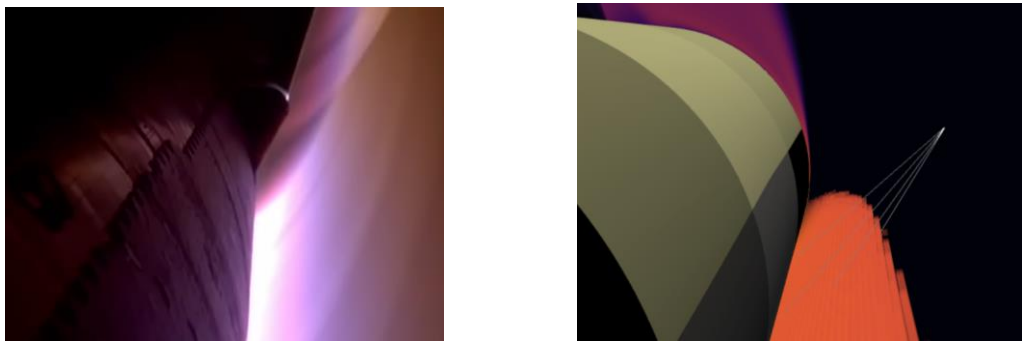


- Data:



- Model:

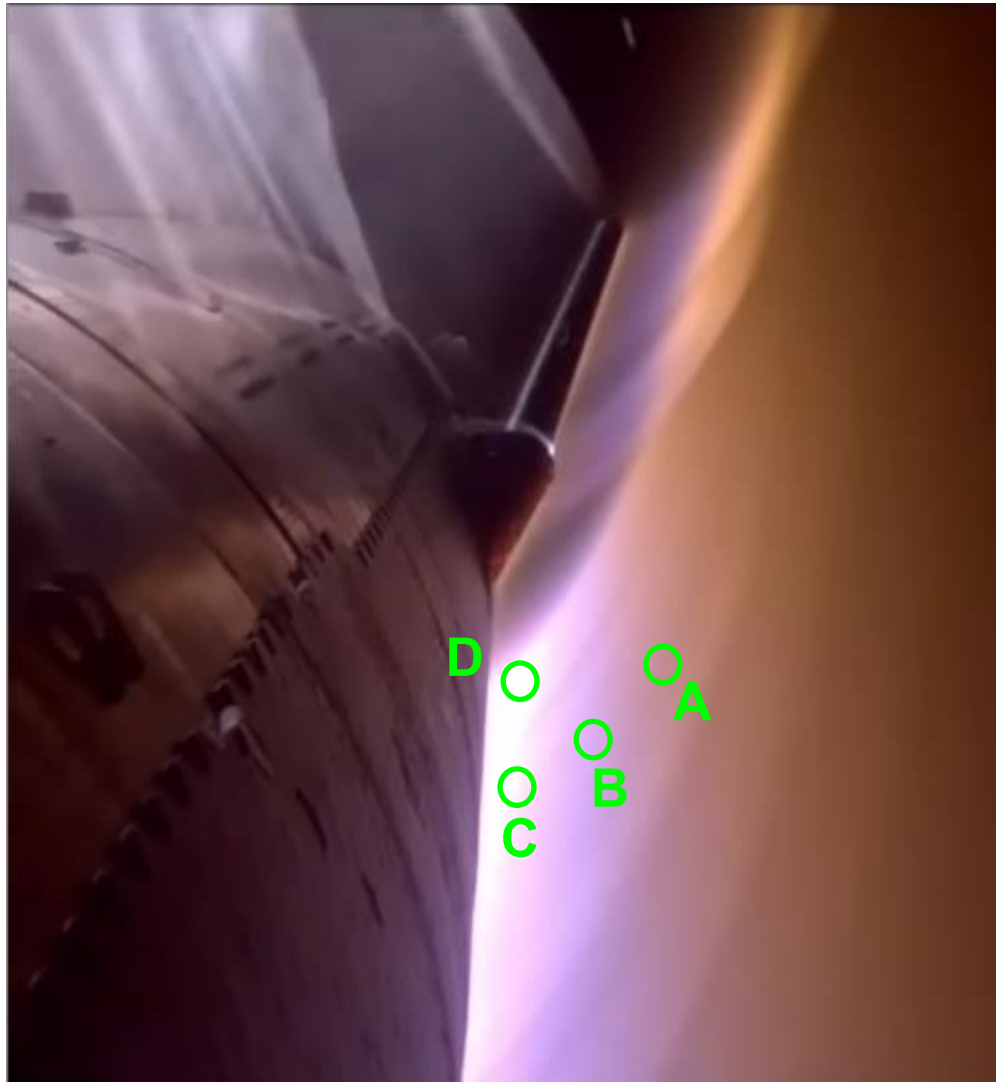




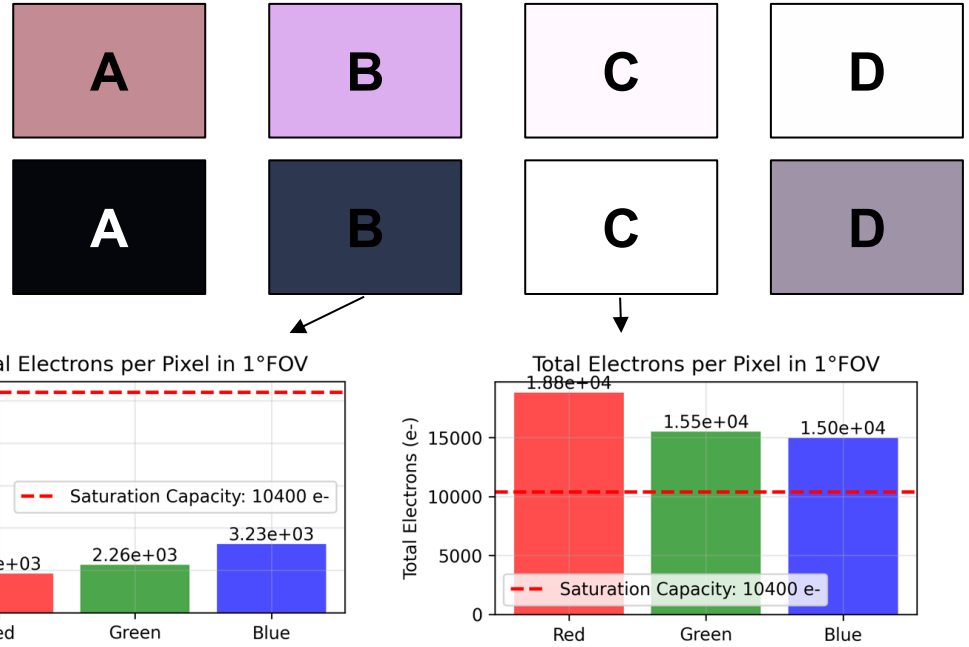
Comparison of shape of >6000K region with/without wing

- Observations:
  - LOS (D) is invalidated by absence of wing in the CFD.
  - Model shortcomings may become evident here:
    - Despite LOS (C) remaining saturated, LOS (A) and (B) are 10% and 60% of the observed averaged RGB brightness, respectively.
    - This may be a result of neglecting ions in LAURA & NEQAIR.

