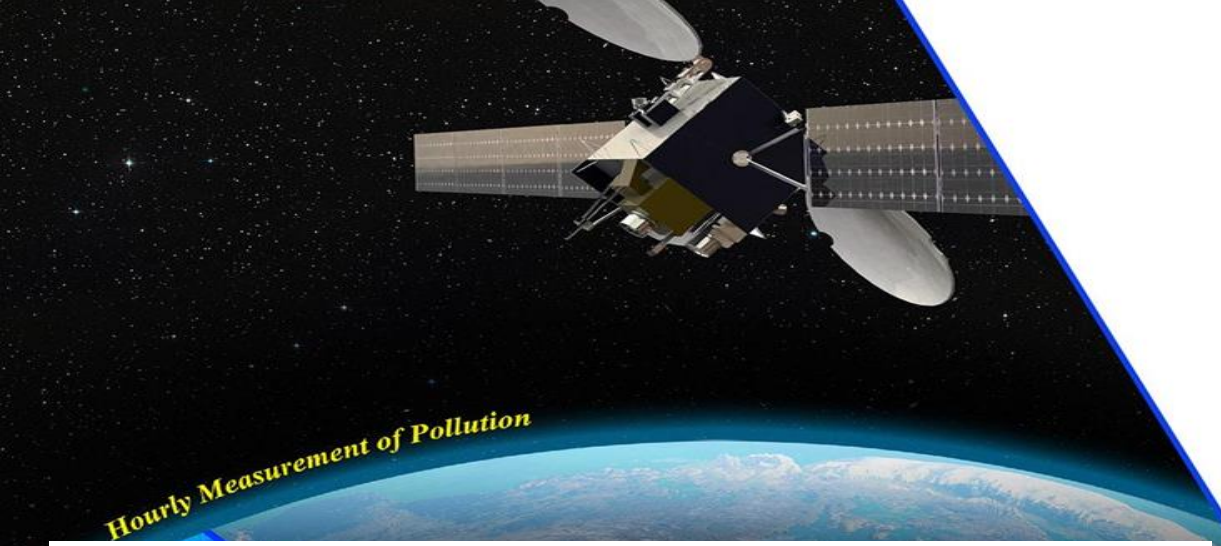


Tropospheric Emissions:
Monitoring of Pollution

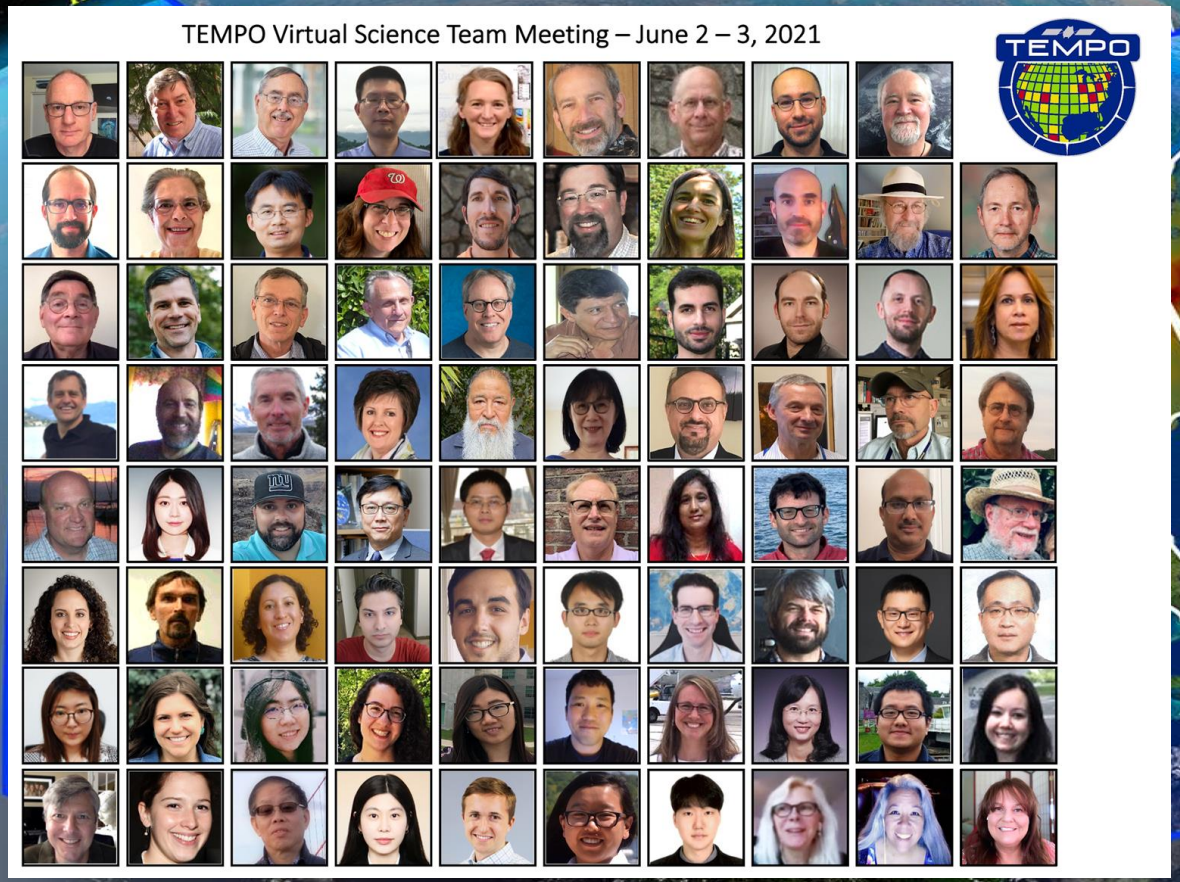
Status of TEMPO (Tropospheric Emissions: Monitoring of Pollution)

