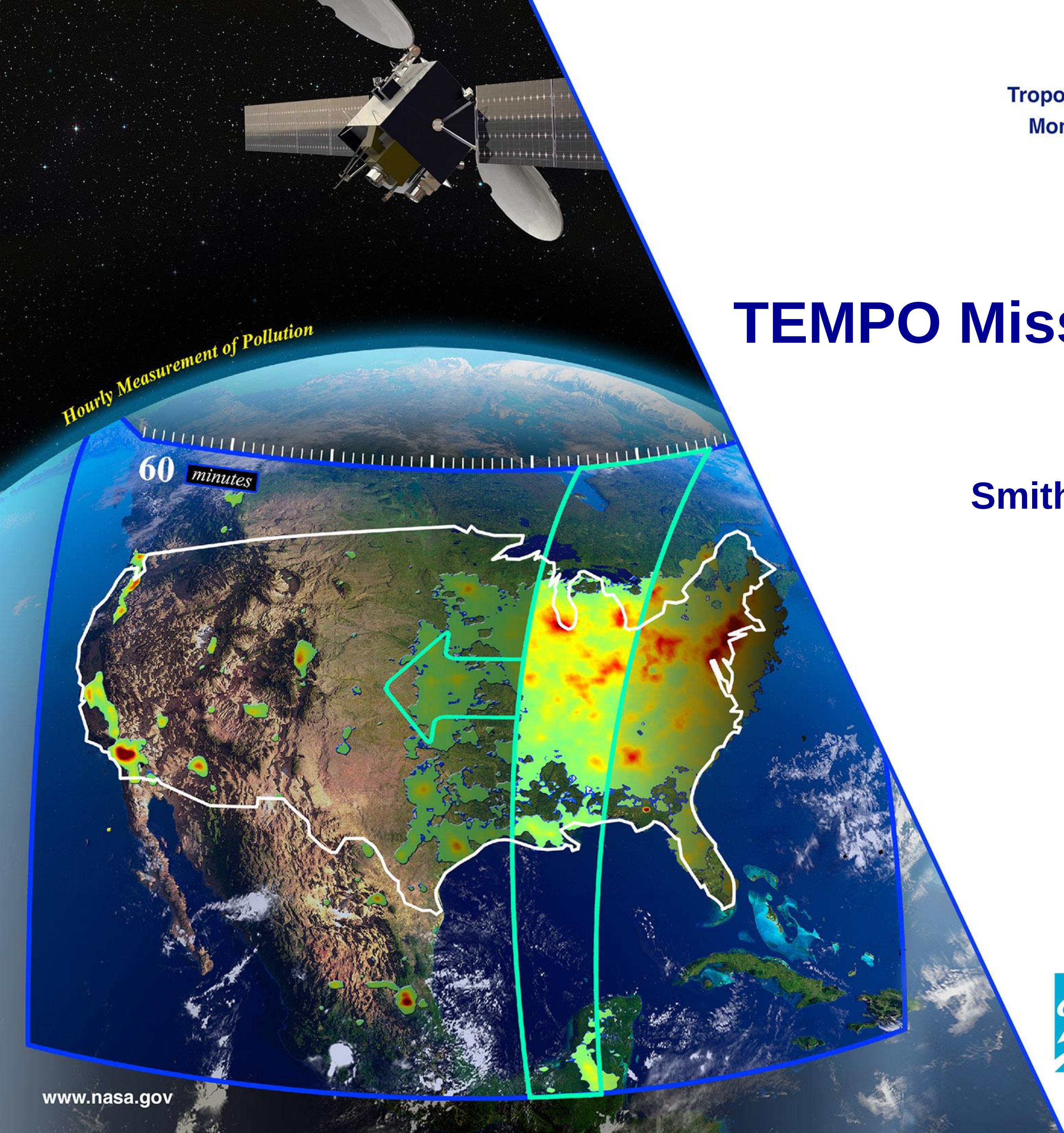
Tropospheric Emissions:
Monitoring of Pollution

TEMPO



TEMPO Mission Overview and Status

Kelly Chance
Smithsonian Astrophysical Observatory

tempo.si.edu

CEOS-ACC-12

October 13, 2016

Ball

Smithsonian

NASA

TEMPO summary

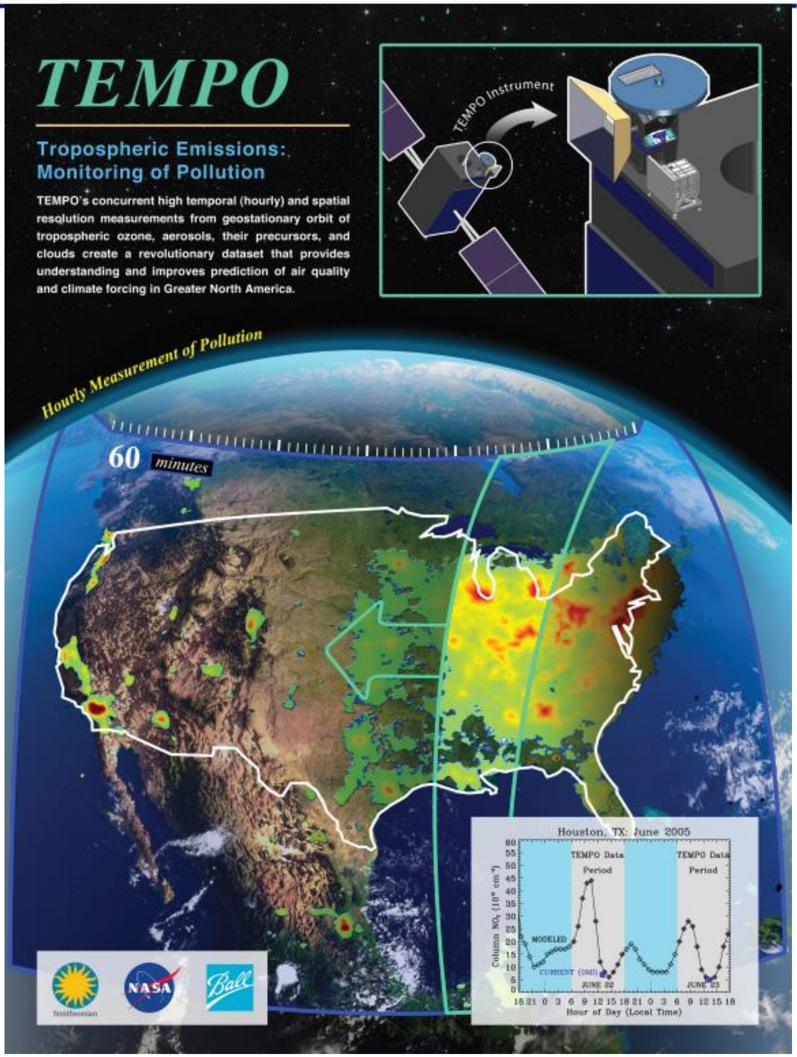
- **Currently on-schedule and on-budget**
  - System Requirements Review and Mission Definition Review in November 2013
  - KDP-B April 2014
  - Most technical issues solved at the preliminary design level, following technical interchange meeting at Ball, April 2014
  - PDR on July 31, 2014
  - Now in Phase C (implementation): KDP-C April 10, 2015
  - Instrument CDR June 2015
  - Ground Systems CDR May 2016
  - Test Readiness Review August 2016
- **Select satellite host 2017+**
  - TEMPO operating longitude and launch date are not known until after host selection
- **Instrument delivery 08/2017 for launch 11/2018 or later, most likely in 2020 or 2021**

Hourly atmospheric pollution from geostationary Earth orbit

TEMPO

Smithsonian NASA

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 Iowa, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, UK, ESA, Spain, Netherlands



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

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

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

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
- **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

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

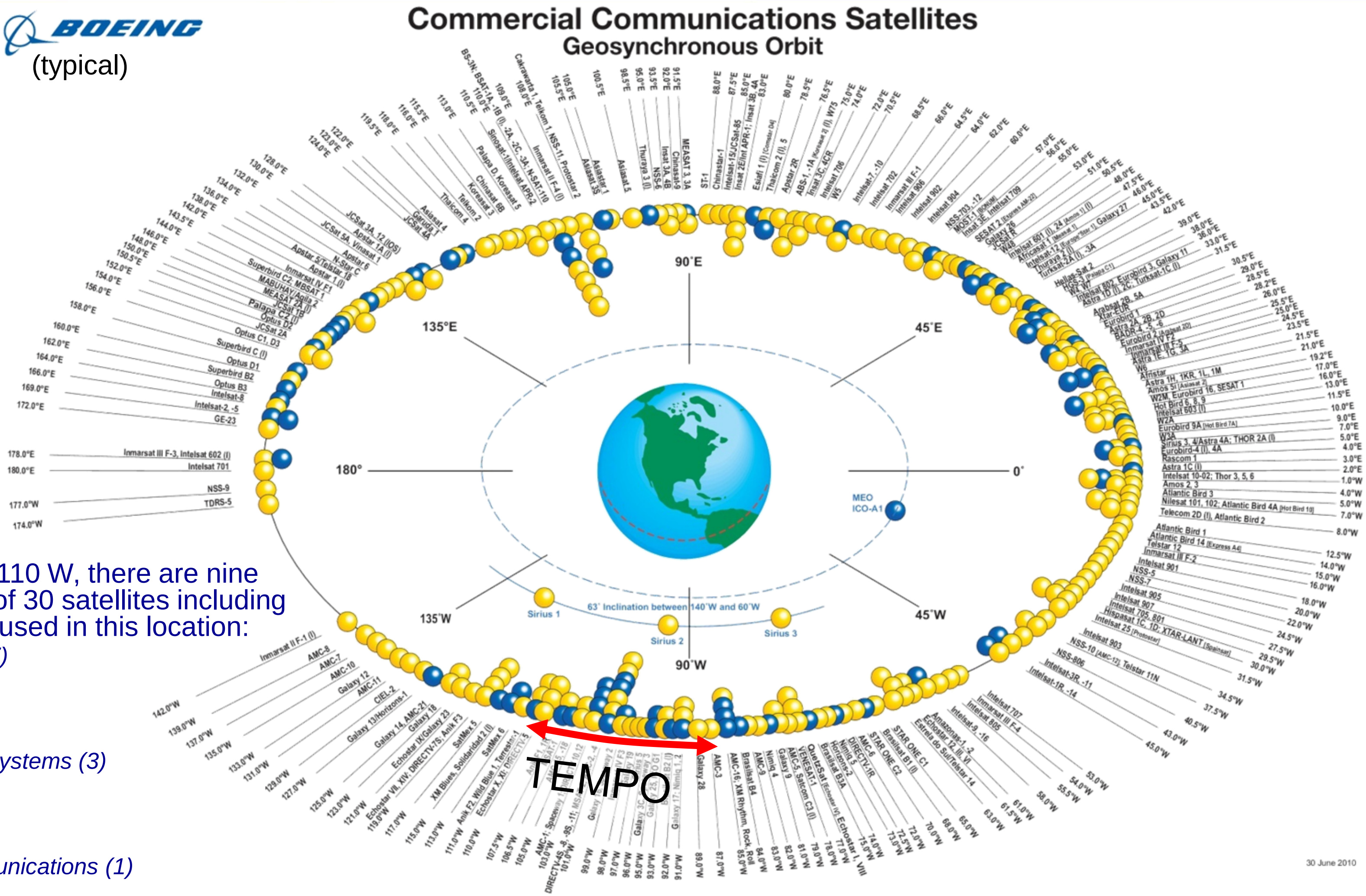
- **Minimal set of products sufficient for constraining air quality**
- **Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N**
- **Data products at urban-regional spatial scales**
  - **Baseline ≤ 60 km^2 at center of Field Of Regard (FOR)**
  - **Threshold ≤ 300 km^2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

