The CCOR Operational Coronagraph Series for Space Weather Forecast

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Abstract

The National Oceanic and Atmospheric Administration (NOAA) funded the U.S. Naval Research Laboratory to develop, build and test the CCOR series of operational solar coronagraphs.

CCOR stands for Compact Coronagraph. It is a series of white-light solar coronagraphs that are dedicated to performing space weather forecasts. It will be used by NOAA's Space Weather Prediction Center (SWPC) to detect Coronal Mass Ejections, determine their trajectory, mass, and speed, in the goal of predicting any geo-effective impact at Earth, or elsewhere in the solar system. The CCOR-1 data will be made publicly available by NOAA's National Center for Environmental Information (NCEI) around April 2025.

The first CCOR, CCOR-1, is installed on the Solar Pointing Platform (SPP) of the Geostationary Operational Environmental Satellite series, GOES, iteration U. GOES-U was launched on June 25, 2024, and was soon renamed GOES-19 after it reached geostationary orbit. CCOR-2 is installed on the SWFO-L1 spacecraft, scheduled for launch in Late 2025, and targeted to be in a Lissajous orbit around the L1 Lagrange point. Finally, a CCOR-3 is planned to be on board the European Space Agency Vigil spacecraft that will orbit around the L5 Lagrange point, scheduled for launch in 2031.

The first lights of CCOR-1 were captured on September 19, 2024, and images have been steadily flowing since then. In this presentation, we provide a short description of the CCOR instrument design and specifications, as well as a comparison of the specifications with existing coronagraphs such as LASCO and PUNCH NFI. We present a sample of movies of CME events captured up until these days. We discuss the Earth shine stray-light, a limitation of the CCOR-1 instrument due to the GOES-19 geostationary orbit. Finally, we present a possible synergy plan between CCOR and PUNCH, for cross-calibration and science observations.

Acknowledgements: This work is sponsored by NOAA.

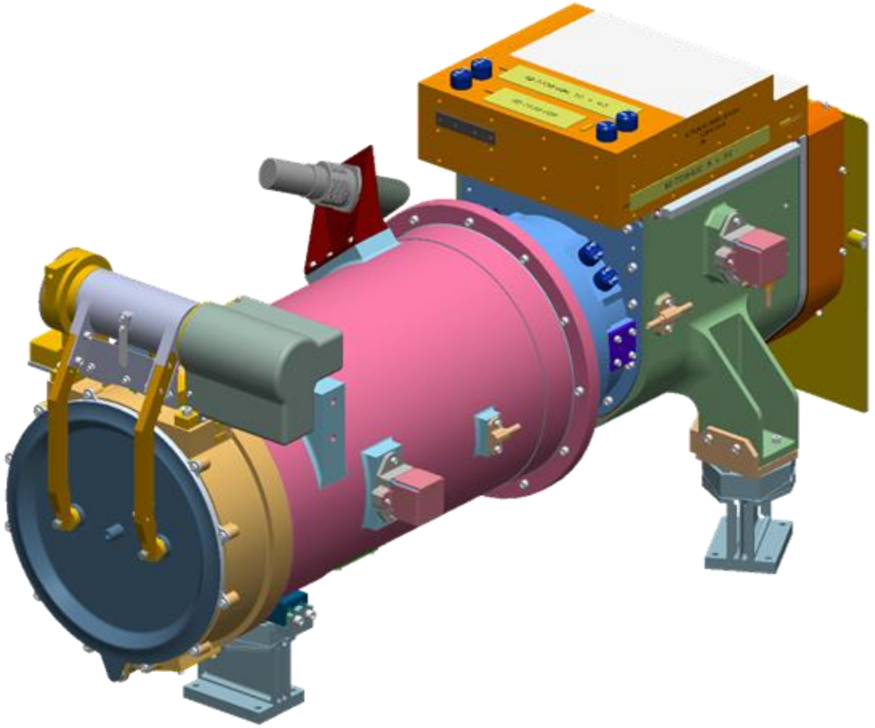
Overview

- **What is CCOR**
- **Movie time**
- **GOES spacecraft orbit: Earth transits and induced stray-light**
- **CCOR Stray-Light**
- **Post Launch Test status**

CCOR in a Nutshell

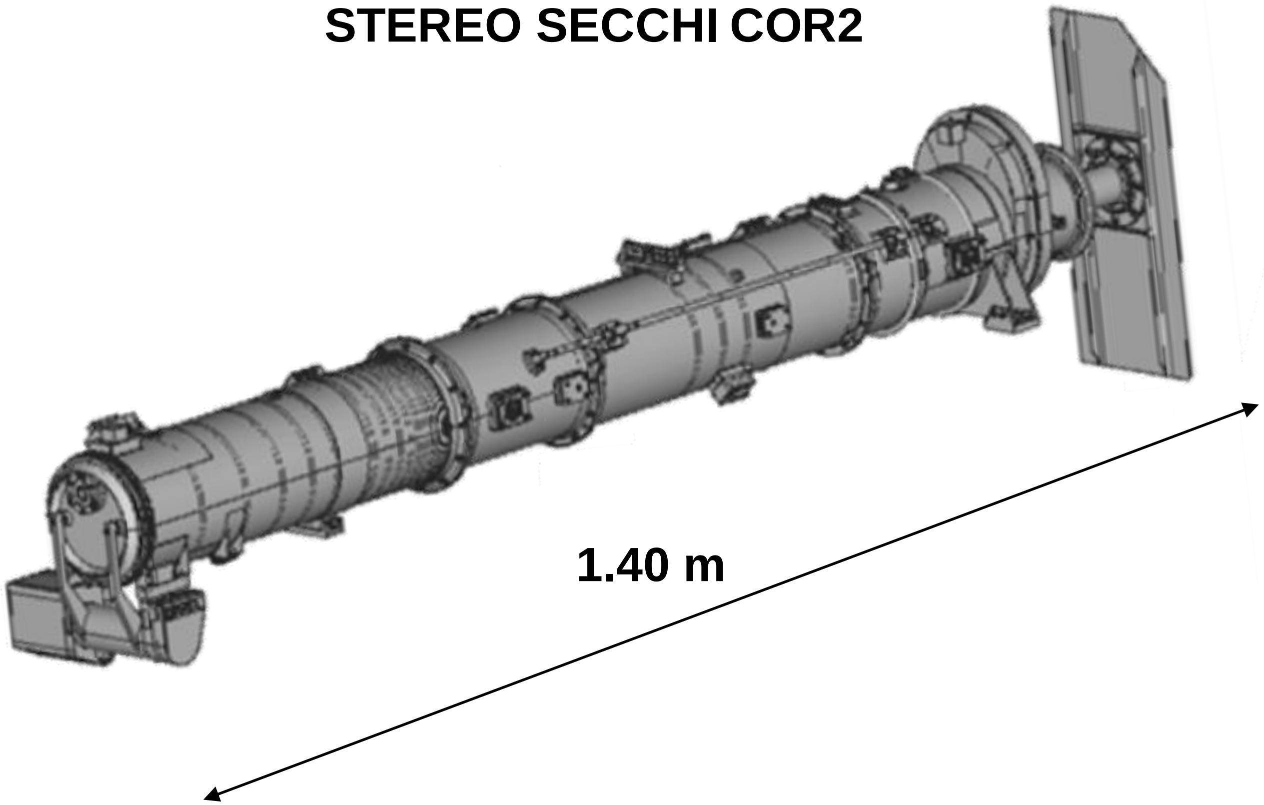
- CCOR is a series of space borne solar coronagraphs that will be operationally used by NOAA's Space Weather Prediction Center (SWPC) to monitor the corona activity, detect CMEs, and predict the Space Weather at Earth.
- Two CCORs were built, and a third one is in the making.
- CCOR-1: GOES-U; Launched: Jun 25, 2024
- CCOR-2: SWFO-L1; Launch: Sep 2025
- CCOR-3: ESA's VIGIL; 2031
- **The data is now made publicly available through NOAA's SWPC, NCEI websites, and NRL website.**
  - https://services.swpc.noaa.gov/products/ccor1/
  - https://www.ncei.noaa.gov/products/space-weather/swfo
  - https://ccor.nrl.navy.mil

CCOR-2 (SWFO-L1)

