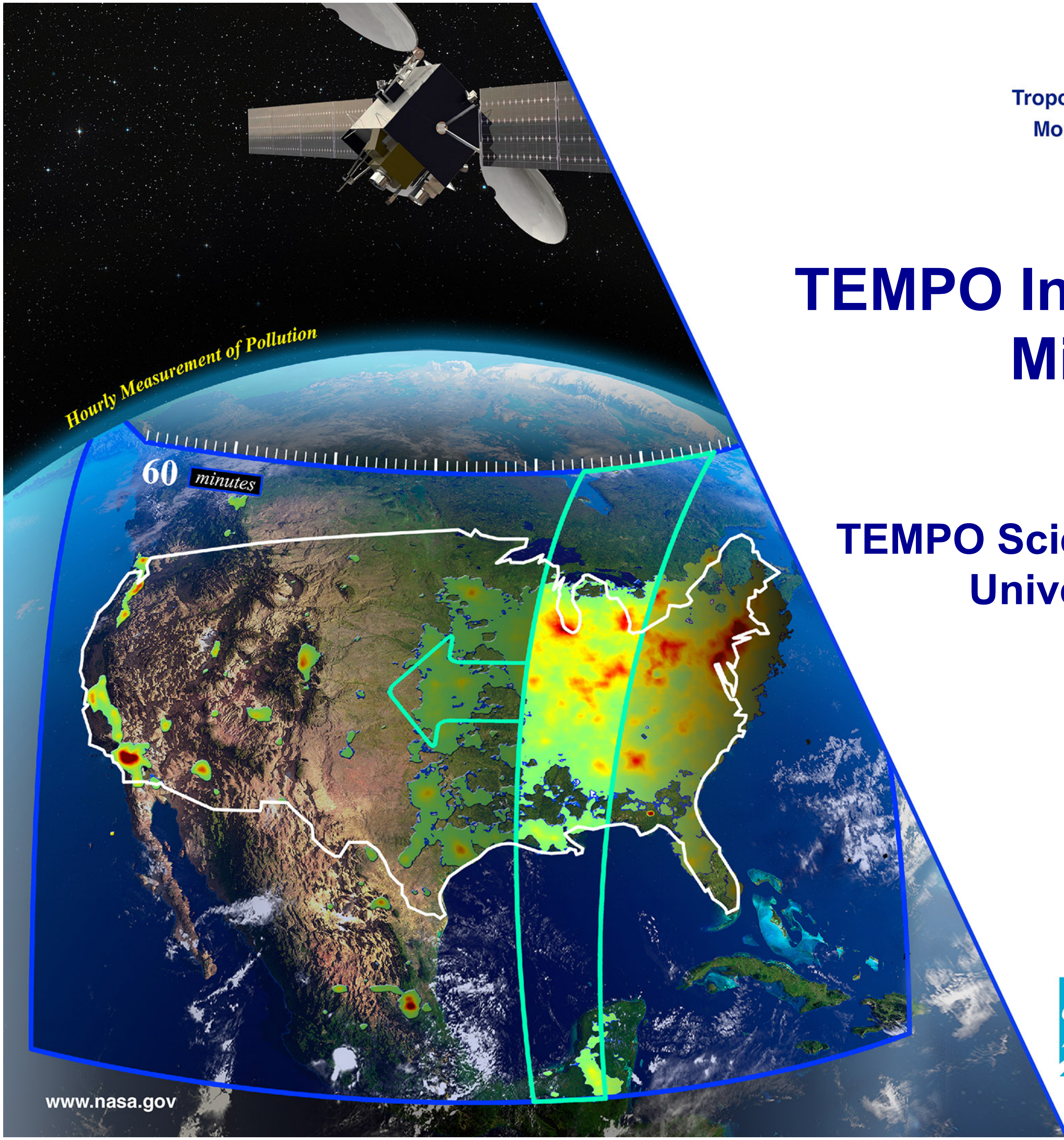


Tropospheric Emissions:
Monitoring of Pollution

TEMPO Instrument and Mission Update

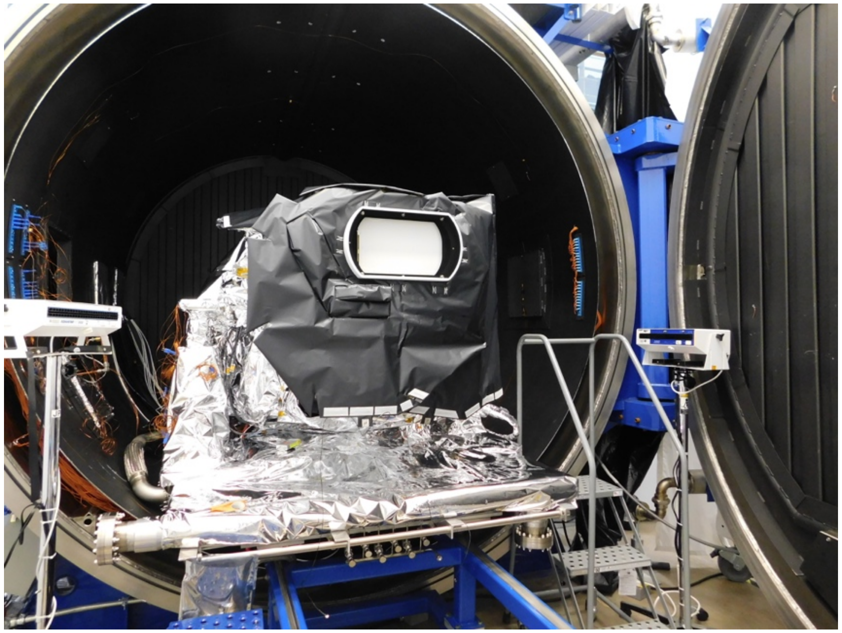
K. Chance

TEMPO Science Team Meeting
University of Wisconsin
June 5, 2019
tempo.si.edu

Smithsonian

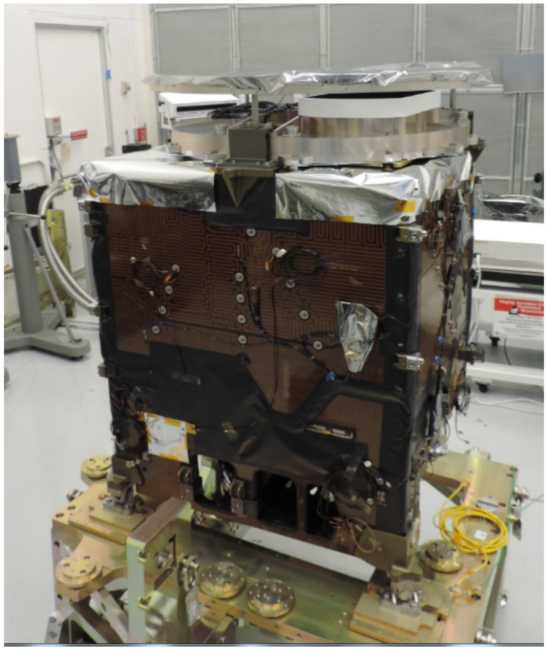
Status of the TEMPO instrument

- The TEMPO instrument successfully completed all environmental testing, was accepted by NASA & SAO, and was safely placed into storage.
- Performance meets or exceeds data product requirements.



Instrument thermal vacuum testing complete

Photo courtesy of Ball Aerospace



Instrument vibration testing complete

Photo courtesy of Ball Aerospace

Status of TEMPO hosting

- NASA, in coordination with the USAF's Space and Missile Systems Center (SMC), released the TEMPO Hosting Services Request for Proposal (RFP) on March 13, 2019.
- The RFP solicited bids to be delivered by April 29, 2019 for a TEMPO Delivery Order under the Hosted Payloads Solutions (HoPS).
- Responses are currently being evaluated by the NASA/USAF team.
- Contract award is planned for approximately July 2019.

TEMPO green paper

- The green paper will be presented at an SPIE meeting in September. It will then become an SPIE publication.

- Please feel free to suggest additions and corrections through at least July. New authors welcome.

TEMPO Science Team organization chart

TEMPO

The end!

Thanks to NASA, ESA, Ball Aerospace & Technologies Corp.

Smithsonian

NASA

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

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

Ball

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POR MI RAZA HABLARÁ EL ESPÍRITU