TEMPO mission concept

- **Geostationary orbit, operating on a commercial telecom satellite**
  - NASA will arrange launch and hosting services (per Earth Venture Instrument scope)
    - 80-115^o W acceptable latitude
    - Specifying satellite environment, accommodation
  - Hourly measurement and telemetry duty cycle for at least ≤70^o SZA
- **TEMPO is low risk with significant space heritage**
  - We proposed SCIAMACHY in 1985, as suggested by the late Dr. Dieter Perner
  - All proposed TEMPO measurements have been made from low Earth orbit satellite instruments to the required precisions by SAO and Science Team members
  - All TEMPO launch algorithms are implementations of currently operational algorithms
    - NASA TOMS-type O_3
    - SO_2, NO_2, H_2CO, $C_2H_2O_2$ from fitting with AMF-weighted cross sections
    - Absorbing Aerosol Index, UV aerosol, Rotational Raman scattering cloud
    - SAO eXceL profile/tropospheric/PBL O_3 for selected geographic targets
- **Example higher-level products: Near-real-time pollution/AQ indices, UV index**
- **TEMPO research products will greatly extend science and applications**
  - **Example research products:** BrO and IO from AMF-normalized cross sections; height-resolved SO_2; additional cloud/aerosol products; vegetation products; additional gases

Geostationary orbit opportunities of interest

(typical)

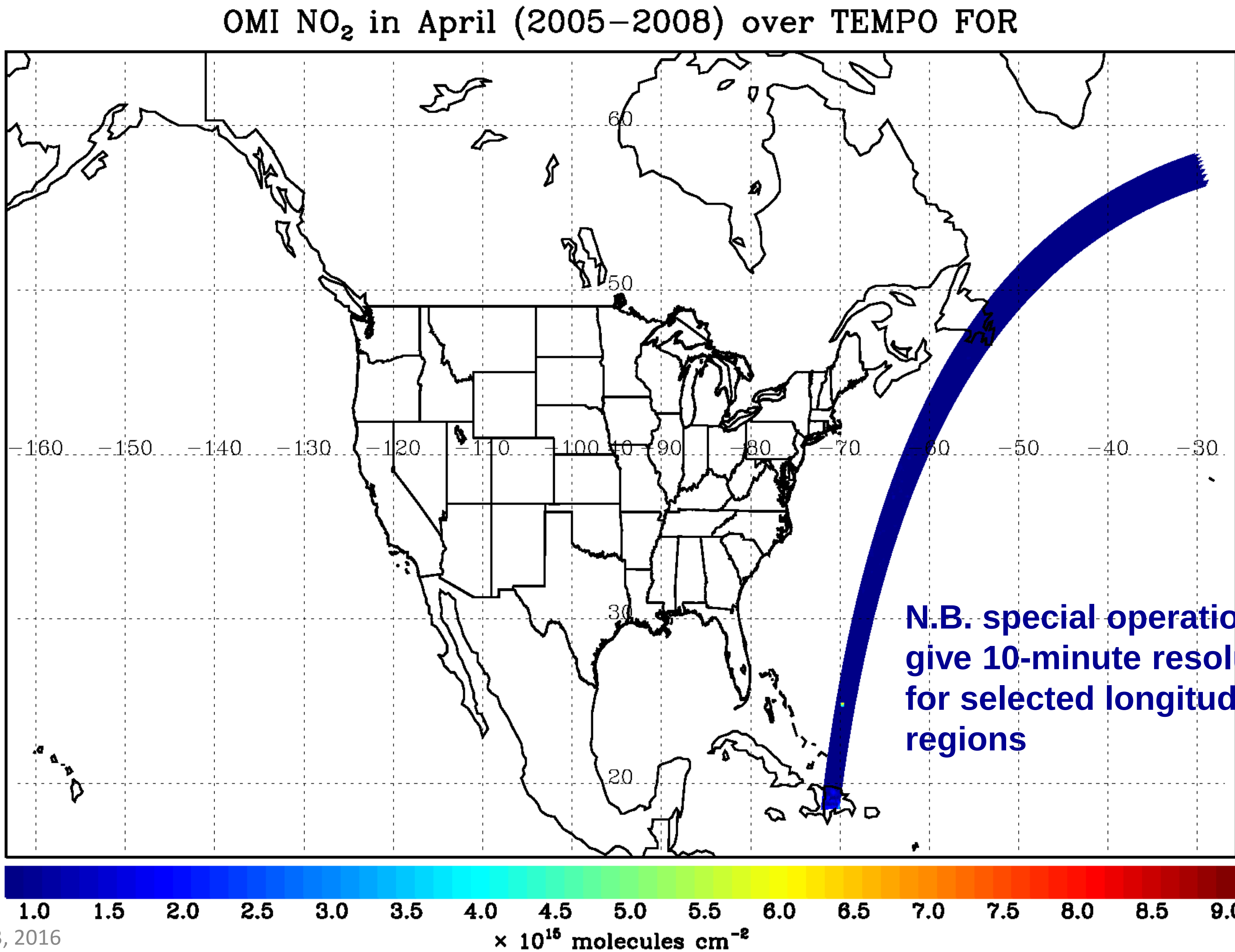


Between 90 W and 110 W, there are nine owner operators of 30 satellites including older models still used in this location:

- *Direct TV Group (7)*
- *AGS (5)*
- *Intelsat (5)*
- *Telesat (4)*
- *Hughes Network Systems (3)*
- *Echostar (2)*
- *SkyTerra (2)*
- *Inmarsat (1)*
- *ICO Global Communications (1)*

