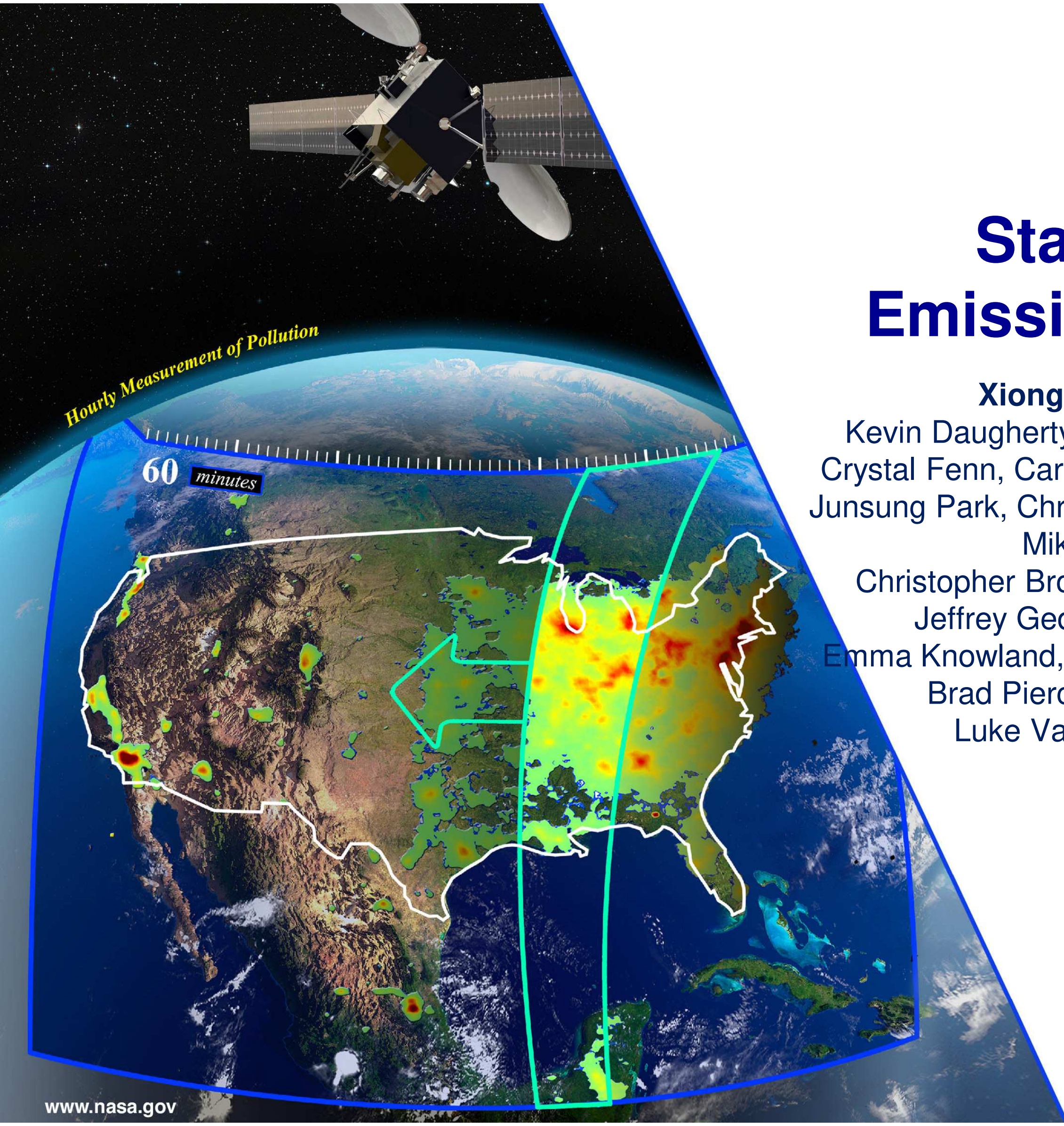


Tropospheric Emissions:
Monitoring of Pollution

Status of TEMPO (Tropospheric Emissions: Monitoring of pollution)

Xiong Liu[1], Kelly Chance, Raid Suleiman, John Houck, John Davis, Kevin Daugherty, David Flittner, David Rosenbaum, Gonzalo Gonzalez Abad, Crystal Fenn, Caroline Nowlan , Huiqun Wang, Heesung Chong, Weizhen Hou, Junsung Park, Christopher Chan Miller, Juseon Bak, Jim Carr, James Szykman, Mike Newchurch, Aaron Naeger, Ronald Cohen, Zolal Ayazpour, Christopher Brown, Zachary Fasnacht, Marcellin Feasson, Jean Fitzmaurice, Jeffrey Geddes, David Haffner, Jay Herman, Joanna Joiner, Laura Judd, Emma Knowland, Xuming Lei, Nischal Mishra, Robert Neece, Ewan O'Sullivan, Brad Pierce, Wenhan Qin, Eric Roback, Justin Strickland, Robert Spurr, Luke Valin, Alexander Vasilkov, Eun-Su Yang, and the TEMPO Team

[1]SAO, CfA | Harvard & Smithsonian

CEOS AC-VC-19 / ACSG Joint Meeting 2023

Brussels, Belgium (Virtual), Oct. 24-27, 2023

Smithsonian

Outline

- TEMPO Science Overview
- TEMPO Commissioning
- TEMPO Instrument and Operation
- TEMPO Data Products and Science Algorithms
- Commissioning Results


Joint STM for TEMPO, GEO-XO ACX, & TOLNet 2023

Hourly Daytime Atmospheric Pollution over North America from the GEO

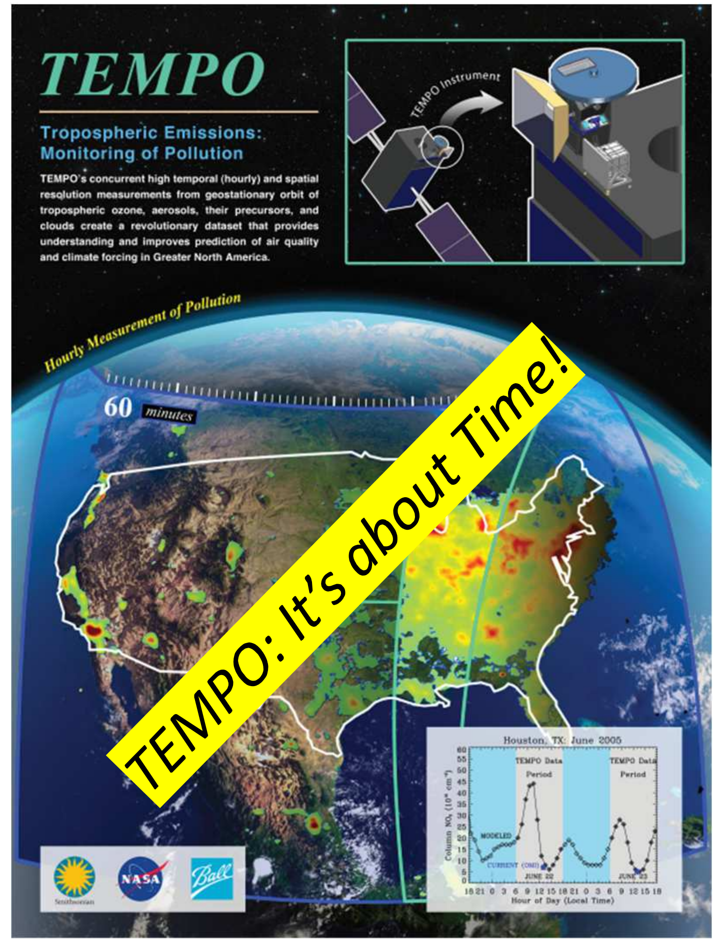
NASA's first Earth Venture Instrument (EVI) selected in 2012 & first hosted payload

PI: Kelly Chance, Smithsonian Astrophysical Observatory (SAO): Science team, ground systems, science data processing center
Instrument Project Management: Kevin Daugherty, NASA LaRC
Instrument Development: Ball Aerospace
Other Institutions: NASA GSFC, NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, UAH, U Iowa, Sitting Bull College, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, U.K., ESA, Spain

Mission Project Management: Kevin Daugherty, NASA LaRC
Host Satellite Provider: Maxar Technologies
Satellite Host: Intelsat (IS-40e)
Launch: SpaceX

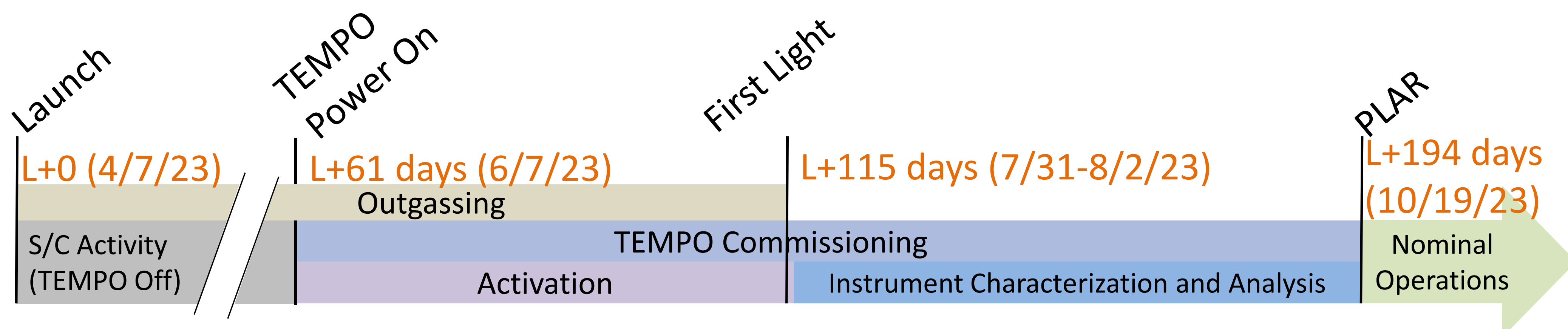
Aligned with NRC Earth Science 2007 Decadal Survey recommendations

- ✓ Makes many of the GEO-CAPE atmospheric measurements



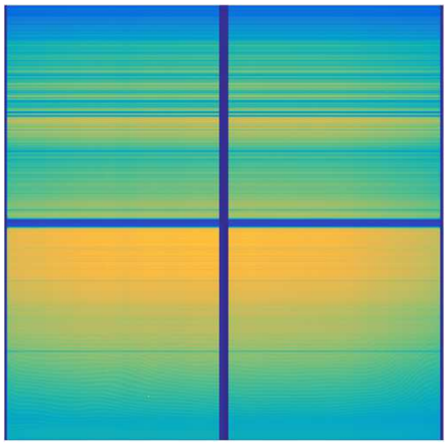
TEMPO Commissioning

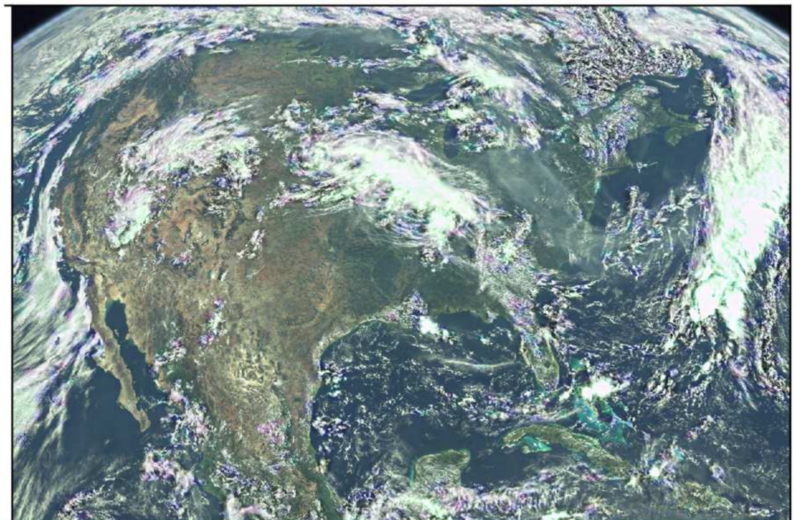
- **TEMPO commissioning: SAO + LaRC + Intelsat + Maxar + Ball + Carr Astronautics**
  - ✓ **TEMPO power on 6/7**
  - ✓ **Dry out (6/9-7/9) and cool down (7/10-7/12)**
  - ✓ **Additional activation: scan mirror tuning, command load testing, etc.**
  - ✓ **First light (7/31-8/2): working/reference diffuser solar & Earth imaging**
  - ✓ **Instrument Characterization and Analysis (ICA) activities**
  - ✓ **Coordinate with AGES+ campaigns in Aug. and Coastal Texas Air Quality Field Campaign in Sep. (no Earth imaging only on 6 days, special observations over LA and Texas)**
- **Start nominal operation on 10/19 after Post Launch Acceptance Review (PLAR) on 10/18-19**



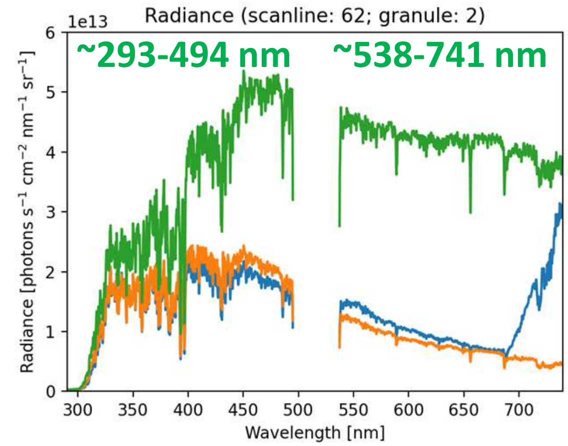
TEMPO Instrument & First Light (8/1-2/2023)

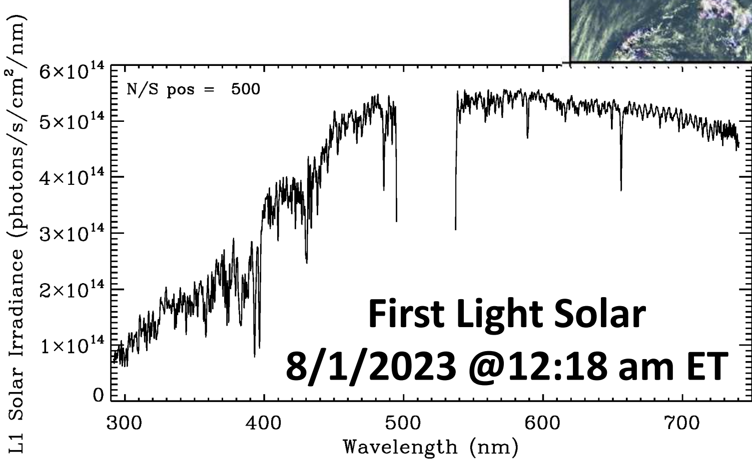
- **Imaging spectrometer measuring solar irradiance and solar backscattered Earth radiance**



