Hyperspectral CoSMIR-H Aircraft Instrument and the WH^{2}yMSIE Campaign

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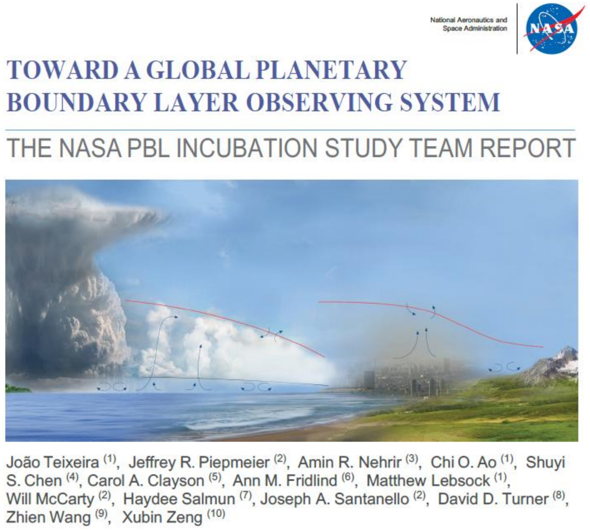
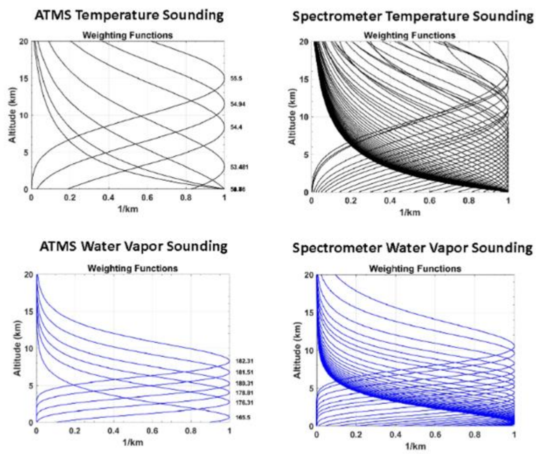
GSICS Annual Meeting

19 March 2025

Introduction



https://science.nasa.gov/earth-science/decadal-pbl



Motivation:
Planetary Boundary Layer (PBL) Study Team Report lists hyperspectral microwave (HMW) sensors as one of the ***"Essential Components"*** of a future global PBL observing system, to provide ***"accurate PBL and free tropospheric three-dimensional (3D) temperature and water vapor structure context"***

Objective:

- Build an airborne HMW sensor and collect observations to demonstrate capability of HMW sounding, especially in the PBL.
- Enhance the airborne CoSMIR instrument with hyperspectral receivers (renamed CoSMIR-H) by utilizing ASIC spectrometers to give **full spectrum coverage at 50-58 GHz and 175-191 GHz** and conduct flights to collect data.

What is Hyperspectral Microwave?

GODDARD EARTH SCIENCES

NASA

Sampling of Papers: 2010-2015

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 49, NO. 1, JANUARY 2011

Hyperspectral Microwave Atmospheric Sounding

William J. Blackwell, *Senior Member, IEEE*, Laura J. Bickmeier, R. Vincent Leslie, Michael L. Pieper, Jenna E. Samra, Chinnawat Surussavadee, *Member, IEEE*, and Carolyn A. Upham

Benefits of a Hyperspectral Microwave Sensor

Applications in Environmental Monitoring and Weather Forecasting

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Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1002/2015JD023331

Microwave hyperspectral measurements for temperature and humidity atmospheric profiling from satellite: The clear-sky case

Key Points:
- A hyperspectral MW instrument could improve temperature & humidity retrieval compared to MetOp-SG
- The main impact from HYMS comes from higher resolution in the O₂ band

Filipe Aires[1,2,3], Catherine Prigent[1,2], Emiliano Orlandi[4], Mathias Milz[5], Patrick Eriksson[6], Susanne Crewell[4], Chung-Chi Lin[7], and Ville Kangas[7]

RMetS
Royal Meteorological Society

Information content on temperature and water vapour from a hyper-spectral microwave sensor

J.-F. Mahfouf,[a*] C. Birman,[a] F. Aires,[b,c] C. Prigent,[c] E. Orlandi[d] and M. Milz[e]

NOAA BAA 2022

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

BROAD AGENCY ANNOUNCEMENT: Demonstrating the Hyperspectral Microwave Sensor (HyMS) and Assessing the Benefits for NOAA/NESDIS

WE2.R18: Hyperspectral Microwave Sounder Science and Technology

Wed, 19 Jul, 10:15 - 11:30 Pacific Time (UTC -7)

Location: Room 18
Session Type: Oral
Session Co-Chairs: Jeffrey Piepmeier, NASA and William Blackwell, MIT Lincoln Laboratory
Track: Community-Contributed Sessions

IGARSS 2023 Special Session

How many channels are needed to be considered “hyperspectral”?

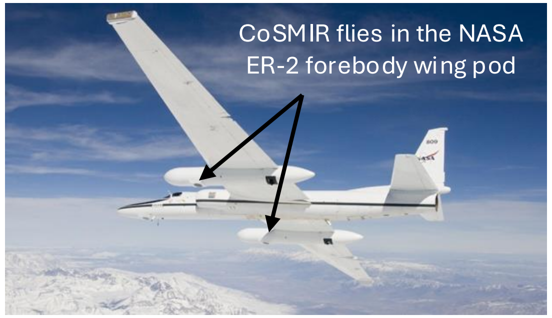
- Infrared Atmospheric Sounding Interferometer (IASI) = 8461 channels
- Microwave = >100 channels

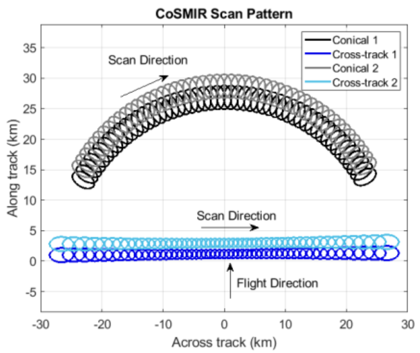
CoSMIR Overview

Conical Scanning Millimeter-wave Imaging Radiometer

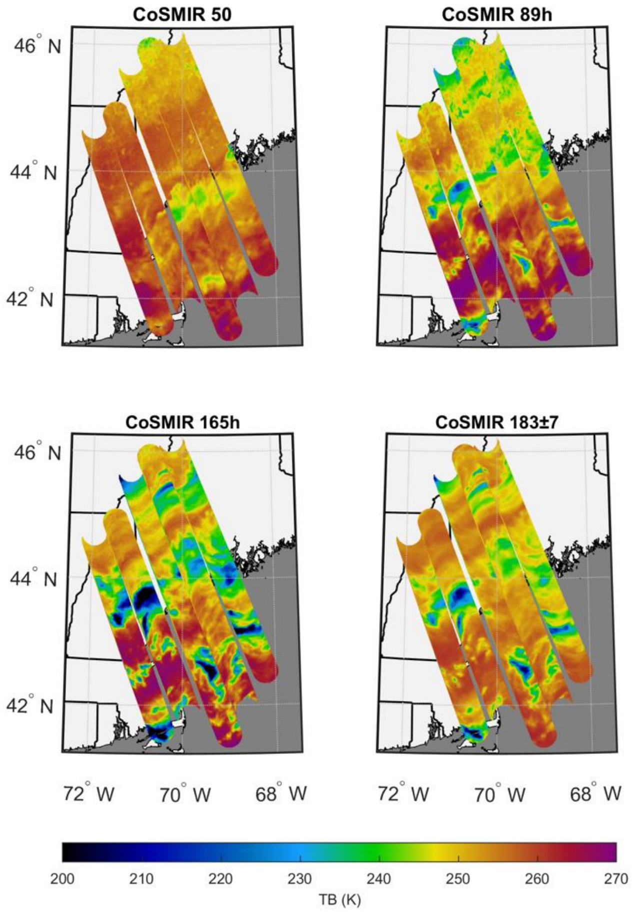
- Programmable scanning airborne radiometer with frequencies from 50 to 183 GHz
- Originally built in the early 2000s for SSMIS cal/val (2004-2005)
- Modified in late 2000s to have frequencies similar to GMI for GPM GV
  - Flew in four GPM GV campaigns (2011-2015)
- Recently flew in IMPACTS (2020/2022)
- Significant upgrade to the receivers in 2023 to become CoSMIR-Hyperspectral

CoSMIR (1)	CoSMIR (2)	GMI
50.3h	50.3h	--
52.8h	52.8h	--
53.6h	--	--
91.665v/h	89.0v/h	89.0v/h
150h	165.5v/h	166v/h
183.31±1h	183.31±1h	--
183.31±3h	183.31±3h	183.31±3v
183.31±6.6h	183.31±7h	183.31±7v





CoSMIR has the unique ability to scan in various modes: fore/aft conical and cross/along-track (right).