Washington University in St. Louis

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
1868

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

THE UNIVERSITY OF IOWA

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY
1885
연세대학교

AD MAJOREM DEI GLORIAM
SAINT LOUIS UNIVERSITY

UNIVERSITY OF MARYLAND BALTIMORE COUNTY
UMBC
1966

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

YORK
UNIVERSITÉ
UNIVERSITY

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS
Science at work

RTS

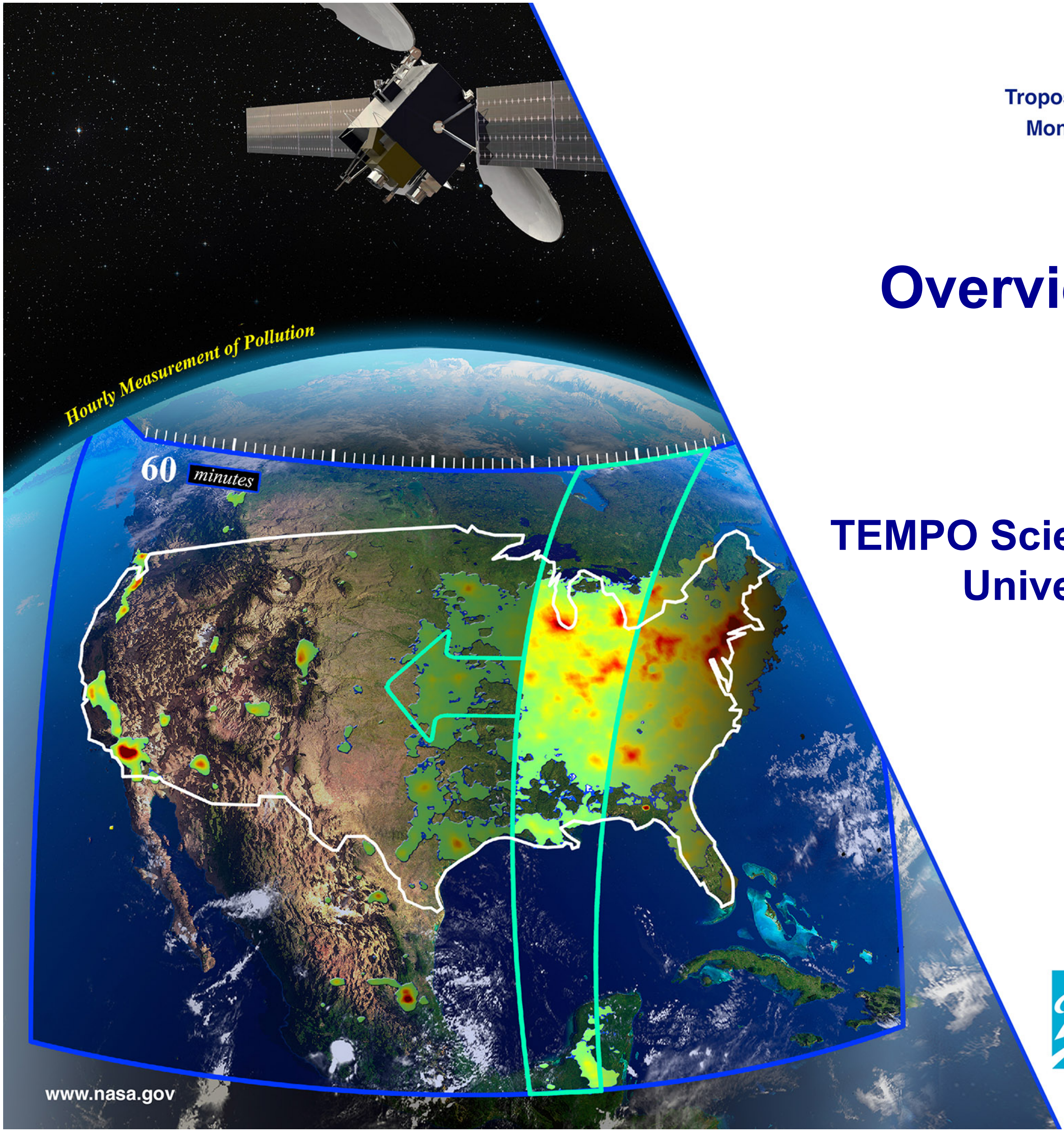
UNIVERSITY OF SASKATCHEWAN
DEO PATRIÆ ET