NEQAIR RGB Results: Ma ≈ 18



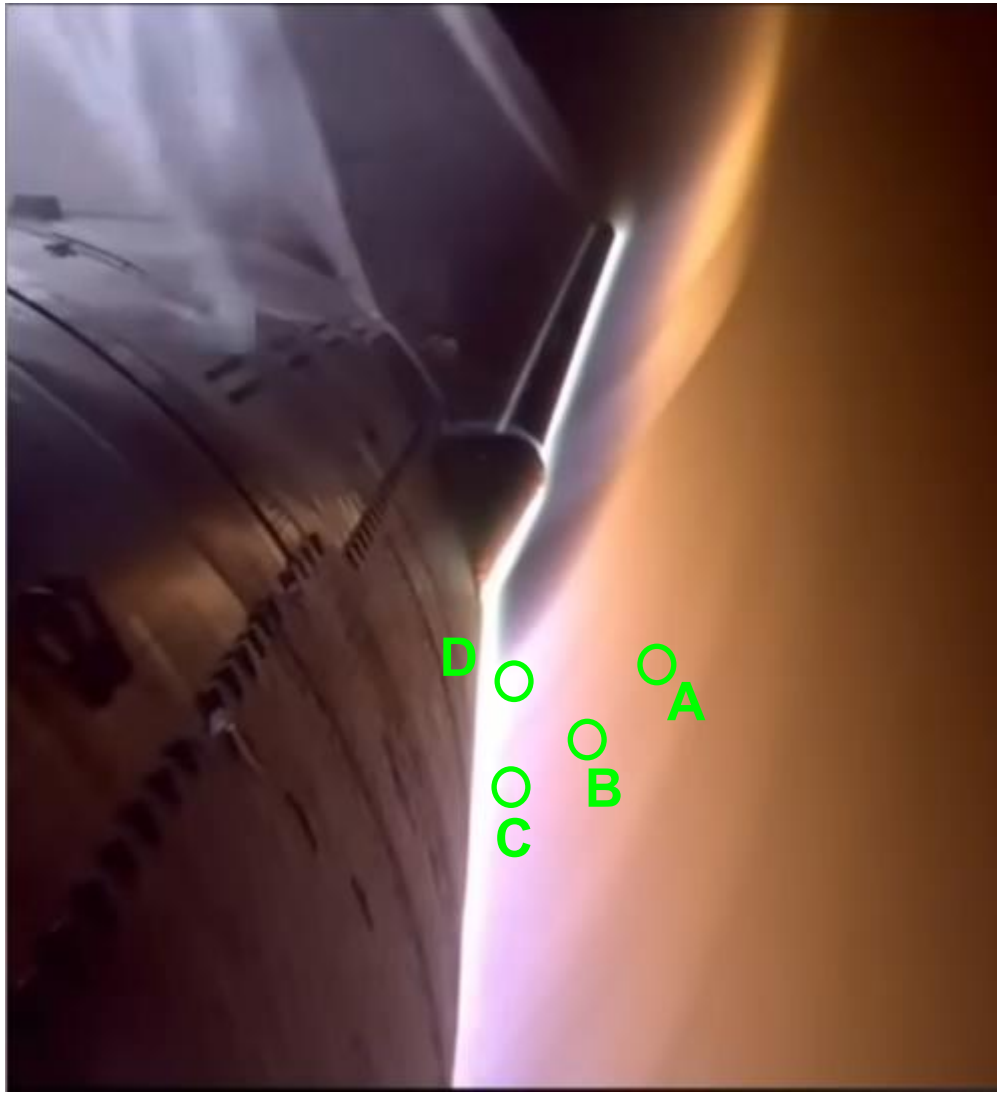
- Data:
- Model:



Total Electrons Per Pixel from LOS(B) and LOS (C)

- Observations
  - LOS (A) and (B) are drastically dimmer than observed data, while (C) remains saturated
    - Further supports lack of ions or some other shortcoming leading to model underpredictions in this region of flow.
  - Wake transitions to a fully separated turbulent state that brightens up the scene

NEQAIR RGB Results: Ma ≈ 17



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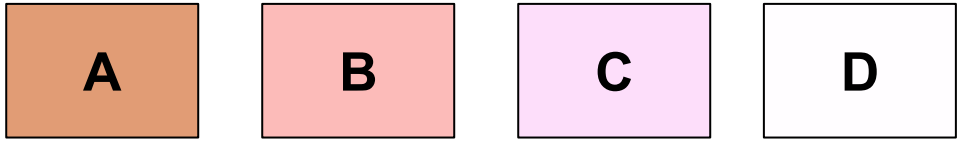
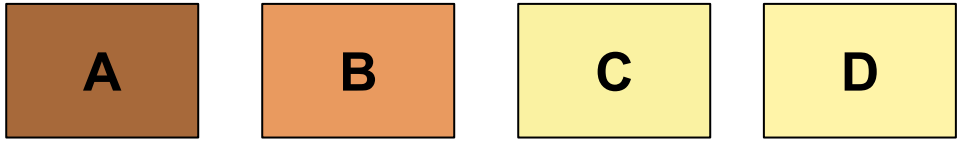


- Model:

- Observations:
  - Model significantly underpredicts brightness at all locations.
    - Camera may have increased its ISO level,
    - There may be a significant shortcoming in the 5 specie LAURA/NEQAIR workflow for visible wavelength emissions at this speed/altitude.
  - Catalytic wall behavior is prominent in view.

NEQAIR RGB Results: Ma ≈ 13

- Data:



- Model:

- Observations:
  - Model significantly underpredicts brightness at all locations.
    - Camera may have increased its ISO level
    - Examined running with model with 1/20s exposure—negligible improvement.
  - ‘Purple-blue’ hue is gone from view. May provide insight into chemistry changes.

Summary

- This work presents a concept for comparing NEQAIR spectral emissions predictions to in-flight video.
  - **Includes several approximations and plenty of uncertainty, which prohibits any comment on NEQAIR's validity.**
  - The concept may be improved with the following:
    - Known camera details (aperture, sensor size, exposure time, ISO level, QE curves, saturation capacity)
    - Known geometry for the camera's / spectrometer's LOS.
    - Precise atmosphere inputs, including accurate freestream species concentrations.
    - A CFD solver that can run more temperature states (DPLR). Ions should be included in species list.
- Lessons learned:
  - Budget more time. Radiatively coupled CFD takes a while to run even on a cluster.
    - LAURA is picky. Blocks must equal ranks for successful restarts. Allot time for debugging.
  - Radiative energy transfer plays a significant role in the flow field solution at these speeds.
  - Use a scientific camera/spectrometer with known specifics and mounting for useful results.
  - Ions and additional temperature states may need modeled for useful comparisons to NEQAIR, particularly in the visible spectrum.
- Goals realized: Gain experience with a Hypersonic CFD code and Radiative heating tools.

APPENDIX

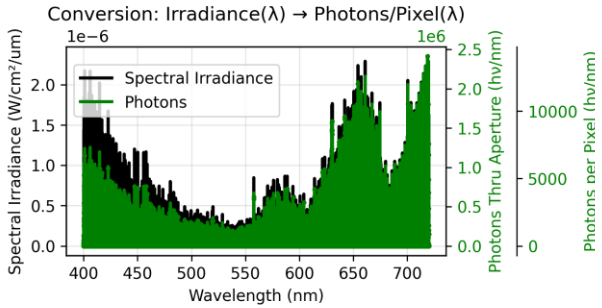
Spectral Analyses of Four Lines of Sight Per CFD Case

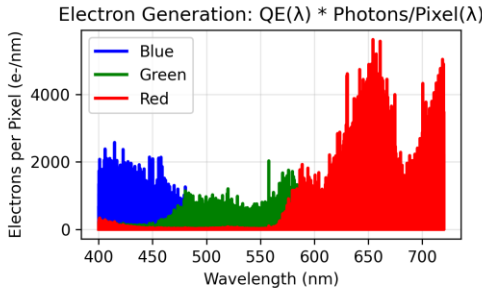
*All cases ran with 1/30s exposure time.

