The end of an era, the beginning of a legacy: SOFIA 6 µm VIPER observations

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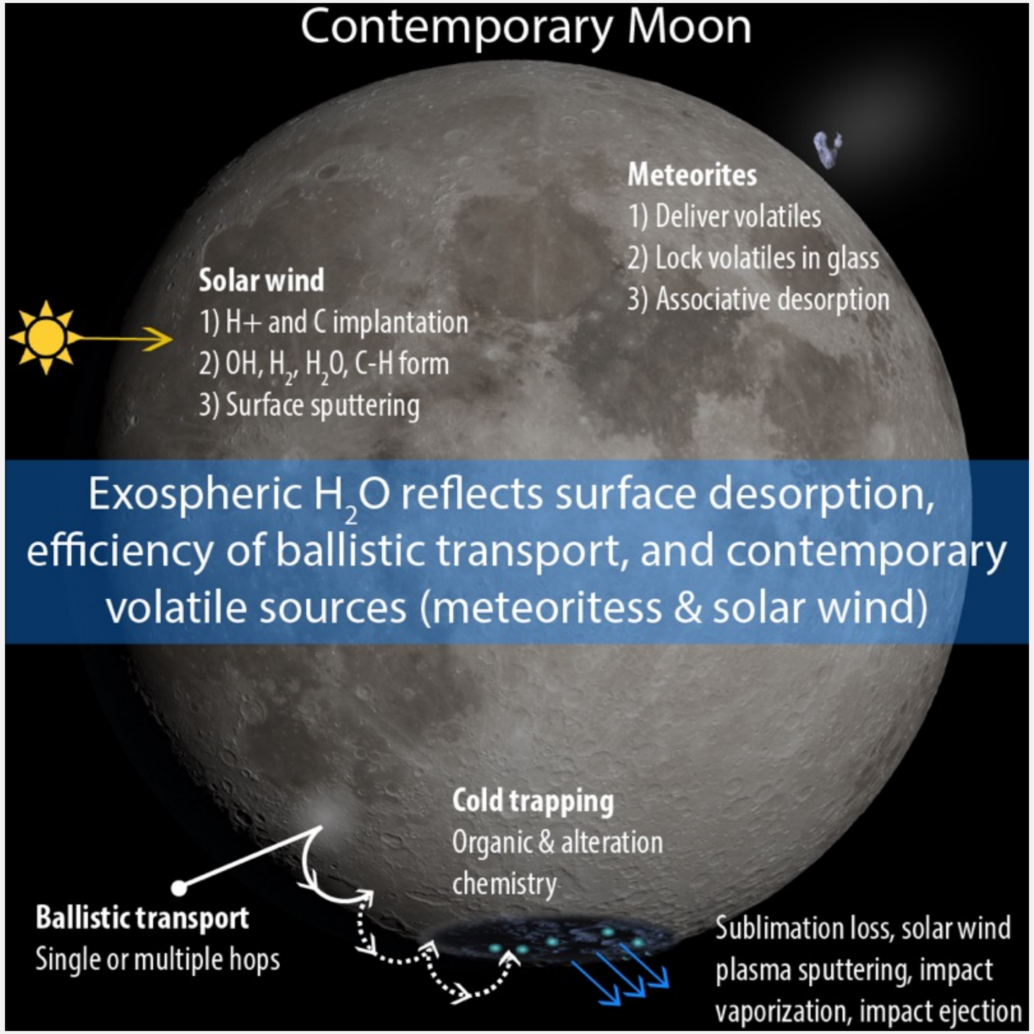
LUNAR WATER

- Of all the lunar volatiles, water is of high interest due its use as a resource for space exploration

- Before water can be used, we must understand its behavior
  - Sources – Solar wind, micrometeorites, comets, wet asteroids
  - Retention – Adsorbed on grains, locked in impact or volcanic glass
  - Abundance – 12 oz bottle of water per cubic meter or tons of ice?
  - Mobility – Can water migrate to the poles?

- In-situ measurements such as those planned by NASA's Volatiles Investigating Polar Exploration Rover (VIPER) and by remote sensing observations can characterize the lunar water cycle



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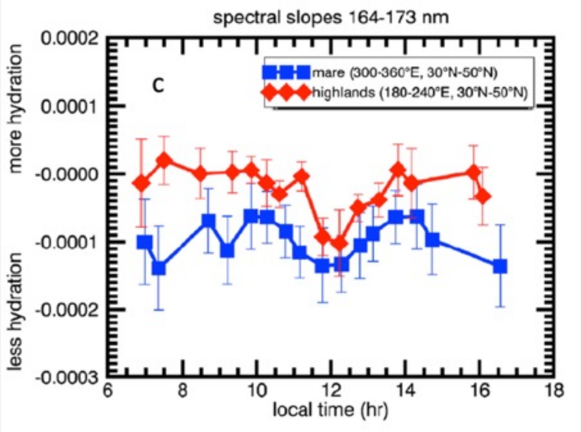
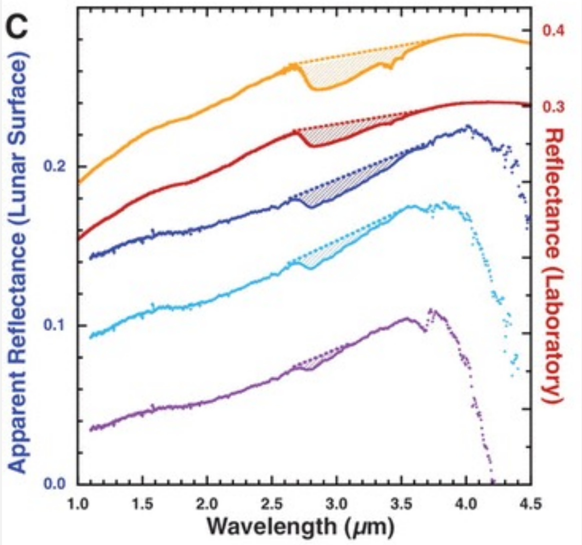
OBSERVATIONS OF LUNAR WATER

- FUV water ice band ratio
  - Diurnal signal observed in both highland and mare regions at mid-latitudes [Hendrix et al., 2019]
  - Suggest the detection H_2O on illuminated Moon assuming adsorbed H_2O behaves like water ice in the FUV
  - However, there is no data on the behavior of adsorbed H_2O in the FUV so <u>cannot rule out OH</u>

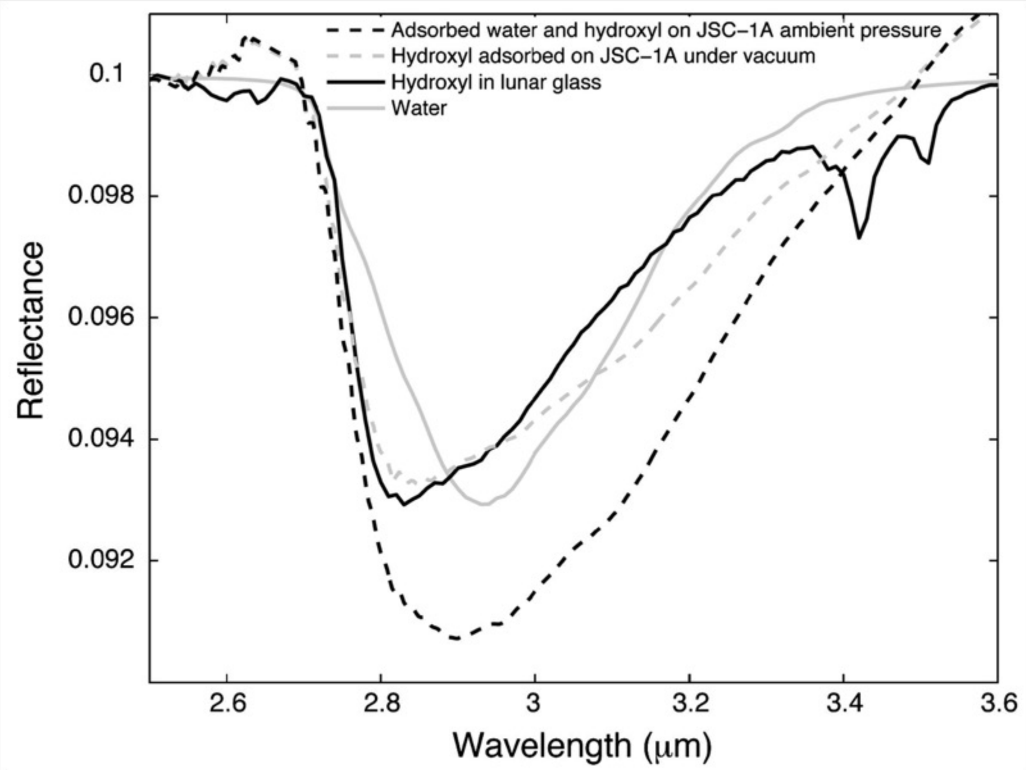


- 3 µm measurements
  - Three instruments on three spacecraft detected a 3 µm absorption feature [Pieters et. al., 2009; Sunshine et. al., 2009; Clark, 2009]
  - Attributed to hydroxyl (OH) and/or molecular water (H_2O)



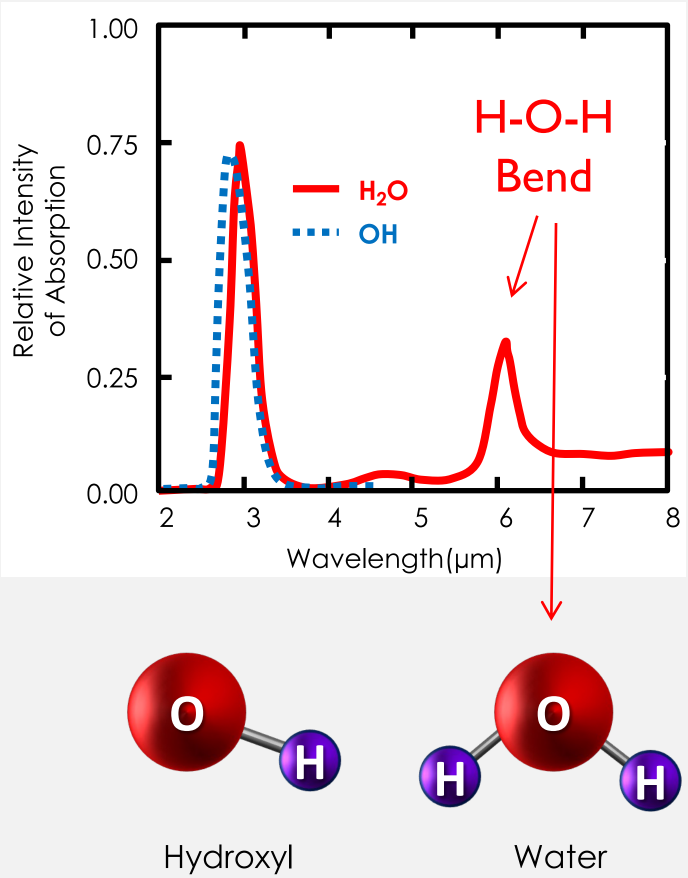
3 MICRON DATA CANNOT DISTINGUISH OH FROM H_2O

- 3 µm band created by symmetric and asymmetric stretch of the O-H bond
  - OH and H_2O exhibit a 3 µm band
- OH attached to metal cations may:
  - Cause variations in the band center
  - Broaden the band
  - Mimic the spectral shape of H_2O at 3 µm
- Band shape of OH attached to metal cations cannot be predicted
  - use of a 3 µm band minimum, depth, shape, or width is not useful for determining the speciation of water [Stolper 1982; Starukhina 2001; McIntosh et al., 2017]
- For this reason, the presence of H_2O on the lunar surface went unknown for almost a decade



