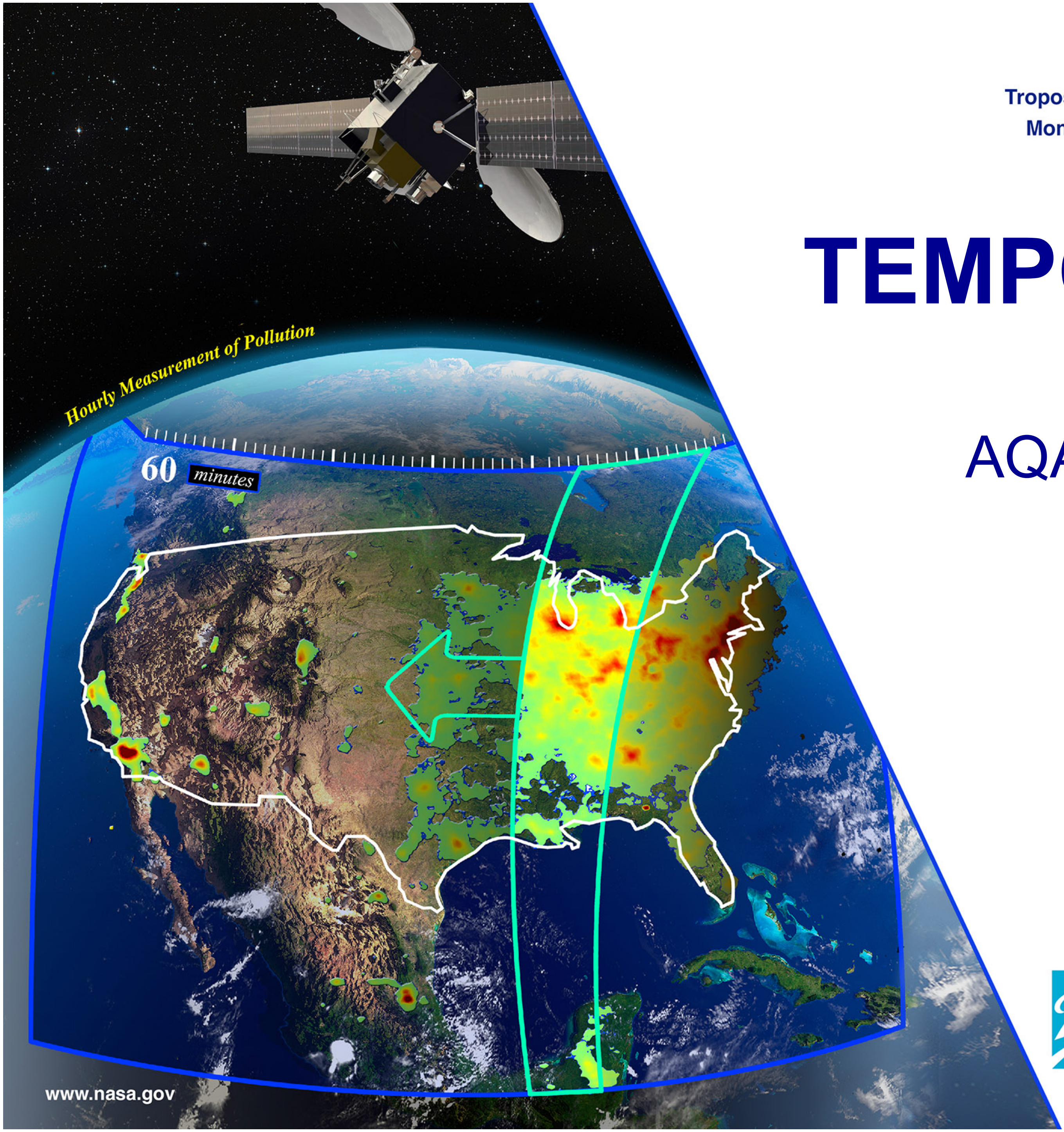


Tropospheric Emissions: Monitoring of Pollution

TEMPO Status

Kelly Chance

AQAST 7 meeting
June 17, 2014

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: Korea, Europe, Canada, Mexico

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

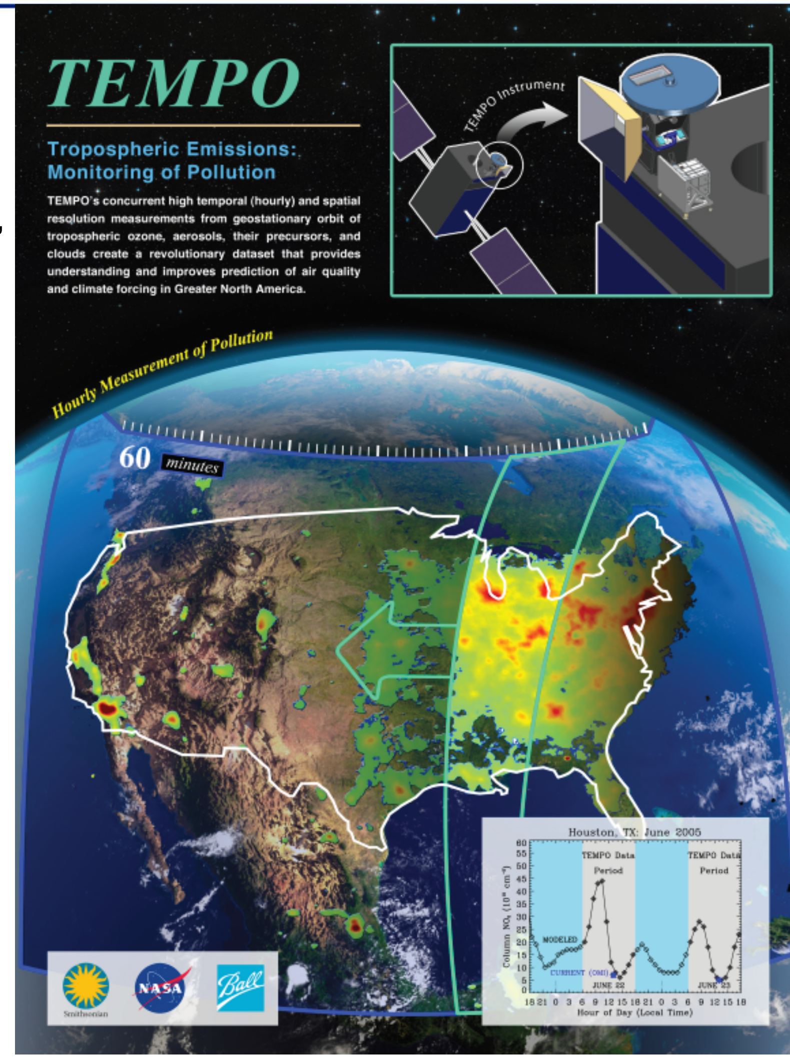
- Instrument delivery May 2017
- NASA will arrange hosting on commercial geostationary communications satellite with launch expected NET 11/2018