TEMPO can be located between 80 – 120 West

TEMPO hourly NO_2 sweep



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

A day in the life

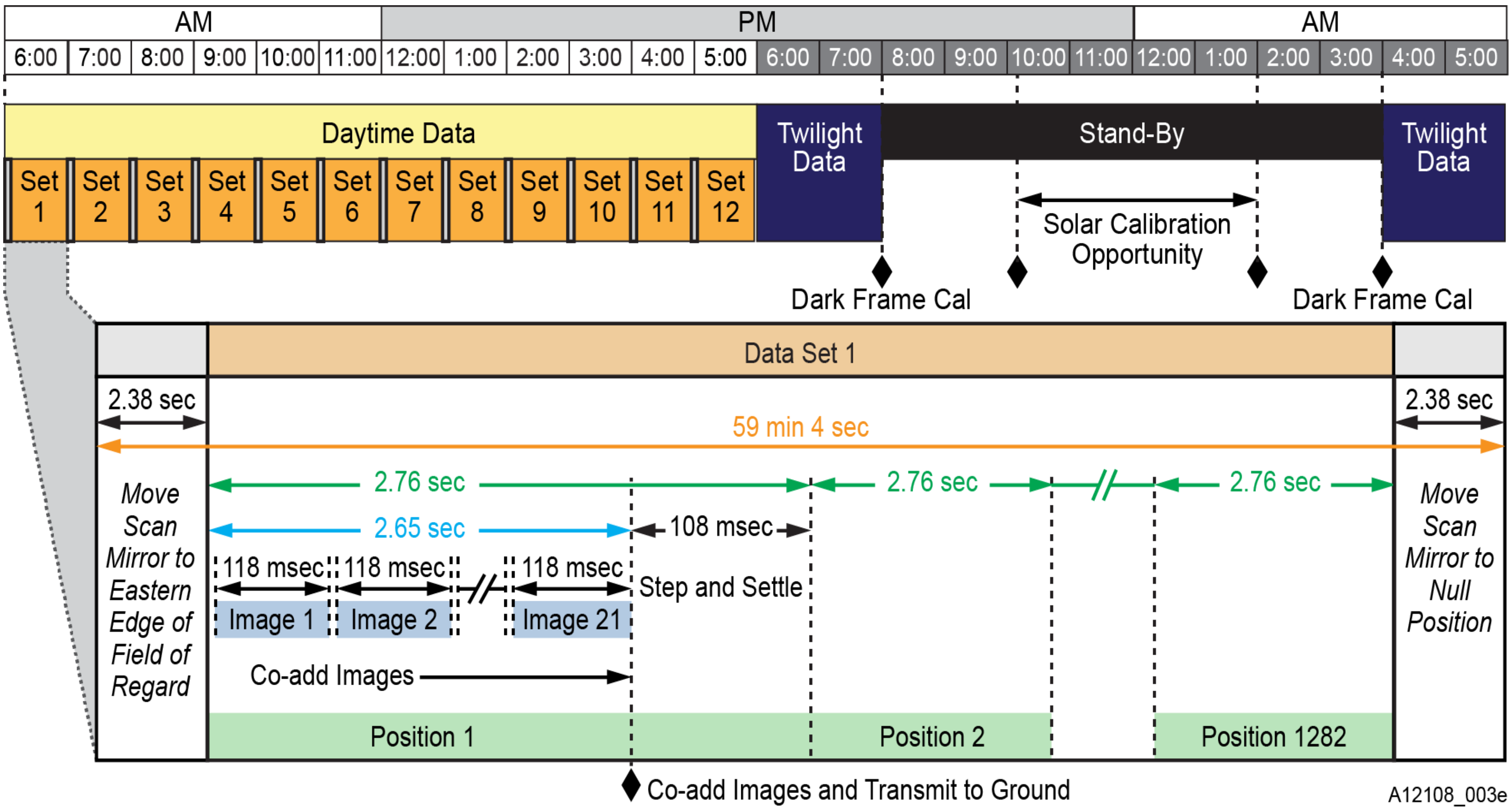
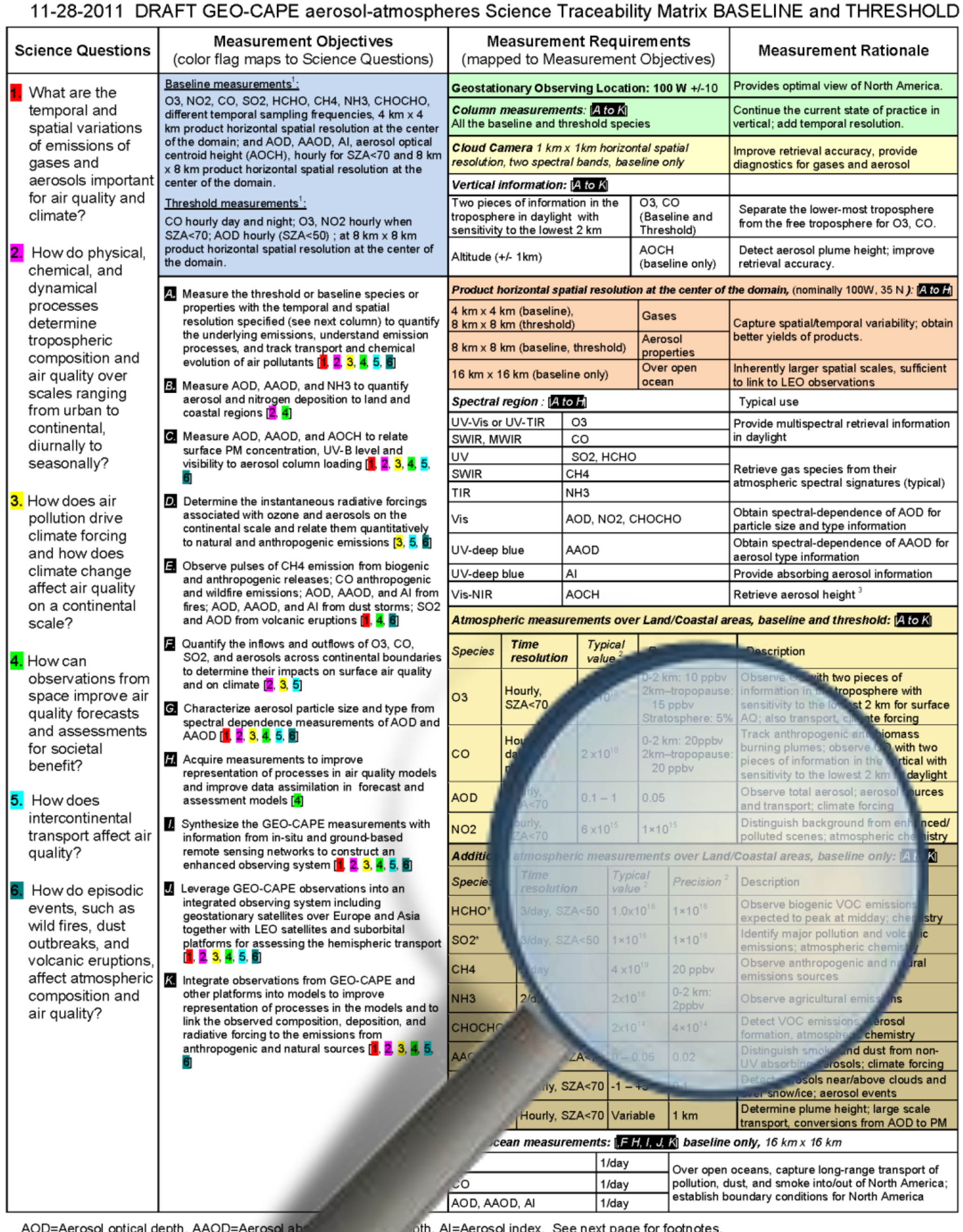


Figure 7. Nominal daily operations for TEMPO instrument.

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**

Measurement Requirements		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]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, da[illegible]	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/d[illegible]	2x10[16]	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO	[illegible]	2x10[14]	4×10[14]	Detect VOC emissions, aerosol formation, atmospheric chemistry
AA[illegible]	[illegible] SZA<[illegible]	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
[illegible]	[illegible]ly, 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]cean 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.

TEMPO

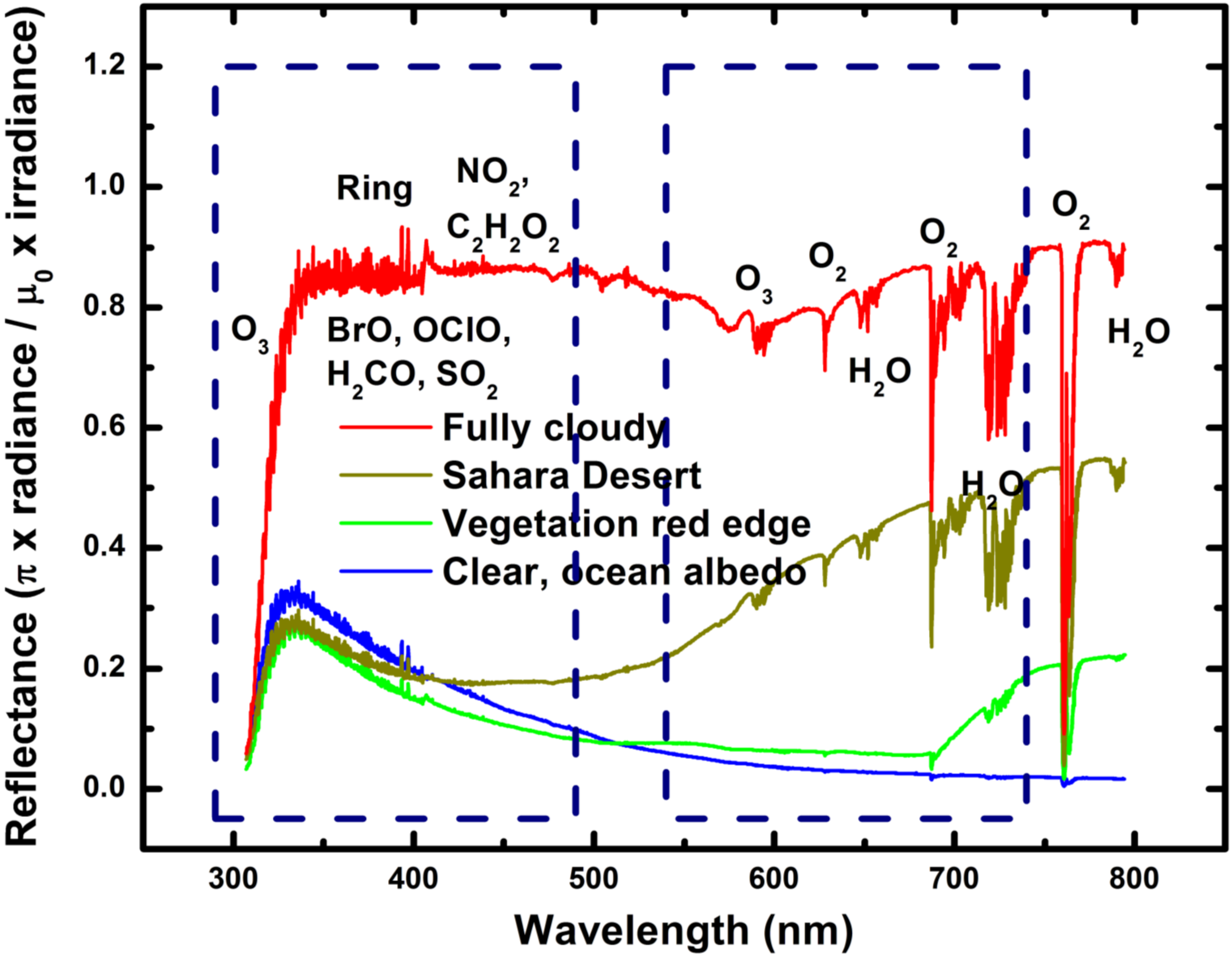
Infrared species

Ultraviolet/ visible species (GOME, TEMPO, etc.)

