Modeling Earth-shine Bias in SKYSURF Database

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Hubble Space Telescope and SKYSURF

- The Hubble Space Telescope (HST) is a space observatory launched by NASA in 1990 named after American astronomer Edwin Hubble.
- HST has made numerous discoveries, including measuring the expansion rate of the universe, studying black holes, observing star and galaxy formations, and providing evidence for dark matter.
- The extragalactic background radiation (EBR) or extragalactic background light (EBL) is a faint glow of light that permeates the entire observable universe and is thought to come from various astrophysical sources.
- There are several sources of diffuse light in the universe, including the extragalactic background light and foreground light.
- Project SKYSURF investigates the source of EBL and contains over 57,000 HST images in 1,100 fields, covering decades of data across three instruments.

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SKYSURF and EBL Measurements

- The measurements of EBL in SKYSURF were found to be different than what would be expected if one were to count all known galaxies.
- This implies the presence of other components contributing to the extra light that must be investigated.
- SKYSURF database covers decades of data across three instruments: Advanced Camera for Surveys (ACS, 2002-2020), Wide Field Planetary Camera 2 (WFPC2, 1994-2009) and Wide Field Camera 3 (WFC3, 2009-2020).
- Extragalactic background light comes from the light of distant quasars and galaxies, while foreground light comes from sources closer to home.
- According to Windhorst et al. (2022), there could also be light from low-surface brightness galaxies causing the discrepancy in EBL measurements.

Potential Revisions to Kelsall ZL Model

- Foreground light sources include Zodiacal Light (ZL), diffuse galactic light, and other sources from inside the Solar System such as Kuiper belt objects and Earth-shine.
- Revised models may need to include collisional processes in the Solar System that can make the Zodiacal dust smaller over time and Solar radiation pressure that may drive these smaller dust particles further out into the Solar System.
- These processes may result in a tenuous ellipsoidal or more spherical cloud of dust around the Sun compared to the known Zodiacal IPD cloud.
- Potential revisions to the Kelsall ZL model are listed in Carleton et al. (2022).

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SKYSURF into the Future

- The project's extensive database covers decades of data across three HST instruments, and its findings have already shown that other components are contributing to the extra light beyond the known galaxies.

- Future SKYSURF papers will investigate the source of this extra light by updating thermal dark signals, Zodiacal Light, and potentially outer solar system sources, and possibly revising the Kelsall ZL model.

Introduction to Earth-shine

- One important element of the foreground light to investigate is Earth-shine.

- Earth-shine is the light that is originating from the Earth itself, captured by the aperture of the Hubble Space Telescope.

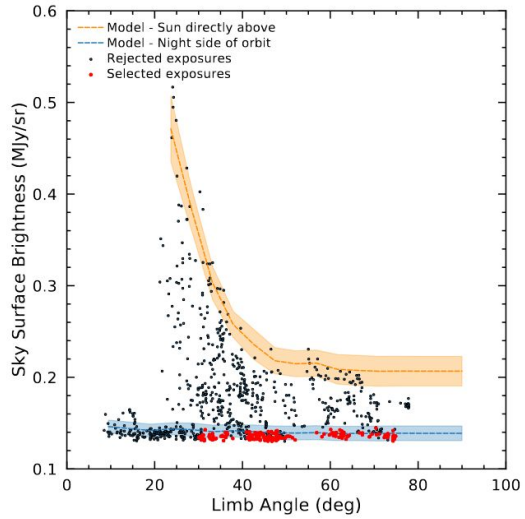
- Earth-shine is an additional source of stray photons that could impact the measurements of sky-brightness found in SKYSURF.

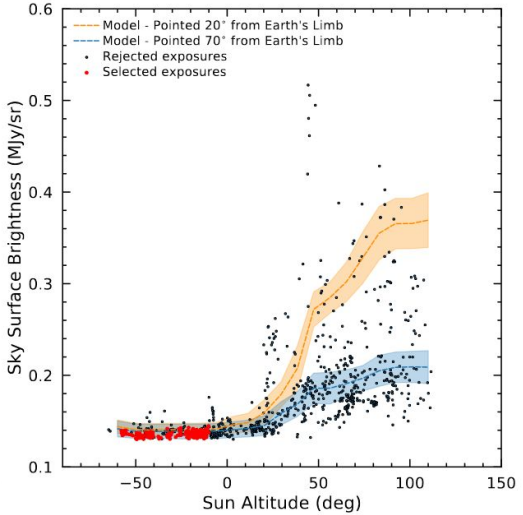
Impact of Earth-shine on Sky Measurements

- Windhorst et al. (2022) Fig.9 shows a strong exponential increase at limb angles between 40−45 deg but still persists at even limb angles of 70−80 deg on the day side of Hubble's orbit.
- The model shows that Earth-shine can be up to ~5 times brighter than the sky brightness signal SKYSURF was wanting to see.
- These findings inspired investigating the impact of Earth-shine on sky measurements.
- The closer the telescope is pointed at the Earth (lower limb angle), the more Earth-shine we would expect to see.

Earth-shine and Hubble's Orbit

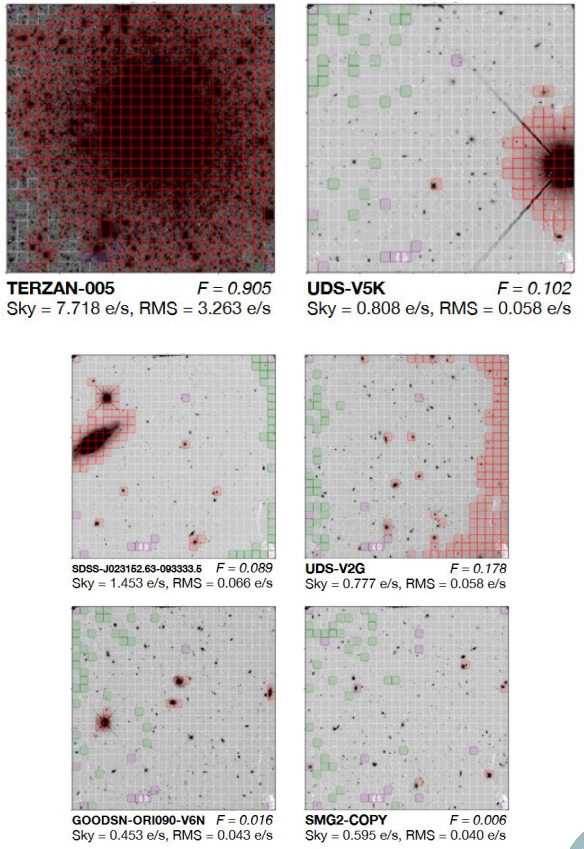
- Fig.9 from Windhorst et al. (2022)
- Top plot shows two models: orbital noon (orange) and orbital night (blue).
    a. The noon shows a pronounced increased sky measurement due to Earth-shine compared to the night model.
- Bottom plot shows two more: the orange model (telescope pointed closer to Earth) shows an increased sky measurement due to Earth-shine compared to the blue model (pointed far from Earth).
    a. Caddy et al. (2022) also showed a noticeable decrease in sky surface brightness measurements at all limb angles on the night side.





