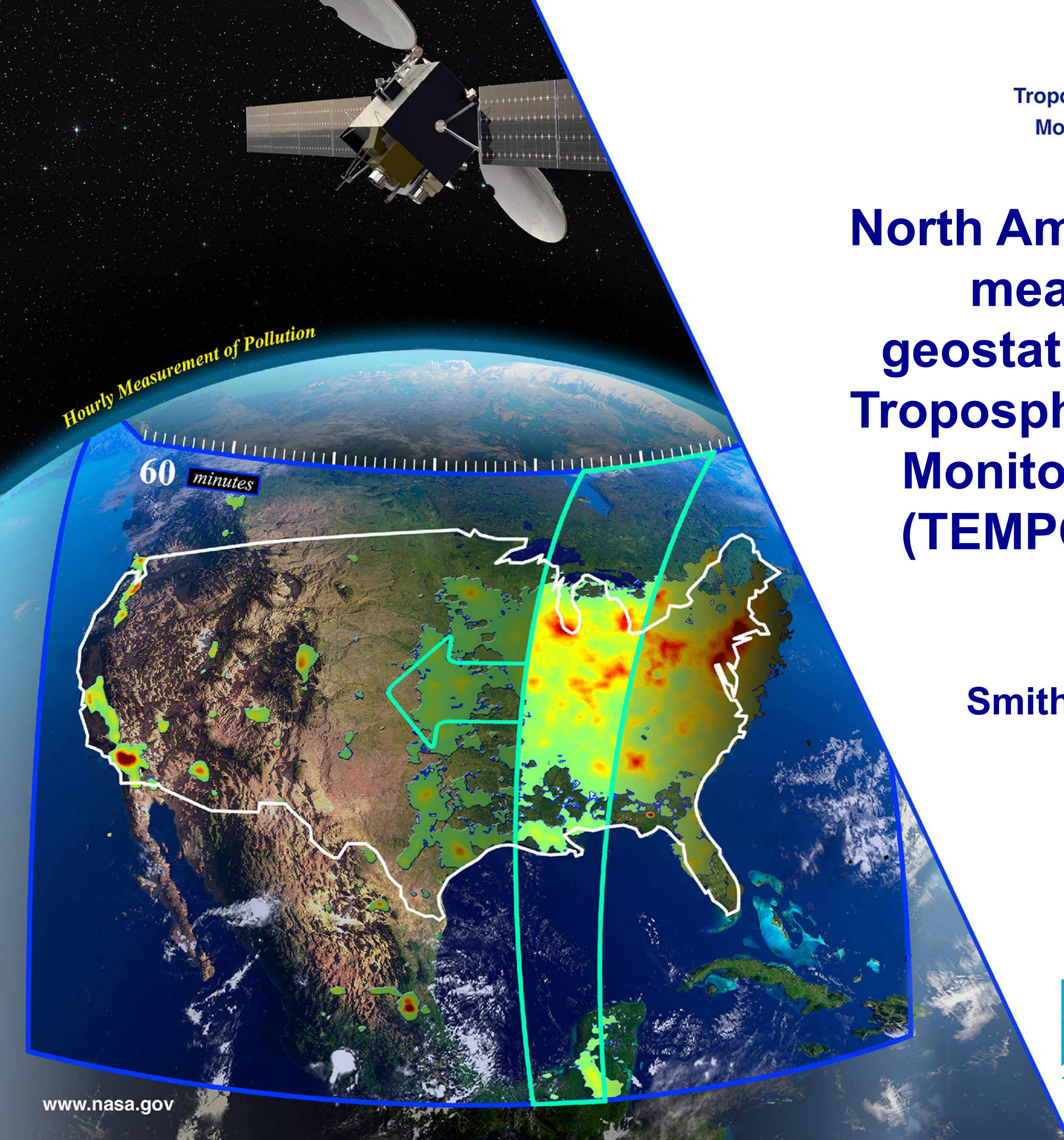


Tropospheric Emissions: Monitoring of Pollution

North American pollution measurements from geostationary orbit with Tropospheric Emissions: Monitoring of Pollution (TEMPO, tempo.si.edu)

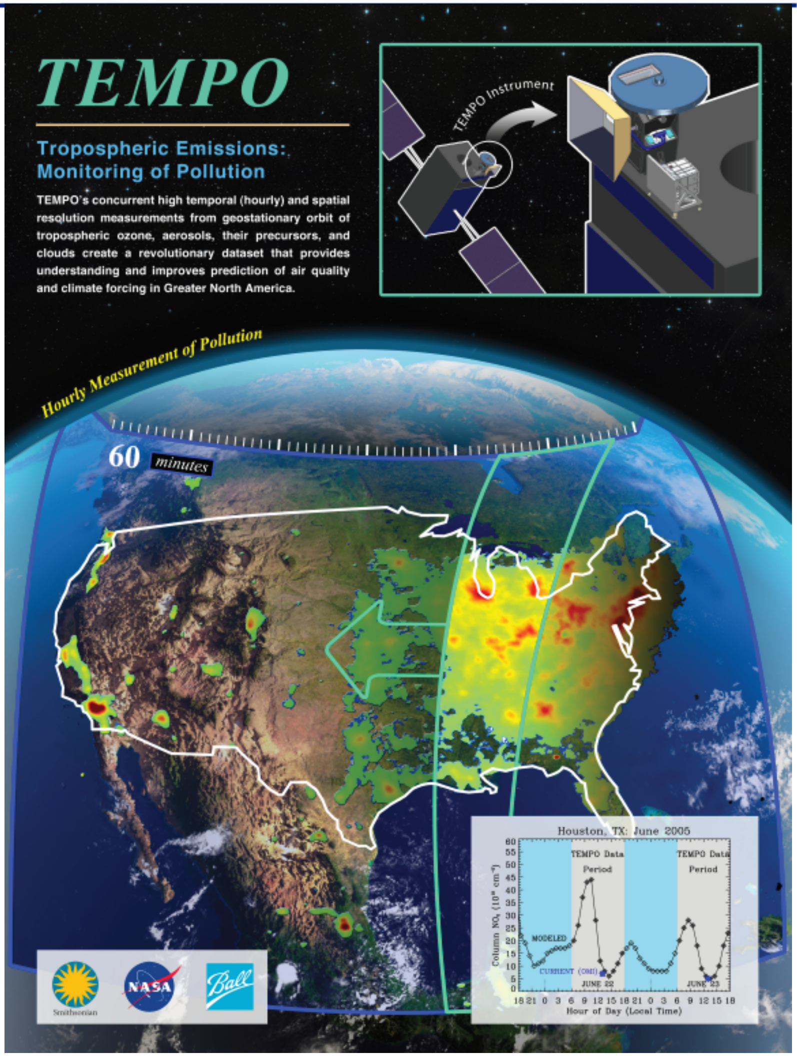
Kelly Chance
Smithsonian Astrophysical Observatory

CEOS AC-VC
May 3, 2018

Smithsonian

Hourly atmospheric pollution from geostationary Earth orbit

PI: Kelly Chance, Smithsonian Astrophysical Observatory
Instrument Development: Ball Aerospace
Project Management: NASA LaRC
Other Institutions: NASA GSFC, NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, U.K., ESA, Spain



Selected Nov. 2012 as NASA's first Earth Venture Instrument

- Instrument delivery 2018
- NASA will arrange hosting on commercial geostationary communications satellite with launch expected NET 11/2019

