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



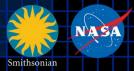


Smithsonian



Measurement of Pollution

### 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

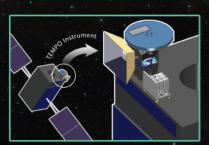
#### Aligned with Earth Science Decadal Survey recommendations

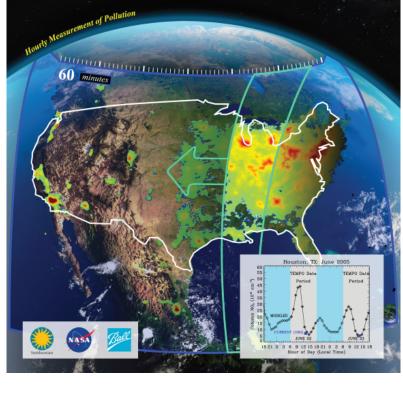
- Makes many of the GEO-CAPE atmosphere measurements
- Responds to the phased implementation recommendation of GEO-CAPE mission design team

### TEMPO

#### Tropospheric Emissions: Monitoring of Pollution

TEMPO's concurrent high temporal (hourly) and spatial resolution measurements from geostationary orbit of tropospheric ozone, aerosols, their precursors, and clouds create a revolutionary dataset that provides understanding and improves prediction of air quality and climate forcing in Greater North America.





#### 5/3/18 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

11-28-2011 DR Science Questions	Ι	Measurement Objectives color flag maps to Science Questions)			<b>ent Requ</b> easuremer			Measurement Rationale	
1. What are the	Ba	seline measurements <sup>1</sup> :	Geostationary Observing Location: 100 W +/-10					Provides optimal view of North America.	
temporal and spatial variations	diff km	NO2, CO, SO2, HCHO, CH4, NH3, CHOCHO, erent temporal sampling frequencies, 4 km x 4 product horizontal spatial resolution at the center		Column measurements: [A to K] All the baseline and threshold species			Continue the current state of practice in vertical; add temporal resolution.		
of emissions of gases and	cer x 8	he domain; and AOD, AAOD, AI, aerosol optical troid height (AOCH), hourly for SZA<70 and 8 kr km product horizontal spatial resolution at the		Cloud Camera 1 km x 1km horizontal spatial resolution, two spectral bands, baseline only			Improve retrieval accuracy, provide diagnostics for gases and aerosol		
aerosols important for air quality and		ter of the domain.		Vertical information: A to K					
climate?	cc	<u>Threshold measurements<sup>1</sup>:</u> CO hourly day and night; O3, NO2 hourly when		Two pieces of information in troposphere in daylight with sensitivity to the lowest 2 km		e O3, CO (Baseline and Threshold)		Separate the lower-most troposphere from the free troposphere for O3, CO.	
<ol> <li>How do physical, chemical, and</li> </ol>	SZA<70; AOD hourly (SZA<50) ; at 8 km x 8 km product horizontal spatial resolution at the center of the domain.		Altitude (+/	Altitude (+/- 1km)		AOCH (baseline only)		Detect aerosol plume height; improve retrieval accuracy.	
dynamical	А.	Measure the threshold or baseline species or	Product ho	orizontal sp	oatial resoluti	ion at th	he center of t	he domain, (nominally 100W, 35 N ): A to H	
processes determine		properties with the temporal and spatial resolution specified (see next column) to quantifi	4 km x 4 kr 8 km x 8 kr	n (baseline n (threshol	e), Id)	Gases		Capture spatial/temporal variability; obtain	
tropospheric		the underlying emissions, understand emission processes, and track transport and chemical	0 1111 / 0 14		e, threshold)	Aerosol		better yields of products.	
composition and air quality over		evolution of air pollutants <mark>[]</mark> , 2, 3, <mark>4</mark> , 5, 6]	16 km x 16			Over open		Inherently larger spatial scales, sufficient	
scales ranging	В.	Measure AOD, AAOD, and NH3 to quantify aerosol and nitrogen deposition to land and	Spectral re		•	ocea	In	to link to LEO observations Typical use	
from urban to continental,		coastal regions [2, 4]	UV-Vis or U	JV-TIR	03			Provide multispectral retrieval information	
diurnally to	C.	Measure AOD, AAOD, and AOCH to relate surface PM concentration, UV-B level and	SWIR, MW	/IR	со			in daylight	
seasonally?		visibility to aerosol column loading <mark>[]</mark> 2, 3, 4, 5,	UV SWIR		SO2, HCH CH4	0		Retrieve gas species from their atmospheric spectral signatures (typical)	
<mark>3.</mark> How does air	Б	Determine the instantaneous radiative forcings	TIR		NH3				
pollution drive climate forcing	Determine the instantaneous radiative forcings associated with occen and aerosols on the continental scale and relate them quantitatively to natural and anthropogenic emissions (3, 5, 5)		Vis	Vis AOD, N		NO2, CHOCHO		Obtain spectral-dependence of AOD for particle size and type information	
and how does			UV-deep b	UV-deep blue AAOE				Obtain spectral-dependence of AAOD for aerosol type information	
climate change	and antihopogenic releases, co antihopogenic		UV-deep blue AI				Provide absorbing aerosol information		
	_	and anthropogenic releases; CO anthropogenic		lue					
climate change affect air quality on a continental		and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO2	Vis-NIR		AOCH			Retrieve aerosol height <sup>3</sup>	
affect air quality		and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO; and AOD from volcanic eruptions []. 4. 6]	Vis-NIR Atmosphe	eric measu	AOCH	er Land	d/Coastal ar		
affect air quality on a continental scale?		and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO: and AOD from volcanic eruptions	Vis-NIR Atmosphe		AOCH Irements ov	er Land	d/Coastal ar	Retrieve aerosol height <sup>3</sup>	
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AOD=Aerosol optical depth, AAOD=Aerosol a

