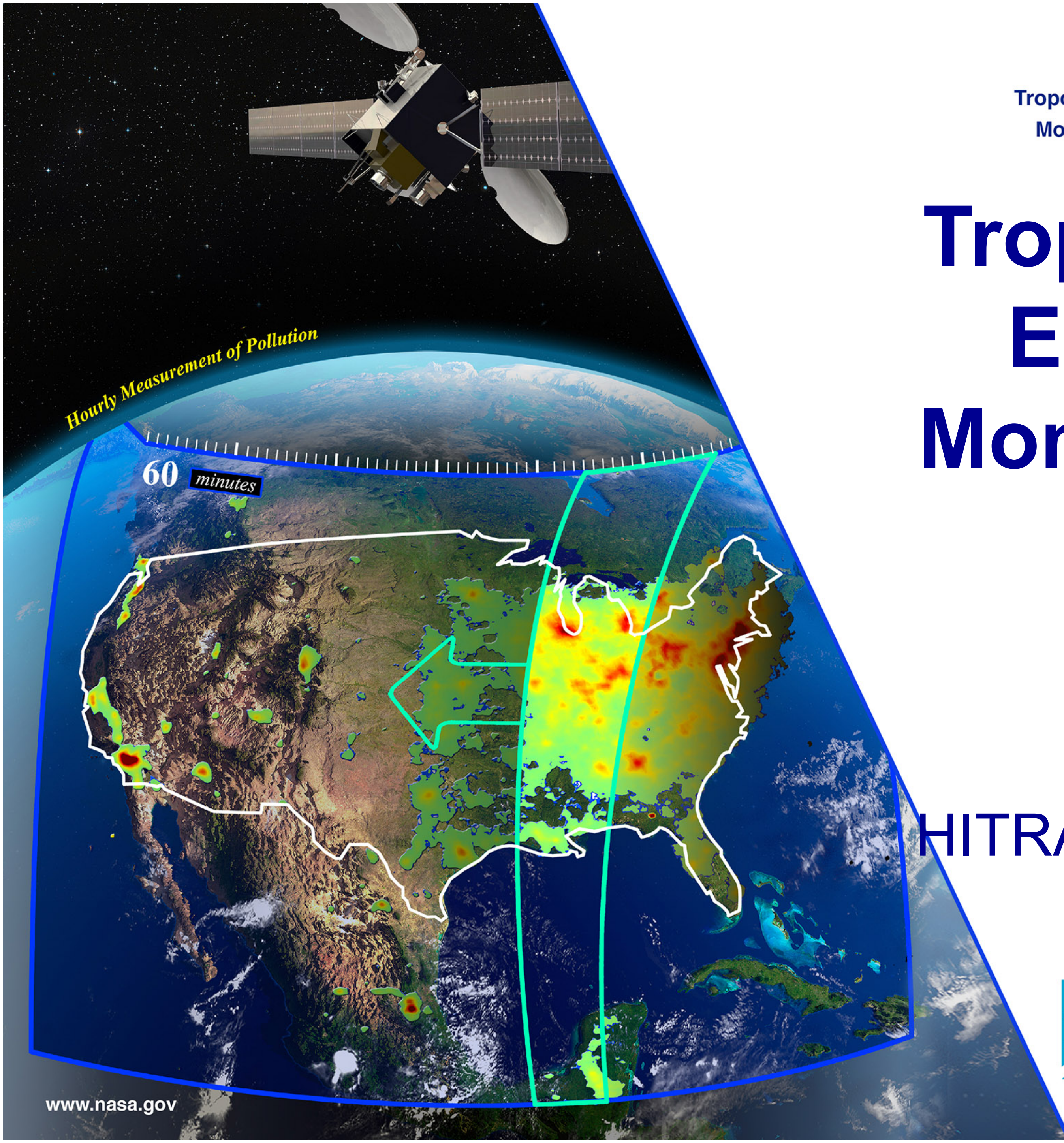


Tropospheric Emissions:
Monitoring of Pollution

Tropospheric Emissions: Monitoring of Pollution (TEMPO)