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

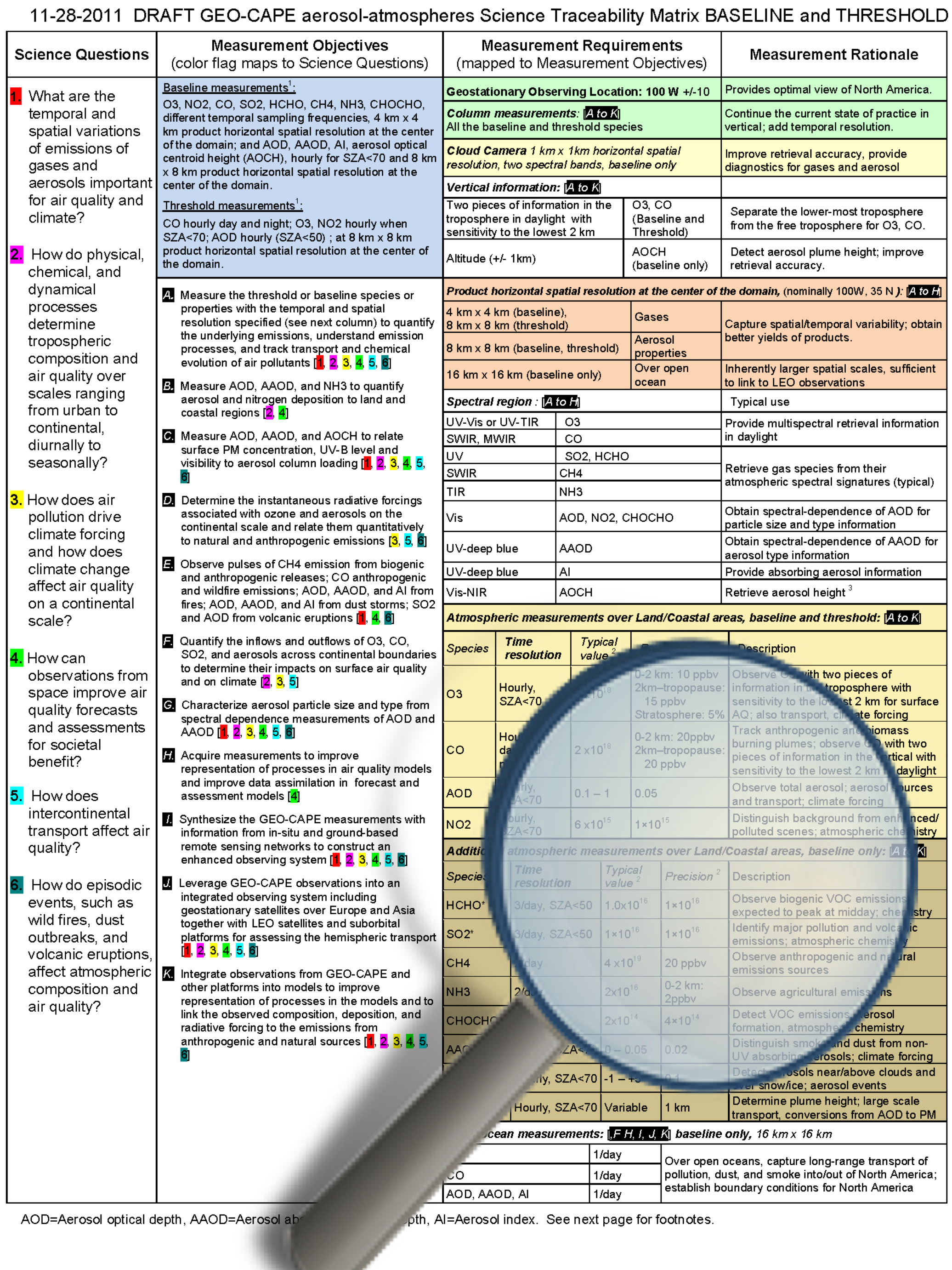
- UV/visible grating spectrometer to measure key elements in tropospheric ozone and aerosol pollution
- Distinguishes boundary layer from free tropospheric & stratospheric ozone

Aligned with Earth Science Decadal Survey recommendations

- Makes many of the GEO-CAPE atmosphere measurements
- Responds to the phased implementation recommendation of GEO-CAPE mission design team

North American component of an international constellation for air quality observations

Air quality requirements from the GEO-CAPE Science Traceability Matrix



11-28-2011 DRAFT GEO-CAPE aerosol-atmospheres Science Traceability Matrix BASELINE and THRESHOLD

Science Questions

1. What are the temporal and spatial variations of emissions of gases and aerosols important for air quality and climate?
2. How do physical, chemical, and dynamical processes determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally?
3. How does air pollution drive climate forcing and how does climate change affect air quality on a continental scale?
4. How can observations from space improve air quality forecasts and assessments for societal benefit?
5. How does intercontinental transport affect air quality?
6. How do episodic events, such as wild fires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality?

Measurement Objectives (color flag maps to Science Questions)

Baseline measurements[1]:

O3, NO2, CO, SO2, HCHO, CH4, NH3, CHOCHO, different temporal sampling frequencies, 4 km x 4 km product horizontal spatial resolution at the center of the domain; and AOD, AAOD, AI, aerosol optical centroid height (AOCH), hourly for SZA<70 and 8 km x 8 km product horizontal spatial resolution at the center of the domain.

Threshold measurements[1]:

CO hourly day and night; O3, NO2 hourly when SZA<70; AOD hourly (SZA<50) ; at 8 km x 8 km product horizontal spatial resolution at the center of the domain.

A. Measure the threshold or baseline species or properties with the temporal and spatial resolution specified (see next column) to quantify the underlying emissions, understand emission processes, and track transport and chemical evolution of air pollutants [1, 2, 3, 4, 5, 6]

B. Measure AOD, AAOD, and NH3 to quantify aerosol and nitrogen deposition to land and coastal regions [2, 4]

C. Measure AOD, AAOD, and AOCH to relate surface PM concentration, UV-B level and visibility to aerosol column loading [1, 2, 3, 4, 5, 6]

D. Determine the instantaneous radiative forcings associated with ozone and aerosols on the continental scale and relate them quantitatively to natural and anthropogenic emissions [3, 5, 6]

E. Observe pulses of CH4 emission from biogenic and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO2 and AOD from volcanic eruptions [1, 4, 6]

F. Quantify the inflows and outflows of O3, CO, SO2, and aerosols across continental boundaries to determine their impacts on surface air quality and on climate [2, 3, 5]

G. Characterize aerosol particle size and type from spectral dependence measurements of AOD and AAOD [1, 2, 3, 4, 5, 6]

H. Acquire measurements to improve representation of processes in air quality models and improve data assimilation in forecast and assessment models [4]

I. Synthesize the GEO-CAPE measurements with information from in-situ and ground-based remote sensing networks to construct an enhanced observing system [1, 2, 3, 4, 5, 6]

J. Leverage GEO-CAPE observations into an integrated observing system including geostationary satellites over Europe and Asia together with LEO satellites and suborbital platforms for assessing the hemispheric transport [1, 2, 3, 4, 5, 6]

K. Integrate observations from GEO-CAPE and other platforms into models to improve representation of processes in the models and to link the observed composition, deposition, and radiative forcing to the emissions from anthropogenic and natural sources [1, 2, 3, 4, 5, 6]

Measurement Requirements (mapped to Measurement Objectives)		Measurement Rationale
Geostationary Observing Location: 100 W +/-10		Provides optimal view of North America.
Column measurements: [A to K] All the baseline and threshold species		Continue the current state of practice in vertical; add temporal resolution.
Cloud Camera *1 km x 1km horizontal spatial resolution, two spectral bands, baseline only*		Improve retrieval accuracy, provide diagnostics for gases and aerosol
Vertical information: [A to K]		
Two pieces of information in the troposphere in daylight with sensitivity to the lowest 2 km	O3, CO (Baseline and Threshold)	Separate the lower-most troposphere from the free troposphere for O3, CO.
Altitude (+/- 1km)	AOCH (baseline only)	Detect aerosol plume height; improve retrieval accuracy.
Product horizontal spatial resolution at the center of the domain, (nominally 100W, 35 N ***):*** [A to H]		
4 km x 4 km (baseline), 8 km x 8 km (threshold)	Gases	Capture spatial/temporal variability; obtain better yields of products.
8 km x 8 km (baseline, threshold)	Aerosol properties	
16 km x 16 km (baseline only)	Over open ocean	Inherently larger spatial scales, sufficient to link to LEO observations
Spectral region *:* [A to H]		Typical use
UV-Vis or UV-TIR	O3	Provide multispectral retrieval information in daylight
SWIR, MWIR	CO	
UV	SO2, HCHO	Retrieve gas species from their atmospheric spectral signatures (typical)
SWIR	CH4	
TIR	NH3	
Vis	AOD, NO2, CHOCHO	Obtain spectral-dependence of AOD for particle size and type information
UV-deep blue	AAOD	Obtain spectral-dependence of AAOD for aerosol type information
UV-deep blue	AI	Provide absorbing aerosol information
Vis-NIR	AOCH	Retrieve aerosol height [3]

Atmospheric measurements over Land/Coastal areas, baseline and threshold: [A to K]

Species	***Time resolution***	*Typical value* [2]	[illegible]	Description
O3	Hourly, SZA<70	[illegible]	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe [illegible] with two pieces of information in [illegible] troposphere with sensitivity to the lo[illegible]st 2 km for surface AQ; also transport, cli[illegible]te forcing
CO	Hou[illegible]	2 x10[18]	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic an[illegible] biomass burning plumes; observe [illegible] with two pieces of information in the [illegible]rtical with sensitivity to the lowest 2 km [illegible] daylight
AOD	[illegible]rly, [illegible]A<70	0.1 – 1	0.05	Observe total aerosol; aerosol [illegible]urces and transport; climate forcing
NO2	[illegible]ourly, [illegible]ZA<70	6 x10[15]	1×10[15]	Distinguish background from enh[illegible]nced/ polluted scenes; atmospheric che[illegible]istry

Additi[illegible] atmospheric measurements over Land/Coastal areas, baseline only: [A t[illegible] K]

Specie[illegible]	*Time resolution*	*Typical value* [2]	*Precision* [2]	Description
HCHO*	3/day, SZA<50	1.0x10[16]	1×10[16]	Observe biogenic VOC emissions expected to peak at midday; che[illegible]istry
SO2*	3/day, SZA<50	1×10[16]	1×10[16]	Identify major pollution and volca[illegible]ic emissions; atmospheric chemis[illegible]y
CH4	[illegible]day	4 x10[19]	20 ppbv	Observe anthropogenic and na[illegible]ural emissions sources
NH3	2/d[illegible]	2x10[16]	0-2 km: 2ppbv	Observe agricultural emiss[illegible]ns
CHOCH[illegible]	[illegible]	2x10[14]	4×10[14]	Detect VOC emissions [illegible]erosol formation, atmosphe[illegible] chemistry
AA[illegible]	[illegible]ZA<[illegible]	0 – 0.05	0.02	Distinguish smo[illegible]nd dust from non-UV absorbin[illegible]erosols; climate forcing
[illegible]	[illegible]ly, SZA<70	-1 – +[illegible]	[illegible]	Detec[illegible]osols near/above clouds and [illegible] snow/ice; aerosol events
[illegible]	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

[illegible]***cean measurements:*** [[illegible]F H, I, J, K] ***baseline only,*** *16 km x 16 km*

[illegible]	1/day	Over open oceans, capture long-range transport of pollution, dust, and smoke into/out of North America; establish boundary conditions for North America
[illegible]CO	1/day	
AOD, AAOD, AI	1/day	

AOD=Aerosol optical depth, AAOD=Aerosol ab[illegible]pth, AI=Aerosol index. See next page for footnotes.