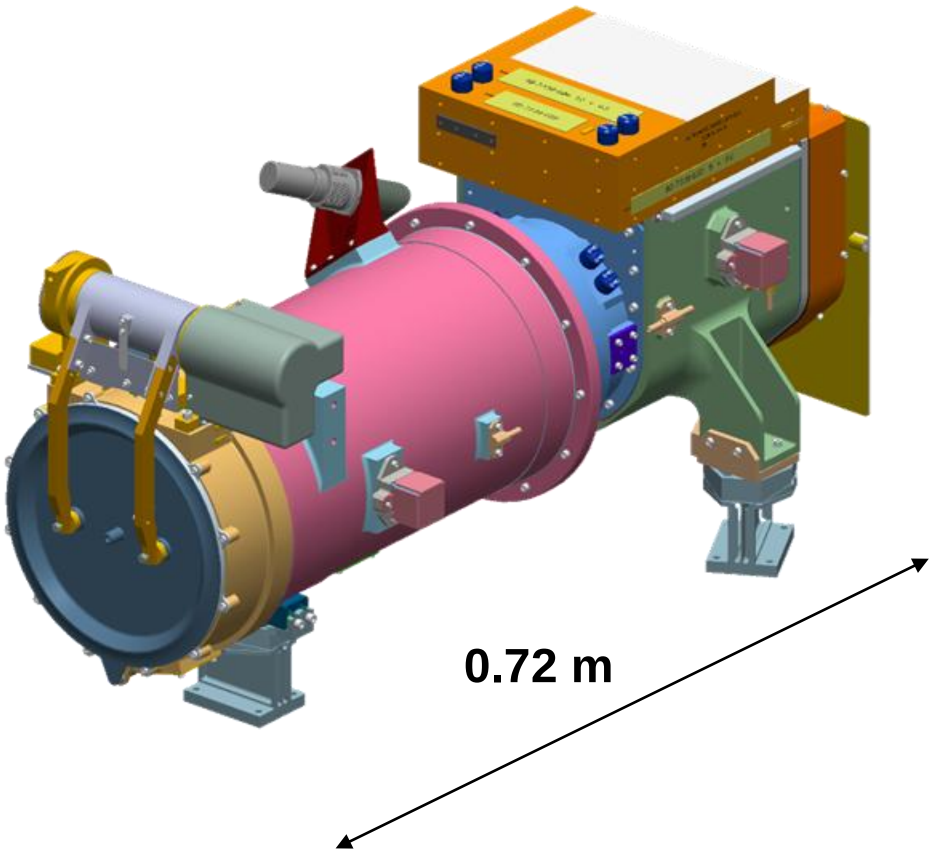


Lyot vs Compact Design

STEREO SECCHI COR2

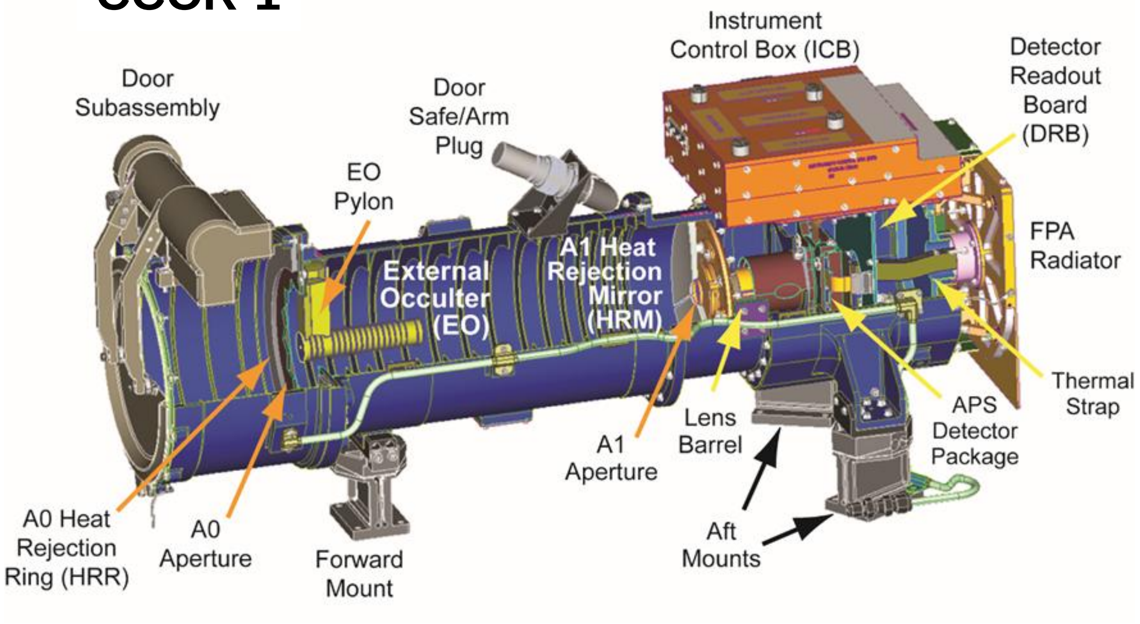


CCOR-2 (SWFO-L1)

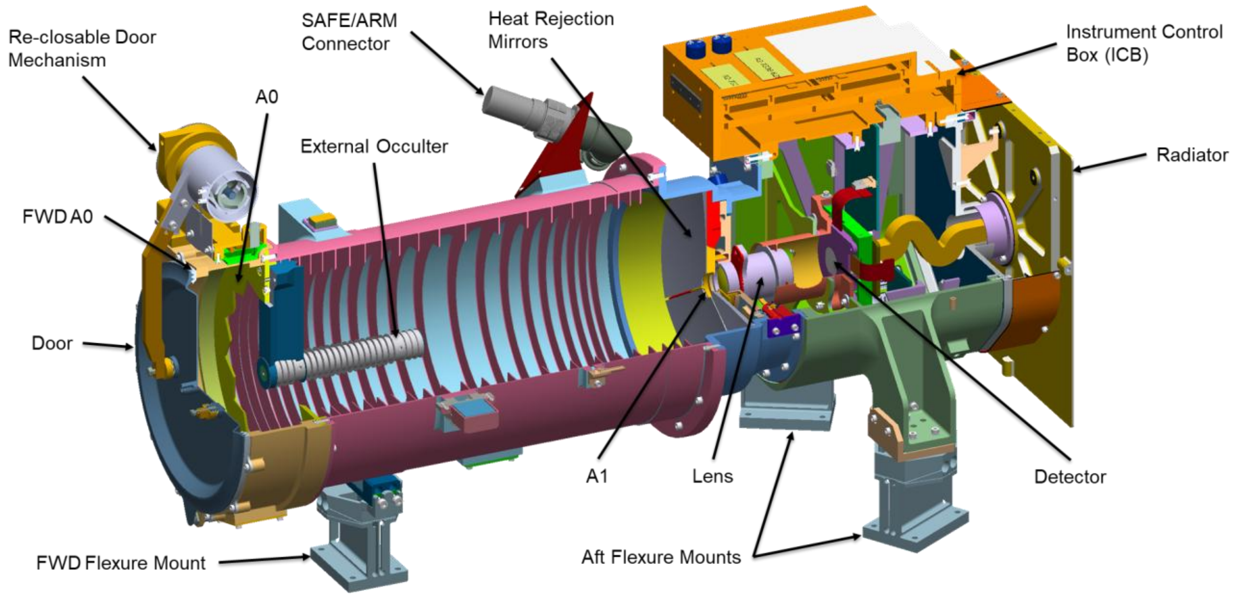


CCOR-1 vs CCOR-2

CCOR-1



CCOR-2



CCOR-1 versus CCOR-2 (and CCOR-3)

- Field-of-view (FOV): CCOR-2's larger FOV will provide more images of the fastest CME's ensuring they are well observed and enabling more accurate modeling
- Spatial Resolution: CCOR-2's larger FOV comes at the expense of spatial resolution
- GEO versus L1 orbit: **CCOR-1 experiences eclipses** that results in images with increased stray-light on 42% of the days of the year. CCOR-2 will not experience eclipses, but will likely not be able to image during certain observatory maneuvers (momentum dumps)

Present and Future Coronagraph Assets

Past/Present

Future

Instrument	FOV [Rsun]	Orbit	Cadence [min]	Launch	Sponsor	Spacecraft
LASCO C2 C3	2 – 30	L1	12	1995	NASA-ESA	SOHO
SECCHI COR-1	1.3 – 4	1AU, off the Sun Earth line		2006	NASA	STEREO
SECCHI COR-2	2 – 15		15	2006	NASA	STEREO
Metis	1.7 – 3	0.28 to 0.91AU		2020	ESA	Solar Orbiter
LST SCI	1.1 – 2.5	Sun-synch (720km)		2022	China	ASO-S (Kuafu-1)
VELC	1.05 – 3	L1		2023	ISRO (India)	Aditya
CCOR-1	**4.0 – 22**	**Earth, geosynch.**	**15**	**Jun 2024**	**NOAA**	**GOES-U**
CODEX	3 – 10	LEO (ISS)		2024	NASA	ISS
ASPIICS	1.08 – 3	LEO		2024	ESA	Proba-3
PUNCH NFI	6 – 32	LEO	8	Apr 2025	NASA	PUNCH
CCOR-2	**3.3 – 26**	**L1**	**15**	**Sep 2025**	**NOAA**	**SWFO-L1**
CCOR-3	3.3 – 26	L5	15	2031	NOAA	VIGIL (ESA)

Same as WISPR →

Reqt Title	CCOR-1	CCOR-2 and CCOR-3
Radial Scene Coverage	4.0 to 22 R_{sun} (actual)	3.3 to 26 R_{sun} (actual)
Image Spatial Resolution, Unbinned	≤ 54 arcsec > 10% MTF	≤ 70 arcsec with > 10% MTF
Detector	2048 x 1920 pixels APS	2048 x 1920 pixels APS
Image Cadence, Nominal Operations	15 min	15 min
Instrument Bandpass	450 to 750 nm	450 to 750 nm