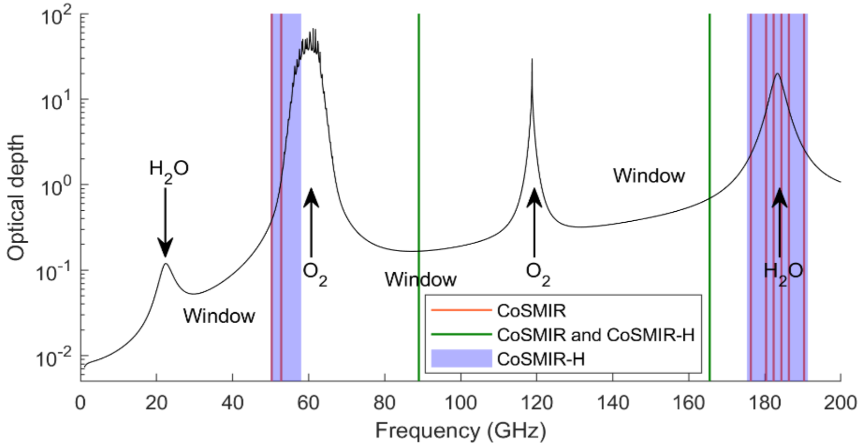


CoSMIR TB from 4 Feb 2022 IMPACTS flight
Rain/snow system over the Northeast USA

CoSMIR → CoSMIR-Hyperspectral

Modified the CoSMIR 50-GHz and 183-GHz receivers to achieve full spectrum (4 MHz resolution) observations at 50-58 GHz (O_2) and 175-191 GHz (H_2O) using six PMCC ASIC spectrometers

ATMS	CoSMIR-H
23.8	--
31.4	--
50-58 (13 channels)	50-58h (~2k channels)
88.2	89v/h
165.5	165.3v/h
183±7-183±1 (5 channels)	175.3-191.3v (~4k channels)



- New receivers
  - 50-GHz and 183-GHz major updates with ASIC spectrometers
  - Used opportunity to update 89- and 165-GHz receivers
- Mechanical structure remained the same
  - Calibration targets and elevation/azimuth axes
  - Reduces cost associated with building a new instrument

- Data System
  - Major updates to handle large volume of data
  - CoSMIR-H is ~3 MB/s vs 1.8 kB/s for CoSMIR
- Software
  - New ground processing software required
  - Combine 4-MHz resolution into channels for science

Channel Set

Channel	Center Frequency (GHz)	Bandwidth (MHz)	Spectral Band (GHz)	Approx. NEDT (K) (70 ms int time)
50-58h	50.002, 50.006,... 57.994, 57.998	3.906	50-50.004, 50.004-50.008,... 57.992-57.996, 57.996-58	1.5
175.3-191.3v	175.302, 175.306,... 191.294, 191.298	3.906	175.3-175.304,175.304-175.308,... 191.292-191.296, 191.296-191.3	3.5
89v	89.0±1.25	1500 (x2)	87.0-88.5 and 89.5-91.0	0.1
89h	89.0±1.25	1500 (x2)	87.0-88.5 and 89.5-91.0	0.1
165v	165.3±1.25	1500 (x2)	163.3-164.8 and 165.8-167.3	0.5
165h	165.3±1.25	1500 (x2)	163.3-164.8 and 165.8-167.3	0.6

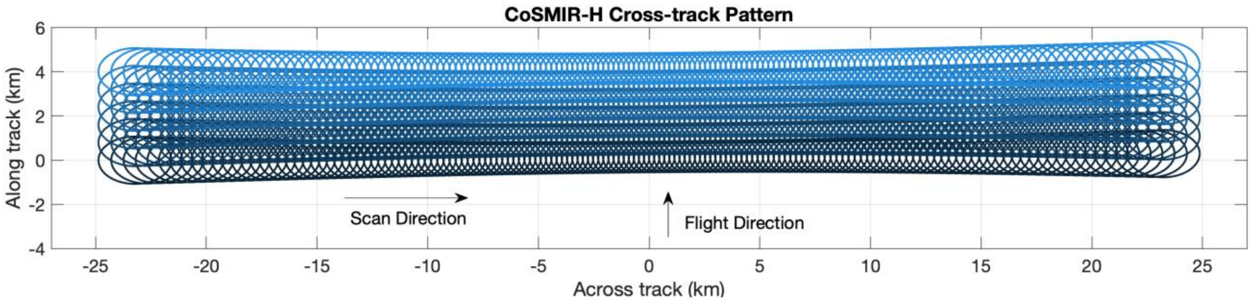
6148 total channels

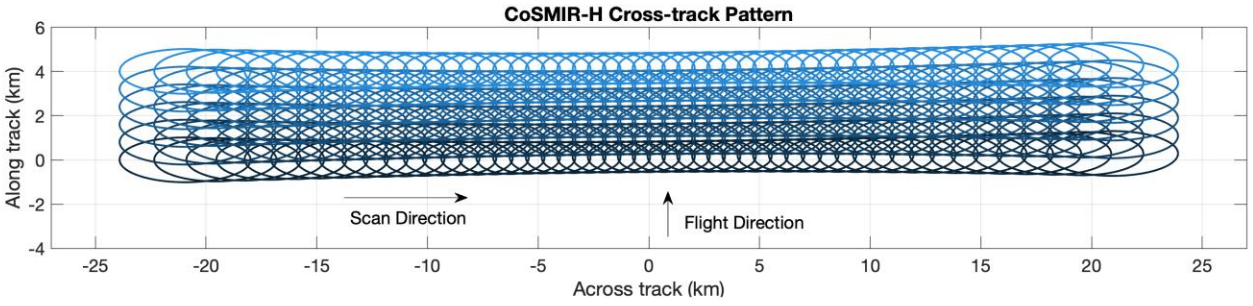
Channel set order in the L1 data product

- 1-2048: 50-58 GHz
- 2049-6144: 175.3-191.3 GHz
- 6145-6148: 89v, 89h, 165v, 165h

Scan Geometry and Spatial Resolution

- Cross-track scan: Scanning left to right (relative to forward direction of aircraft), -48.2° to 48.2° elevation angle (NOT mixed polarization)
- Half-power beamwidth: ~4.5° at 50-58 GHz, ~4.0° at 89/165/183 GHz
- Nadir footprint: 1.6x1.6 km (50-58 GHz) and 1.4x1.4 km (89-183 GHz) for ER-2 (20 km altitude)
- Off-nadir footprint at 48.2°: 2.4x3.6 km (50-58 GHz) and 2.1x3.2 km (89-183 GHz) for ER-2 (20 km altitude)



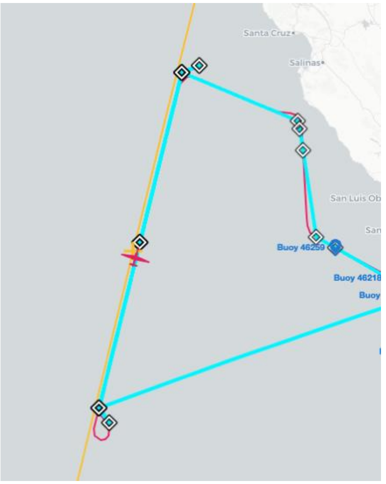


(Top) Ground track pattern for 151 scan positions at 10 ms integration time.
(Bottom) Ground track pattern for 51 scan positions, averaging 7 pixels to give 70 ms integration time. This is the scan geometry included in the L1 files.

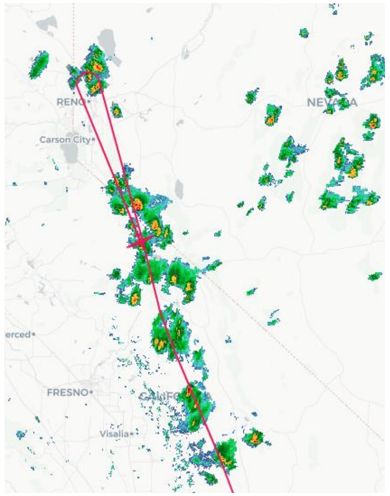
New footprint size with 70 ms averaging (4.0° beamwidth)
Nadir: 1.4x2.8 km
Off-nadir: 2.1x6.4 km

CoSMIR-H Engineering Check Flights

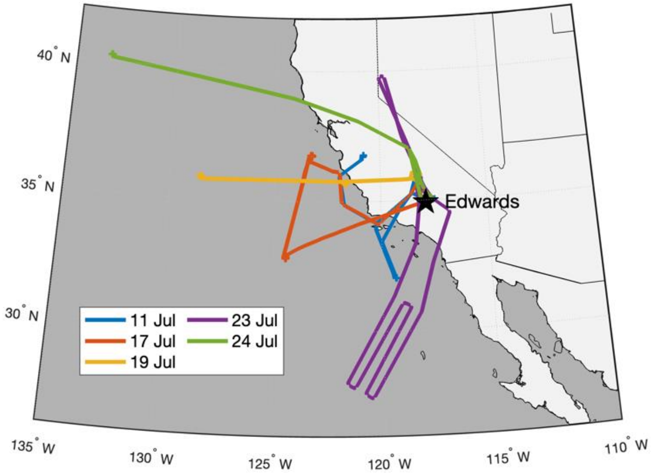
- Successful engineering check flights on the ER-2 in July 2024
  - CoSMIR-H and MBARS flew together
    - MBARS: Microwave Barometric Radar, PI: Matt Walker-McLinden
  - Five total flights, ~19 hours of observations
- Preparations for the WH^{2}yMSIE campaign
  - Issues noticed during the check flights allowed us to further optimize CoSMIR-H prior to flying again in WH^{2}yMSIE



MetOp-B Overpass



Convection Observations



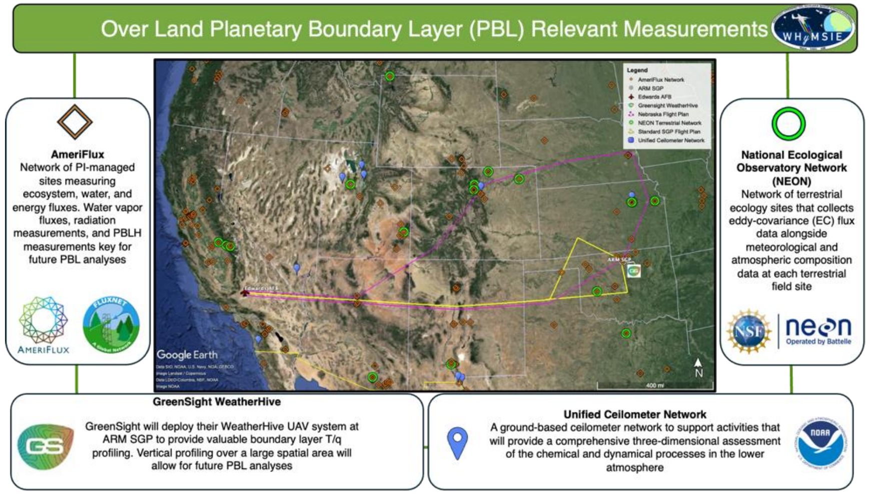
Flight Tracks

(Top) CoSMIR-H and MBARS teams perform instrument check outs prior to first flight. (Bottom) ER-2 lands at Edwards AFB after a flight. (Credit: NASA AFRC)