Infrared species

Ultraviolet/ visible species (GOME, SCIA, OMI, OMPS, TEMPO, etc.)

Atmospheric measurements over Land/Coastal areas, baseline and threshold: [A to K]				
Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
O3	Hourly, SZA<70	9 x10^{18}	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe O3 with two pieces of information in the troposphere with sensitivity to the lowest 2 km for surface AQ; also transport, climate forcing
CO	Hourly, day and night	2 x10^{18}	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic and biomass burning plumes; observe CO with two pieces of information in the vertical with sensitivity to the lowest 2 km in daylight
AOD	Hourly, SZA<70	0.1 – 1	0.05	Observe total aerosol; aerosol sources and transport; climate forcing
NO2	Hourly, SZA<70	6 x10^{15}	1×10^{15}	Distinguish background from enhanced/ polluted scenes; atmospheric chemistry

Additional atmospheric measurements over Land/Coastal areas, baseline only: [A to K]				
Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
HCHO*	3/day, SZA<50	1.0x10^{16}	1×10^{16}	Observe biogenic VOC emissions, expected to peak at midday; chemistry
SO2*	3/day, SZA<50	1×10^{16}	1×10^{16}	Identify major pollution and volcanic emissions; atmospheric chemistry
CH4	2/day	4 x10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2x10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO*	2/day	2x10^{14}	4×10^{14}	Detect VOC emissions, aerosol formation, atmospheric chemistry
AAOD	Hourly, SZA<70	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
AI	Hourly, SZA<70	-1 – +5	0.1	Detect aerosols near/above clouds and over snow/ice; aerosol events
AOCH	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

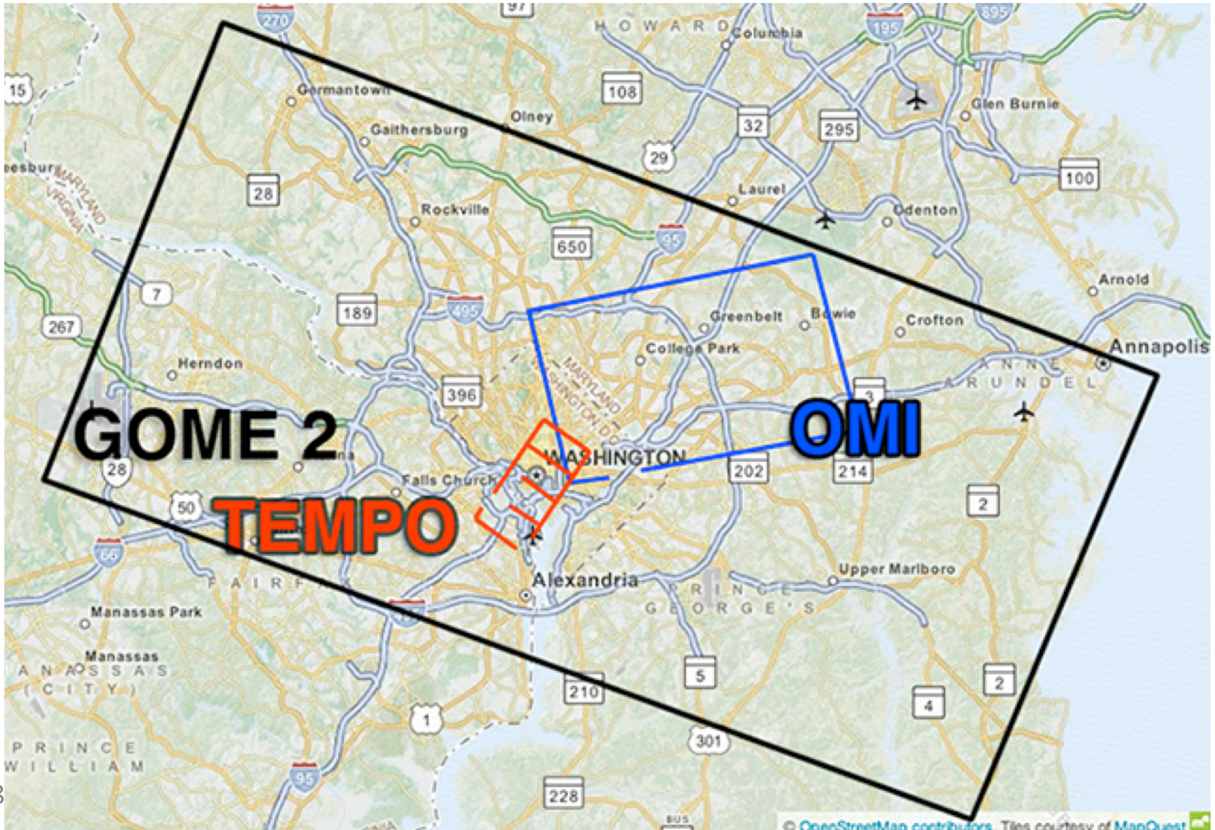
Baseline and threshold data products

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

- **Minimal set of products sufficient for constraining air quality**
- **Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N**
- **Data products at urban-regional spatial scales**
  - **Baseline ≤ 60 km^2 at center of Field Of Regard (FOR)**
  - **Threshold ≤ 300 km^2 at center of FOR**
- **Temporal scales to resolve diurnal changes in pollutant distributions**
- **Geolocation uncertainty of less than 4 km**
- **Mission duration, subject to instrument availability**
  - **Baseline 20 months**
  - **Threshold 12 months**

Coverage comparisons

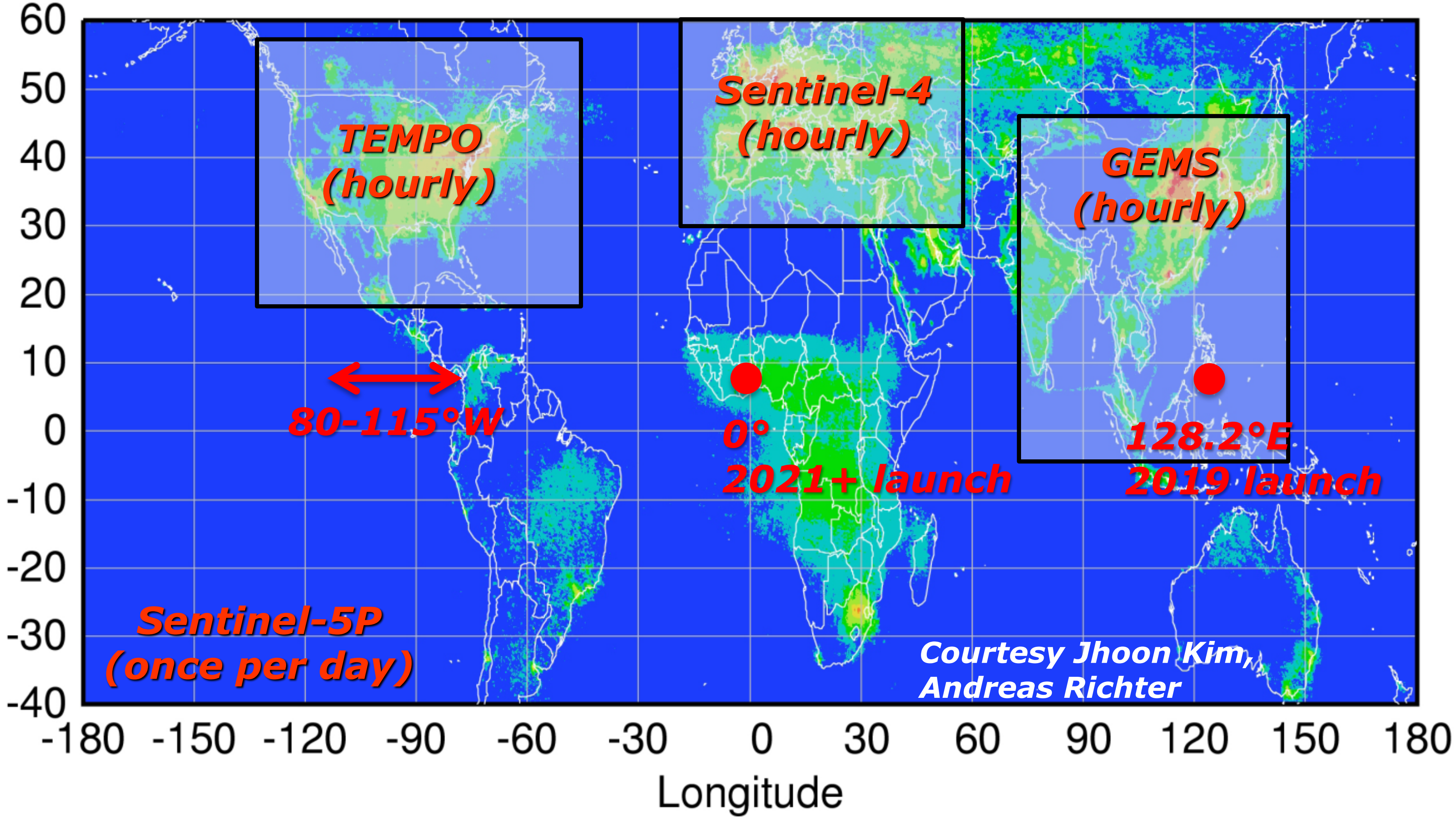
- **Spatial resolution: allows tracking pollution at sub-urban scale**
  - **GEO at 100°W: 2.1 km N/S × 4.7 km E/W = 9.8 km^2 (native) at center of FOR (36.5°N, 100°W)**
  - **Full resolution for NO_2, HCHO, total O_3 products**
  - **Co-add 4 N/S pixels for O_3 profile product: 8.4 km N/S × 4.7 km E/W**



~ 1/300 of GOME-2

~ 1/30 of OMI

Global pollution monitoring constellation



TEMPO Science Team, non-U.S.

