Using Lunar Observations to Radiometrically Assess the CUMULOS' Visible Camera

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Outline

- CUMULOS Sensor
- Objective and Lunar Cal Overview
- Observed Anomalies
  - *DN Dips Along FPA*
  - *Ghost Imaging*
- Lunar Calibration
  - *Explanation of the ROLO Model*
  - *Application and Results of the ROLO Model*
- Summary

The CubeSat Multispectral Observation System (CUMULOS)

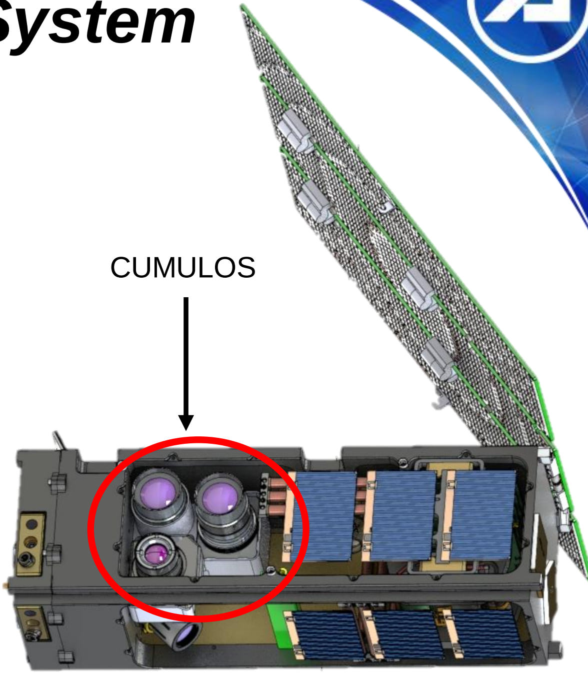
- The NASA payload (ISARA), Aerospace bus, was launched from NASA Wallops on Nov 12, 2017 ISARA goal is to demonstrate downlink data rates for CubeSats to >100 Mbps. NASA's ISARA will transmit a Ka tone to ground station. Experiment consists on measuring antenna pattern.

- CUMULOS operations commenced on 8 June 2018 following the successful completion of the ISARA mission

- Primary Requirement:
  - *To develop **optimal methods for the operation** of passively cooled COTS sensors and cameras and determine their **suitability to perform weather/environmental monitoring** missions*

- CUMULOS: 3 <u>COTS</u> cameras (1U) in a 3U CubeSat
  - *<u>Visible camera</u>* – ***0.4 – 0.8 µm;***
    - CMOS chip (Aptina MT9M001C12STM)
    - 1280 x 1024 pixels
  - *SWIR camera* – ***0.9 - 1.7µm***
  - *LWIR camera* – ***7.5 - 15.5µm***

- No requirements on calibration accuracy or precision



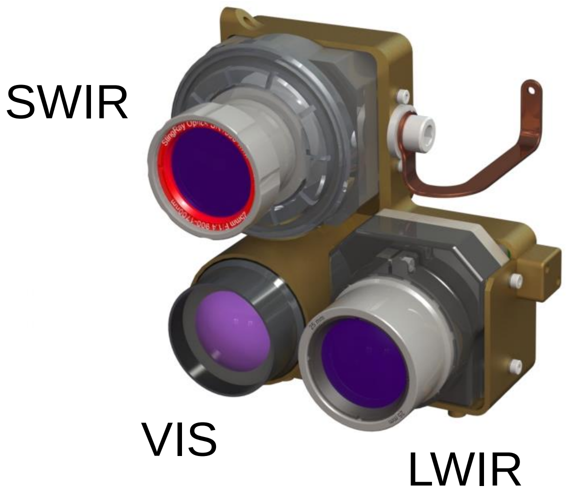
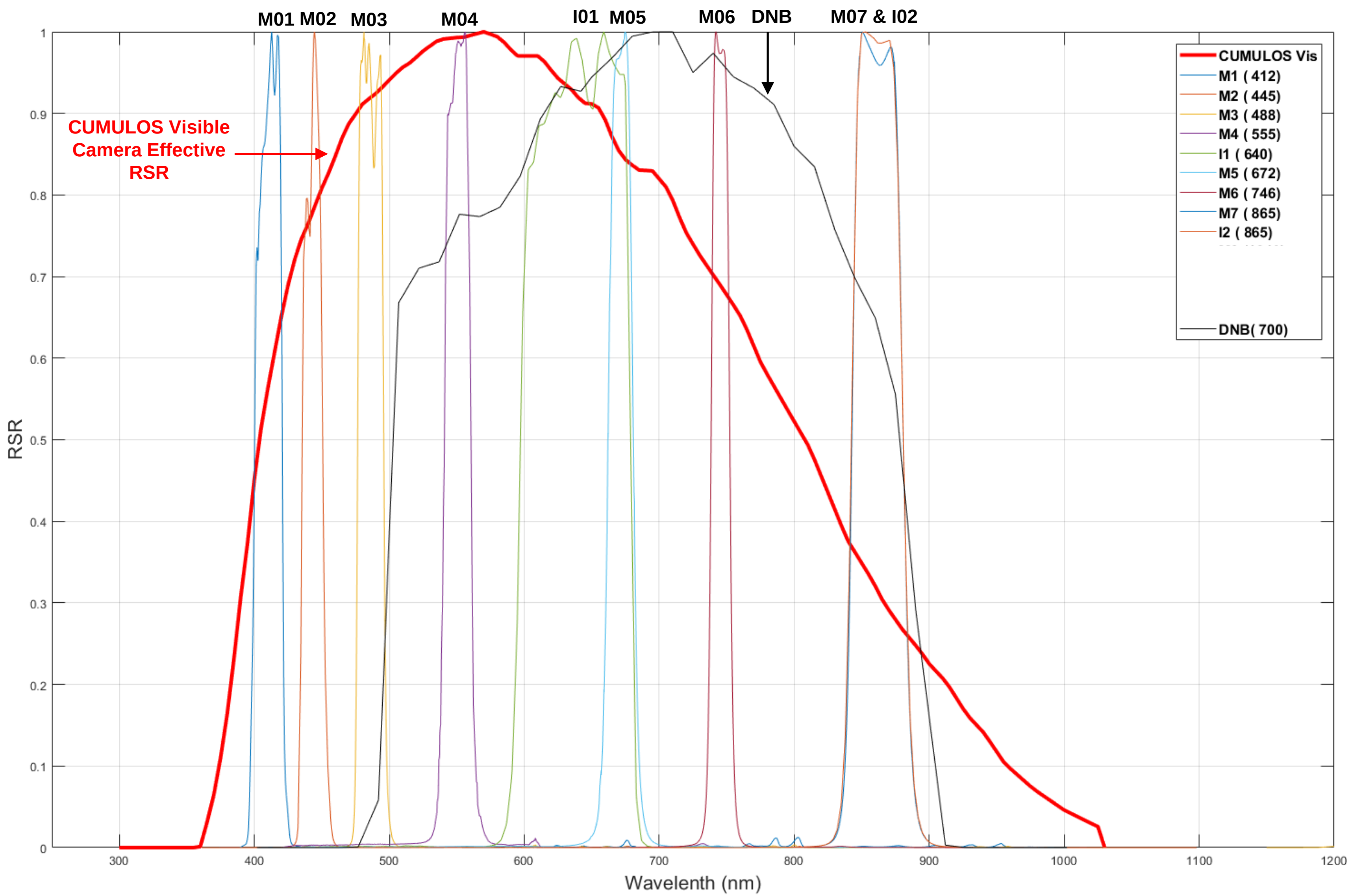


Image and slide content from

[1] Ardila, David et. al., "The CubeSat Multispectral Observation System (CUMULOS)", CalCon 2016 Presentation by the Aerospace Corp