UNIQUE CAPABILITY OF SOFIA

- The 6 μm spectral region:
  - Inaccessible from the ground-based observatories
  - Lacking in existing or planned lunar spacecraft
- SOFIA was the only observatory capable of measuring the water molecule in its non-icy state
  - Measures the 6 μm H-O-H fundamental bending mode of water
  - Strictly due to H_2O without confusion from OH
  - Operates above 99.9% of water vapor in the atmosphere
  - SOFIA FORCAST instrument spectral range from 5 to 8 μm
  - ~2 to 4 km spatial resolution at the center of the Moon



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ALL OBSERVATIONS OF THE MOON

Flight number	UT Date	Number Images	Reference region	Targets
F499 JADIZA	2018-08-31	12	Mare Serenitatis	Clavius
F751 OCTAVIA	2021-06-23	138	Mare Fecunditatus	Moretus
F752 OPRAH	2021-06-30	180	Highland near Pythagoras	Goldschmidt, EudoxusA, Theophilus, Bushing, Pentland, Clavius
F826 JESSICA	2022-02-17	160	Mare Fecunditatis, Mare Procellarum	VIPER region
F828 JACOB	2022-02-18	71	Mare Procellarum	Water behavior
F867 PEPE	2022-05-11	250	Mare Fecunditatis	Copernicus, Mare hydration anomaly, Water behavior
F868 PAVEL	2022-05-12	255	Mare Fecunditatus	Gruithuisen domes, Aristarchus, Mersenius, Mare hydration anomaly, Water behavior
F869 PAMELA	2022-05-13	268	Mare Fecunditatus	Water behavior
F870 PRATIK	2022-05-17	300	Mare Fecunditatis, Mare Procellarum	Gruithuisen domes, Aristarchus, Reiner Gamma, Mersenius, Water behavior
F871 PHINEUS	2022-05-18	322	Mare Procellarum	Proclus, Gruithuisen domes, Reiner Gamma, North pole, Water behavior
F872 PANDORA	2022-05-19	240	Mare Tranquilitas, Mare Procellarum	Gruithuisen domes, Water behavior
F910 VOLKER	2022-09-07	234	Mare Fecunditatis	North pole region
F911 VIKRAM	20220908	350	Mare Fecunditatus	North pole region
F912 VENTURE	2022-09-09	310	Mare Fecunditatis, Mare Procellarum	South pole region
F913 VIVIAN	2022-09-14	173	Mare Tranquilitatis, Mare Procellarum	Apollo 11, 17, Goldschmidt, Theophilus, Humorum pyroclastic, Kepler
F914 VULCAN	2022-09-15	147	Mare Procellarum	Plato, Mairan domes, Sulpicius Gallus pyroclastic, Apollo 16, Theophilus, Tycho
F915 VIRGIL	2022-09-17	237	Mare Procellarum	Apollo 14, Aristarchus, Sinus Aestuum pyroclastic, Rima Bode pyroclastic, Humorum Pyroclastic

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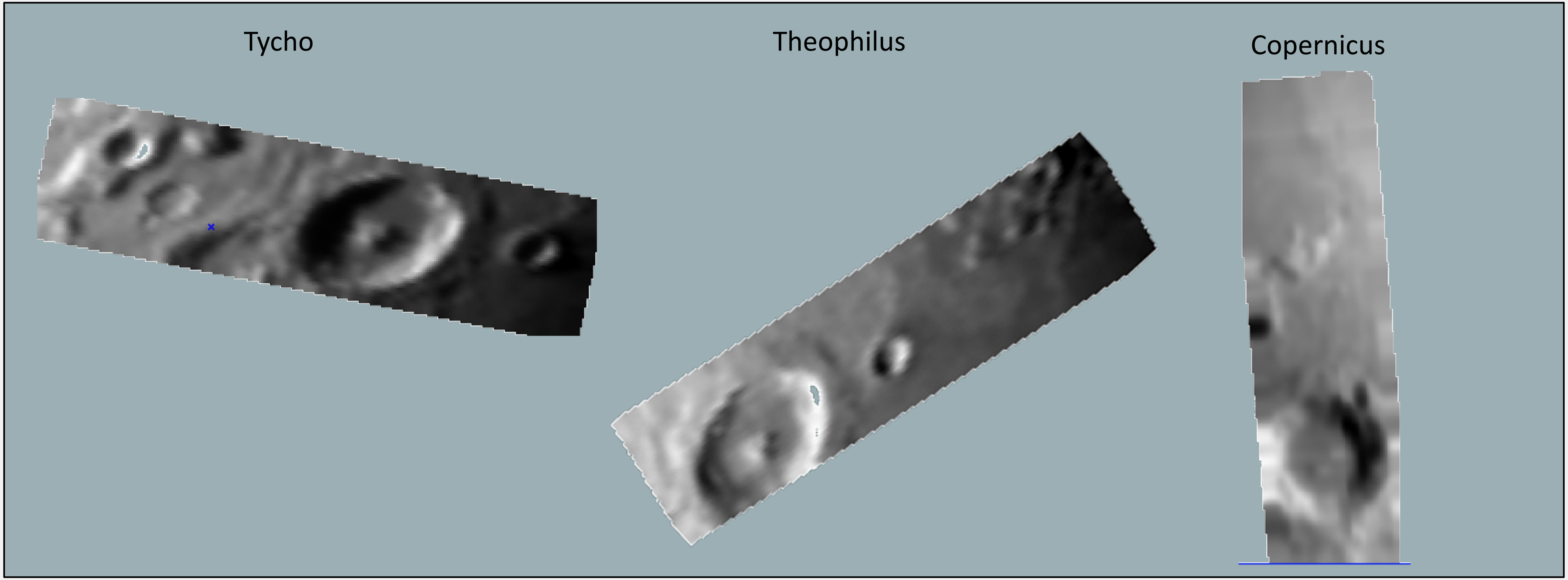
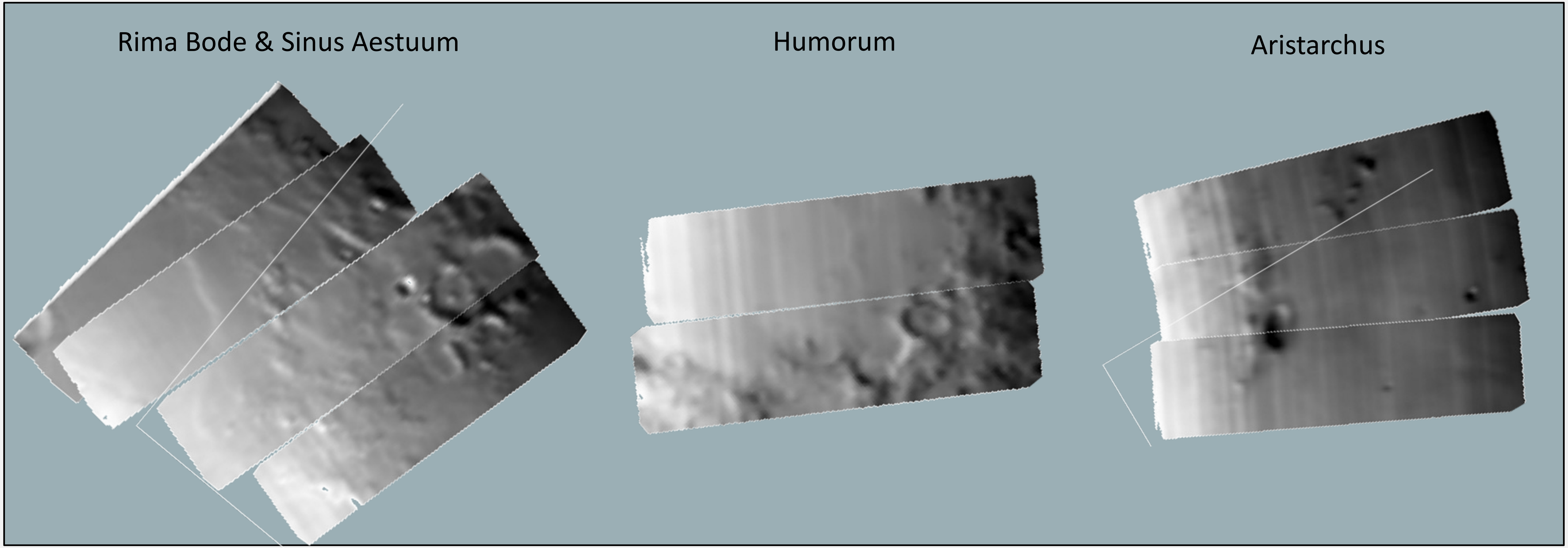
CENTRAL PEAKS



VOLCANIC DEPOSITS



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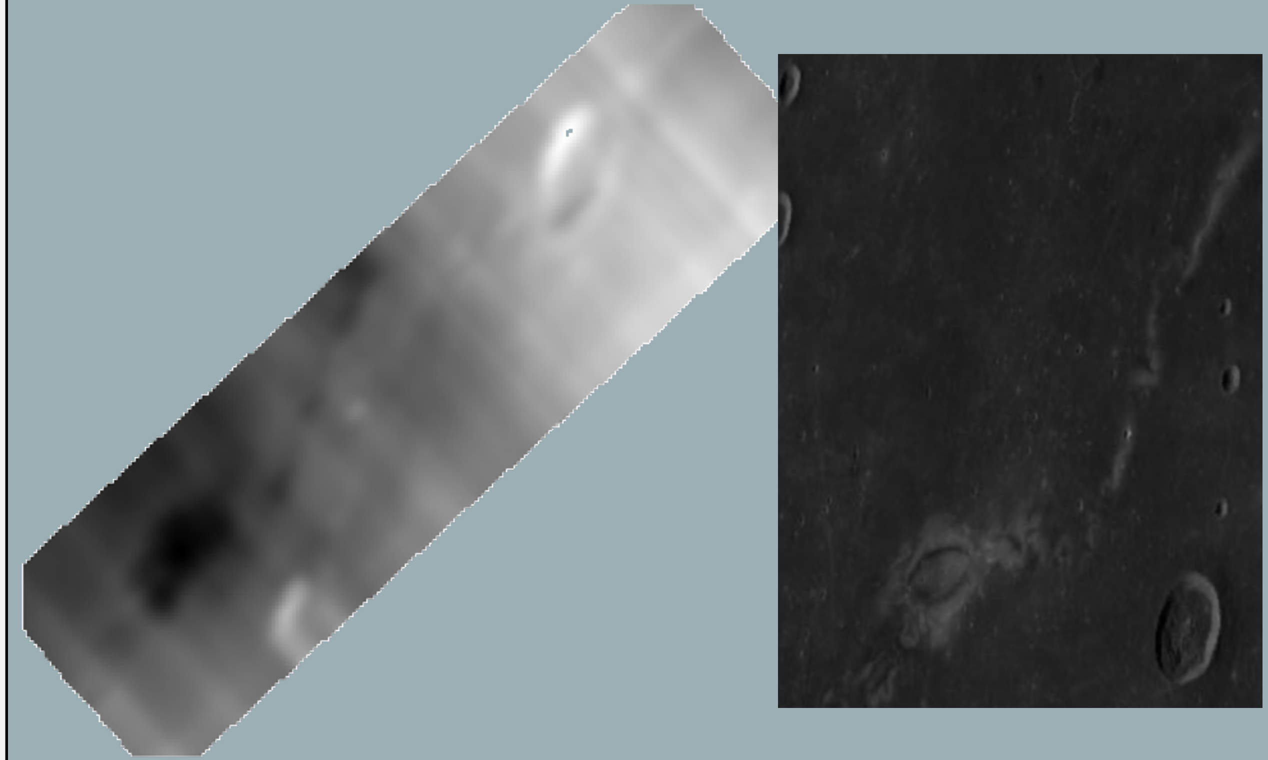
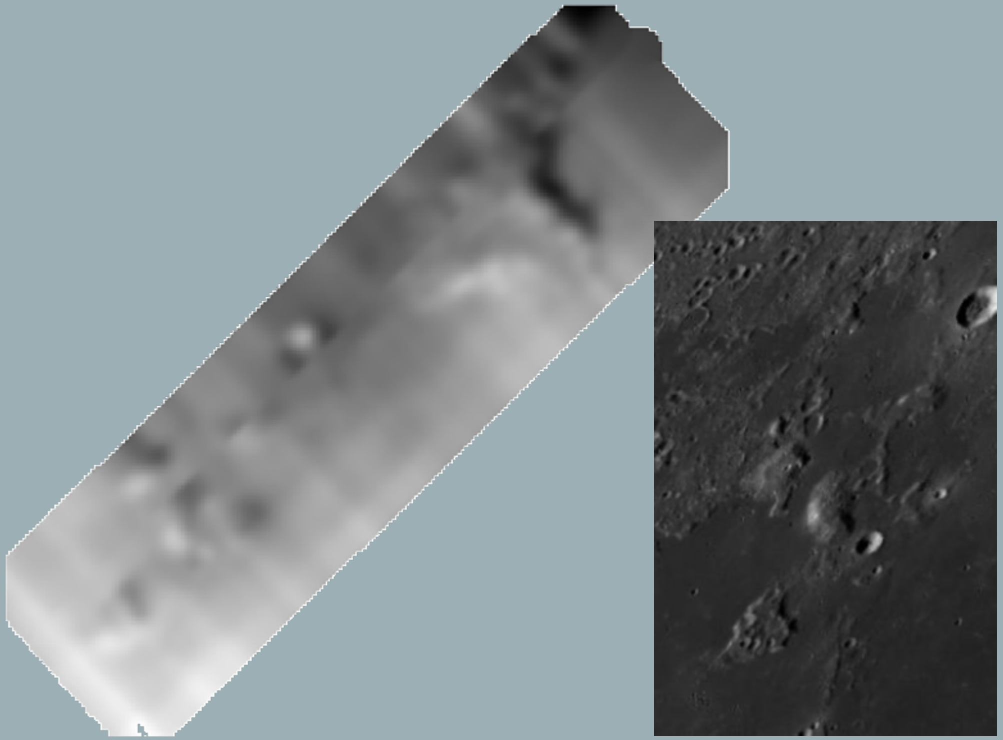
COMMERCIAL LUNAR PAYLOAD SERVICES LANDING SITES