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
- Exploits extensive measurement heritage from LEO missions
- Distinguishes boundary layer from free tropospheric & stratospheric ozone

Aligned with Earth Science Decadal Survey recommendations

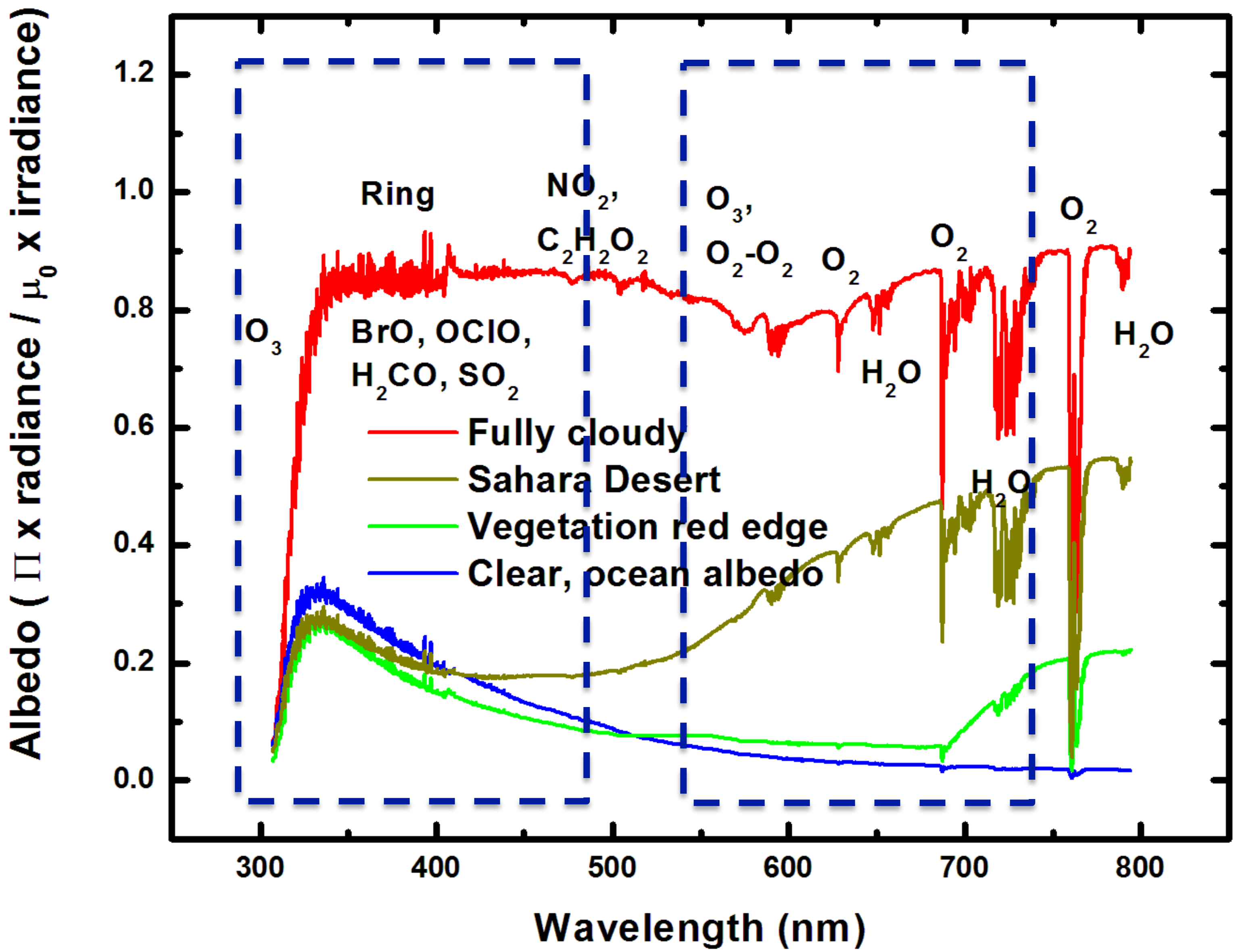
- Makes many of the GEO-CAPE atmosphere measurements
- Responds to the phased implementation recommendation of GEO-CAPE mission design team



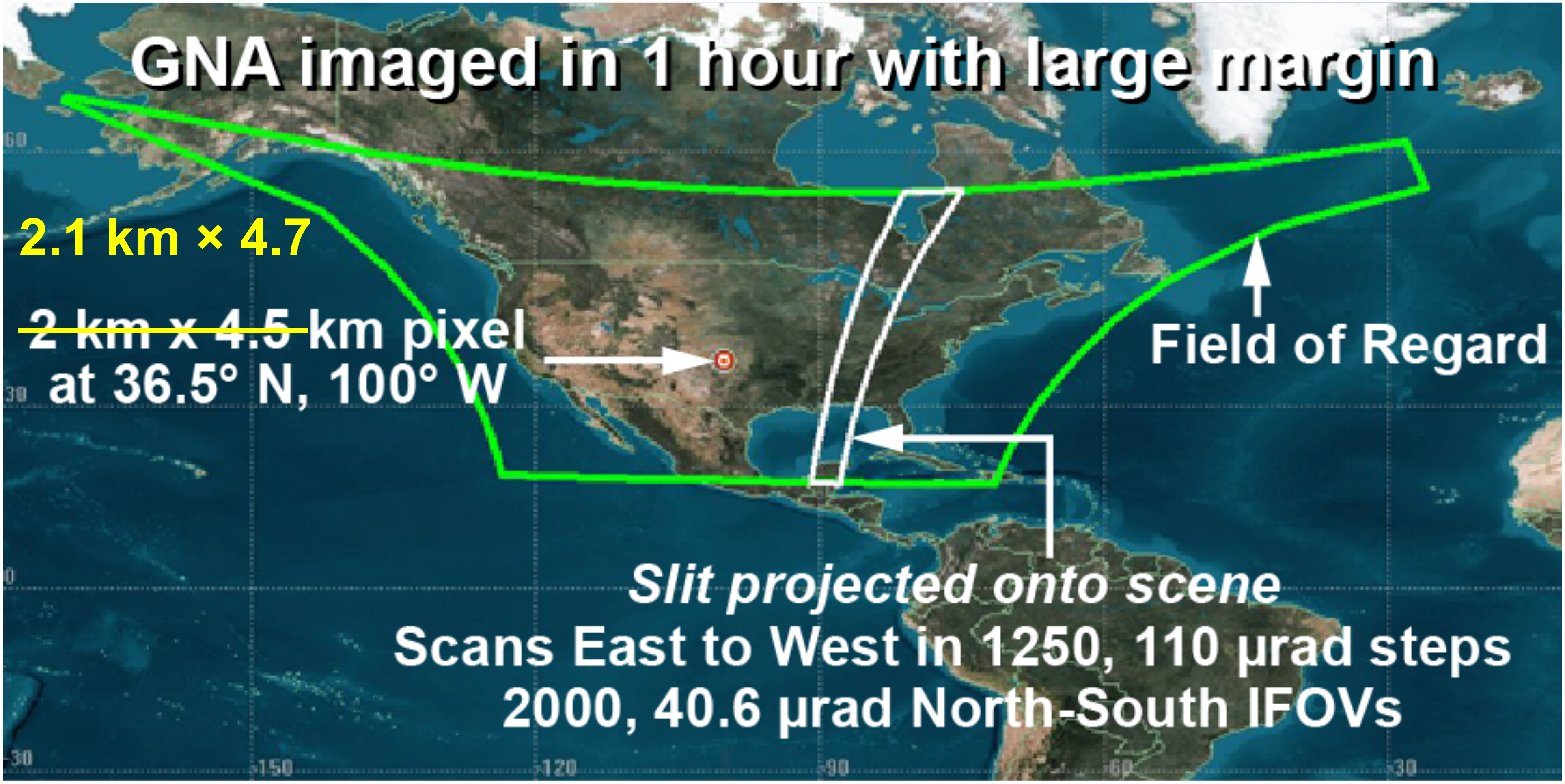
North American component of an international constellation for air quality observations