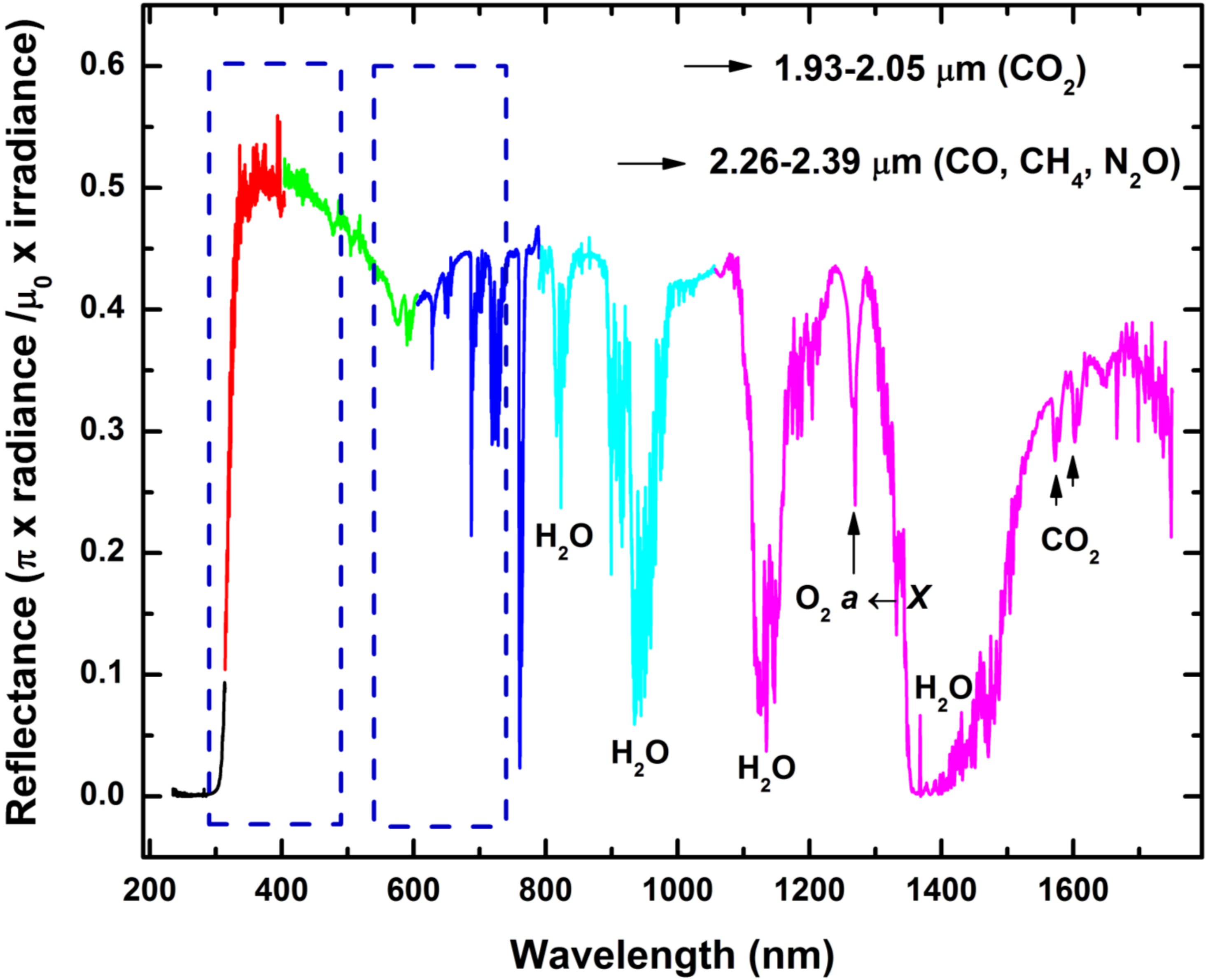
Atmospheric measurements over Land/Coastal areas, baseline and threshold: [A to K]				
Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
O3	Hourly, SZA<70	9 x10^{18}	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe O3 with two pieces of information in the troposphere 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

Typical TEMPO-range spectra (from ESA GOME-1)



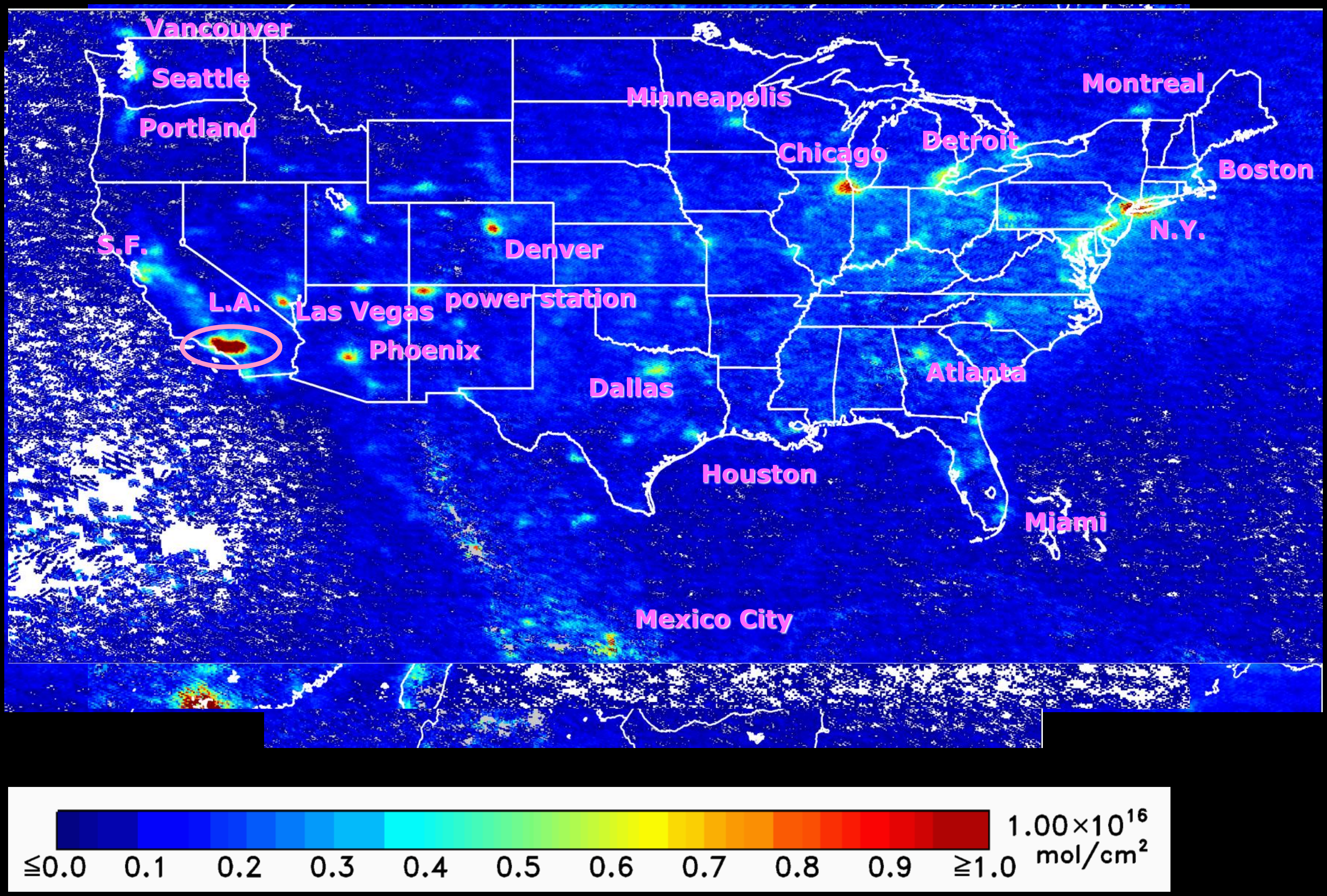
Typical TEMPO-range spectra (from SCIAMACHY, 2002-2012)