Kelly Chance

on behalf of The TEMPO Team

Center for Astrophysics | Harvard & Smithsonian

kchance@cfa.harvard.edu



The 13th International GEMS Workshop
November 11, 2022

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Ball

Smithsonian

NASA

Hourly daytime atmospheric pollution over North America from the GEO

NASA's first Earth Venture Instrument (EVI) selected in 2012 & first host payload
PI: Kelly Chance, SAO: STM, ground systems, science data processing center
Instrument Development: Ball Aerospace
Instrument Project Management: NASA LaRC, PM: Kevin Daugherty
Other Institutions: NASA GSFC, NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, UAH, U Nebraska, Sitting Bull College, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, U.K., ESA, Spain

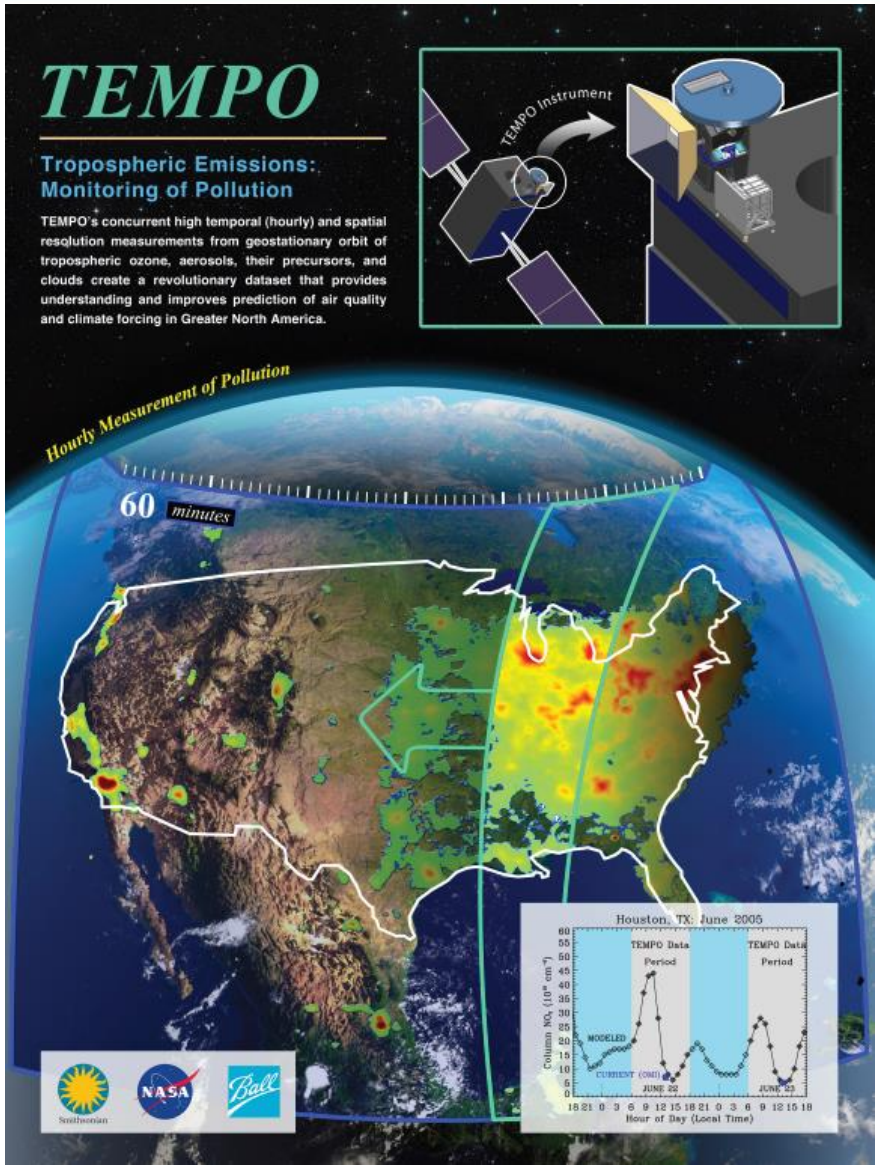
Mission Project Management: NASA LaRC, current PM: Kevin Daugherty
Host Satellite Provider: Maxar Technologies
Satellite Host: Intelsat (IS-40e)
Launch: SpaceX

Provides hourly daylight observations to capture rapidly varying emissions & chemistry important for air quality

- UV/visible grating spectrometer to measure key elements in tropospheric ozone and aerosol pollution
- Distinguishes boundary layer from free tropospheric & stratospheric ozone

Aligned with Earth Science 2007 Decadal Survey recommendations

- Makes many of the GEO-CAPE atmospheric measurements
- Responds to the phased implementation recommendation of GEO-CAPE mission design team along with GeoCarb and GLIMR



North American Component of An International Geostationary Air Quality Constellation