pth, Al=Aerosol index. See next page for footnotes.

## Infrared species

Autosphene medsurements over Zuna obustur dreds, susenne und threshold. [Hora								
Species	Time resolution	Typical value <sup>2</sup>	Precision <sup>2</sup>		Description			
03	Hourly, SZA<70 9 x10 <sup>18</sup>		2km- 15	m: 10 ppbv -tropopause: ppbv osphere: 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 <sup>18</sup>	2km-tropopause:		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 <sup>15</sup>		1×10 <sup>15</sup>		Distinguish background from enhanced/ polluted scenes; atmospheric chemistry			
Addition	Additional atmospheric measurements over Land/Coastal areas, baseline only: A to K							
Species Time Typical Precision <sup>2</sup> Description								

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

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

Species	Time resolution	Typical value <sup>2</sup>	Precision <sup>2</sup>	Description			
нсно*	3/day, SZA<50	1.0x10 <sup>16</sup>	1×10 <sup>16</sup>	Observe biogenic VOC emissions, expected to peak at midday; chemistry			
SO2*	3/day, SZA<50	1×10 <sup>16</sup>	1×10 <sup>16</sup>	Identify major pollution and volcanic emissions; atmospheric chemistry			
CH4	2/day	4 x10 <sup>19</sup>	20 ppbv	Observe anthropogenic and natural emissions sources			
NH3	2/day	2x10 <sup>16</sup>	0-2 km: 2ppbv	Observe agricultural emissions			
сносно*	2/day	2x10 <sup>14</sup>	4×10 <sup>14</sup>	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			
АОСН	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM			

# TEMPO

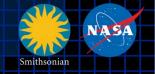
## Baseline and threshold data products



Species/Products	Required Precision	Temporal Revisit
0-2 km O₃ (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O <sub>3</sub>	10 ppbv	1 hour
Total O <sub>3</sub>	3%	1 hour
Tropospheric NO <sub>2</sub>	$1.0 \times 10^{15}$ molecules cm <sup>-2</sup>	1 hour
Tropospheric H <sub>2</sub> CO	$1.0 \times 10^{16}$ molecules cm <sup>-2</sup>	3 hour
Tropospheric SO <sub>2</sub>	$1.0 \times 10^{16}$ molecules cm <sup>-2</sup>	3 hour
Tropospheric C <sub>2</sub> H <sub>2</sub> O <sub>2</sub>	$4.0 \times 10^{14}$ molecules cm <sup>-2</sup>	3 hour
Aerosol Optical Depth	0.10	1 hour