RSR Comparisons

SNPP VIIRS and CUMULOS Visible Camera

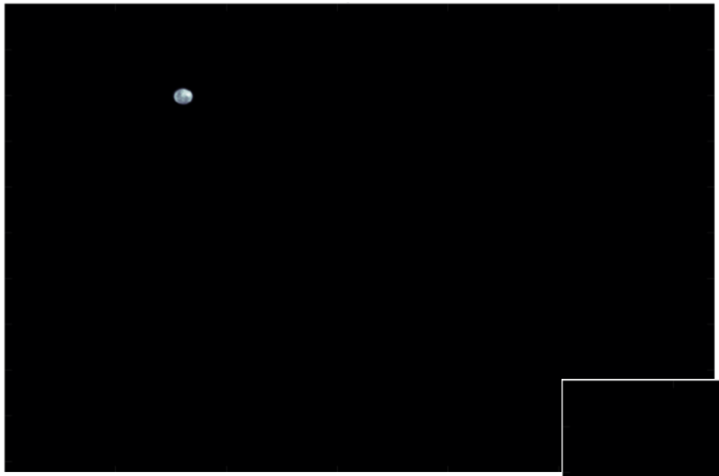


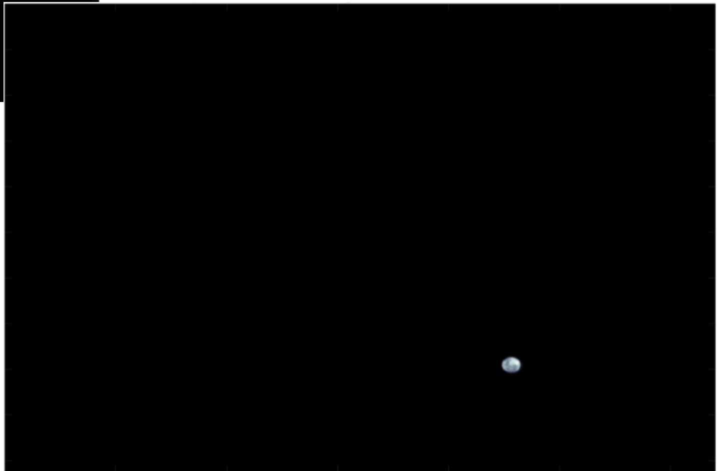
Objective and Lunar Cal Overview

- Motivation: COTS sensors without onboard calibrators will only increase given the pLEO/CubeSat mentality and using the Moon to radiometrically assess said sensors is of absolute importance
- This effort was funded by The Aerospace Corporation's FY19 Independent Research and Development (IRAD) program with a goal of utilizing the Moon to radiometrically assess the CUMULOS Visible Camera
- Process:
  - *Sampling CUMULOS' FPA:*
    - Given the data downlink limitations it was near impossible to sample the entire Visible Camera with the Moon. Camera does not have zooming capability so to image entire FPA.
    - Observe Moon at center and four quadrants of the FPA
  - *Apply Flat Field Correction derived from lab tests*
  - *Dark Current Offsets were determined from neighboring (before and after) dark space collects about lunar collects*
    - Dark Current Offset Trending was assessed and determined negligible in change (fraction of a DN)