NCAR

KNMI

Environment and Climate Change Canada

Environnement et Changement climatique Canada



Tropospheric Emissions:
Monitoring of Pollution

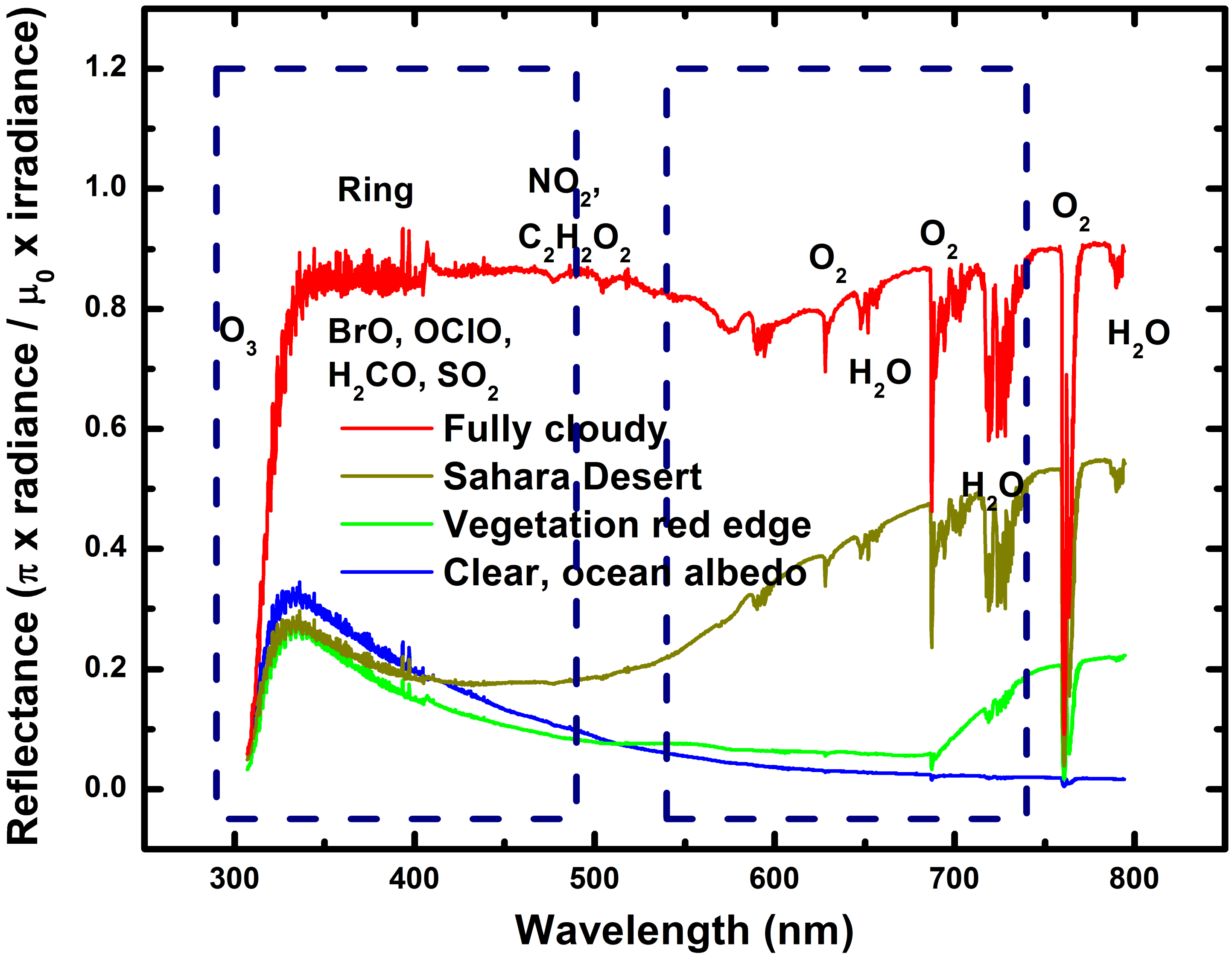
Overview of TEMPO Capabilities

K. Chance

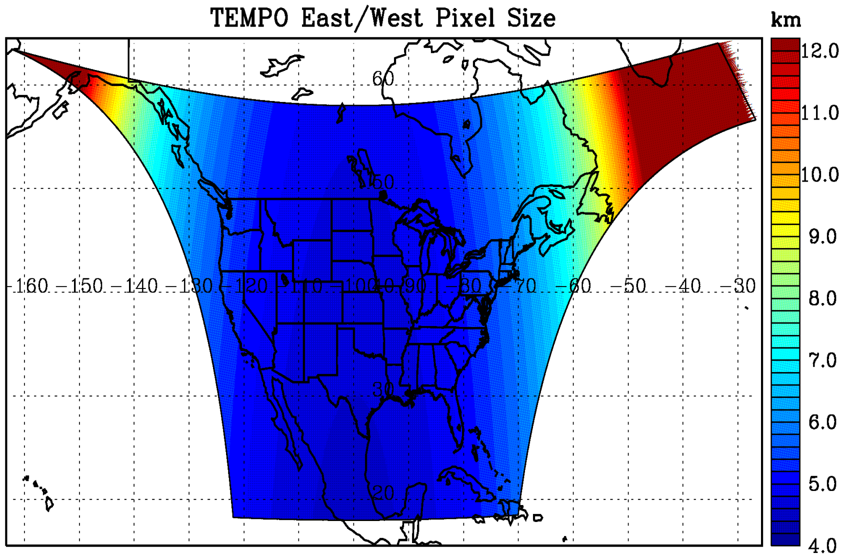
TEMPO Science Team Meeting
University of Wisconsin
June 4-6, 2019
tempo.si.edu