WH²yMSIE Campaign: Oct/Nov 2024

Westcoast and Heartland Hyperspectral Microwave Sensor Intensive Experiment

- NOAA Joint Ventures Partnership program to collect an extended CoSMIR-H dataset over a variety of atmospheric and surface conditions in Oct-Nov 2024
- WH²yMSIE also included several complementary sensors funded by NASA on the ER-2 and the G-III aircraft to demonstrate the benefits of a remote sensing instrument suite for measuring the PBL



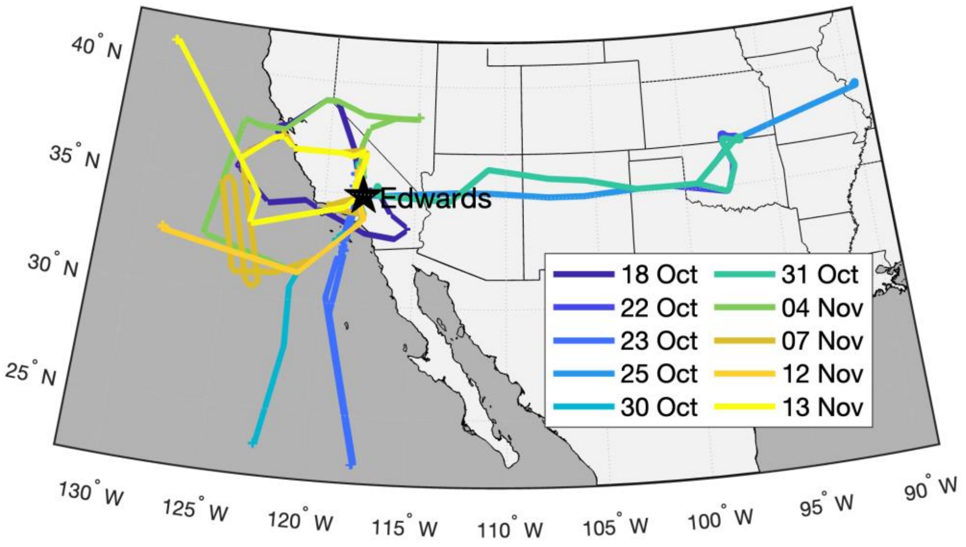
ER-2 payload
Hyperspectral microwave (CoSMIR-H)
Hyperspectral infrared (NAST-I and S-HIS)
Low frequency microwave radiometer (AMPR)
Visible/infrared imager (MASTER)
Backscatter lidar (CPL)
W-band radar (CRS) or pressure radar (MBARS)
GPS Radio Occultation (ARO)

G-III payload
Differential absorption lidar (HALO)
Doppler wind lidar (AWP)
Dropsondes

https://earth.gsfc.nasa.gov/climate/campaigns/WHyMSIE

WH²yMSIE Flights Overview

- Ten total flights, ~43.5 hours of CoSMIR-H observations (~54 flight hours)
- Mix of over-land and over-ocean
- Consisted of mostly clear sky observations
- G-III joined the ER-2 for second half of the campaign

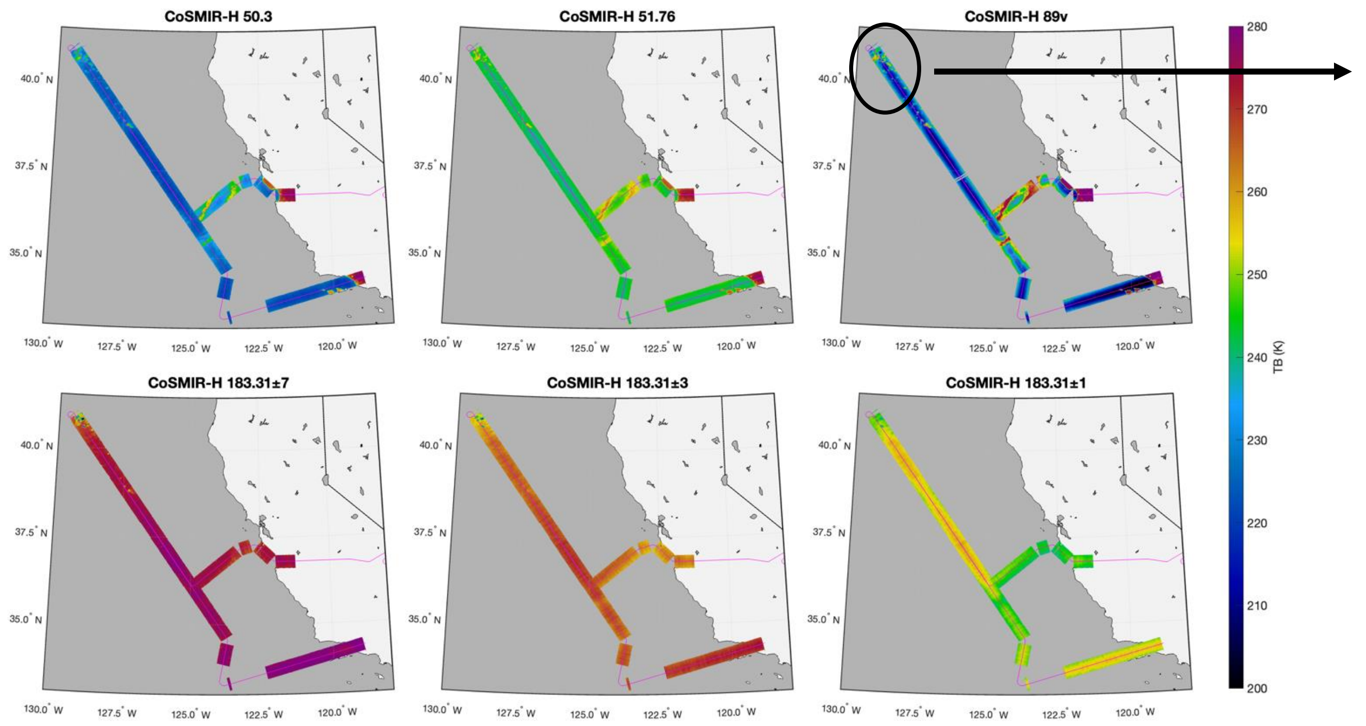


Flight Date	Approx. hours CoSMIR-H data	Observations/Location
10/18	2:50	Clear-sky over ocean and land. Flew over Lake Tahoe and Salton Sea.
10/22	5:13	Over-land out and back flight to ARM SGP. Flew over several NWS radiosonde sites and NSSL. Clear sky except some high clouds over New Mexico.
10/23	4:03	Clear-sky over-ocean with a NOAA21 overpass at 21:05 UTC. Also close to the AWS ground-track for an overpass at 18:52 UTC.
10/25	6:41	Over-land out and back flight to Scott AFB with overflights of several NWS radiosonde sites and ARM SGP. Clear sky except for very low clouds over Scott.
10/30	4:09	Over-ocean coordinated G-III flight with an EarthCARE overpass at 22:20 UTC. Clear-ish sky on the northern part of the flight path, very low puffy clouds (<2 km cloud top) on the southern EarthCARE overpass leg.
10/31	5:28	Over-land flight to ARM SGP. Flew over several NWS radiosonde sites and NSSL. G-III coordinated for the flight legs in Arizona.
11/04	3:54	Over-ocean targeting clear-sky AWS overpass at 19:20 UTC with over-land flight legs of Lake Tahoe and Railroad Valley. Fully coordinated with G-III.
11/07	4:44	Over-ocean targeting NOAA21 overpass at 21:25 UTC. Mostly clear sky except far southern parts of overpass legs. Fully coordinated with G-III.
11/12	3:35	Over-ocean out and back flight targeting slight pressure gradient and clear/cloudy transitions. No G-III coordination.
11/13	3:00	Over-ocean targeting an atmospheric river and pressure gradient with G-III coordination. ER-2 had to RTB early and did not go over Catalina Island like in the flight plan.

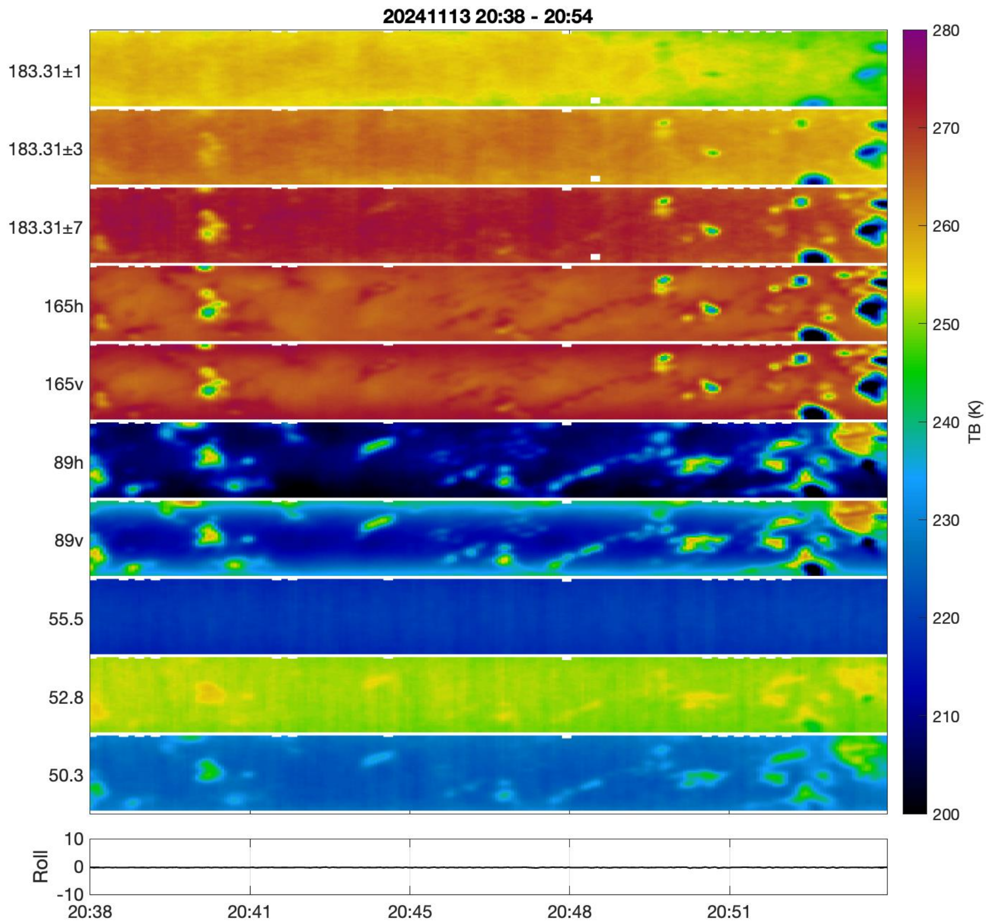
ER-2 only ocean	ER-2 only land	ER2-/G-III coordinated