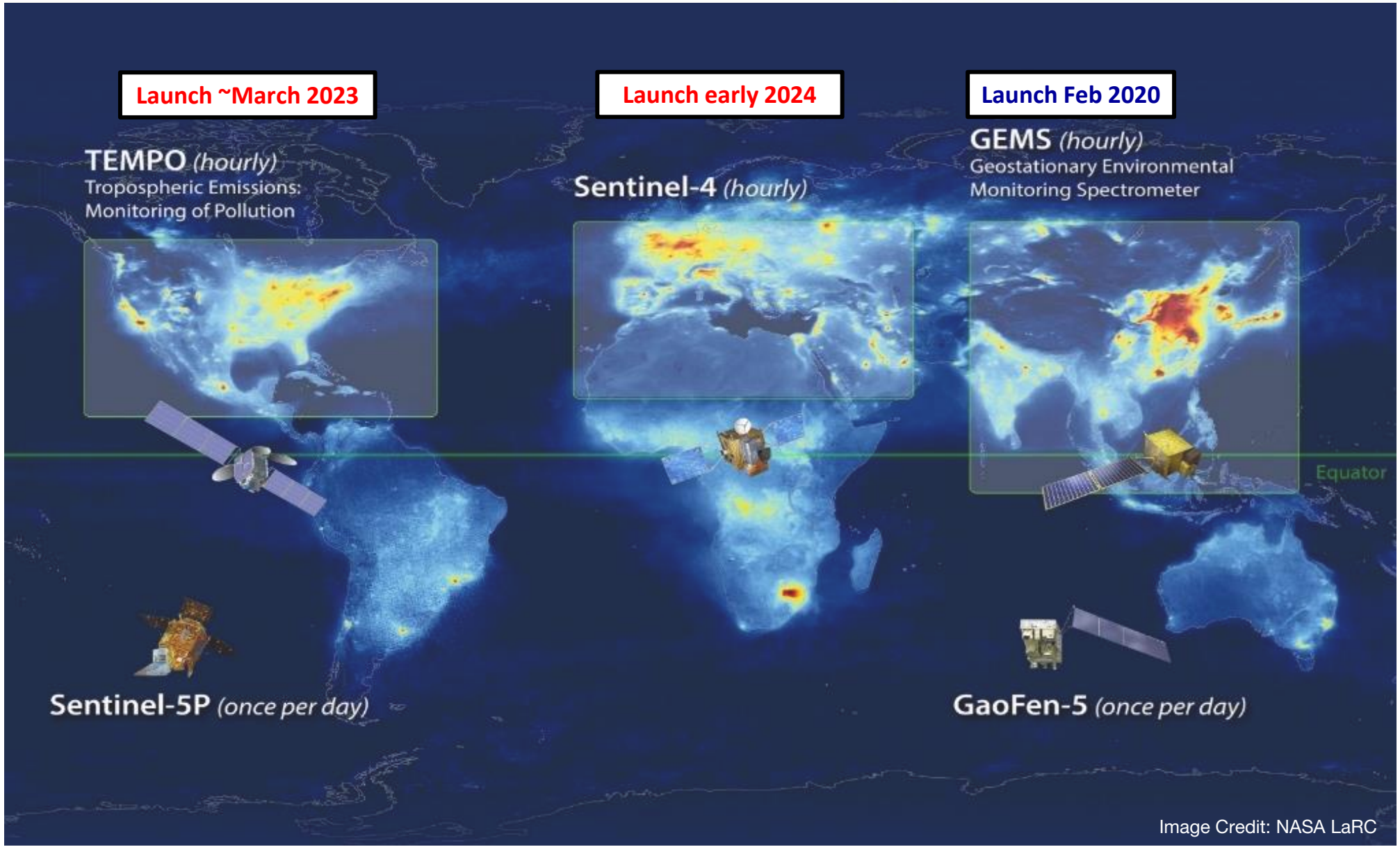
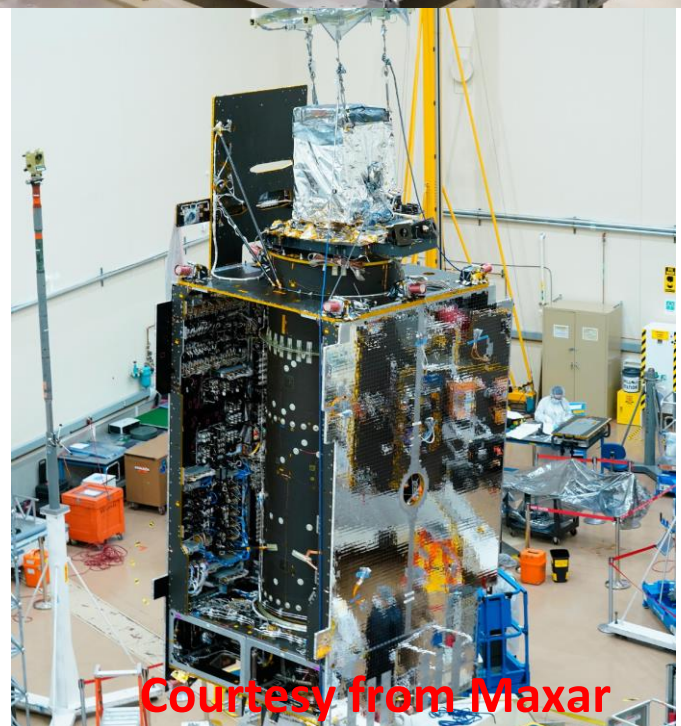