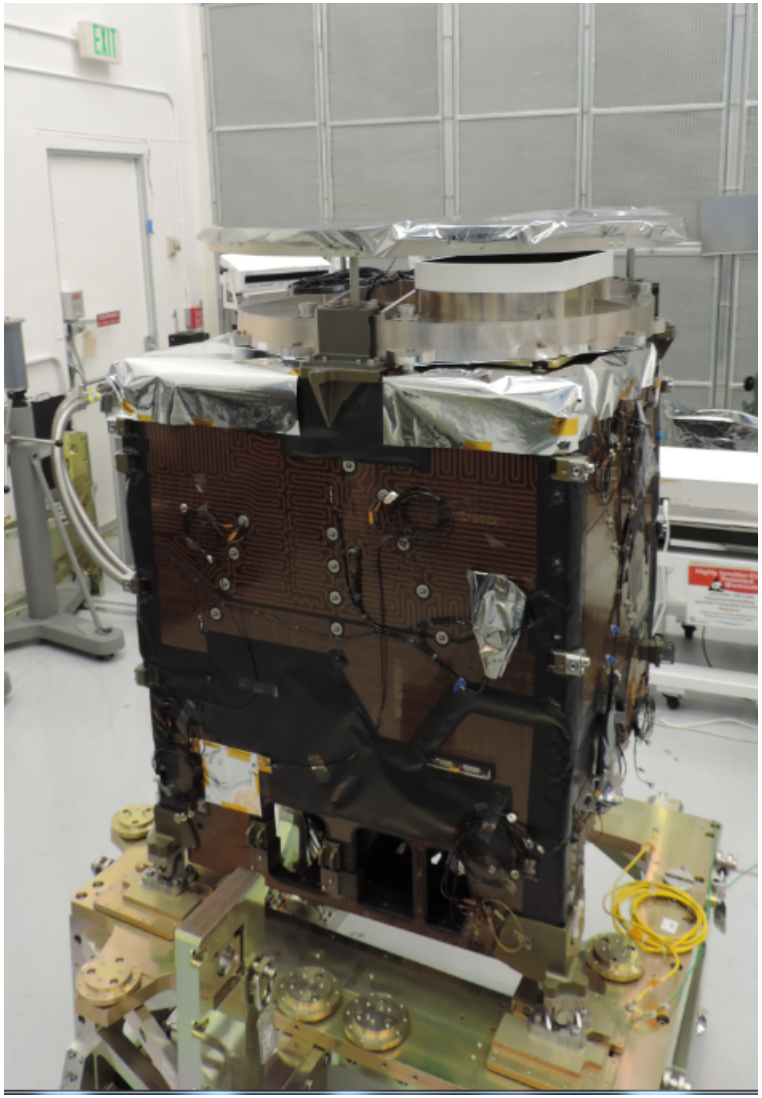
Team Member	Institution	Role	Responsibility
Randall Martin	Dalhousie U.	Collaborator	Atmospheric modeling, air mass factors, AQI development
Chris McLinden	Environment Canada	Collaborator	Canadian air quality coordination
Michel Grutter de la Mora	UNAM, Mexico	Collaborator	Mexican air quality coordination
Gabriel Vazquez	UNAM, Mexico	Collaborator	Mexican air quality, algorithm physics
Amparo Martinez	INECC, Mexico	Collaborator	Mexican environmental pollution and health
J. Victor Hugo Paramo Figeuroa	INECC, Mexico	Collaborator	Mexican environmental pollution and health
Brian Kerridge	Rutherford Appleton Laboratory, UK	Collaborator	Ozone profiling studies, algorithm development
Paul Palmer	Edinburgh U., UK	Collaborator	Atmospheric modeling, process studies
Alfonso Saiz-Lopez	CSIC, Spain	Collaborator	Atmospheric modeling, process studies
Juan Carlos Antuña Marrero	GOAC, Cuba	Collaborator	Cuban Science team lead, Cuban air quality
Osvaldo Cuesta	GOAC, Cuba	Collaborator	TEMPO validation, Cuban air quality
René Estevan Arredondo	GOAC, Cuba	Collaborator	TEMPO validation, Cuban air quality
J. Kim	Yonsei U.	Collaborators, Science Advisory Panel	Korean GEMS, CEOS constellation of GEO pollution monitoring
C.T. McElroy	York U. Canada		CSA PHEOS, CEOS constellation of GEO pollution monitoring
B. Veihelmann	ESA		ESA Sentinel-4, CEOS constellation of GEO pollution monitoring
J.P. Veefkind	KNMI		ESA Sentinel-5P (TROPOMI)

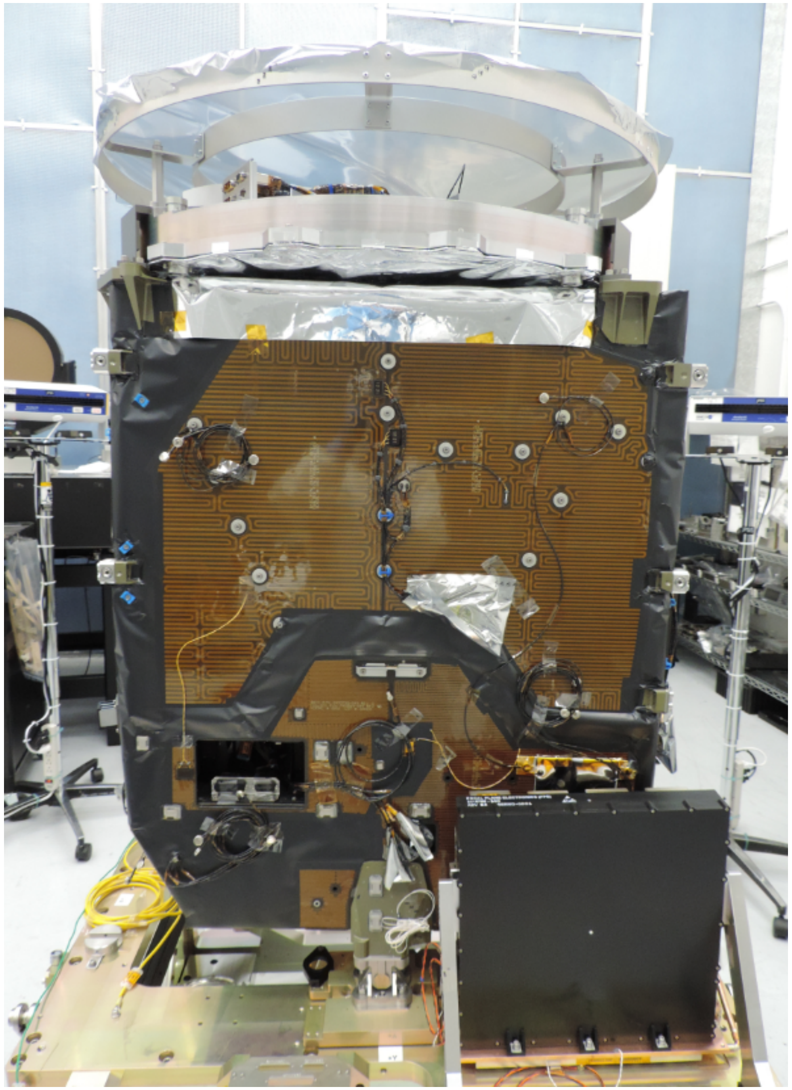
TEMPO status

- Currently on-budget and close to on-schedule
- Select commercial geostationary satellite host 2018+
  - Probably Jan-Feb 2019
  - TEMPO operating longitude and launch date are not known until after host selection
- Instrument delivery 2018 for launch 2019 or later, most likely in 2020 or 2021