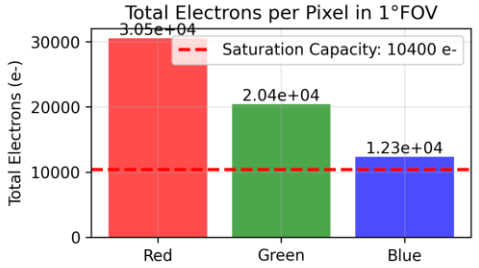
**All RGB results are normalized against an assumed full well saturation capacity

NEQAIR Post Processing: Ma ≈ 25, V = 26428 km/h

Spectral Analysis for LOS (A)



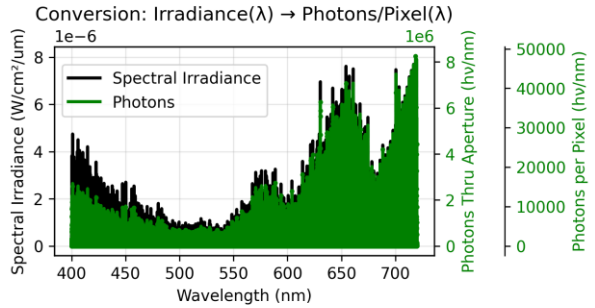


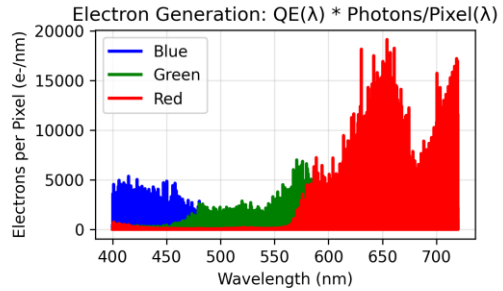


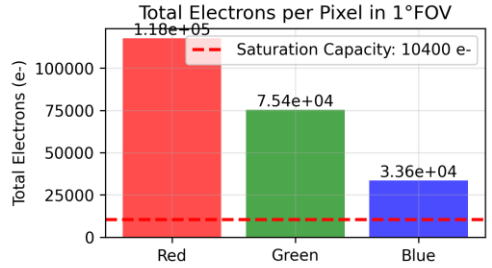
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (B)



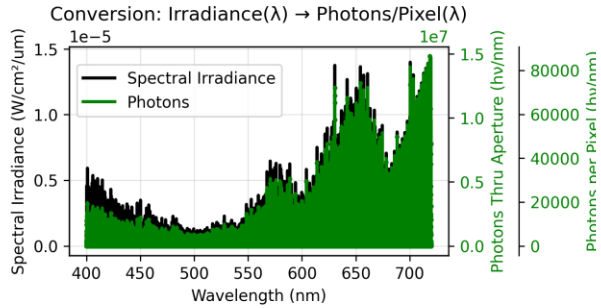


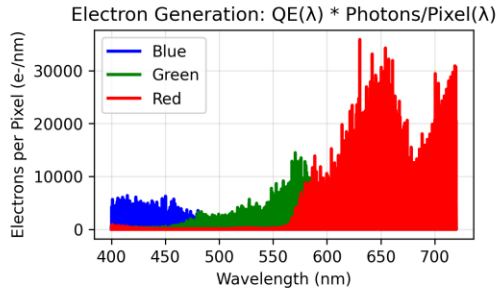


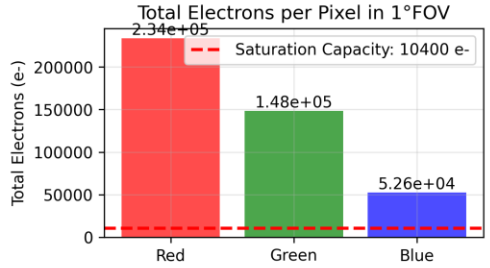
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (C)



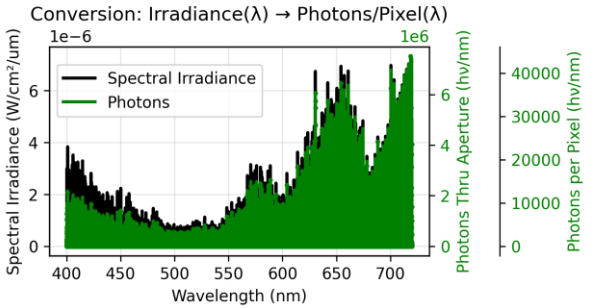


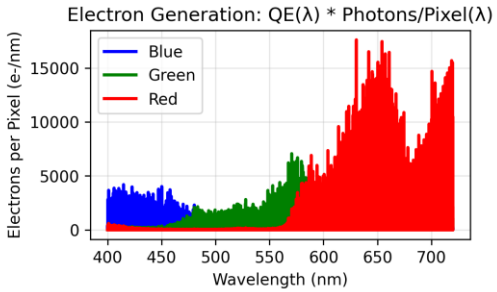


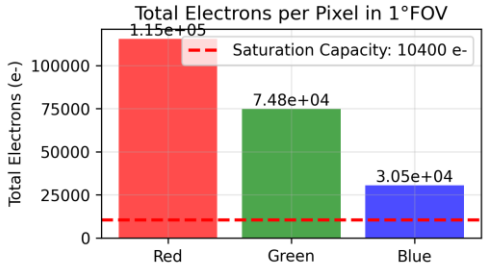
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (D)





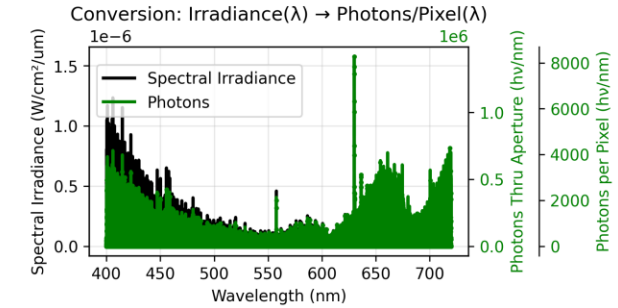


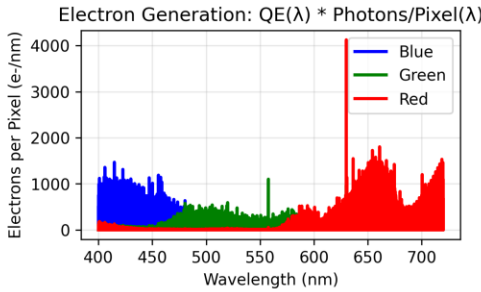
Resulting Color

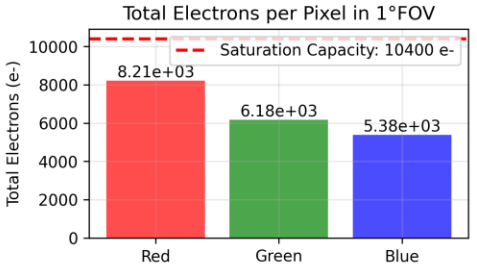
RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

NEQAIR Post Processing: Ma ≈ 22, V = 24113 km/h

Spectral Analysis for LOS (A)