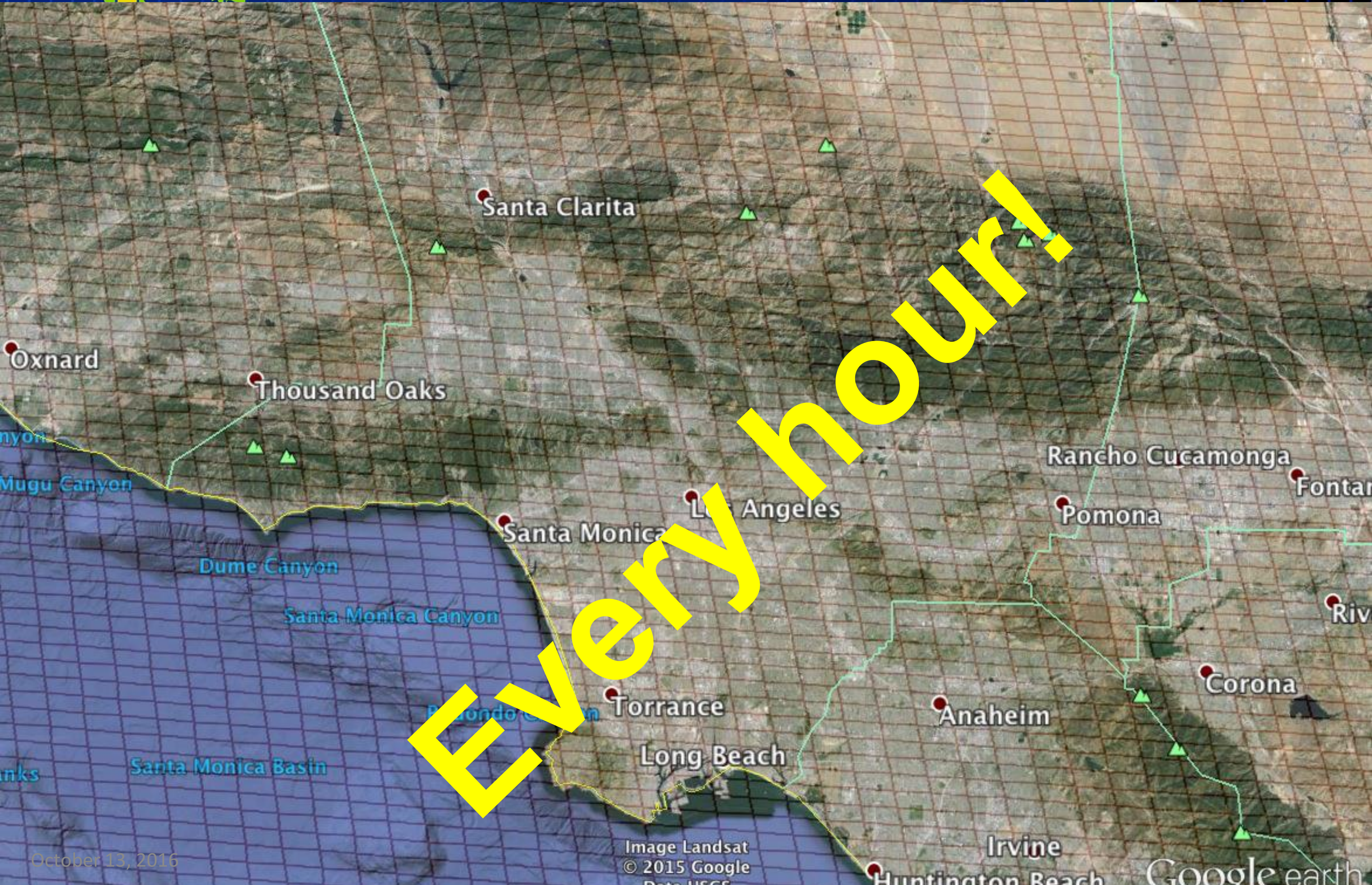
LEO measurement capability

A full, minimally-redundant, set of polluting gases, plus aerosols and clouds is now measured to very high precision from satellites. Ultraviolet and visible spectroscopy of backscattered radiation provides O_3 (including profiles and tropospheric O_3), NO_2 (for NO_x), H_2CO and $C_2H_2O_2$ (for VOCs), SO_2, H_2O, O_2-O_2, N_2 and O_2 Raman scattering, and halogen oxides (BrO, ClO, IO, OClO). Satellite spectrometers we planned since 1985 began making these measurements in 1995.

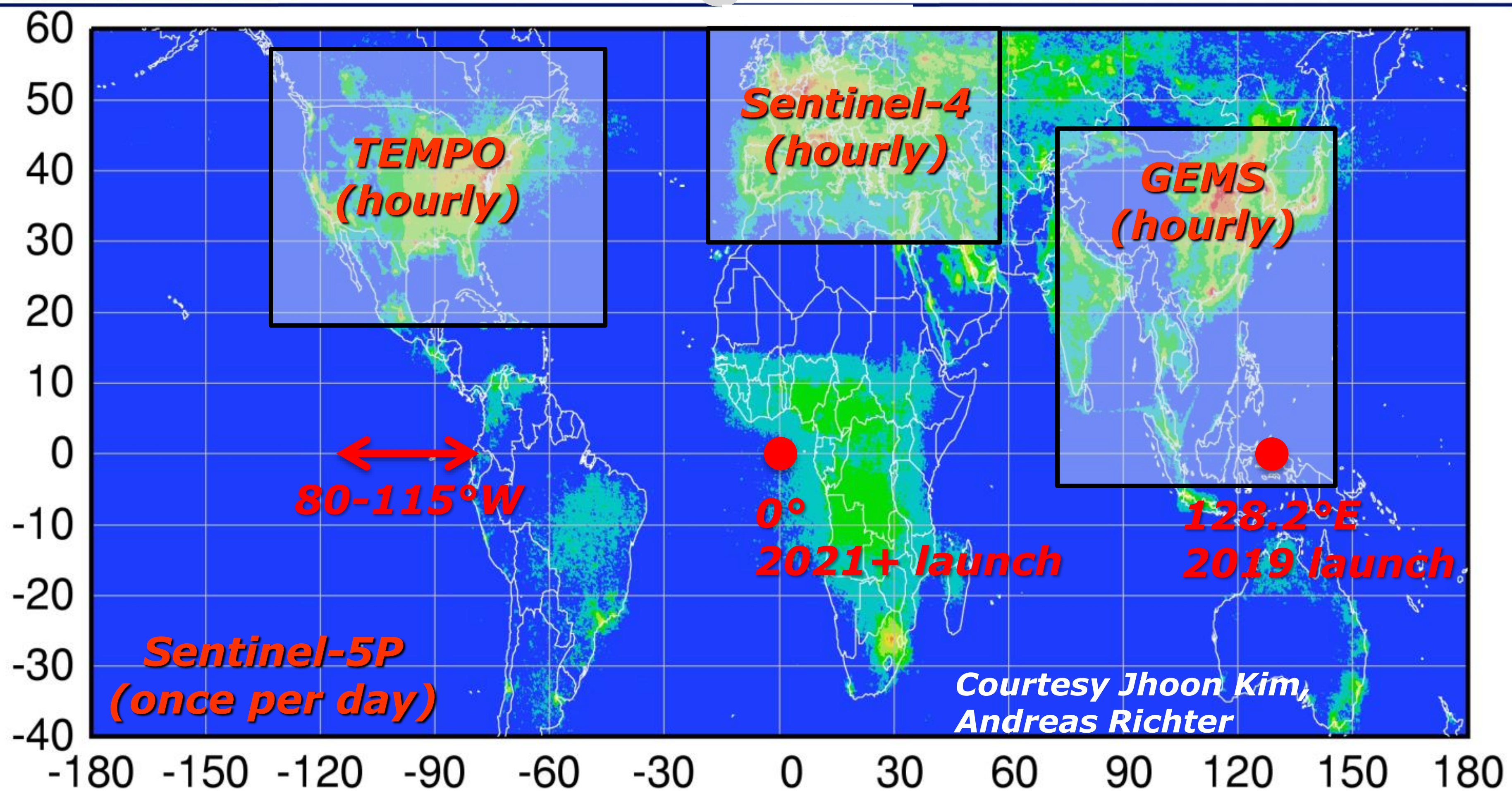
NO_2


Vancouver
Seattle
Portland
Minneapolis
Montreal
Chicago
Detroit
Boston
N.Y.
S.F.
Denver
L.A.
Las Vegas
power station
Phoenix
Dallas
Atlanta
Houston
Miami
Mexico City
≦0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 ≧1.0
1.00×10^16 mol/cm^2

Los Angeles coverage



Global pollution monitoring constellation



Policy-relevant science and environmental services enabled by common observations

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support United Nations Convention on Long Range Transboundary Air Pollution

TEMPO launch algorithms

NO_2, SO_2, H_2CO, $C_2H_2O_2$ vertical columns

Direct fitting to TEMPO radiances

AMF-corrected reference spectra, Ring effect, etc.

DOAS option available to trade more speed for less accuracy, if necessary

Research products could include H_2O, BrO, OClO, IO

O_3 profiles, tropospheric O_3

eXceL optimal-estimation method developed @ SAO for GOME, OMI

May be extended to SO_2, especially volcanic SO_2

TOMS-type ozone retrieval included for heritage

Aerosol products from OMI heritage: AOD, AAOD, Aerosol Index

Advanced/improved products likely developed @ GSFC, U. Nebraska

Cloud Products from OMI heritage: CF, CTP

Advanced/improved products likely developed @ GSFC

UVB research product based on OMI heritage (FMI, GSFC)

Nighttime research products include city lights

Default Launch Data Products

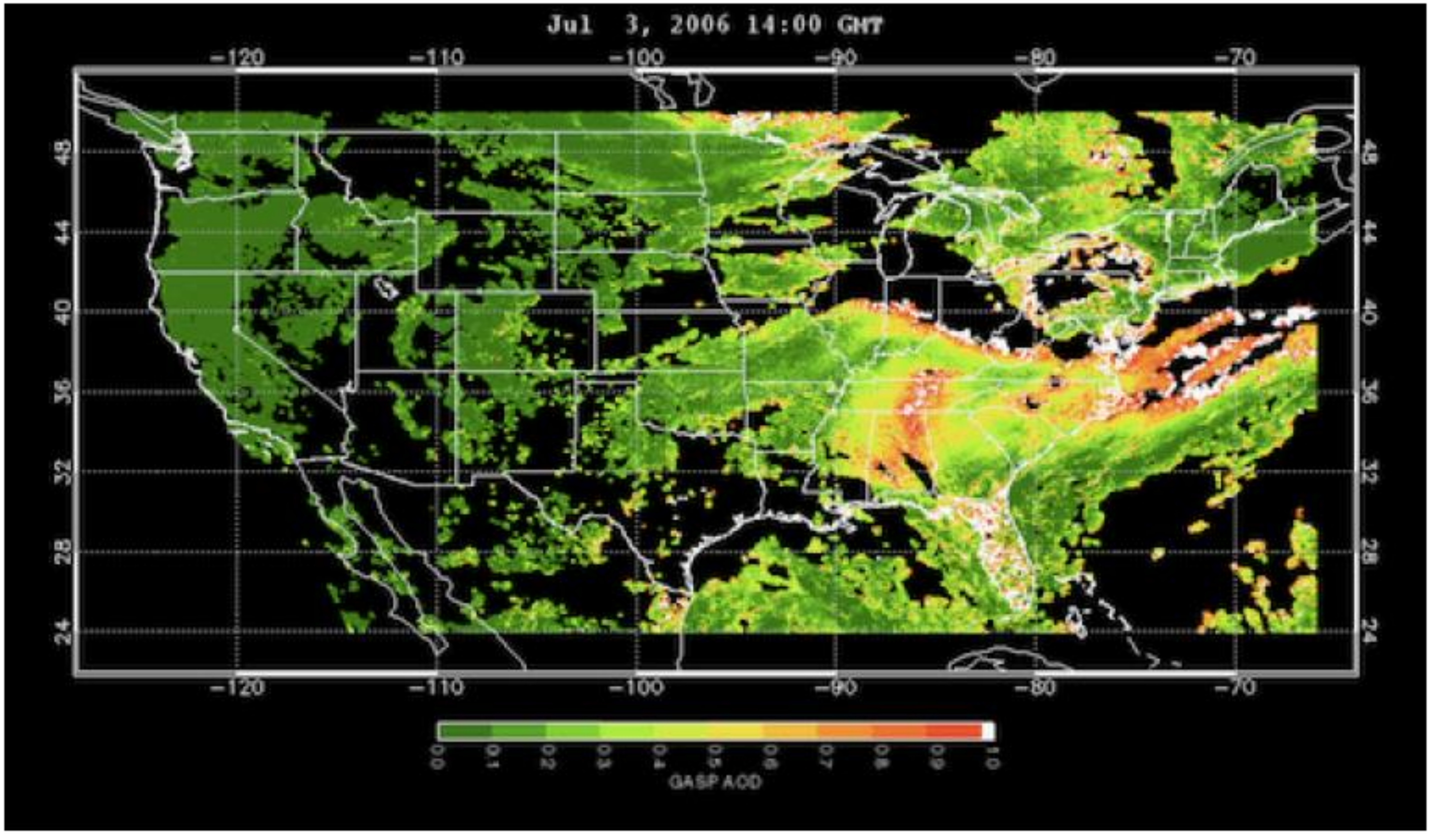
Product	Algorithm	Hourly Coverage @ ≤ 4.5 × 8 km^2
O_3	TOMS-Vn	15 - 50.25°N, 60 - 130°W
O_3	XL optimal estimation	Selected urban areas and burning regions
NO_2	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
SO_2	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
H_2CO	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
$C_2H_2O_2$	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
Aerosol OD and SSA	AERUV	15 - 50.25°N, 60 - 130°W
Cloud pressure and fraction	CLDRR	15 - 50.25°N, 60 - 130°W
UBV and Eryth. dose	UVB	15 - 50.25°N, 60 - 130°W
AQ indices	L3-L4 based	15 - 50.25°N, 60 - 130°W