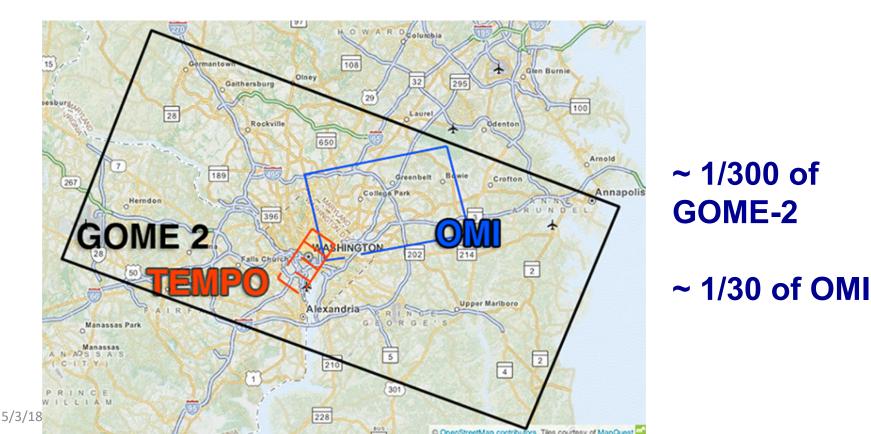
- Minimal set of products sufficient for constraining air quality
- Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N
- Data products at urban-regional spatial scales
  - Baseline ≤ 60 km<sup>2</sup> at center of Field Of Regard (FOR)
  - Threshold  $\leq$  300 km<sup>2</sup> 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



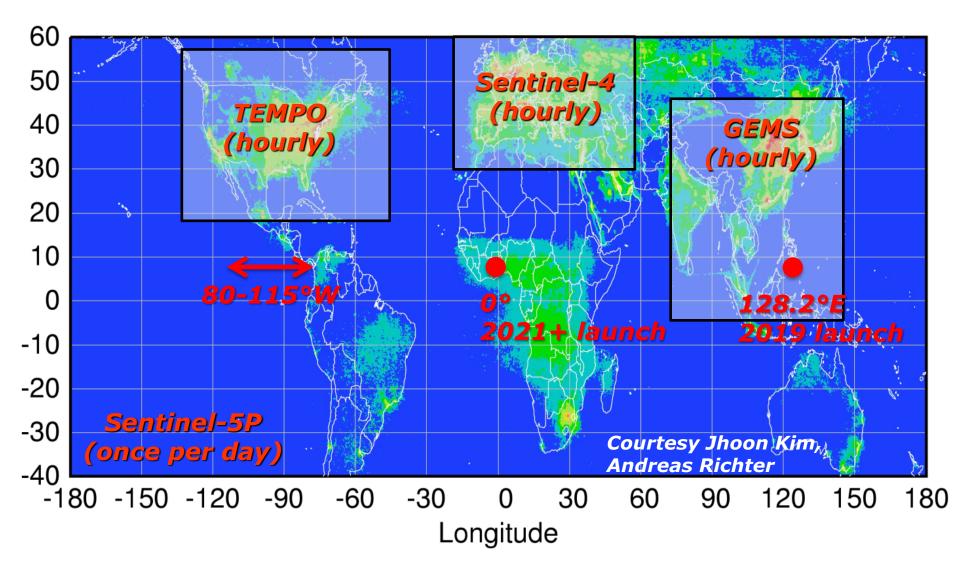


6

- 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<sup>2</sup> (native) at center of FOR (36.5°N, 100°W)
  - Full resolution for NO<sub>2</sub>, HCHO, total O<sub>3</sub> products
  - Co-add 4 N/S pixels for O<sub>3</sub> profile product: 8.4 km N/S × 4.7 km E/W

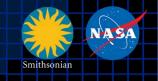


# Global pollution





## 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.		Korean GEMS, CEOS constellation of GEO pollution monitoring
C.T. McElroy	York U. Canada	Collaborators,	CSA PHEOS, CEOS constellation of GEO pollution monitoring
B. Veihelmann	ESA	Science Advisory Panel	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 onschedule
- 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**