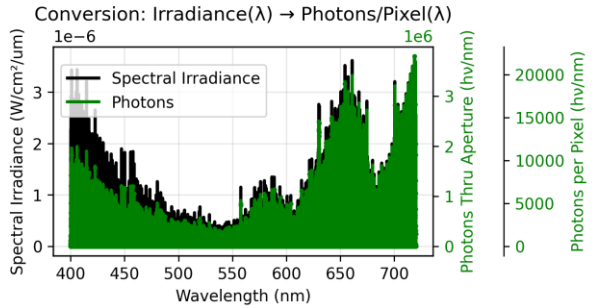


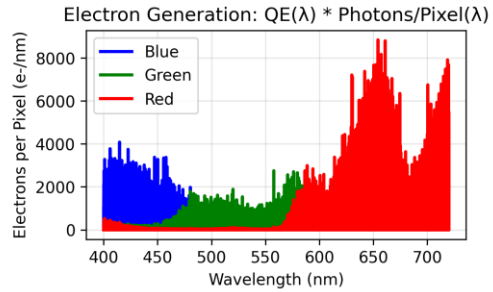


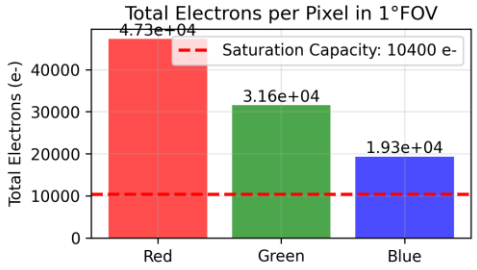
Resulting Color

RGB Analysis Summary
RGB Values: (201, 151, 132)
Hex Color: #C99784
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (B)



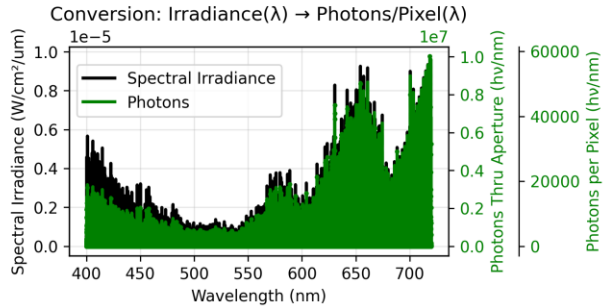


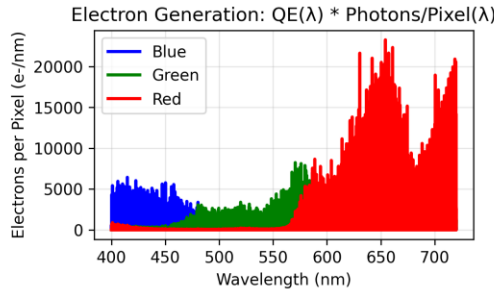


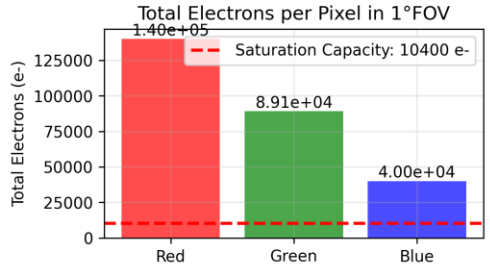
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (C)



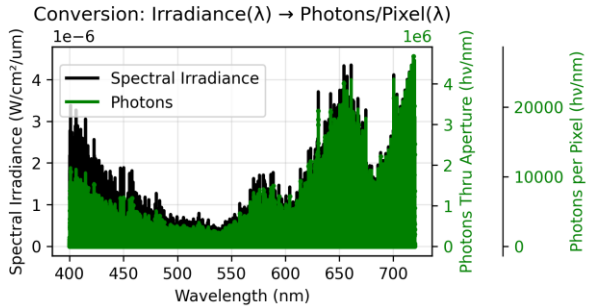


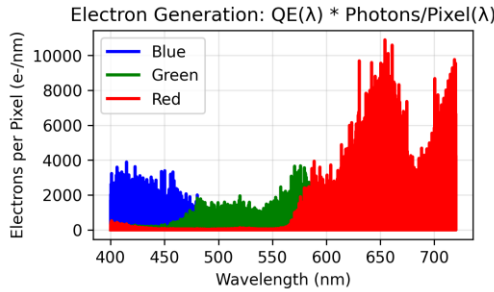


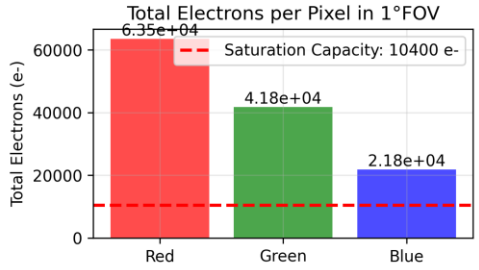
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (D)