CUMULOS Lunar Collect

Feb 19, 2019 at 116 us Integration

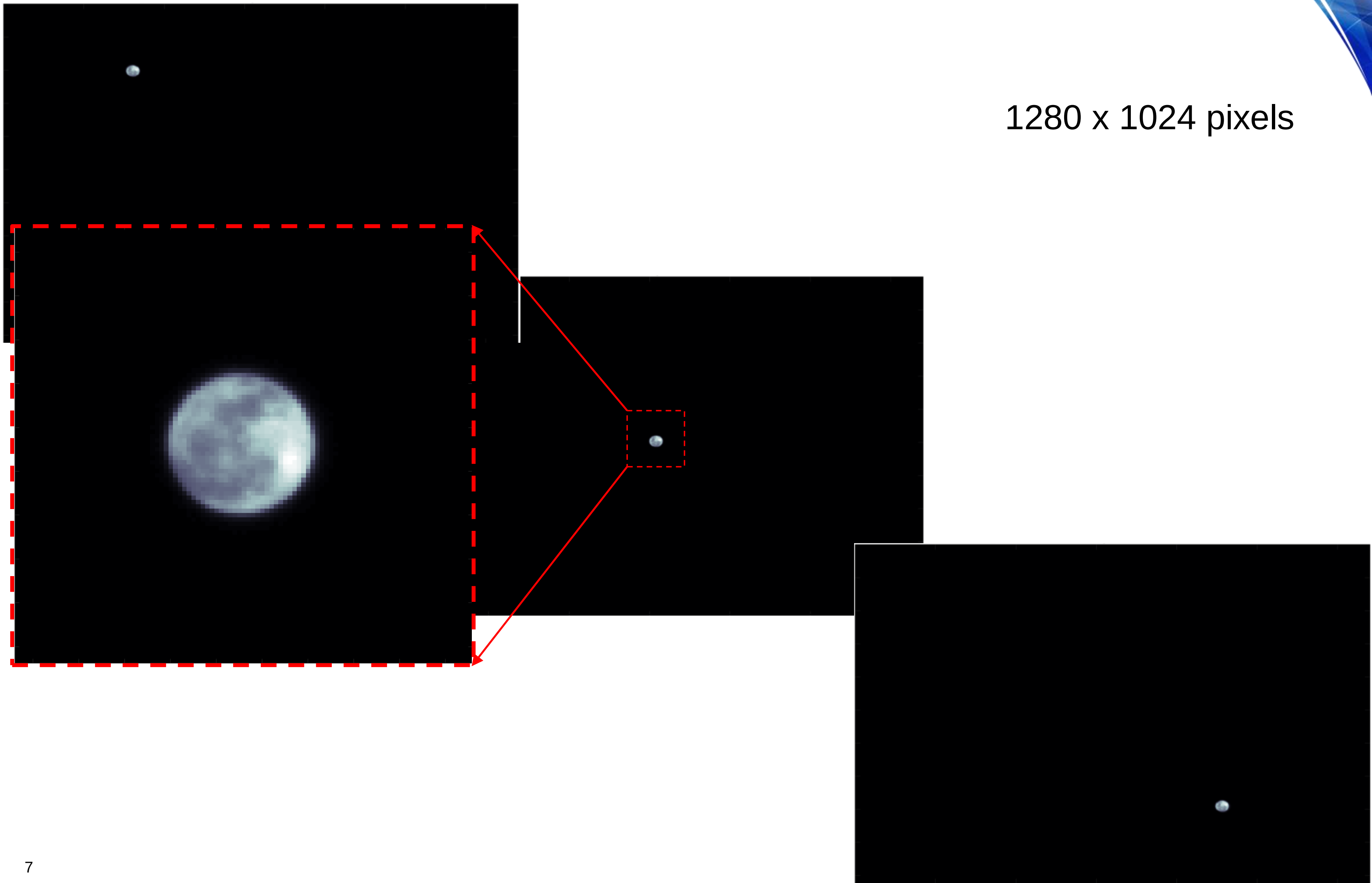




1280 x 1024 pixels

CUMULOS Lunar Collect

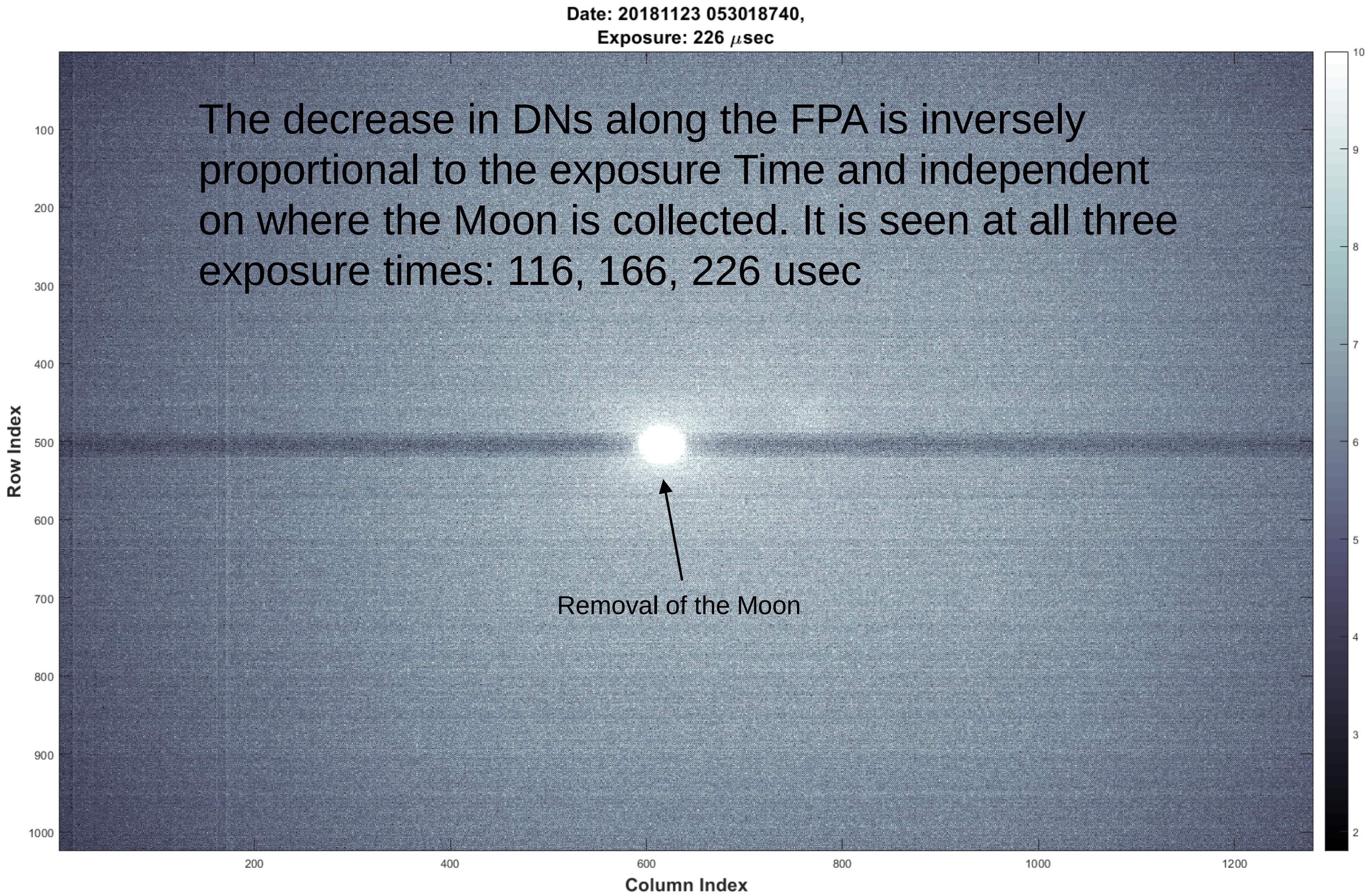
Feb 19, 2019 at 116 us Integration



1280 x 1024 pixels

Anomalies: Dip in DNs

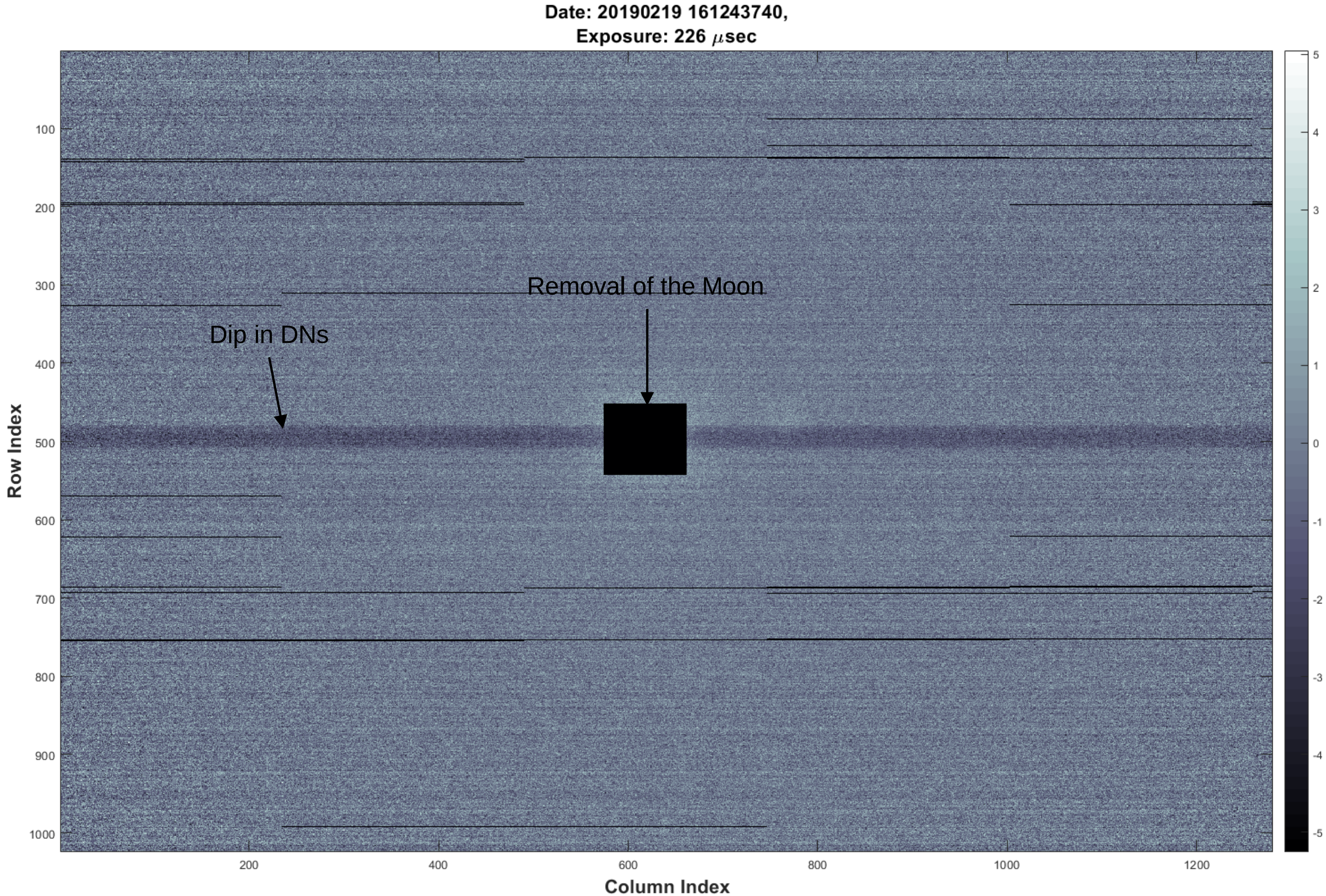
Dip in DNs



No Dark field nor Flat field applied

Dip in DNs

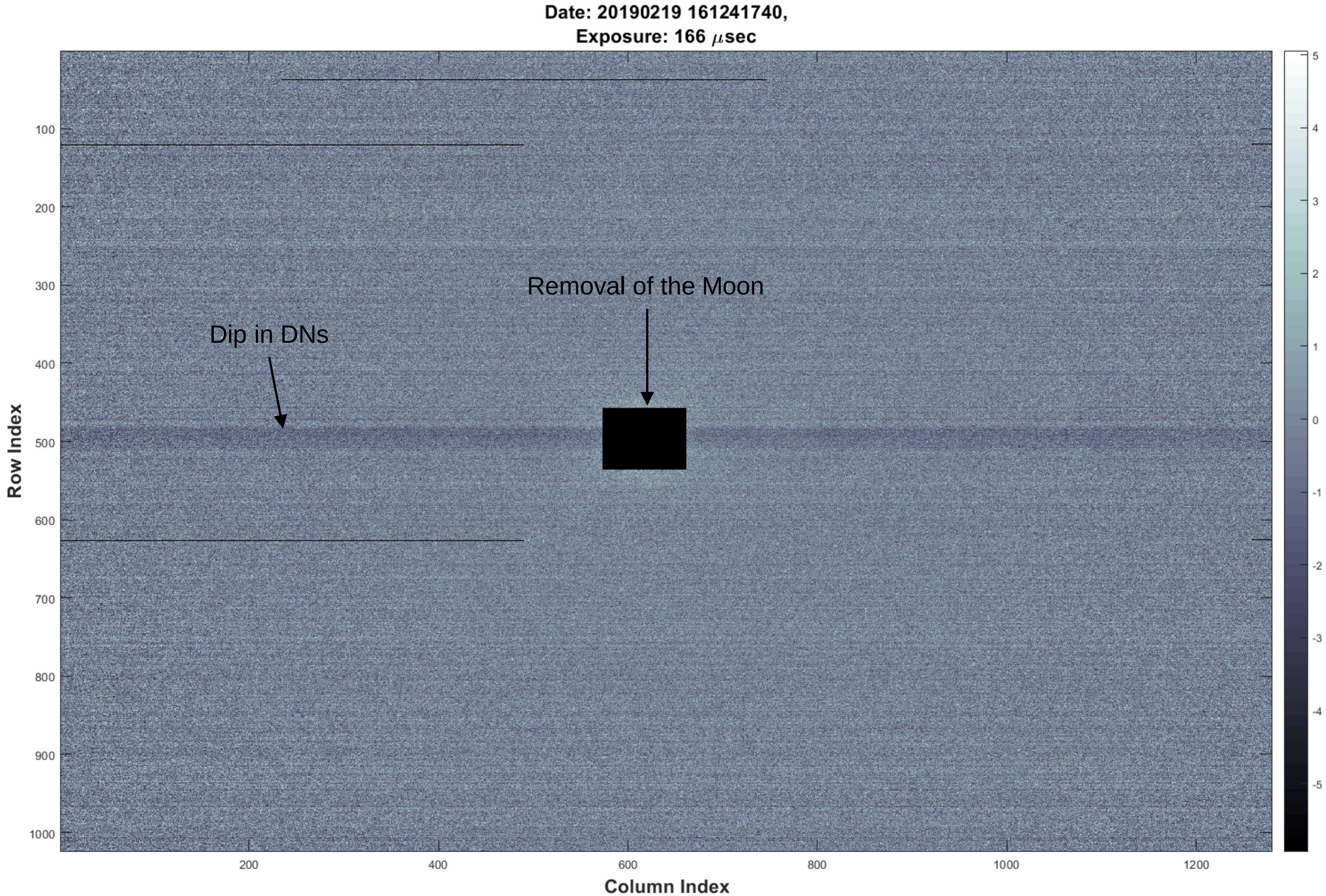
Exposure Time: 226 us



Dark field and Flat field applied

Dip in DNs