CoSMIR-H Observation Highlights

Atmospheric River: 13 Nov



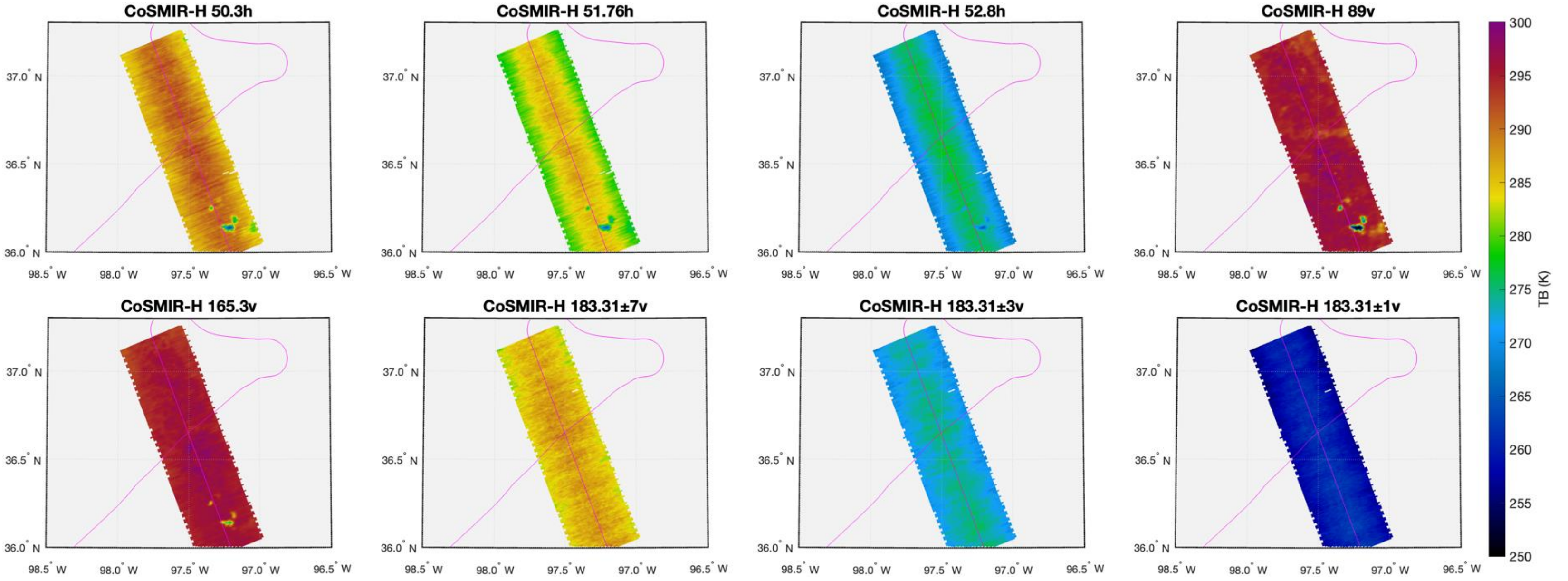
CoSMIR-H selected channels for the 11/13 atmospheric river flight. Precipitation can be seen in the 50/89 GHz channels and ice scattering in the 183 GHz channels on the north side of the leg.

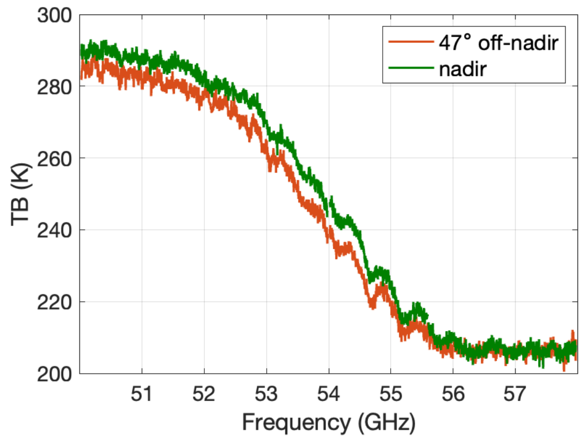


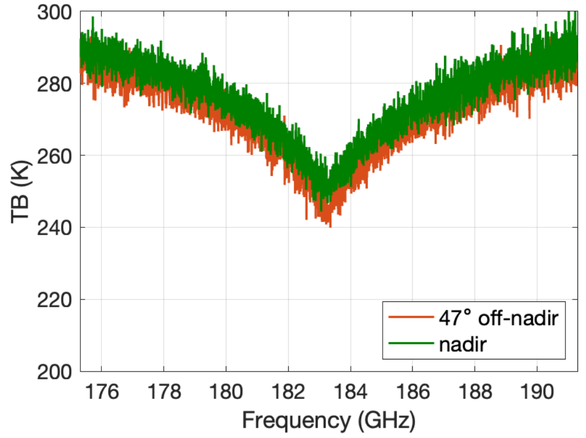
50-GHz and 183-GHz channels are created by averaging the 4-MHz bins into ATMS-equivalent bandwidths

CoSMIR-H Observation Highlights

Clear sky over ARM SGP site (Oklahoma, USA): 22 Oct



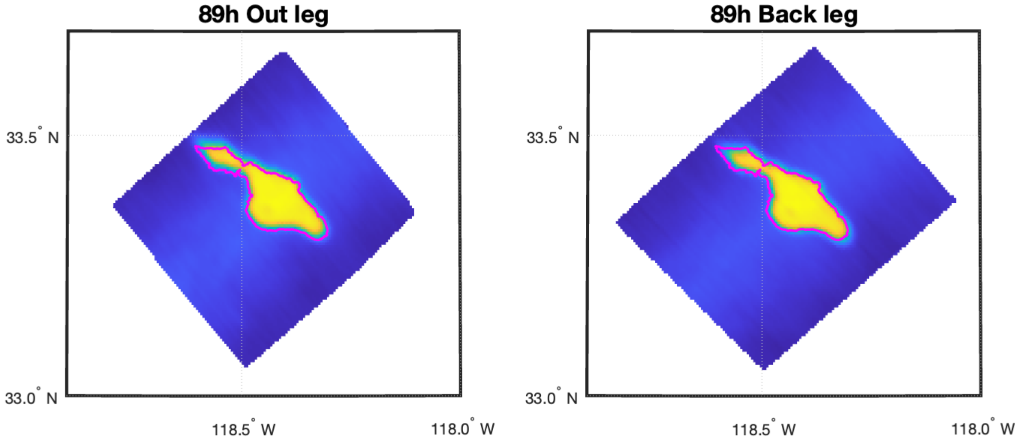




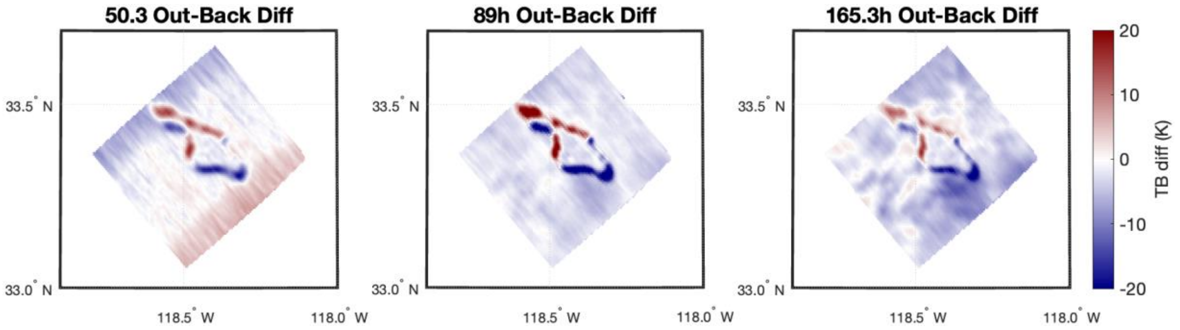
(Top) Selected band-averaged (ATMS-equivalent) channel observations. SGP central facility site where the pink lines intersect (aircraft ground track).
(Right) TB as a function of frequency at SGP overpass