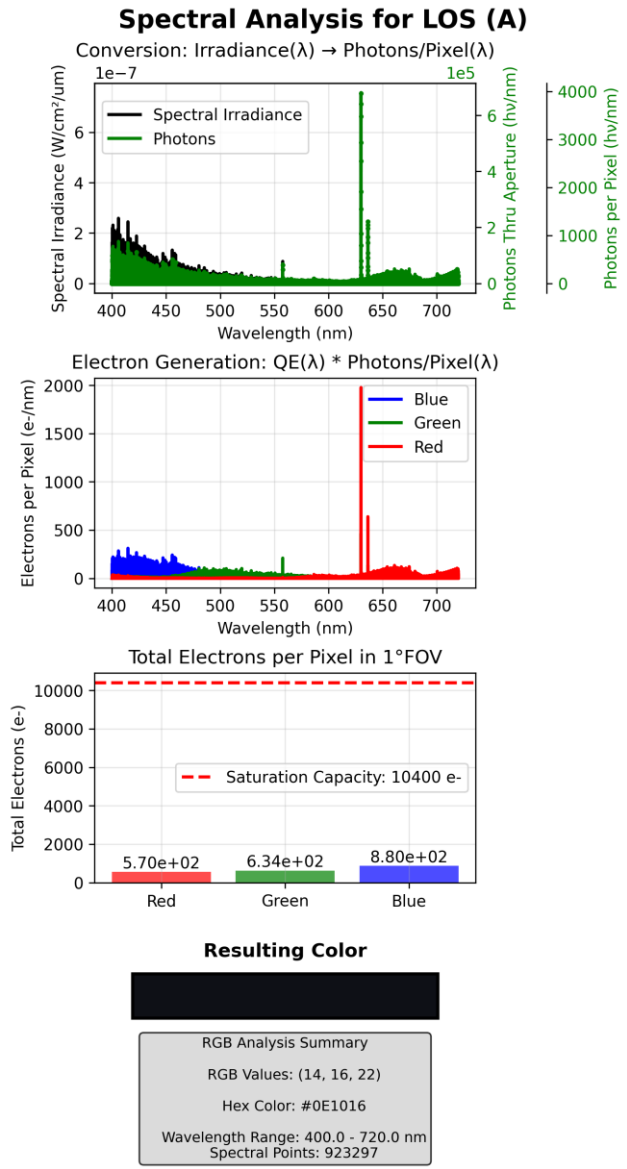


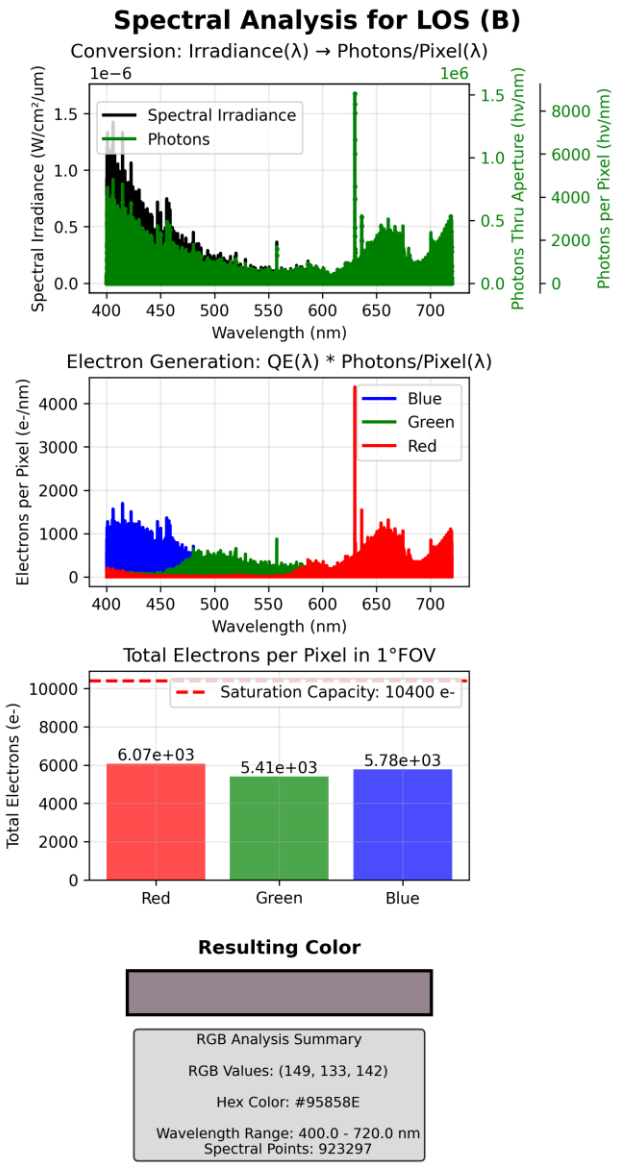


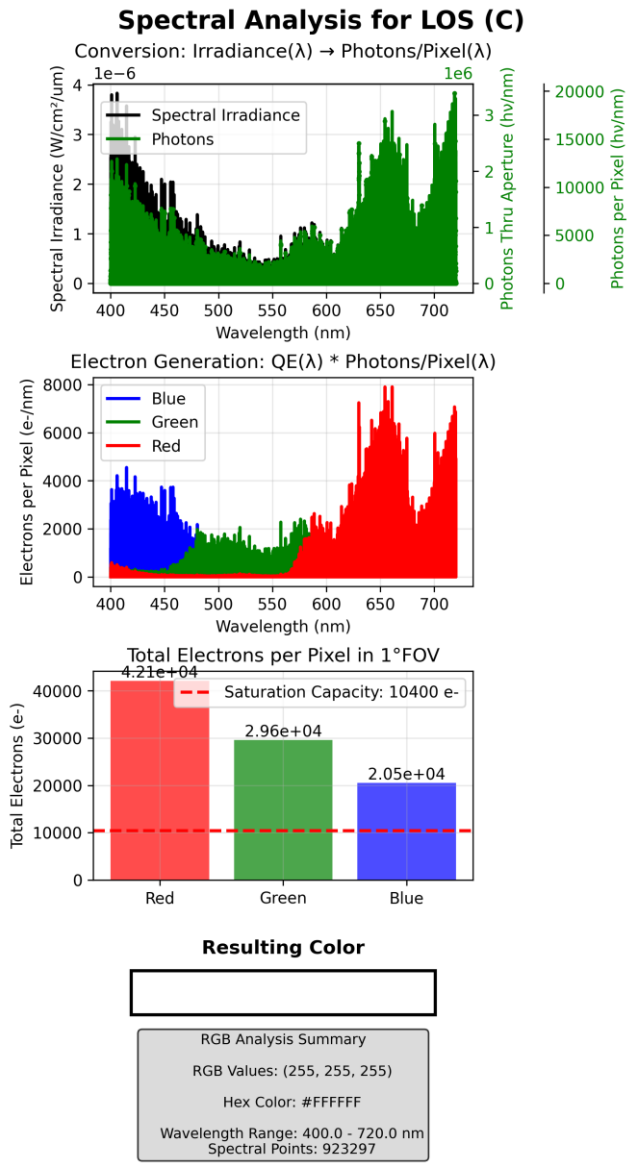
Resulting Color

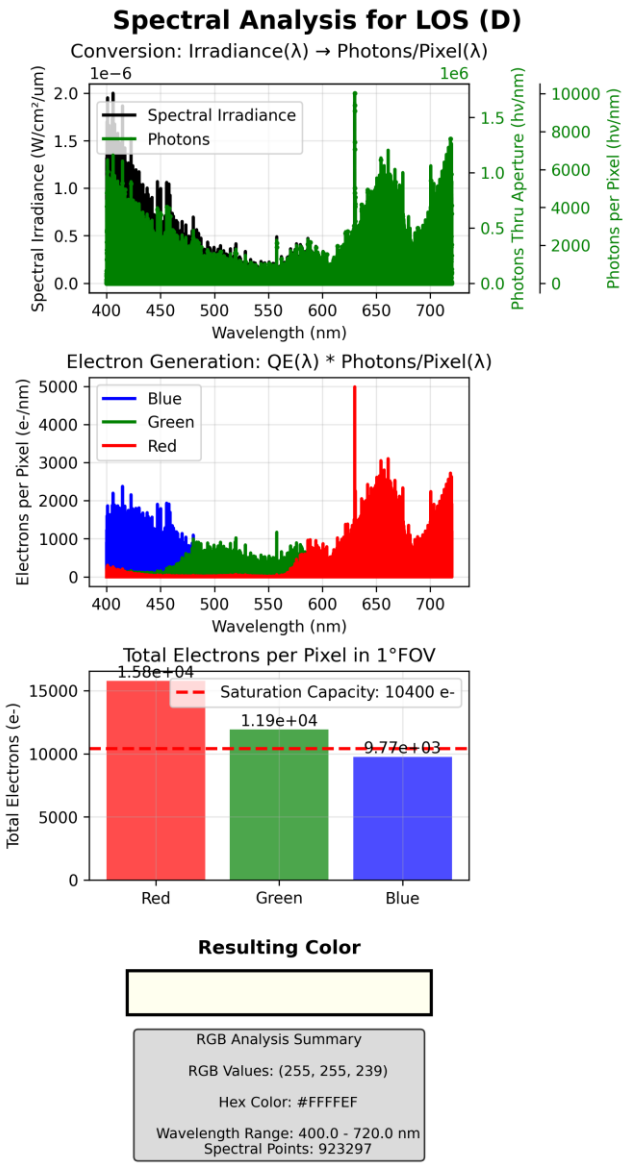
RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

NEQAIR Post Processing: Ma ≈ 20, V = 22101 km/h



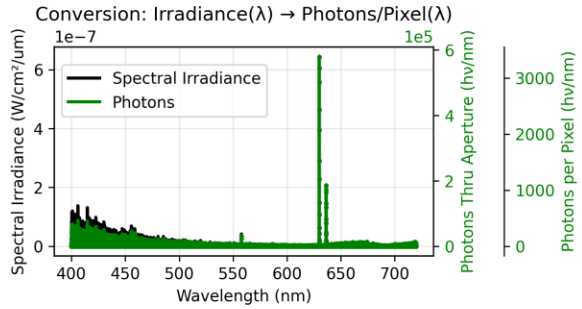


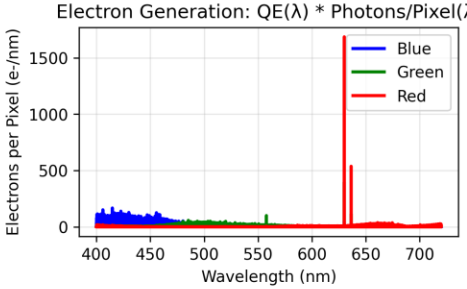


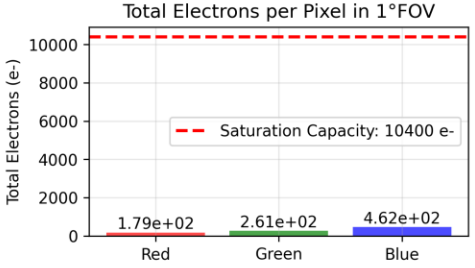


NEQAIR Post Processing: Ma ≈ 19, V = 20993 km/h

Spectral Analysis for LOS (A)