Image Credit: NASA LaRC

TEMPO Status

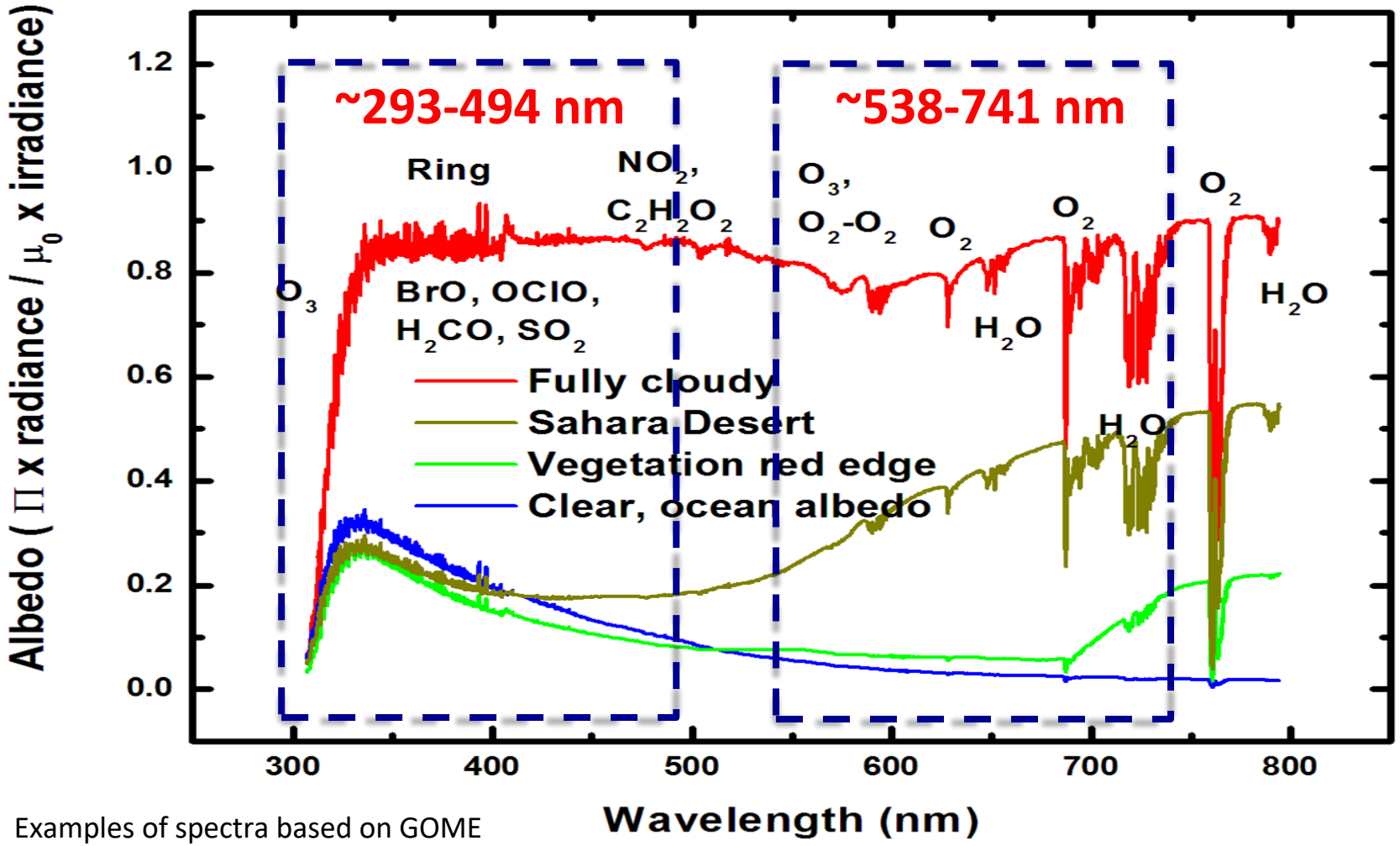


Crews recently completed the first fully integrated powered testing of TEMPO, instrument on Intelsat IS40e at Maxar Technologies' satellite manufacturing facility in Palo Alto, California.
Credits: Image courtesy of Maxar Technologies

- **Instrument delivery by Ball Aerospace in Nov. 2018**
- **Host satellite provider: Maxar selected in July 2019**
- **Host: Intelsat 40e selected in 02/2020.**
- **TEMPO sensor fully integrated onto IS-40e on 6/30/2022. SCTV completed.**
- **Operation/Mission Readiness Review (ORR/MRR) in Jan. 2022**
- **Launch on SpaceX Falcon 9 on 3/13/2023**