Calibration: Pointing Correction

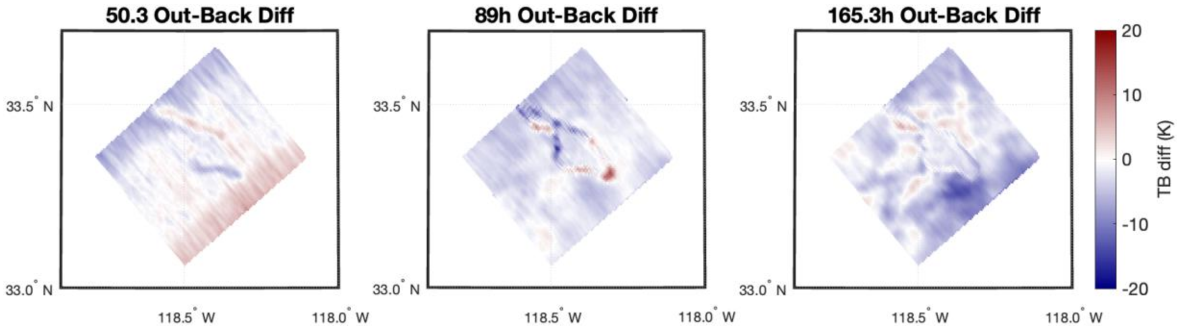
- 12 Nov out and back flight over Catalina Island provides excellent opportunity for geolocation checks
- Derive a pitch/roll offset using the coastlines from the out and back legs
  - Similar to doing ascending-descending differences for satellite geolocation



Before correction



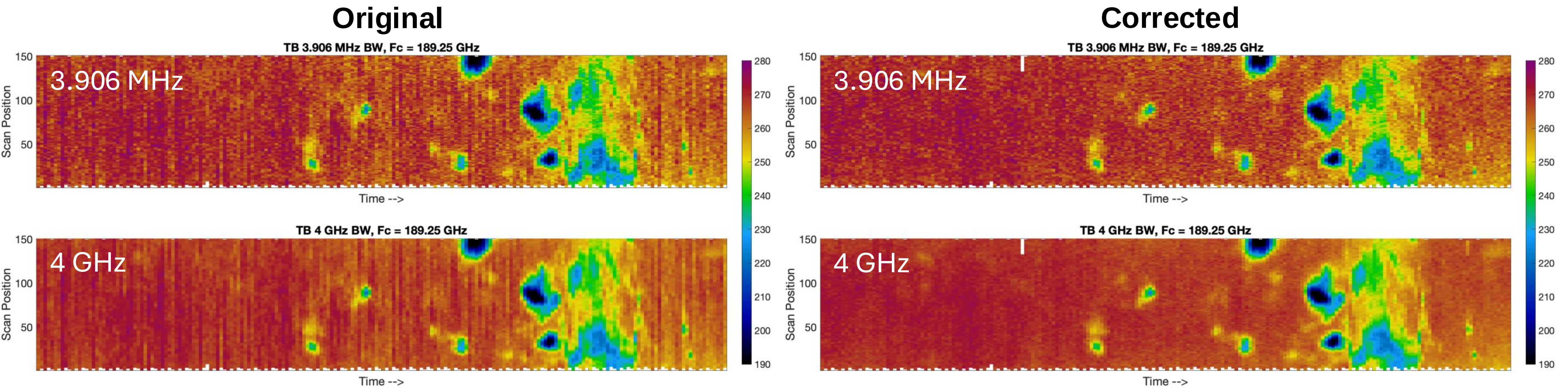
After correction



0° pitch, 1.6° roll offsets

Calibration: Striping Correction

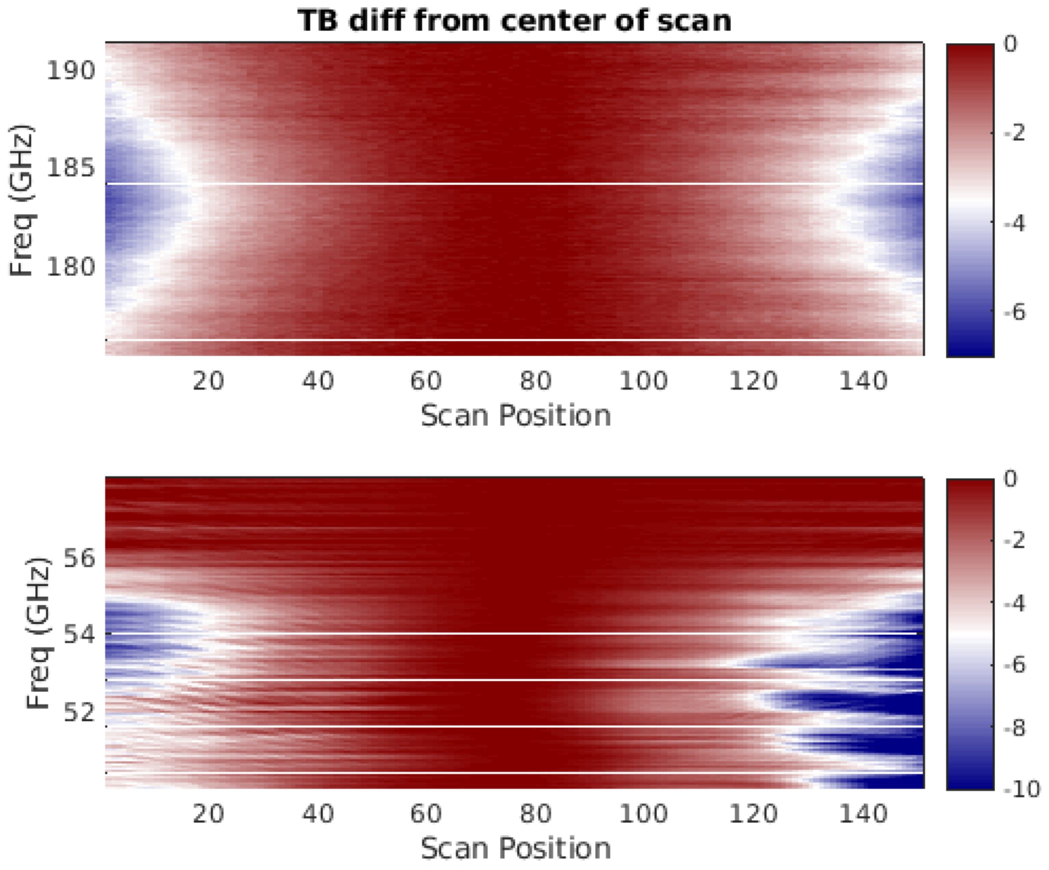
- Significant striping (i.e. flicker or 1/f noise) was noticed in the 183-GHz hyperspectral channels
- Correction was developed and applied for the first data release, but we are continuing to investigate other methods to remove the noise
- Conducting laboratory measurements to better characterize and mitigate the noise for future measurements



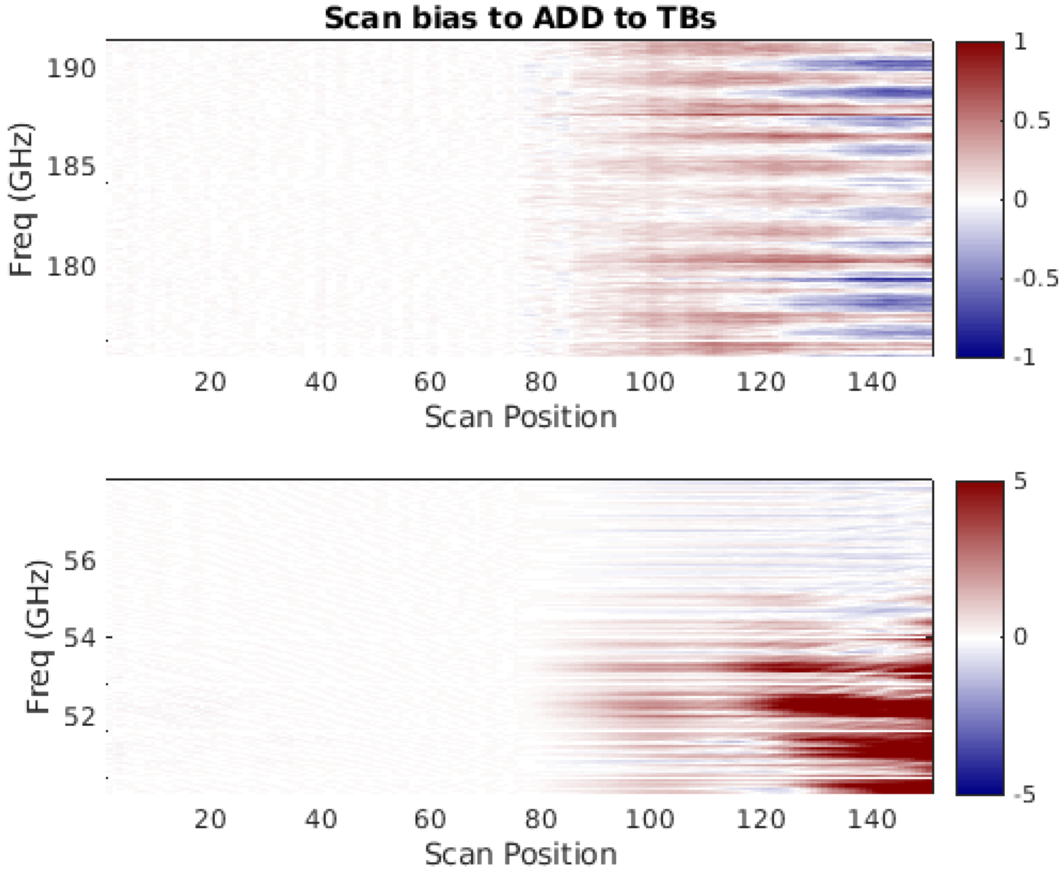
1/f noise correction significantly reduces the TB striping while maintaining the fine geophysical features.