The view from GEO

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

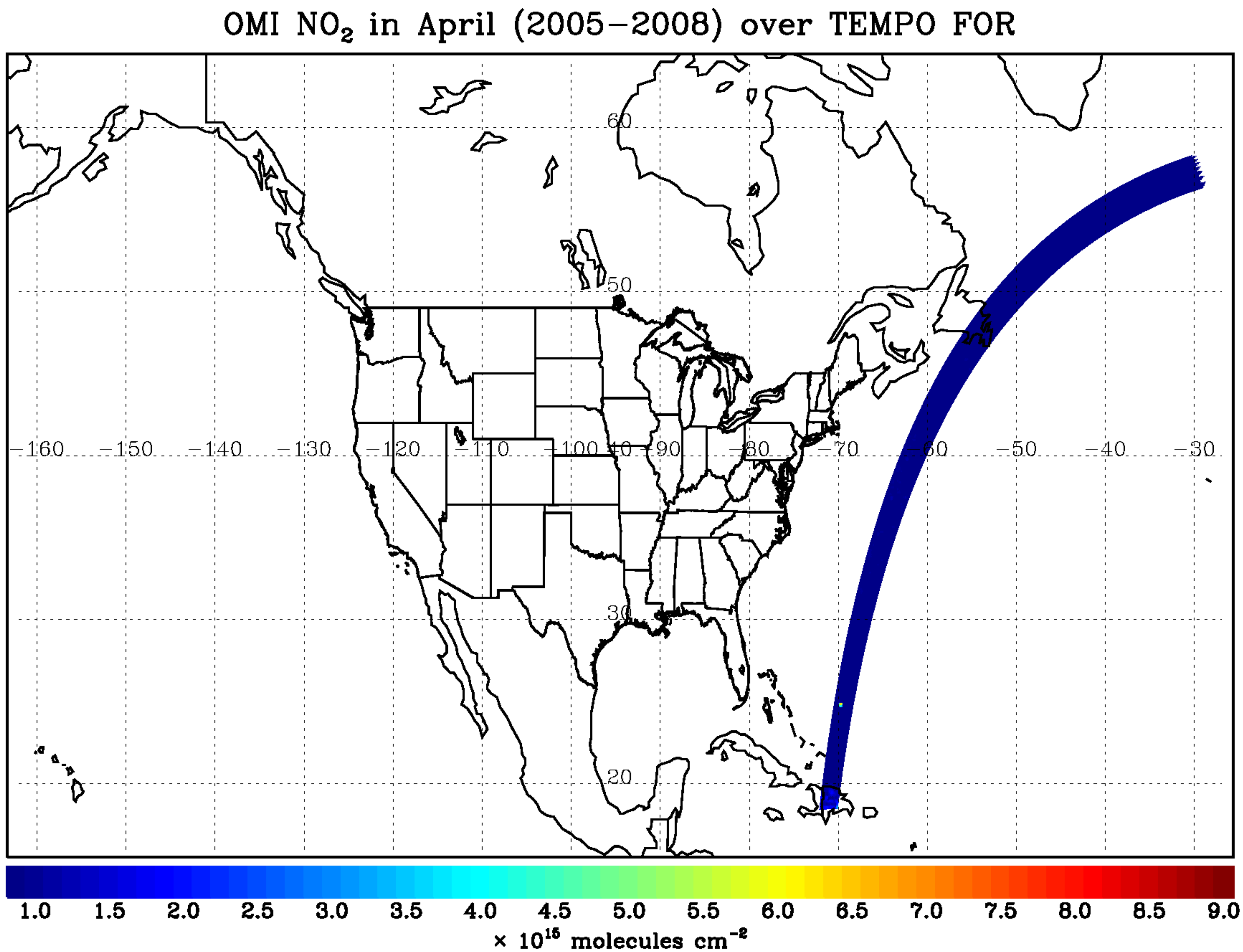


TEMPO footprint, ground sample distance and field of regard

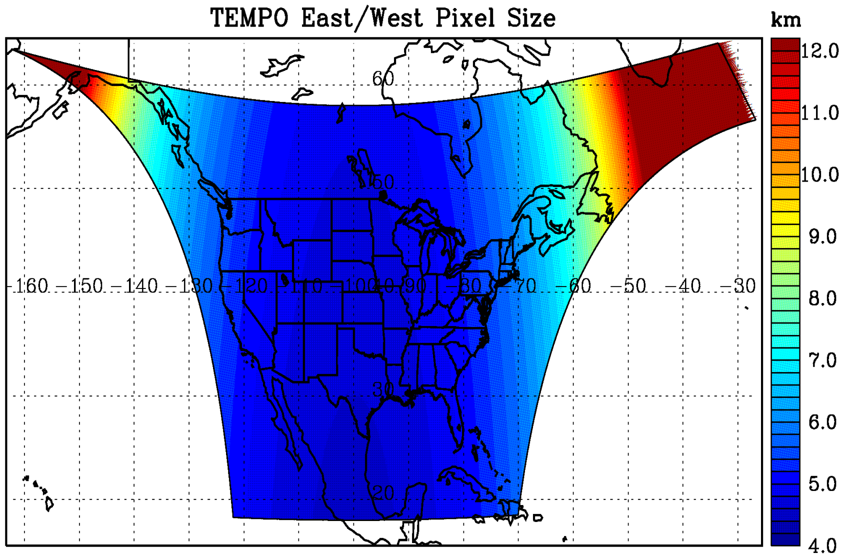


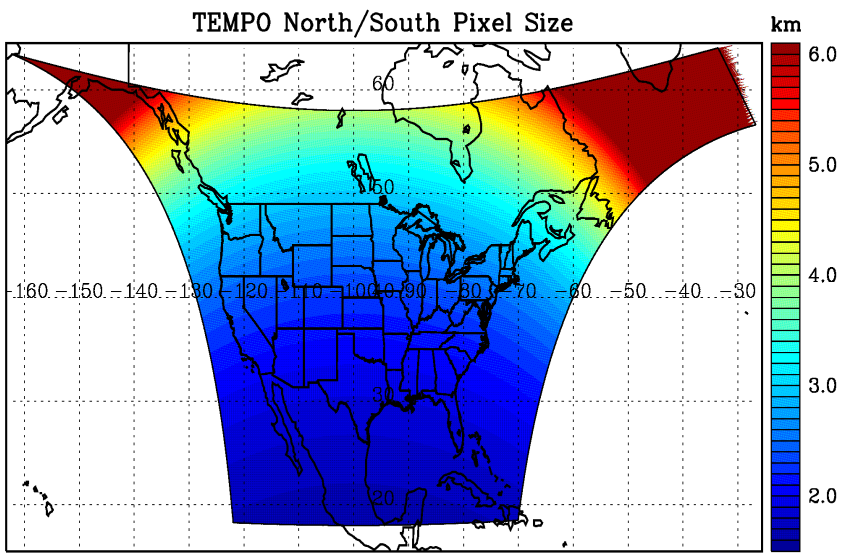
Each 2.1 km × 4.7 km pixel is a 2K element spectrum from 290-740 nm
GEO platform selected by NASA for viewing Greater North America

TEMPO hourly NO_2 sweep



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.

TEMPO baseline products

TEMPO has a minimally-redundant measurement set for air quality.

Near-real time products will allow for pollution alerts, chemical weather, app-based local air quality.

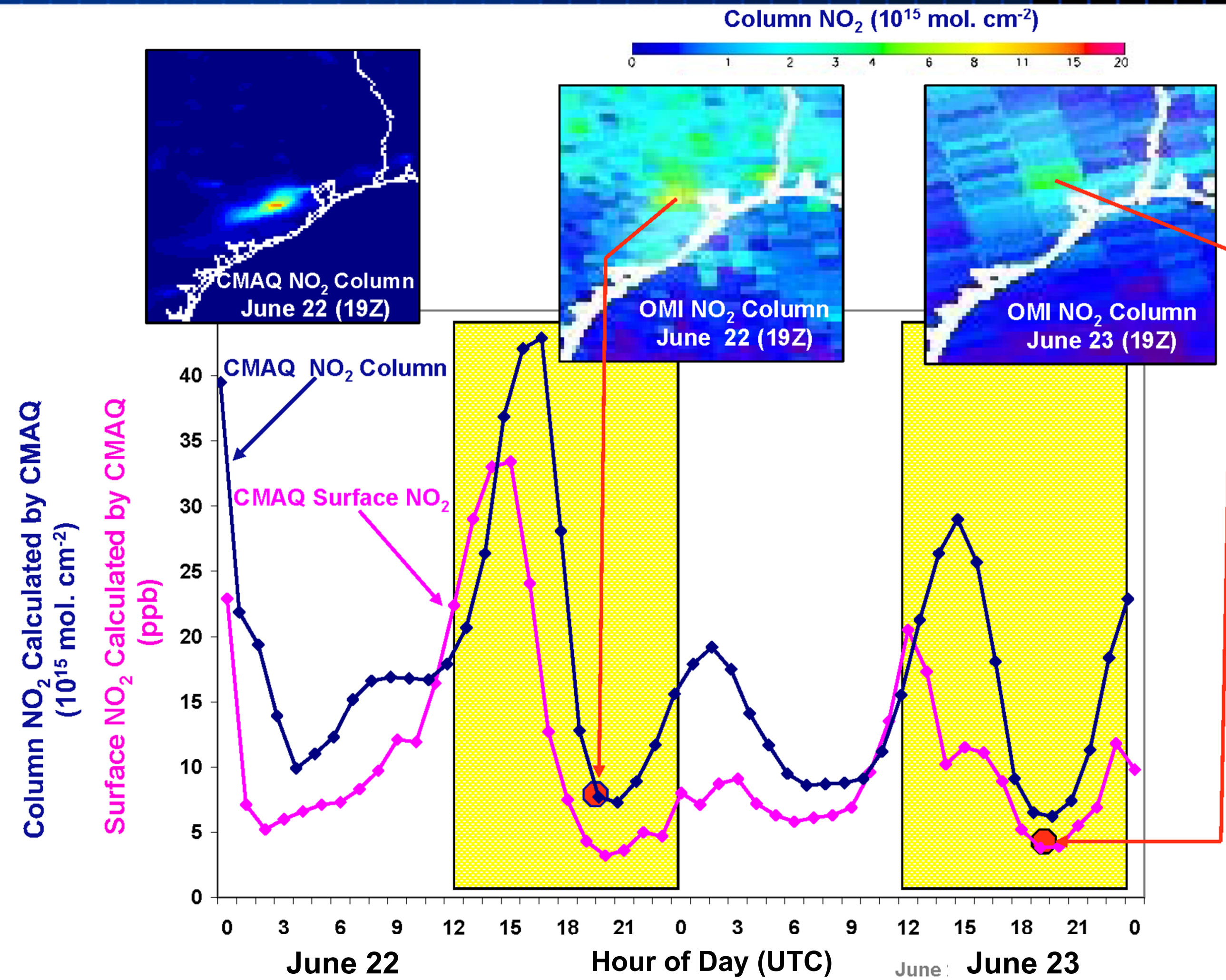
Species/Products		Typical value[2]	Required Precision	Expected Precision[3]	
				Worst	Nominal
O_3 Profile	0-2 km (ppb)	40	10	9.15	9.00
	FT (ppb) [4]	50	10	5.03	4.95
	SOC [4]	8×10^3	5%	0.81%	0.76%
Total O_3		9×10^3	3%	1.54%	1.47%
NO_2*		6	1.00	0.65	0.45
H_2CO* (3/day)		10	10.0	2.30	1.95
SO_2* (3/day)		10	10.0	8.54	5.70
$C_2H_2O_2$* (3/day)		0.2	0.40	0.23	0.17
AOD		0.1 – 1	0.05	0.041	0.034
AAOD		0 – 0.05	0.03	0.025	0.020
Aerosol Index (AI)		-1 – +5	0.2	0.16	0.13
CF [4]		0 - 1	0.05	0.015	0.011
CTP (hPa) [4]		200–900	100	85.0	60.0

[1] Spatial Resolution: 8×4.5 km^2 at the center of the domain. Time resolution: Hourly, unless noted.
[2] Typical values. Units are 10^{15} molecules•cm^{-2} for gases and unitless for aerosols/clouds, unless specified.
[3] Expected precision is viewing condition dependent; results for worst and nominal cases.
[4] FT, free troposphere: 2 km-tropopause, SOC: stratospheric O_3 column, CF: cloud fraction, CTP: cloud top pressure.
* = background value. Pollution is higher, and in starred constituents, the precision is applied to polluted cases.

Threshold products at 8×9km^2 at 80 min. time resolution.