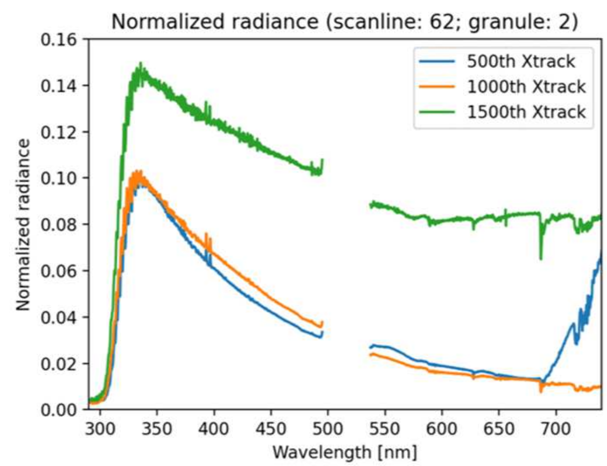


First Light Earth 8/2/2023
@11:13-12:16 ET
RGB Image



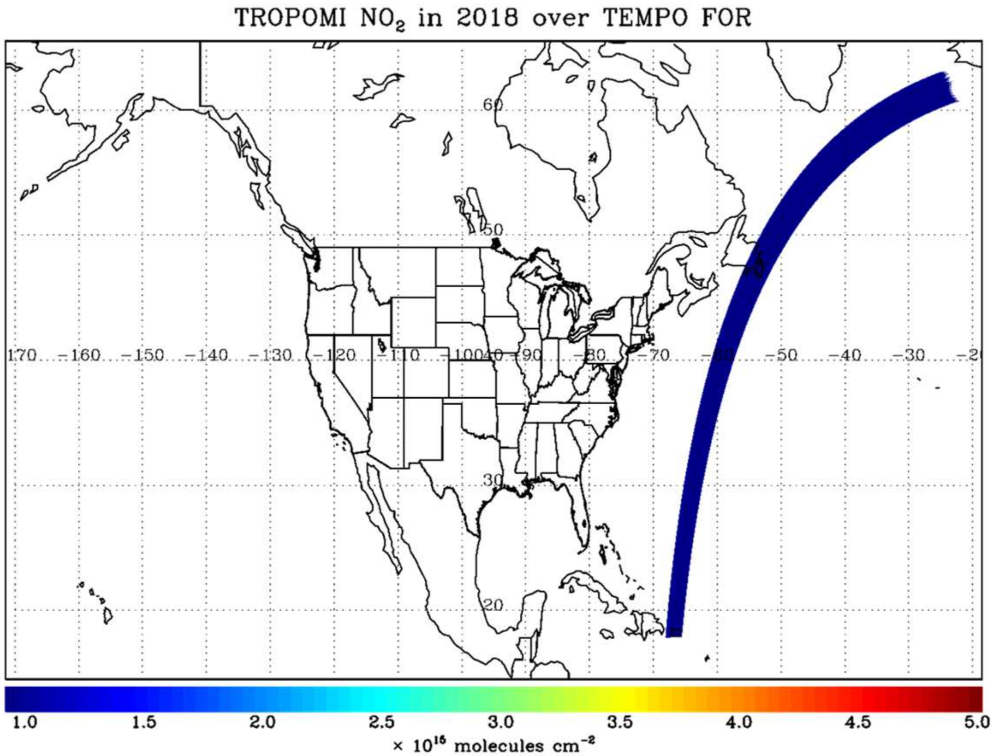


First Light Solar
8/1/2023 @12:18 am ET



TEMPO Operation

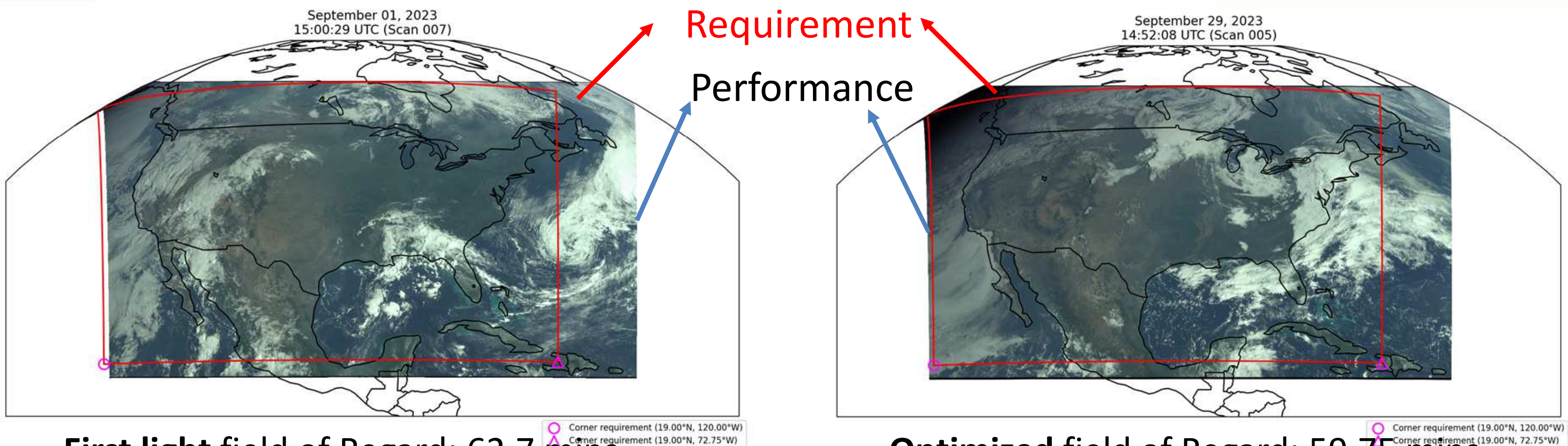
- **Operate on geostationary communications satellite Intelsat 40e (IS-40e) at 91 ° W**



- Field of regard is optimized to cover both Puerto Rico and Canadian tar sands.
- S5p-TROPOMI NO_2 product oversampled by Kang Sun.

- **Nominal:** Scan Field of Regard (FOR) in 1 hour
  - ~ 2K N/S pixels × 1200 steps/hr, ~ 2.4 M pixels/hr, daily # spatial pixels ~TROPOMI
  - 2 × 4.75 km^2 @center of FOR, from 8 km^2 at Mexico City to 21 km^2 at Canadian Tar Sands
- **Optimized scan**: in the early morning and late afternoon, daylight portion of FOR, higher temporal resolution
- **High-time scan (up to 25%)**: selected portion of FOR at higher temporal resolution (e.g., <= 10 mins), can oversample to effectively increase spatial resolution

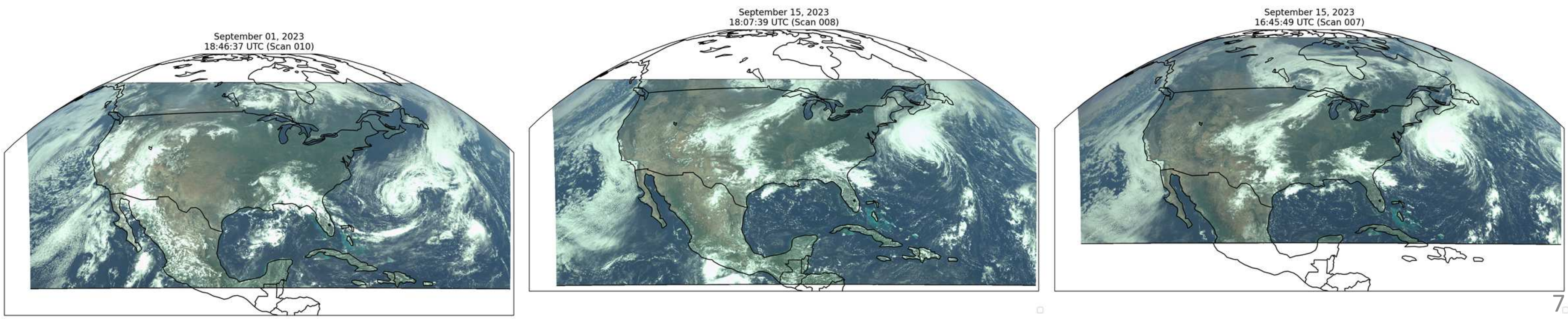
Field of Regard



First light field of Regard: 62.7 mins
(100 ms integration time, 26 coadds, 61.5 μrad)

Optimized field of Regard: 59.75 mins
(100 ms integration time, 26 coadds, 64 μrad)

Fields of regard characterization (FOR mapping) with different N-S SMA angles



Baseline and Threshold Measurements Requirements

Species/Products	Required Precision	Temporal Revisit*
0-2 km O_3 (Selected Scenes) **Baseline only**	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric SO_2	**1.0×10^{16} molecules cm^{-2}**	**3 hour**
Tropospheric $C_2H_2O_2$	**4.0×10^{14} molecules cm^{-2}**	**3 hour**
Aerosol Optical Depth	**0.10**	**1 hour**

* # of hourly measurements to be averaged to achieve required precision
- Mission duration: 20 months for baseline, 12 months for threshold
- Spatial resolution: < 60 km^2 for baseline (4 native pixels coadded), < 300 km^2 for threshold

- **Aerosols, SO_2, $C_2H_2O_2$ were removed from baseline products during KDPC**
- **Cloud product (cloud fraction, cloud pressure): used in trace gas/aerosol retrievals**

TEMPO Data Products
Baseline + SNWG TEMPO NRT

Level	Product	Algorithm	Major Outputs	A Priori (L2)	Res km^2 *	Freq/Size
L0	**Digital counts**	Raw to L0	Reconstructed/reformatted digital counts		2.0 x 4.75	Daily/hourly
L1-b	**Irradiance** NRT	SAO L0-1	Calibrated & quality flags			daily
	Radiance NRT	SAO L0-1	Geolocated, calibrated, viewing, geolocation & quality flags		2.0 x 4.75	Hourly, granule
L2	**Cloud** NRT	OMI O_2-O_2	Cloud fraction, cloud pressure	GEOS-CF	2.0 x 4.75	Hourly, granule
	O_3 profile	SAO O_3 profile	O_3 profile, total/strat/trop/0-2 km O_3 column, errors, a priori, AKs	Climatology+ GEOS-CF	>= 8.0 x 4.75**	Hourly, granule
	Total O_3	TOMS V8.5	Total O_3, AI, cloud fraction	Climatology	2.0 x 4.75	Hourly, granule
	NO_2 NRT	SAO trace gas, BU strat./trop. sep.	SCD, strat./trop. VCD, error, shape factor, scattering weights	GEOS-CF	2.0 x 4.75	Hourly, granule
	HCHO NRT	SAO trace gas	SCD, VCD, error, shape factor, scattering weights	GEOS-CF	2.0 x 4.75	Hourly, granule
L3	**Gridded L2**	SAO L2-3	Same as L2		2 x 2 (?)	Hourly, scan

* Spatial resolution at center of FOR. ** Might be at 8 x 9.5 km^2

Satellite Needs Working Group (SNWG) will fund TEMPO NRT products (L2 products < 3 hours from observation time): 11/1/2023-10/30/2025, NOAA to produce NRT aerosol products

Science Algorithms

- **Launch-ready Science Data Processing Center (SDPC) V4 software completed in Mar 2023**
- **Algorithm mostly based on OMI heritage algorithms except for new L0-1b processor including Imaging Navigation and Registration (INR) using GOES-R by Carr Astronautics**
- **SAO trace gas algorithm (HCHO, NO_2): spectral fitting to derive Slant Column Densities (SCDs), calculate air mass factor (AMFs) and derive Vertical Column Densities (VCDs)**
  - ✓ NO_2 requires stratospheric/tropospheric separation based on spatial filtering method (Geddes et al., 2018)
- **Cloud algorithm: SAO O_2-O_2 fitting + NASA GSFC's O_2-O_2 cloud at ~477/466 nm**
- **Total ozone algorithm: heritage TOMS V8.5, using ozone absorbing and non ozone absorbing pairs to derive total ozone column**
- **Ozone profile algorithm: heritage SAO OMI O_3 profile, using 290-340, 540-650 nm, retrieve O_3 profile at 24 layers, including total, stratospheric, tropospheric, and 0-2 km O_3**
- **Main L1-2 algorithms updates include:**
  - ✓ NASA GMAO's GEOS-CF trace gas profiles and meteorology
  - ✓ Hourly resolved monthly mean Geometry-dependent Lambertian Equivalent Reflectivity (GLER) climatology

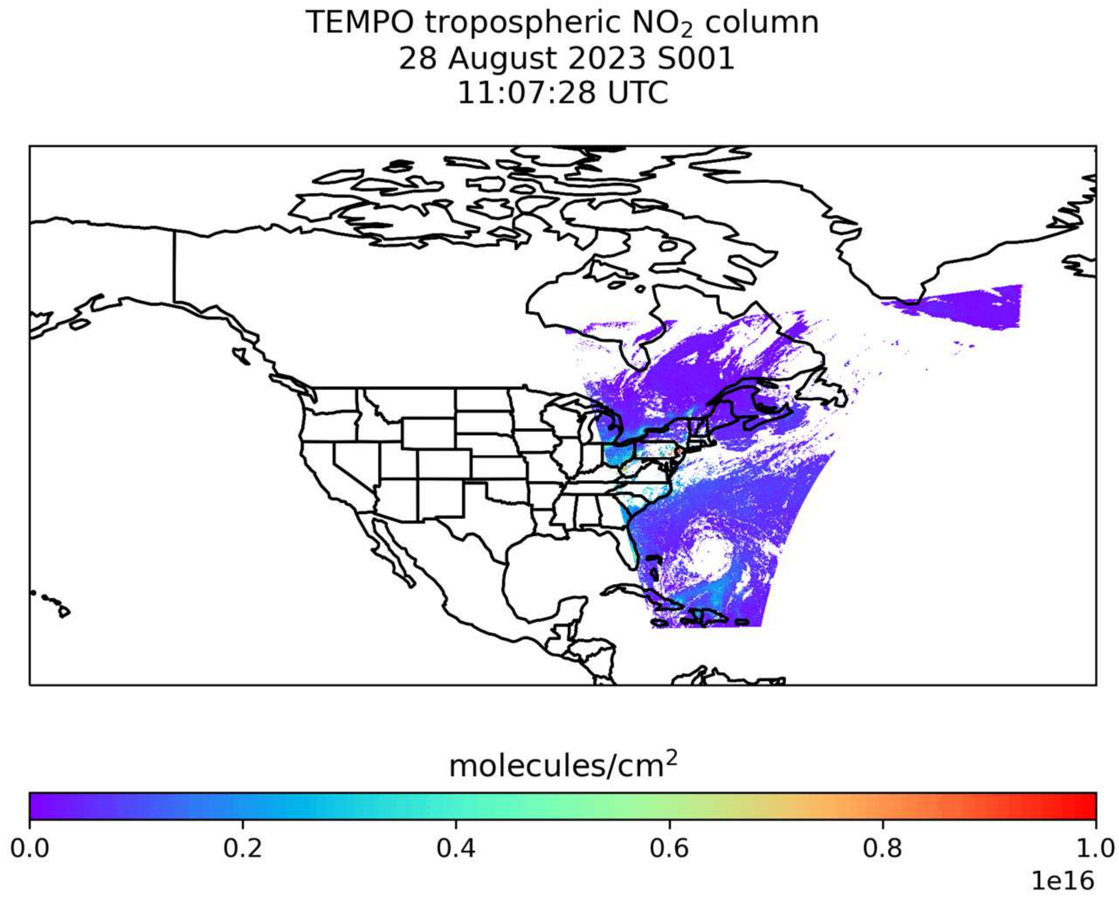
First Light NO_2 Images Release

- **Planning and Coordination:**
  - NASA LaRC+HQ+ESD, SAO/CfA/Smithsonian, Ball, Intelsat, Maxar
  - NASA Science Visualization Studio