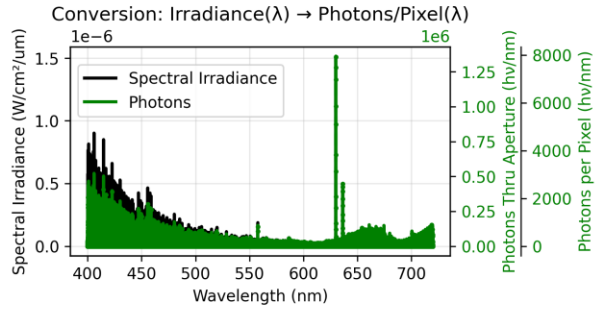


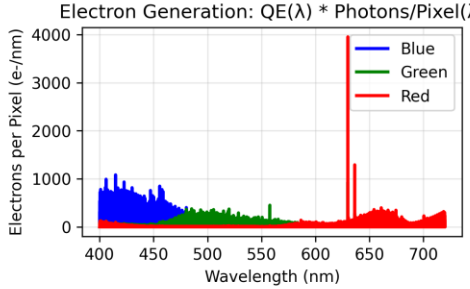


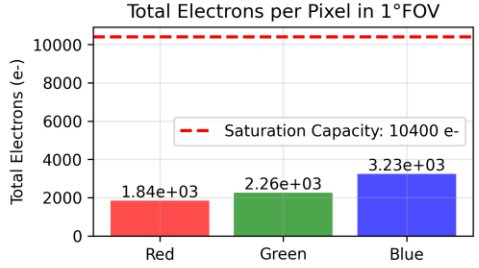
Resulting Color

RGB Analysis Summary
RGB Values: (4, 6, 11)
Hex Color: #04060B
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (B)



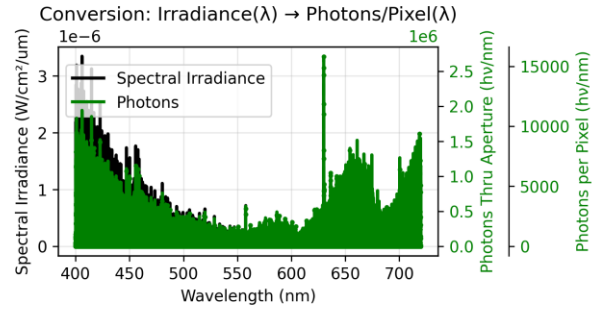


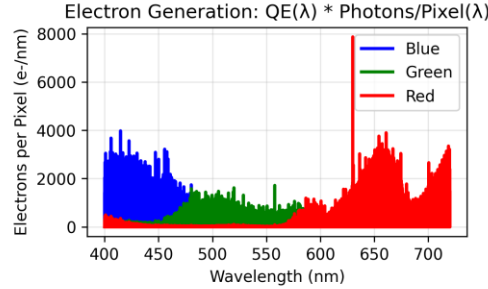


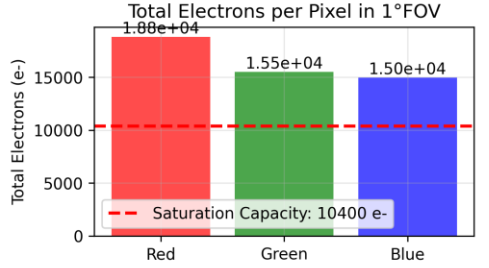
Resulting Color

RGB Analysis Summary
RGB Values: (45, 55, 79)
Hex Color: #2D374F
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (C)



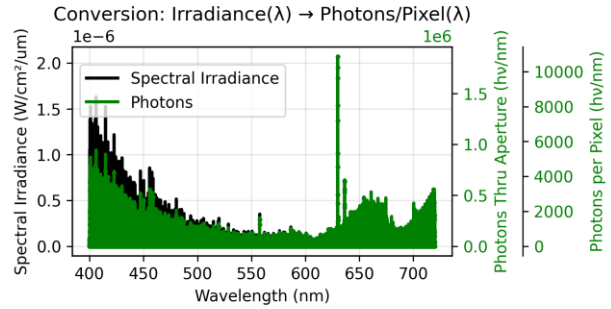


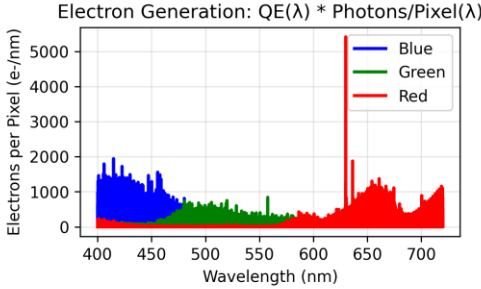


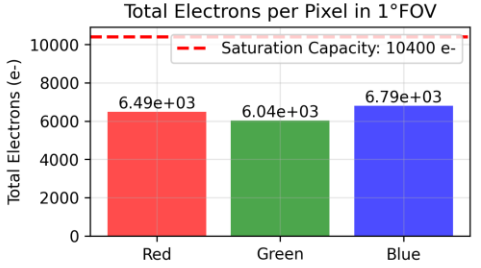
Resulting Color

RGB Analysis Summary
RGB Values: (255, 255, 255)
Hex Color: #FFFFFF
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (D)





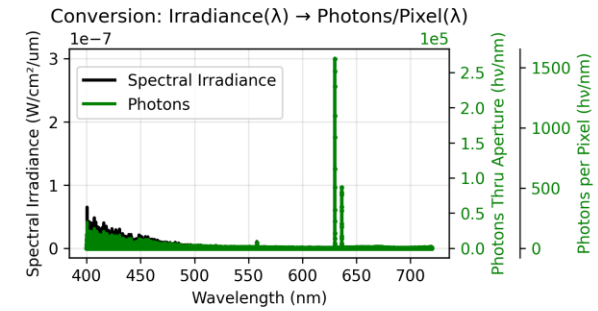


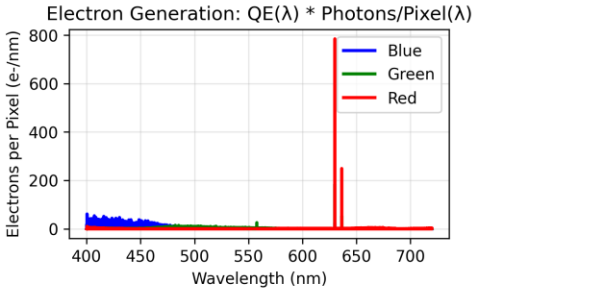
Resulting Color

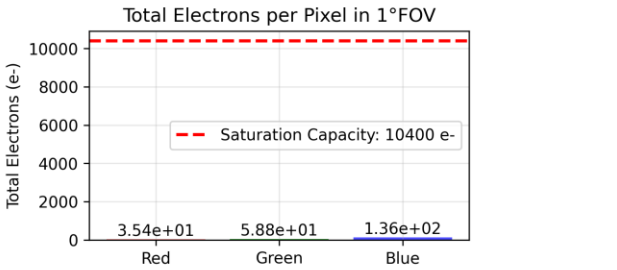
RGB Analysis Summary
RGB Values: (159, 148, 167)
Hex Color: #9F94A7
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