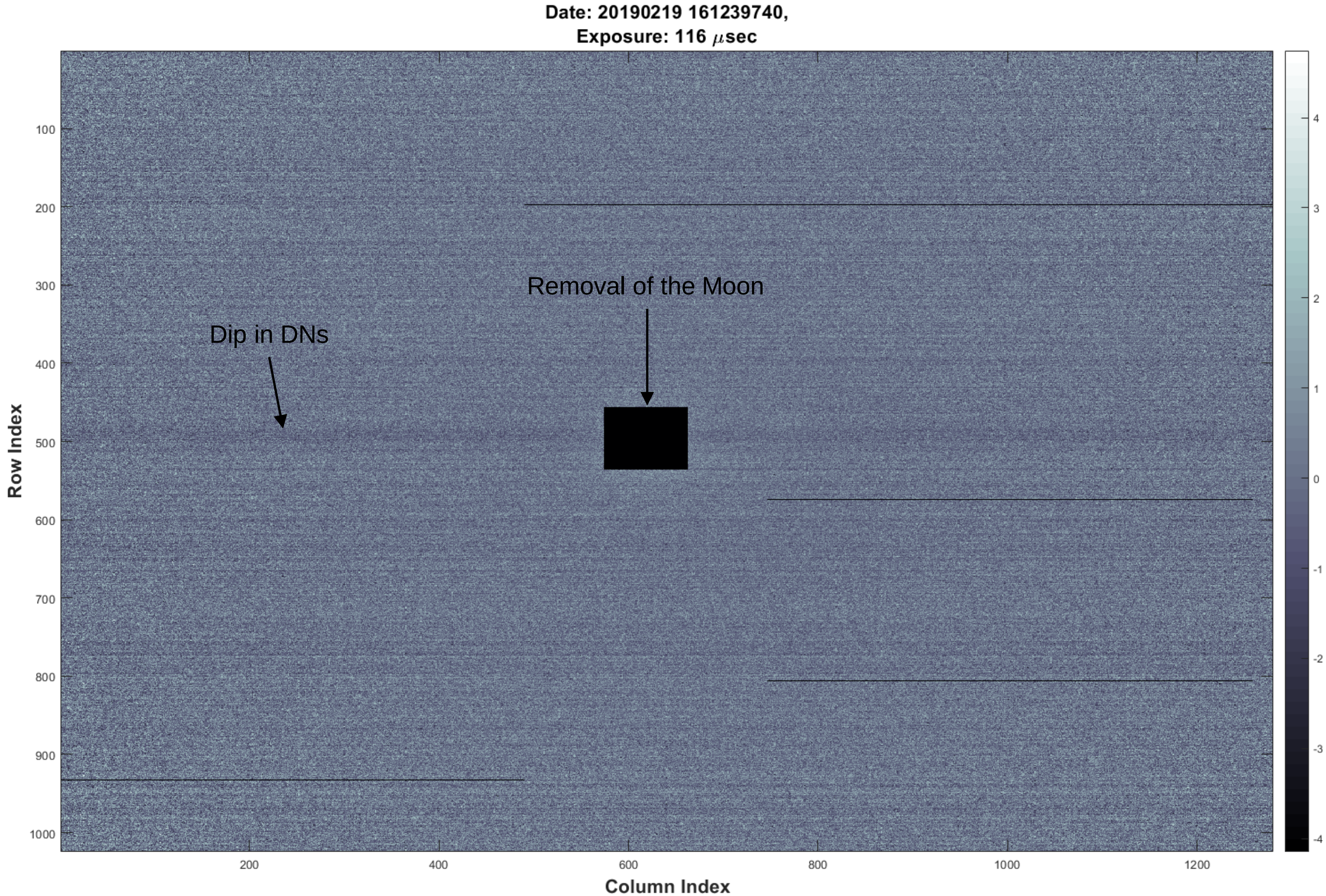
Exposure Time: 166 us



Dark field and Flat field applied

Dip in DNs

Exposure Time: 116 us

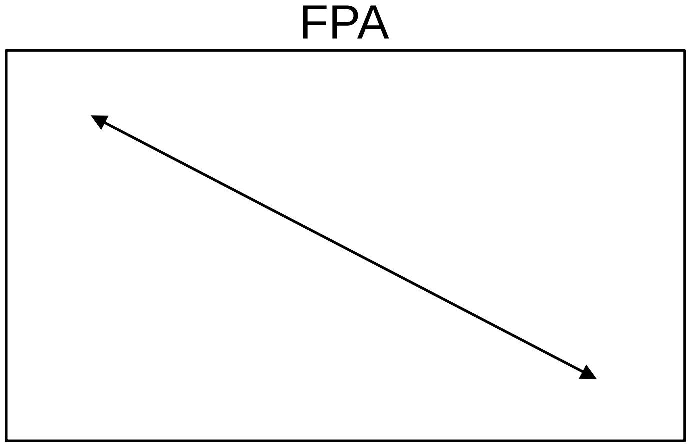


Dark field and Flat field applied

Anomalies: Ghosting / Retro-Reflection

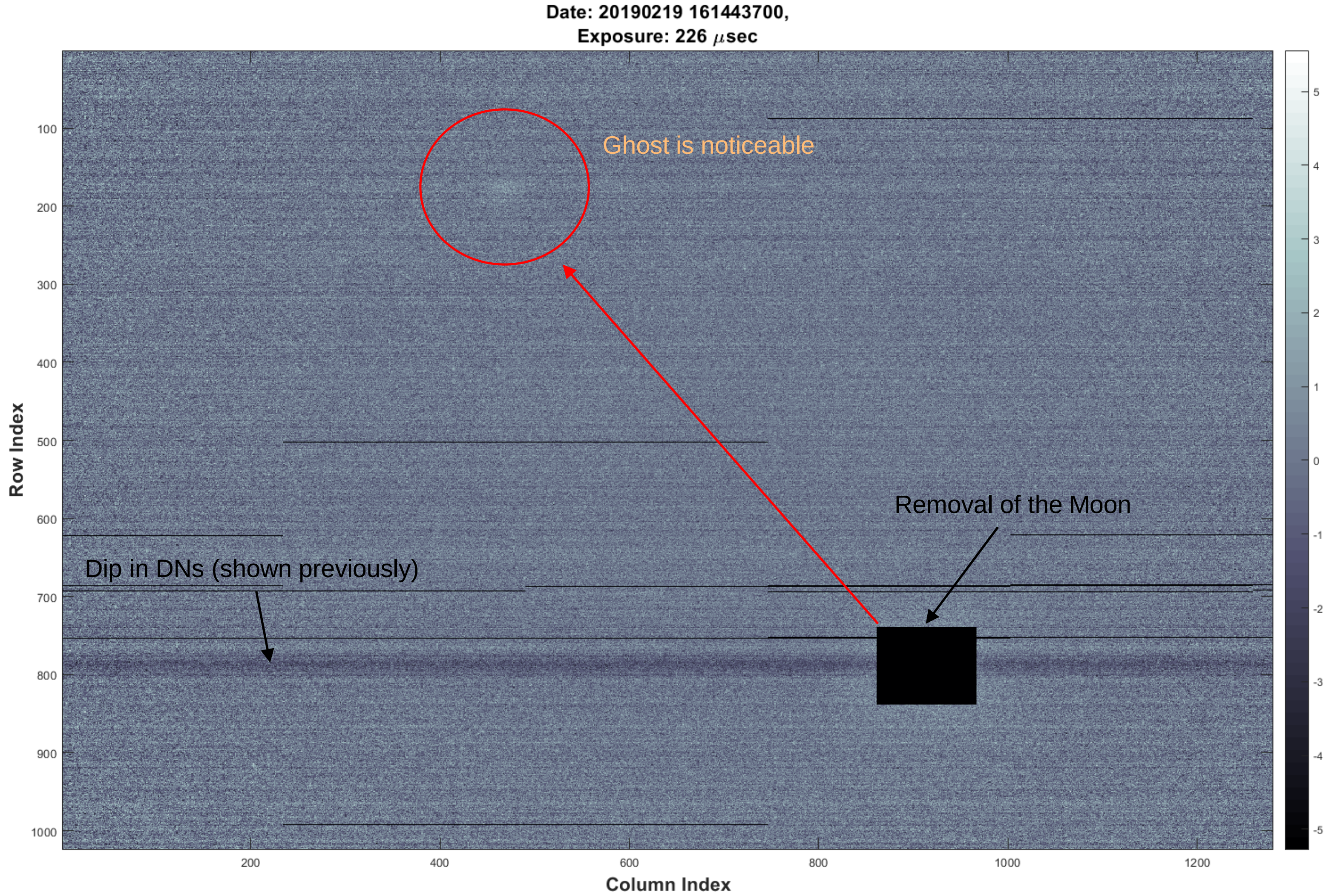
Ghosting or Retro-Reflection

- There are unexpected patterns during Lunar collects that are away from the Moon on a certain part of the FPA for Exposure times 116 and 226 usec.
- These patterns are seen before and after flat-field and dark subtraction is applied and are believed to be ghost images
- What is a ghost image?
  - *A feature or shape at the focal plane of a camera or other **optical** instrument that is not present in an actual scene, or an unfocused duplicate image that is overlaid upon a desired image. **Ghost** images, or ghosts, are caused by reflections from the surfaces of lenses.*
- Ghost image is only noticed when the Moon is observed in the center, upper left, or lower right quadrants