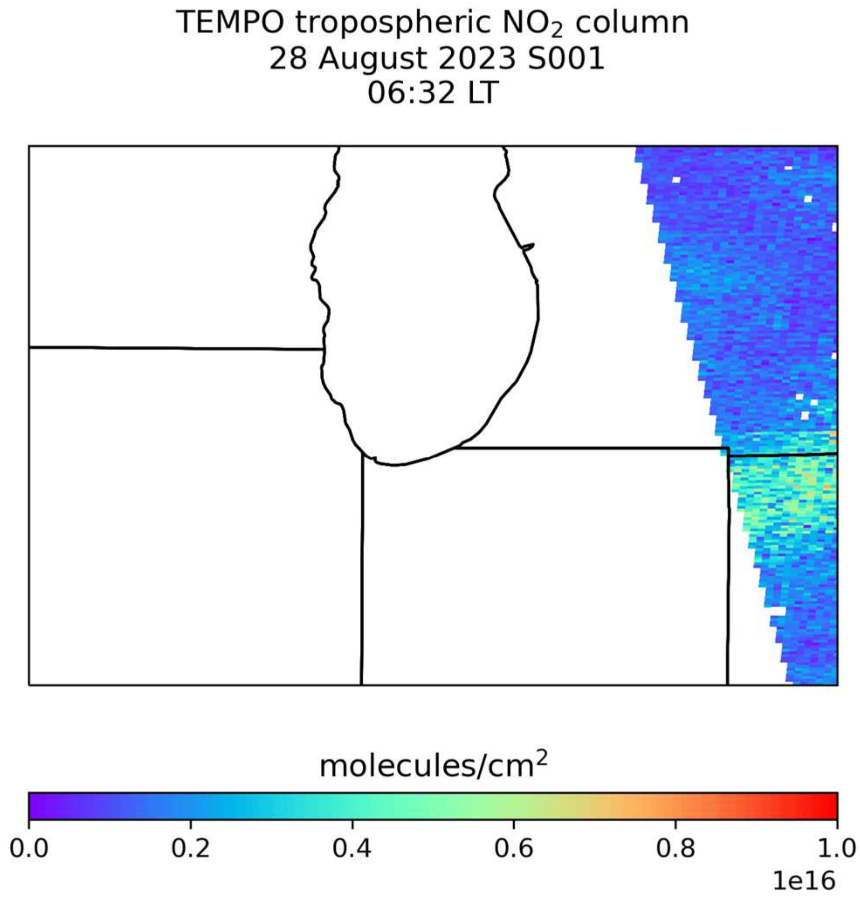
- **Algorithm Updates for First Light Release:**
  - No radiance wavelength calibration
  - Large wavelength shift of ~0.4-0.6 nm, use initial wavelength grid for radiance from calibrated first working solar
  - No straylight correction and polarization correction
  - Specialized Image Navigation and Registration (INR)
  - Optimization in clouds
  - Optimization in NO_2


02 Aug 2023 11:11 EDT
Nitrogen Dioxide Tropospheric Column Density
25 50 75 100 125 150
x10^14 / cm^2
Credit: NASA Scientific Visualization Studio

28 August 2023: Full Field of Regard

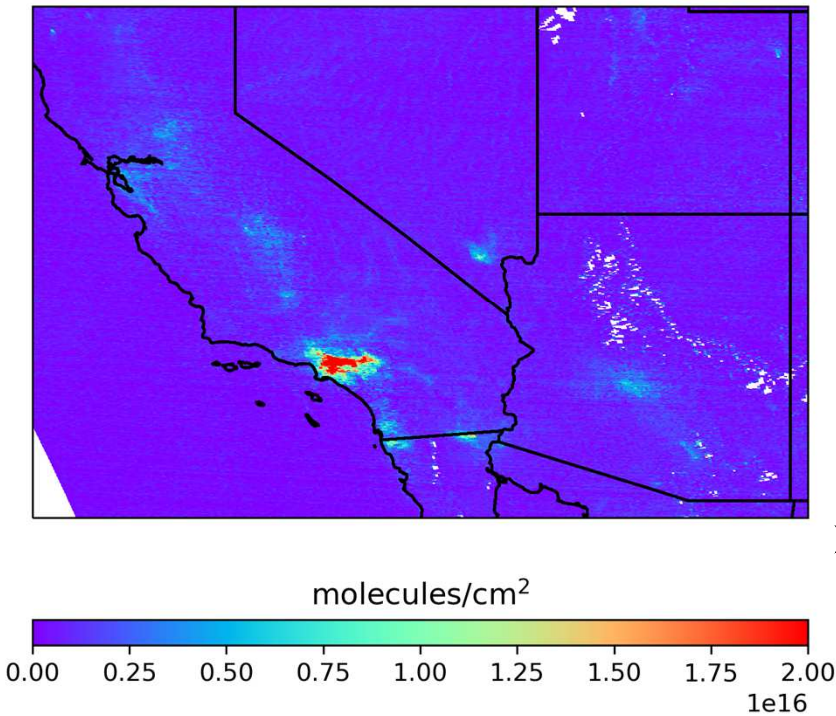


28 August 2023: Chicago



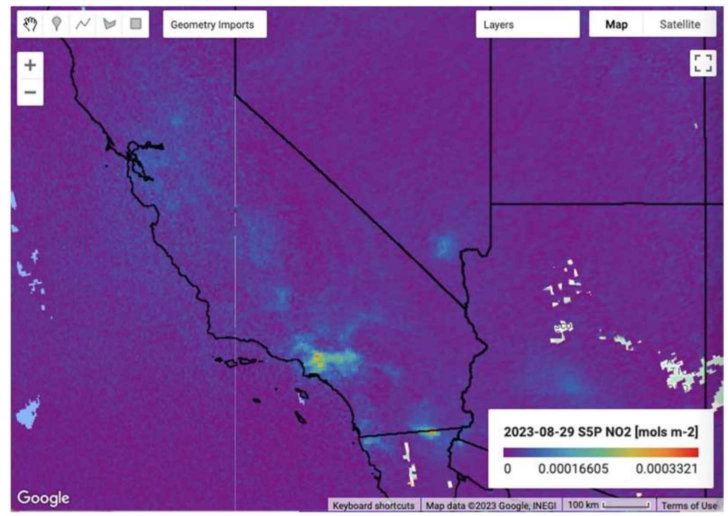
TEMPO and TROPOMI NO_2 CA/NV/AZ/UT, 29 August 2023

TEMPO tropospheric NO_2 column
29 August 2023 S012
20:24:00 UTC



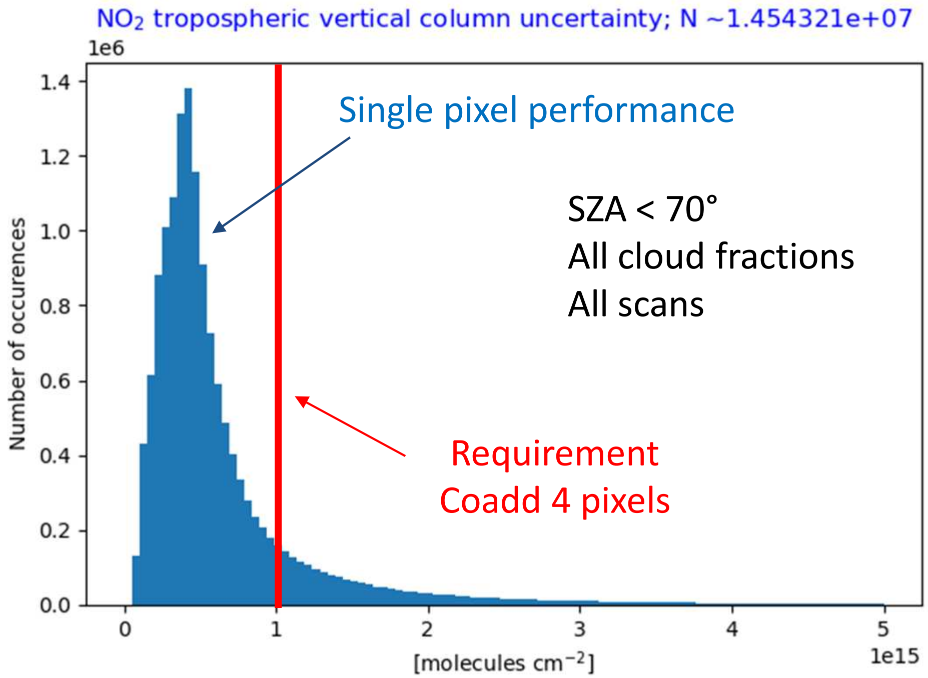
Cloud fraction < 0.5

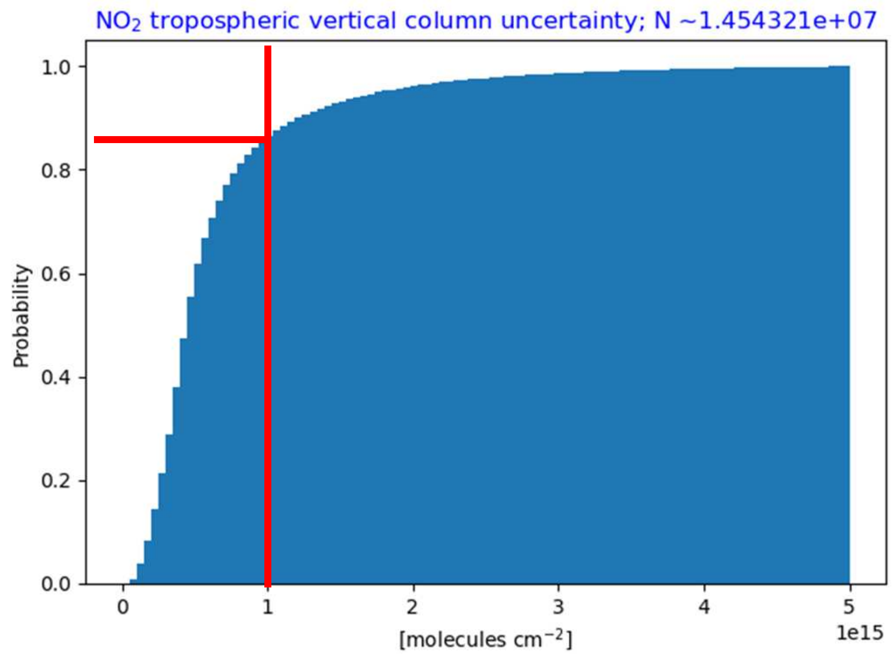
TROPOMI Level 3 tropospheric NO_2



- **TEMPO vs TROPOMI shows spatial agreement in tropospheric NO_2. Differences are not unexpected:**
  - ✓ [Lorente et al., 2019]: Differences in air mass factor (AMF) inputs (e.g. model profiles, surface reflectance) can cause differences of up to 42% in polluted NO_2 retrievals
  - ✓ Verhoelst et al. [2021]: lower TROPOMI NO_2 by 51% in polluted areas.

NO_2 Tropospheric Column Uncertainties
29 August – 1 September

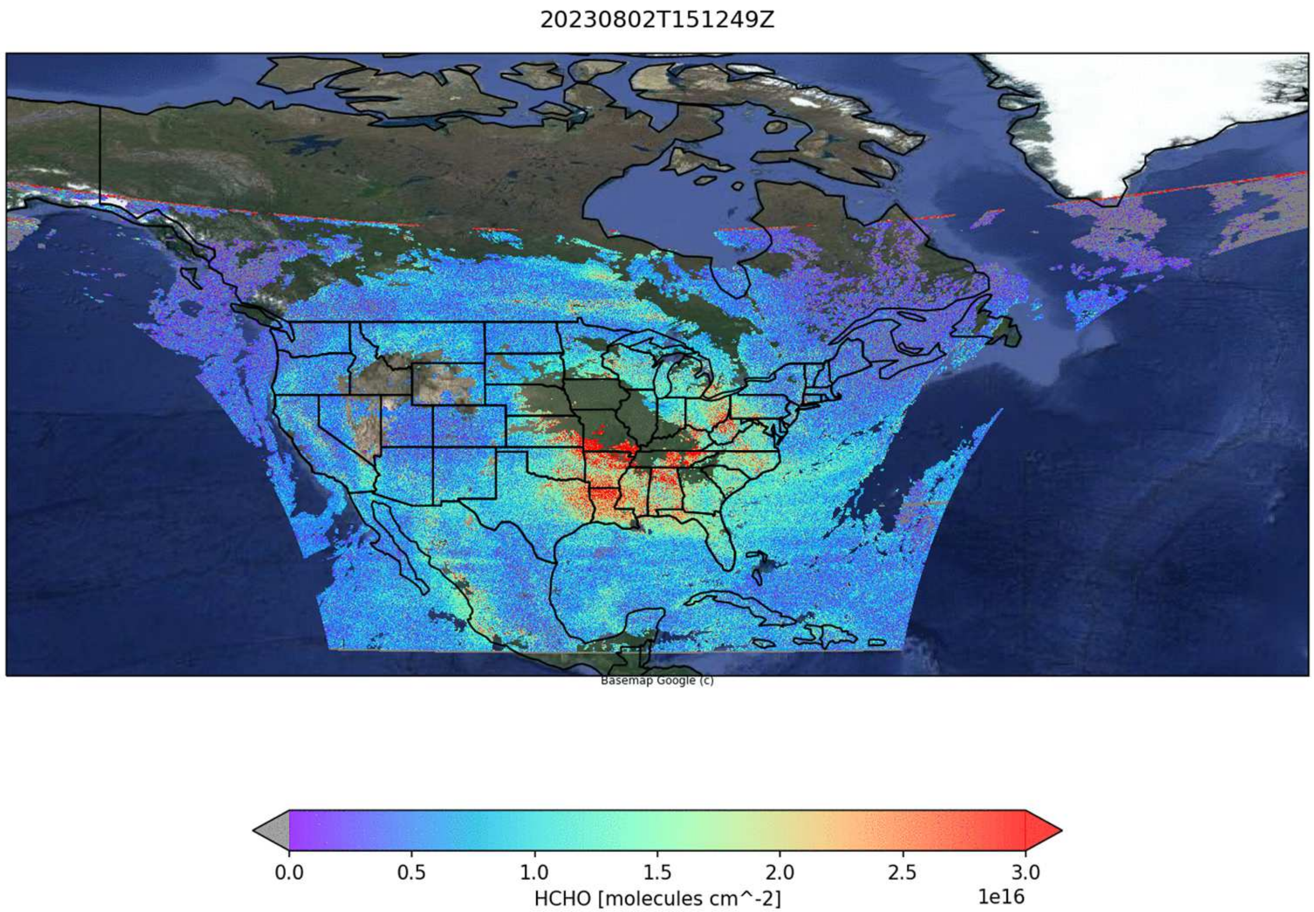




- NO_2 uncertainty requirement = 1×10^{15} molecules/cm^2 **(with 4 pixels coadded)**
- Median uncertainty = 0.46×10^{15} molecules/cm^2 (SZA < 70°, all cloud fractions)
- 95% of measurements have uncertainties < 1×10^{15} molecules/cm^2 for cloud-free conditions ($f_c \leq 0.1$)

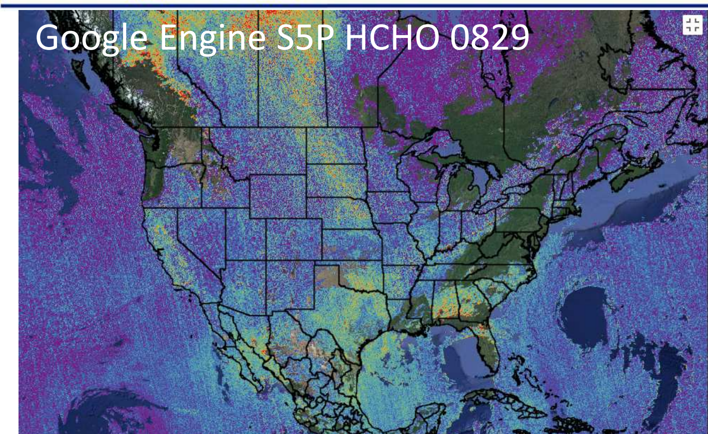
TEMPO NO_2 meets the requirement for 95% of cloud-free scenes with **no pixel coadding**!