Reiner Gamma

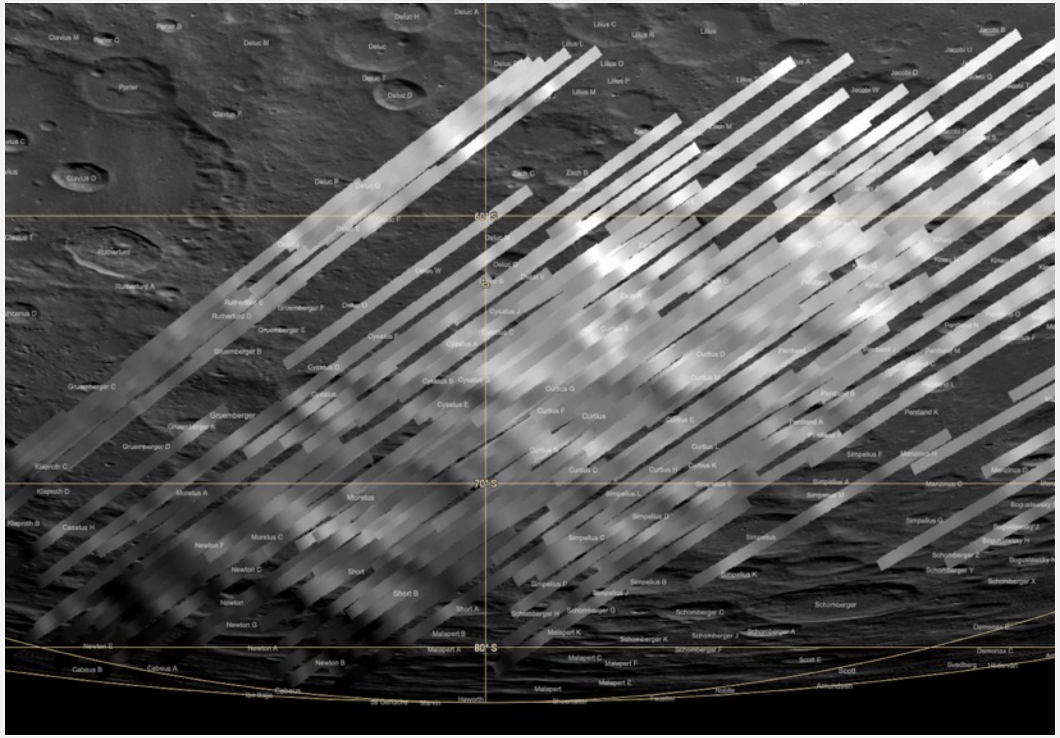


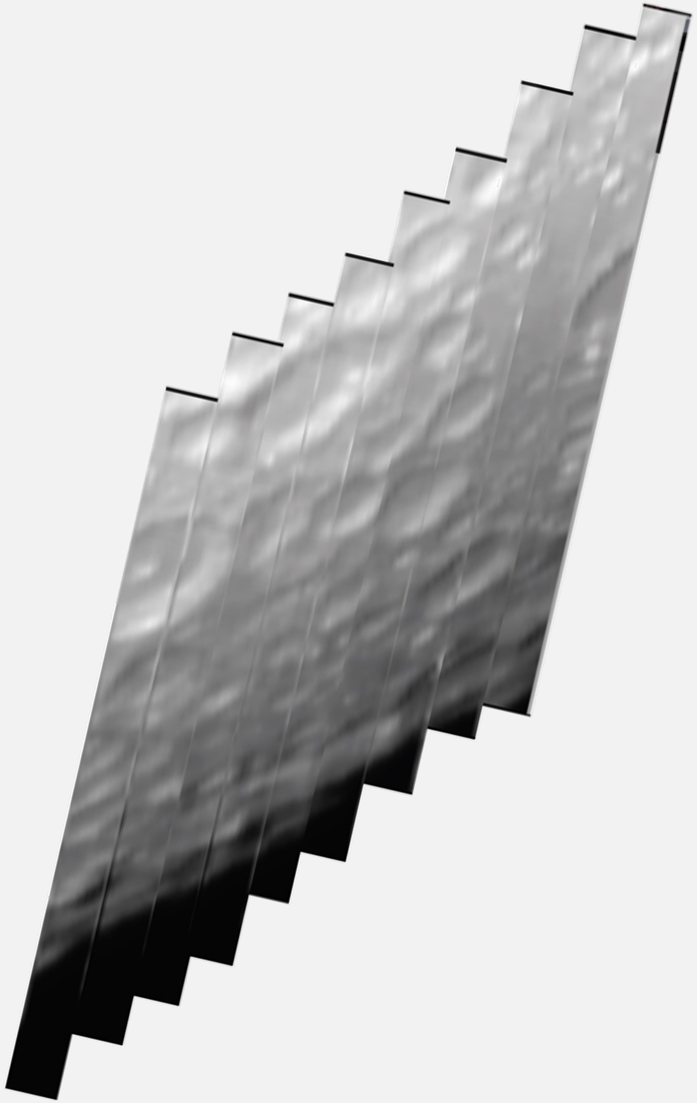
Gruithuisen domes



DATA FOR TODAY'S DISCUSSION

- F751 OCTAVIA on June 23, 2021
  - Target: Moretus crater   Reference: Mare Fecunditatus
- F826 JESSICA on February 17, 2022
  - Target: VIPER region   Reference: Mare Fecunditatis, Mare Procellarum





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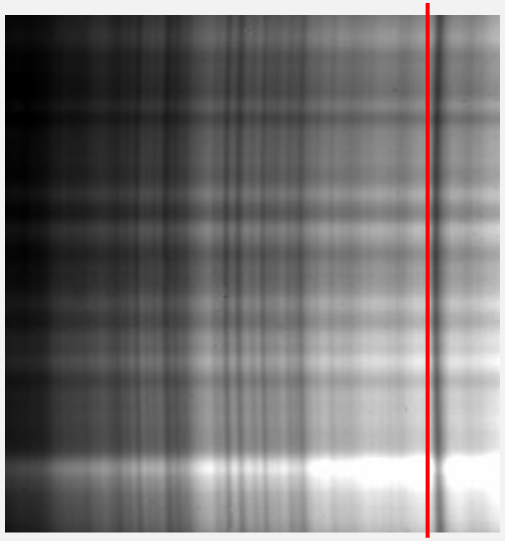
OVERVIEW OF DATA PROCESSING

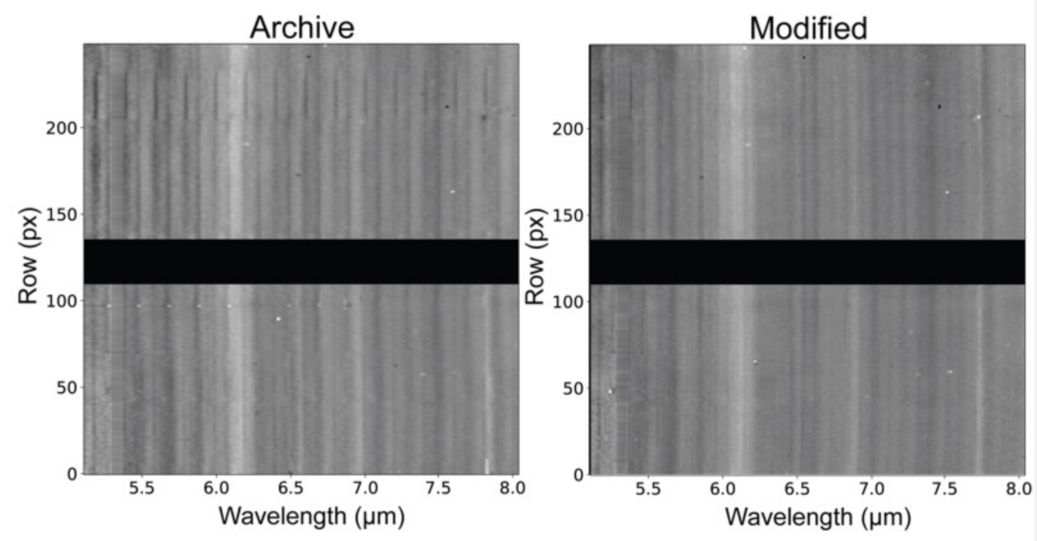


Processing data through the FORCAST pipeline revealed issues for mitigation

- Most important is a systematic variation in wavelength position with row
  - Spectral lines are curved
  - ATRAN models using a single wavelength calibration show registration artifacts
  - The wavelength calibration was updated using the known position of atmospheric lines so that each row shares the same wavelength calibration

- Pipeline ATRAN models have single digit increments of precipitable water, giving rise to significant residual water vapor artifacts
  - Increasing the model increments from 1.0 to 0.1 μm greatly improved the fits

- Jailbar artifacts at the ~1% level remain after pipeline processing
  - Interpolating jailbar columns prior to insertion into the pipeline mitigated this issue



Processing with the FORCAST pipeline with these input modifications yield excellent results