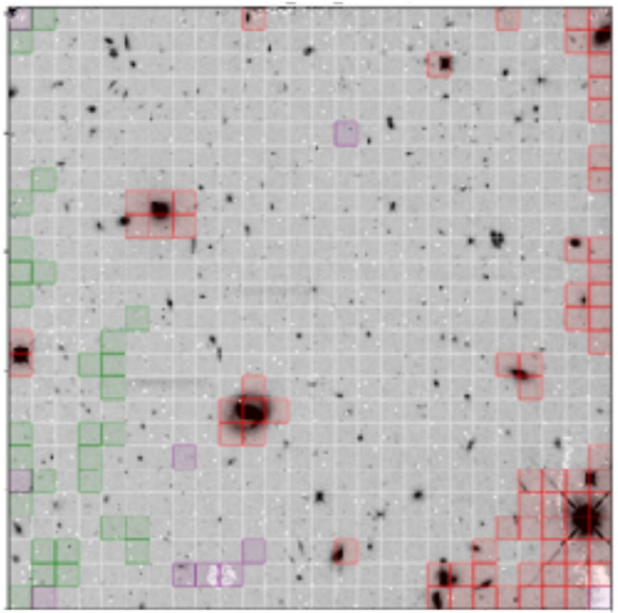
Data

- The dataset used for this research is a subset of the SKYSURF data, which was obtained from the WFC3 camera on the HST.
- Not all images in the HST archive were used for SKYSURF and consequently this research, as some images were rejected for various reasons.
- To avoid errors in the sky-value calculation, only a few large and bright objects were included in the retrieved images.
- The images were further filtered based on their sub-regions, and those with too many bright regions or bad pixel regions were rejected from the database.



Sky-Correction

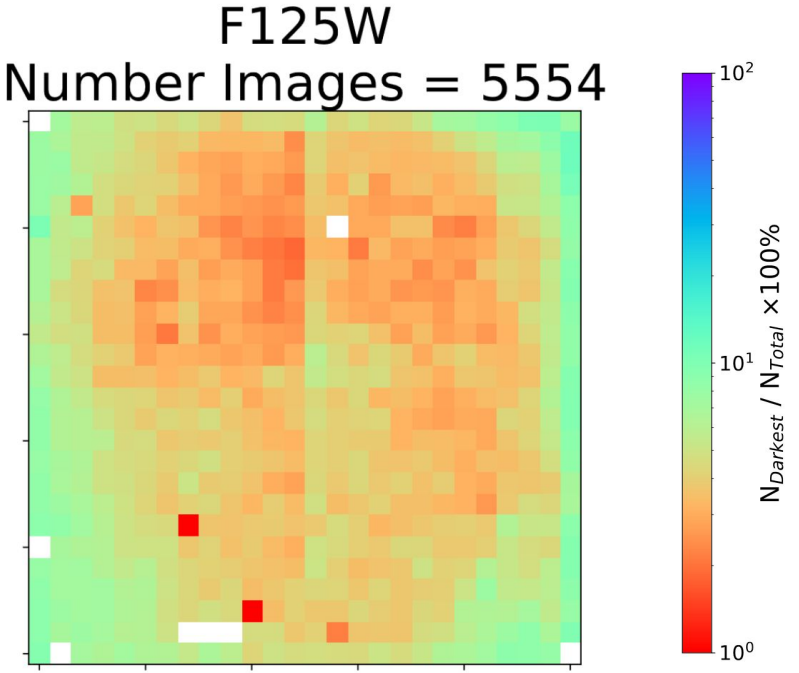
- Sky-Correction (SKYCOR) measures the correction to a sky-brightness value of an image.
- A more negative value of SKYCOR implies the measured sky value was corrected down.
- A more positive value implies the measured sky value was corrected up.



RXJ1532-WFC3PAR1 *F = 0.104*
Sky = 0.492 e/s, RMS = 0.040 e/s

SKYCOR Calculation

- WFC3IR doesn't have a mechanical shutter, so integration times are determined purely electronically.
- SKYCOR is calculated as the difference between the exposure sky value and the read sky value.
- Read sky value is obtained from breaking the image into sections and aggressively sigma clipping the pixel values in each box.
- The image was sourced from O'Brien *et al.* (2023).



SKYCOR Variable

- SKYCOR variable is sensitive to quickly changing parts of the background, like Earth-shine and dark current.

- Earth-shine is the most significant factor.

- Contamination from nearby bright sources and thermal emission from the telescope could also introduce errors.

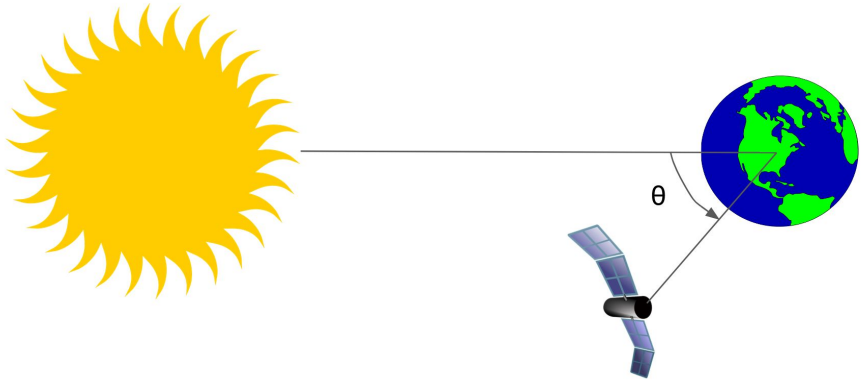
SKYCOR Modeling

- Since Earth-shine is the only factor that changes quickly, the change in background can be modeled accurately using the SKYCOR variable.

- Modeling the background is difficult due to many factors contributing to the overall background level.