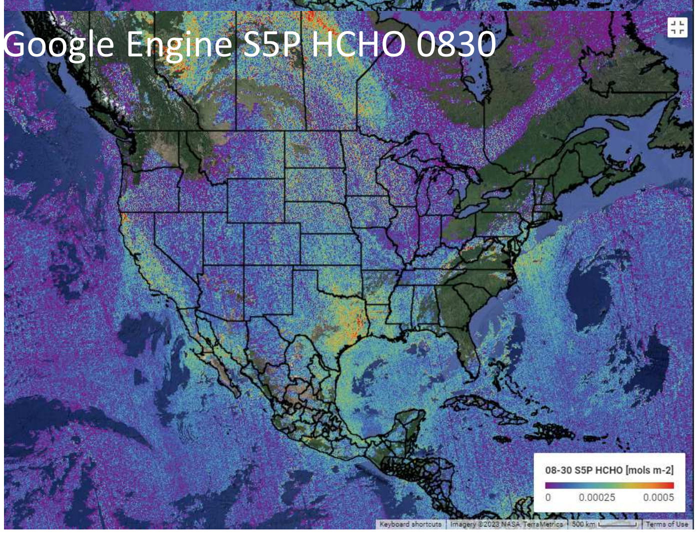
First Light HCHO (2 August 2023)

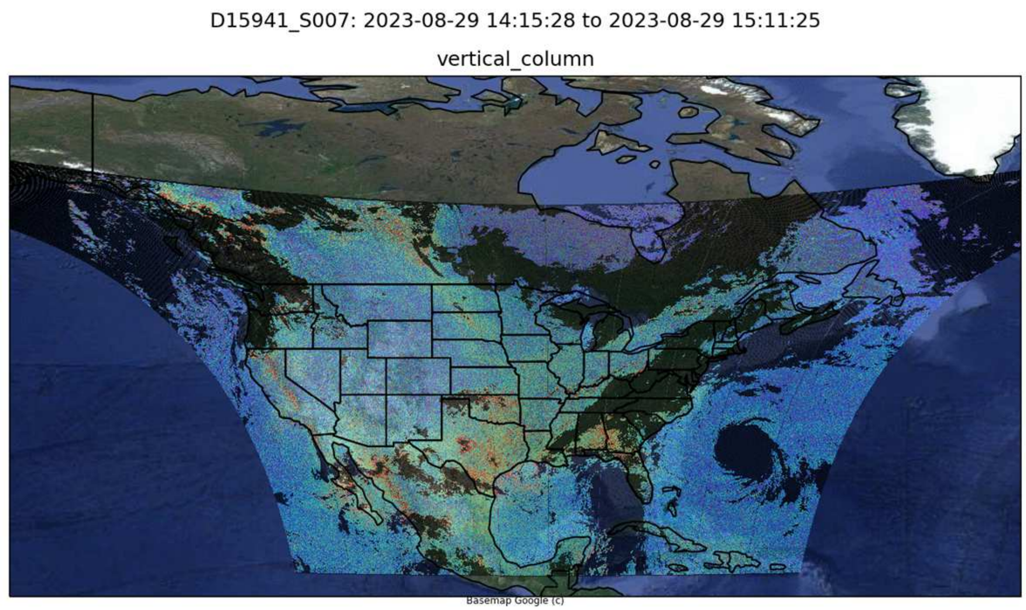


- **Switched to use radiance reference after first light images releases (due to systematic positive biases in the southern edge)**

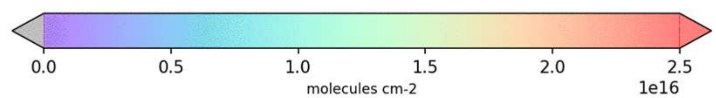
TEMPO and TROPOM HCHO (29-30 August 2023)





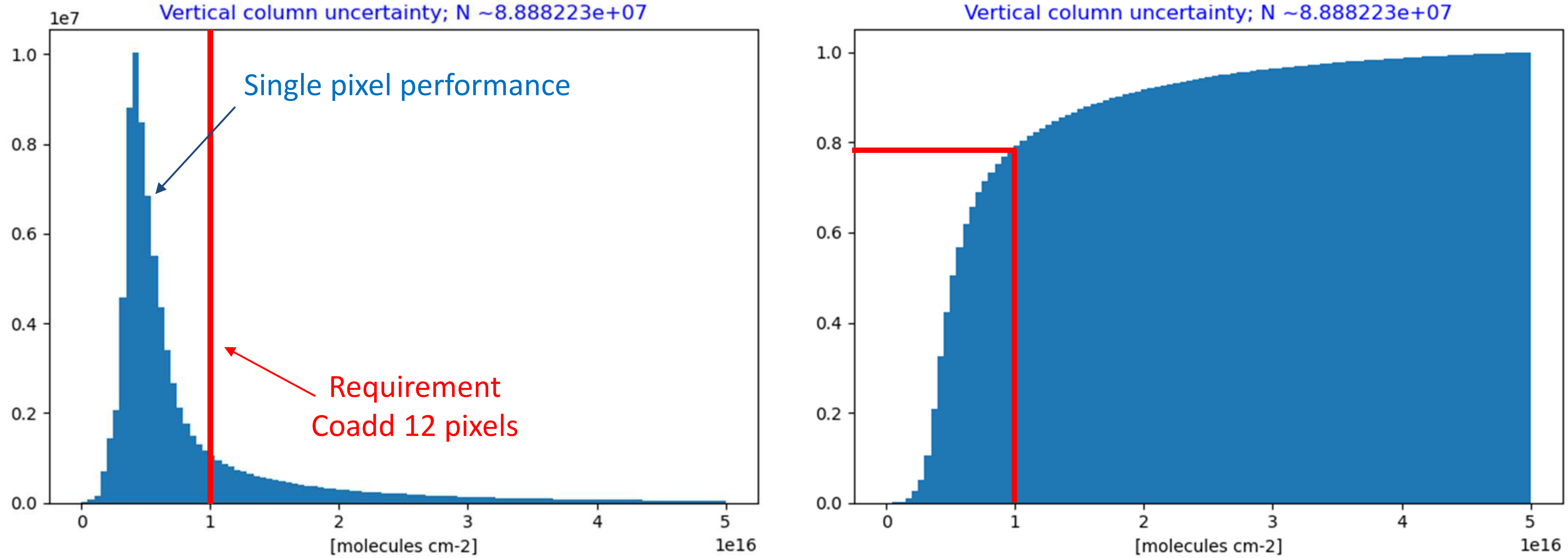


TEMPO HCHO 0829-0830 (scans close to S5P overpass)



- TEMPO vs TROPOMI shows spatial agreement in HCHO columns. Systematic biases are expected associated with AMF, radiance reference and background corrections.

HCHO Column Uncertainties
29-30 August 2023

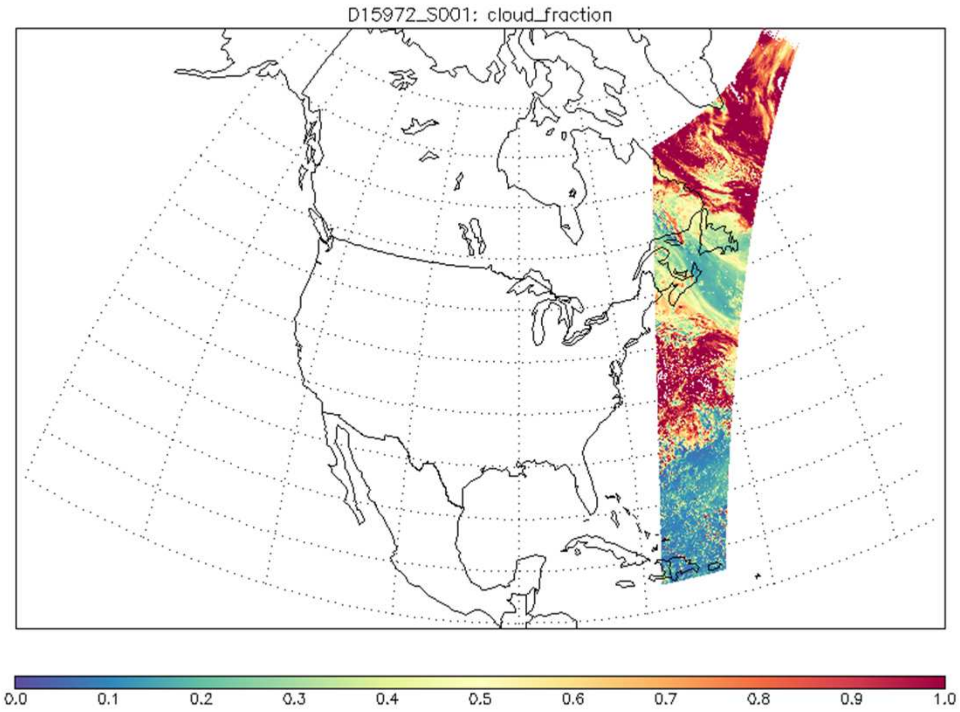


- HCHO uncertainty requirement = 1 x 10^{16} molecules/cm^2 (**with 12 observations**)
- Median uncertainty = 5.5 x 10^{15} molecules/cm^2 (SZA < 70˚, all cloud conditions)
- 93% of observations have uncertainties < 1x10^{16} molecules/cm^2 (SZA < 70˚, $f_c \leq 0.1$)

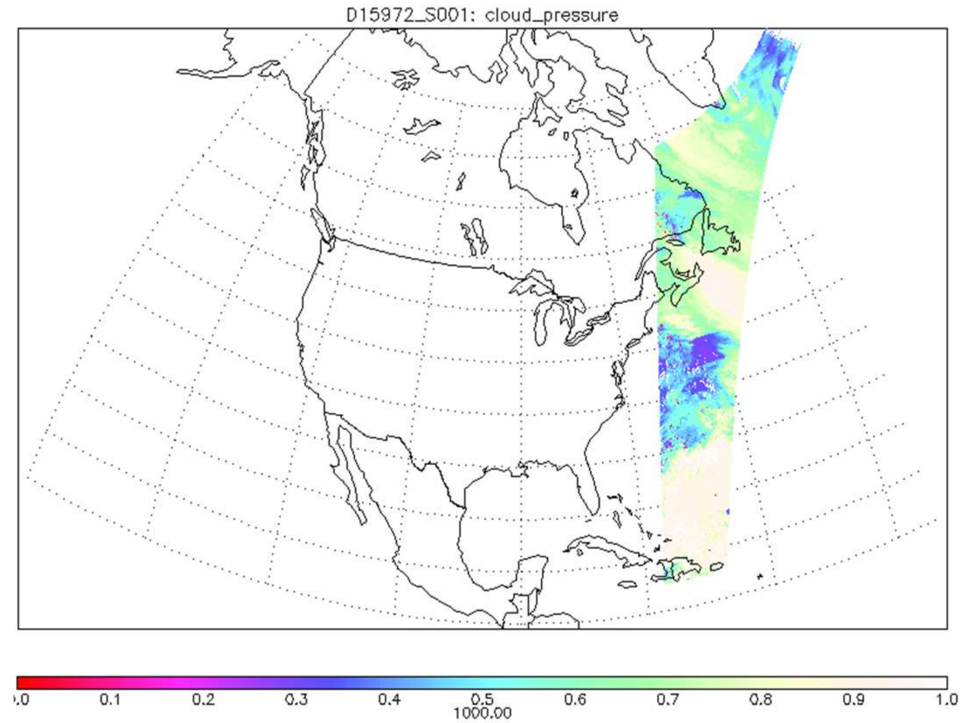
TEMPO HCHO meets the requirement for 93% of cloud-free scenes with **no pixel coadding**!

Cloud Products (29 September 2023)

Cloud fraction



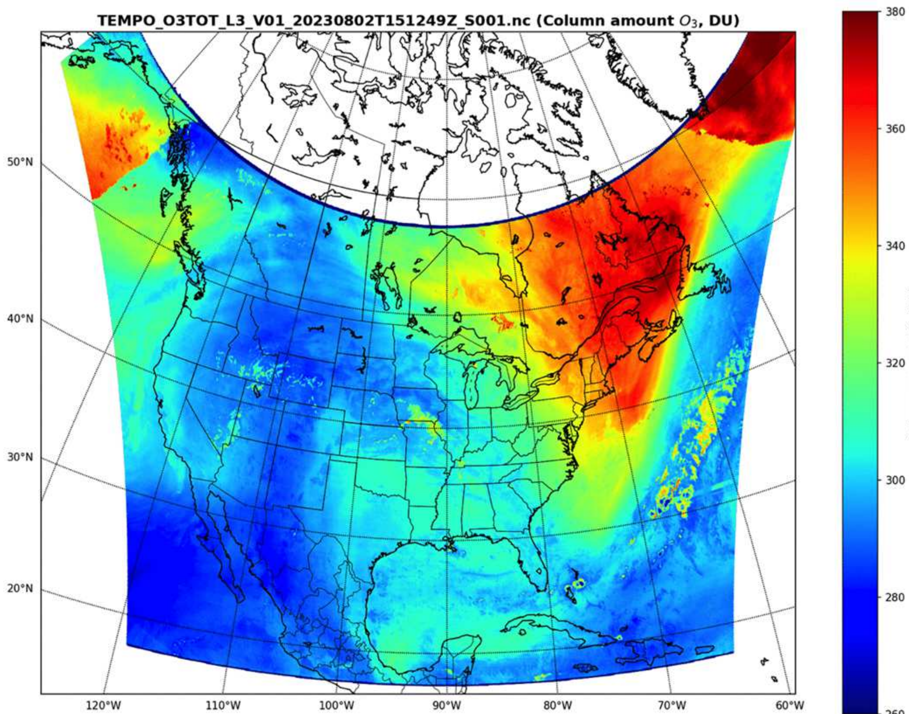
Cloud pressure



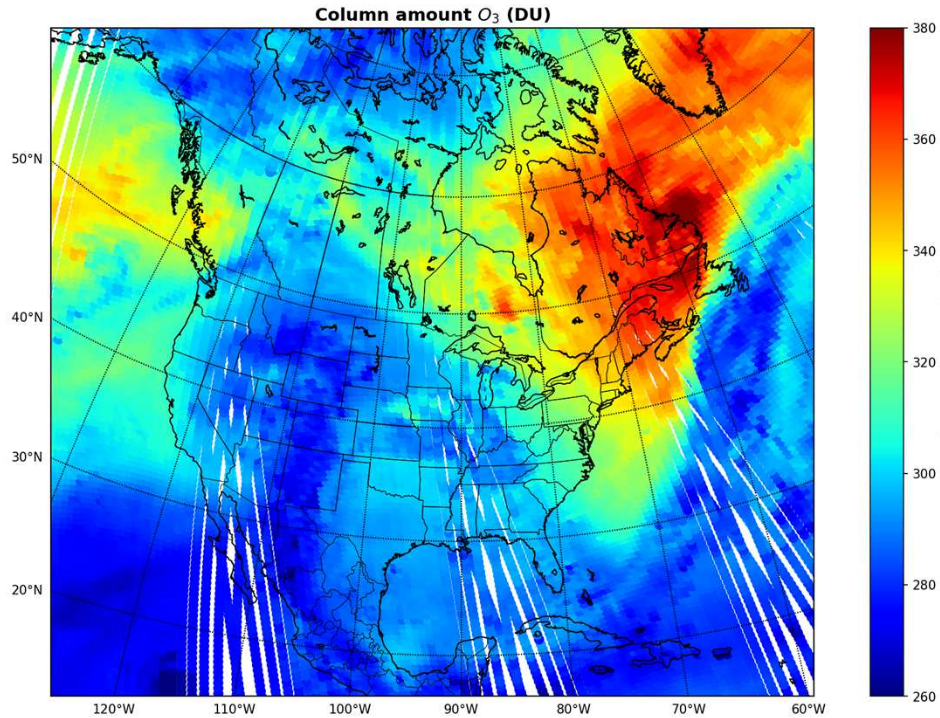
- Saturation causes no retrieval under very cloudy conditions.