Secondary and Improved Data Products

Product	Algorithm	Hourly Coverage @ ≤ 4.5×8 km^2
O_3	XL optimal estimation	15 - 50.25°N, 60 - 130°W (or, extended regions)
BrO	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
H_2O	Direct fitting, AMF (λ)	15 - 50.25°N, 60 - 130°W
Aerosols	AERUV+	15 - 50.25°N, 60 - 130°W
Clouds	CLDRR+	15 - 50.25°N, 60 - 130°W
SO_2	Height-resolved	15 - 50.25°N, 60 - 130°W

www.epa.gov/rsig

TEMPO will use the EPA's Remote Sensing Information Gateway (RSIG) for subsetting, visualization, and product distribution – *to make TEMPO YOUR instrument*



J. Szykman for more information

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]

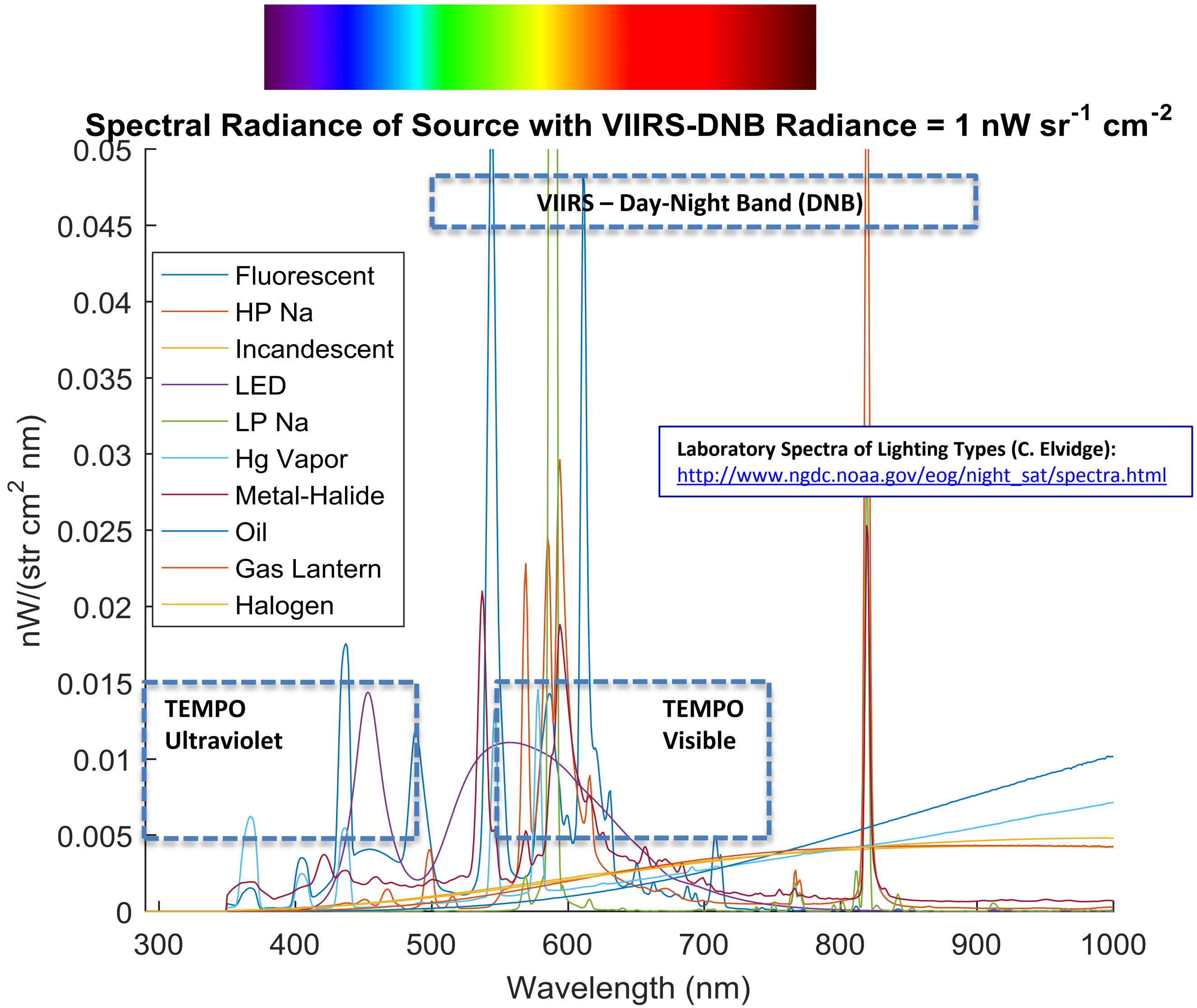
Cooper et al., for example, propose a satellite-based multipollutant index using the WHO Air Quality Guidelines (AQG):

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

- 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.

City lights spectroscopic signatures



TEMPO

The end!

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

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INSMET

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
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

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1868

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY
1885
연세대학교

UNIVERSITY OF MARYLAND BALTIMORE COUNTY
UMBC
1966

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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

THE UNIVERSITY OF IOWA

YORK
UNIVERSITÉ
UNIVERSITY

NCAR

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS
Science at work

RT S

KNMI

Environment and Climate Change Canada
Environnement et Changement climatique Canada

TEMPO

Backups

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CARR ASTRONAUTICS
Science at work

RTS

NCAR

KNMI

Environment and Climate Change Canada
Environnement et Changement climatique Canada

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.

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, 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, probably 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].

Halogens

BrO will be produced at launch, assuming stratospheric AMFs. Scientific studies will correct retrievals for tropospheric content. **IO** was first measured from by SAO space 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 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.

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 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 product is the downward spectral irradiance at the ground (in W m^{-2} nm^{-1}) and the erythemally weighted irradiance (in W m^{-2}).

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).

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 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-R and GOES-S satellites for aerosol retrievals, reducing AOD and fine mode AOD uncertainties from 30% to 10% and from 40% to 20%.

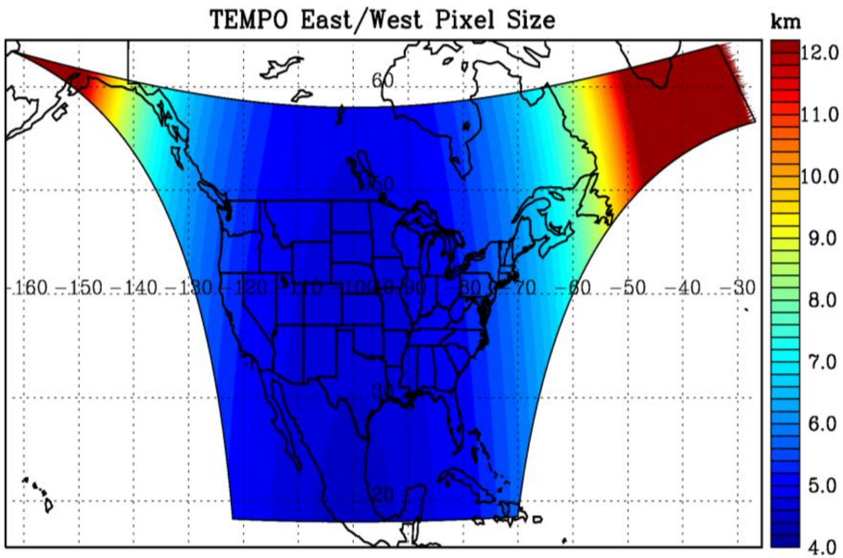
TEMPO Science Team, U.S.