Why geostationary? High temporal and spatial resolution

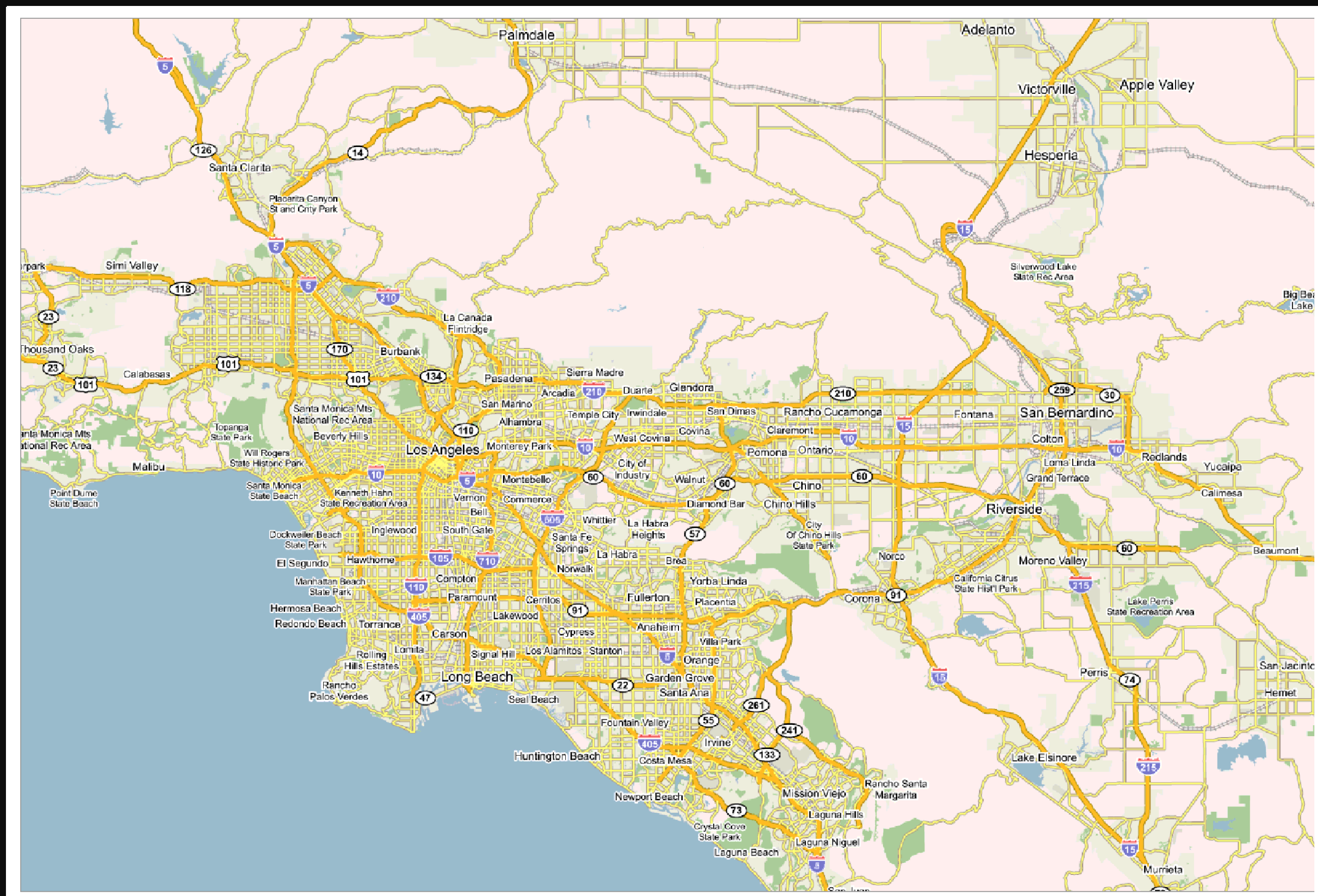
Hourly NO_2 surface concentration and integrated column calculated by CMAQ air quality model: Houston, TX, June 22-23, 2005



LEO observations provide limited information on <u>rapidly varying</u> emissions, chemistry, & transport

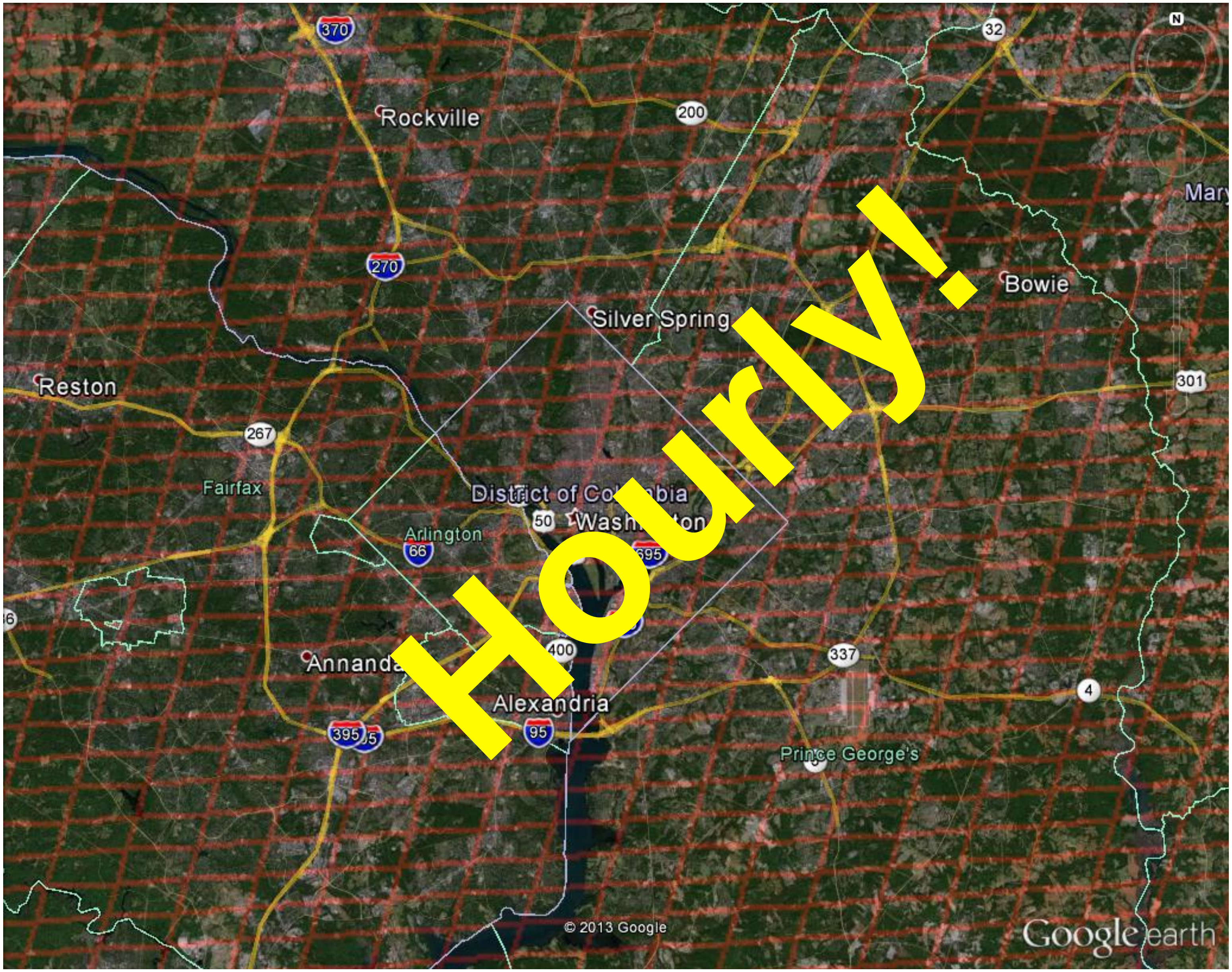
GEO will provide observations at temporal and spatial scales highly relevant to air quality processes