First Light Total Ozone (02 August 2023)

- Similar spatial distribution with OMPS total ozone
- Total ozone will be further improved with improved radiometric calibration (e.g., image processing, straylight correction)



TEMPO

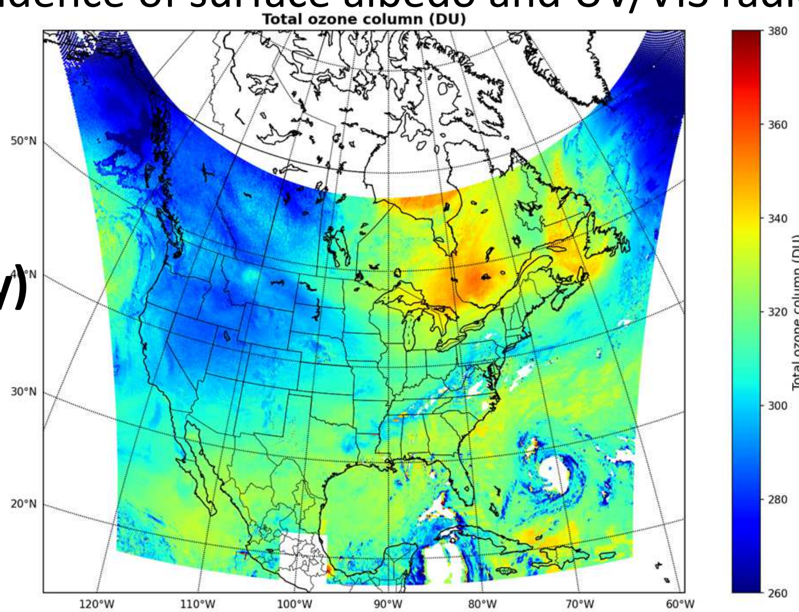


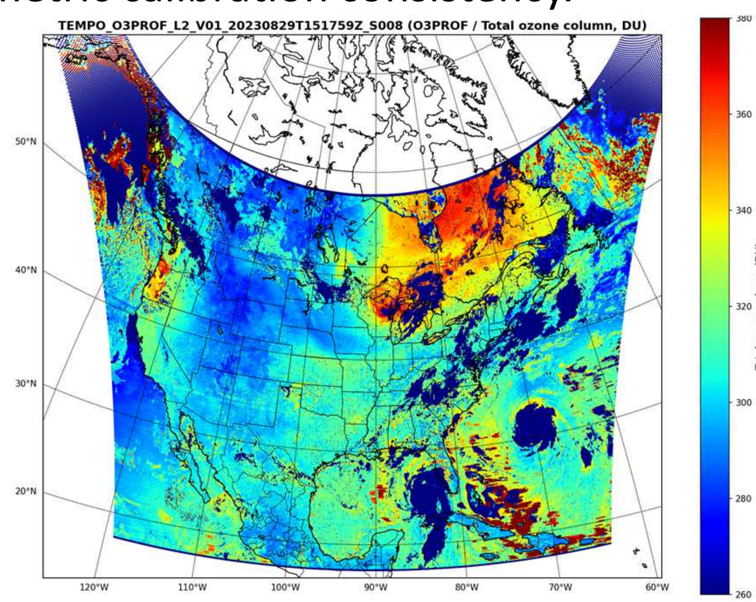
OMPS

Total Ozone from Ozone Profile Product: UV (8/28) vs. UV/VIS (8/29)

- Large total ozone bias due to large positive biases (~20-30%) in radiance below ~305 nm, and the fitting of a first-order wavelength dependent surface albedo. Necessary to improve UV radiometric calibration (e.g., solar diffuser BTDF, image processing, straylight correction) and derive soft calibration
- Less stable with UV/VIS retrievals than UV only retrievals. In addition, need to improve VIS spectral dependence of surface albedo and UV/VIS radiometric calibration consistency.

Ozone Profile (UV only) on 8/28

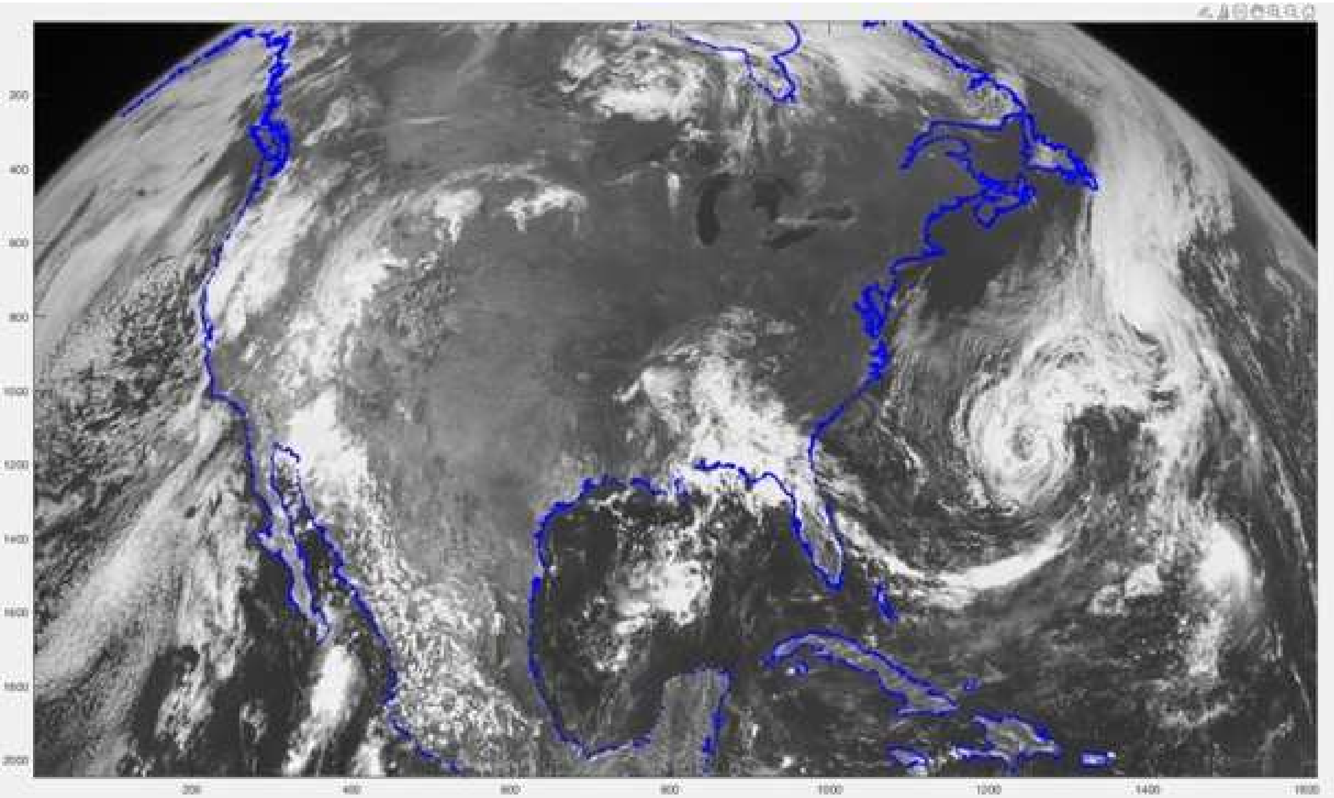




Ozone Profile (UV/VIS) on 8/29

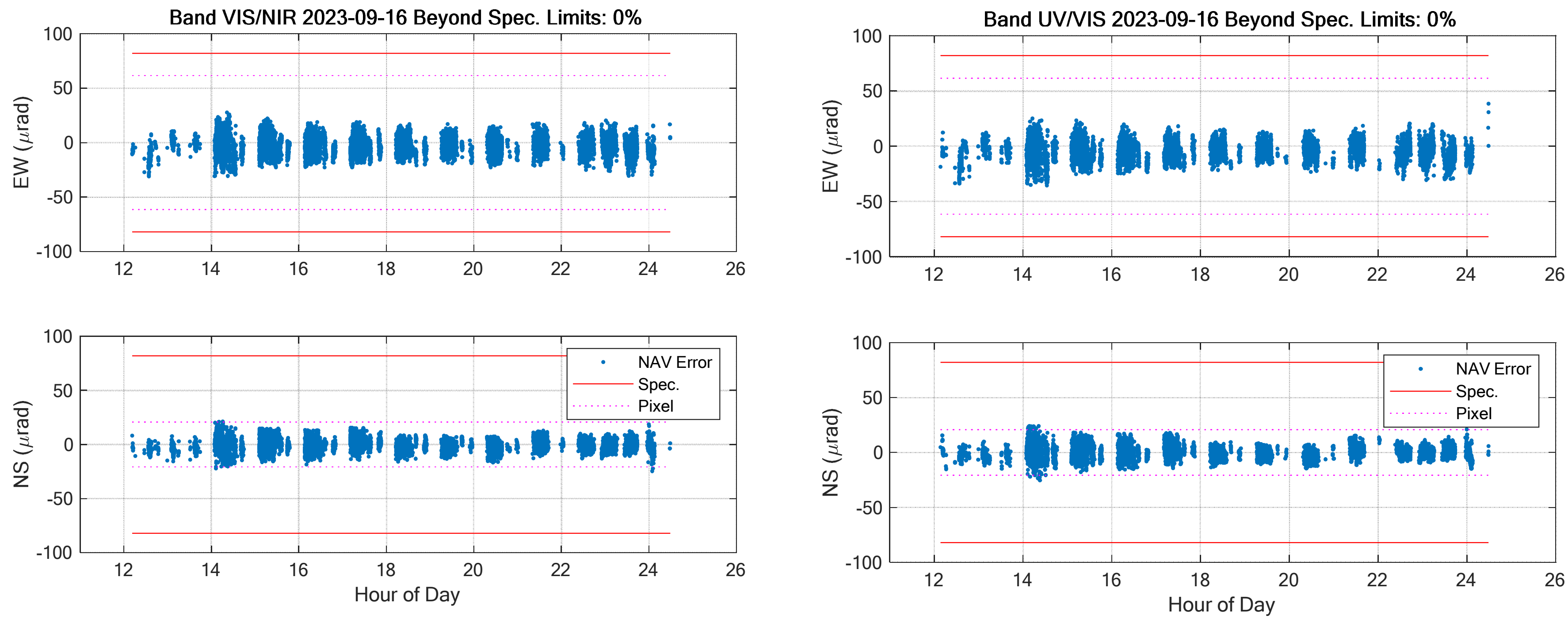
Ozone profile algorithm has been tested and we know how to improve the data product!

INR (Image Navigation and Registration) Status



- **INR Requirements are Met**
  - ✓ Navigation error limits exceeded < 0.27% (3s) of evaluations (Pass)
  - ✓ Optimized scanning performs worse at start of day due to low illumination, which is improved with GPS enabled (since 9/9)
- **Consistent NS biases observed in UV/VIS, which will be corrected in the next release**
- **Special observation still requires a separate INR configuration to reduce geolocation errors.**

Optimized Scanning (GPSR): September 16
Next INR Release



	EW Mean	EW Std	NS Mean	NS Std	Out of Limit
VIS/NIR	-2.0981	6.0594	-1.4832	4.1732	0
UV/VIS	-3.3226	6.1935	-0.128	4.3225	0

Algorithm Status and Outlook

- **First SDPC update (SDPC v4.1) approved on 10/16: INR, L0-1b, cloud, NO_2, HCHO, after testing ~11 days of processing**
  - ✓ INR: working well for hourly/optimized scans
  - ✓ L0-1b: gain/nonlinearity, bad pixel map, improved saturation flagging, Octant phase (odd/even)
  - ✓ Further optimization in cloud and NO_2
  - ✓ Major changes to HCHO: radiance reference, and background correction
  - ✓ All the data products have been sent to ASDC since Oct. 17
  - ✓ In the process of sharing with the TEMPO validation & science team from ASDC

- **Forward work toward public release**
  - ✓ INR: correct UV/VIS bias, use a special configuration for special observation
  - ✓ L0-1: BTDF correction, reference BTDF, improved wavelength calibration, improved CCD image processing steps, straylight correction
  - ✓ Optimizations to cloud, NO_2 and HCHO
  - ✓ Updates to Ozone Profile Retrieval (first UV only, then UV/VIS)

Plan for Nominal Operation & Public Release

Data Product	Description	Time beyond On-Orbit Checkout (OOC) to deliver initial data	Maximum data latency after first release for ≥ 80% of products
Level 0	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
Level 1b	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
Level 2	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO
Level 3	Derived Gridded Geophysical Data Products	6 months	1 month after completion of data accumulation required for individual geophysical products

- **Baseline mission (Phase E, 20 months, 10/2023-6/2025), NASA senior/extension review**
- **Data products sent to ASDC for archival and distribution**
- **Working on providing earlier access to TEMPO validation/science team**
- **Plan for initial public release of baseline products at ASDC after algorithm verification, product validation, algorithm optimization/improvement: ~2/2024 for L1b, ~4/2024 for L2/L3**

Summary

- Started nominal operation on Oct. 19 after a successful TEMPO commissioning phase and Post Launch Acceptance Review (PLAR)
- TEMPO is providing revolutionary hourly daytime atmospheric pollution measurements at high spatial resolution over North America
- Most data products (L1b, cloud, NO_2, HCHO, total O_3) are in good quality at this early stage, showing that the TEMPO instrument and science algorithms are working very well
- We have a good understanding about the improvements needed for the ozone profile product before the public release.

NASA

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Ball

MAXAR

INTELSAT

SPACEX

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

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA 1868

UAH
THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY

SAINT LOUIS
UNIVERSITY

WASHINGTON UNIVERSITY IN ST. LOUIS 1853

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

UMBC
UNIVERSITY OF MARYLAND BALTIMORE COUNTY
1966

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

THE UNIVERSITY
OF IOWA

YORK
UNIVERSITÉ
UNIVERSITY

INECC
INSTITUTO NACIONAL
DE ECOLOGÍA
Y CAMBIO CLIMÁTICO

INSMET

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL
INSTITUTE

CARR
ASTRONAUTICS
Science at work

RTS

NCAR

Environment and
Climate Change Canada

Environnement et
Changement climatique Canada

KNMI

NASA

TEMPO

TEMPO

TEMPO Commissioning

- **Instrument Characterization activities**
  - ✓ Dark current measurements vs. integration time, take dark current after every hourly scans
  - ✓ Solar measurements at solar angle 30 vs. time, different boresight angles, repeated solar measurements, working vs reference
  - ✓ Saturation (different integration times, 50 ms, 100 ms, 178 ms)
  - ✓ Spatial performance (61.5/62.5/63.6/64.6 urad, 10%, 20%, 40%, 50%, 60%, 80% step size over NY, Western Gulf, LA)
  - ✓ Field of regard (full E/W extent at dy=0 on 9/1, full E/W extent at max/min dy on 9/15)
  - ✓ Side slither (fix dx, move N/S only over NY, western Gulf and LA)
  - ✓ City lights
  - ✓ Scanning: CONOPS scanning (hourly), optimized scanning, special observations (~10 mins, interleaved 10 mins + hourly scans), nominal operation
- **Coordinate with AGES+ campaign in Aug. and Coastal Texas Air Quality Field Campaign in Sep. (no Earth imaging only on 8/3, 8/10, 8/13, 8/14, 8/24, 9/8, 10 mins special observation on 8/23, 10 mins+1hr FOR on 8/27, twilight on 8/30 for supermoon, 2 hours of special observations over Texas on 9/11, 9/17-19)**