Calibration: Scan Bias Correction

Some significant scan biases were noticed in the 50-GHz channels on the right side of the scan



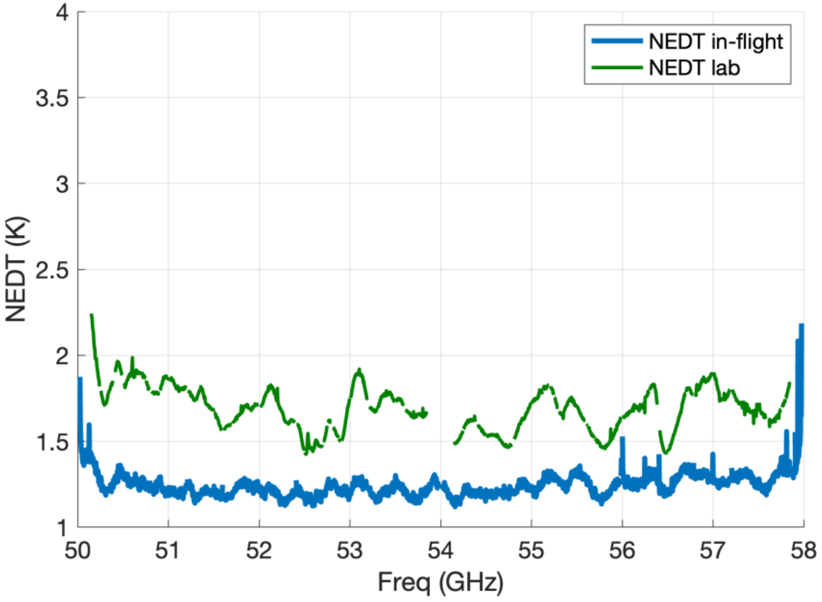
Used difference with the left side of the scan to calculate a bias for the right side.

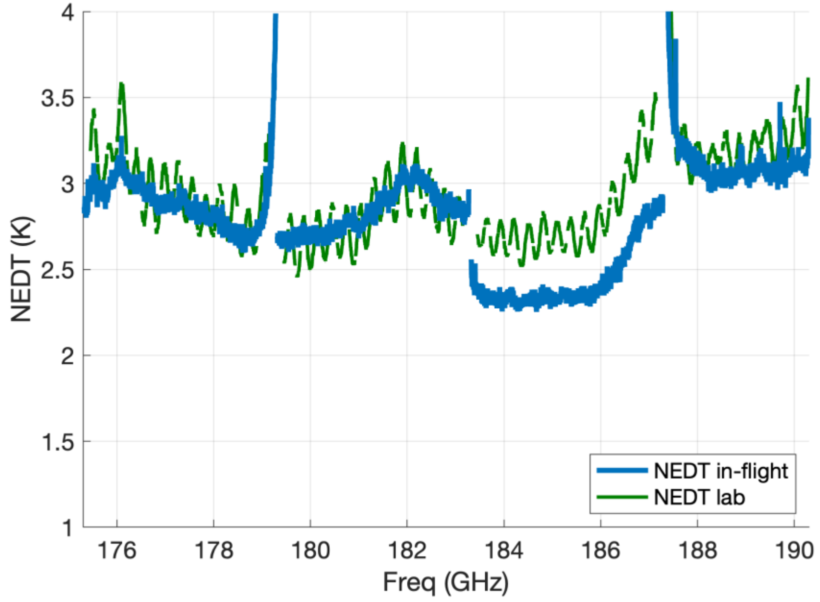


NEDT Analysis

- Laboratory measurements of the receiver noise temperature (T_R) as a function of frequency were made prior to WH^2yMSIE using the onboard hot target and an LN_2 target
- NEDT is estimated from these measurements and is compared with in-flight NEDT calculations for 70 ms integration time (τ) and 4 MHz bandwidth (B)
- The in-flight NEDT shows very good results within what is expected. Work is currently being done to calculate the in-flight NEDT when the 4-MHz bins are averaged into wider bandwidths

$$NEDT = \frac{T_A + T_R}{\sqrt{B\tau}}$$



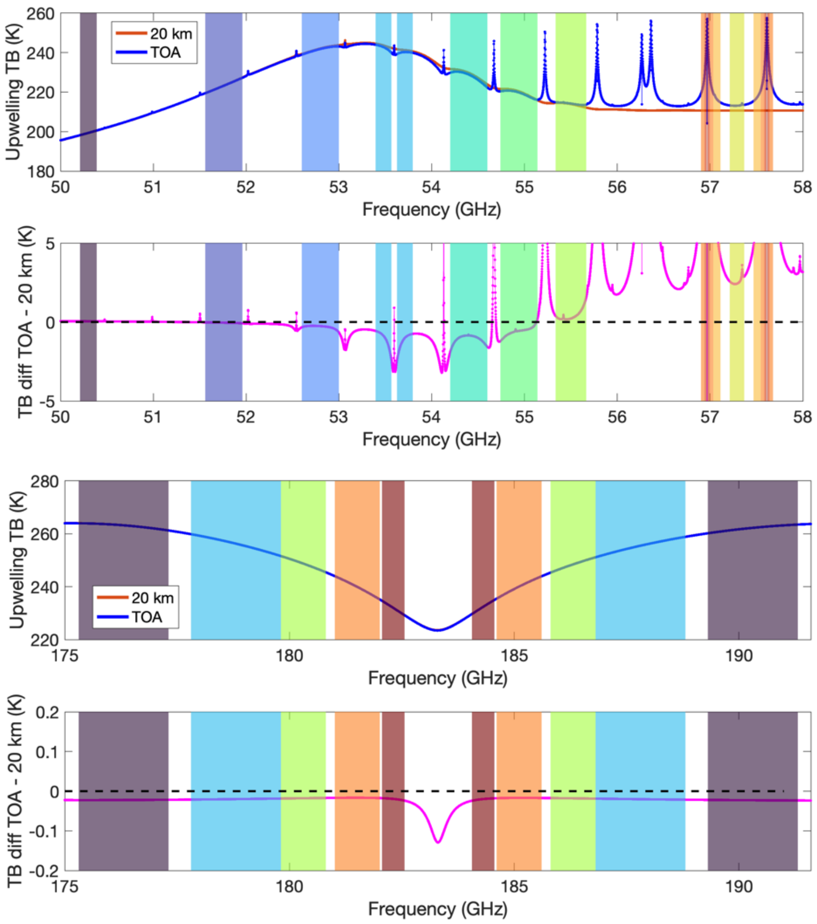


Validation: Comparison with ATMS

ATMS Freq (GHz)	ATMS Bandwidth (MHz)	S-NPP ATMS Measured NEDT (K)	CoSMIR-H Expected NEDT* (K)
50.3	180	0.37	TBD
51.76	400	0.28	TBD
52.8	400	0.28	TBD
53.596±0.115	170	0.29	TBD
54.4	400	0.27	TBD
54.94	400	0.27	TBD
55.5	330	0.29	TBD
57.290.344 [f_0]	155	0.43	TBD
f_0±0.217	78	0.56	TBD
f_0±0.322±0.048	36	0.59	TBD
f_0±0.322±0.022	16	0.86	TBD
f_0±0.322±0.010	8	1.23	TBD
f_0±0.322±0.0045	3	1.95	TBD
183.31±7.0	2000	0.38	TBD
183.31±4.5	2000	0.46	TBD
183.31±3.0	1000	0.54	TBD
183.31±1.8	1000	0.59	TBD
183.31±1.0	500	0.73	TBD

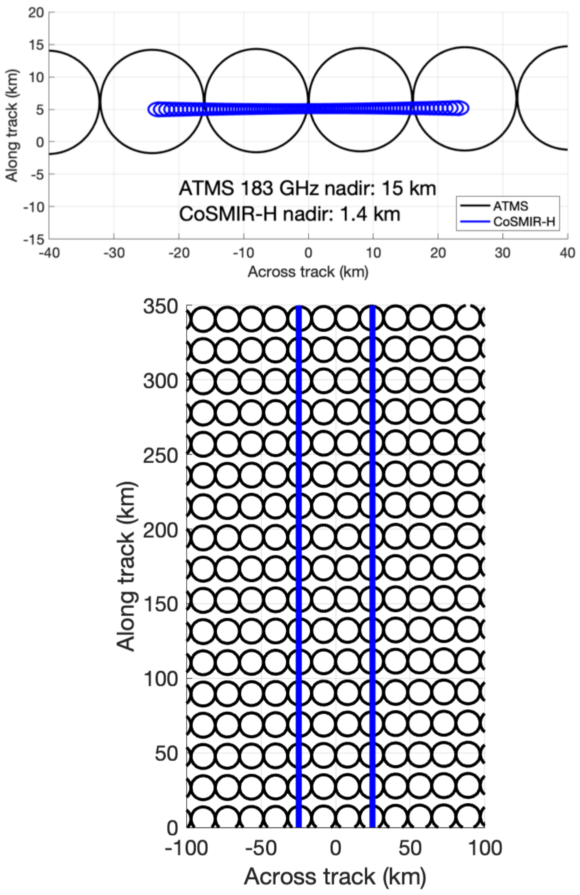
*Currently working on calculations

Upwelling TB comparison: TOA vs 20 km



Stratospheric O_2 sounding channels show significant differences from ATMS but the differences in the H_2O sounding channels should be negligible.