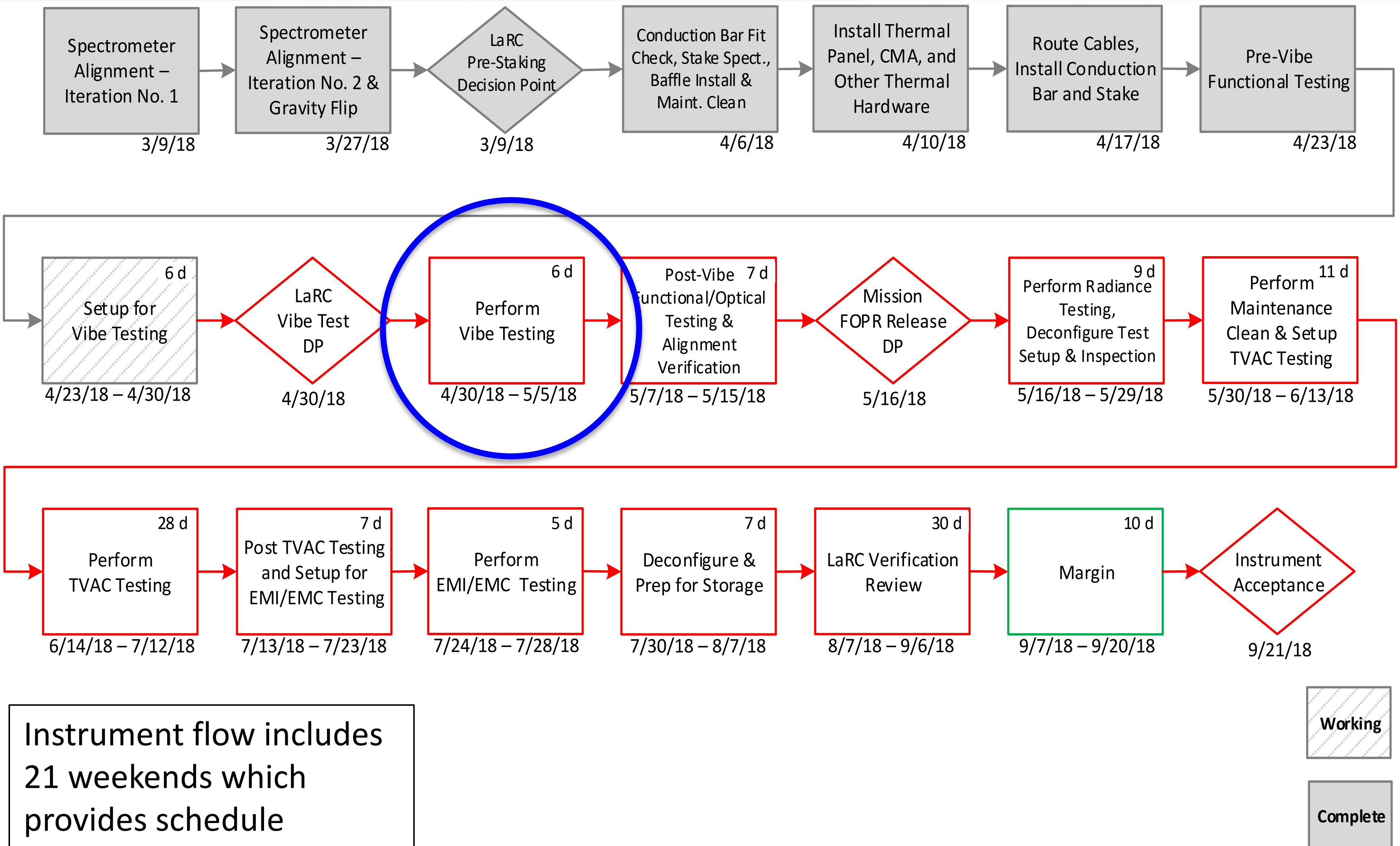
Spectrometer and telescope integrated, aligned

As of April 11





AI&T flowchart week of 4/22/18



Instrument flow includes 21 weekends which provides schedule flexibility

Pre-decision schedule

tempo.si.edu

TEMPO green paper on science studies

tempo.si.edu/presentations.html

Tropospheric Emissions: Monitoring of Pollution

Home | TEMPO Project | News | Gallery | Public Outreach | For Scientists

Presentations

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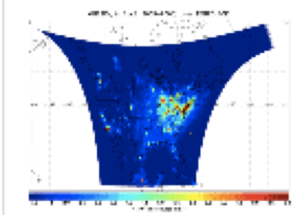
TEMPO Presentations

- Draft TEMPO Green Paper
- TEMPO Fact Sheet
- North American pollution measurements from geostationary orbit with Tropospheric Emissions: Monitoring of Pollution (TEMPO) PowerPoint
- Strategies for Stratosphere-Troposphere Separation of Nitrogen Dioxide Columns from the TEMPO Geostationary Instrument. AGU Fall 2016 pdf
- TEMPO System Test Readiness Review, August 2016 pdf
- Medición de contaminantes atmosféricos desde plataformas satelitales (principalmente TEMPO), Encuentro Nacional de Respuestas al Cambio Climático: Calidad del Aire, Mitigación y Adaptación, El Instituto Nacional de Ecología y Cambio Climático, Mexico, 2016 pptx
- Tropospheric Emissions: Monitoring of Pollution (TEMPO) - status and potential science studies, ESA Living Planet Symposium, 2016 pptx
- Status of Tropospheric Emissions: Monitoring of Pollution, AGU Fall 2015, pptx
- Converting Paper into Hardware: A Status of the TEMPO Instrument Design and Manufacturing, AGU Fall 2015 pptx
- Overview of TEMPO for the 11th meeting of the Atmospheric Composition Constellation group of the Committee on Earth Observation Satellites, April 2015 pptx
- A TEMPO for the Middle East, 11th Conference of the Arab Union for Astronomy and Space Sciences (AUASS), December 2014 pptx
- Implementation of Tropospheric Emissions: Monitoring of Pollution (TEMPO), Korean GEMS Science Team Meeting, October 2014 pptx
- Tropospheric Emissions: Monitoring of Pollution (TEMPO) Status, June 2014 pptx pdf
- Status of the first NASA EV-I Project, Tropospheric Emissions: Monitoring of Pollution (TEMPO), AGU Fall 2013 pptx
- TEMPO overview pptx



Each daylight hour, the TEMPO instrument will scan North America from East to West to measure the changing concentrations of ozone, nitrogen dioxide, and other pollutants.

© KNMI/NASB/ESA/SAO provided by Xiong Liu.

Science Team Meetings

May-June 2017
June 2016
May 2015
May 2014
July 2013

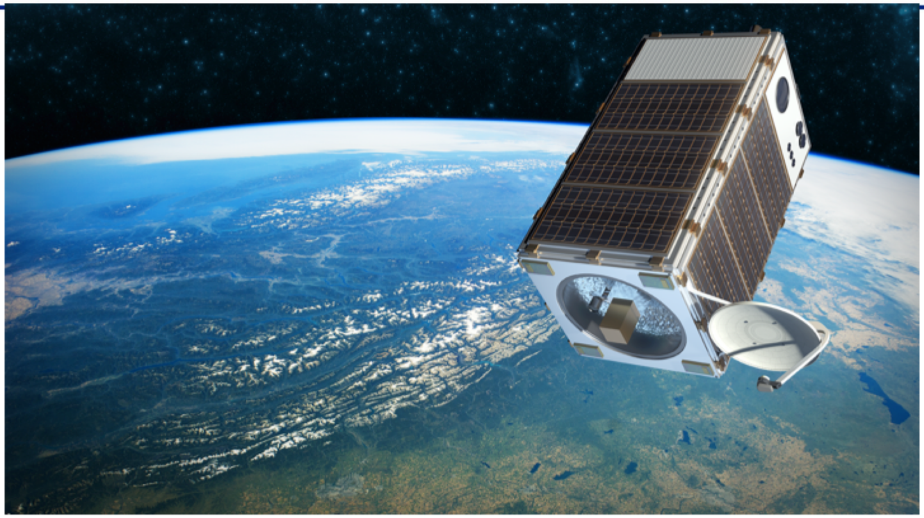
Applications Workshop

July 2016

Validation Workshop

April 2017

Dessert: MethaneSAT!



Artist's conception of MethaneSAT (Environmental Defense Fund)

The Environmental Defense Fund has partnered with the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) and the Smithsonian Astrophysical Observatory (SAO) to develop and launch MethaneSAT into orbit in 2020 or 2021. MethaneSAT is a part of TED's new Audacious Project for supporting world-changing ideas.

While much of the attention on greenhouse warming has properly focused on carbon dioxide (CO_2) emissions, methane (CH_4) emissions cause about a quarter of the global warming. Much of the CH_4 emissions come from leakage and other practices by the oil and natural gas industries. Reducing these emissions will have substantial economic as well as environmental benefit.

MethaneSAT will measure CH_4 from oil and gas fields of up to 200 kilometer cross-orbit size globally from space at 1 kilometer resolution. Fields accounting for more than 80% of global oil and gas productions will be monitored on a weekly basis or better. MethaneSAT will additionally measure CH_4 from feedlots, landfills, cities, and natural sources.

MethaneSAT spectroscopic measurements will be processed into CH_4 abundances at the SAO, piggybacking on the ground systems developed for the Smithsonian/NASA space mission Tropospheric Emissions: Monitoring of Pollution (TEMPO; tempo.si.edu). Harvard SEAS scientists will perform the inversions necessary to precisely determine source emissions and apportionment from these abundances. Data will be freely, publicly available to the industry, scientists, governments, and any other interested users.

Smithsonian Astrophysical Observatory

EDF ENVIRONMENTAL DEFENSE FUND® Finding the ways that work

HARVARD John A. Paulson School of Engineering and Applied Sciences

TEMPO

The end!