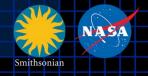
5/3/18

NASA

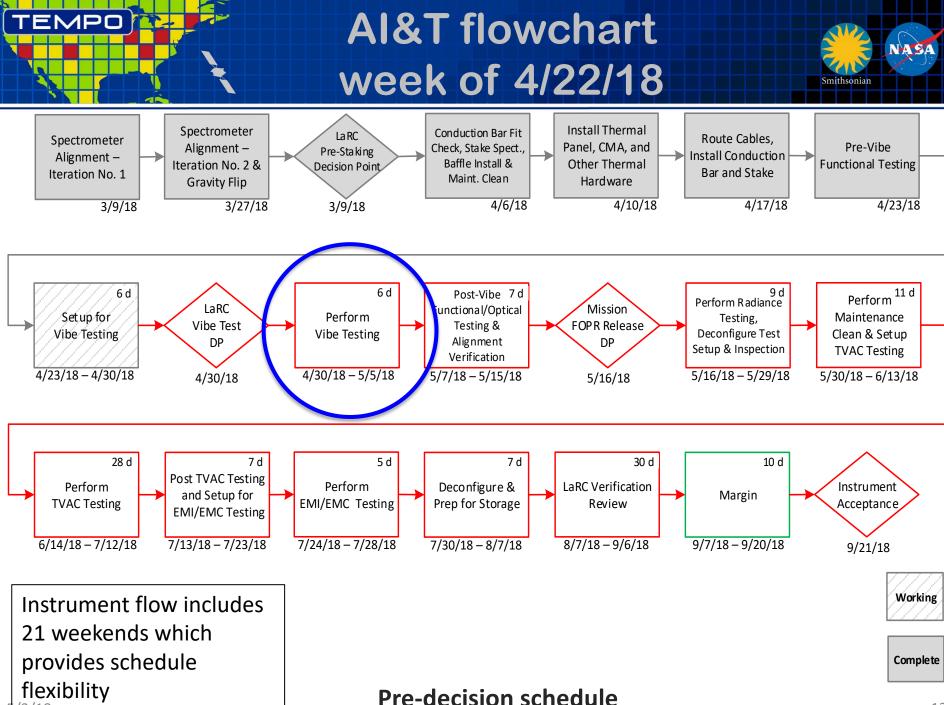
Smithsonian



As of April 11







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**TEMPO** green

studies

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paper on science



Tropospheric Emissions: Monitoring of Pollution

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#### 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, Mitigatión 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

#### Science Team Meetings

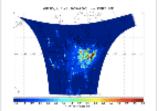
May-June 2017 June 2016 May 2015 May 2014 July 2013

#### **Applications Workshop**

July 2016

#### Validation Workshop

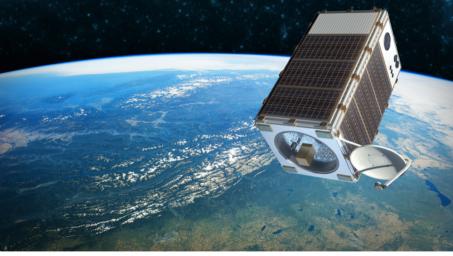
April 2017



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/IASB/ESA/SAO provided by Xiong Liu.

# 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> from feedlots, landfills, cities, and natural sources.

MethaneSAT spectroscopic measurements will be processed into CH<sub>4</sub> 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.





HARVARD John A. Paulson School of Engineering and Applied Sciences

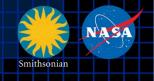
Smithsonian Astrophysical Observatory

Smithsonian





PO





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Spectroscopy and radiative transfer are rapidly growing fields within atmospheric and planetary science with implications for weather, climate, biogeochemical cycles, air quality on Earth, as well as the physics and evolution of planetary atmospheres in our solar system and beyond. Remote sensing and modeling atmospheric composition of the Earth, of other planets in our solar system, or of planets orbiting other stars requires detailed knowledge of how radiation and matter interact in planetary atmospheres. This includes knowledge of how stellar or thermal radiation propagates through atmospheres, how that propagation affects radiative forcing of climate, how atmospheric pollutants and greenhouse gases produce unique spectroscopic signatures, how the properties of atmospheres may be quantitatively measured, and how those measurements relate to physical properties. This book provides readers with fundamental knowledge, enabling them to performing quantitative research on atmospheres.

The book is intended for graduate students or for advanced undergraduates. It spans across principles through applications, with sufficient background for students without prior experience in either spectroscopy or radiative transfer. Courses based on this book are intended to be accompanied by the development of increasing sophisticated atmospheric and spectroscopic modeling capability (ideally, the student develops a computer model for simulation of atmospheric spectra from microwave through ultraviolet).

Kelly Chance is a Senior Physicist at the Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics, and the Principle Investigator for the NASA/Smithsonian Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument.

Randall V. Martin is Professor and Arthur B. McDonald Chair of Research Excellence at Dalhousie University and Research Associate at the Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics.

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Spectroscopy & Radiative Transfer of Planetary Atmospheres

OXFORD

CHANCE MARTIN

Spectroscopy & **Radiative Transfer** of Planetary Atmospheres

Smithsonian

**KELLY CHANCE & RANDALL V. MARTIN** 



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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):

$$SATMPI = \frac{PM_{2.5}}{AQG_{PM2.5}} \left[ 1 + \frac{NO_2}{AQG_{NO_2}} \right]$$

- 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%.