NEQAIR Post Processing: Ma ≈ 17, V = 19342 km/h

Spectral Analysis for LOS (A)



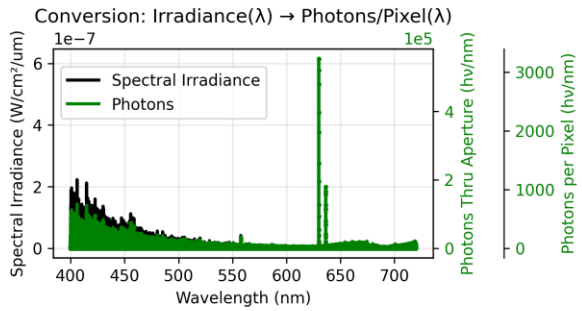


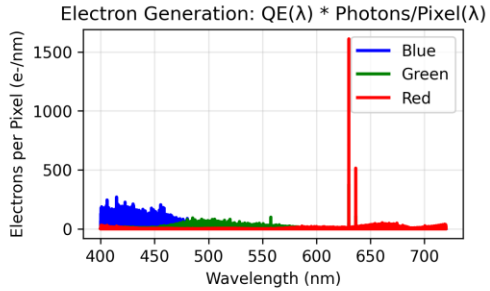


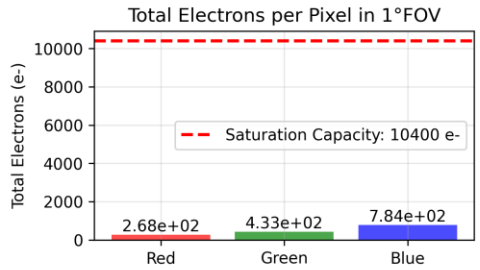
Resulting Color

RGB Analysis Summary
RGB Values: (1, 1, 3)
Hex Color: #010103
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (B)



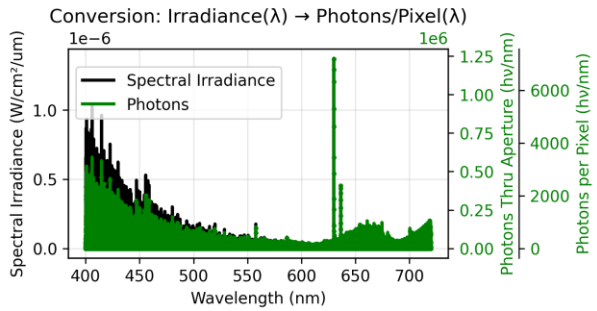


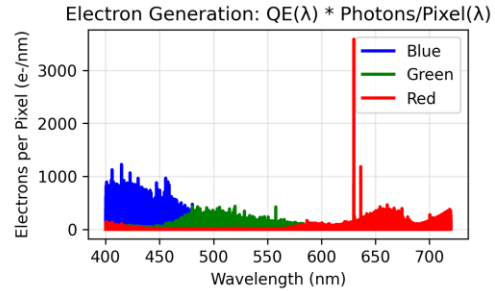


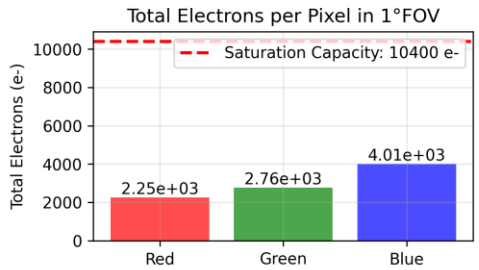
Resulting Color

RGB Analysis Summary
RGB Values: (7, 11, 19)
Hex Color: #070B13
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

Spectral Analysis for LOS (C)



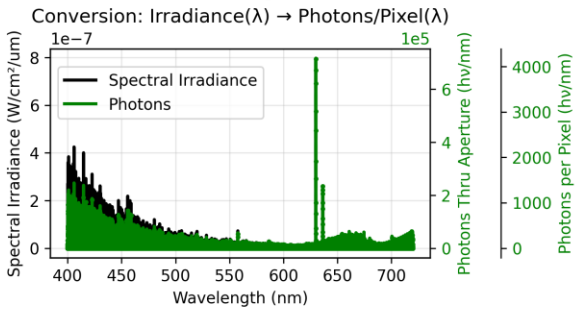


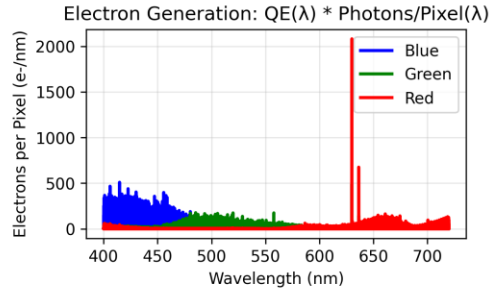


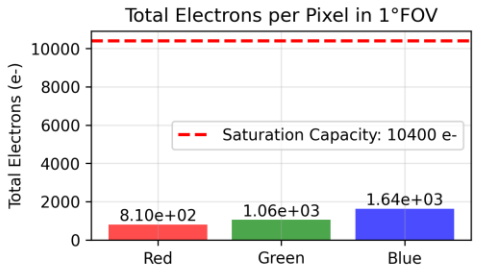
Resulting Color

RGB Analysis Summary
RGB Values: (55, 68, 98)
Hex Color: #374462
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