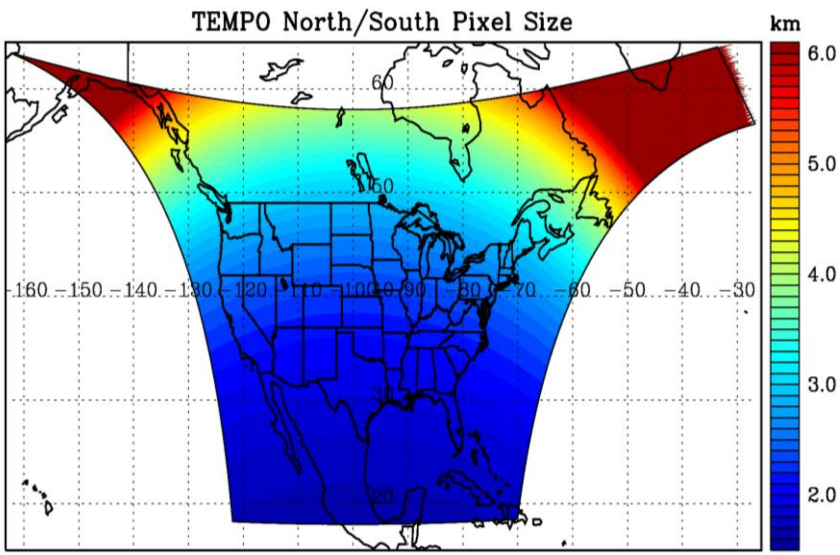
Team Member	Institution	Role	Responsibility
K. Chance	SAO	PI	Overall science development; **Level 1b, H_2CO, $C_2H_2O_2$**
X. Liu	SAO	Deputy PI	Science development, data processing; **O_3 profile, tropospheric O_3**
J. Al-Saadi	LaRC	Deputy PS	Project science development
J. Carr	Carr Astronautics	Co-I	**INR Modeling and algorithm**
M. Chin	GSFC	Co-I	Aerosol science
R. Cohen	U.C. Berkeley	Co-I	NO_2 validation, atmospheric chemistry modeling, process studies
D. Edwards	NCAR	Co-I	VOC science, synergy with carbon monoxide measurements
J. Fishman	St. Louis U.	Co-I	AQ impact on agriculture and the biosphere
D. Flittner	LaRC	Project Scientist	Overall project development; STM; instrument cal./char.
J. Herman	UMBC	Co-I	Validation (PANDORA measurements)
D. Jacob	Harvard	Co-I	Science requirements, atmospheric modeling, process studies
S. Janz	GSFC	Co-I	Instrument calibration and characterization
J. Joiner	GSFC	Co-I	**Cloud, total O_3, TOA shortwave flux research product**
N. Krotkov	GSFC	Co-I	**NO_2, SO_2, UVB**
M. Newchurch	U. Alabama Huntsville	Co-I	Validation (O_3 sondes, O_3 lidar)
R.B. Pierce	NOAA/NESDIS	Co-I	AQ modeling, data assimilation
R. Spurr	RT Solutions, Inc.	Co-I	**Radiative transfer modeling for algorithm development**
R. Suleiman	SAO	Co-I, Data Mgr.	Managing science data processing, **BrO, H_2O, and L3 products**
J. Szykman	EPA	Co-I	AIRNow AQI development, validation (PANDORA measurements)
O. Torres	GSFC	Co-I	**UV aerosol product, AI**
J. Wang	U. Nebraska	Co-I	Synergy w/GOES-R ABI, **aerosol research products**
J. Leitch	Ball Aerospace	Collaborator	Aircraft validation, instrument calibration and characterization
D. Neil	LaRC	Collaborator	GEO-CAPE mission design team member

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 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 oil 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.

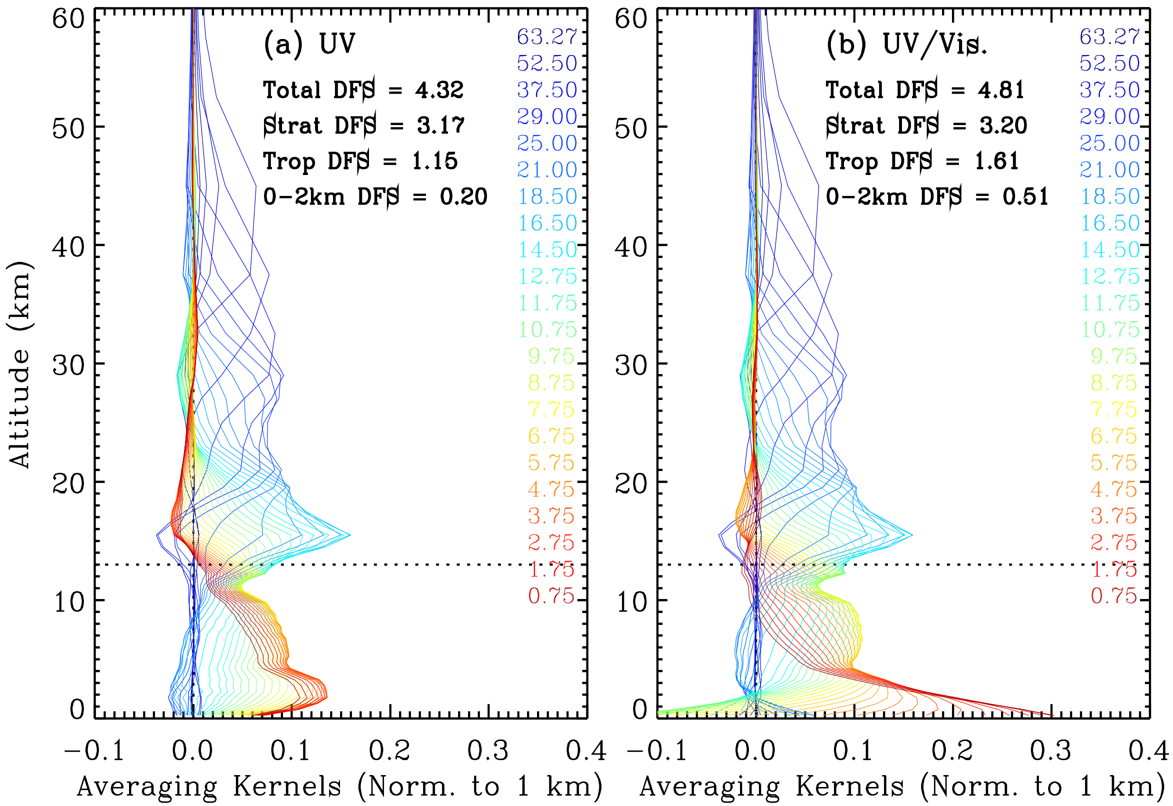
Low Earth orbit: Sun-synchronous nadir heritage

Instrument	Detectors	Spectral Coverage [nm]	Spectral Res. [nm]	Ground Pixel Size [km^2]	Global Coverage
GOME-1 (1995-2011)	Linear Arrays	240-790	0.2-0.4	40 × 320 (40 × 80 zoom)	3 days
SCIAMACHY (2002-2012)	Linear Arrays	240-2380	0.2-1.5	30 × 30/60/90 30 × 120/240	6 days
OMI (2004)	2-D CCD	270-500	0.42-0.63	13 × 24 - 42 × 162	daily
GOME-2a,b (2006, 2012)	Linear Arrays	240-790	0.24-0.53	40 × 80 (40 × 10 zoom)	near-daily
OMPS-1 (2011)	2-D CCDs	250-380	0.42-1.0	50 × 50	daily

Previous experience (since 1985 at SAO and MPI)

Scientific and operational measurements of pollutants O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$ (& CO, CH_4, BrO, OClO, ClO, IO, H_2O, O_2-O_2, Raman, aerosol, ….)

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.

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?

Table D.2-3 TEMPO STM[1] clearly links science questions with instrument and investigaton requirements.

Science Questions	Science Objective
Q1. What are the temporal and spatial variations of emissions of gases and aerosols important for AQ and climate? **Q2**. How do physical, chemical, and dynamical processes determine tropospheric composition and AQ over scales ranging from urban to continental, diurnally to seasonally?	-High temporal resolution measurements to capture changes in pollutant gas distributions. - High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas. - Measurement of major elements in tropospheric O_3 chemistry cycle, including multispectral measurements to improve sensing of lower-tropospheric O_3, with precision to clearly distinguish pollutants from background levels
Q3. How do episodic events affect atmospheric composition and AQ?	- Observe aerosol optical properties with high temporal and spatial resolution for quantifying and tracking evolution of aerosol loading.
Q4. How does AQ drive climate forcing and climate change affect AQ on a continental scale?	- Determine the instantaneous radiative forcings associated with O_3 and aerosols on the continental scale.
Q5. How can observations from space improve AQ forecasts and assessments for societal benefit?	- Integrate observations from TEMPO and other platforms into models to improve representation of processes in the models and construct an enhanced observing system.
Q6. How does intercontinental transport affect AQ?	- Quantify the flow of pollutants across continental boundaries; Join a global observing system.

Science Measurement Requirement: Observables	Science Measurement Requirement: Physical Parameters
Spatially imaged & spectrally resolved, solar backscattered earth radiance, spanning spectral windows suitable for retrievals of O_3, NO_2, H_2CO, SO_2 and $C_2H_2O_2$ at spatial scales comparable to regional atmospheric chemistry models. Multispectral data in suitable O_3 absorption bands to provide vertical distribution information. Spectral radiance measurements with suitable quality (SNR) to provide multiple measurements over daylight hours for solar zenith angle < 70°. Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles <70°.	Relevant absorption bands for trace gases & windows for aerosols Solar irradiance spectrally resolved over spectral range
No additional observable requirements	No additional physical requirements
No additional observable requirements	No additional physical requirements

Instrument Function Requirements: Parameter	Req.	Predicted
Spectral Range	290-690 nm	290-690 nm
Spectral Resolution	0.6 nm	0.6 nm
Spectral Sampling	0.2 nm	0.2 nm
Baseline Trace gas column densities (10^{15} cm^{-2}), unless noted, hourly @ 8×4.5 km^2		

Species	Precision	Band	Signal to Noise (hourly) Req.	Signal to Noise (hourly) Predicted
O_3:0-2 km	10 ppbv	O_3:Vis (546-648 nm) O_3: UV (303-345 nm)	958 1122	1254 1635
O_3#: FT	10 ppbv			
O_3#: SOC	5%			
O_3#: Total	3%			
NO_2#	1.00	423-451 nm	1233	1910
H_2CO# (3/day)	10.0	327-354 nm	487	2094
SO_2# (3/day)	10.0	305-345 nm	1297	1820
$C_2H_2O_2$# (2/day)	0.40	433-457 nm	1350	2331