TEMPO Instrument

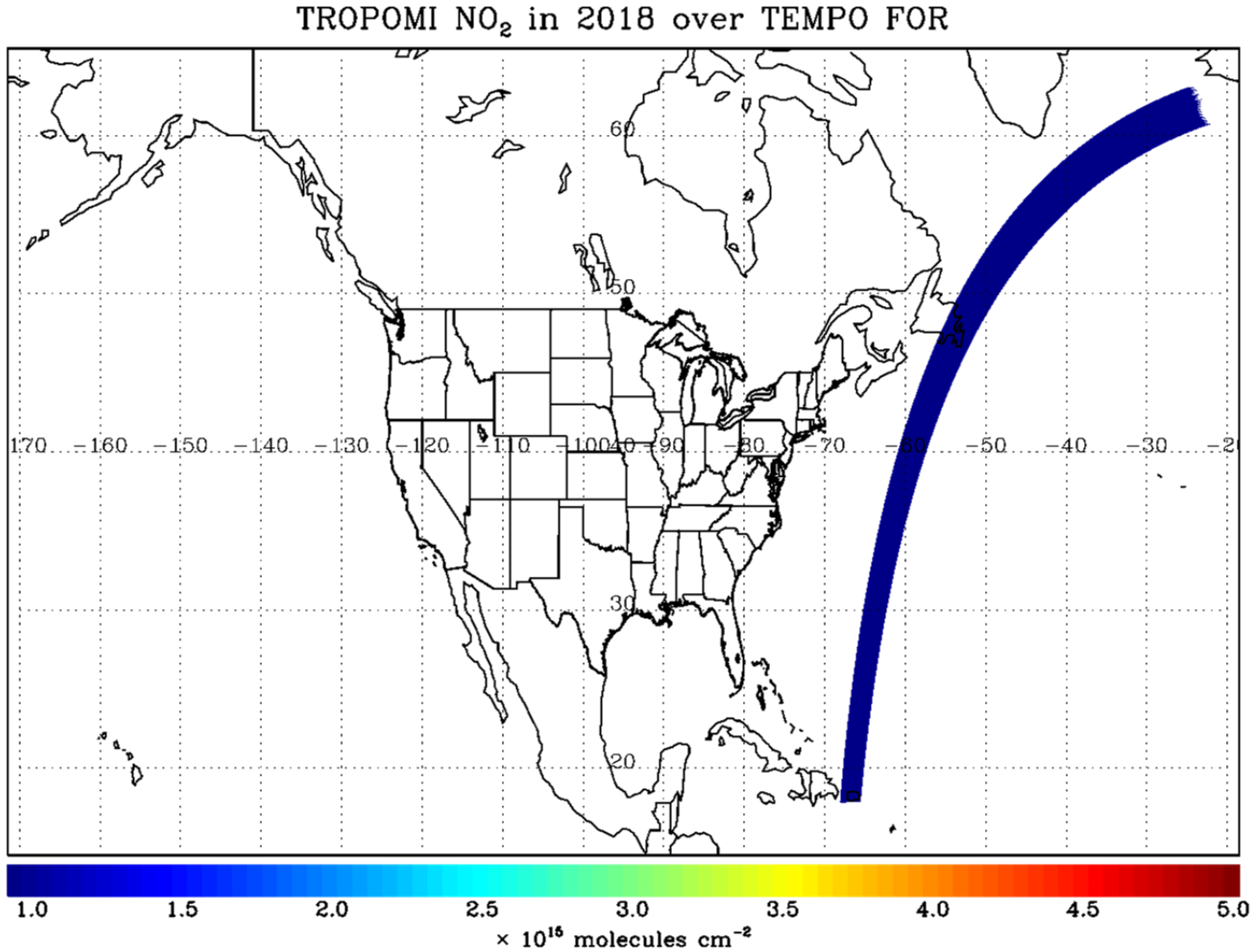
- Imaging grating spectrometer measuring solar backscattered Earth radiance
  - 2 channels (1 focal plane but with 2 2-D 2 k x 1k detectors): ~293-494 + 538-741 nm
  - ~0.6 nm FWHM, ~0.2 nm sampling



Examples of spectra based on GOME

TEMPO Operation

❑ Operate on geostationary communications satellite Intelsat 40e (IS40e) at 91 ° W



- Field of regard is optimized to cover both Puerto Rico and Canadian tar sands.
- S5p-TROPOMI NO2 product oversampled by Kang Sun.

- **Nominal:** Scan FOR in 1 hour with 10 granules
- ~ 2K N/S pixels x 1226 steps/hr, ~ 2.5 M pixels/hr, daily # spatial pixels ~TROPOMI
- 2 x 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)

Baseline and Threshold Products (Variables) & 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

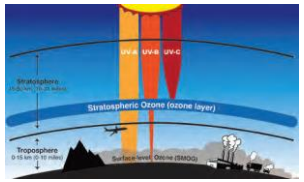
* # of hourly measurements to be averaged to achieve required precision

- Mission duration: 20 months for baseline
- Spatial resolution: < 60 km^2 for baseline (4 native pixels coadded)

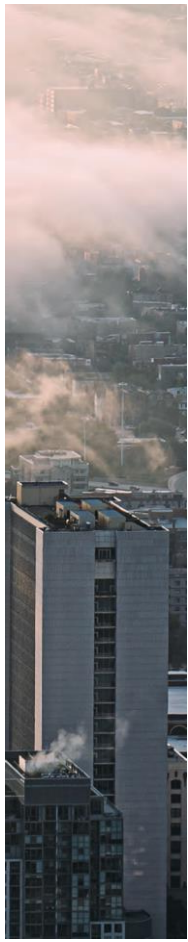
❑Aerosols, SO_2, $C_2H_2O_2$ were removed from baseline products during KDPC

❑Cloud product (cloud fraction, cloud pressure): used in trace gas/aerosol retrievals

TEMPO Data Products
(Inc. Proposed NRT & Additional Products)



Level	Product	Algorithm	Major Outputs	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 O2-O2	Cloud fraction, cloud pressure	2.0 x 4.75	Hourly, granule
	O_3 profile	SAO O3 profile	O3 profile, total/strat/trop/0-2 km O3 column, errors, a priori, AKs	<= 8.0 x 4.75**	Hourly, granule
	Total O_3	TOMS V8.5	Total O3, AI, cloud fraction	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	2.0 x 4.75	Hourly, granule
	H_2CO NRT	SAO trace gas	SCD, VCD, error, shape factor, scattering weights	2.0 x 4.75	Hourly, granule
	$C_2H_2O_2$	SAO trace gas		2.0 x 4.75	Hourly, granule
	H_2O	SAO trace gas		2.0 x 4.75	Hourly, granule
	BrO	SAO trace gas		2.0 x 4.75	Hourly, granule
	Aerosol NRT	**OMAERUV+UI AOCH**	AAI, UVAOD, UVSSA, AOCH, VISAOD	**8.0 x 4.75**	**Hourly, granule**
	SO_2	OMSO2 PCA	SCD, VCD (PBL,TRL,TRM,TRU,STL)	2.0 x 4.75	Hourly, granule
	TEMPO/GOES-R Synerg. product	GOES-R products on TEMPO pixels	Radiance, aerosol, cloud & mask, fire/hotspot, snow/ice, rainfall, precipitable water, land/sea surface T, lightning	2.0 x 4.75	Hourly, granule
L3	**Gridded L2**	SAO L2-3	Same as L2	2 x 2 (?)	Hourly, scan
L4	**UVB**	GEMS/GSFC UVB	UV irradiance, erythemal irradiance, UVI	TBD	Hourly, scan