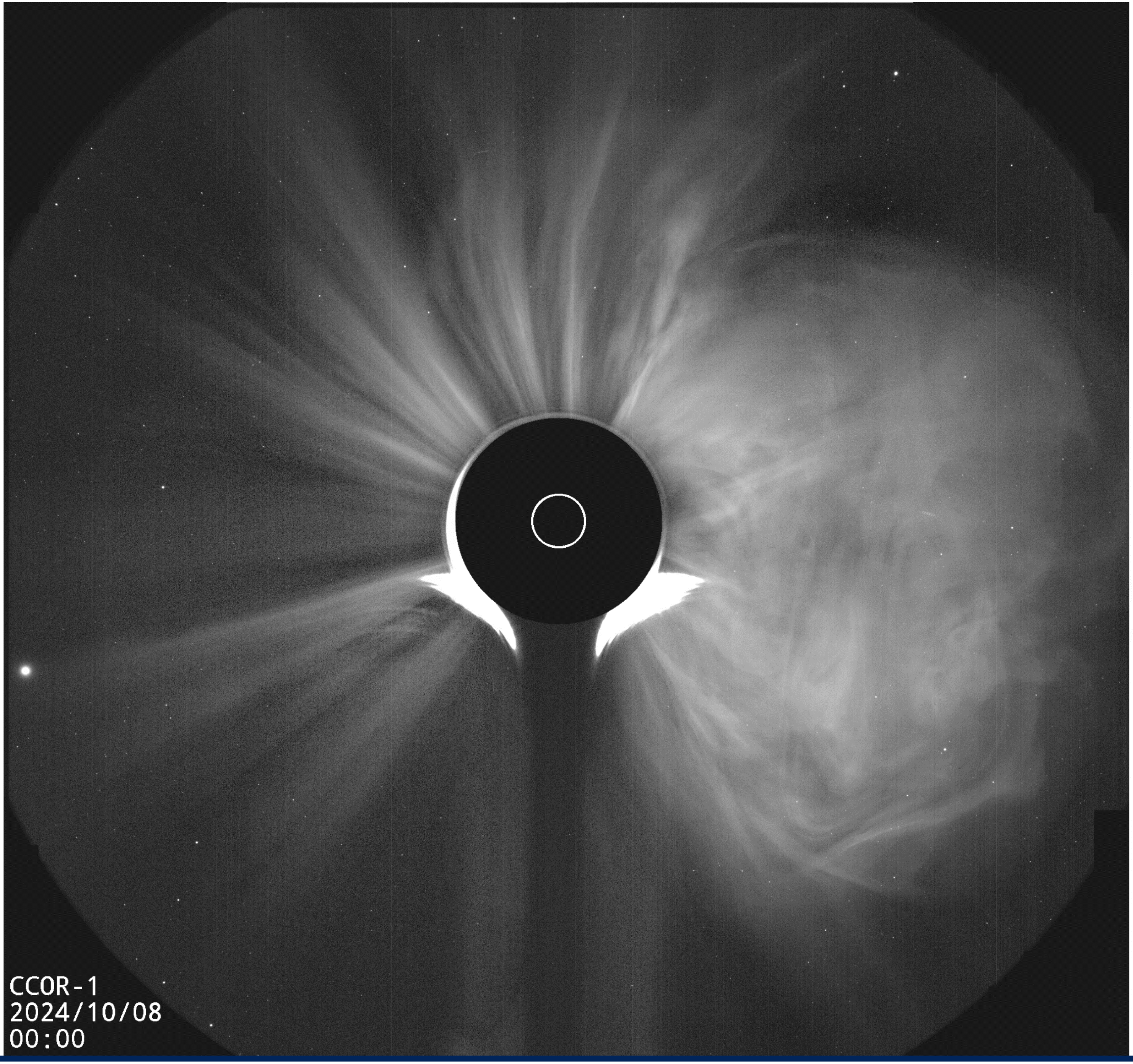
Comet TsuShinShan ATLAS

2024/10/08 11:00
- Change of temperature setpoint

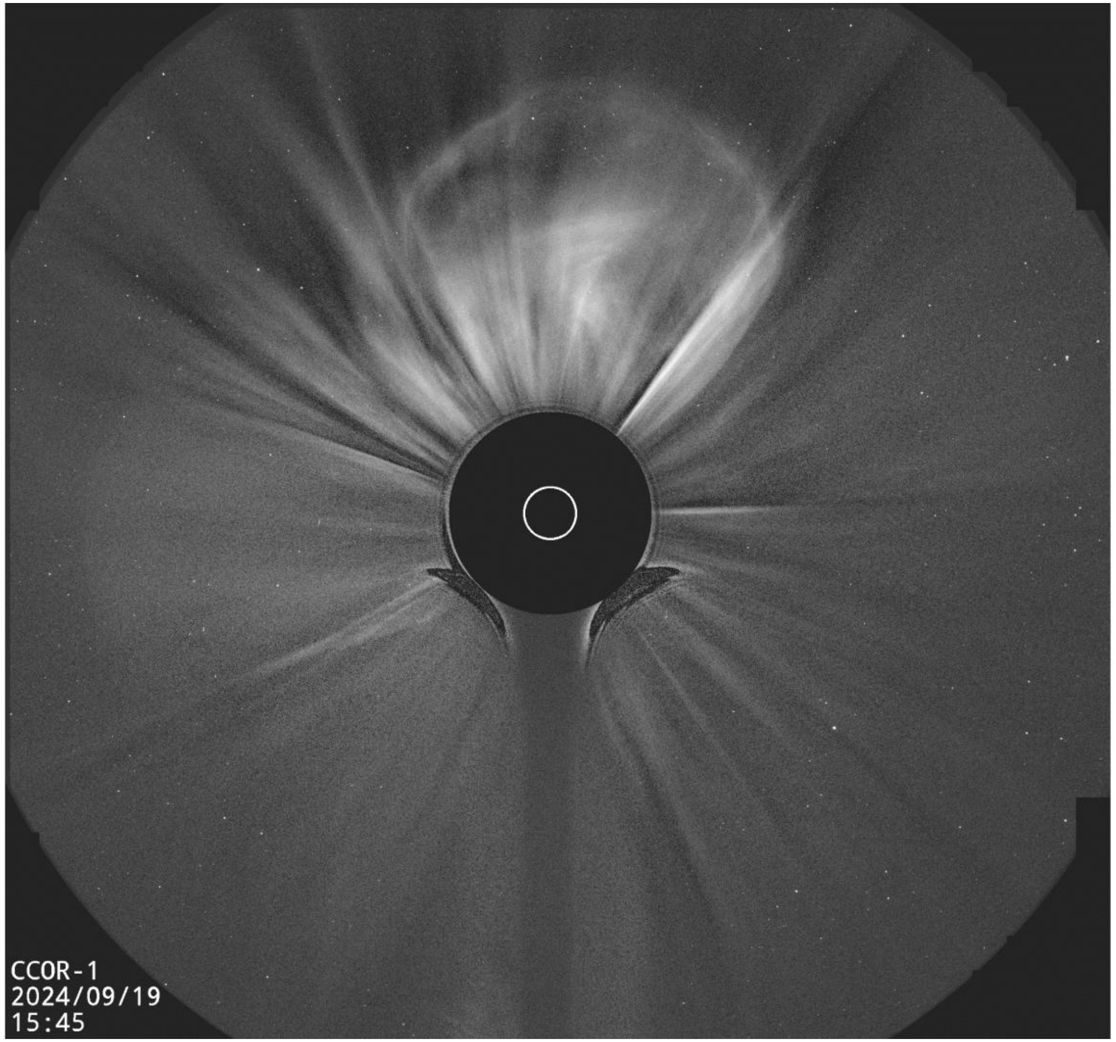
2024/10/13 18:30
- Change of Exposure time from 5s (avg 5) to 8.5s (avg 3)

Earth transit every day between 5:00 and 7:00 UT

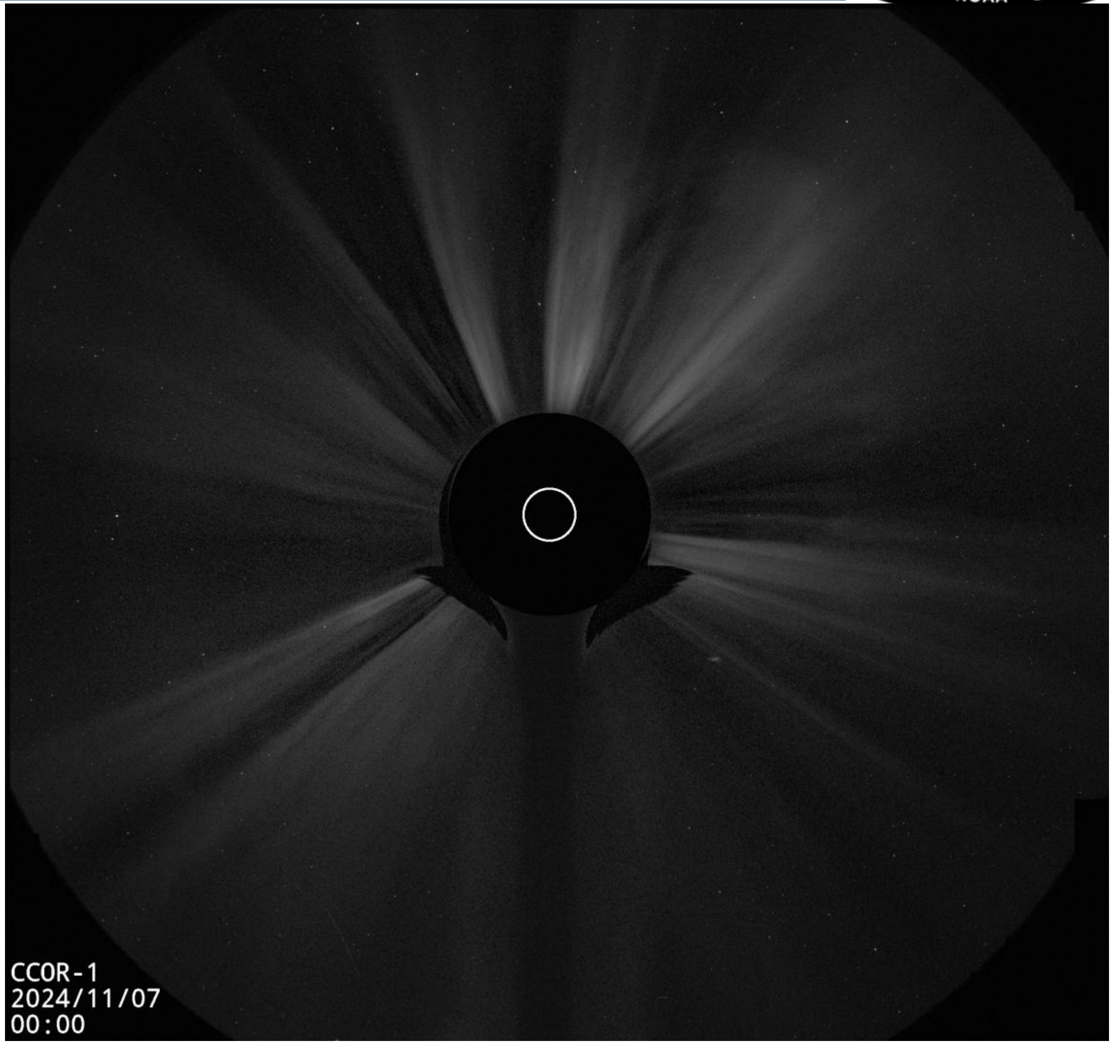
- **The fast halo CME *at 10/09 0230UT* caused the famous Oct. 2024 geomagnetic storm! (Oct. 11, 3rd strongest of 2024, min. Dst -335nT)**