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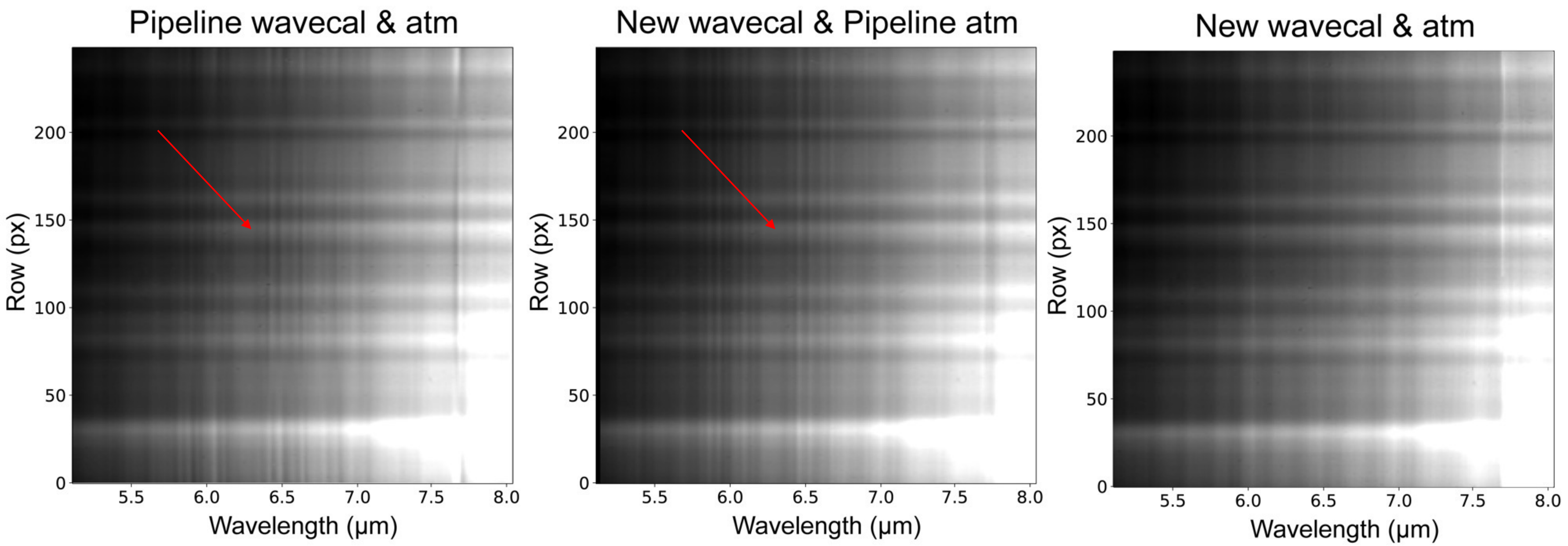
PROCESSING COMPARISON



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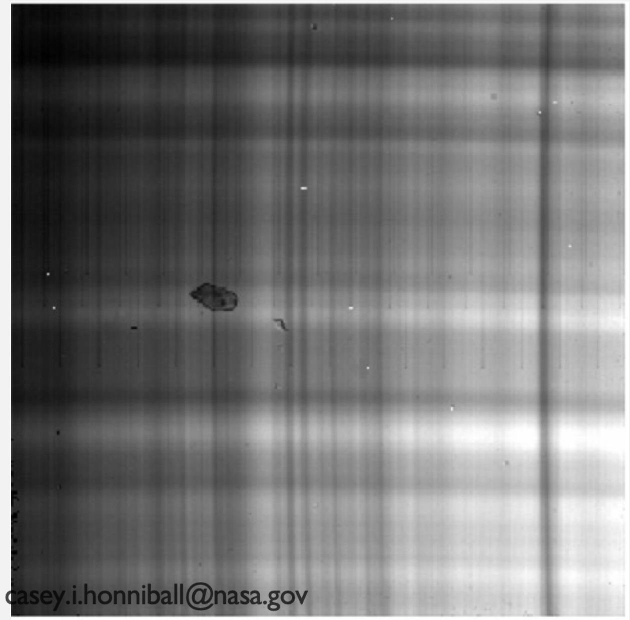
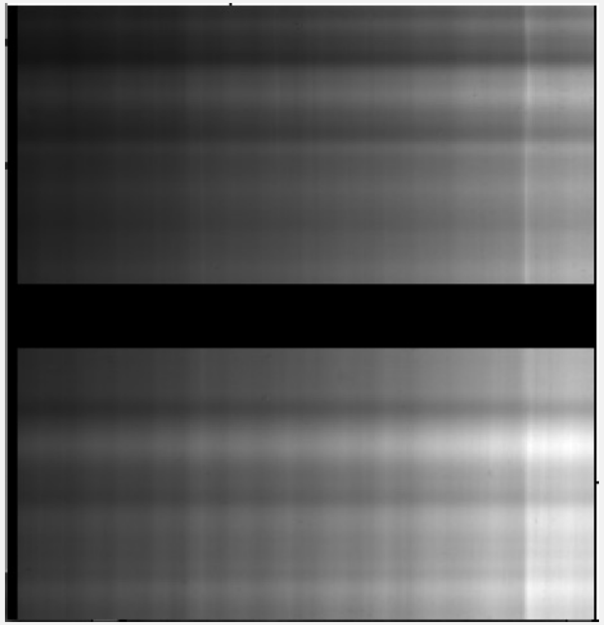
CORRECT OSCILLATION

- Oscillatory artifact appears in calibrated flux data
  - Correction of it requires a lunar reference
- Apply oscillation images to Moretus frames (Moretus/oscillation)
  - Preserves flux values
- Smudge on the array causes the center of the image to be spectrally unusable (black bands)

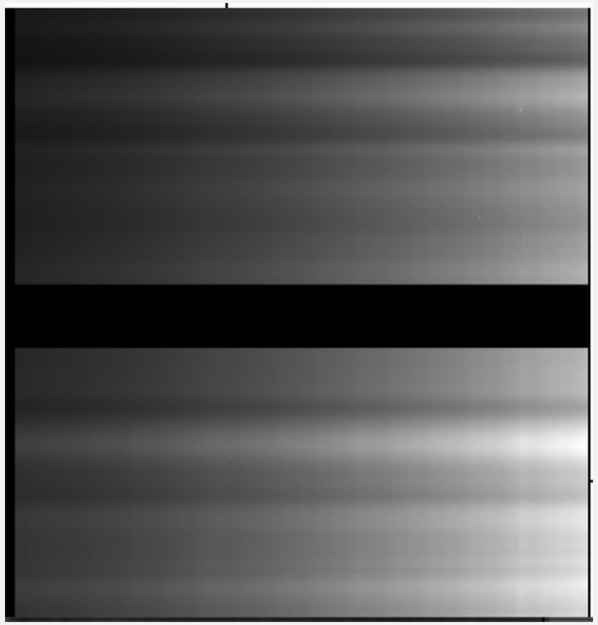
Raw Moretus

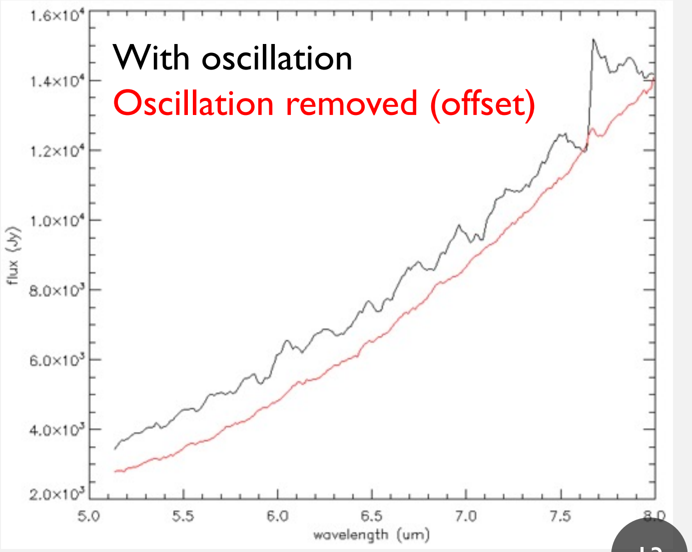


Flux wavelength & atmospherically corrected



Oscillation removed





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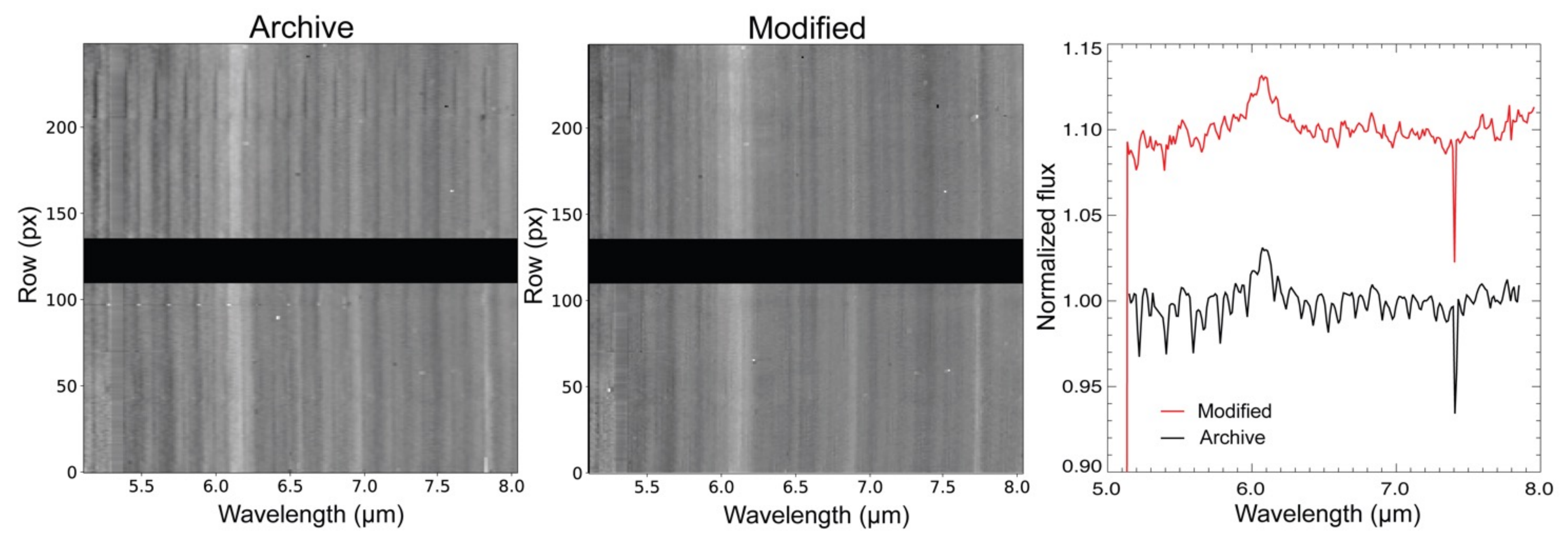
ADDITIONAL CLEANING

- Some residual oscillation and jailbars remain in both the archived and modified processes

- To further clean the spectra, we apply an FFT to each line in the continuum removed spectral images
  - In FFT space mask every ~15th pixel to zero