Black: launch-ready baseline products; **green**/**orange**/**purple**: additional products

Proposed NRT (L1b <~1 hr, L2 cloud <~1.5 hr, L2/3 trace gas < ~2.5 hrs)**:** from SNWG, NASA+NOAA OMB, NOAA to produce aerosol NRT

NRT data products timeline, 4-5 months behind baseline products (1/2024 start NRT processing, 6/2024: public release)

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

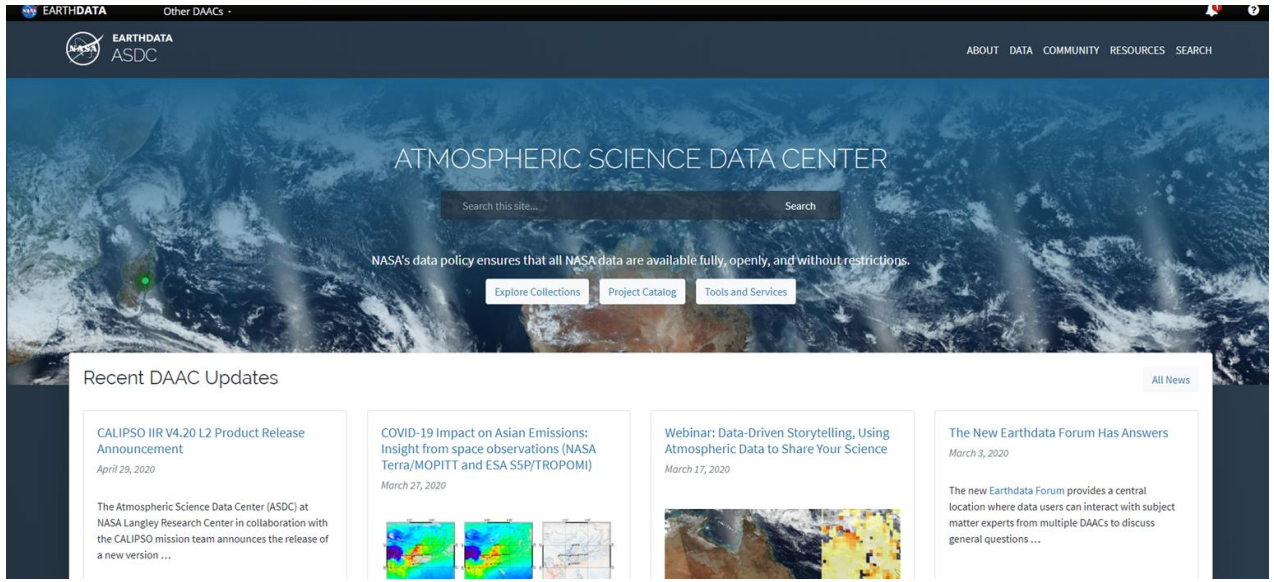
Algorithm Development Status & Plan

- SDPC V3 (launch ready) completed in Feb. 2022
- Algorithm mostly based on OMI heritage algorithms except for new L0-1b processor (including INR using GOES-R from Carr Astronautics)
- Updates to L1-2 algorithms (O_3 profile, NO_2, HCHO, cloud, total O_3):
  - Adapted for TEMPO in NetCDF-4 format
  - Add visible to SAO UV O3 profile algorithm, SAO trace gas algorithm with adapted NASA strat/trop separation for NO2
  - CLDO4[new]: SAO O_2-O_2 fitting + GSFC's O_2-O_2 cloud at ~477/466 nm (Huiqun Wang, Eun-Su Yang, Alexander Vasilkov)
  - NASA GMAO's GEOS-CF trace gas profiles and meteorology (Emma Knowland and GMAO)
  - Hourly resolved monthly mean Geometry-dependent Lambertian Equivalent Reflectivity (GLER) climatology (Christopher Chan Miller, Wenhan Qin, Zachary Fasnacht)
- Development of other products
  - CHOCHO, H_2O, BrO: will use SAO's trace gas algorithm
  - SO_2: OMI PCA SO_2 algorithm adapted for TEMPO/GEMS from synthetic/GEMS data (Can Li)
  - Aerosols: being adapted from OMI/TROPOMI AERUV algorithm (Omar's team), from EPIC/TROPOMI Aerosol Layer Height algorithm using O_2-A/B (Jun Wang's team)
- Continue to make minor updates to improve beyond V3
  - Further improvements using synthetic and GEMS data: destriping, radiance reference & background correction, cross section updates, empirical correction
- Algorithm refinement/optimization during commissioning (Jun-Sep 2023) and nominal operation