Hubble-Sun Right Ascension

- Right ascension is the angular distance of an object along the celestial equator
- Measured eastward from the vernal equinox, the point where the ecliptic and celestial equator intersect
- By comparing the RA of Hubble and that of the Sun, we can deduce the orbital position of HST during a particular exposure
- HST-Sun RA difference of 0 means HST is directly between the Earth and the Sun in its orbit, while 180 means HST is completely opposite of the Sun



Appearance of Earth's Limb

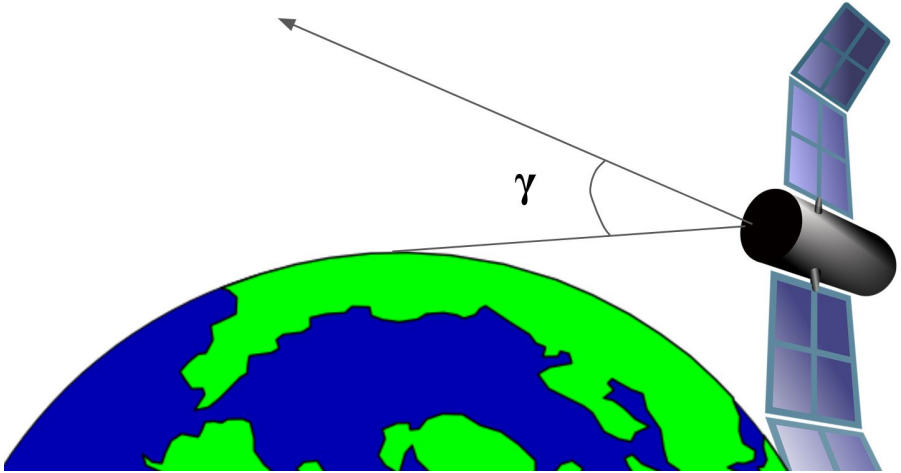
- The Earth's limb refers to the edge or boundary of the Earth as seen from space.
- The Earth's limb is where the planet's atmosphere meets outer space and marks the outer limit of the Earth's gravitational influence.
- The appearance of the Earth's limb varies depending on the observer's location and the angle of the Sun.
- When the Sun is directly behind the Earth, the limb appears as a bright.
- When the Sun is at a different angle, the Earth's limb can appear dark.

Appearance of Earth's Limb

Image source: NASA

Diagram of Earth Limb Angle

- Earth Limb Angle (ELA) and its relationship with the pointing vector of HST's aperture.
- The angle γ represents the angle between the pointing vector of HST's aperture and a line that goes from the center of the aperture to the edge of the Earth's limb.

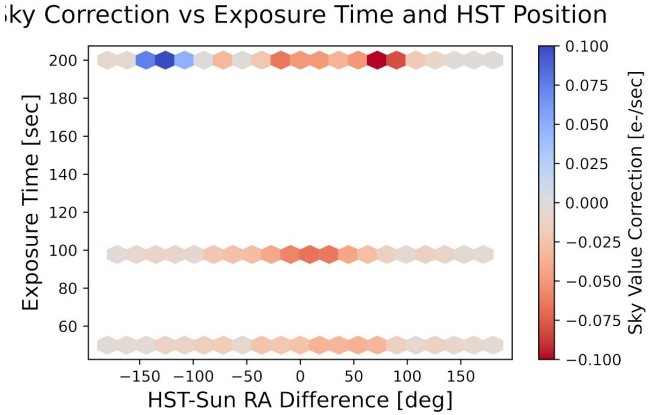


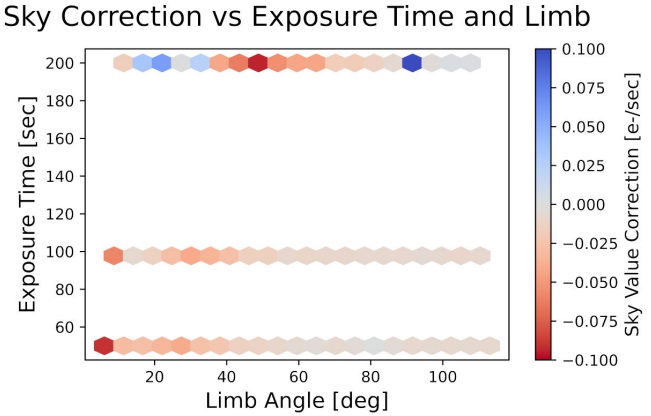
Initial Filtering Algorithm

- Two-step approach for filtering and matching data files
- Elimination of exposures with duration less than 50 seconds
- Matching of remaining FIT files with their corresponding Jitter file extension
- Removal of unmatched images from final data set
- 42,254 exposure readouts passed through this initial algorithm

Further Filtering

- Need for further filtering to eliminate erroneous exposures
- Removal of exposures with readout times greater than or less than 100 sec due to higher frequency of anomalous visits
- Anomalous effects apparent in the first few reads of a visit potentially due to the detector
- Separation of data into exposures taken on day and night side of Earth
- Separation based on HST-Sun RA angular difference values of +67 deg and −67 deg





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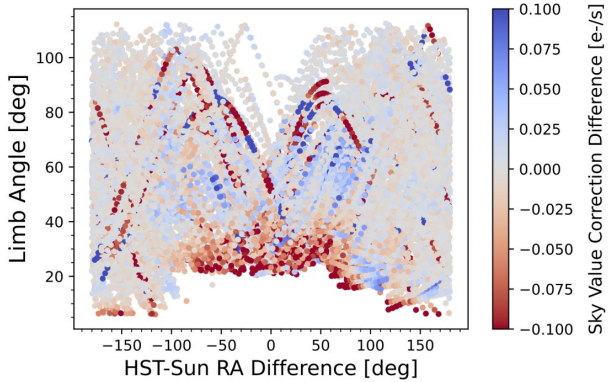
F125W Observed Sky Correction Change 50sec



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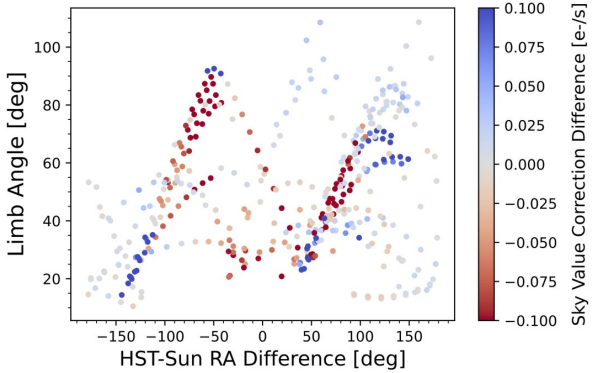