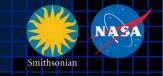


**Morning and evening higher-frequency scans** The optimized data collection scan pattern during mornings and evenings provides multiple advantages for addressing TEMPO science questions. The increased frequency of scans coincides with peaks in vehicle miles traveled on each coast.

**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.

# TEMPO

# NO<sub>x</sub> studies



**Lightning NO**<sub>x</sub> Interpretation of satellite measurements of tropospheric NO<sub>2</sub> and O<sub>3</sub>, and upper tropospheric HNO<sub>3</sub> lead to an overall estimate of 6 ± 2 Tg N y<sup>-1</sup> from lightning [Martin et al., 2007]. TEMPO measurements, including tropospheric NO<sub>2</sub> and O<sub>3</sub>, 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<sub>x</sub>** Jaeglé et al. [2005] estimate 2.5 - 4.5 TgN y<sup>-1</sup> are emitted globally from nitrogen-fertilized soils, still highly uncertain. The US a posteriori estimate for 2000 is  $0.86 \pm 1.7$  TgN y<sup>-1</sup>. For Central America it is  $1.5 \pm 1.6$  TgN y<sup>-1</sup>. 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<sub>x</sub> emissions may also improve estimated of lightning NO<sub>x</sub> emissions [Martin *et al.* 2000].

### Pn 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<sup>-2</sup>)  $n_{1}m_{1}^{1}$  and the erythemally weighted irradiance (in W m<sup>-2</sup>).

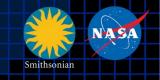
## NASA analysis schedule week of 4/22/18

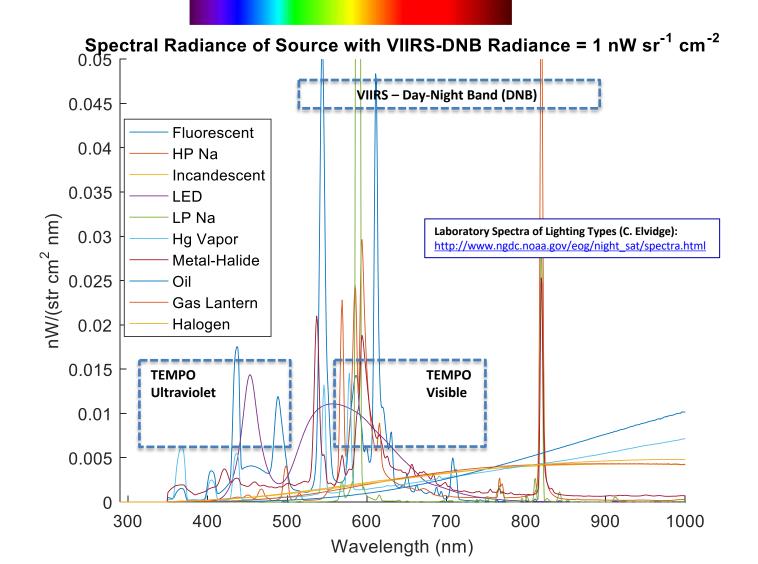


BUID Milestone	Milestone / Task	Estimated Completion Date as of 3/16/18	Current Estimated Completion Date	Actual Completion Date	Notes
835	Spectrometer Install & Alignment Iteration No. 1	3/9/18		3/9/18	Integration began - 11/17/17 Alignment began - 12/14/17 HAR investigation began - 12/27/17 Alignment complete - 3/9/18
	Troubleshoot Alignment HAR			2/14/18	<ul> <li>HAR investigation started 12/27/17</li> <li>1. Inspect spectrometer for mechanical interference - complete 1/9/18</li> <li>2. Perform telescope optics push-pull test - complete 1/10/18</li> <li>3. Optical modeling iterations to simulate the observed optical behavior - complete 1/15/18</li> <li>4. DIT Electronics analysis, modeling, and resolution - complete 2/14/18</li> </ul>
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		