More Movies

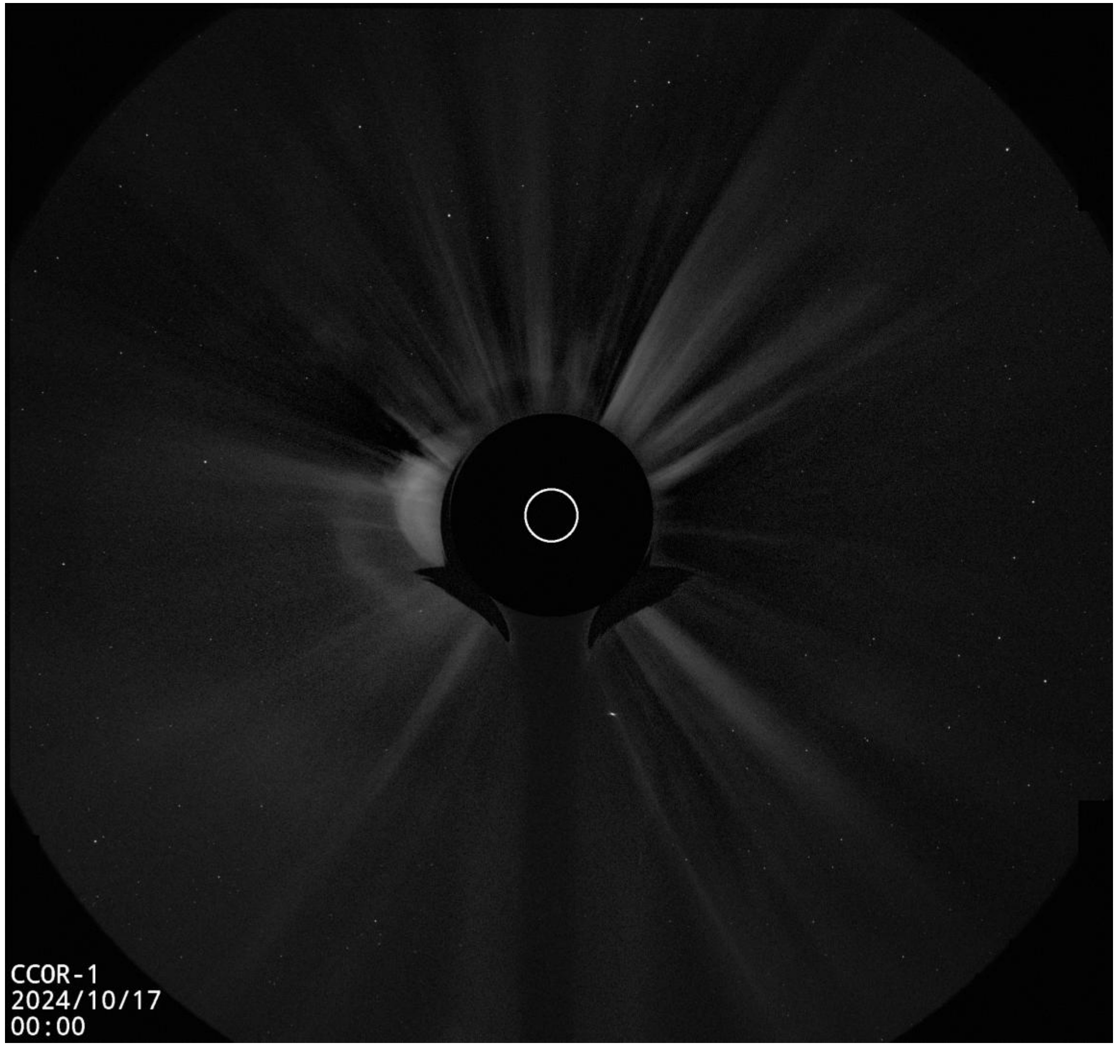


First Light

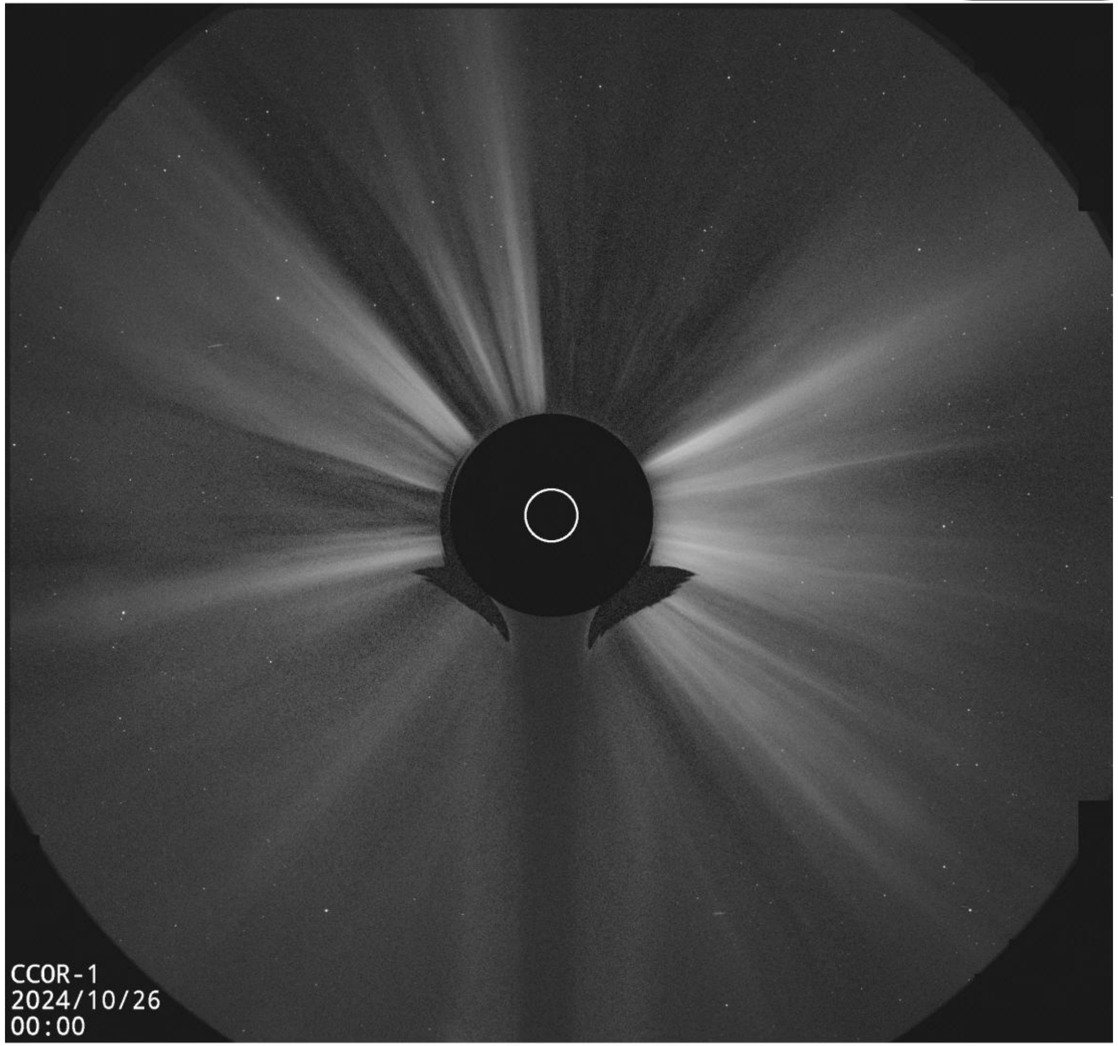


Filament Eruption

More Movies

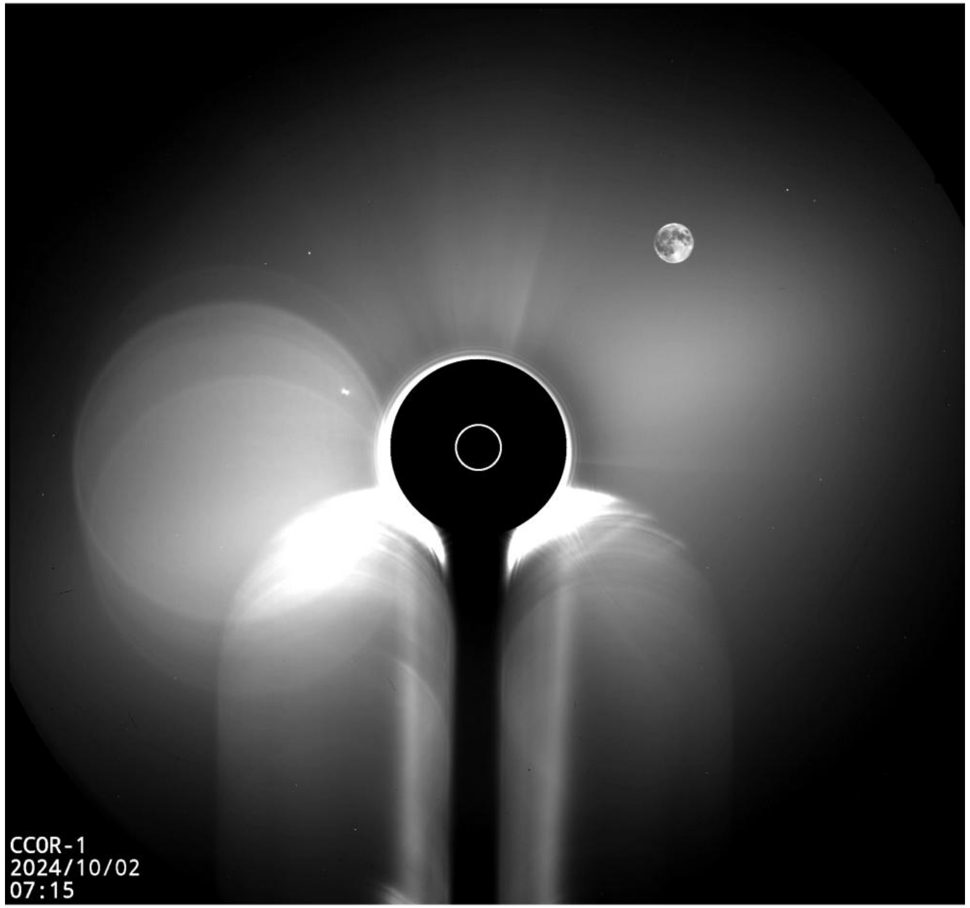


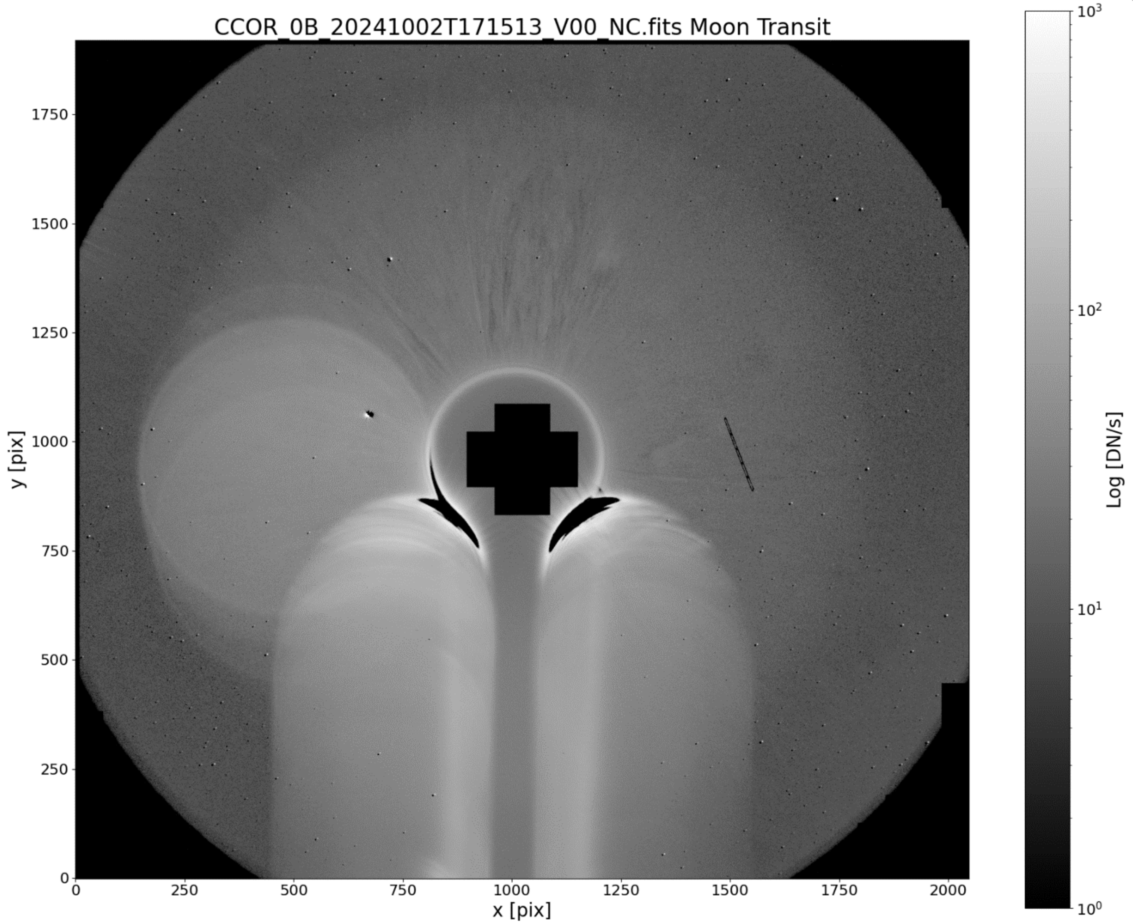
CME and Earth Transit



Halo and Comet ATLAS

Moon Transits and Partial Solar Eclipses