Baseline Aerosol/Cloud properties hourly @ 8×4.5 km^2

Property	Precision	Band	Signal to Noise Req.	Signal to Noise Predicted
AOD#	0.05	354, 388 nm	1000	1596
AAOD#	0.03			
AI#	0.2			
CF#	0.05	346-354 nm	600	1608
CTP#	100 mb			

Albedo Calibration	Req.	Predicted
λ-dependent	< 1%	0.5%
λ-independent	< 3%	2.0%
Spectral Accuracy	<0.02 nm	<0.02 nm
Polarization Factor	<5%UV, ≤20% Vis	≤4%UV, ≤20% Vis
Geolocation Accuracy	4.0 km	2.8 km
FOR	CONUS	GNA
Imaging Time	1 hr	1 hr
IFOV: N/S×E/W *	2×4.5 km^2	2×4.5 km^2
GSD E/W *	4.0 km	4.0 km
MTF: N/S×E/W	0.3×0.3	0.50×0.46

Investigation Requirements

1-year mission lifetime (minimum)

On-orbit Calibration

FOR encompasses CONUS and adjacent areas

GEO Longitude: Preferred: 100W Acceptable: 75W – 137W

GEO Bus Pointing: Control <0.1° Knowledge <0.04°

Provide near-real-time products to user communities within 2 hrs to enable assimilation into chemical models (NOAA & EPA) and use by smart-phone applications

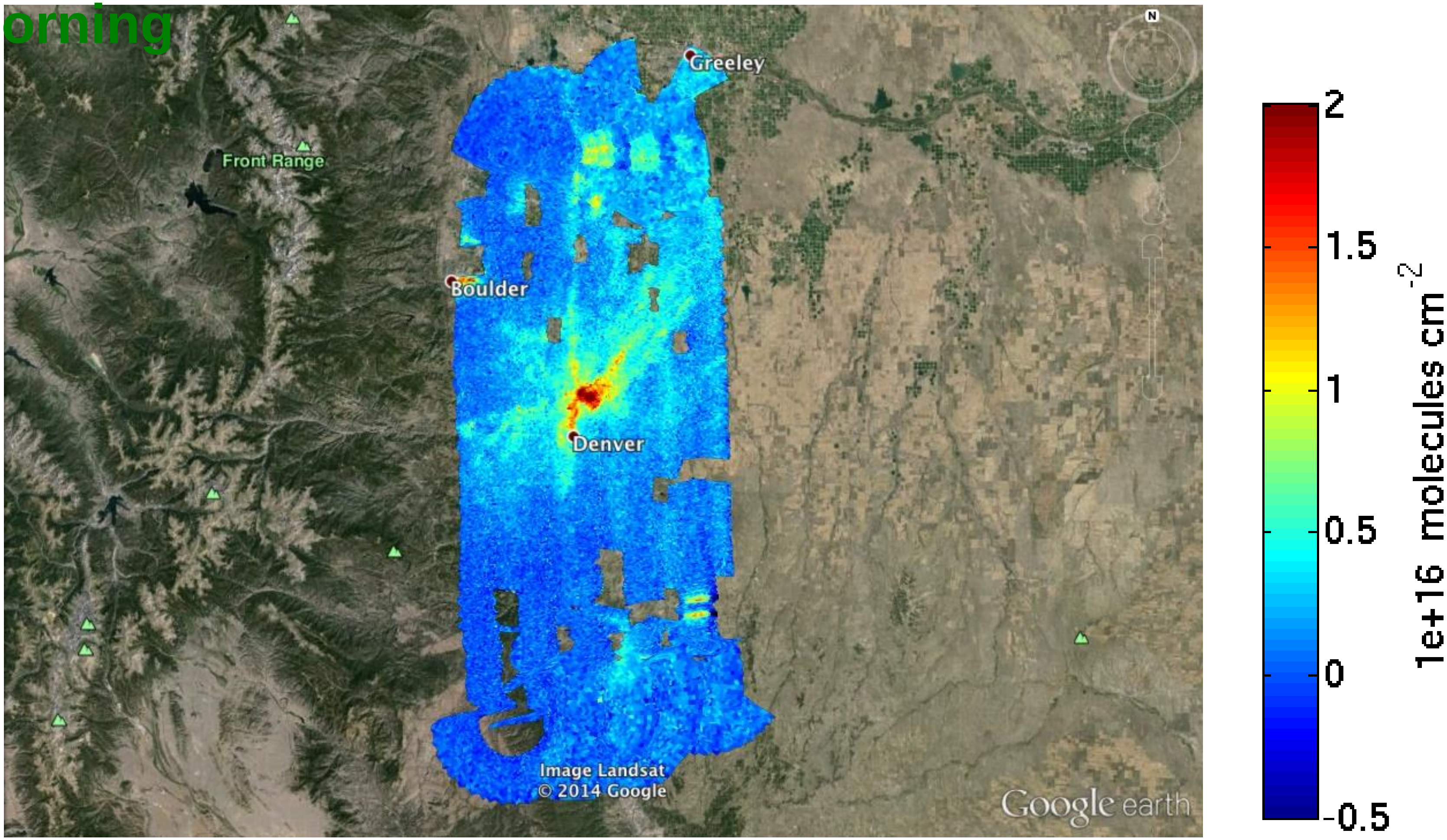
Archive and distribute TEMPO science data products

[1]FT=Free Troposphere (2km-tropopause), SOC=Stratospheric Ozone Column, AOD=Aerosol optical depth, AAOD=Aerosol absorption optical depth, AI=Aerosol index, CF=Cloud Fraction & CTP=Cloud Top Pressure, Albedo=Radiance/Irradiance, FOR=Field Of Regard, IFOV=Instantaneous Field Of View, GSD=Ground Sample Distance. *Projected to 36.5°N,100°W from GEO 100°W. # Threshold Products at 8×9km^2 and 80-minute intervals instead of hourly.

TEMPO measurements will capture the diurnal cycle of pollutant emissions

GeoTASO NO_2 Slant Column, 02 August 2014

Morning



Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

TEMPO

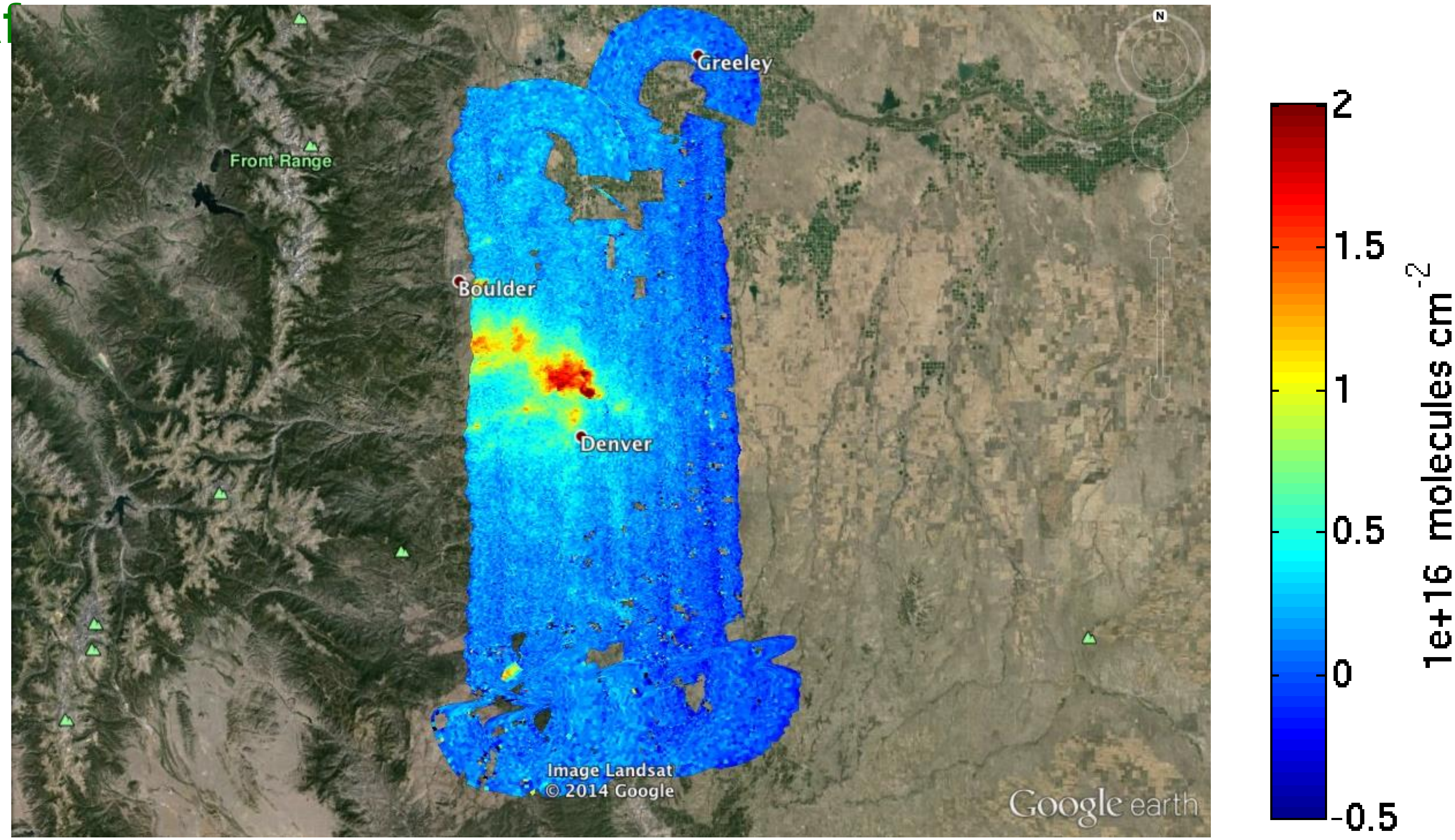
TEMPO measurements will capture the diurnal cycle of pollutant emissions

Smithsonian

NASA

GeoTASO NO_2 Slant Column, 02 August 2014

Af



Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

TEMPO template