**IPO** 

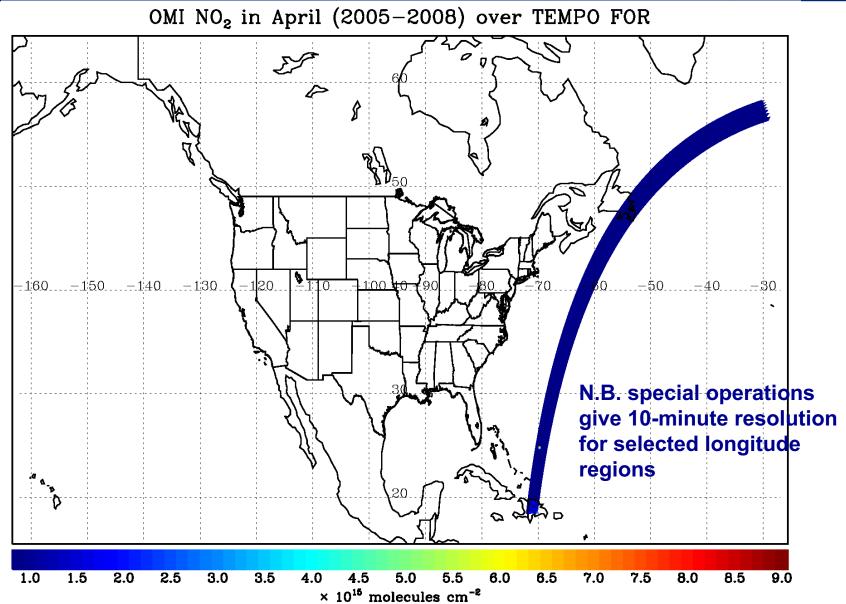
## City lights spectroscopic signatures





 $\mathbf{D}\mathbf{O}$ 

## **TEMPO** hourly NO<sub>2</sub> sweep

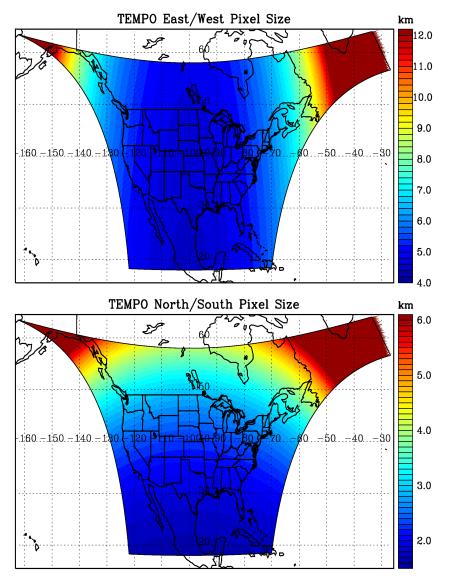


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NASA

mithsoniar

**TEMPO** footprint (GEO at 100° W)



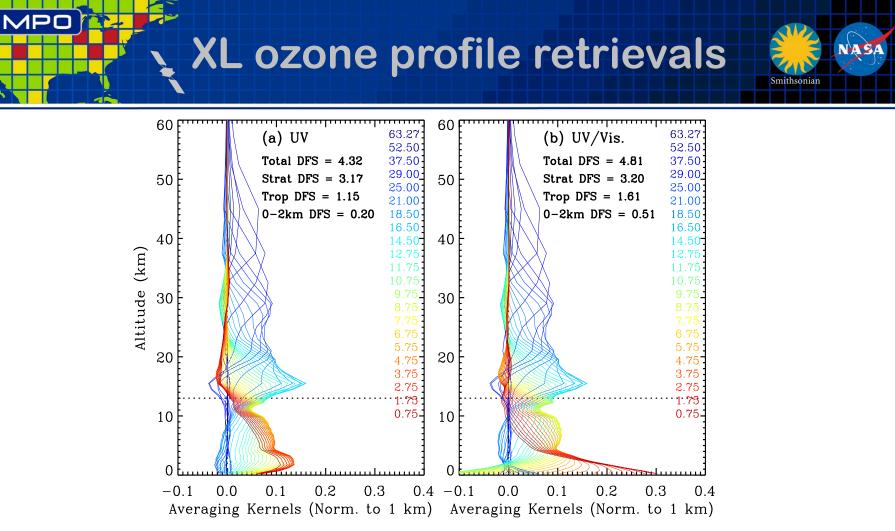
Location	N/S (km)	E/W (km)	GSA (km²)
36.5°N, 100°W	2.11	4.65	9.8
Washington, DC	2.37	5.36	11.9
Seattle	2.99	5.46	14.9
Los Angeles	2.09	5.04	10.2
Boston	2.71	5.90	14.1
Miami	1.83	5.04	9.0
Mexico City	1.65	4.54	7.5
Canadian tar sands	3.94	5.05	19.2

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.

NASA

Smithsonian



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.

# TEMPO

# Template