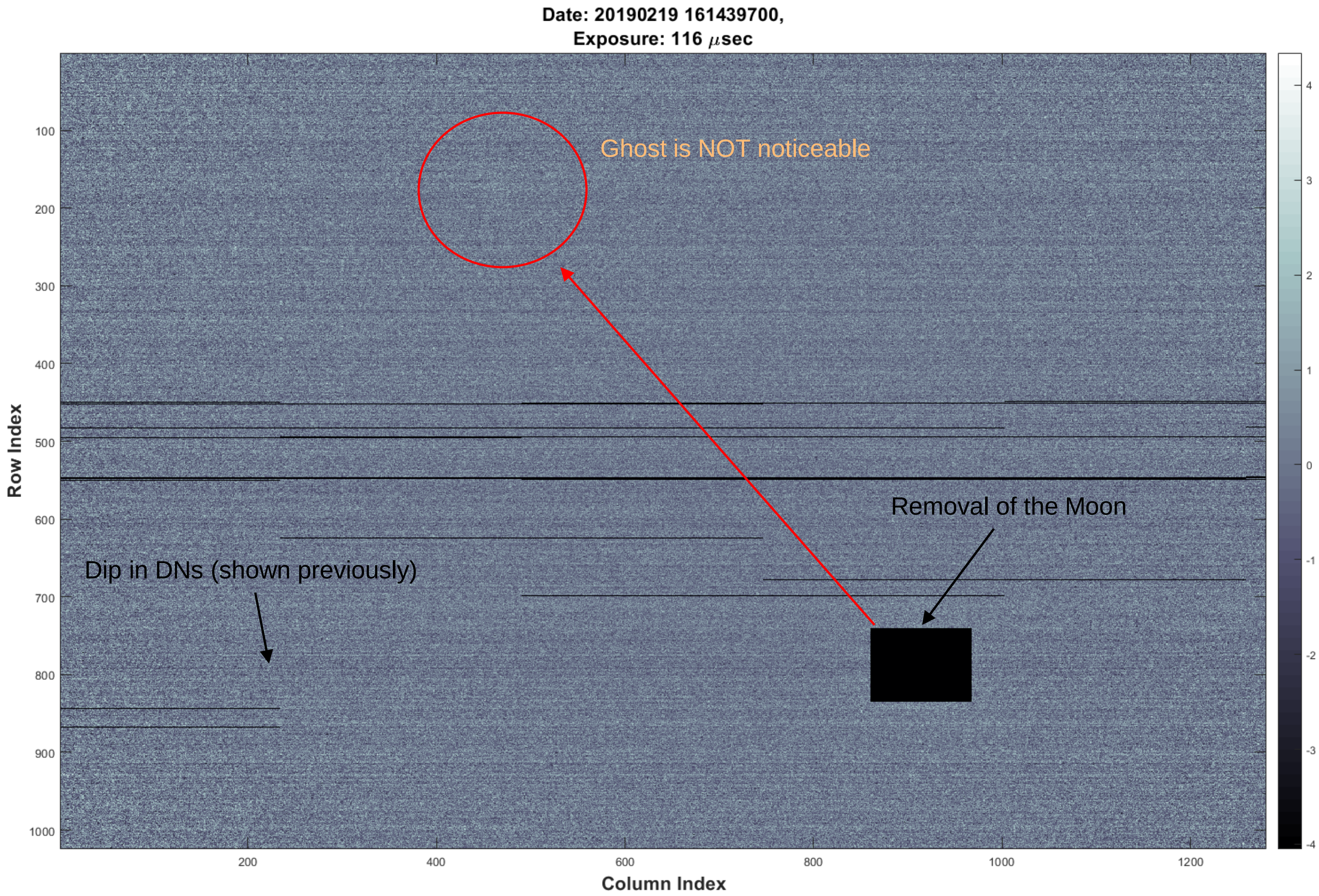
Ghost Image

Exposure 226 usec



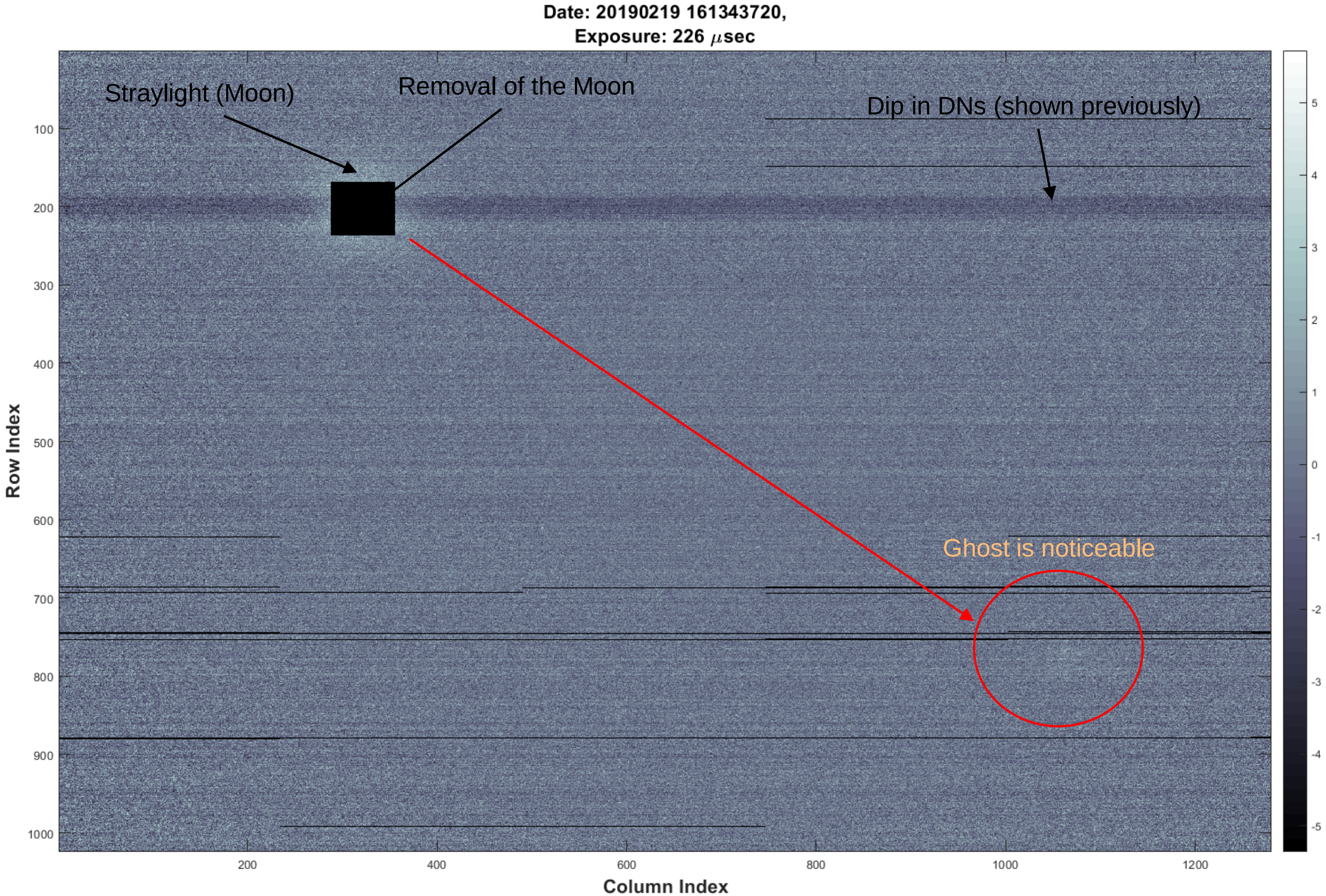
Ghost Image

Exposure 116 usec



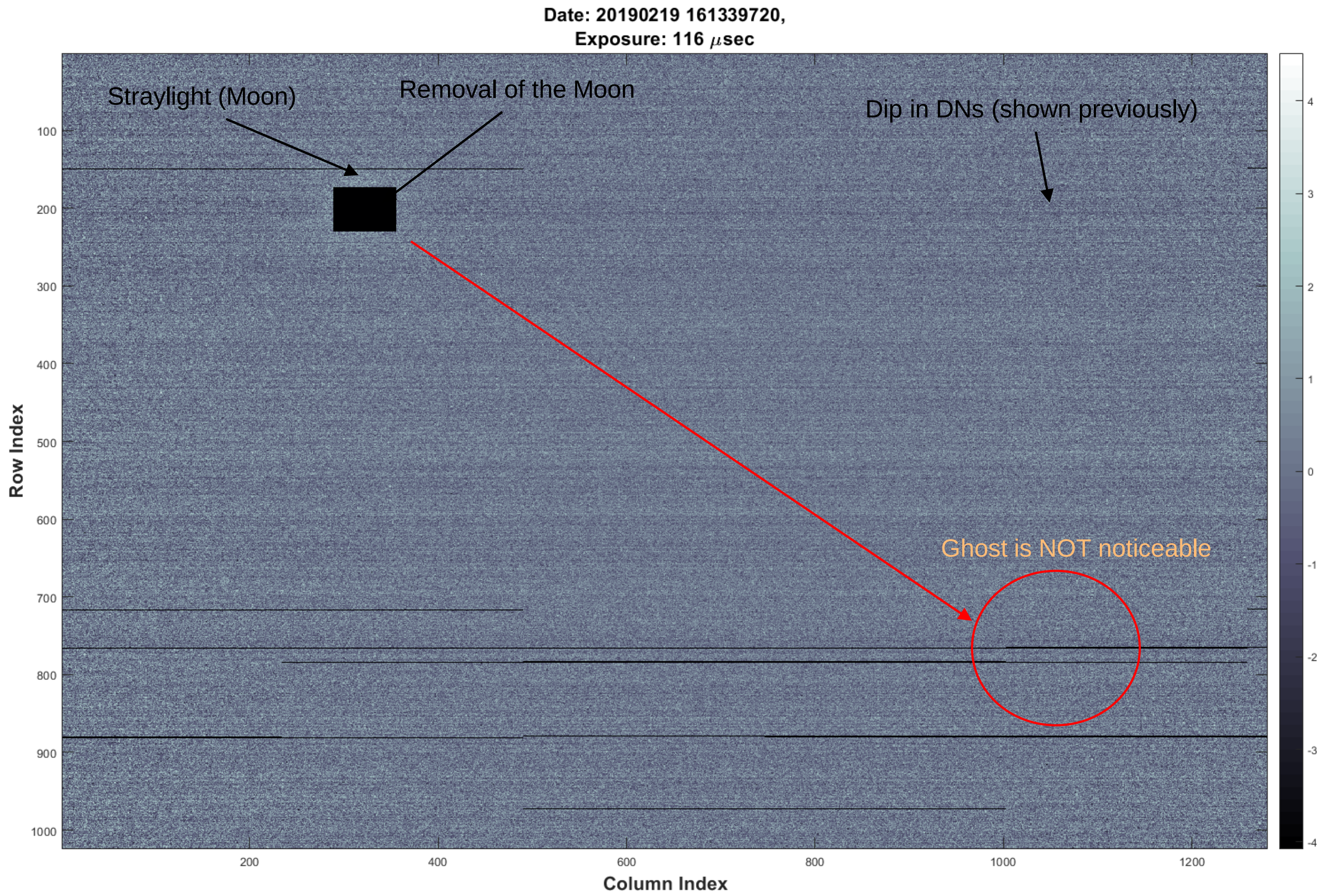
Ghost Image

Exposure 226 usec



Ghost Image

Exposure 116 usec



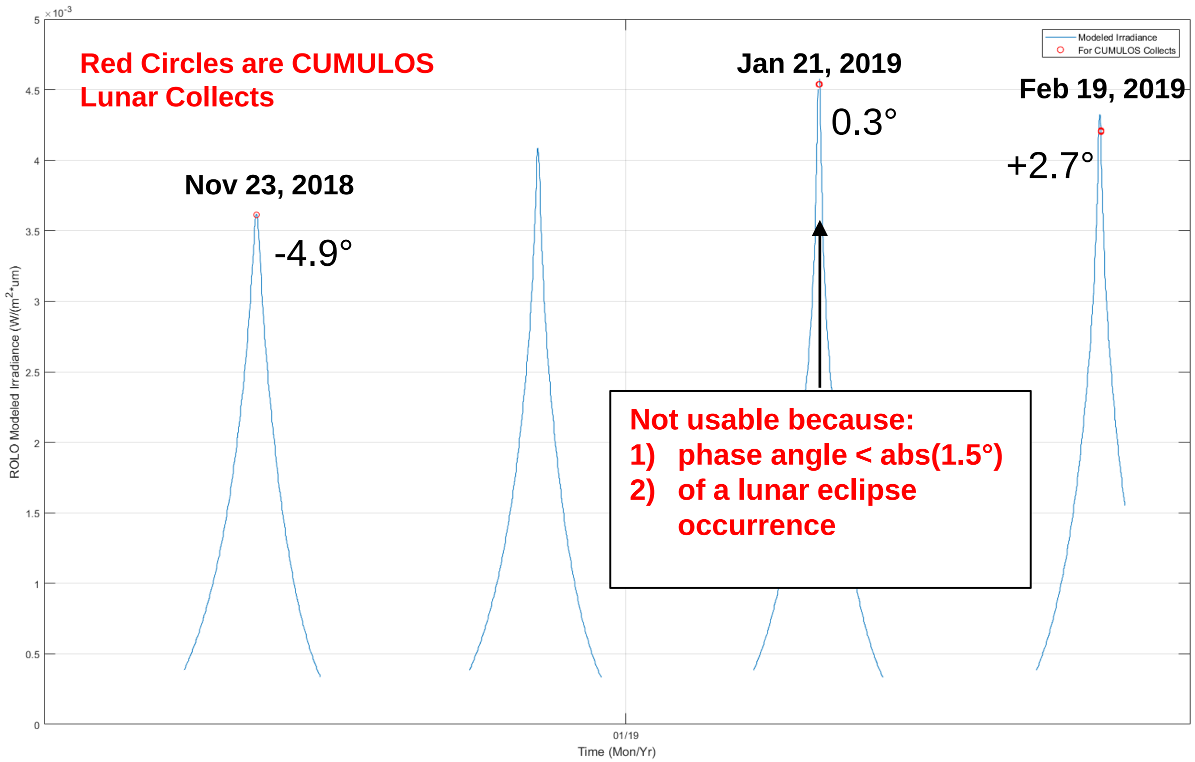
Lunar Observations and Model

Using the Moon for Radiometric Cal Assessment

- The Moon is a stable calibration source
  - *Tidal lock so does not rotate with respect to the observer*
  - *Most significant variation in Lunar Disk irradiance is due to phase change*
- NOAA and NASA uses observations of the Moon in conjunction with a Lunar Model (ROLO) for calibration purposes to determine long-term radiometric stability for VIIRS and MODIS, respectively, even though these sensors have on-board calibrators
- The USGS Robotic Lunar Observatory (ROLO) model
  - Kieffer, H., Stone, T., "The Spectral Irradiance Of The Moon" June 2005
  - *was developed using 6+ years of ground-based observations*