Footprint/swath comparison



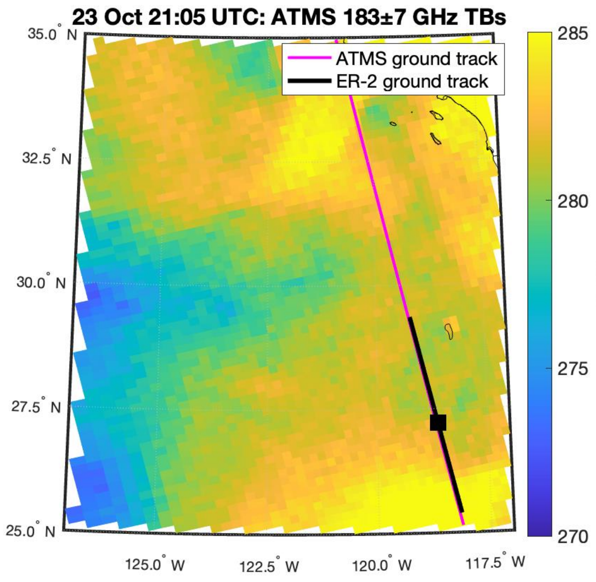
ATMS underflights over homogeneous scenes to compare observations

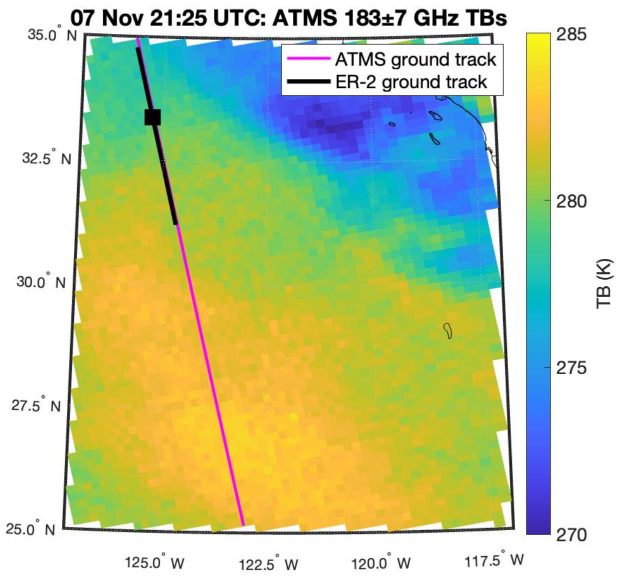
NOAA21 Satellite Underflights

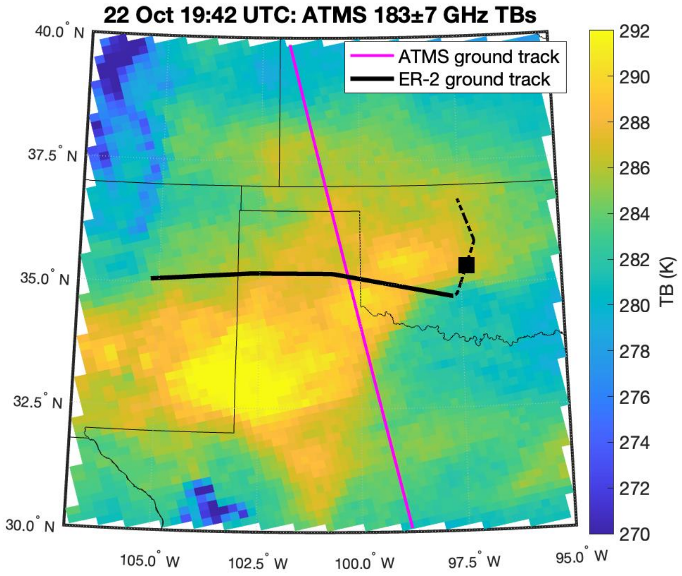
- Two primary underflights
  - Ocean clear-sky
  - ~30-minute aircraft flight track along NOAA21 satellite track
- One 'underflight of opportunity'
  - NOAA21 intersected over-land flight track ~30 min after the ER-2

- CoSMIR-H 4-MHz frequency bins averaged to approximate ATMS channel bands using NOAA21 spectral response functions

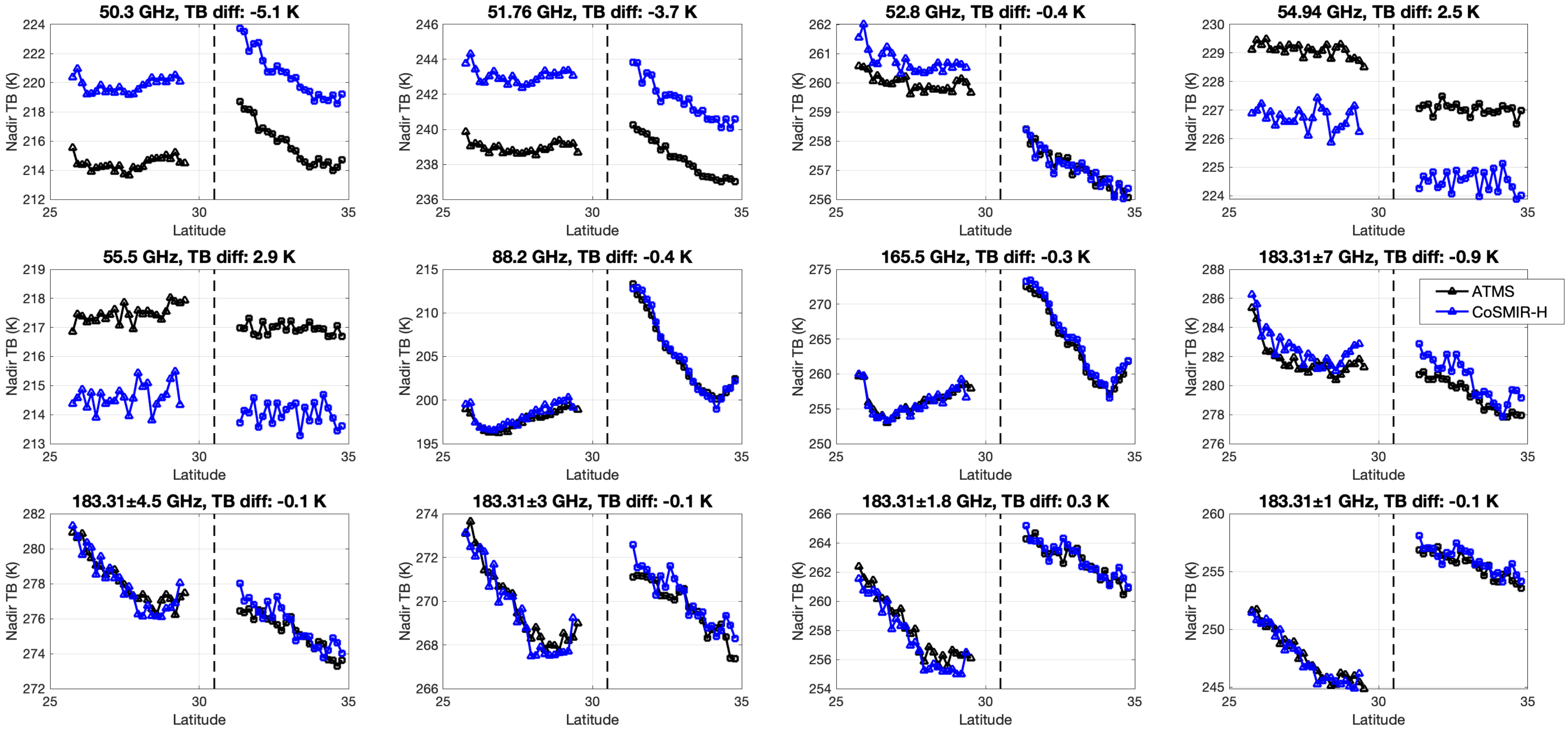
Comparisons on the next two slides show very good agreement with ATMS