Thanks to NASA, ESA, Ball Aerospace & Technologies Corp., The Boeing Company

Smithsonian

NASA

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INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

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

Ball

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POR MI RAZA HABLARÁ EL ESPÍRITU

DALHOUSIE UNIVERSITY

AD MAJOREM DEI GLORIAM
SAINT LOUIS UNIVERSITY

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
1868

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY
1885
연세대학교

UNIVERSITY OF MARYLAND BALTIMORE COUNTY
UMBC
1966

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

THE UNIVERSITY OF IOWA

YORK
UNIVERSITÉ
UNIVERSITY

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS
Science at work

RT S

NCAR

KNMI

Environment and Climate Change Canada

Environnement et Changement climatique Canada

Backups

Smithsonian

NASA

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS
Science at work

NCAR

KNMI

Environment and Climate Change Canada
Environnement et Changement climatique Canada

TEMPO

Now available from OUP!

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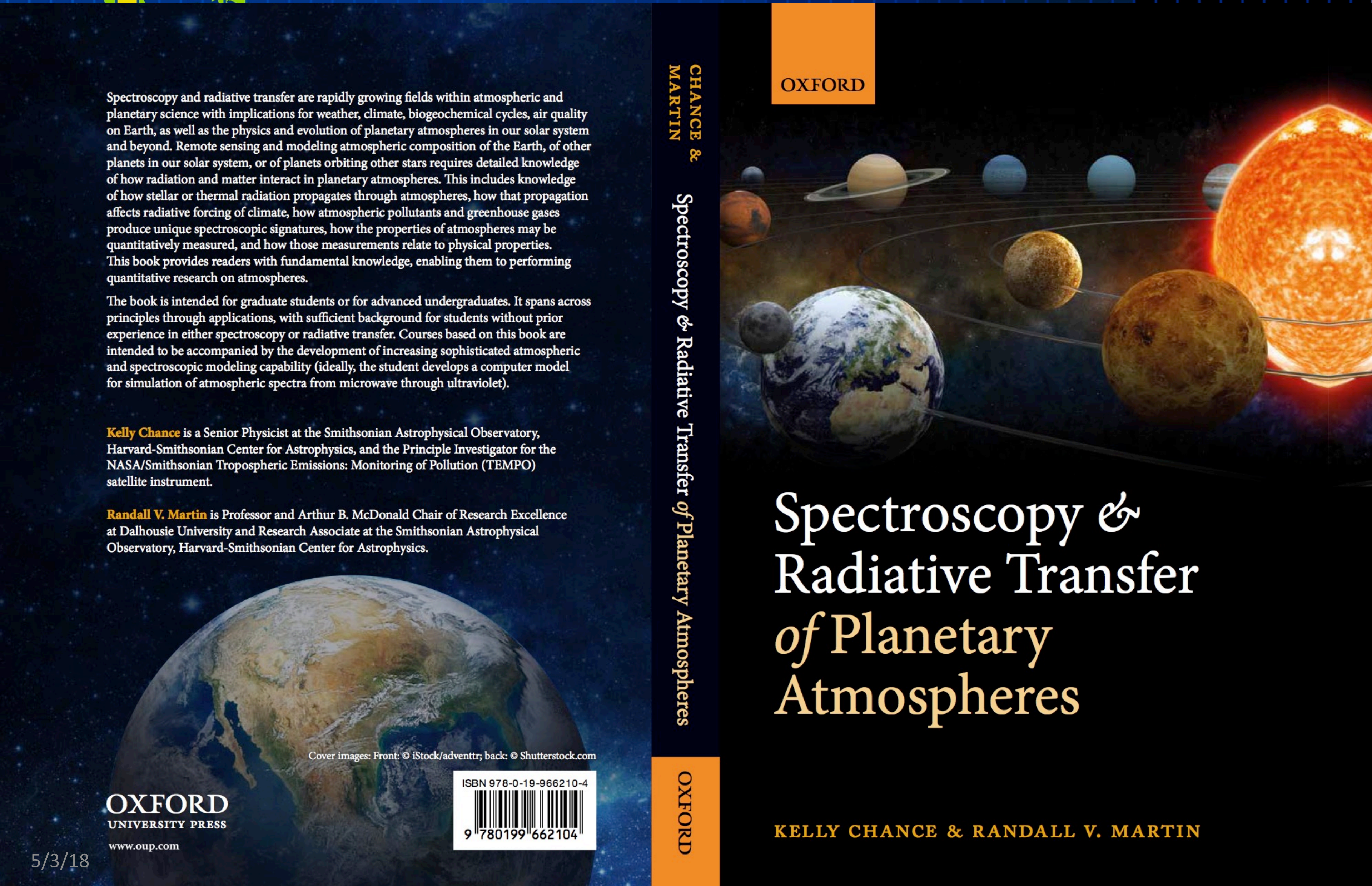


Air quality and health

TEMPO's hourly measurements allow better understanding of the complex chemistry and dynamics that drive **air quality on short timescales**. The density of TEMPO data is ideally suited for data assimilation into chemical models for both air quality forecasting and for better constraints on emissions that lead to air quality exceedances. Planning is underway to combine TEMPO with regional air quality models to **improve EPA air quality indices and to directly supply the public with near real time pollution reports and forecasts through website and mobile applications**. As a case study, an OSSE for the Intermountain West was performed to explore the potential of geostationary ozone measurements from TEMPO to improve monitoring of ozone exceedances and the role of background ozone in causing these exceedances (Zoogman *et al*. 2014).

AQ indices

What is an AQ index?”

“The Canadian Air Quality Health Index is a multipollutant index based on the sum of PM2.5, NO_2, and O_3,weighted by their contribution to mortality in daily time-series study across Canadian cities.” [Cooper et al., 2012]

Cooper et al., for example, propose a satellite-based multipollutant index using the WHO Air Quality Guidelines (AQG):

$$\mathrm{SATMPI} = \frac{\mathrm{PM}_{2.5}}{\mathrm{AQG}_{PM\,2.5}}\left[1 + \frac{\mathrm{NO}_2}{\mathrm{AQG}_{\mathrm{NO}_2}}\right]$$

- Can we define different indices as appropriate to locations, seasons, times?
- Might they be formulated using RSIG?
- Might assimilation be included?

Cooper, M., R.V. Martin, A. van Donkelaar, L. Lamsal, M. Brauer, and J. Brook, A satellite-based multi-pollutant index of global air quality, *Env. Sci. and Tech*., **46**, 8523-8524, 2012.

Clouds and aerosols

Clouds The launch cloud algorithm is be based on the rotational Raman scattering (RRS) cloud algorithm that was developed for OMI by NASA GSFC. Retrieved cloud pressures from OMCLDRR are not at the geometrical center of the cloud, but rather at the optical centroid pressure (OCP) of the cloud. **Additional** cloud products are possible using the O_2-O_2 collision complex and/or the O_2 *B* band.

Aerosols TEMPO's launch algorithm for retrieving aerosols will be based upon the OMI aerosol algorithm that uses the sensitivity of near-UV observations to particle absorption to retrieve **absorbing aerosol index** (AAI), **aerosol optical depth** (AOD) and **single scattering albedo** (SSA). TEMPO may be used together with the advanced baseline imager (ABI) instruments on the NOAA GOES-16 and GOES-17 satellites, particularly the 1.37μm bands, for aerosol retrievals, reducing AOD and fine mode AOD uncertainties from 30% to 10% and from 40% to 20%.

Traffic, biomass burning

Morning and evening higher-frequency scans The optimized data collection scan pattern during mornings and evenings provides multiple advantages for addressing TEMPO science questions. The increased frequency of scans coincides with peaks in vehicle miles traveled on each coast.

Biomass burning The unexplained variability in ozone production from fires is of particular interest. The suite of NO_2, H_2CO, $C_2H_2O_2$, O_3, H_2O, and aerosol measurements from TEMPO is well suited to investigating how the chemical processing of primary fire emissions effects the secondary formation of VOCs and ozone. For particularly important fires it is possible to command special TEMPO observations at even shorter than hourly revisit time, as short as 10 minutes.

NO_x studies

Lightning NO_x Interpretation of satellite measurements of tropospheric NO_2 and O_3, and upper tropospheric HNO_3 lead to an overall estimate of 6 ± 2 Tg N y^{-1} from lightning [Martin et al., 2007]. TEMPO measurements, including tropospheric NO_2 and O_3, can be made for time periods and longitudinal bands selected to coincide with large thunderstorm activity, including outflow regions, with fairly short notice.

Soil NO_x Jaeglé et al. [2005] estimate 2.5 - 4.5 TgN y^{-1} are emitted globally from nitrogen-fertilized soils, still highly uncertain. The US a posteriori estimate for 2000 is 0.86 ± 1.7 TgN y^{-1}. For Central America it is 1.5 ± 1.6 TgN y^{-1}. They note an underestimate of NO release by nitrogen-fertilized croplands as well as an underestimate of rain-induced emissions from semiarid soils.

TEMPO is able to follow the temporal evolution of emissions from croplands after fertilizer application and from rain-induced emissions from semi-arid soils. Higher than hourly time resolution over selected regions may be accomplished by special observations. Improved constraints on soil NO_x emissions may also improve estimated of lightning NO_x emissions [Martin *et al*. 2000].