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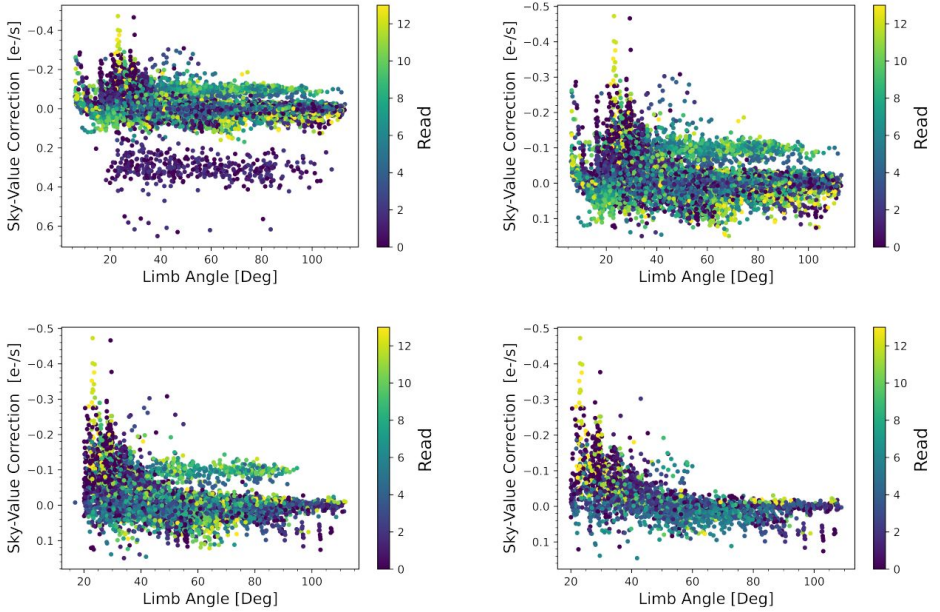

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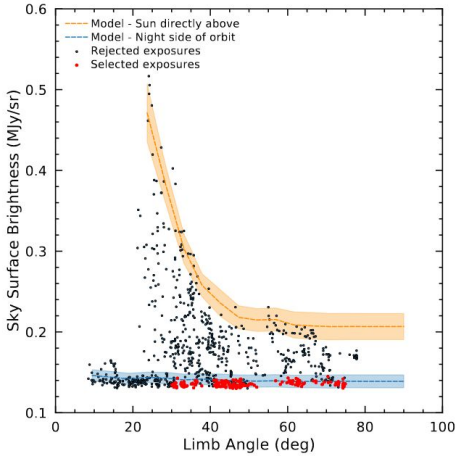
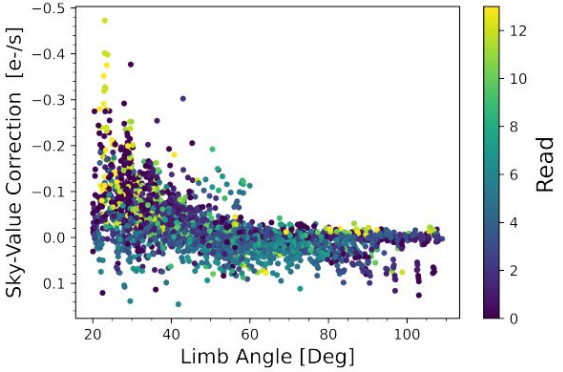


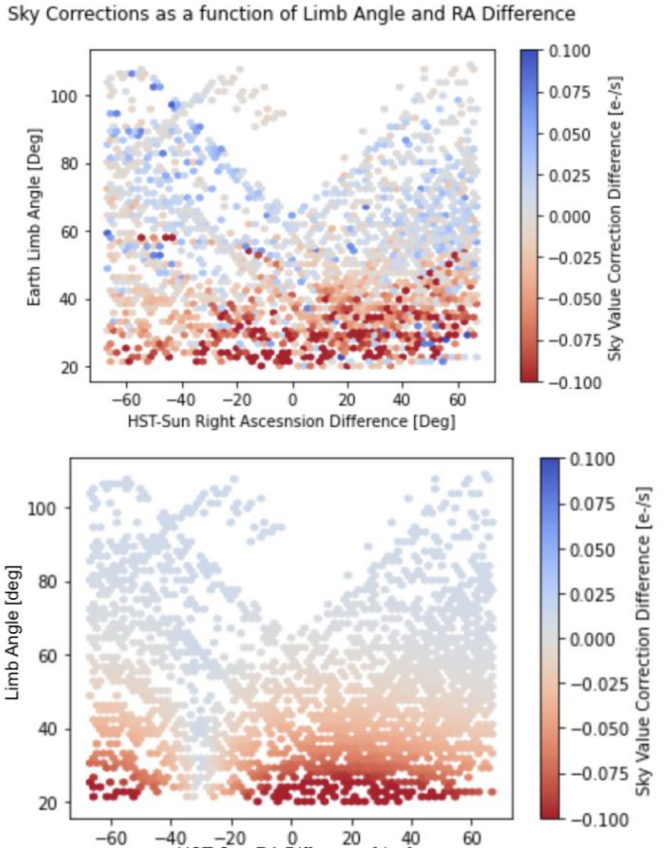


Final Data Set

- Final data set consisting of 15,479 readouts after heavy filtering
- Confidence in results due to large enough data set
- The 200 and 50 sec integration times show more abnormalities than 100 sec likely due to other effects beyond earth-shine bias
- 200 sec exposures seem especially prone to additional effects that are not yet fully understood

Introduction to Models

- The original model was assumed to be an inverse exponential function with respect to limb angle and HST-Sun RA difference.
- This model was not flexible enough to capture the earth-shine effect in detail but did work well on the dayside of HST's orbit.



Introduction to Models

- To fine-tune the model, trigonometric functions were added to capture the effect of HST's orbital position and pointing vector on the amount of light in the column of view due to earth-shine photons.
- HST-RA difference was selected to be a cosine term
    a. Maximum at 0 deg (HST directly between the Sun and Earth)
    b. Minimum at 180 deg (HST directly opposite from Sun compared to Earth)
- Limb Angle was chosen to be a cos^2 term
    a. Maximum at 0 deg (looking directly at limb)
    b. Minimum at 90 deg (pointing directly perpendicular to the limb and Earth’s surface)
    c. All limb values will be between 0 deg and 90 deg

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The Model Function

- The model function is the result of fine-tuning the original model to capture the earth-shine effect in detail.
- The fit parameters for this function were found using SciPy's optimization tool and are given in Table 3.1.

$$\left(a + b\cos(c(\theta_{RA} + d)) + f\cos^2(g(\gamma_L + h))\right) * e^{-(j+k|\theta_{RA}+d|+m(\gamma_L+h))}$$

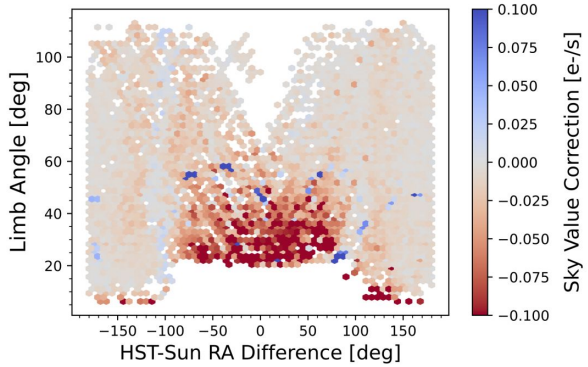
Fit Parameter	Value
a	-1.002
b	1.076
c	-4.896e-7
d	-1.060e+1
f	-1.325e-1