TEMPO Data Products Distribution

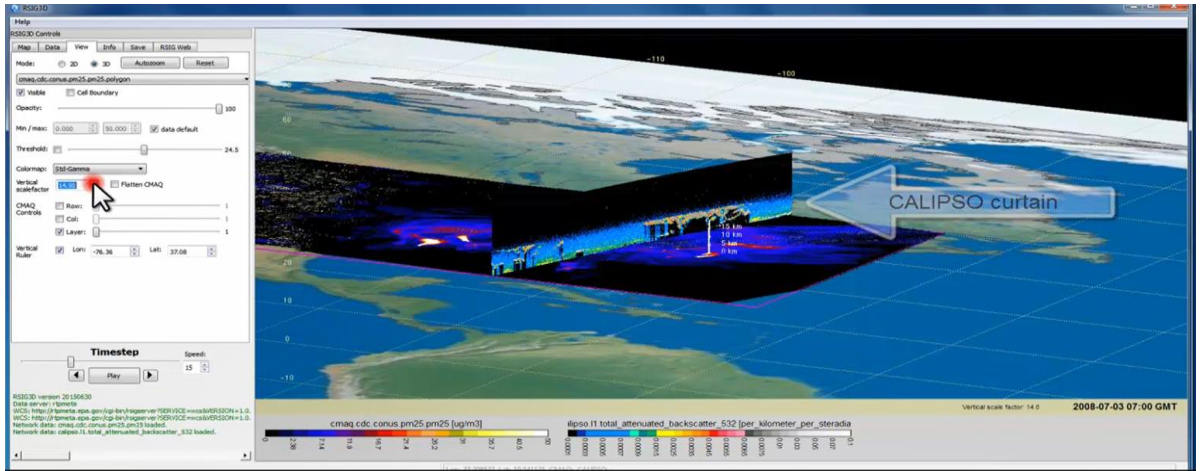
ASDC Data Archival & Distribution: Tools and Services

- ✓ 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



EPA RSIG3D Gateway

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

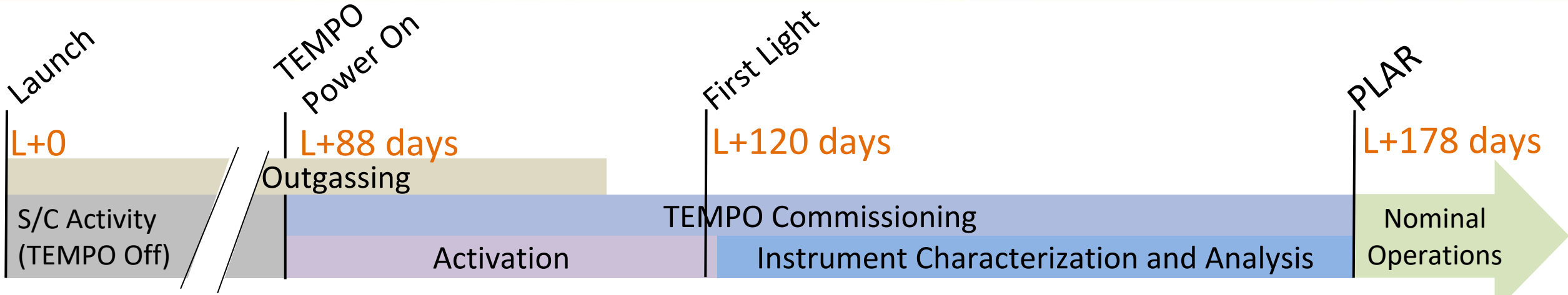


User Support and Other Resources

Earthdata Login https://urs.earthdata.nasa.gov
Earthdata Forum https://forum.earthdata.nasa.gov/
ASDC User Support support-asdc@earthdata.nasa.gov

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

Commissioning Timeline & Data Release Plan



*L+# days are approximate and will be refined as we finalize commissioning details

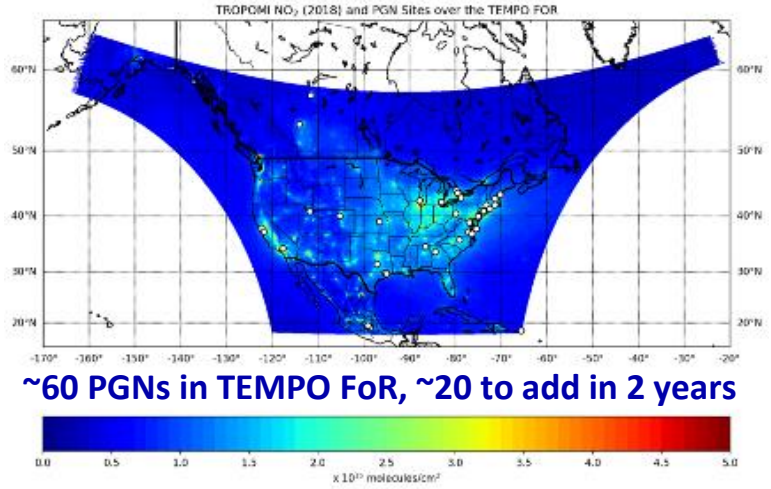
Activity	Intelsat
LEOP: Orbit Transfer	2 Weeks
Spacecraft Bus IOT	1 Week
Payload IOT	4 Weeks
Drift to Location	4 Weeks (TBD) 60º drift to 91ºW
Commercial Services (Onboarding Customers)	1 Week
TEMPO Commissioning Begins	Expect L+12 Weeks

- TEMPO commissioning: 06/15-9/15/2023, first light ~7/15/2023
- Nominal operation after PLAR: ~9/15/2023
- Plan for initial public release of baseline products at ASDC (L1b in ~4 mons, L2/3 in ~6 mons after PLAR): L1b, 1/2024; L2/3, 3/2024
- Provide baseline data products to validation team priori to the public release via ASDC.