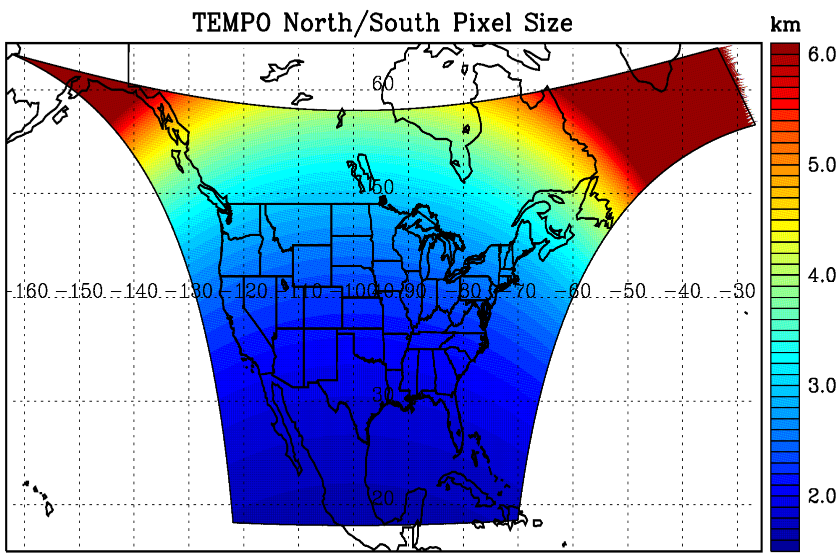
Smithsonian

TEMPO spectral coverage



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

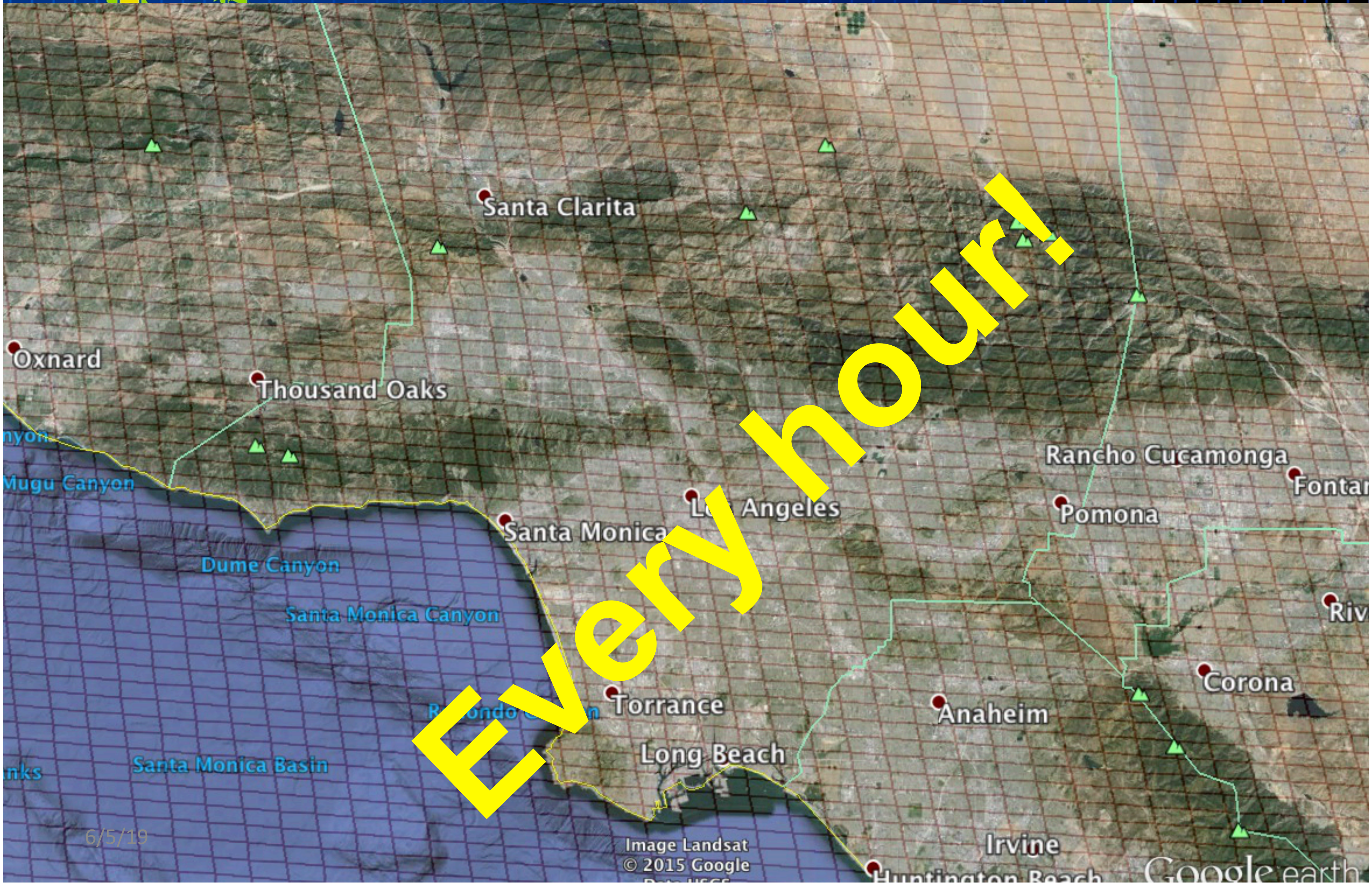
Assumes 2000 N/S pixels

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

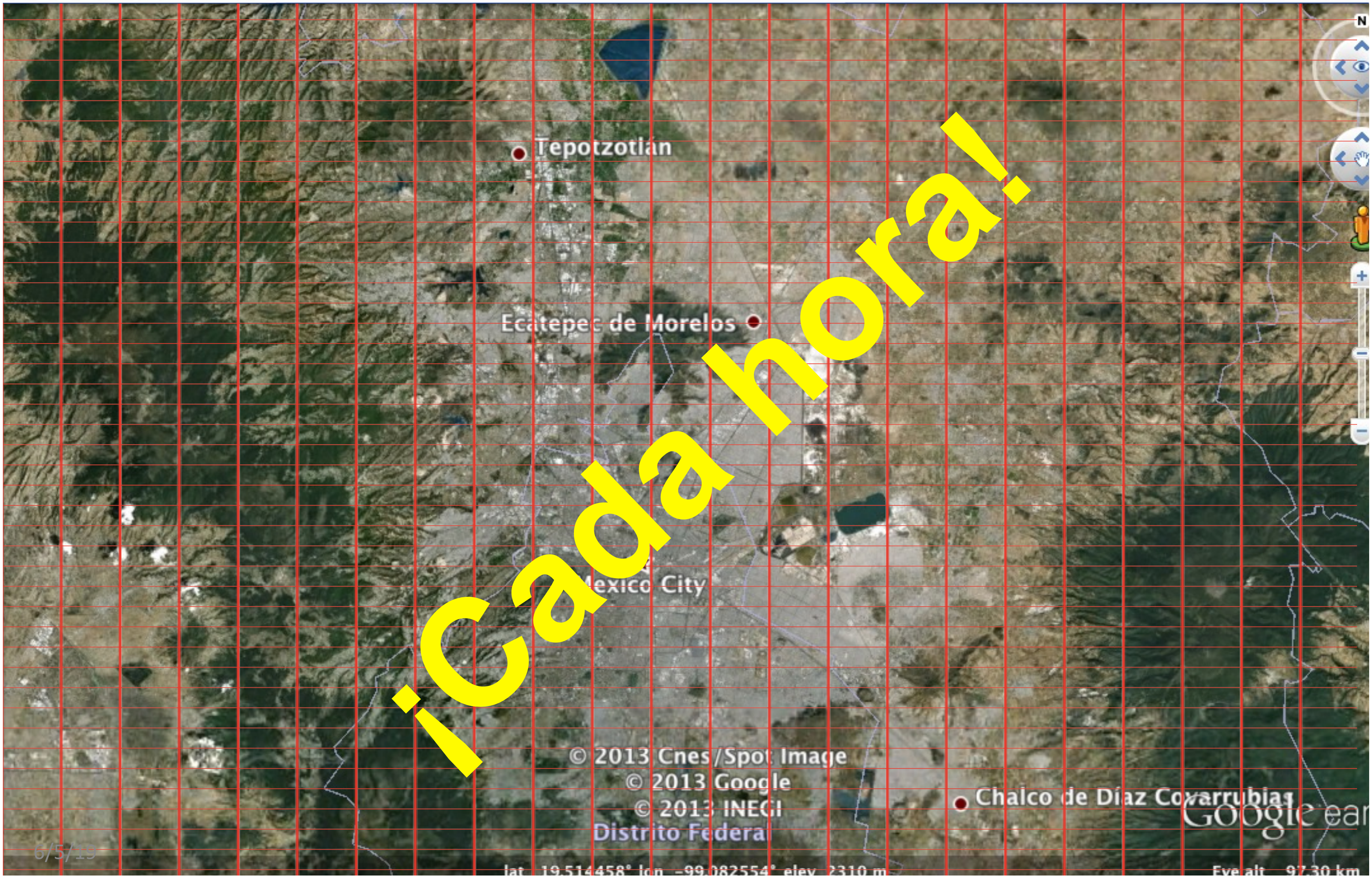
DC and Baltimore coverage

TEMPO hourly footprints overlaid on the Baltimore-Washington metropolitan area. The footprint size here is 2.4 km N/S × 5.4 km E/W. Map created using Google Earth/Landsat Imagery.

Los Angeles coverage



Mexico City coverage



TEMPO instrument

TEMPO instrument characteristics	
Wavelength range	290-490 + 540-740 nm
Spectral resolution	0.6 nm FWHM
Spectral sampling	0.2 nm
Maximum S/N	2700 @ 330-340 nm, EOL
Spatial resolution	2.1×4.5 km^2 @ 36.5N, 100W
Spectra per hour	2000 N/S × 1250 E/W