  - *applicable 0.35 – 2.45 um (bounds current CUMULOS spectrum response)*
  - *absolute uncertainty: 5-10% (irradiance scale)*
- Process:
  - *Utilize implementation of USGS Robotic Lunar Observatory (ROLO) model (previous IRAD)*
  - *Aerospace Satellite Orbit Analysis Program (SOAP) used for orbital and body geometry and image processing techniques to determine Moon-illuminated Pixels*
  - *Irradiance of CUMULOS is calculated using the DN coefficient provided by Dee Pack's Alpha-Lyra star calibration (methodology presented during this Conference)*

CUMULOS Lunar Collects

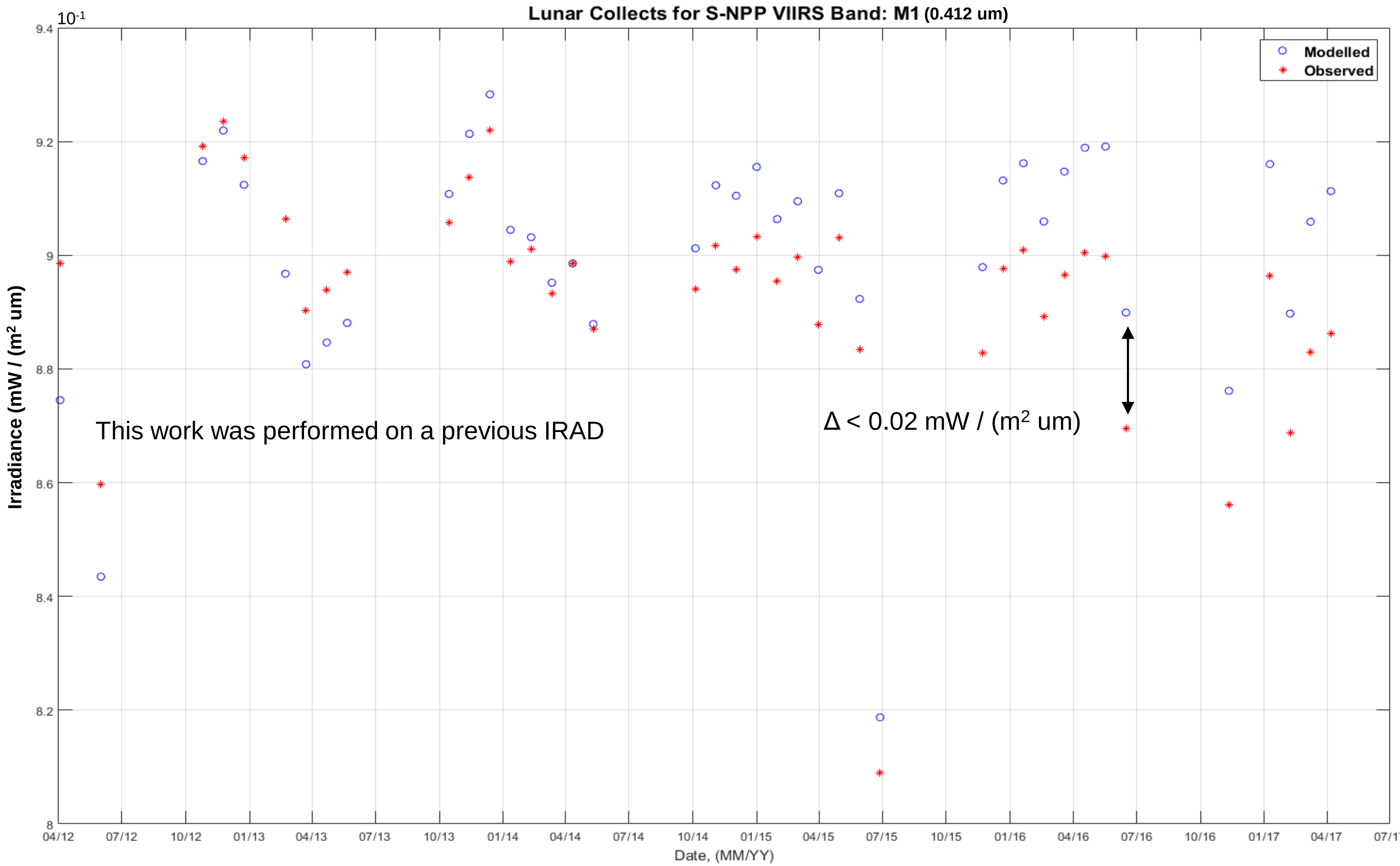
- Even though there have been three exposure times to collect the Moon (116,166, and 226 us) the latter 2 saturate when capturing the Moon
- To Date 116 us Exposure Time Lunar Collects
  - *2 Collects: 23-Nov-2018, Phase Angle: -4.9°*
  - *6 Collects: 21-Jan-2019, Phase Angle: 0.3°*
  - *6 Collects: 19-Feb-2019, Phase Angle: 2.7°*