NO_2 over Los Angeles



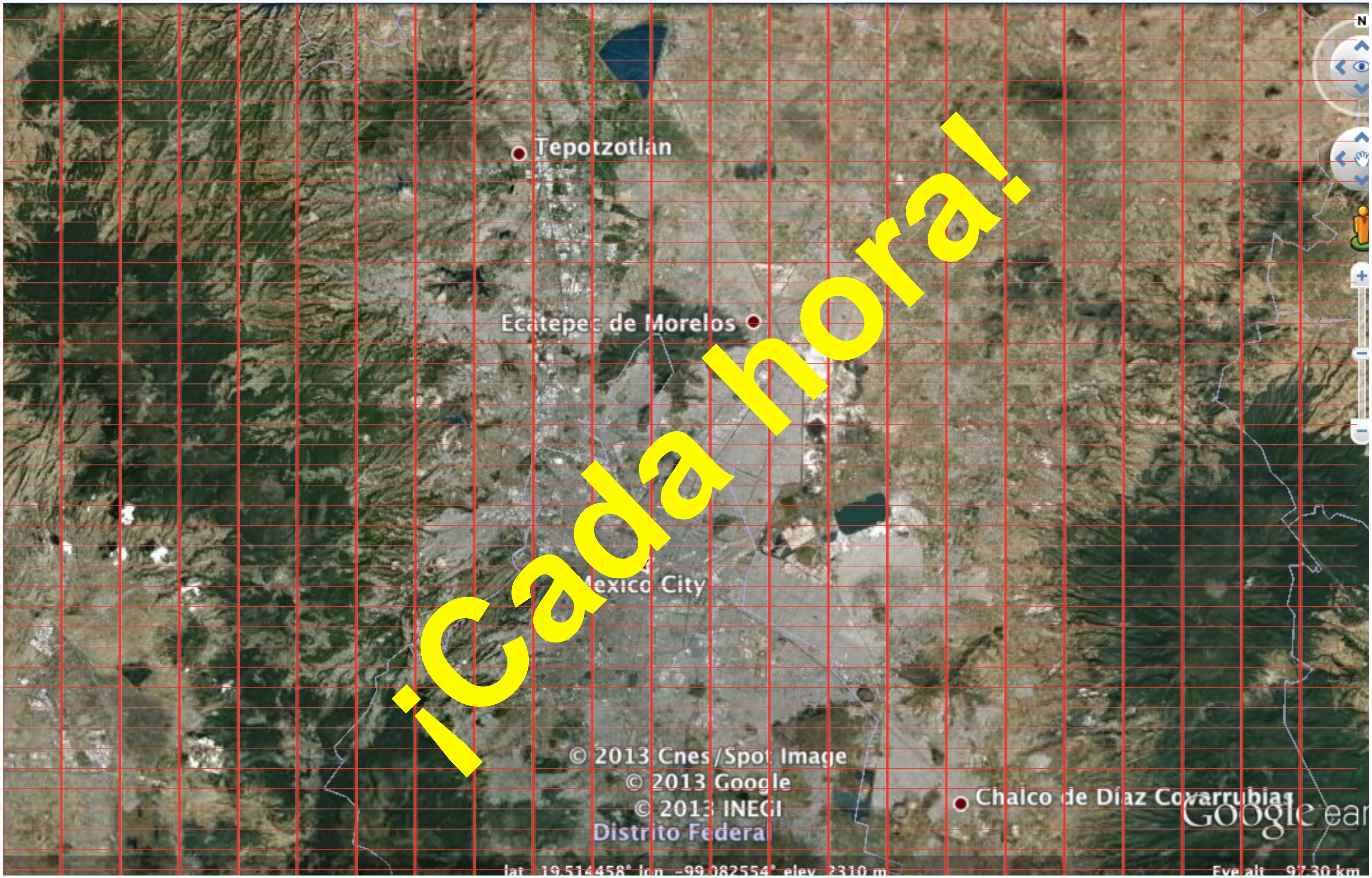
Courtesy T. Kurosu

Washington, DC coverage



TEMPO

Mexico City coverage

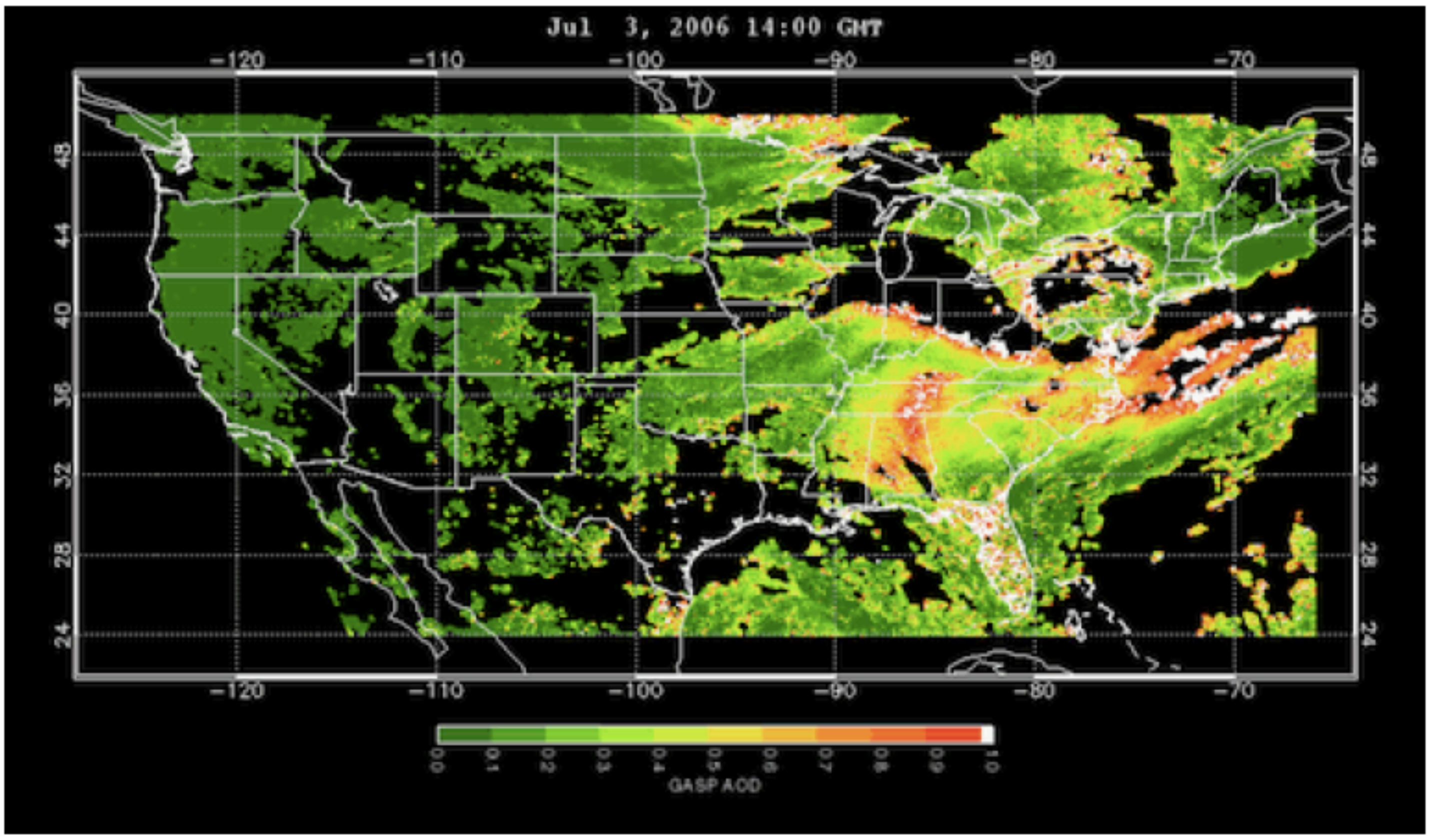


TEMPO

www.epa.gov/rsig

Smithsonian NASA

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



TEMPO Summary

- TEMPO is a pathfinder for NASA
  - The first mission under the stringently cost-capped Earth Venture Instrument program
  - First use of a competitively selected commercial host satellite
- Currently on-schedule and on-budget
  - Passed System Requirements Review and Mission Definition Review in November 2013
  - Passed KDP-B April 2014, now in Phase B
  - Most technical issues solved at the preliminary design level, following technical interchange meeting at Ball, April 2014
  - PDR scheduled for late July 2014
- Commercial satellite host selection and Instrument CDR summer 2015
  - TEMPO operating longitude and launch date are not known until after host selection
- Instrument delivery 05/2017 for launch no earlier than 11/2018

The End!

6/17/14

Backups

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

***Implementation of SO_2, $C_2H_2O_2$, and aerosol algorithms is deferred until after successful instrument PDR**

- **Likely ~October 2015**
- **No impact on instrument design capability**
- **All products still ready for launch once approved**

- **Minimal set of products sufficient for constraining air quality**
- **Field of Regard (FOR) is Greater North America, depending on host satellite selected:**
  - **At least 19°N to 57.5°N near 100°W**
  - **At least 67°W to 125°W near 42°N**
- **Data products at urban-regional spatial scales**
  - **Baseline ≤ 60 km^2 at center of FOR**
  - **Capability for retrieval at native pixel resolution (approx. 2.1 km x 4.7 km) when SNR allows**
- **Geolocation uncertainty of less than 4 km**
- **Temporal scales to resolve diurnal changes in pollutant distributions**
- **Mission duration, subject to instrument availability**
  - **Baseline 20 months**
  - **Threshold 12 months**

TEMPO Science Traceability Matrix

Science Questions

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?

Q3. How do episodic events affect atmospheric composition and AQ?

Q4. How does AQ drive climate forcing and climate change affect AQ on a continental scale?

Q5. How can observations from space improve AQ forecasts and assessments for societal benefit?

Q6. How does trans-boundary transport affect AQ?

Science Objective

A. High temporal resolution measurements to capture changes in pollutant gas distributions. [Q1, Q2, Q3, Q4, Q5, Q6]

B. High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas. [Q1, Q2, Q3, Q5, Q6]

C. 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. [Q1, Q2, Q4, Q5, Q6]

D. Observe aerosol optical properties with high temporal and spatial resolution for quantifying and tracking evolution of aerosol loading. [Q1, Q2, Q3, Q4, Q5, Q6]