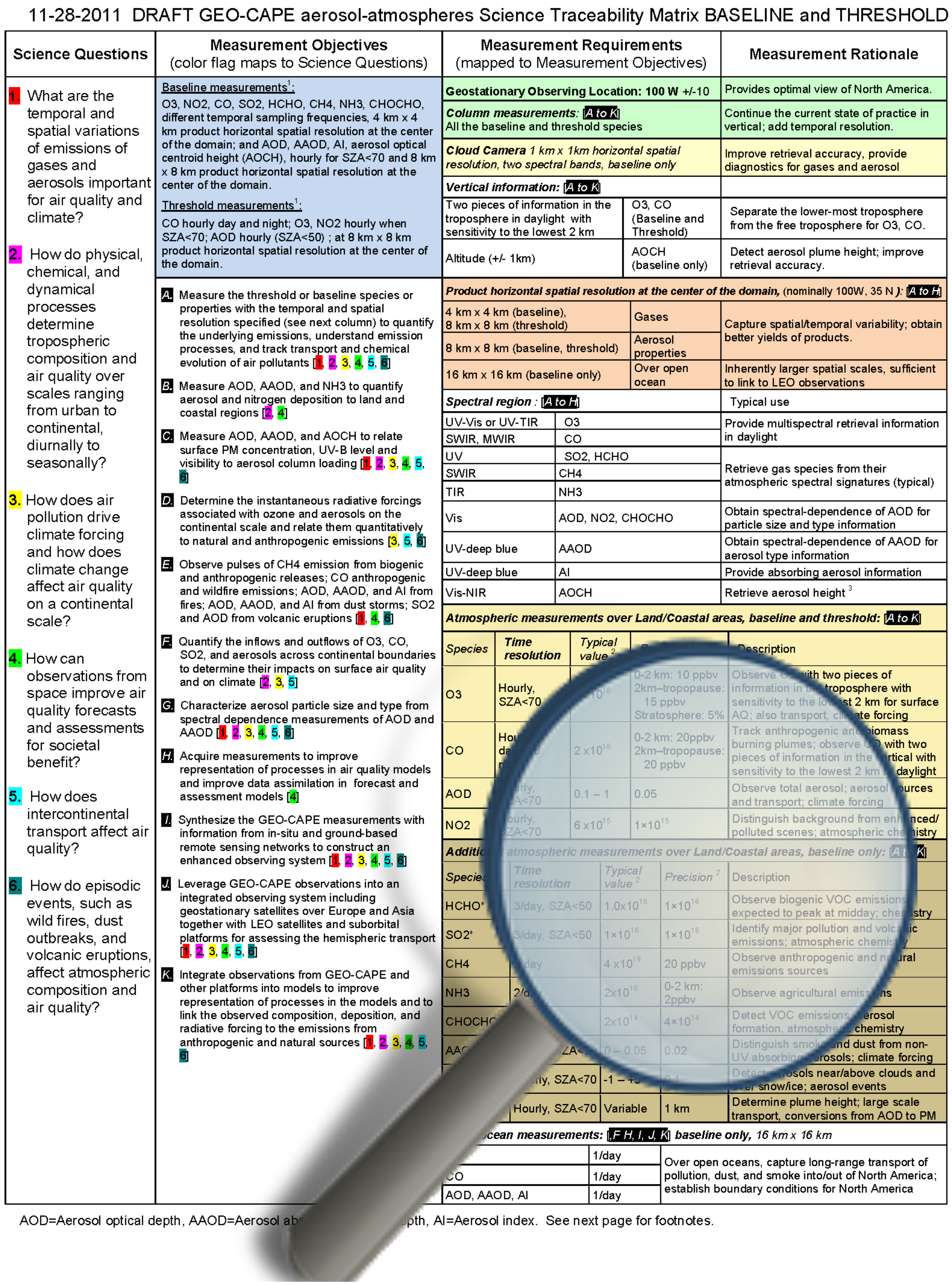
TEMPO

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**
- **Up to 25% special observations, with 10 minute or better resolution**
- **Additional products include H_2O, HONO, BrO, IO, UV index**
- **Geolocation uncertainty of less than 4 km**
- **Mission duration, subject to instrument availability**
  - **Baseline 20 months**
  - **Threshold 12 months**
  - **Extendable in 2-year increments**

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 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	[illegible]/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	[illegible]	2x10[14]	4×10[14]	Detect VOC emissions, aerosol formation, atmospheric chemistry
AAOD	[illegible] SZA<70	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
[illegible]	Hourly, SZA<70	-1 – +5	0.1	Detect aerosols near/above clouds and over snow/ice; aerosol events