Fit Parameter	Value
g	-1.247
h	-1.888+1
j	-9.310e-1
k	1.082
m	1.552

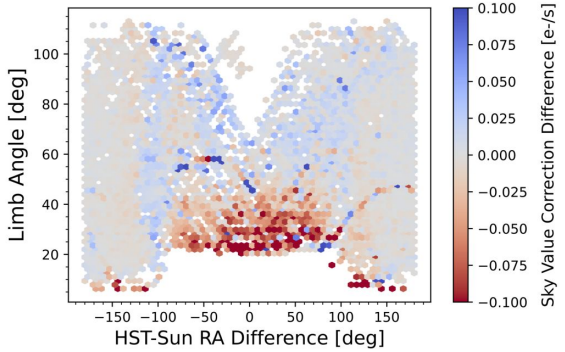
Observed Sky Corrections and Changes

- Top: Observed SKYCOR values for each exposure
- Bottom: Difference between SKYCOR value for an individual read and the average for the exposure.
- SKYCOR values tend to be corrected more the closer to the Earth-exclusion zone
- Indicates Earth-shine effect at work

F125W Observed Sky Corrections

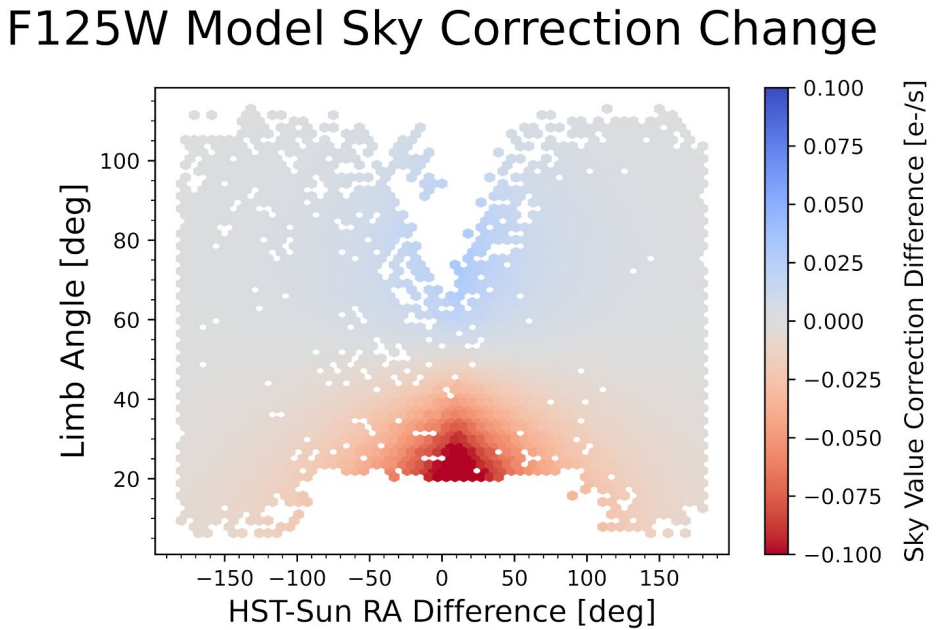


F125W Observed Sky Correction Change



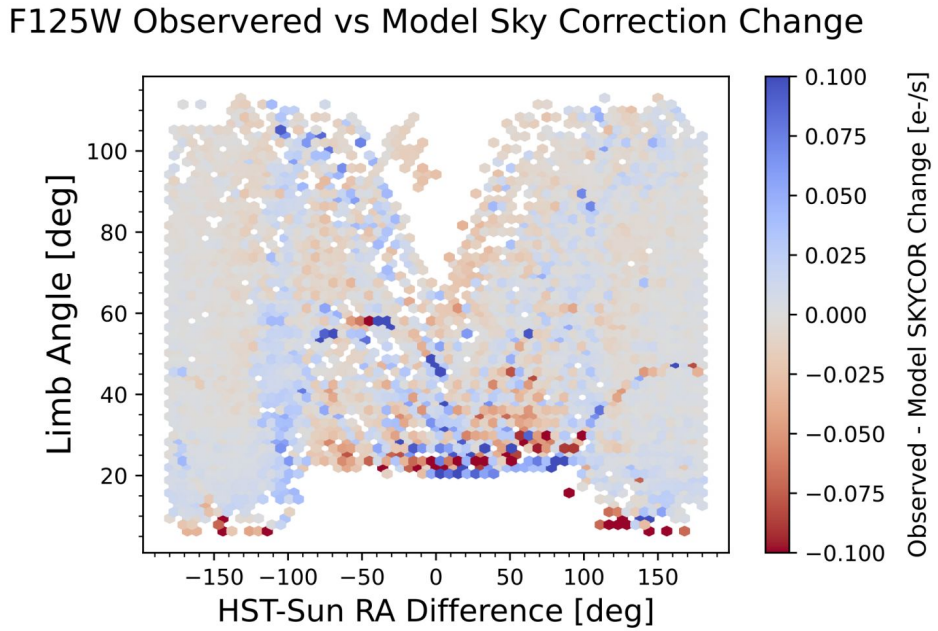
Modeled Changes in Sky Correction

- Prediction of high negative SKYCOR change on the day side of HST's orbit and at low limb angles
- Effect turns over and becomes more and more positive at high limb angles on the day side
- Earth-shine influence minimal on the night side of Earth and more apparent closer to the Earth-exclusion zone



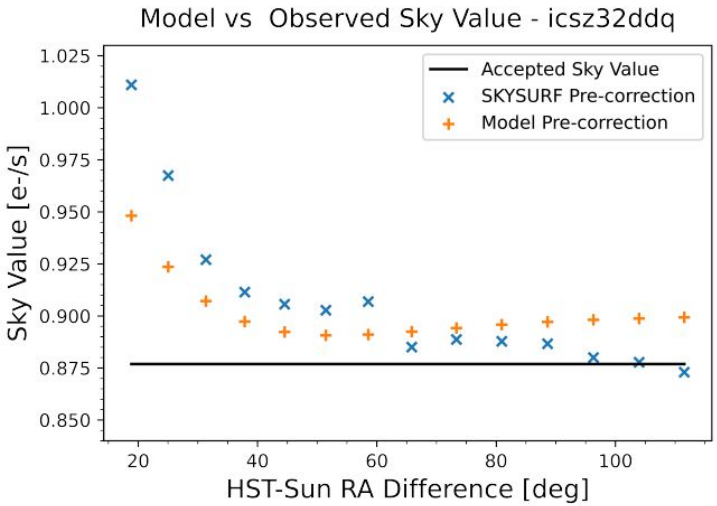
Observed vs Model SKYCOR Change

- Grey indicates accuracy of model to data.
- More positive/blue shades suggest model predicts lower impact on SKYCOR values than observational data indicates.
- Model generally predicts lower impact on SKYCOR values than appears in observational data.
- Underestimation leaves room for future improvements in Earth-shine model and for other factors.