- The modified FFT images are used to characterize the 6 μm BAND



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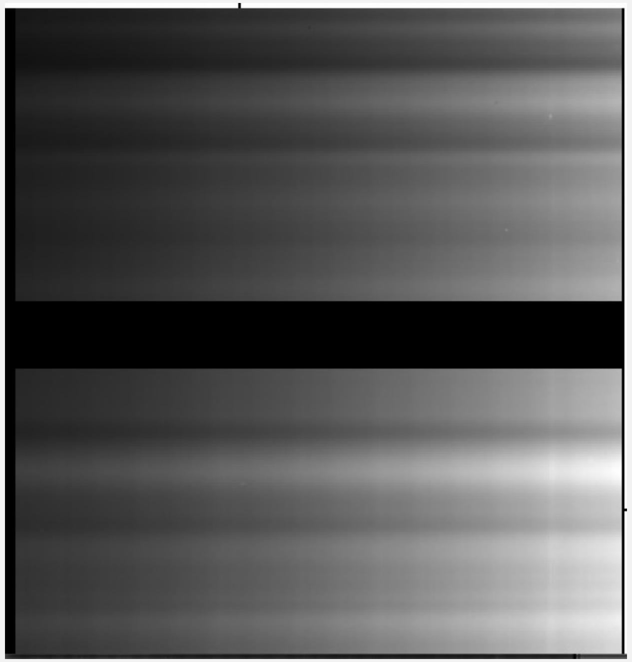
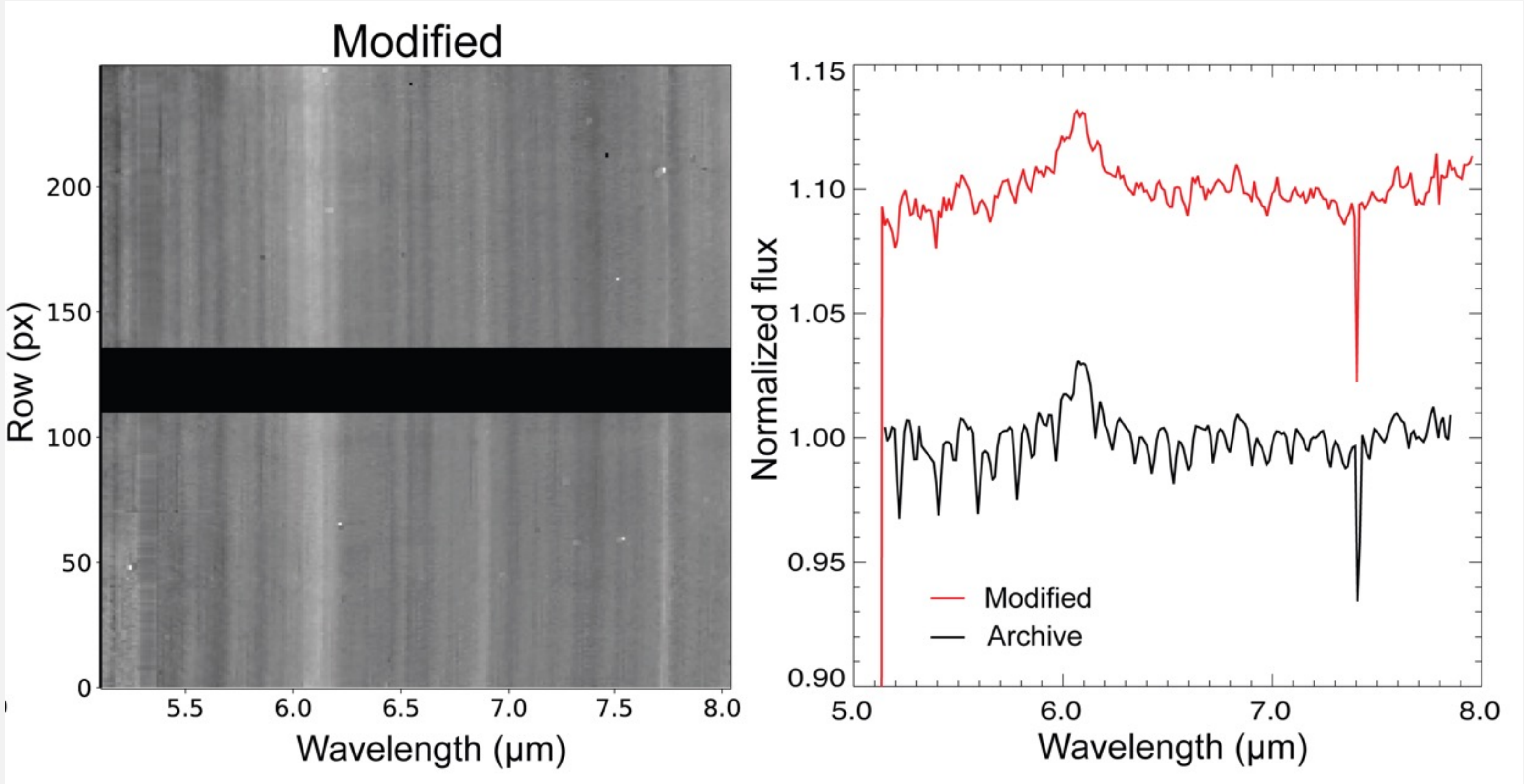
PROCESSING CONCLUSION

It is extremely important to note that the only <u>required</u> modification we made is the wavelength calibration

- All other modifications make small changes that clean up the final spectral image and spectra
- If no modifications are made the data still show the 6 µm band and it can still be characterized, however, we caution if the correction to the wavelength calibration is not performed the band centers will be incorrect

Oscillation removed





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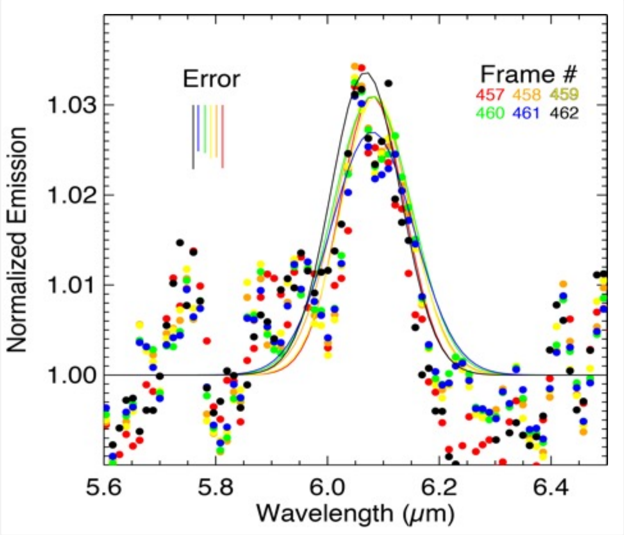
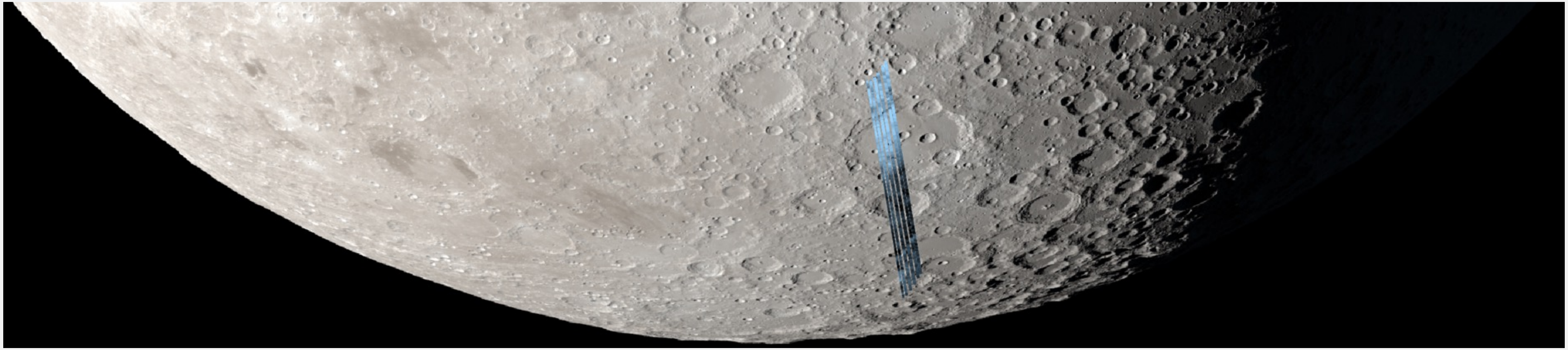
FIRST DIRECT DETECTION OF WATER

- In 2020 we reported the detection of a 6 μm emission feature on the sunlit lunar surface using SOFIA
- First time we can be confident H_2O exists on surfaces outside permanent shadows
- Clavius crater region shows 100 to 400 ppm H_2O





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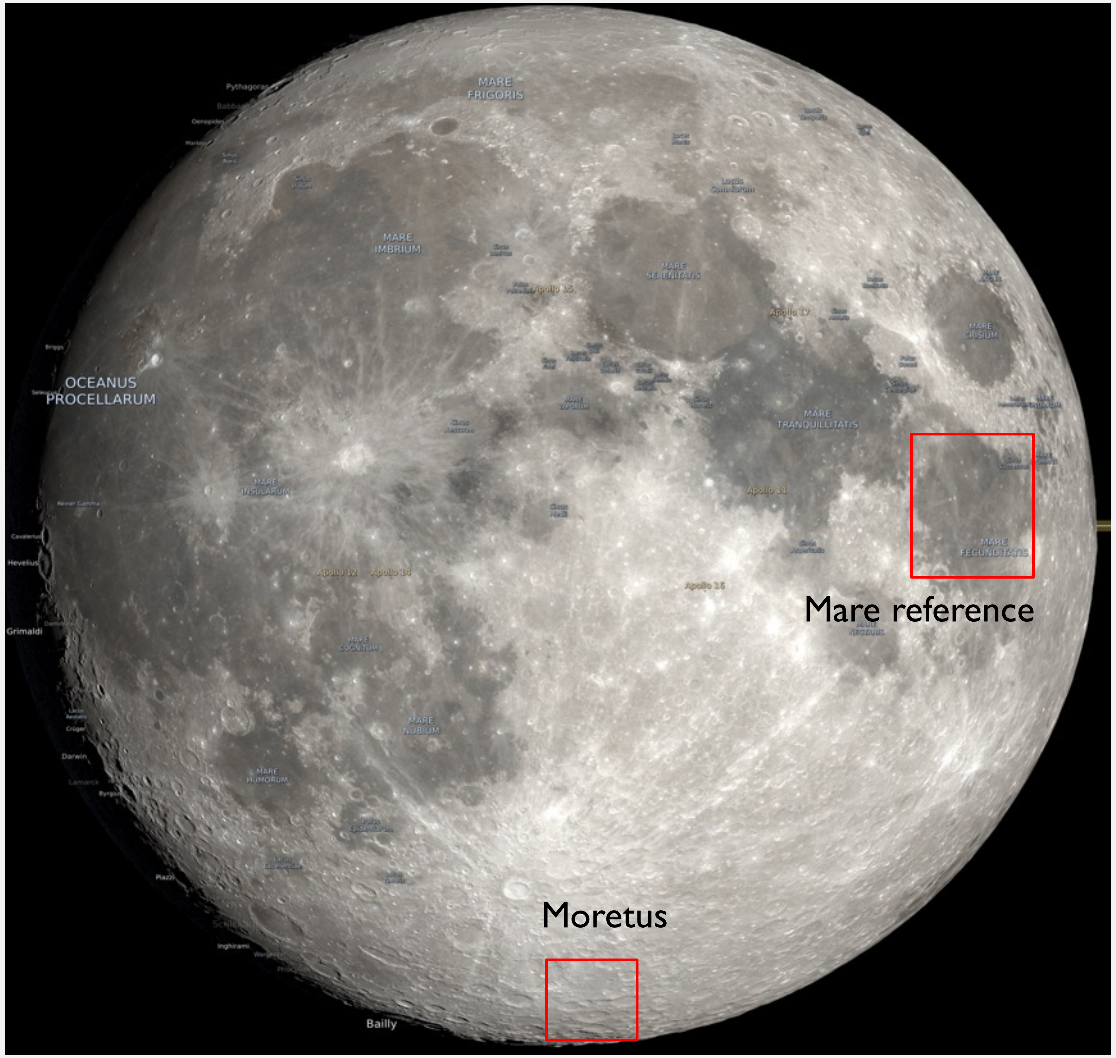
FOLLOW UP OBSERVATIONS

- High southern latitudes near Moretus crater mapped on June 23rd 2021
- Technical goal: Demonstrate FORCAST could be used as an imaging spectrometer
- Scientific goal: Confirm Honniball et al., 2020 detection and map water at high southern latitudes to look at spatial variations
- Data collected flight FO751on 6/23/2021
  - 94 Moretus crater frames – slit scanning
  - 32 mare reference frames – no scan