[illegible]	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

[illegible] ocean measurements: [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
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.

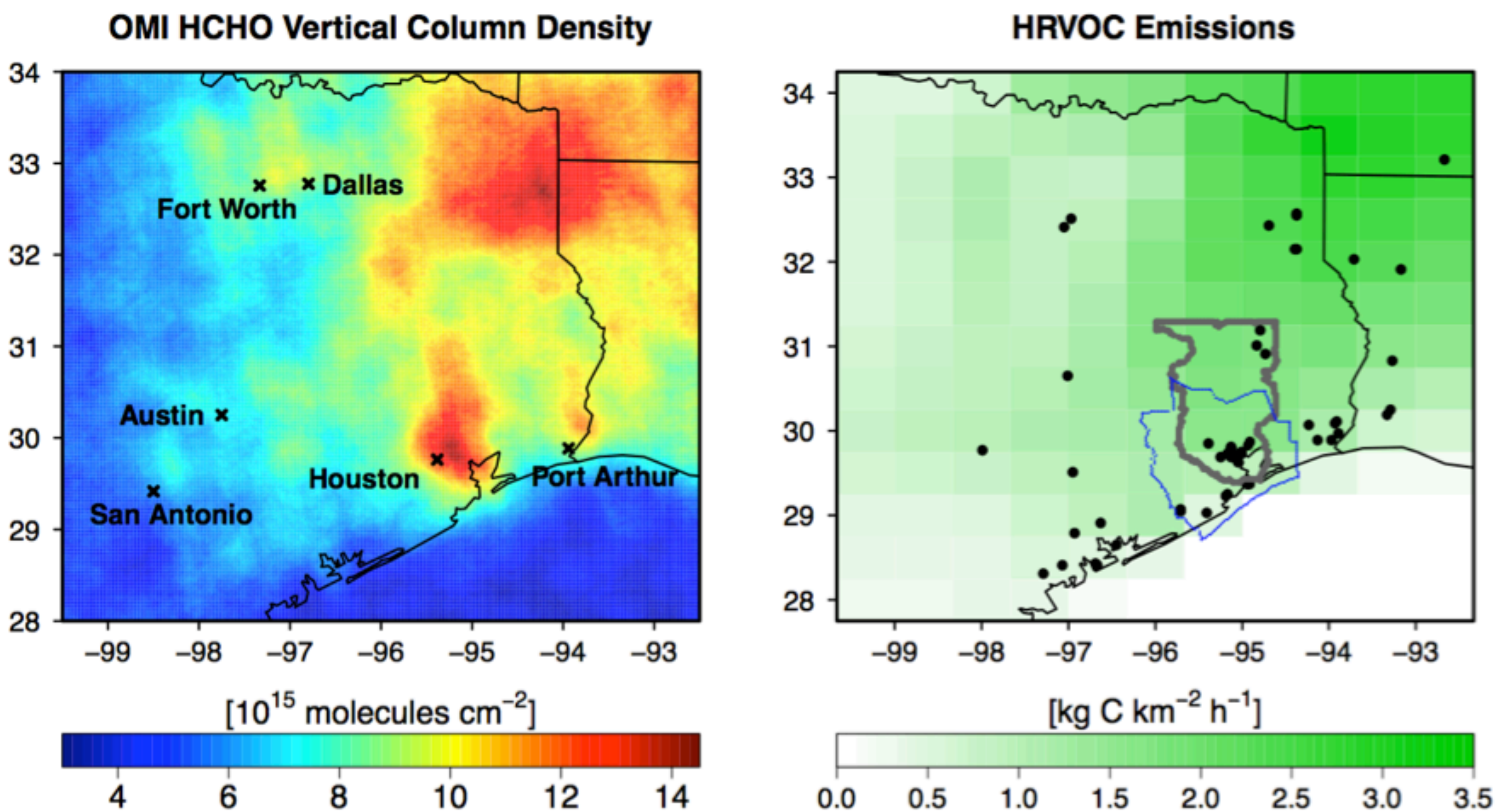
Infrared species

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	9×10^{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	2×10^{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	6×10^{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	1.0×10^{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	4×10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2×10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO*	2/day	2×10^{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

Oversampling
Lei Zhu *et al.*, 2014



TEMPO

The end!