Model vs Data for Randomly Selected Visits

- Model does a good job at modeling SKYSURF pre-correction sky measurements
- Good job at modeling sky-corrections
- Effect could be due to impact of dark currents as telescope moves from day to night side of Earth



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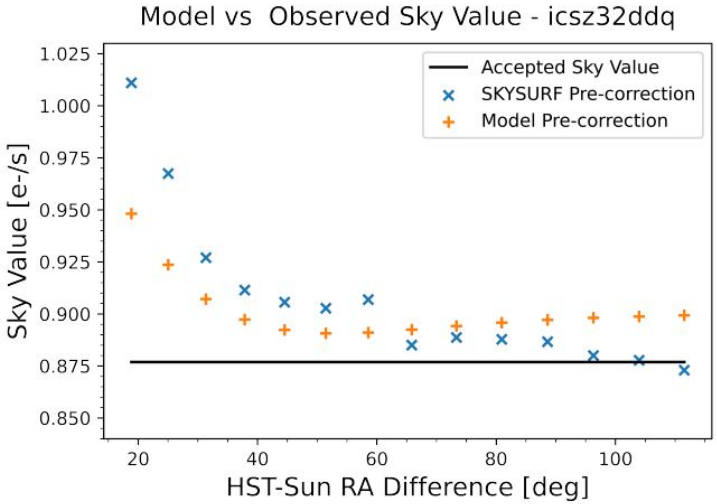

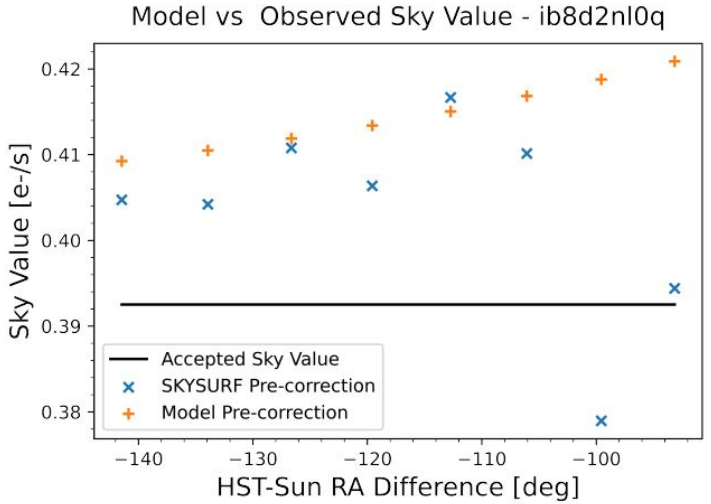

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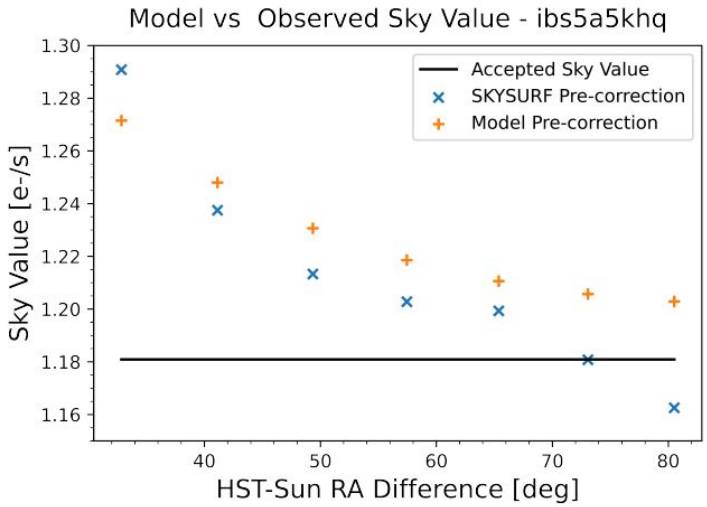

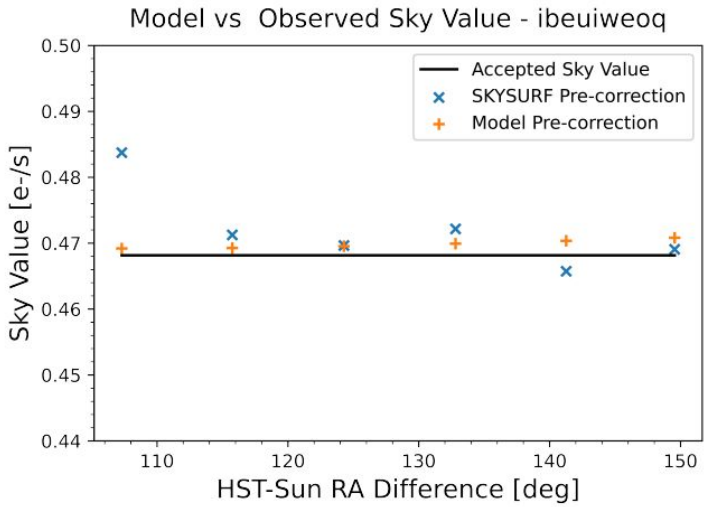

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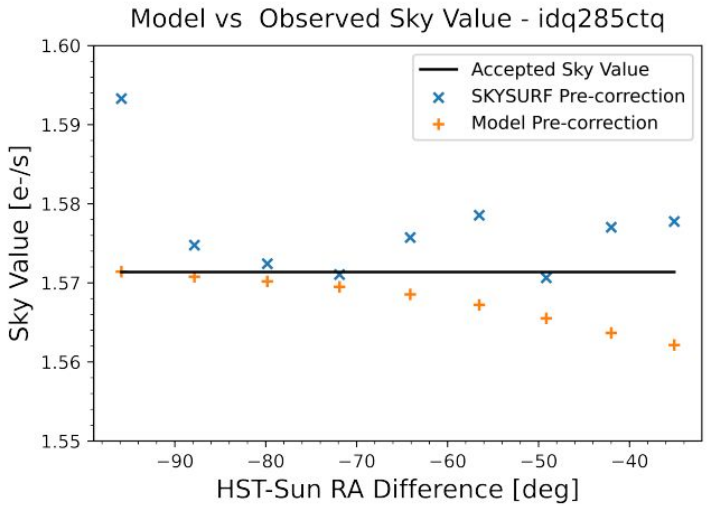
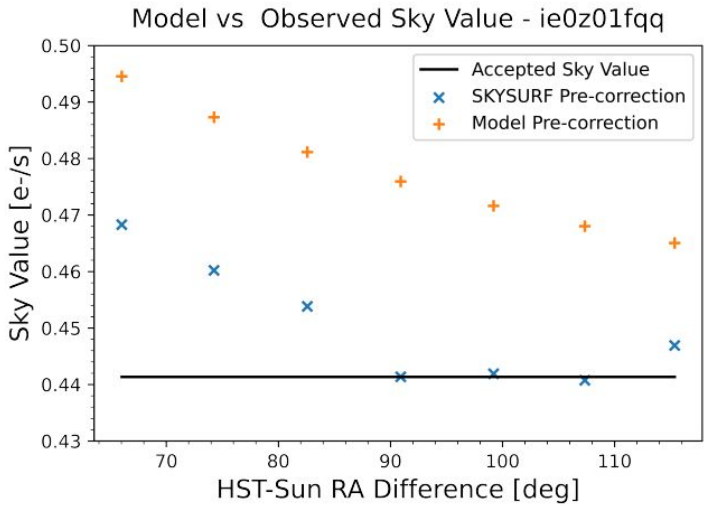