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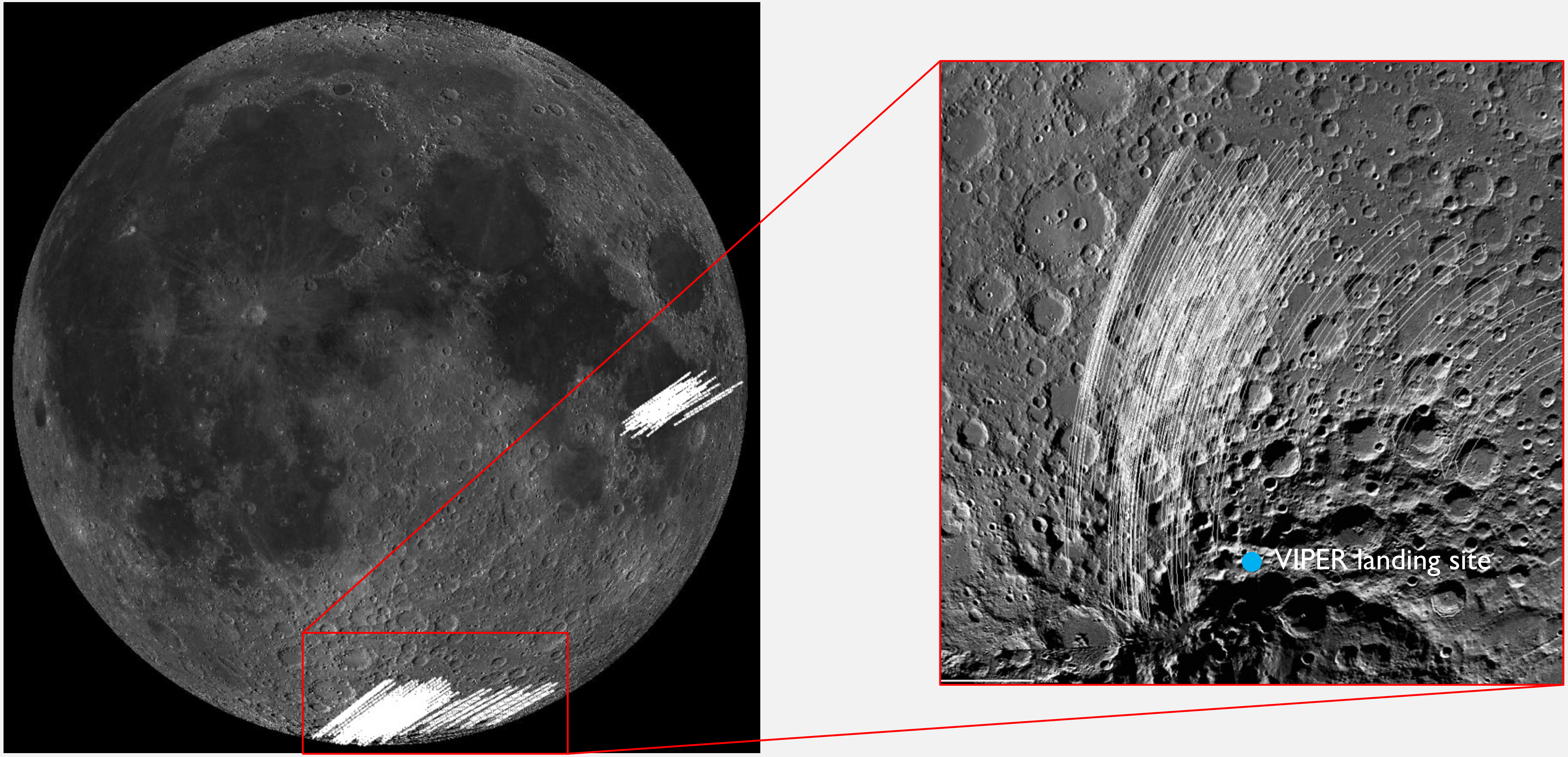
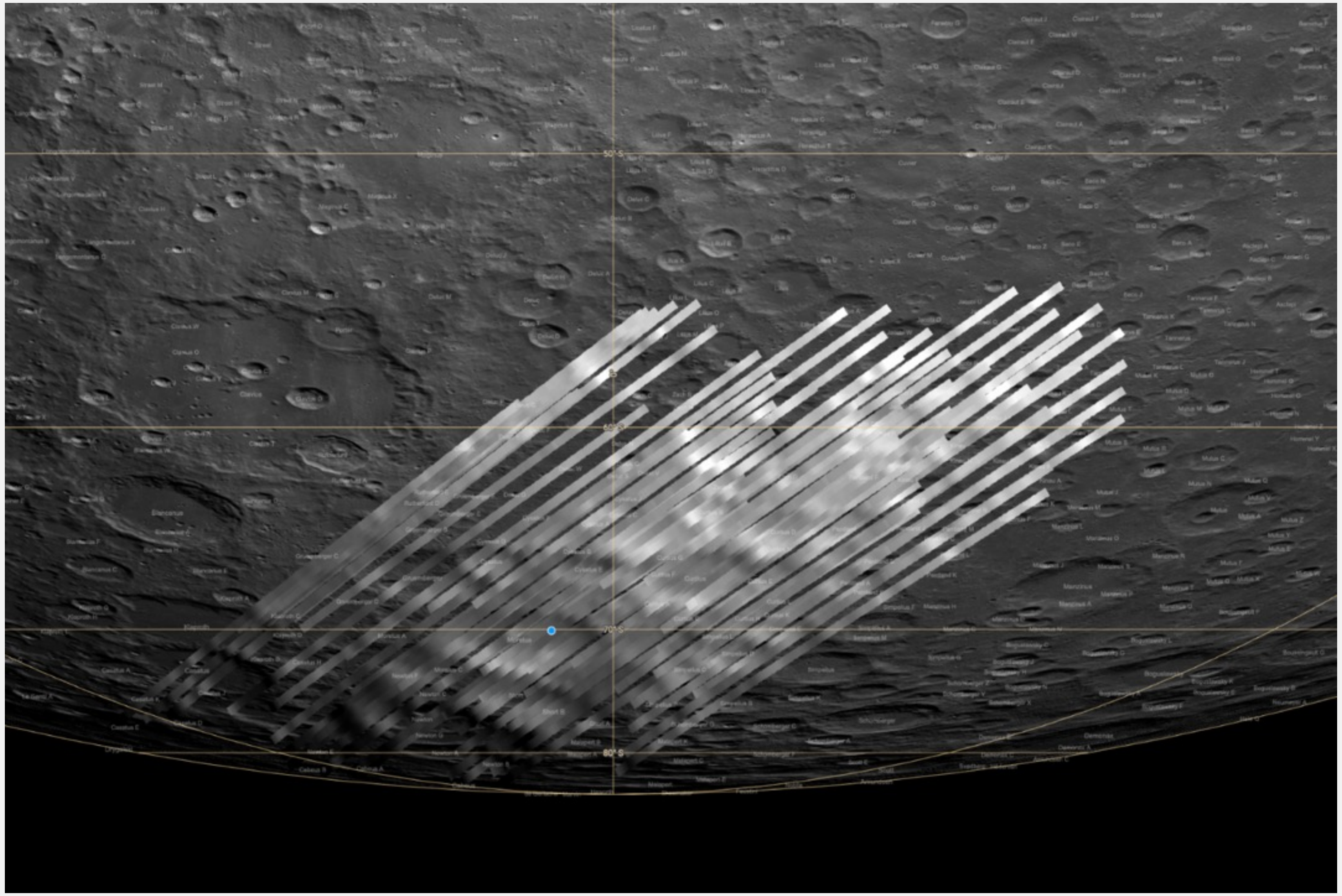
MAPPING FORCAST SLIT ONTO MOON – MORETUS



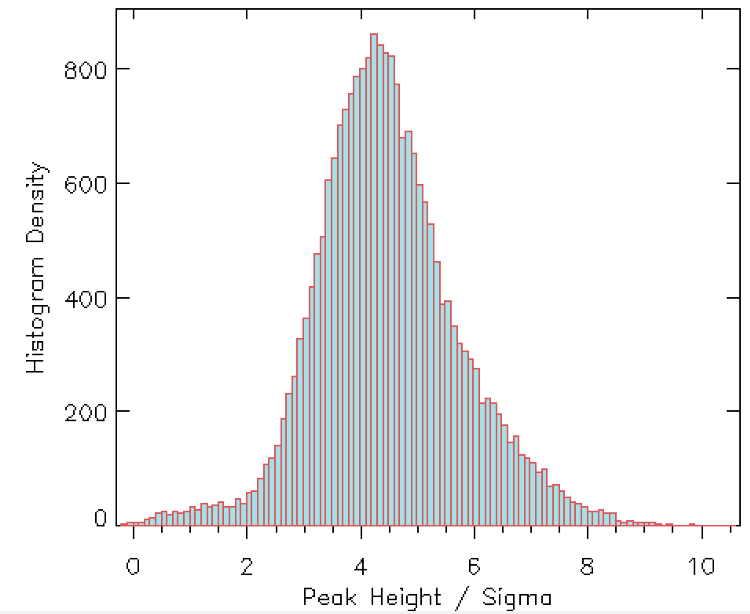
FORCAST FLUX MAP

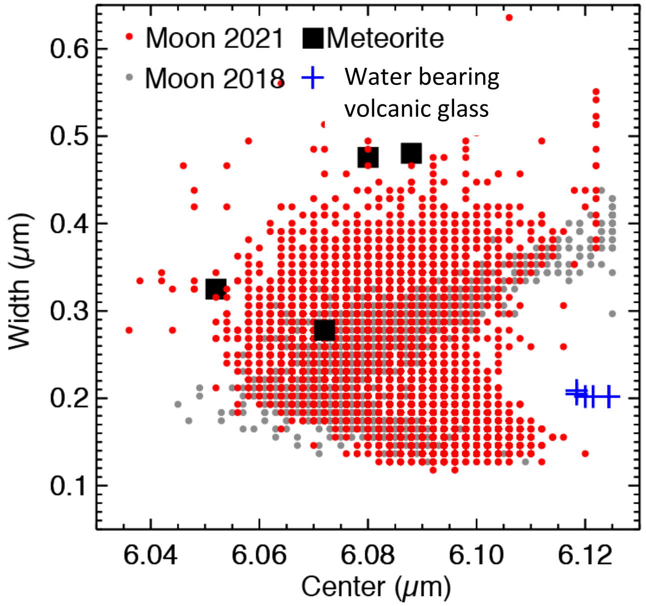
- Part of the flight was perfecting mapping efforts
- During the last scan, the telescope operators were confident in the mapping procedure and produced a small map without gaps between slits
- Mapping efforts have result in consistent and larger maps for data acquired in February

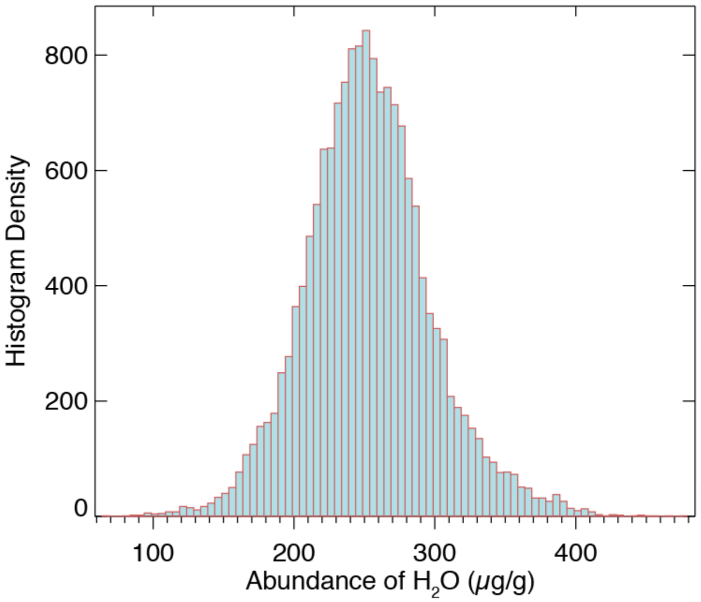


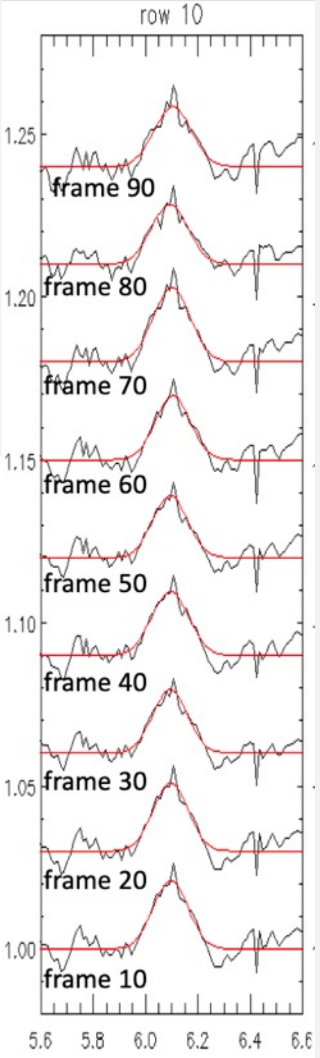
6 µm BAND CHARACTERIZATION

- A 6 µm band is observed in all spectra acquired in the Moretus crater region
- Zscore shows majority of bands are above the 95% confidence level
- Band centers and widths of 2021 data consistent with previous flight and laboratory measurements of water bearing material
- Abundance of water between 100 to 400 ppm H_2O