TEMPO Software/Algorithm Teams

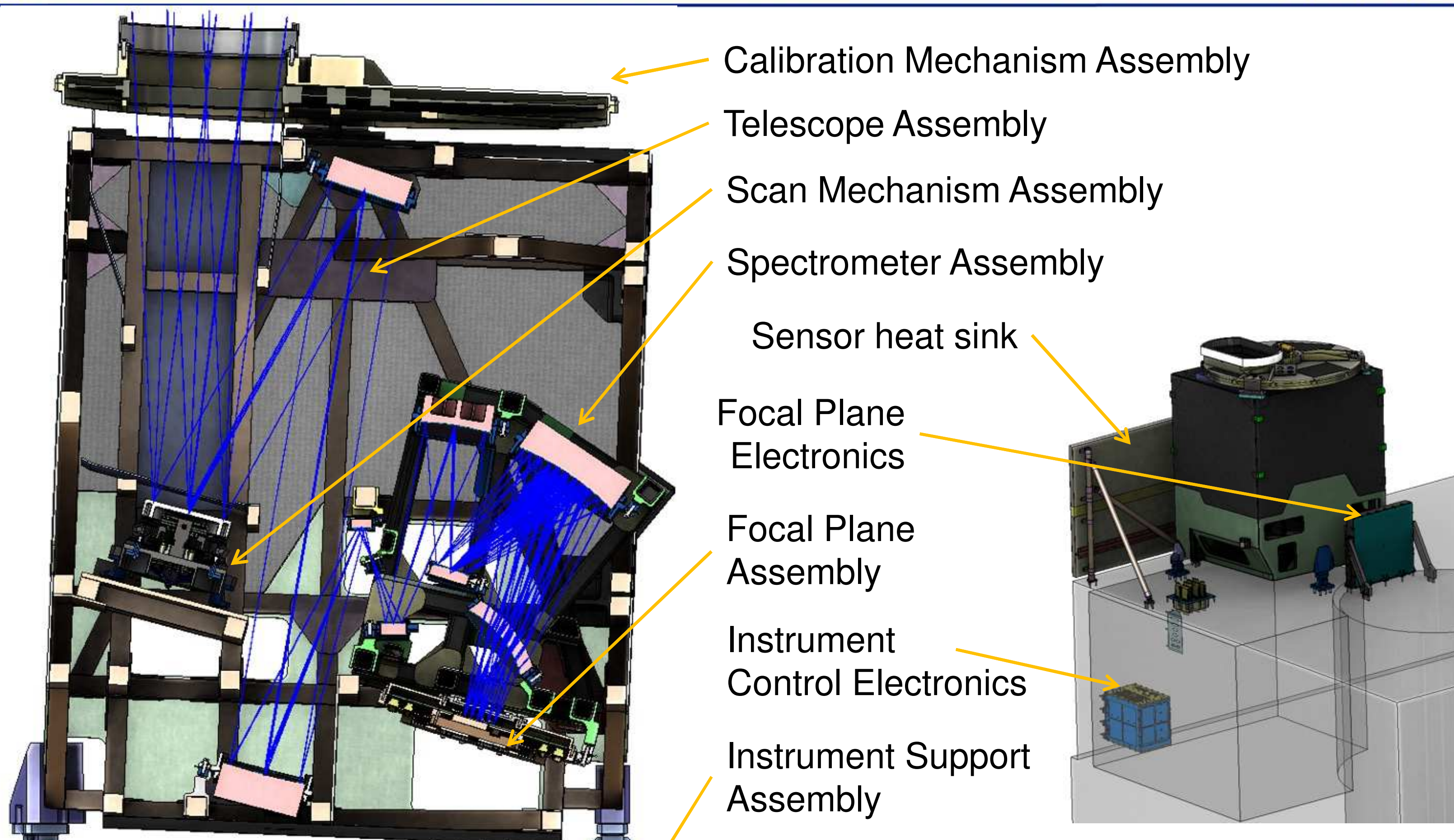
Operational Algorithm	Personnel
Instrument Operation Center (IOC) including Raw-L0	John Davis
L0-1b	**Heesung Chong**, John Houck, Weizhen Hou, Xiong Liu, Dave Flittner, Jim Carr, Chris Chan Miller
Ozone profile	**Xiong Liu**, Junsung Park, Juseon Bak
Total ozone	Dave Haffner, Joanna Joiner
Nitrogen dioxide	**Caroline Nowlan**, Gonzalo González Abad, Jeff Geddes, Chris Chan Miller
Formaldehyde	**Gonzalo González Abad**, Caroline Nowlan, Chris Chan Miller
Clouds	**Huiqun (Helen) Wang**, Alexander Vasilkov, Eun-Su Yang, Joanna Joiner
Science Data Processing Center Operational Implementation & Processing Pipeline	Joh Houck

TEMPO Instrument and Measurement Characteristics

Volume, Mass, Average Power	1.4 m x 1.1 m x 1.2 m, 137kg, 138W
Detector size	Two 2048 (spatial) x 1028 (spectral)
Wavelength range	UV band: ~293 - 494 nm, Visible band: 538 - 741 nm
Spectral resolution	~0.6 nm @FWHM(0.54-0.63 nm)
Spectral sampling	~0.2 nm or ~3 pixels /FWHM (2.7-3.2)
Spectral co-registration[1]	< 0.1 pixel (for UV, visible, UV/visible)
Orbit	GEO (35786 km), 91.0°W above equator
Instantaneous FOV	41.49 μrad (N/S) x 129.20 μrad (E/W)
MTF @Nyquist	0.31-0.41 N/S x 0.38-0.49 E/W
Field of view[2]	4.92° N/S x 8.64° E/W
Spatial resolution	2.0 km (N/S) x 4.75 km (E/W) km @center of FOR
Temporal resolution[3]	~1 hour, ~3s snapshot / mirror step
Spectra per hour[2,3,4]	2035 N/S (cross-track) x 1226 E/W (mirror step)
Maximum SNR[5]	1350 @ 330 - 340 nm, EOL

[1]Smile, keystone, and UV/visible co-alignment are within 0.1 pixel.
[2]Assume 123μrad E/W mirror step size (6.2μrad overlap) & 1226 steps as in left Fig.
[3]Nominal mode.
[4]2035 out of 2048 spatial pixels are valid; 1016 out of spectral 1028 pixels are valid.
[5]For the nominal radiance.

TEMPO Instrument



Credit: Ball

TEMPO Data Products Distribution

Slides from Jeff Walters, Tim Larson at TEMPO STM 2020 & EAWNov2021

ASDC Data Archival & Distribution: Tools and Services

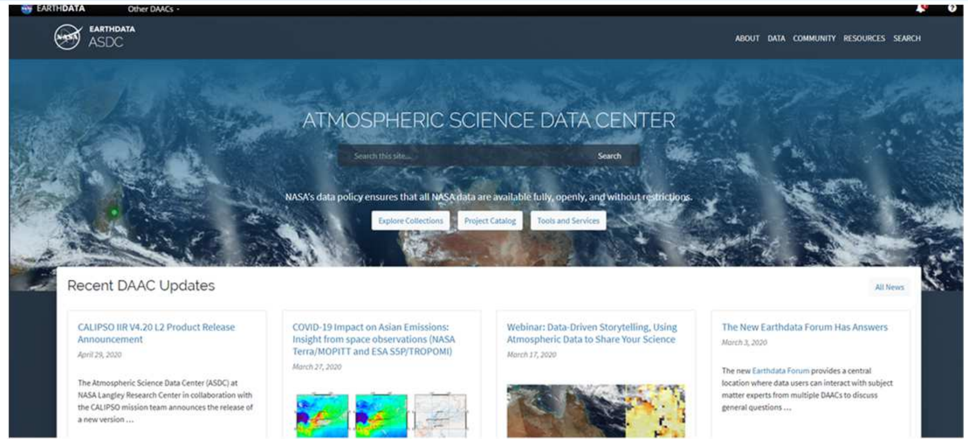
- ✓ NASA Earthdata Search
  - CMR Search ∘ Metadata
- ✓ NASA WorldView
  - GIBS API ∘ visualization
- ✓ Harmony and OPeNDAP
  - ∘ transform ∘ subsetting
  - ∘ reformatting ∘ distribution
- ✓ HTTPS data access
  - ∘ datapool
  - ∘ permanent URL/direct access
  - ∘ enables scripts/workflow
- ✓ Geospatial Web Services
  - ∘ WCS ∘ WMS ∘ ArcGIS Image Service
- ✓ Example scripts
  - ∘ Python/Jupyter Notebook
  - ∘ R scripts
  - ∘ contributed tutorials/scripts

User Support and Other Resources

Earthdata Login https://urs.earthdata.nasa.gov

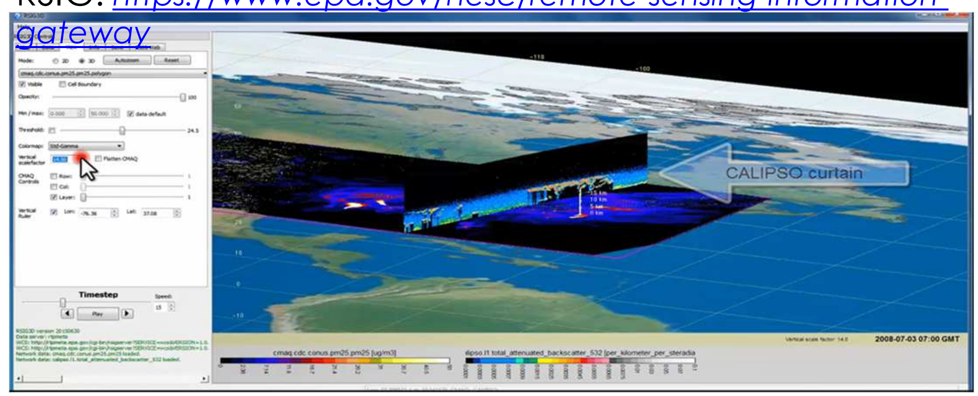
Earthdata Forum https://forum.earthdata.nasa.gov/

ASDC User Support support-asdc@earthdata.nasa.gov

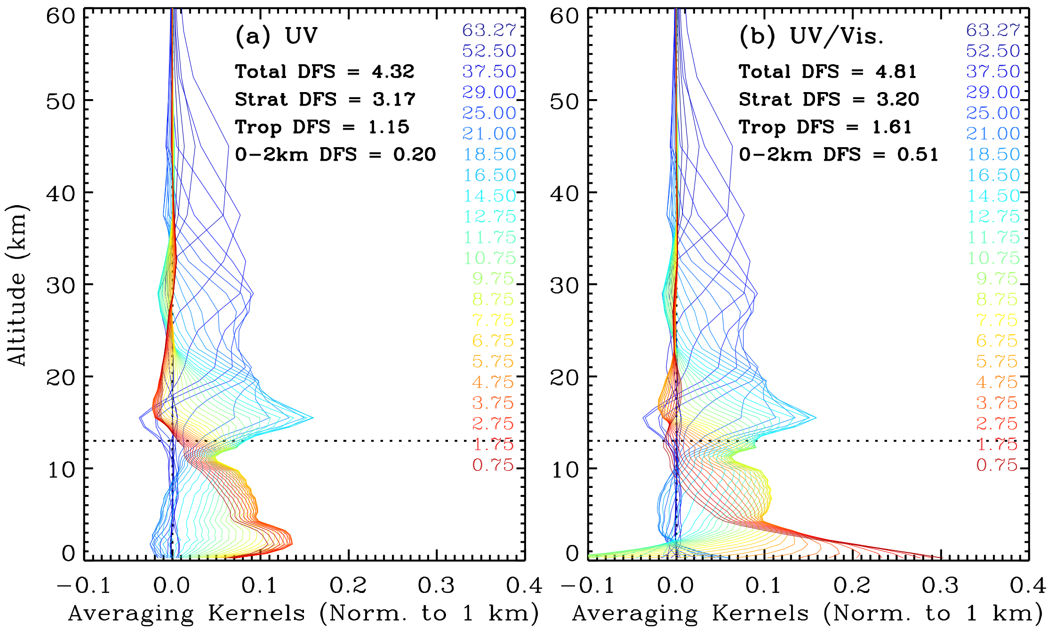


EPA RSIG3D Gateway

TEMPO data can be served directly through the EPA RSIG. *https://www.epa.gov/hesc/remote-sensing-information-gateway*



Including Visible to Improve Tropospheric Ozone Retrieval Sensitivity



- This example is for solar zenith angle =25, viewing zenith angle 45, relative azimuthal angle 86, Signal to noise Ratio (SNR) with 4 pixels coadded
- Add visible to improve retrieval sensitivity in the lower troposphere and help separate free tropospheric O_3 from boundary layer O_3
- Under ideal conditions: 3-5 total Degree of Freedom for Signal (DFS) with up to ~1.5 in the troposphere, and up to ~0.5 DFS in 0-2 km

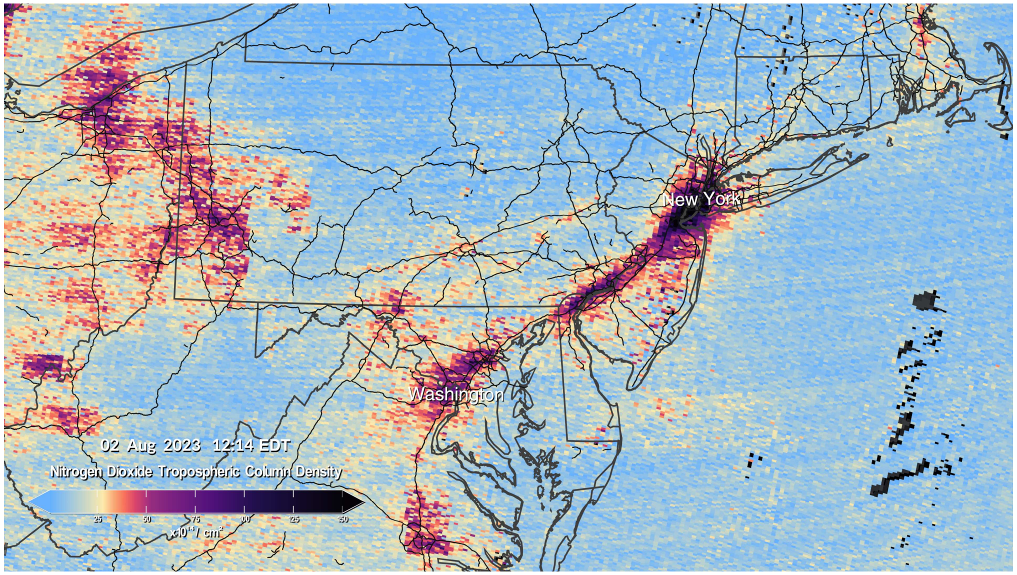
- Adapted from OMI (Liu et al., 2010): Spectral fitting + VLIDORT + Optimal Estimation (OE) from Fitting windows: 293-345 nm, 540-650 nm
- Retrieve partial O_3 columns at ~24 layers (bottom layer is 0-2 km above the surface) as well as total, stratospheric, and tropospheric O_3 columns, other trace gases, and auxiliary parameters.
- A priori: a combination of tropopause-based climatology (Bak et al., 2013) with diurnally-resolved GEOS-CF data