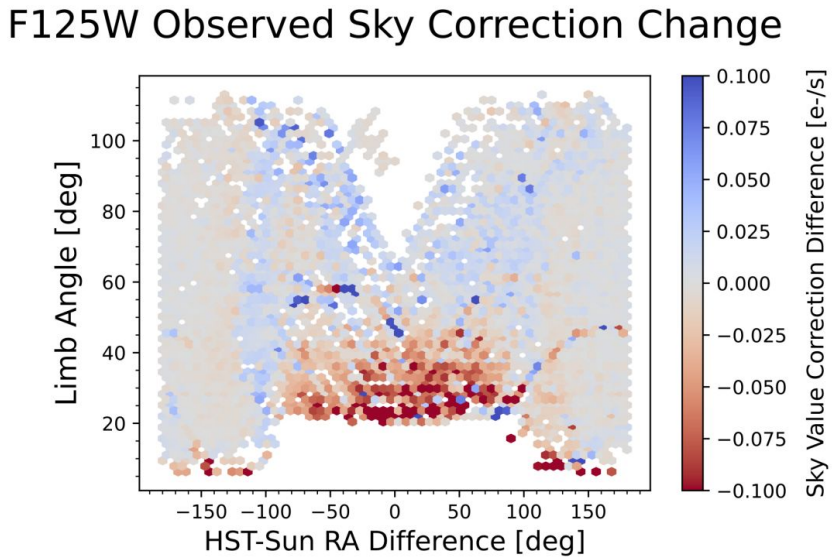
Model Conclusions

- Model predicts high negative SKYCOR change in a specific region on the day side of HST's orbit and at low limb angles, consistent with observational data

- Underestimation of model leaves room for future improvements in Earth-shine model and understanding of other factors beyond Earth-shine

Limitations and Future Directions

- Streaks of consistent SKYCOR and SKYCOR change (-100 deg and +100 deg) could be due to dark currents in the IR detector
- More investigation required to determine cause
- Room for future improvements in Earth-shine model and for understanding other factors beyond Earth-shine



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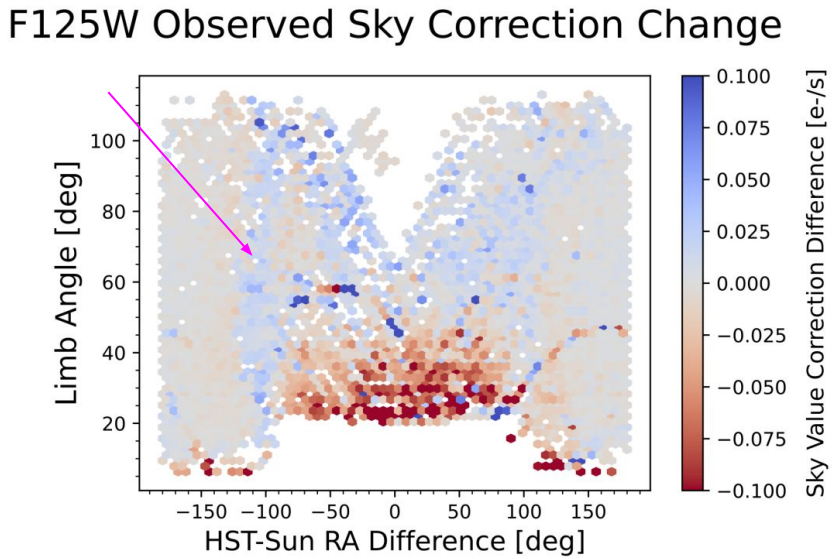

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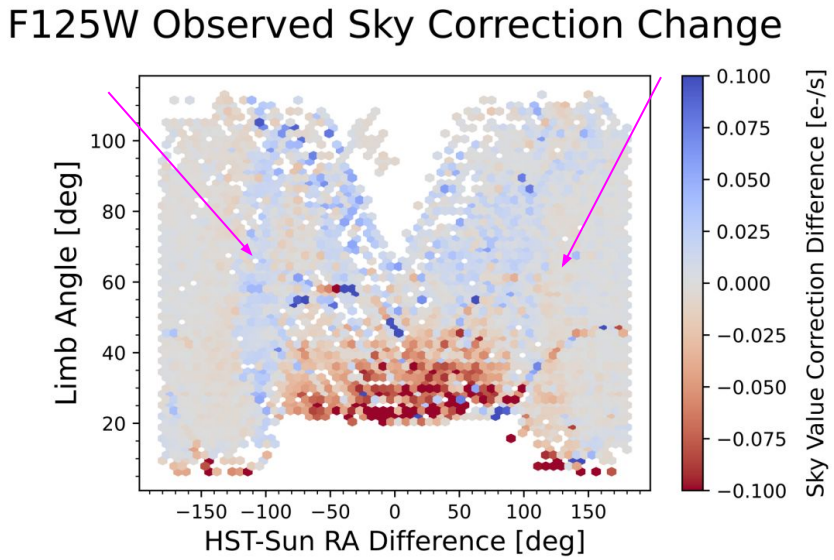