Spectral indicators

Fluorescence and other spectral indicators Solar-induced fluorescence (SIF) from chlorophyll over both land and ocean will be measured. In terrestrial vegetation, chlorophyll fluorescence is emitted at red to far-red wavelengths (~650-800 nm) with two broad peaks near 685 and 740 nm, known as the red and far-red emission features. Oceanic SIF is emitted exclusively in the red feature. SIF measurements have been used for studies of **tropical dynamics**, **primary productivity**, the length of the **carbon uptake** period, and **drought responses**, while ocean measurements have been used to detect red **tides** and to conduct studies on the physiology, phenology, and productivity of **phytoplankton**. TEMPO can retrieve both red and far-red SIF by utilizing the property that SIF fills in solar Fraunhofer and atmospheric absorption lines in backscattered spectra normalized by a reference (*e.g.*, the solar spectrum) that does not contain SIF.

TEMPO will also be capable of measuring **spectral indices developed for estimating foliage pigment contents and concentrations**. Spectral approaches for estimating pigment contents apply generally to leaves and not the full canopy. A single spectrally invariant parameter, the **Directional Area Scattering Factor** (DASF), relates canopy-measured spectral indices to pigment concentrations at the leaf scale.

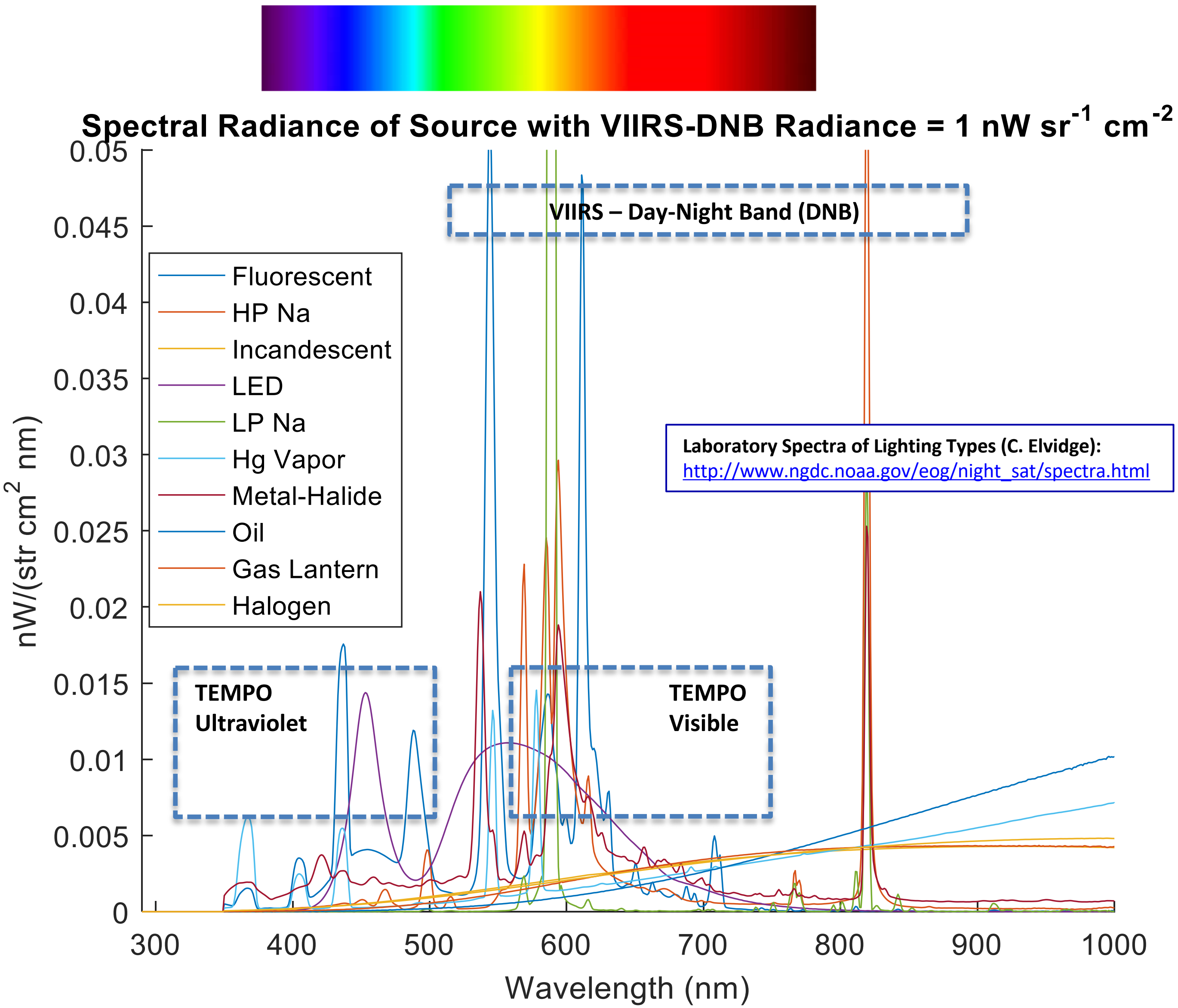
UVB TEMPO measurements of daily UV exposures build upon heritage from OMI and TROPOMI measurements. Hourly cloud measurements from TEMPO allow taking into account diurnal cloud variability, which has not been previously possible. The OMI UV algorithm is based on the TOMS UV algorithm. The specific products are the downward spectral irradiance at the ground (in W m^{-2} nm^{-1}) and the erythemally weighted irradiance (in W m^{-2}).

NASA analysis schedule week of 4/22/18

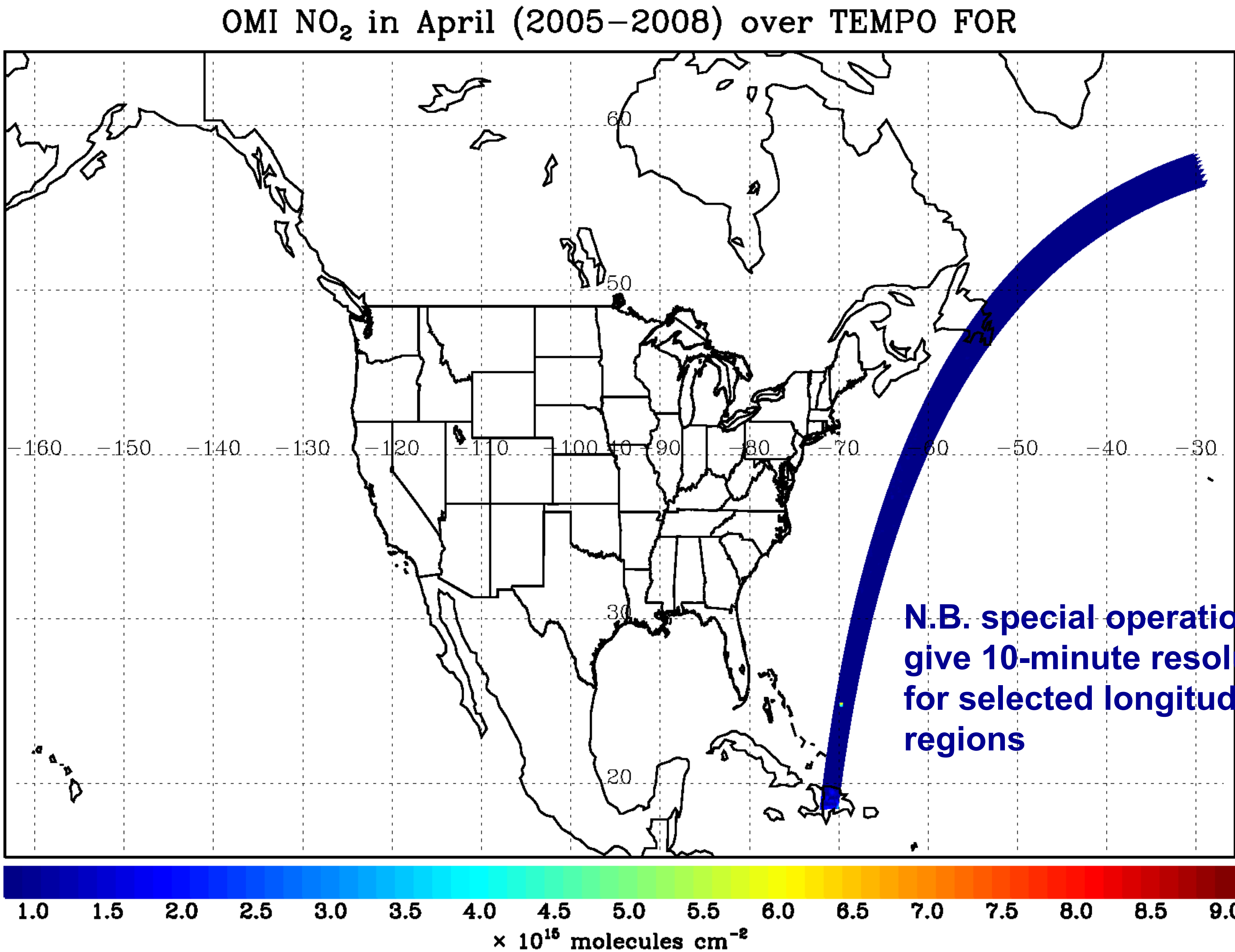
BUID Milestone	Milestone / Task	Estimated Completion Date as of 3/16/18	Current Estimated Completion Date	Actual Completion Date	Notes
835	Spectrometer Install & Alignment Iteration No. 1	**3/9/18**		**3/9/18**	Integration began - 11/17/17 Alignment began - 12/14/17 HAR investigation began - 12/27/17 Alignment complete - 3/9/18
	Troubleshoot Alignment HAR			**2/14/18**	HAR investigation started 12/27/17 1. Inspect spectrometer for mechanical interference - complete 1/9/18 2. Perform telescope optics push-pull test - complete 1/10/18 3. Optical modeling iterations to simulate the observed optical behavior - complete 1/15/18 4. DIT Electronics analysis, modeling, and resolution - complete 2/14/18
840	Spectrometer Install & Alignment Iteration No. 2 & Gravity Flip	**3/26/18**		**3/27/18**	Alignment process extended due to anomaly resolution requiring DITCE mapping
847	Pre-Staking Review	**3/27/18**		**3/28/18**	
845	Stake Spectrometer, Baffle Install & Maintenance Clean	**4/6/18**		**4/6/18**	
13881	Pre-Harness MLI & Thermal Installs	**4/16/18**		**4/10/18**	
13488	Install Conduction Bar & Stake Fasteners	**4/27/18**		**4/17/18**	
13482	Perform Pre-Vibe Functional/Optical Testing and Data Analysis	**5/3/18**		**4/23/18**	
13494	Setup for Vibe Testing	**5/14/18**	**4/30/18**		
893	Perform Vibe Testing	**5/22/18**	**5/5/18**		
892	Perform Post Vibe Alignment and Functional Verification Testing	**6/1/18**	**5/15/18**		
13487	Deconfigure Test Setup & Inspection	**6/13/18**	**5/25/18**		
5866	Setup for TVAC Testing	**6/29/18**	**6/13/18**		
890	Perform TVAC Testing	**7/28/18**	**7/12/18**		
13497	Post TVAC Testing and Setup for EMI/EMC Testing	**8/7/18**	**7/23/18**		
886	Perform EMI/EMC Testing	**8/12/18**	**7/28/18**		
859	Prep for Storage	**8/21/18**	**8/7/18**		
3628	Instrument Acceptance	**9/21/18**	**9/21/18**		