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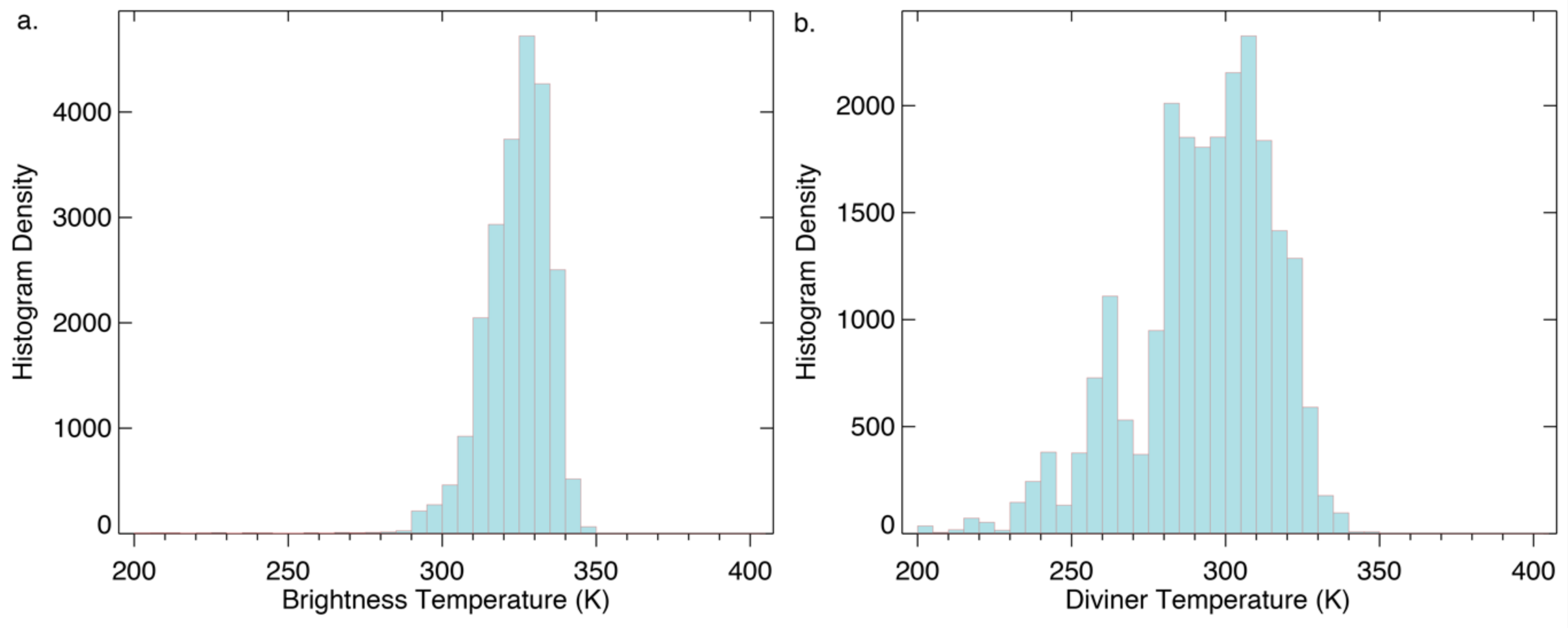
LUNAR TEMPERATURES

- Flux derived brightness temperatures in the range of Lunar Reconnaissance Orbiter Diviner Lunar Radiometer temperatures for the same latitude, longitude, and lunar time of day

- Indicates accurate flux calibration

SOFIA

Lunar Orbital Radiometry



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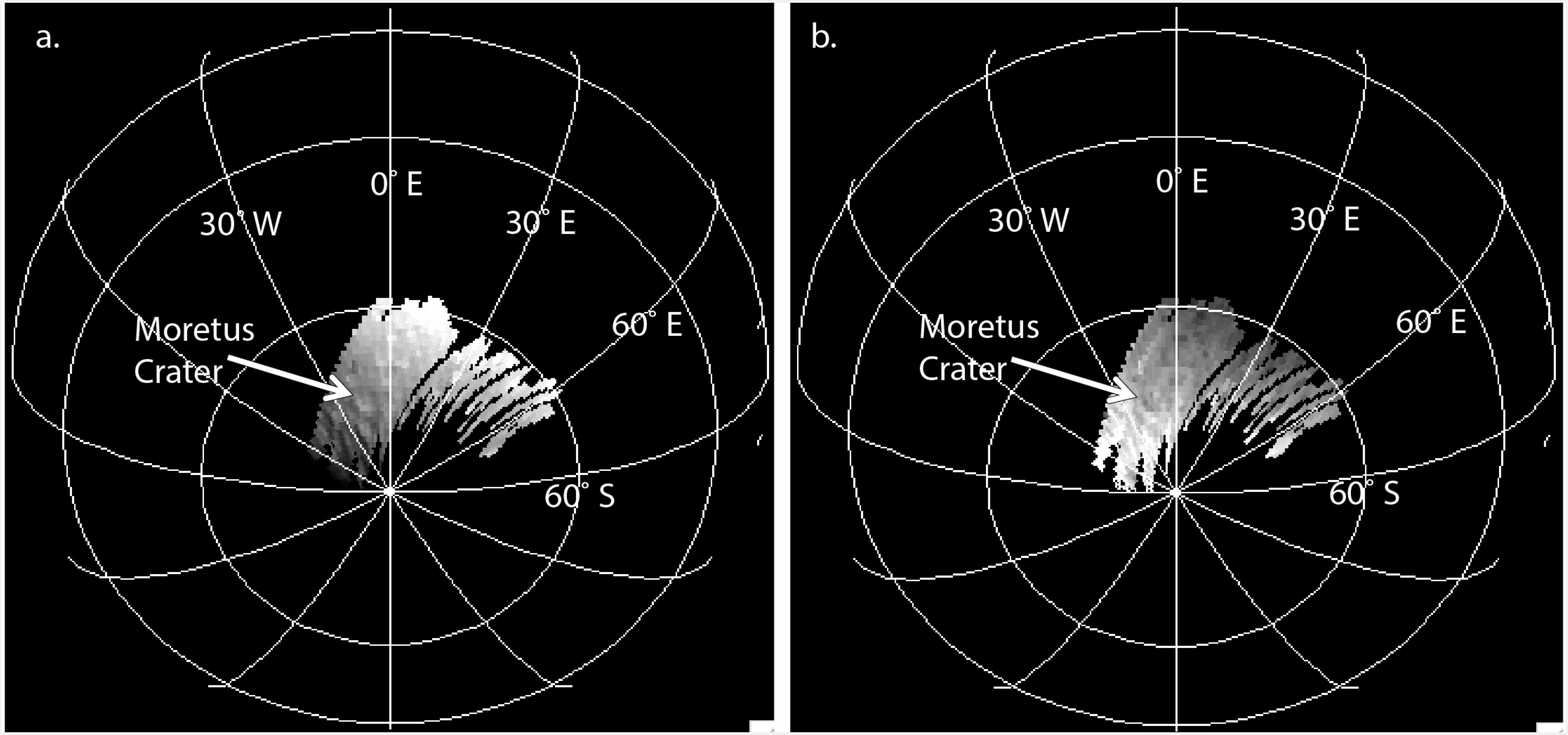
MAP OF 6 μm LUNAR WATER

- Craters and other topographic features are readily apparent in the flux image
- At high incidence angles, lunar thermal emission is dominated by local slopes resulting in images that appear very similar to visible images of the Moon
- 6 μm peak height shows higher abundances of water measured at higher latitudes and inverse correlation with flux

Flux

6 μm Peak Height



Honniball, C. I., P. G. Lucey, A. Arredondo, W. T. Reach, and E. R. Malaret. 2022. "Regional map of molecular water at high southern latitudes on the Moon using 6 μm data from the Stratospheric Observatory For Infrared Astronomy." *Geophysical Research Letters*, [10.1029/2022gl097786]

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STORAGE OF WATER

- Honniball et al. (2020) concluded that water is trapped in glass and not able to migrate

- If all observed water (~200 ppm) is exchangeable with the exosphere, then the exospheric density of water would be ~10^{18} to 3×10^{9} molecules per cubic cm far above limits of Benna et al. 2019, based on mass spectroscopic water measurements from lunar orbit

- This suggests most of the water **is not exchangeable**, and supports the contention by Honniball et al. (2020) that the water sensed by SOFIA+FORCAST cannot be that of migrating water

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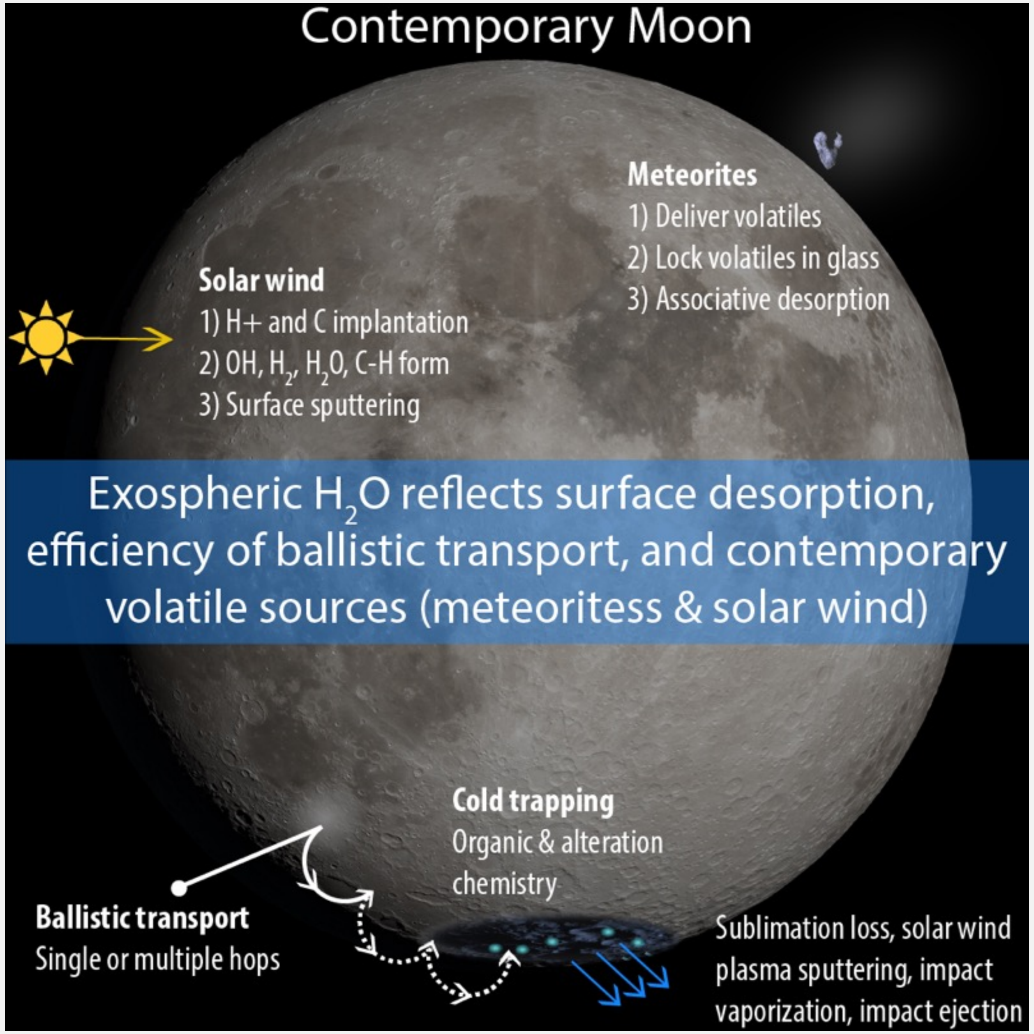
IMPLICATIONS FOR MODELS