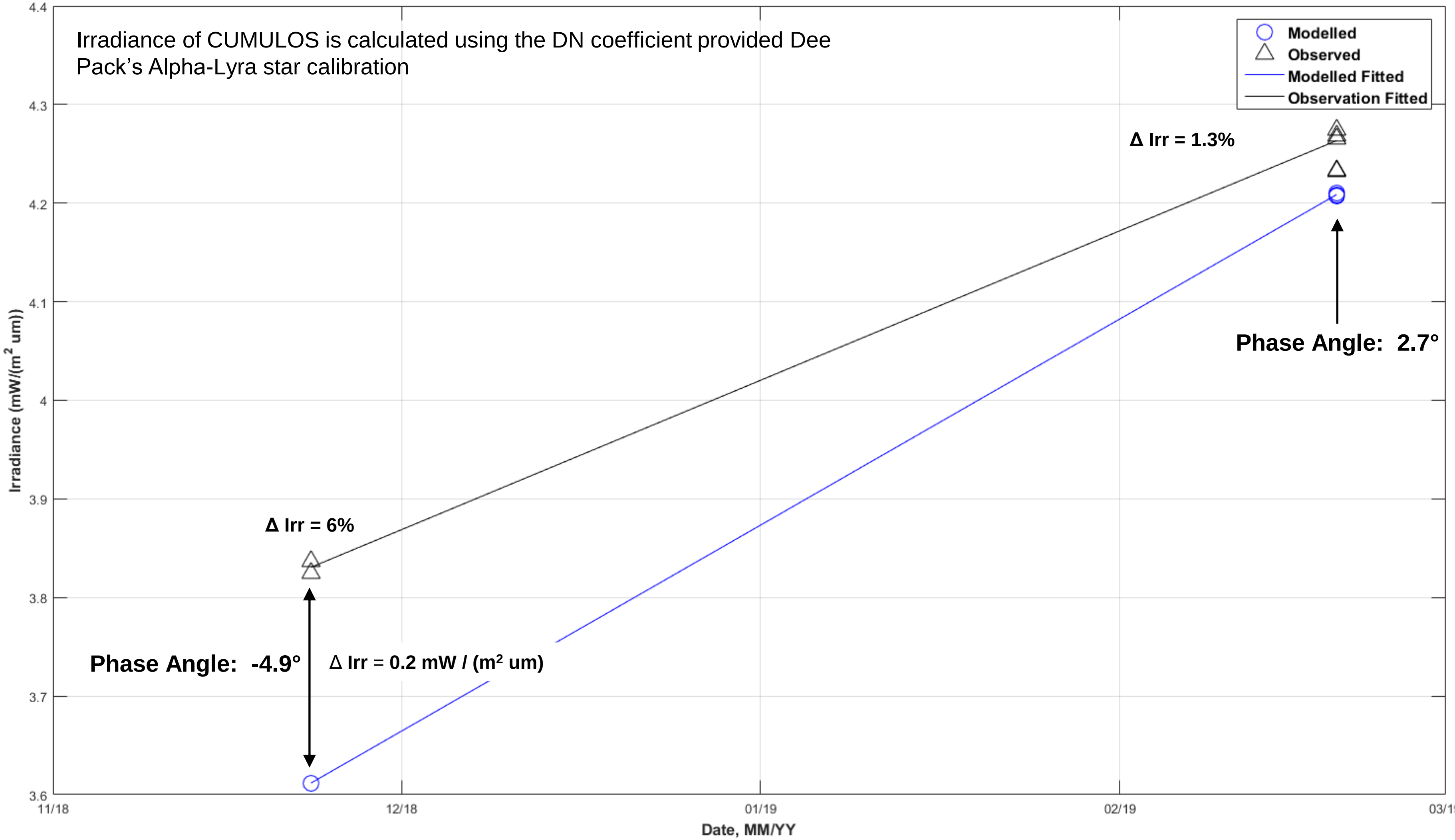
Comparing VIIRS Model to Observations

S-NPP VIIRS Band M1

Phase Angle Range: -50.4° to -55.4 ° (<u>40 Collects over 5 years</u>)

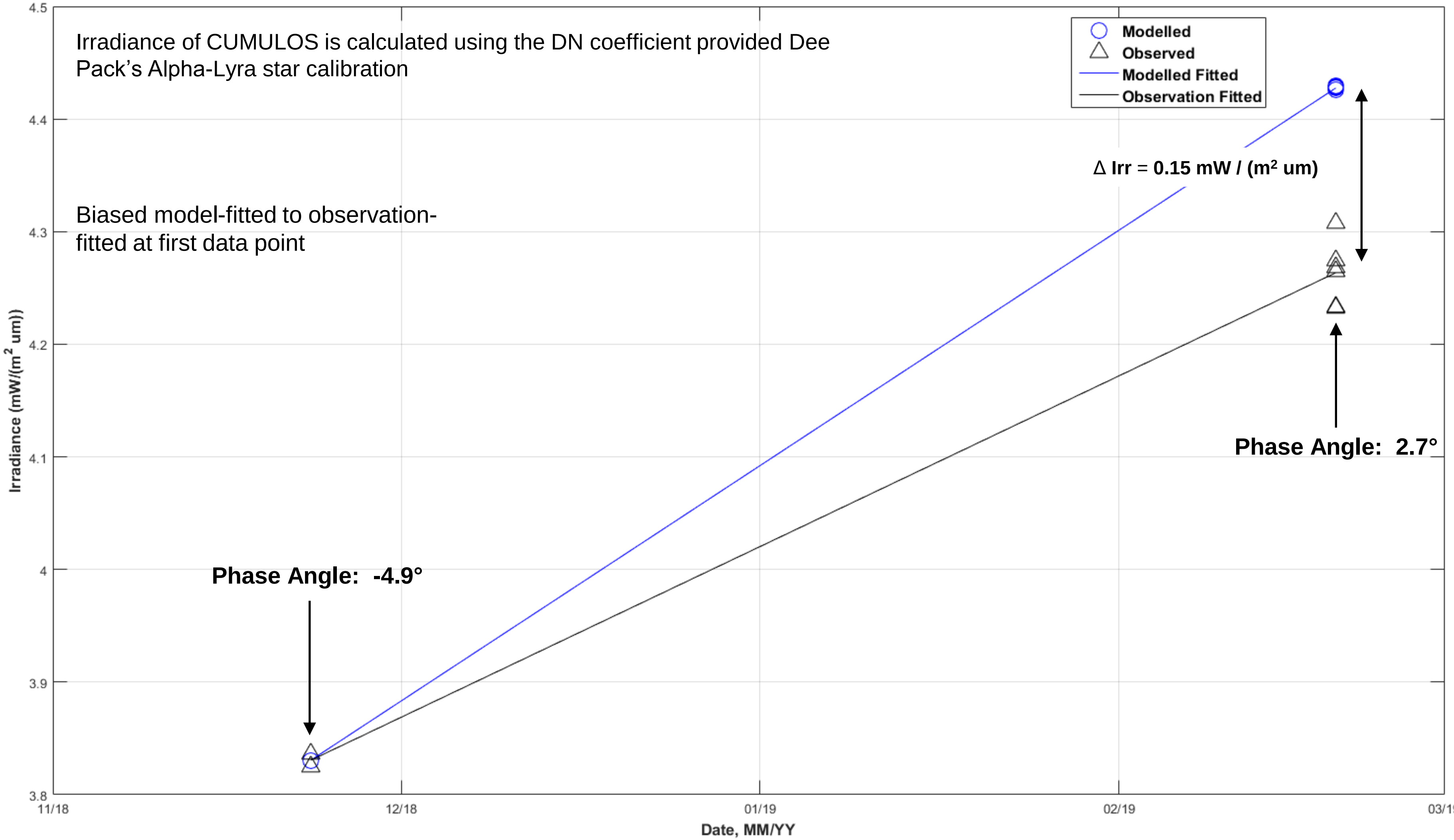


Comparing CUMULOS Model to Observations



Comparing CUMULOS Model to Observations

Biasing Model towards Observation



Summary

- The Moon was used to assess the CUMULOS Visible Camera upon ISARA CubeSat
  - *There have been unexpected anomalies using the Moon*
    - Ghost Imaging
    - Light Sensitivity correlation to FPA detectors (DN Dip)
  - *Based on the ROLO model it has been determined that the CUMULOS Visible camera requires additional radiometric biasing for 116 us exposure time*
- Desired Future:
  - *Perform a more extensive validation of our implementation of the ROLO Model with GSICS Implementation of the ROLO (GIRO) Model values*
  - *Apply this ROLO work to future Aerospace Corp and Gov/Private industry sensors*
- Lessons Learned:
  - *More Lunar Collects are always good (we already knew this)*
  - *In the absence of using ROLO one can still use the Moon for more than just radiometric trending (Expect the unexpected)*
- COTS sensors without onboard calibrators will only increase given the pLEO/ CubeSat mentality and using the Moon to radiometrically assess said sensors is of absolute importance

Thank You