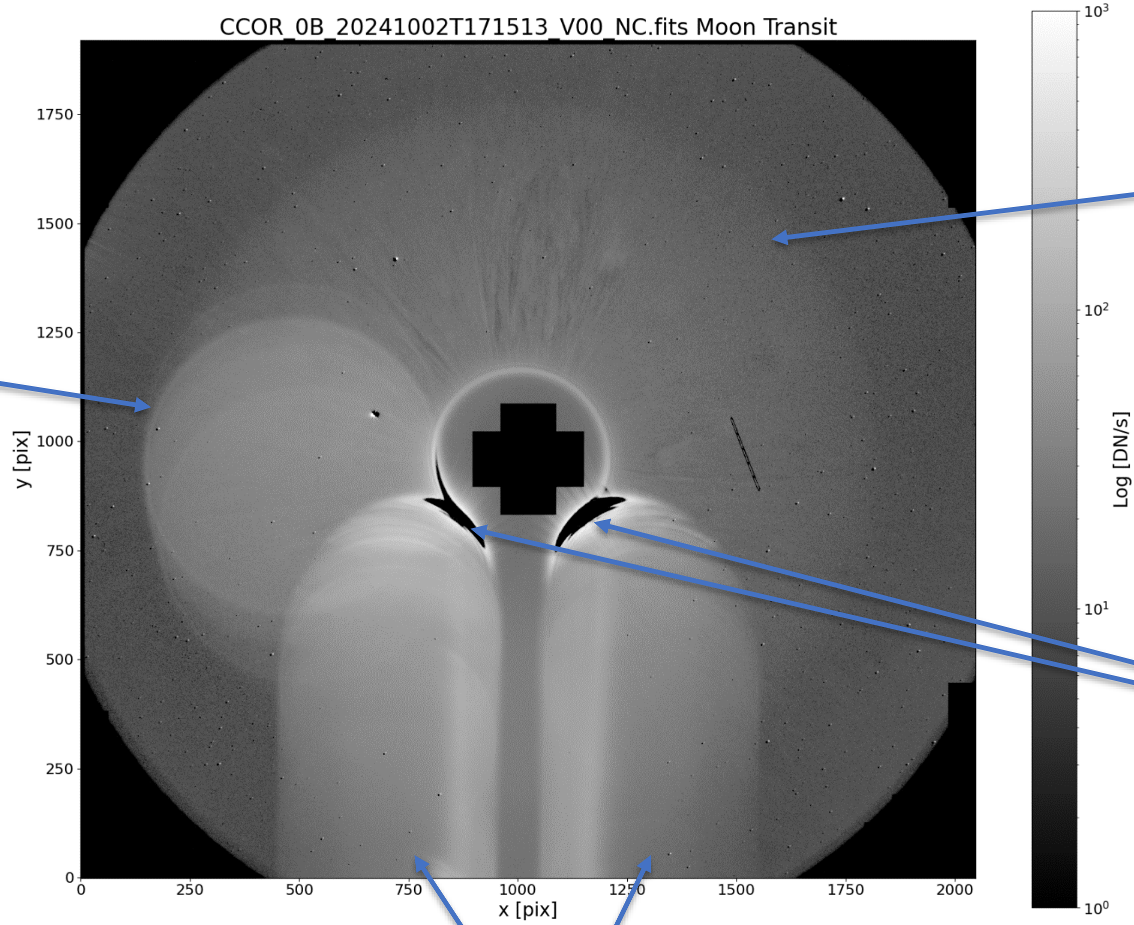


Partial eclipse at 17:15

- ➢ This allowed to directly measure the stray-light

Straight difference between post-eclipse (18:00 UT) and eclipse image. Need additional post processing but all the expected stray-light features are present.