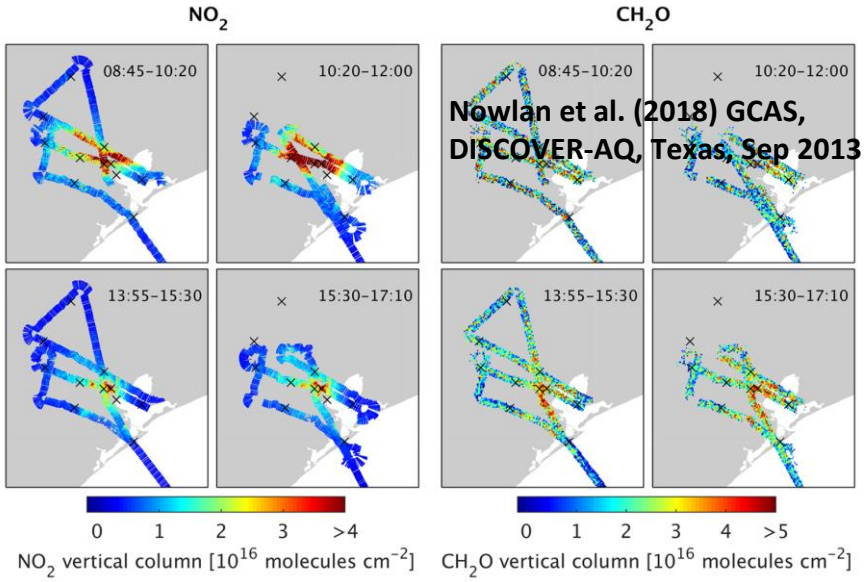
TEMPO Validation Plan

- TEMPO PLRA has a bare minimum validation requirements (3 Pandoras, 1 month per season)
- Jim Szykman is leading development of best-of-effort 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/

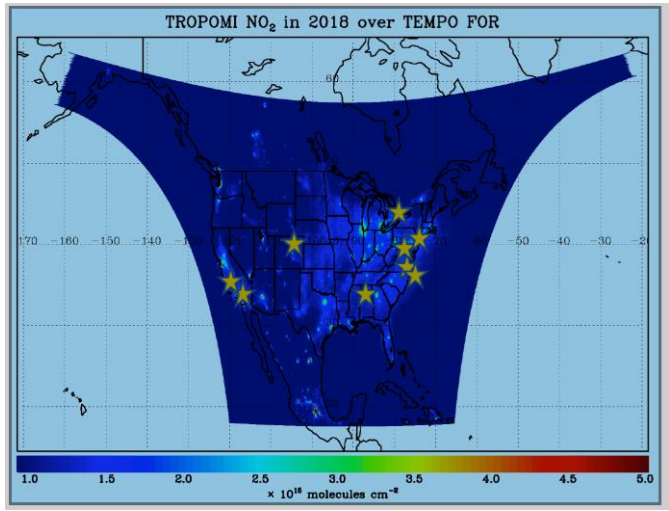


~60 PGNs in TEMPO FoR, ~20 to add in 2 years



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

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



- Airborne instruments: GEO-TASO, GCAS, HSRL-2, SeaRey UAV
- Other instruments: ozonesonde, MAXDOAS, FTIR, Dobson/Brewer, AERONET, …
- Planned flight campaigns like STAQS, AEROMMA, GOTHAAM during June-Aug 2003, provide integrated approaches linking TEMPO Science, Applications, and Validation

TEMPO Green Paper: Chemistry Experiments with TEMPO

NORMAL TIME RESOLUTION STUDIES

Air quality and health

Ultraviolet exposure

Biomass burning

Synergistic GOES-16/17 Products

Advanced aerosol products

Soil NO_x after fertilizer application and after rainfall

Solar-induced fluorescence from chlorophyll

Foliage studies

Mapping NO_2 and SO_2 dry deposition at high resolution

Crop and forest damage from ground-level ozone

Halogen oxide studies in coastal and lake regions

Air pollution from oil and gas fields

Night light measurements resolving lighting type

Ship tracks, drilling platform plumes, and other concentrated sources.

Water vapor studies

The TEMPO Green Paper living document at http://tempo.si.edu/publications.html

Volcanoes

Socio-economic studies

National pollution inventories

Regional and local transport of pollutants

Sea breeze studies for Florida and Cuba

Transboundary pollution gradients

Transatlantic dust transport

Early Adopters are key to building the TEMPO Green Paper!

High-time special observations can be requested at: https://weather.msfc.nasa.gov/tempo/green_paper.html

HIGH TIME RESOLUTION EXPERIMENTS

Lightning NO_x

Morning and evening higher-frequency scans

Dwell-time studies and temporal selection to improve detection limits

Exploring the value of TEMPO in assessing pollution transport during upslope flows

Tidal effects on estuarine circulation and outflow plumes

Air quality responses to sudden changes in emissions

Cloud field correlation with pollution

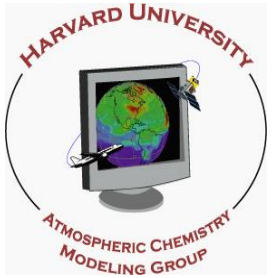
Agricultural soil NO_x emissions and air quality

We are on track to be ready for the TEMPO launch in March 2023.

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

MAXAR

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE



SAINT LOUIS UNIVERSITY

Environment and Climate Change Canada

Environnement et Changement climatique Canada

Research Products

- TEMPO research products will greatly extend science and applications
  - OClO, IO, HNO_2, NO_3, volcanic (SO_2 plume height and VCD)
  - Additional/improved cloud with O_2-O_2 bands / O_2-B bands
  - Additional aerosol products from hyperspectral spectra, O_2-B and O_2-O_2-bands, and TEMPO + GOES-R synergy at @U Iowa, NOAA, GSFC
  - Vegetation/Ocean Color products: vegetation indices, Growth Primary Productivity (GPP), Solar Induced fluorescence (SIF), ocean color
  - Surface albedo/BRDF products
  - Diurnal out-going shortwave radiation and cloud forcing
  - Night lights: allows discrimination between lightning types
  - Higher-level products: Near-real-time pollution/AQ indices