E. Determine the instantaneous radiative forcings associated with O_3 and aerosols on the continental scale. [Q3, Q4, Q6]

F. Integrate observations from TEMPO and other platforms into models to improve representation of processes in the models and construct an enhanced observing system. [Q1, Q2, Q3, Q5, Q6]

G. Quantify the flow of pollutants across boundaries (physical & political); Join a global observing system. [Q2, Q3, Q4, Q5, Q6]

Science Measurement Requirement

Observables

Spatially imaged & spectrally resolved, solar backscattered earth radiance, spanning spectral windows suitable for retrievals of O_3, NO_2, H_2CO, SO_2 and $C_2H_2O_2$. [A, B, C, E, F, G]

Measurements at spatial scales comparable to regional atmospheric chemistry models. [A, B, C, D, F, G]

Multispectral data in suitable O_3 absorption bands to provide vertical distribution information. [A, B, C, E, F, G]

Spectral radiance measurements with suitable quality (SNR) to provide multiple measurements over daylight hours (solar zenith angle < 70°) at precisions to distinguish pollutants from background levels. [A to G]

Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles <70°. [B, D, E, F, G]

Physical Parameters / Instrument Function Requirements

Physical Parameters		Parameter	Required	Predicted
Baseline#* Trace gas column densities (10^{15} cm^{-2}) hourly @ 8.9 km x 5.2 km				
Species	Precision	Band	Signal to Noise	
O_3: 0-2 km	10 ppbv	O_3:Vis (540-650 nm)	≥1413	1765
O_3: FT	10 ppbv	O_3: UV (290-345 nm)	≥1032	1247
O_3: SOC	5%			
O_3: Total	3%			
NO_2	1.00	423-451 nm	≥781	2604
H_2CO	17.3	327-354 nm	≥742	2266
SO_2	17.3	305-330 nm	≥1100	1328
$C_2H_2O_2$	0.70	433-465 nm	≥1972	2670
Baseline#* Aerosol/Cloud properties hourly @ 8.9 km x 5.2 km				
Property	Precision	Band	Signal to Noise	
AOD	0.10	354, 388 nm	≥1414	2158
AAOD	0.06			
AI	0.2			
CF	0.05	346-354 nm	≥1200	2222
COCP	100 mb			
Spectral Imaging Requirements				
Relevant absorption bands for trace gases & windows for aerosols		Spectral Range (nm)	290-490, 540-740	290-490, 540-740
		Spectral Resolution (nm)	≤0.6	0.6
		Spectral Sampling (nm)	< 0.22	0.2
Radiometric Requirements				
Solar irradiance and Earth backscattered radiance spectrally resolved over spectral range		Wavelength-dependent Albedo Calibration Uncert. (%)	≤1	0.8
		Wavelength-independent Albedo Calibration Uncert. (%)	≤2	2.0
		Spectral Uncertainty (nm)	< 0.02	< 0.02
		Polarization Factor (%)	<5 UV, <20 Vis	≤4 UV, <20 Vis
Spatial Imaging Requirements				
Observations at relevant urban to synoptic scales and multiple times during daytime		Revisit Time (hr)	≤1	1
		FOR	CONUS	GNA
		Geolocation Uncertainty (km)	<4.0	2.8
		IFOV*: N/S × E/W (km)	≤2.2 × ≤5.2	2.2 × 5.2
		E/W Oversampling (%)	7.5 ± 2.5	7.5
		MTF of IFOV*: N/S × E/W	≥0.16 × ≥0.30	0.16 × 0.36