TEMPO

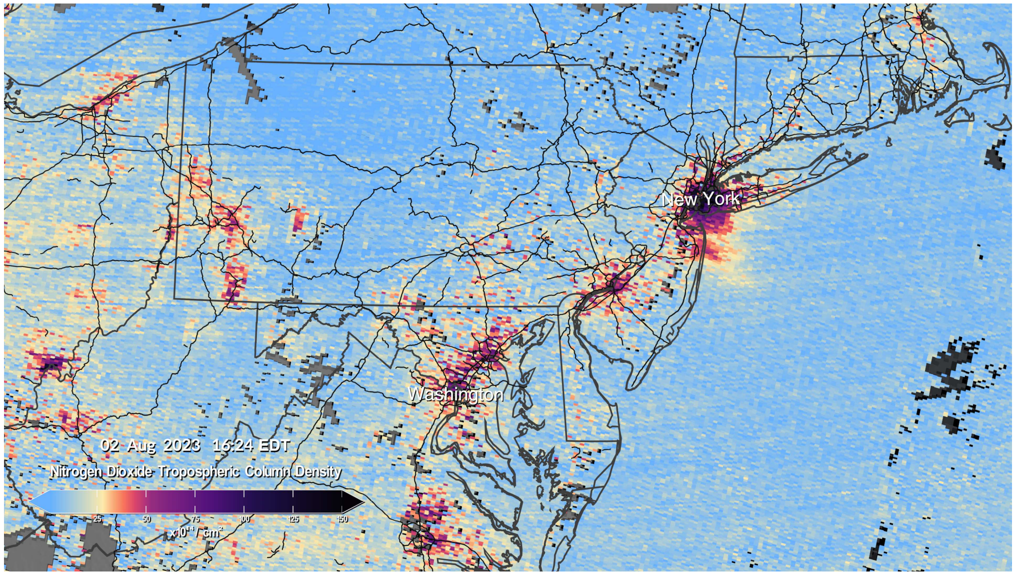
Nitrogen Dioxide

August 2, 2023

12:14 PM



4:24 PM

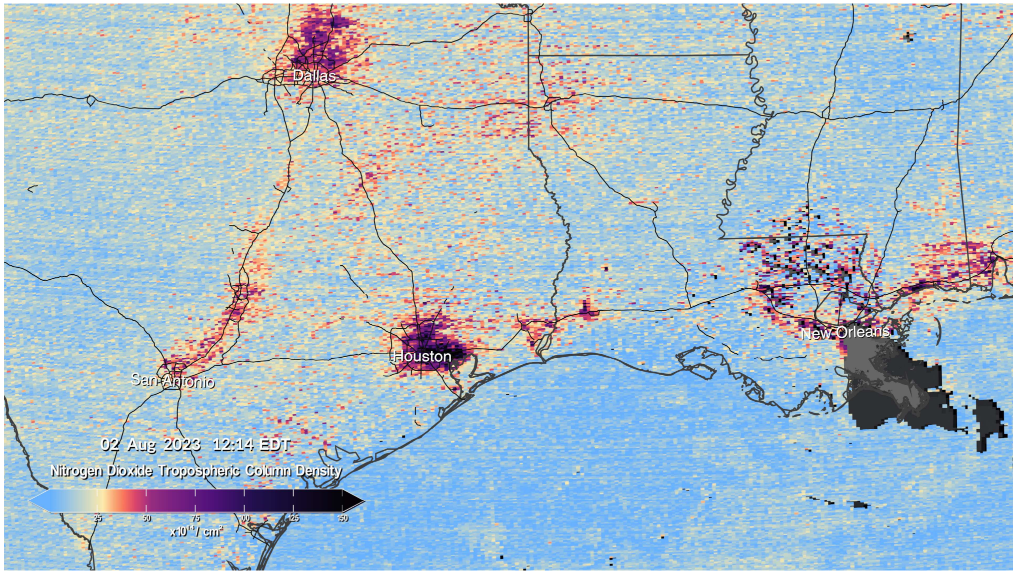


Credit: NASA Scientific Visualization Studio

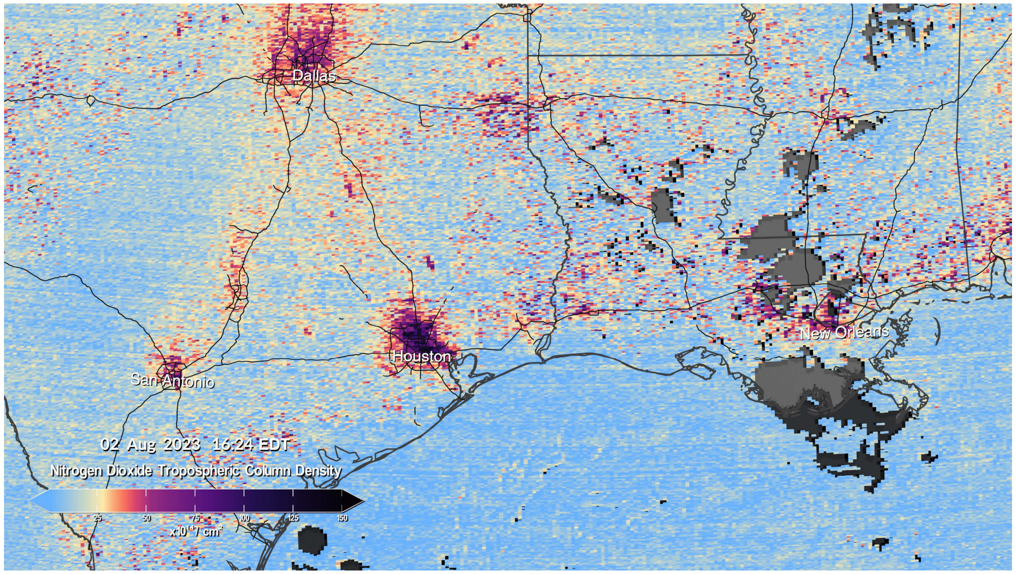
Nitrogen Dioxide

August 2, 2023

11:14 AM



3:24 PM

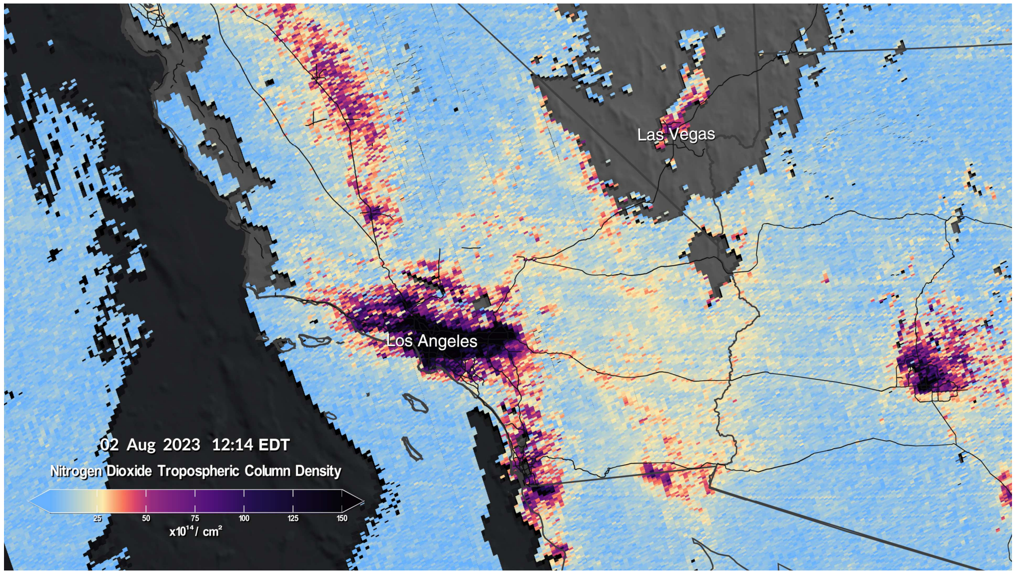


Credit: NASA Scientific Visualization Studio

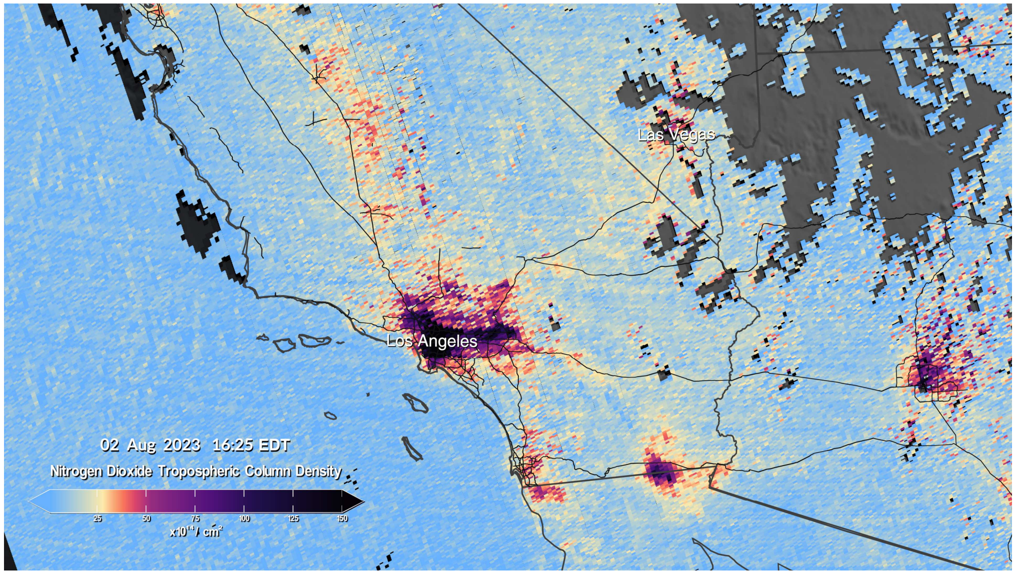
Nitrogen Dioxide

August 2, 2023

9:14 AM

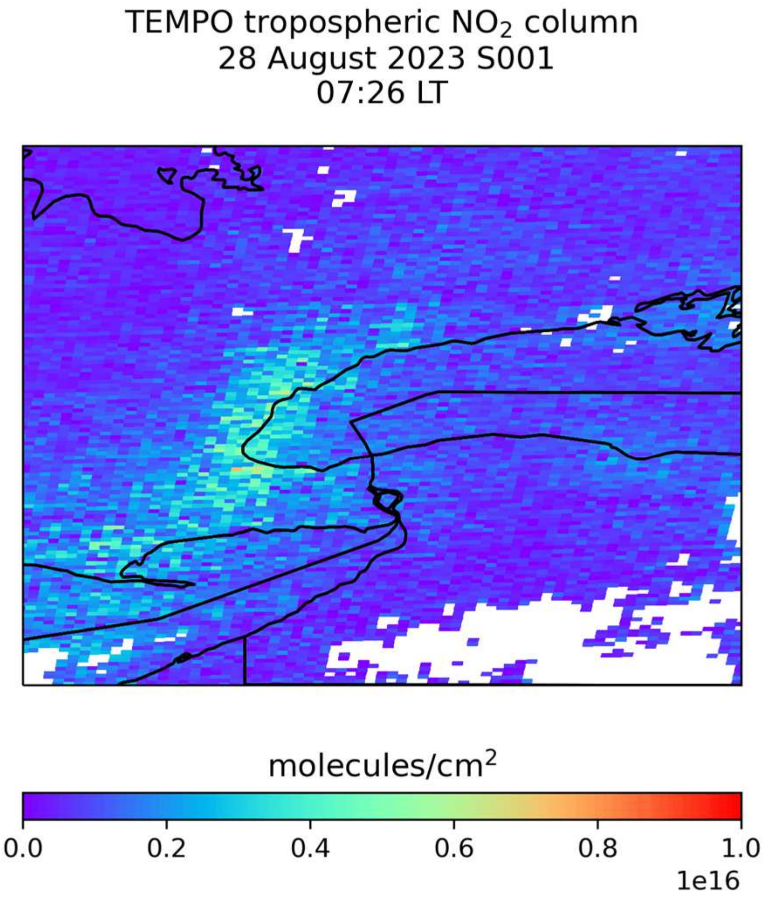


1:25 PM

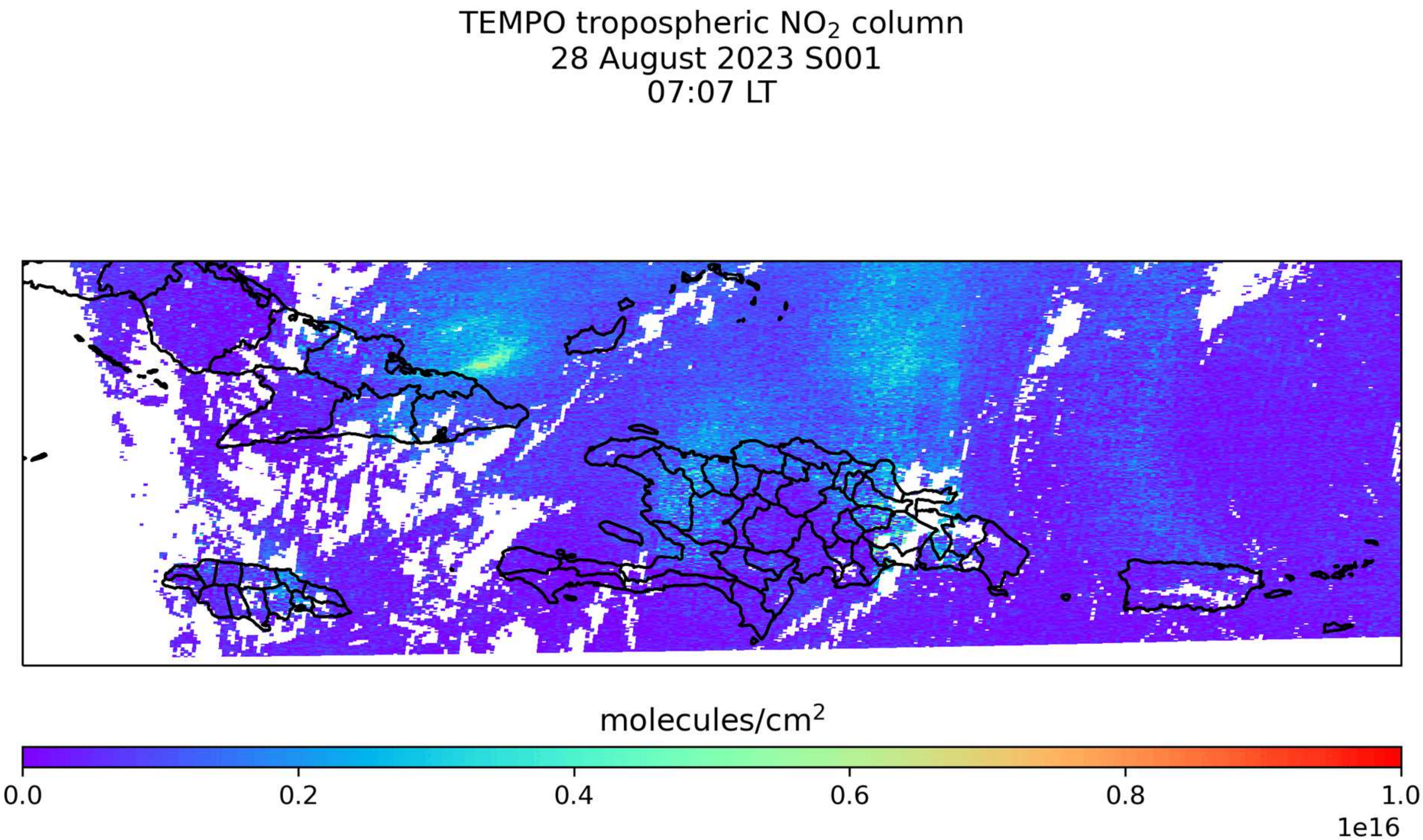


Credit: NASA Scientific Visualization Studio

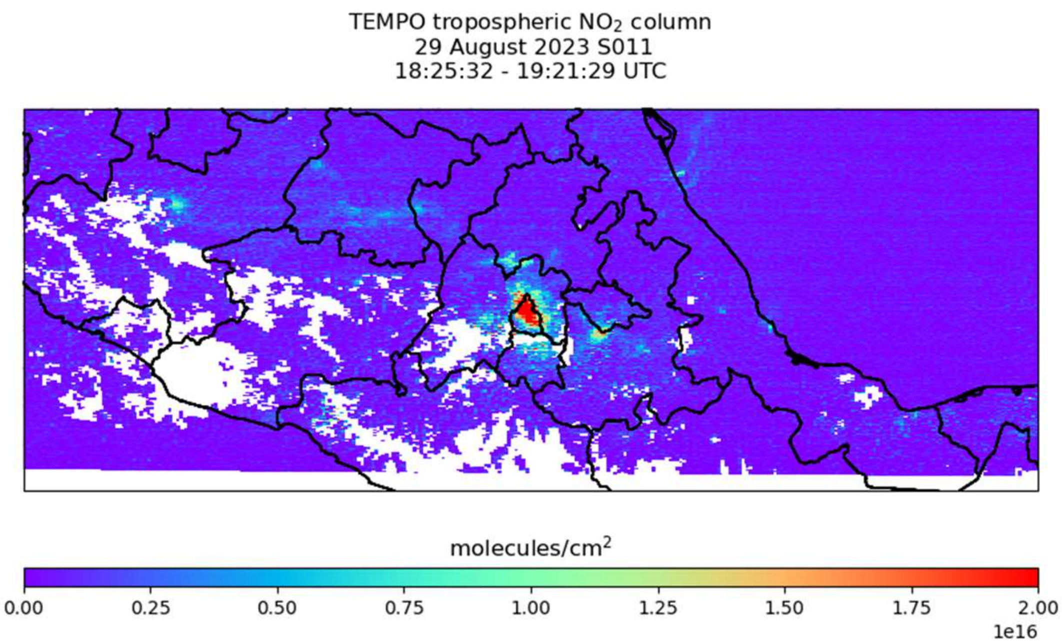
28 August 2023: Toronto



28 August 2023: Caribbean

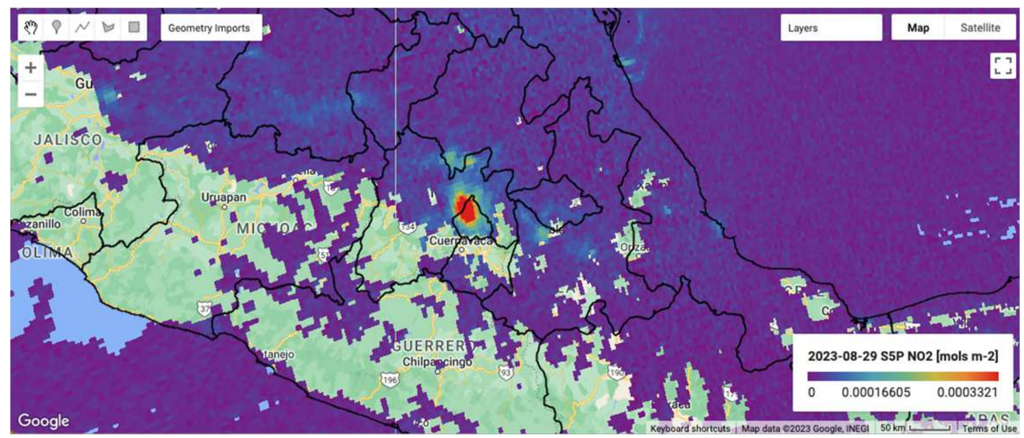


TEMPO and TROPOMI NO_2
Mexico City, 29 August 2023



Cloud fraction < 0.5

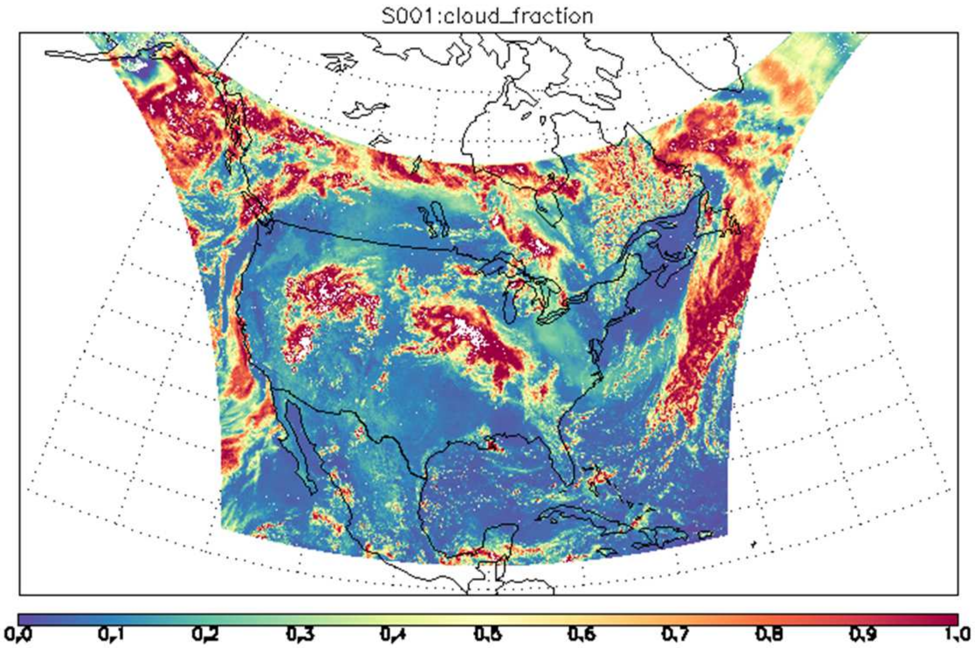
TROPOMI Level 3 tropospheric NO_2



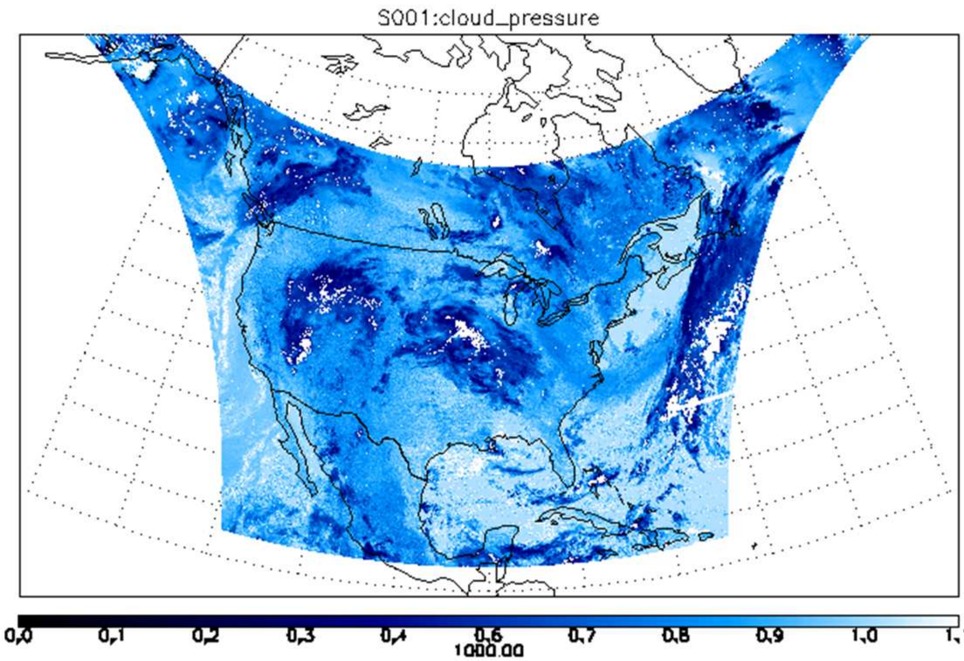
First Light: Cloud Products

First Light comm3 S001-S006

Cloud fraction



Cloud pressure

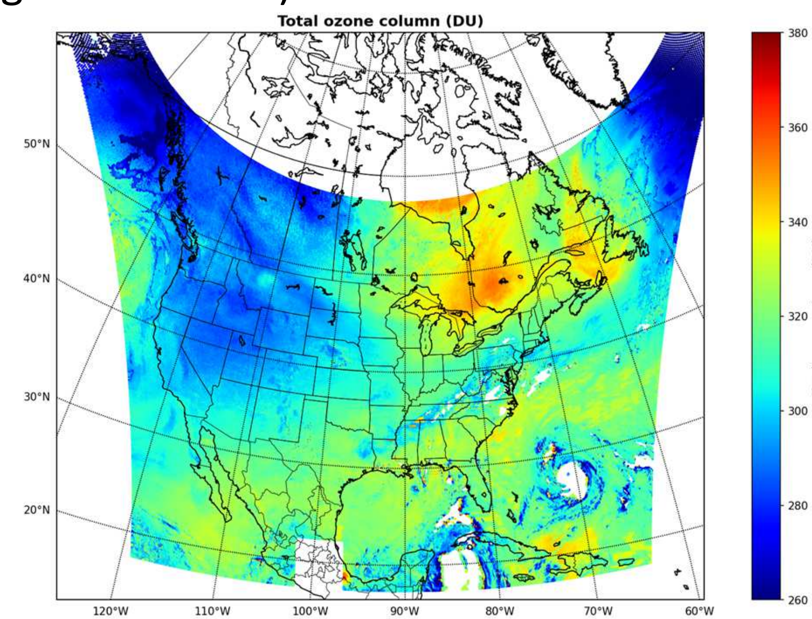


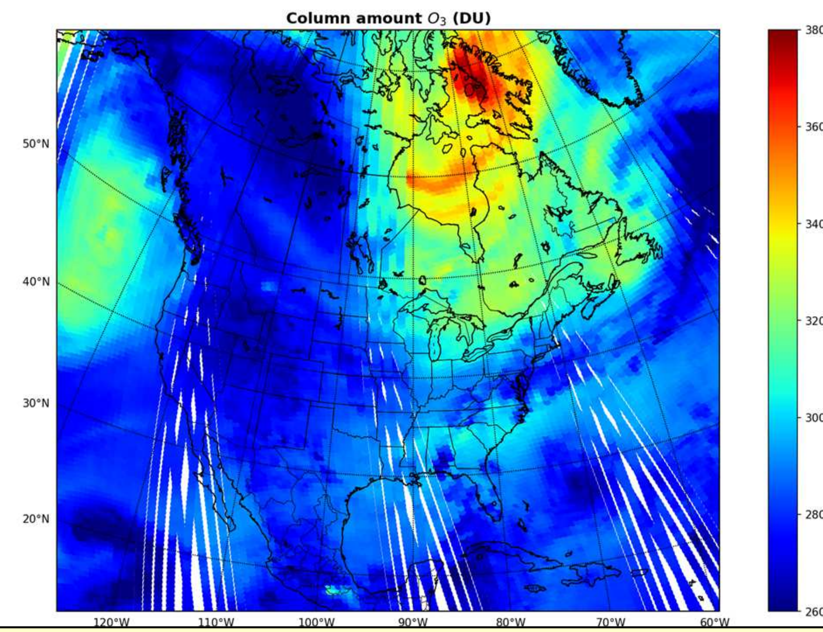
- **Saturation causes some retrieval failure under cloudy conditions.**

Total Ozone from Ozone Profile Product: UV only 8/28

- Large total ozone bias due to large positive biases (~20-30%) in radiance below ~305 nm, and the fitting of a first-order wavelength dependent surface albedo
- It is necessary to improve L0-1b radiometric calibration (e.g., solar diffuser BTDF, image processing, straylight correction) and derive soft calibration

TEMPO Ozone Profile





OMPS

Ozone profile algorithm has been tested and we know how to improve the data product!

L1b Requirements

- L1b products: Spectral Radiance, Irradiance and Uncertainty, Spectral Scale, Geo-location (lat/lon)
- PLRA: no requirement for radiance or irradiance, geolocation accuracy < 4km
- Instrument design & performance requirements were derived from L2 precision req.
- Signal to Noise Ratio (SNR) was the dominate factor for radiance performance
- Radiometric Uncertainty: < 4% (1-sigma) for both irradiance & radiance
- Albedo uncertainty: wavelength independent < 2%, dependent < 1%
- Long-term (20 months) radiometric drift detection: < 0.9%
- Nonlinearity: <2% of 98% well response, and knowledge (after corr.) < 0.5% from 2-98% of well response
- Pre-launch Wavelength mapping uncertainty: < 0.02 nm
- Spectral stability (within 24 hours): < 0.1 nm for radiance & irradiance
- Spectral co-registration error: < 0.7 pixel between 2 bands, < 0.4 pixel within UV or visible bands

Table of SNR req. and with Beginning of Life (BOL) as-built performance (4 Pixels coadded)

Earth-View TEMPO Signal to Noise Ratio (SNR) Verification Summary

Req Number	Requirement			BOL SNR		EOL SNR	
	Atmospheric Constituent	Wavelength (nm)	SNR Requirement e- / e-	As-Measured SNR	Margin	Predicted EOL SNR	Margin
IRD-320 TSS-59	O3	290	19.6	N/A	N/A	N/A	N/A
	O3	300	46.1	49	5.4%	45	-2.4%
	O3	305	161.9	191	17.8%	178	10.1%
	O3	310	377	471	24.9%	447	18.5%