Stray-Light Features



Circular halo due to the occulter

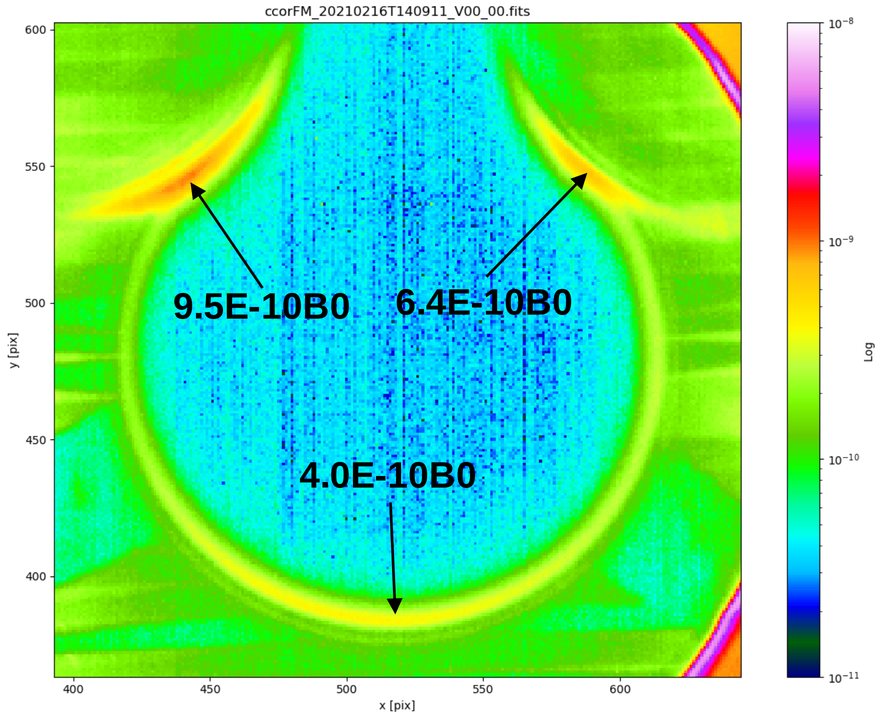
Default on the occulter (was observed during ground testing)

Diffraction saturation at the junction between the occulter and the pylon (See Next Slides)

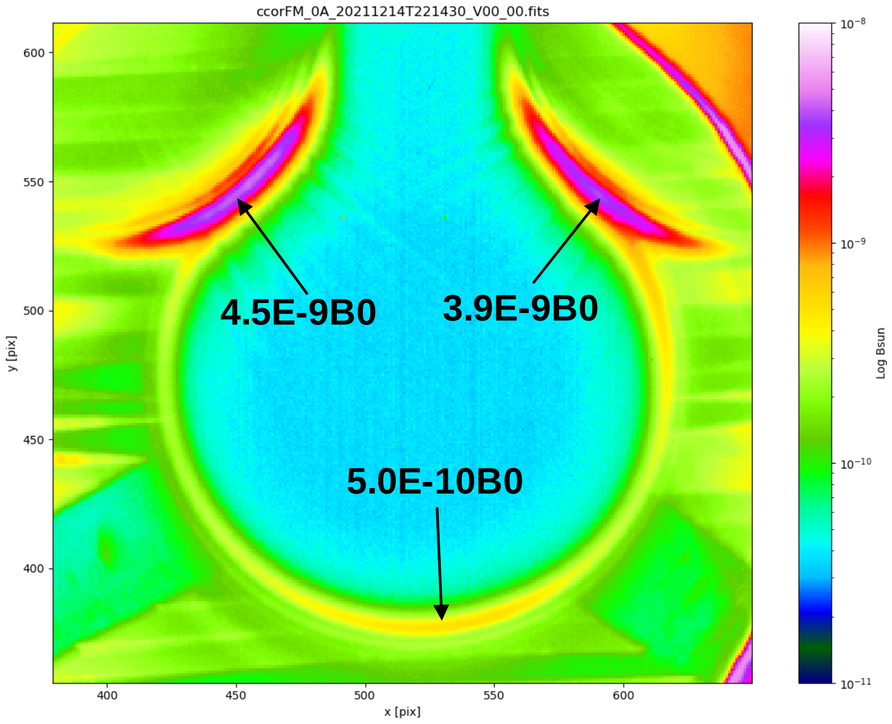
Stars and dust tracks need to be filtered out

Pylon stray-light

Stray-Light: Diffraction Pattern Observed During Ground Testing



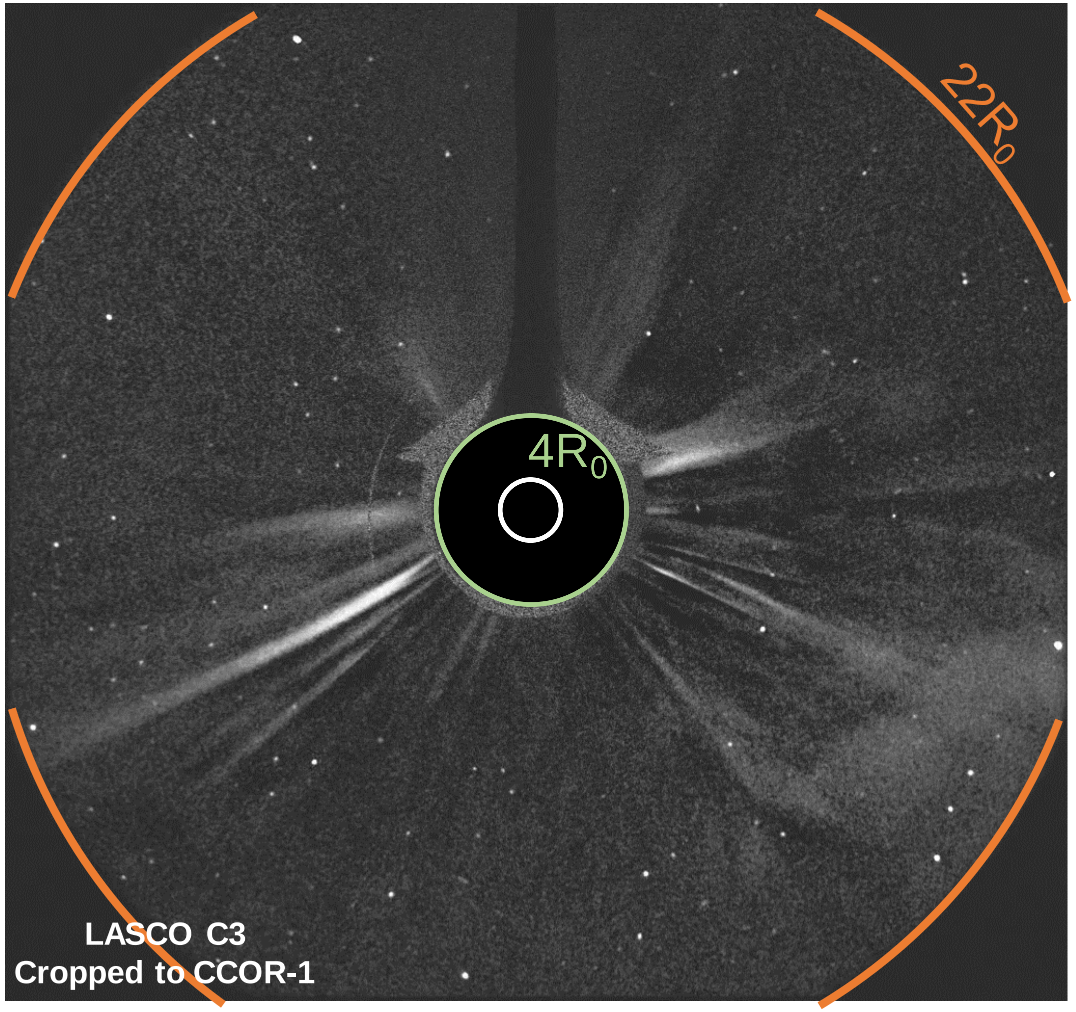
Diffraction pattern, pre-environment
(Feb 16, 2021)



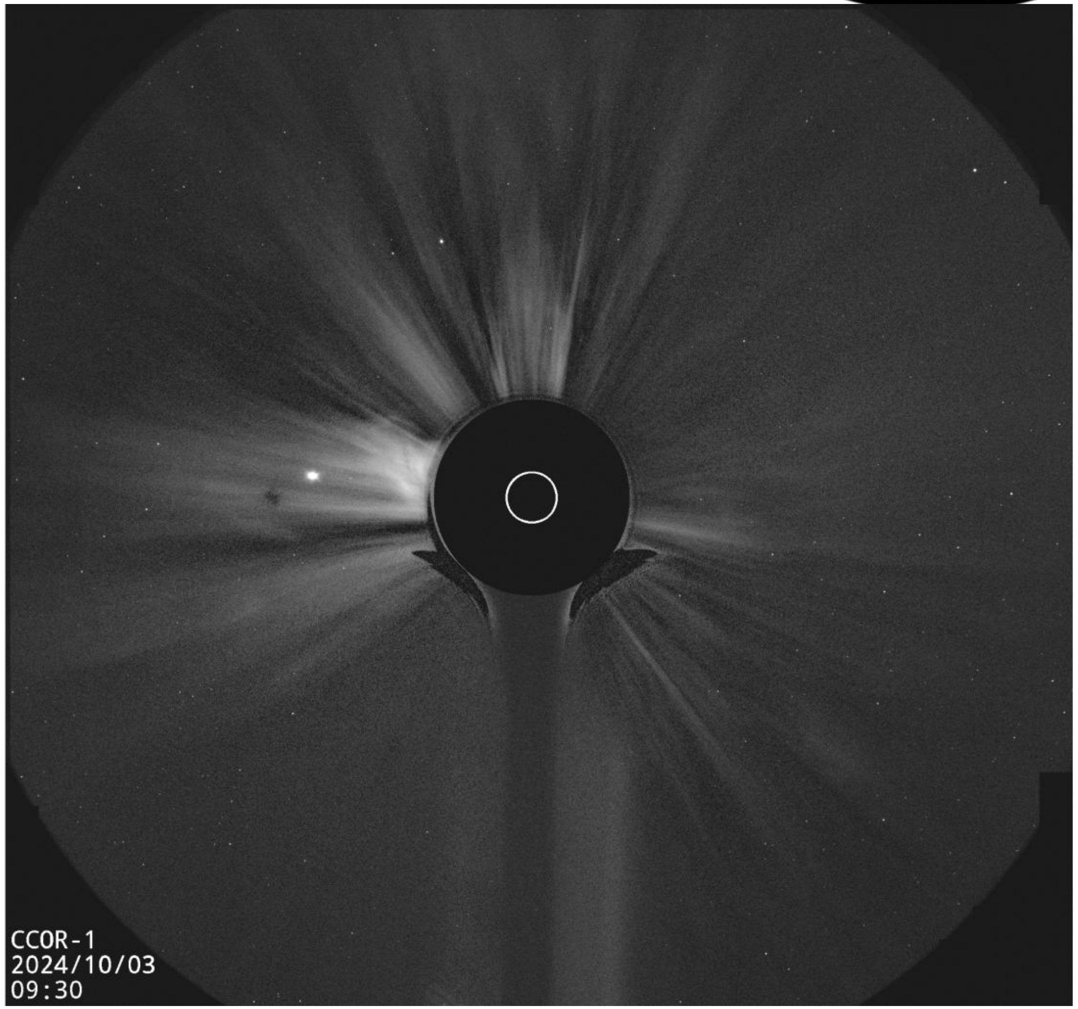
Diffraction pattern, post-environment
(Dec 14, 2021)