Smithsonian

NASA

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

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

Ball

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

Washington University in St. Louis

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA 1868
LET THERE BE LIGHT

UAH
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

THE UNIVERSITY OF IOWA

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY 1885

AD MAJOREM DEI GLORIAM
SAINT LOUIS UNIVERSITY

UNIVERSITY OF MARYLAND BALTIMORE COUNTY
UMBC
1966

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

YORK
UNIVERSITÉ
UNIVERSITY

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS
Science at work

RTS

UNIVERSITY OF SASKATCHEWAN

NCAR

KNMI

Environment and Climate Change Canada
Environnement et Changement climatique Canada

TEMPO 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?

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).

Aerosols and clouds

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 will derive its pointing from one of the **GOES-17** or **GOES-17** satellites and is thus automatically co-registered. TEMPO may be used together with the advanced baseline imager (ABI) instrument, particularly the 1.37μm bands, for aerosol retrievals, reducing AOD and fine mode AOD uncertainties from 30% to 10% and from 40% to 20%.

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.

TEMPO instrument concept

- **Measurement technique**
  - Imaging grating spectrometer measuring solar backscattered Earth radiance
  - Spectral band & resolution: 290-490 + 540-740 nm @ 0.6 nm FWHM, 0.2 nm sampling
  - 2 2-D, 2k×1k, detectors image the full spectral range for each geospatial scene
- **Field of Regard (FOR) and duty cycle**
  - Mexico City/Yucatan, Cuba to the Canadian oil sands, Atlantic to Pacific
  - Instrument slit aligned N/S and swept across the FOR in the E/W direction, producing a radiance map of Greater North America in one hour
  - **10 minutes!**
- **Spatial resolution**
  - 2.1 km N/S × 4.7 km E/W native pixel resolution (9.8 km^2)
  - Co-add/cloud clear as needed for specific data products
- **Standard data products and sampling rates**
  - Most sampled hourly, including eXceL O_3 (troposphere, PBL)
  - NO_2, H_2CO, $C_2H_2O_2$, SO_2 sampled hourly (average results for ≥ 3/day if needed)
  - Nominal spatial resolution 8.4 km N/S × 4.7 km E/W at center of domain (can often measure 2.1 km N/S × 4.7 km E/W)
  - Measurement requirements met up to 50^o for SO_2, 70^o SZA for other products

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}).

Data products, science studies (the Green Paper), special operations

Volcanic **SO_2** (column amount and plume altitude is a potential research product.
Diurnal out-going **shortwave radiation and cloud forcing** is a potential research product.

Nighttime **"city lights"** products, which represent anthropogenic activities at the same spatial resolution as air quality products, may be produced twice per day (late evening and early morning) as a research product. Meeting TEMPO measurement requirements for NO_2 (visible) implies the sensitivity for city lights products over the CONUS within a 2-hour period at 2×4.5 km^2 to 1.1×10^{-8} W cm^{-2} sr^{-1} μm^{-1}.

Several additional **first-measurement molecules** are being studied.

H_2O will be produced at launch from the 7v vibrational polyad at 445 nm. Water vapor retrieved from the visible spectrum has good sensitivity to the planetary boundary layer, since the absorption is optically thin, and is available over both the land and ocean. The hourly coverage of TEMPO will greatly improve the knowledge of water vapor's diurnal cycle and make rapid variations in time readily observed.

Halogens

BrO will be produced at launch, assuming stratospheric AMFs. Scientific studies will correct retrievals for tropospheric content. **IO** was first measured from space by SAO using SCIAMACHY spectra [Saiz-Lopez *et al*., 2007]. It will be produced as a scientific product, particularly for coastal studies, assuming AMFs appropriate to lower tropospheric loading.

The atmospheric chemistry of halogen oxides over the ocean, and in particular in coastal regions, can play important roles in ozone destruction, oxidizing capacity, and dimethylsulfide oxidation to form cloud-condensation nuclei [Saiz-Lopez and von Glasow, 2012]. The budgets and distribution of reactive halogens along the coastal areas of North America are poorly known. Therefore, providing a measure of the budgets and diurnal evolution of coastal halogen oxides is necessary to understand their role in atmospheric photochemistry of coastal regions. Previous ground-based observations have shown enhanced levels (at a few pptv) of halogen oxides over coastal locations with respect to their background concentrations over the remote marine boundary layer [Simpson et al., 2015]. Previous global satellite instruments lacked the sensitivity and spatial resolution to detect the presence of active halogen chemistry over mid-latitude coastal areas. TEMPO observations together with atmospheric models will allow examination of the processes linking ocean halogen emissions and their potential impact on the oxidizing capacity of coastal environments of North America.

TEMPO also performs **hourly measurements of one of the world's largest salt lakes: the Great Salt Lake in Utah**. Measurements over Salt Lake City show the highest concentrations of BrO over the globe. Hourly measurement at a high spatial resolution can improve understanding of BrO production in salt lakes.