Pre-decision schedule

City lights spectroscopic signatures

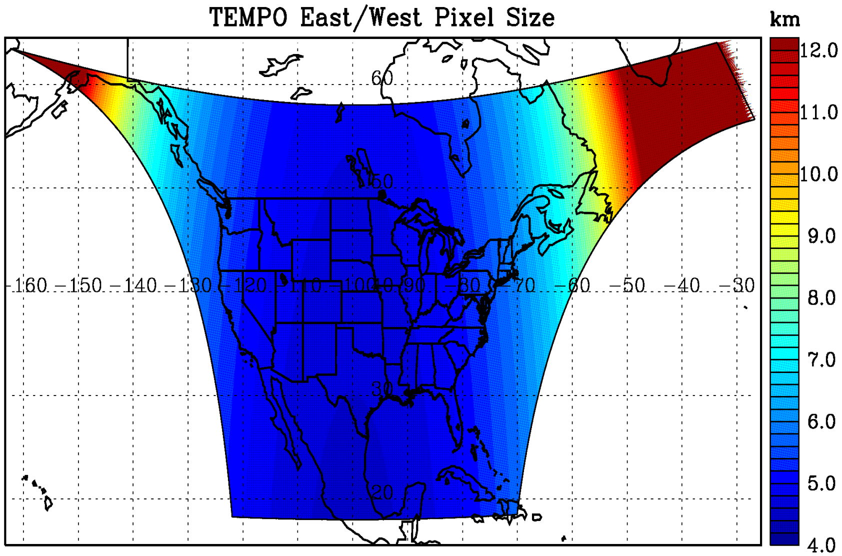


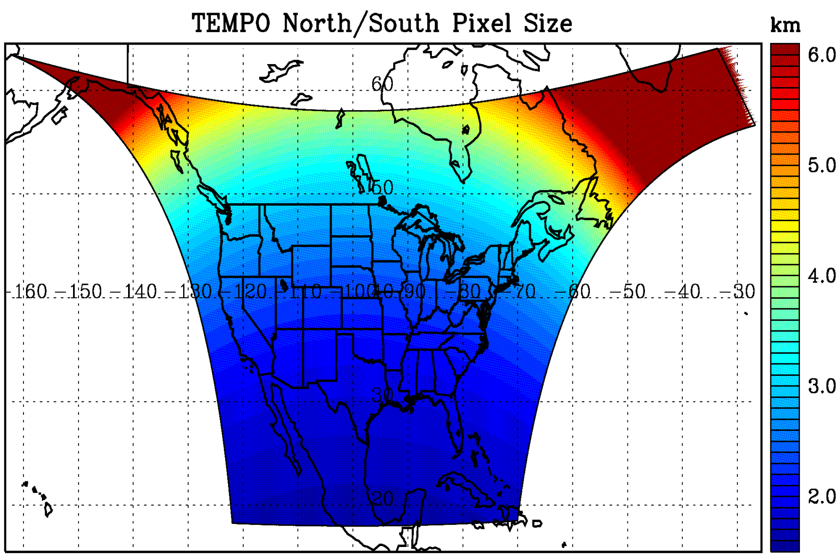
TEMPO hourly NO_2 sweep



N.B. special operations give 10-minute resolution for selected longitude regions

TEMPO footprint (GEO at 100° W)



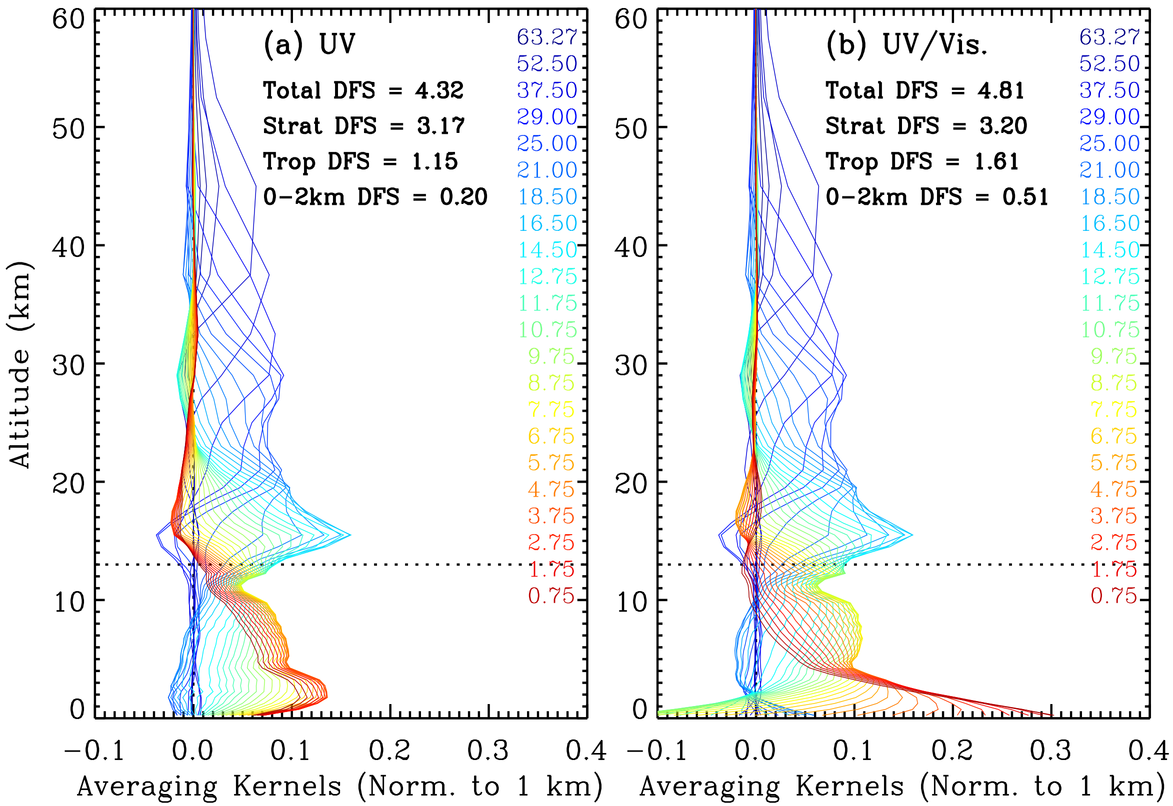


Location	N/S (km)	E/W (km)	GSA (km^2)
36.5°N, 100°W	2.11	4.65	9.8
Washington, DC	2.37	5.36	11.9
Seattle	2.99	5.46	14.9
Los Angeles	2.09	5.04	10.2
Boston	2.71	5.90	14.1
Miami	1.83	5.04	9.0
Mexico City	1.65	4.54	7.5
Canadian tar sands	3.94	5.05	19.2

Assumes 2000 N/S pixels

For GEO at 80°W, pixel size at 36.5°N, 100°W is 2.2 km × 5.2 km.

XL ozone profile retrievals



Retrieval averaging kernels based on iterative nonlinear retrievals from synthetic TEMPO radiances with the signal to noise ratio (SNR) estimated using the TEMPO SNR model at instrument critical design review in June 2015 for (a) UV (290-345 nm) retrievals and (b) UV/Visible (290-345 nm, 540-650 nm) retrievals for clear-sky condition and vegetation surface with solar zenith angle 25°, viewing zenith angle 45° and relative azimuthal angle 86°. DFS is degrees of freedom for signal, the trace of the averaging kernel matrix, which is an indicator of the number of pieces of independent information in the solution.

Template