- **The occulter moved during the vibration test.**
- Increase of a factor 5.4 on average of left and right of the diffraction features at the top of the occulter.
- The rest of the diffraction pattern increased by 20%.
- The increase was localized to a small area in the inner field. No impact on the rest of the FOV: **It was decided to proceed without any rework.**
- The artificial sun used for this test is only 10% of the real sun, so it does not saturate in these images.
- Probably some additional shift with respect to the SUVI Guide Telescope occurred during the launch.

CCOR-1: Expected vs Actual Data

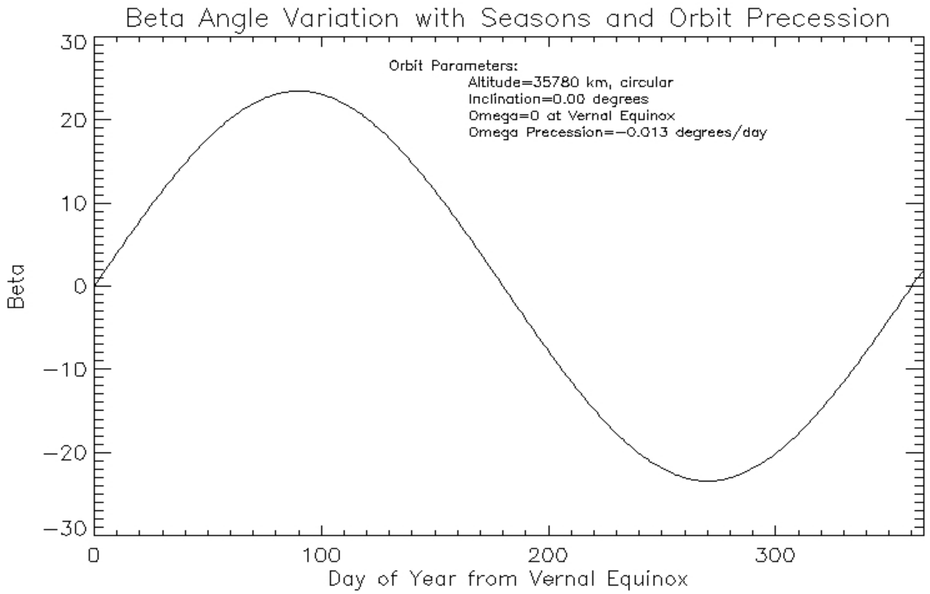


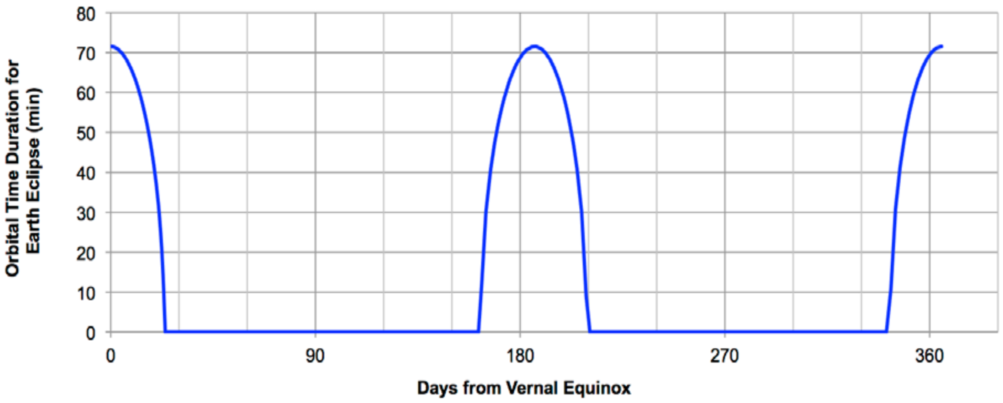
CCOR Proxy Data:
Halo CME, Feb 17, 2000, minimum background subtracted.



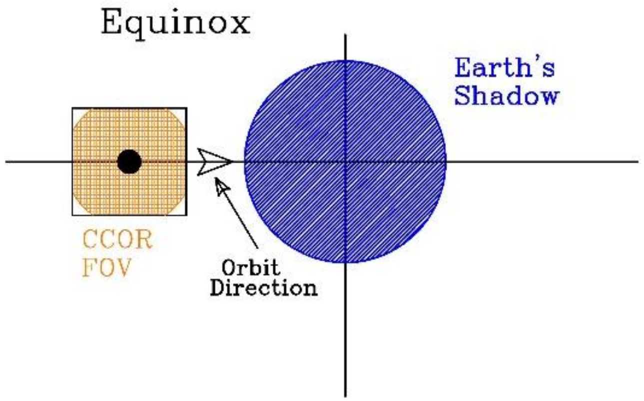
CCOR flight data:
Halo CME, Oct 3, 2024, minimum background subtracted.

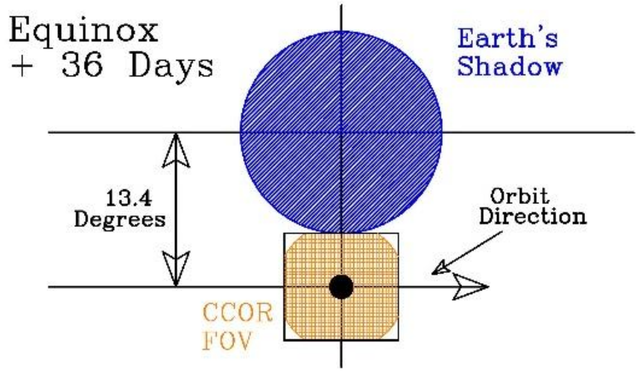
Earth Eclipses and Earth Shine Stray-Light





- From the orbit of GOES, the Earth subtends an angle of 17.2°.
- On the vernal and autumnal equinoxes CCOR is fully eclipsed by the Earth during a portion of the orbit.
- As the Earth moves away from the equinox, the GOES orbit beta angle changes, and Earth's "image" in the CCOR FOV moves down (or up, depending on the season).
- When beta exceeds 13.4° (~day 36 after an equinox), Earth no longer eclipses the CCOR FOV.
- The Earth still induces some stray-light when its limb is within 20° of CCOR's boresight.
- GOES will perform a yaw flip at every equinox.