	O3	320	1220	1664	36.4%	1621	32.8%
	O3, H2CO	330	2003	2829	41.2%	2779	38.7%
	O3, H2CO, Cloud	340	2013	2867	42.4%	2827	40.4%
	H2CO, Cloud	350	1414	2717	92.1%	2685	89.9%
	NO2	420	836	2138	155.8%	2127	154.4%
	NO2	430	675	1681	149.0%	1670	147.4%
	NO2	450	733	1875	155.8%	1865	154.4%
	Cloud	490	1176	1886	60.4%	1879	59.8%
	O3	540	1109	1813	63.5%	1806	62.9%
	O3	600	987	1577	59.8%	1571	59.1%
	O3	650	898	1383	54.0%	1376	53.2%
	Cloud	690	820	1195	45.8%	1188	44.9%

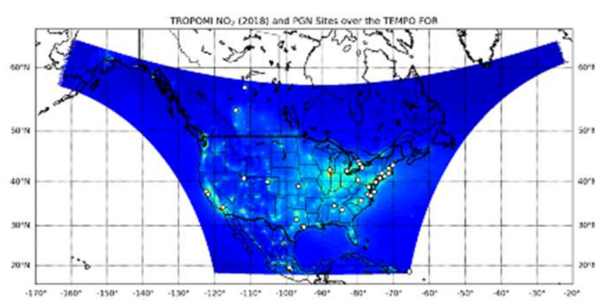
Calibration and L1b Validation

- Verify and update image correction steps in the L0-1 processing during Commissioning Phase (~L+1~L+3 months, ~90 days)
  - System linearity, zero-input, relative gains, saturation blooming, dark current variation and temperature-dependent correction, check quality flags, evolution of solar diffuser, noise calculation, straylight
- Assess wavelength calibration and its performance
  - Will assess performance of routine processing (wavelength calibration in both L0-1b & L1-2 via high-resolution solar reference and atmospheric absorption)
  - Pre-launch measured instrument line shape will be compared with that derived from solar irradiance
- Assess radiometric calibration using a multi-pronged approach
  - Internal assessment of images, Assess performance of routine processing
  - Comparison solar irradiance with solar reference and correlative contemporaneous sensors (e.g., OMPS, TROPOMI, GOME-2, EPIC, MODIS, VIIRS)
  - Comparison with radiative transfer simulation
- Assess geo-location methodology with Image Navigation and Registration (INR) during commissioning phase, accuracy and uncertainty
  - Imagery: assess registration offset of fiducial points not used in INR, using other reference imagery
  - L2: assess bias and variance in registration offset of known point sources of NO_2

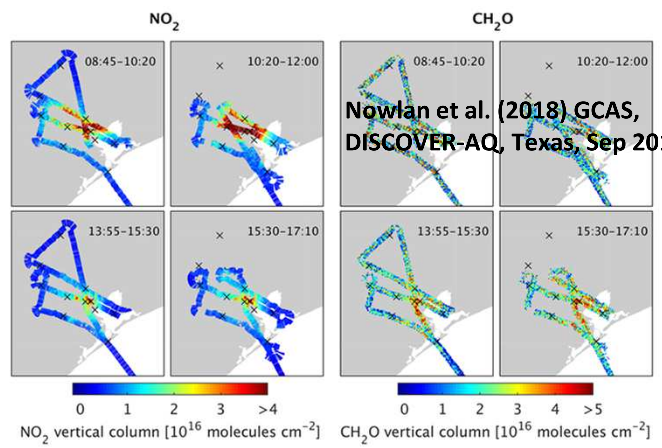
TEMPO L2 Science Validation Plan

- TEMPO PLRA has a bare minimum validation requirements (3 Pandoras, 1 month per season)
- Jim Szykman has led the development of best-efforts basis validation plan: beta, provisional, full
- Use satellite observations (i.e., LEO and EPIC/DSCOVR) for cross validations
- Pandora & Pandonia Global Network (PGN): validate NO_2, HCHO, total O_3 and diurnal variation
- TOLNet: 8 LIDAR instruments by time of launch to validate tropospheric O_3 & 0-2 km O_3 and diurnal variation

https://www.pandonia-global-network.org/

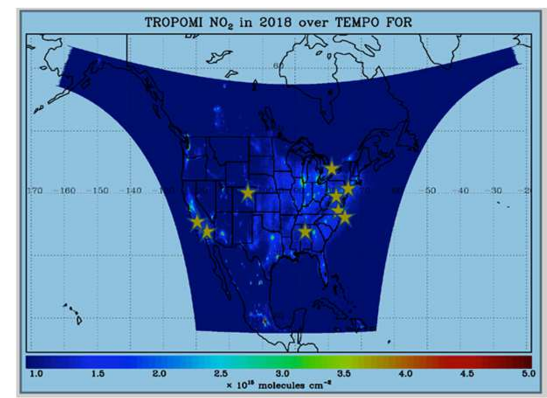


~60 PGNs in TEMPO FoR, ~20 to add in 2 years



Nowlan et al. (2018) GCAS, DISCOVER-AQ, Texas, Sep 2013

www-air.larc.nasa.gov/missions/TOLNet/



- Airborne instruments: GEO-TASO, GCAS, HSRL-2, IAGOS, SeaRey UAV
- Other instruments: ozonesonde, Dobson/Brewer, MAXDOAS, FTIR, AERONET, …
- Planned flight campaigns AGES+ (e.g., STAQS, AEROMMA+CUPiDS, GOTHAAM) during June-Aug 2003, provide integrated approaches linking TEMPO science, applications, and validation
- Evaluation with chemistry transport models and data assimilation.