- Our data are consistent with two models:
- Jones et al. (2018)
  - Hydroxyl is eroded from low latitudes through recombinant desorption (OH+OH = H_2O+H)
  - Water is formed from pre-existing hydroxyl then trapped in impact glass (Zhu et al., 2019)
- Tucker et al. (2019)
  - Hydrogen diffuses through the surface creating metastable hydroxyl
  - Surface need only be hydrogenated
- Based on our surface abundance, ballistic migration is inconsistent with the exospheric limits imposed by LADEE
- We measured the temporal variability of the 6 μm water band to test if our conclusion is supported by weak or absent variations of water on the surface

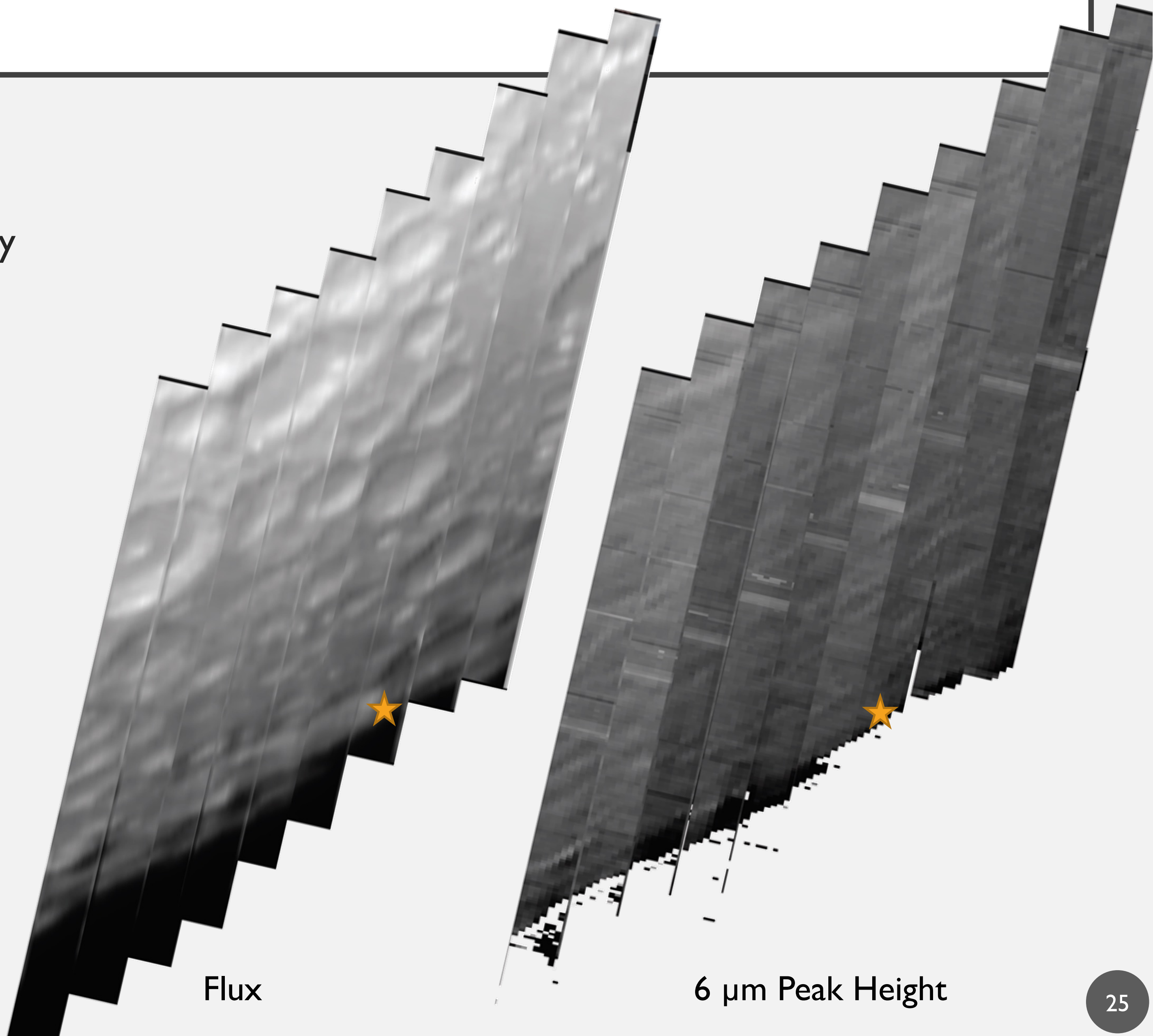


MAPPING THE VIPER REGION – PRELIMINARY RESULTS

- Mapped the VIPER landing site and region in February 2022

- Working on producing maps of water across the region

- Place VIPER measurements of water and hydration into regional context
  - Constraints on how much water is present in the VIPER NIRVSS 3 μm measurements
  - Enhanced water on the southern rim of Nobile



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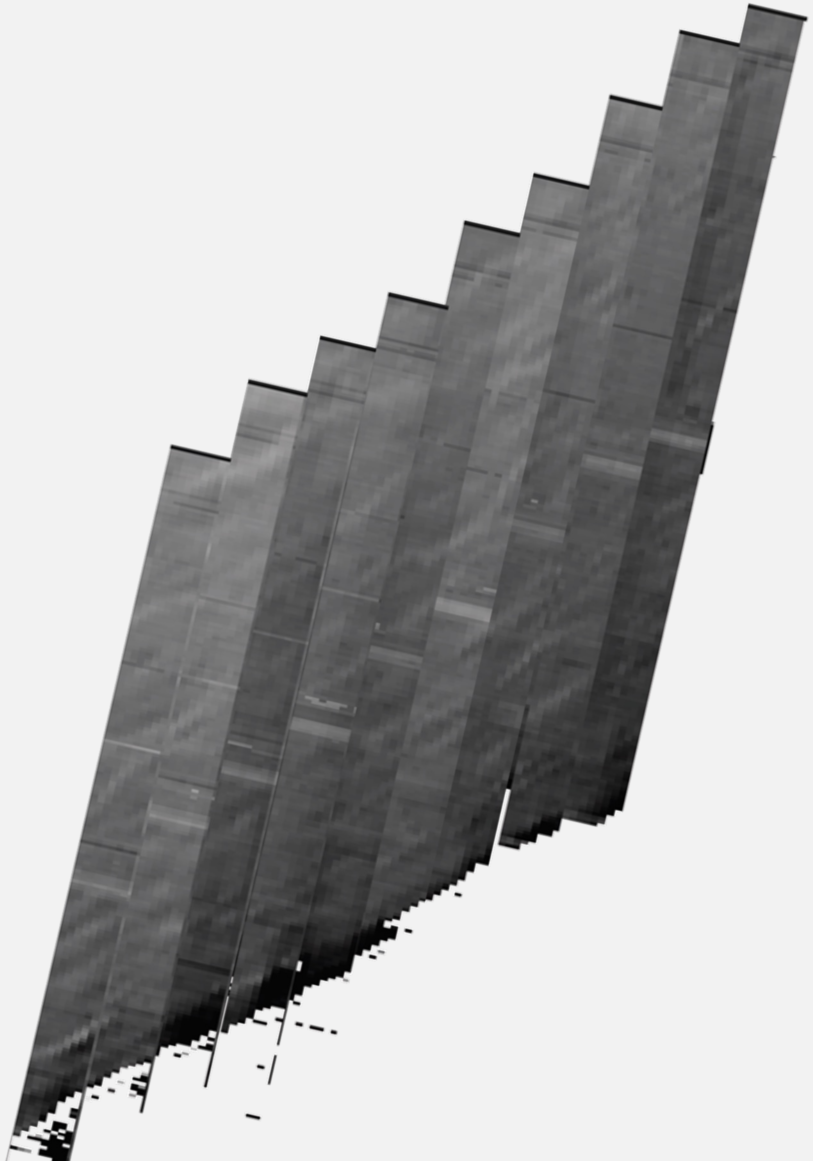
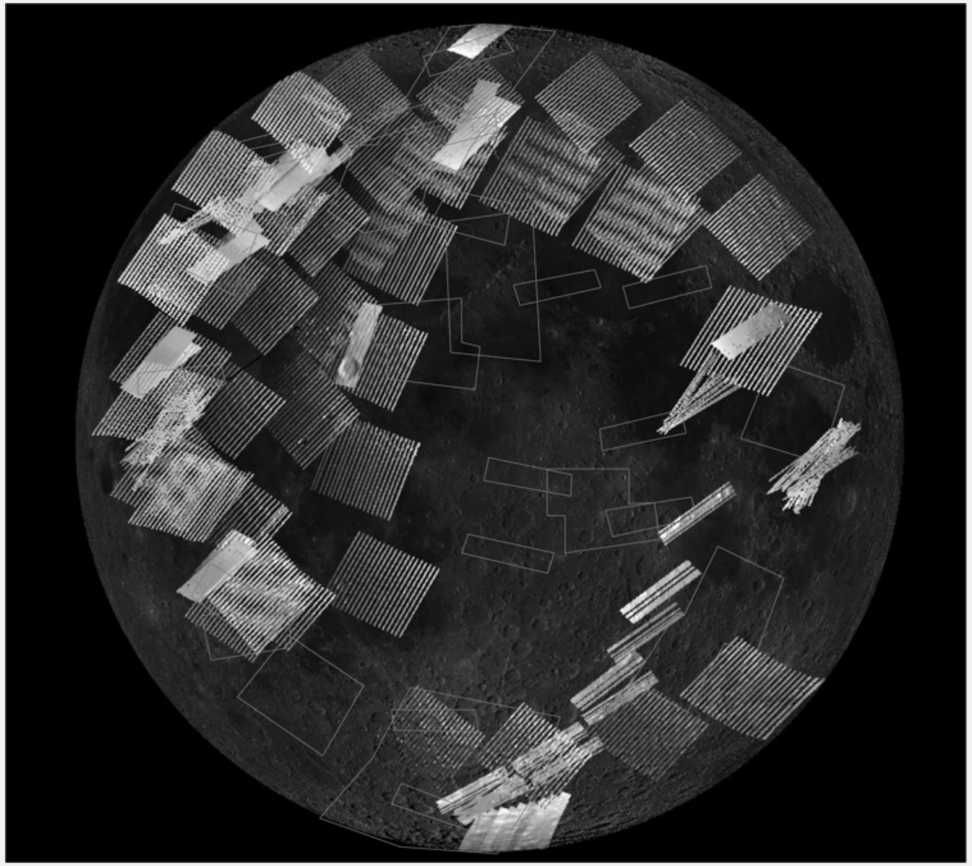
CURRENT ISSUES WITH THE VIPER DATA

- Each tile in the water map has different values than its neighbors causing bright and dark tiles
  - Removing the average spectrum improves the map quality
- The large scale gradient of the water map appears to have more water at lower latitudes, opposite of previous observations
  - Possibly due to the reference temperature gradient being opposite the target temperature gradient



THANK YOU!

- August 2018 and June 2021 observations show an increase in water with increasing latitude
  - Abundances in the 100 to 400 ppm H2O range
  - Based on lunar temperatures and LADEE measurements, water is likely trapped
- February 2022 observations show a decrease in water with increasing latitude
  - Which is correct? Could the reference temperature gradient flip the trend?
  - Some topographic features show enhanced water while others do not
  - Strong peak of water on the southern rim of Nobile may be of interest to VIPER
- Much more data to be processed and interpreted!



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