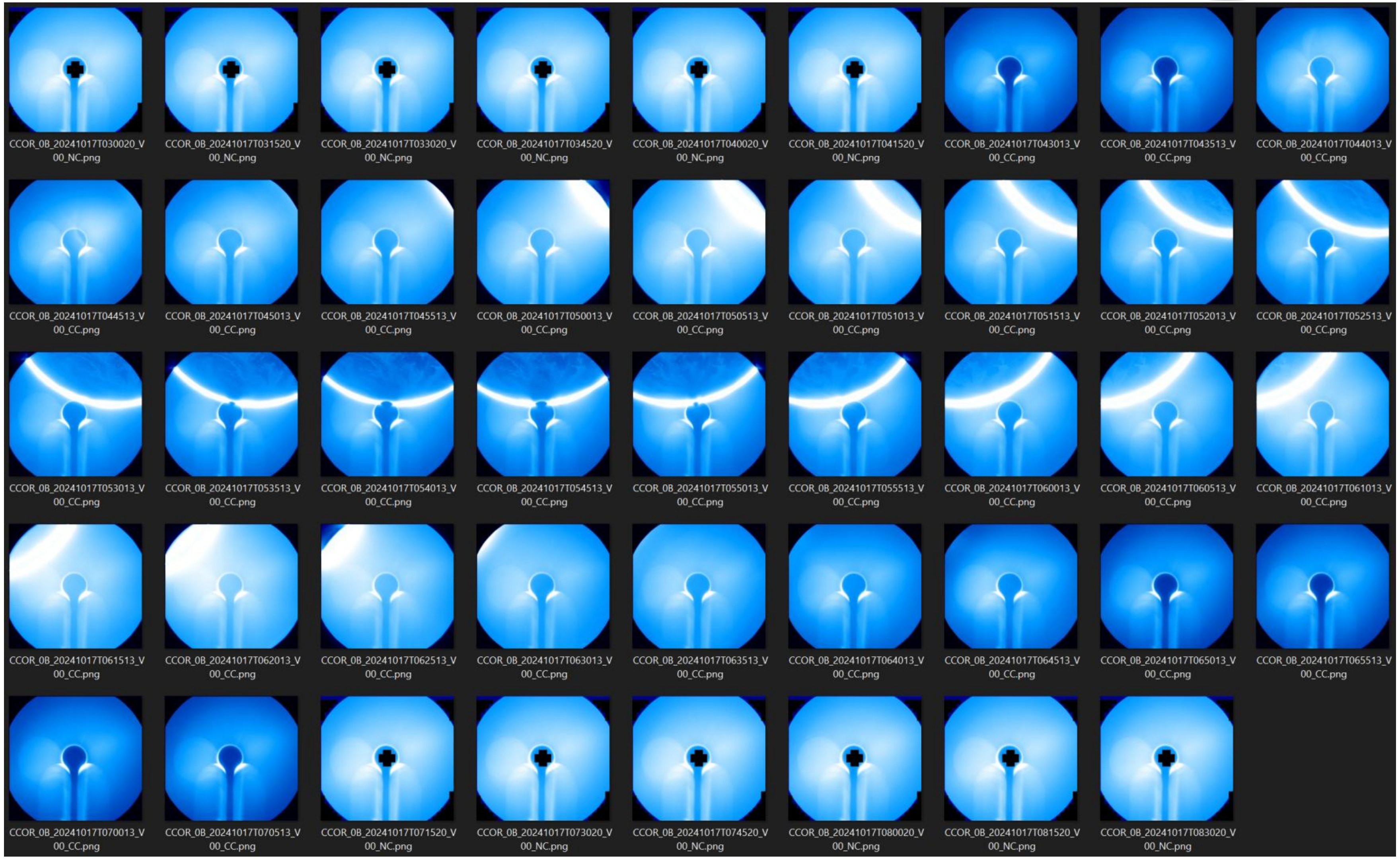




Extraction of Earth Shine for Oct 17

By subtracting a combination of the pre and post Earth transit images we obtain only the Earth shine stray-light.

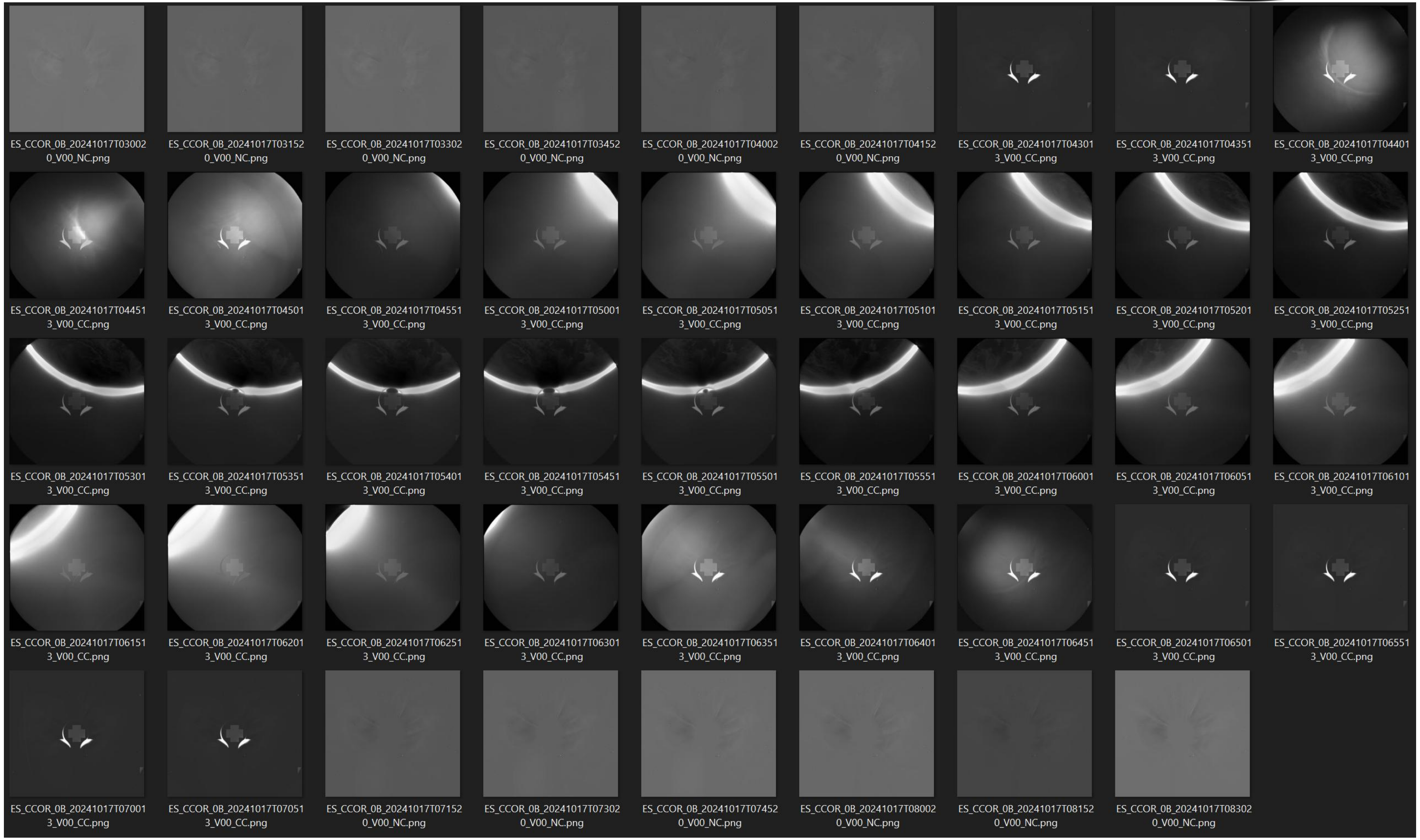
On the right: raw sequence of images for the Oct 17, 2024, Earth transit.



Extraction of Earth Shine for Oct 17

By subtracting a combination of the pre and post Earth transit images we obtain only the Earth shine stray-light.

On the right: Earth shine only of the sequence of images for the Oct 17, 2024, Earth transit.



Earth Shine Summary as of Jan 2025

- The observed Earth Shine varies with two parameters, the orbit beta angle (coarsely) and the position in the orbit (finely). It is observed to be significant, defined loosely as > 10^{-11} Bsun, from equinox to 55 days post-equinox. The period in the orbit when it is significant changes with the day post-equinox as the orbit beta angle increases. That period is ±20^{o} of orbit (equivalent to ±1.3 hours) centered at orbital midnight at equinox. The period shrinks to ±13^{o} on day 39 when the image of the limb just grazes the edge of the field of view. It shrinks further to ±5^{o} by day 50. After that 55-day period it is small but still detectable even at solstice, when the beta angle reaches its maximum. **It is suggested that as the year progresses towards the next equinox, and beyond to the next solstice, further data be gathered with an eye towards building a sufficiently large data base.**

Earth Shine Modeling Plan

- Goal: build a model of the Earth shine based on observations:
  - Earth Shine = function of:
    - Day of Year (or days from the nearest equinox)
    - Time before or after orbital midnight

- For each Earth Transit, subtract a combination of pre and post eclipse images to obtain only the Earth shine contribution.
- The Earth transits repeats and should be more or less symmetric by periods of 3 months, from equinoxes to solstices, or vice versa: the model can potentially be updated every 3 months.
- For each time related to the orbital midnight, we will fit the image brightness vs observation day.
  - The task is difficult:
    - The Earth is never at the same place.
    - The signal we want to recover is about 1% of the total brightness collected. Therefore, we need a model that is accurate to about 1% or better.
    - There could be some effect due to the Earth atmosphere (& north pole vs. south pole difference).
    - High spatial and temporal frequency features will be difficult to model.

- Bottom line: the images will never be as clean as when the earth is away, but still, we can do something to recover the coronal signal and allow forecasters to detect CMEs.

Calibration & Validation Activities

Parameter	Measured Pre-flight	Measured On-orbit	Frequency of Measurement	Frequency of Data Report
Calibration factor	Yes	Yes	Monthly	Annually
Vignetting function	Yes (detector and telescope)	Yes	Annually	Annually
Pointing Offset	No	Yes	Quarterly	Annually
Diffraction Pattern	Yes	Yes	Annually	Annually
Occulter Brightness	Yes	Yes	Weekly	Quarterly
Earthshine	No	Yes	Daily	Quarterly
Detector Temp	No	Yes	Daily (non-eclipse) Hourly (eclipse)	Annually
LED test	Yes	Yes	Quarterly	Annually
Detector defects	Yes	Yes	Quarterly	Annually
Bias	Yes	Yes	Daily	Annually
Cosmic Rays	No	Yes	Quarterly	Annually

Goal: monitor and trend the instrument performances throughout its lifetime.

Conclusions

- **CCOR-1 is behaving as expected 👍**
- **Post Launch Tests done: fine tuning of the instrument parameters is done.**
- **Earth shine stray-light difficult to mitigate but no surprise here, we knew from the start of the project that it was going to be a challenge.**
- **Instrument paper in progress, expected to be published in the first half of 2025.**
- **CCOR-1 is NOW OPERATIONAL!**
  - **Data is available to the public, from NOAA's SWPC (real time) and NCEI (retrospective) web sites.**

https://services.swpc.noaa.gov/products/ccor1/

https://www.ncei.noaa.gov/products/space-weather/swfo

https://ccor.nrl.navy.mil

PUNCH-CCOR Work Synergy Plan

- **Cross calibration:**
  - **Photometry**
  - **Stray-light**
  - **Earth shine**

- **Solar wind and CME feature tracking**
  - **Relies on position and pointing knowledge, as well as field distortion.**
    - **Use the standard WCS FITS keywords, in both heliocentric and celestial coordinate frames.**
  - **Update NRL's CME modeling tool (which includes the GCS model and other models) to include PUNCH data, as well as CCOR and any other imagers.**