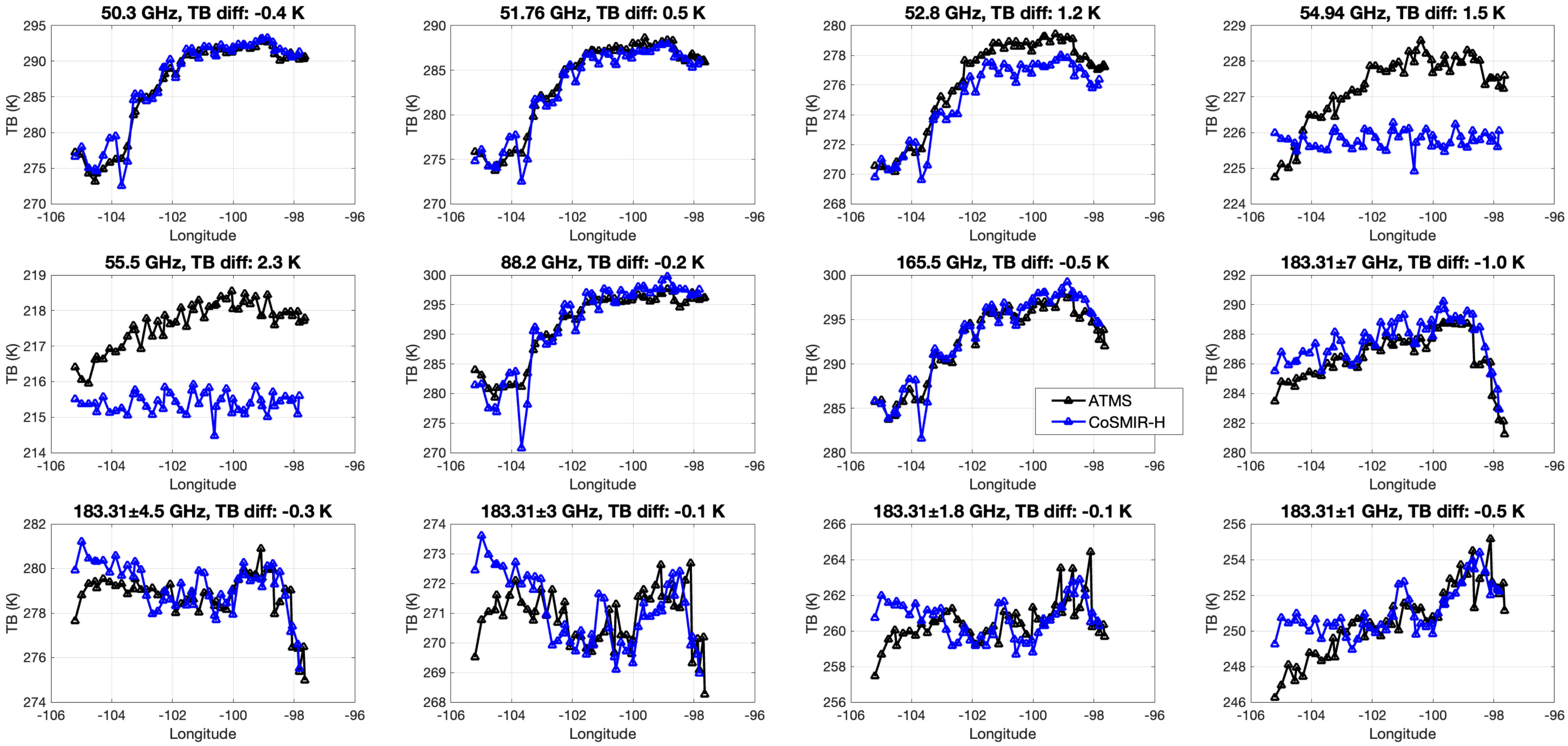




Ocean Clear-Sky: 23 Oct and 07 Nov

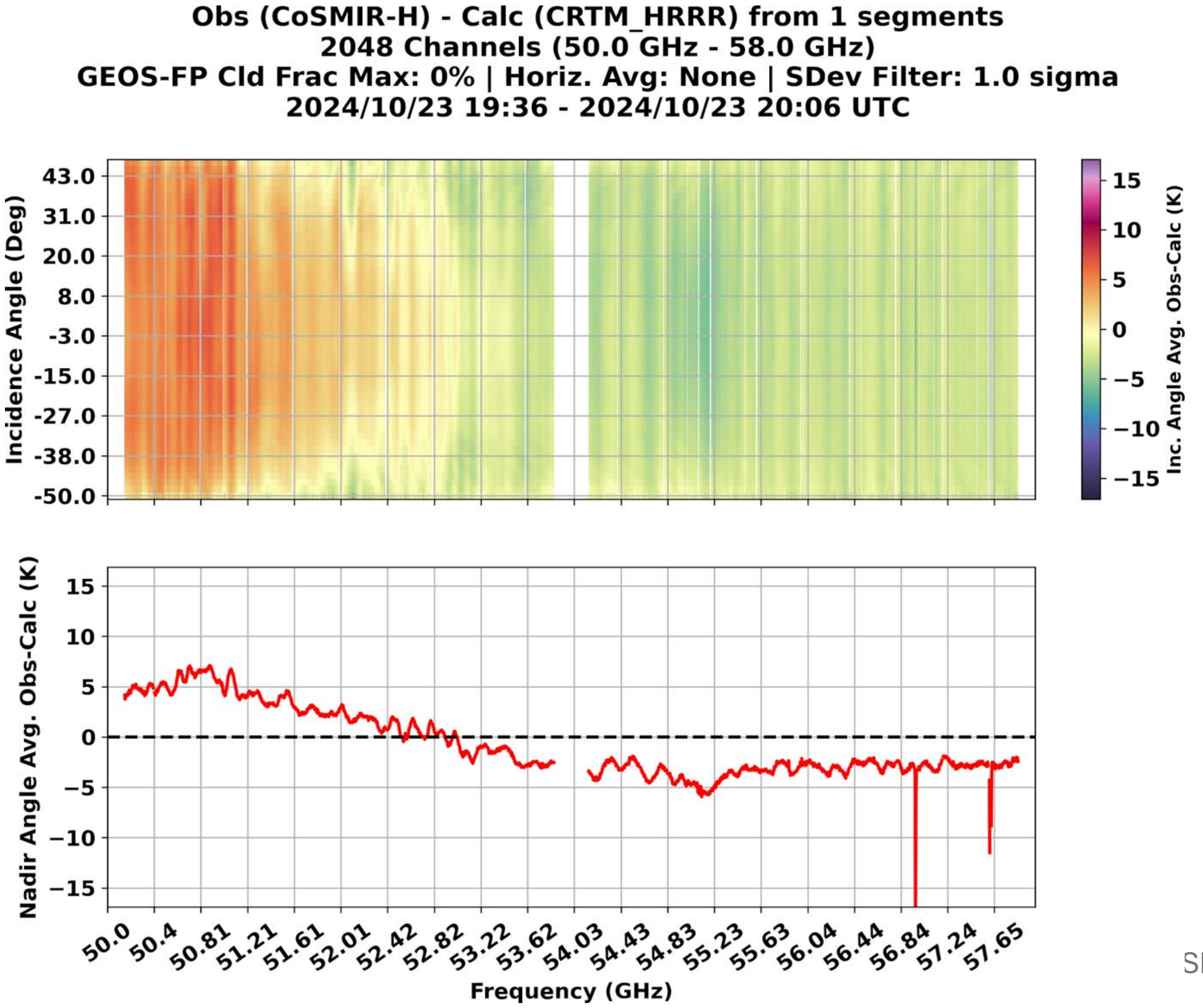


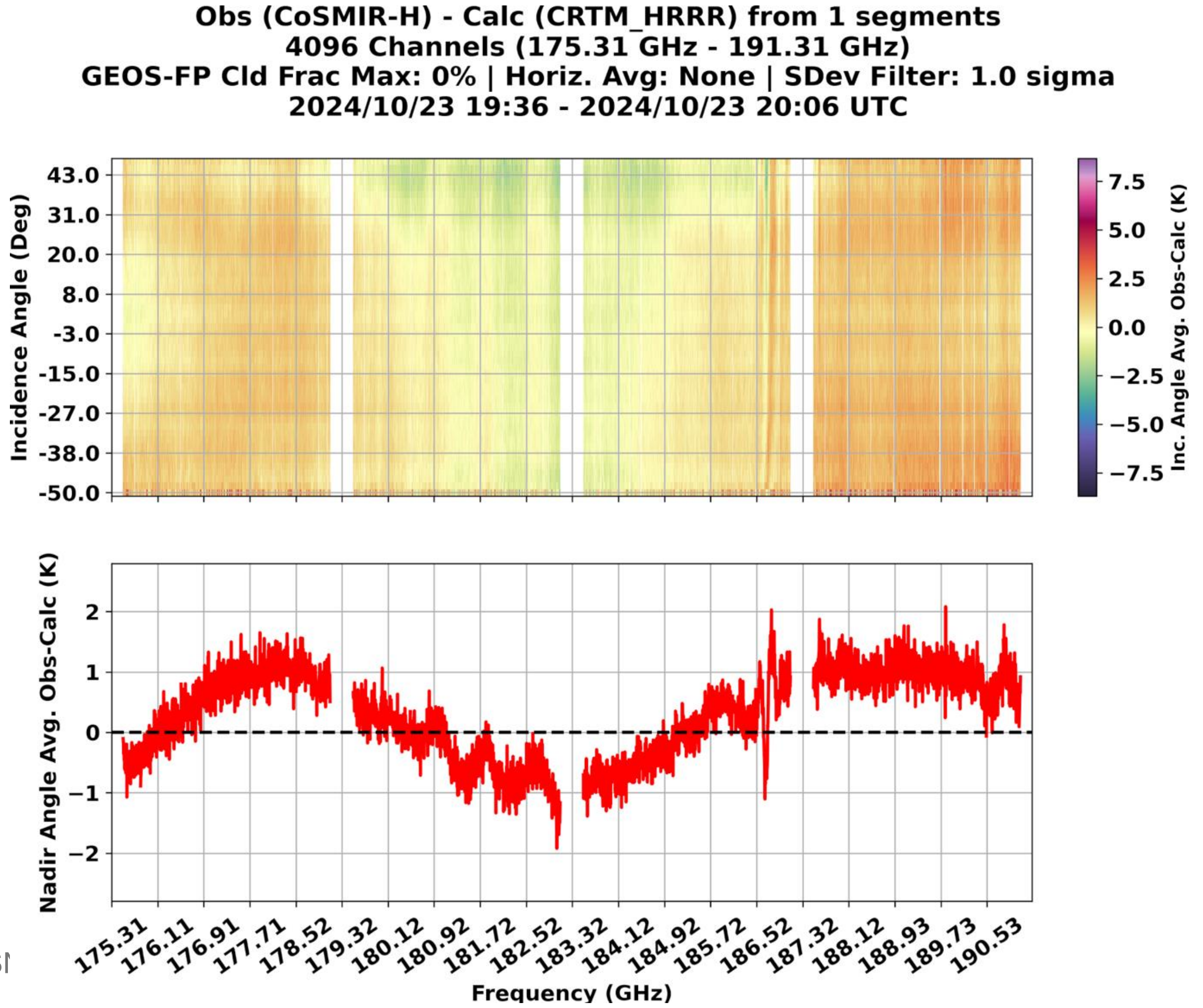
Land Overpass of Opportunity: 22 Oct



Validation: Comparison with RTM

Over-ocean clear-sky CoSMIR-H observed TB spectrum (obs) compared with simulated TB from the Community Radiative Transfer Model CRTM (calc)





Level 1 Data Product

- L1 data files contain full spectrum: 6148 channels
- Example file name: whymsie-cosmirh_ER2_20241022_S172056_E175100_R0_crosstrack.nc
- Files are identified with the flight date and the start (S) and end (E) time in 30-min segments
- Each file ~900 MB

Variable names included in the Level 1 data files

UTC Time	Aircraft Nav Data	Sensor Specific
Year	AC_Altitude	Tb
Month	AC_Pitch	Quality
DayOfMonth	AC_Roll	IncidenceAngle
Hour	AC_Heading	Latitude
Minute	AC_Latitude	Longitude
Second	AC_Longitude	Azimuth
MilliSecond	AC_Speed	Elevation
	AC_SolarZenith	SensorPitch
		SensorRoll

Summary

- The airborne hyperspectral microwave sounder CoSMIR-H performed well during flights and collected a quality dataset
- Level 1 calibrated brightness temperature dataset is available for download
- Thanks to NASA ESTO and NOAA's Joint Venture Partnerships program for funding this exciting project

Data download: **https://www-air.larc.nasa.gov/cgi-bin/ArcView/whymsie**

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