Investigation Requirements

Mission lifetime: 1-yr (Threshold), 20-mon (Baseline), 10-yr (Goal)

Orbit Longitude °W: 90-110 (Preferred), 75-137 (Acceptable)

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

On-orbit Calibration, Validation, Verification

FOR encompasses CONUS and adjacent areas

Provide near-real-time products to user communities within 2.5-hr to enable assimilation into chemical models (NOAA & EPA) and use by smart-phone applications

Distribute and archive TEMPO science data products

TEMPO science team

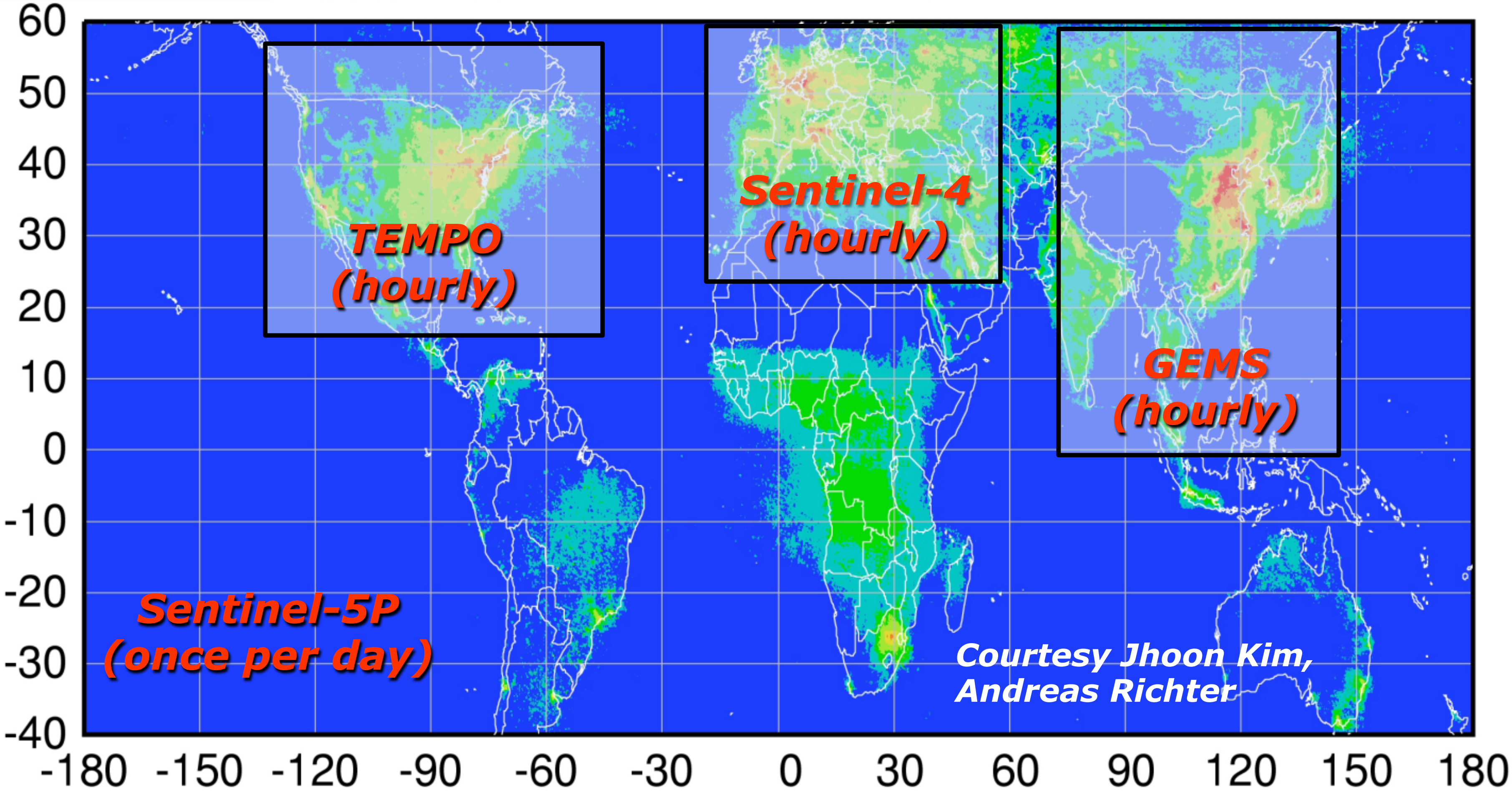
Team Member	Institution	Role	Responsibility
K. Chance	SAO	PI	Overall science development; **Level 1b, H_2CO, $C_2H_2O_2$**
X. Liu	SAO	Deputy PI	Science development, data processing; **O_3 profile, tropospheric O_3**
J. Al-Saadi	LaRC	Deputy PS	Project science development
J. Carr	Carr Astronautics	Co-I	**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
R. 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
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

Meeting emphasis

TEMPO science studies during and after commissioning

- Fluorescence
- Lightning NO_x
- Soil NO_x
- NO/NO_2 at high dawn and dusk time resolution
- Forest fires at high time resolution
- Subsampling and spatial resolution
- ●●●●

Global pollution monitoring constellation (2018-2020)



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

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

PLRA Table 1

- **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**

Data Product Definitions and Details

Data Product	Description	Time beyond on-orbit checkout to deliver initial data	Maximum data latency after first release for ≥ 80% of all products†
Level 0	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
Level 1b	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
Level 2	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO
Level 3	Derived Gridded Geophysical Data Products	6 months	1 month after completion of data accumulation required for individual geophysical products

All original observation data and standard science data products listed here, along with the scientific source code for algorithm software, coefficients, and ancillary data used to generate these products, shall be delivered to the designated NASA SMD/ESD-assigned DAAC within six months of completion of the prime mission. *Data products are publicly distributed during the mission*.

†80% of the products, not 80% of the product types, will be produced within this latency time.

TEMPO