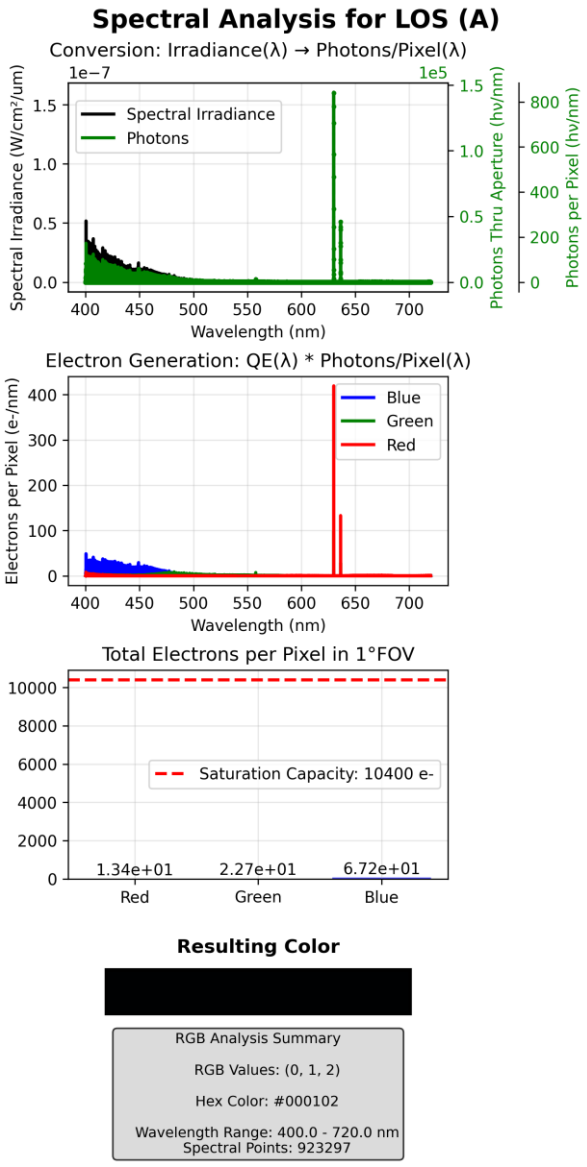
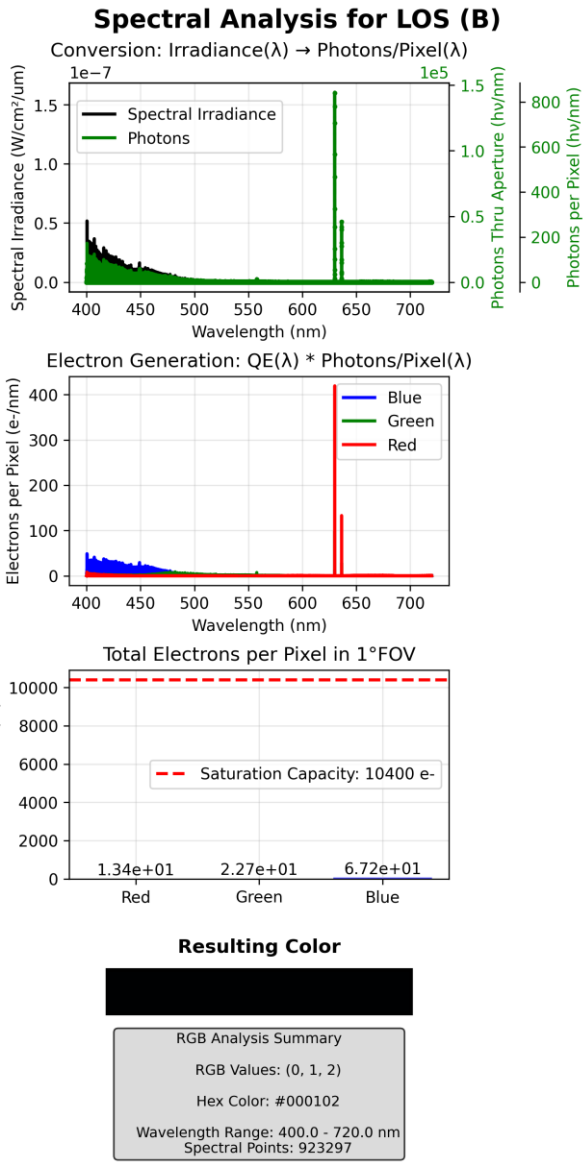
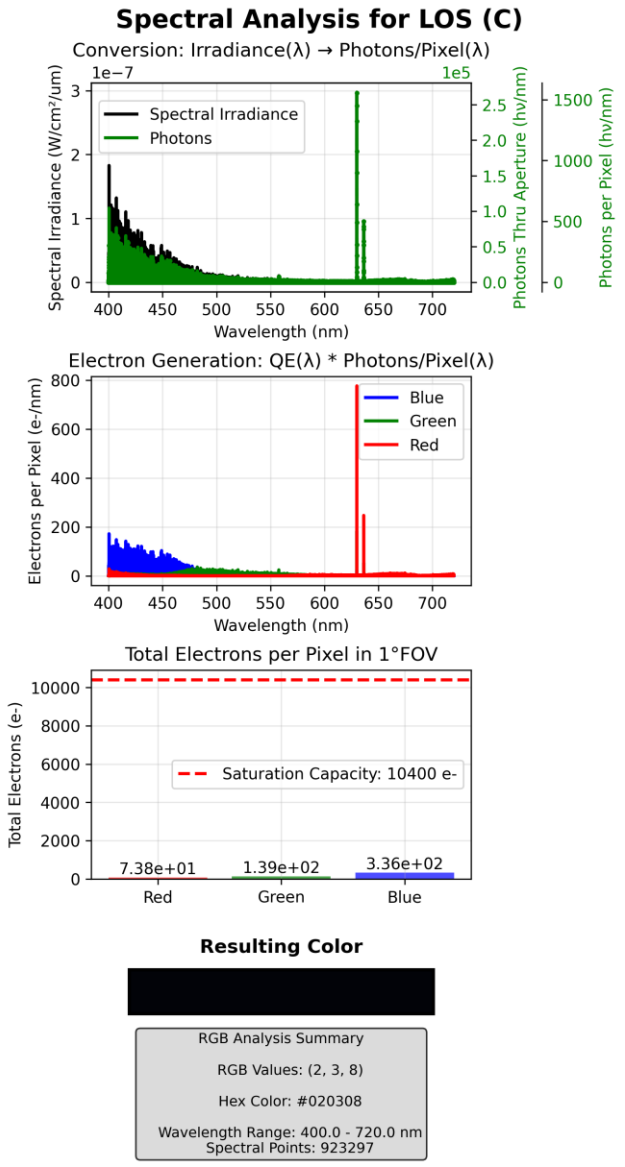
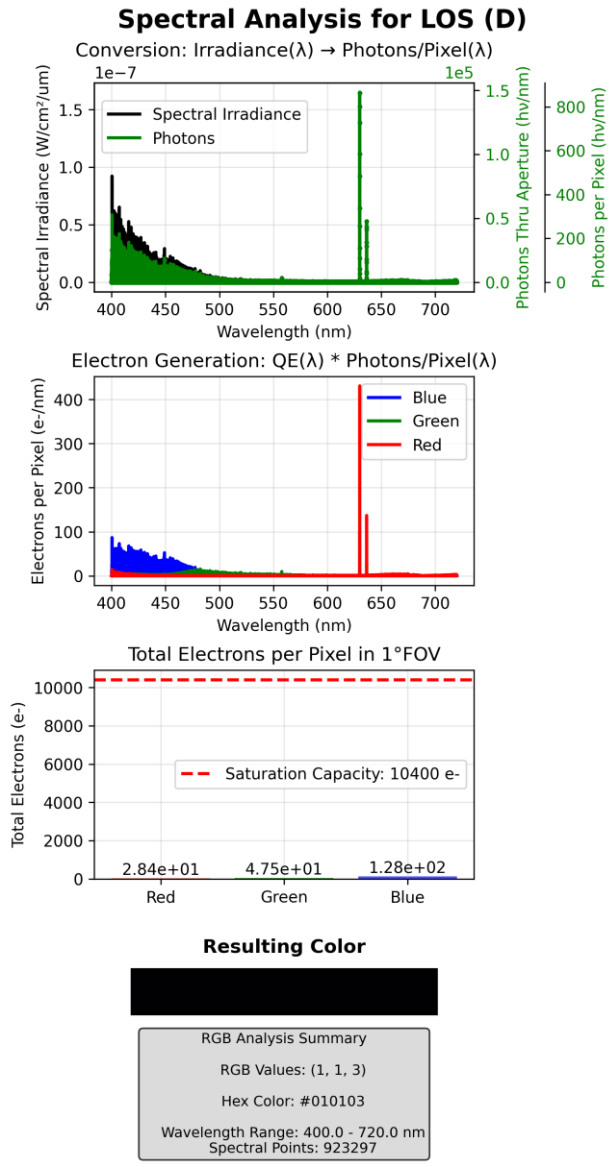
Spectral Analysis for LOS (D)







Resulting Color

RGB Analysis Summary
RGB Values: (20, 26, 40)
Hex Color: #141A28
Wavelength Range: 400.0 - 720.0 nm
Spectral Points: 923297

NEQAIR Post Processing: Ma ≈ 13, V = 15395 km/h