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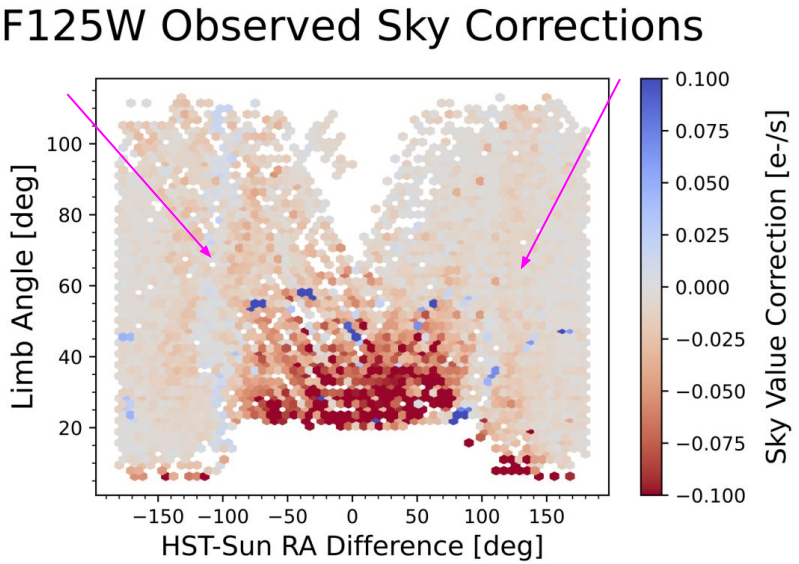
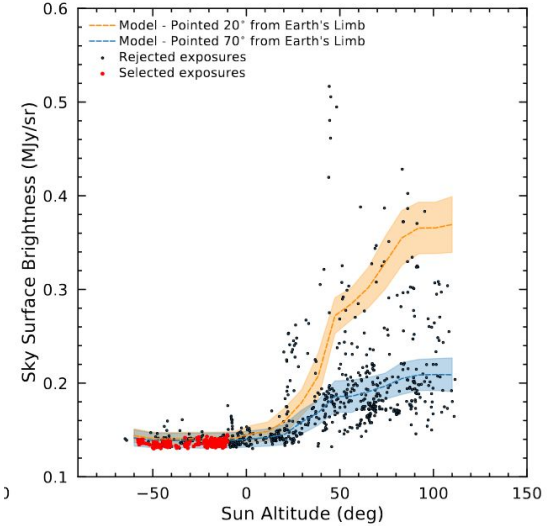
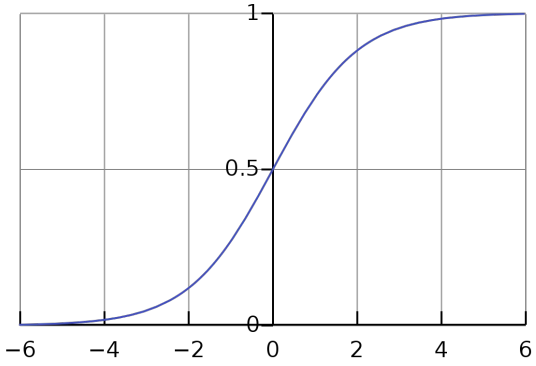


Steps to Improve Model Performance

- Overall, the model estimates the effect of Earth-shine on SKYSURF data well.
- Modeling a logistic relationship instead of an exponential can provide a more spread-out function of HST-Sun RA difference.
- This logistic function can better match the sun altitude model from Fig.9 from Windhorst et al. (2022).
- Including a function that takes into account the exposure time of the image can further improve the model fit.





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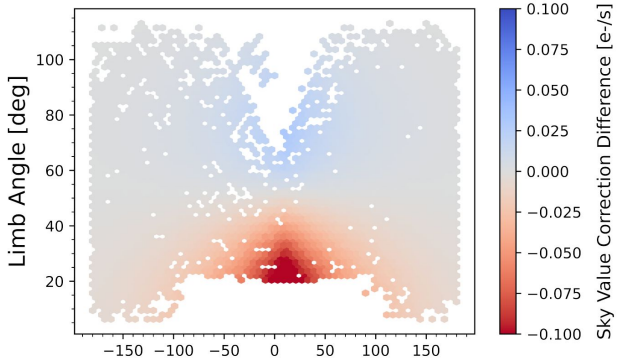
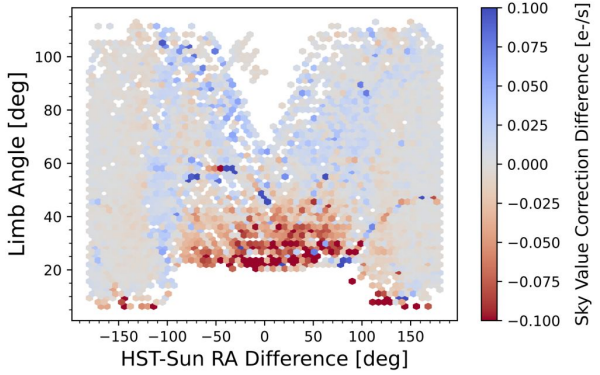
F125W Model Sky Correction Change

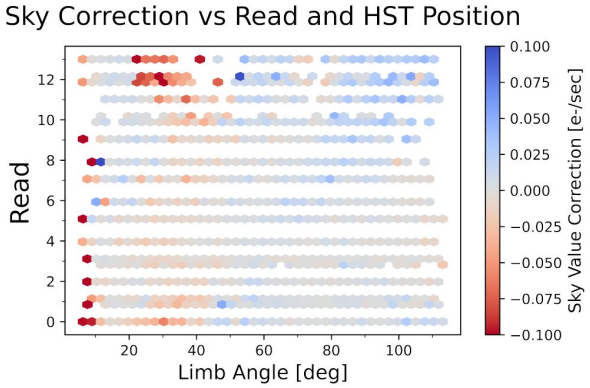


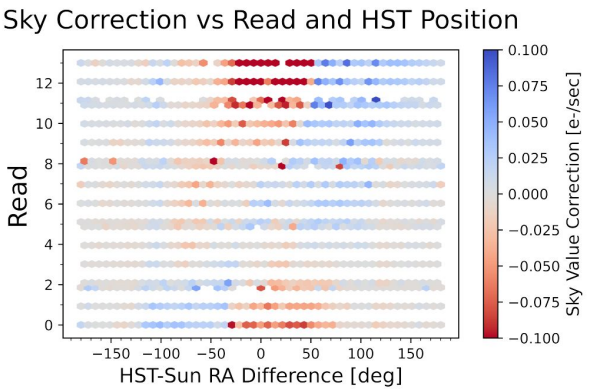
F125W Observed Sky Correction Change



Relationship Between SKYCOR and Read

- There is a relationship between SKYCOR and which read an exposure is in a certain set of exposures.
- Earliest and the latest reads tend to have the most stark change of SKYCOR values.
- This could be due to:
  a. Exposures typically starting at approximately the same place in the orbit
  b. The IR detector utilizes non-destructive readouts.





Utilizing Weather Satellites for Earth-shine

- Including the influence of what is beneath HST utilizing GPS and weather satellite data can improve the model further.
- Caddy et al. (2022) utilizes the CERES satellite and CERES shortwave 0.3 − 5μm filter to estimate Earth-shine for HST filter F850LP in the GOODS North field.
- Other weather satellites that operate in the wavelength analogous to F125W that can be utilized for this include GOES-R, Himawari 8/9, and Fengyun-4A/B.
    a. Bonus, these satellites are geosynchronous so they can provide both day and night data.

Thank You