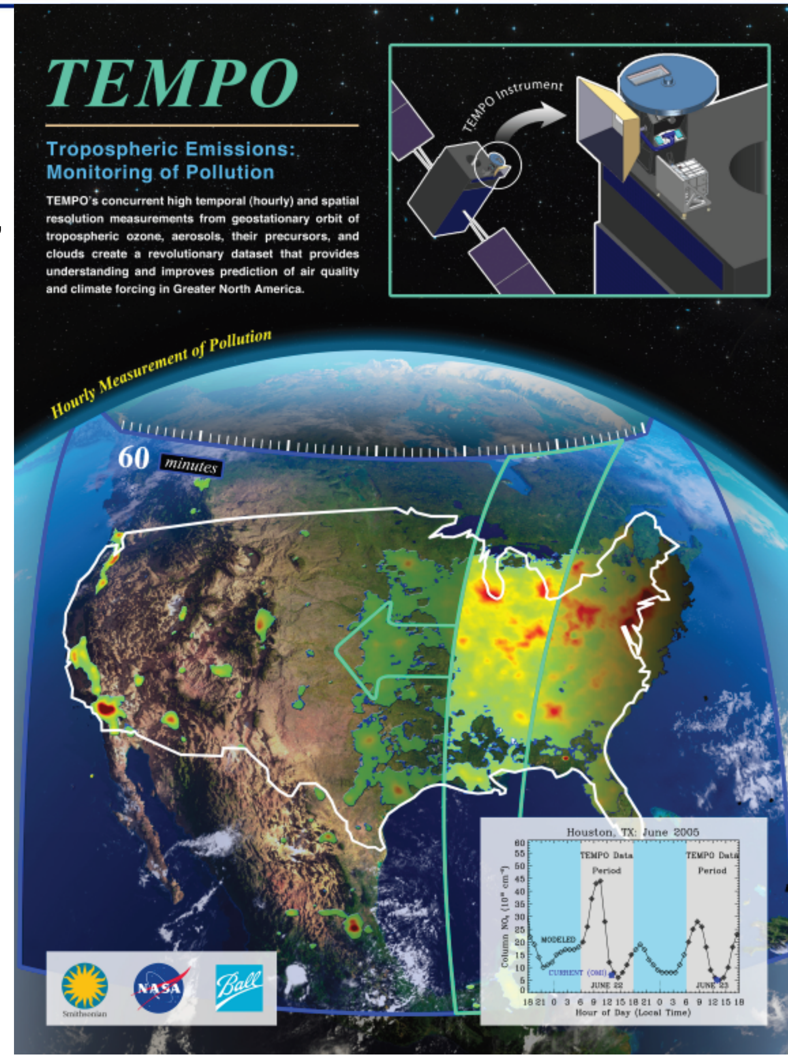
Kelly Chance

HITRAN Conference
June 23, 2014

Smithsonian

Hourly atmospheric pollution from geostationary Earth orbit

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

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	Collaborators, Science Advisory Panel	CSA PHEOS, CEOS constellation of GEO pollution monitoring
B. Veihelmann	ESA	Collaborators, Science Advisory Panel	ESA Sentinel-4, CEOS constellation of GEO pollution monitoring

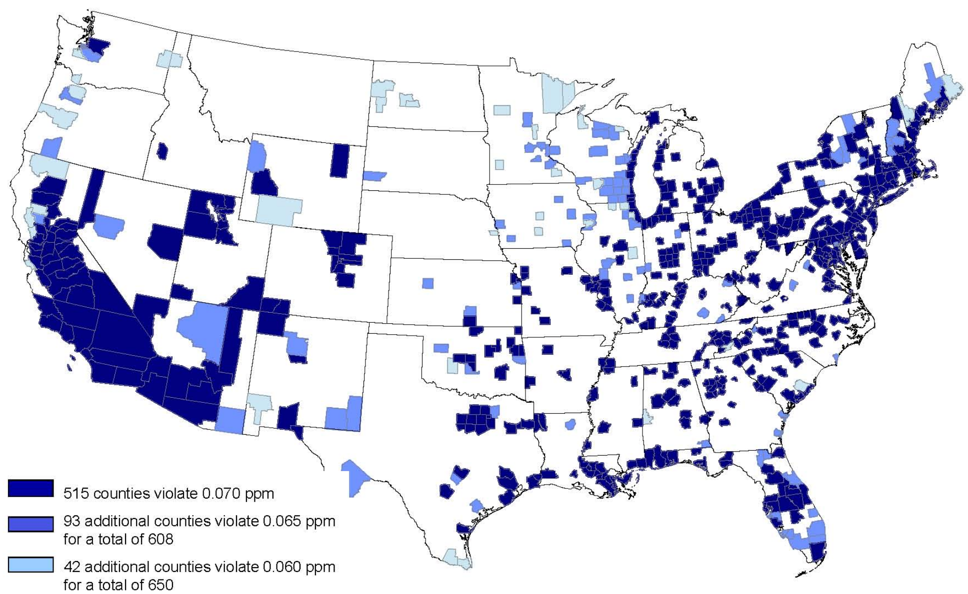
TEMPO science overview

- As air quality standards become more stringent, more of the US may exceed the standards.
- New and transient pollution sources (e.g., vehicular traffic, oil & gas development, trans-boundary pollution) will become more important but are <u>very</u> difficult to monitor from ground networks.
- Air quality, climate change, and energy policies must increasingly be considered together.
- TEMPO measurements will provide data to help solve these national challenges.

Counties Violating Ground-level Ozone Standards

(Based on 2006 – 2008 Air Quality Data)

EPA will not designate areas as nonattainment on these data, but likely on 2008 – 2010 data which are expected to show improved air quality.



Notes:
1. No monitored counties outside the continental U.S. violate.
2. EPA is proposing to determine compliance with a revised primary ozone standard by rounding the 3-year average to three decimal places.

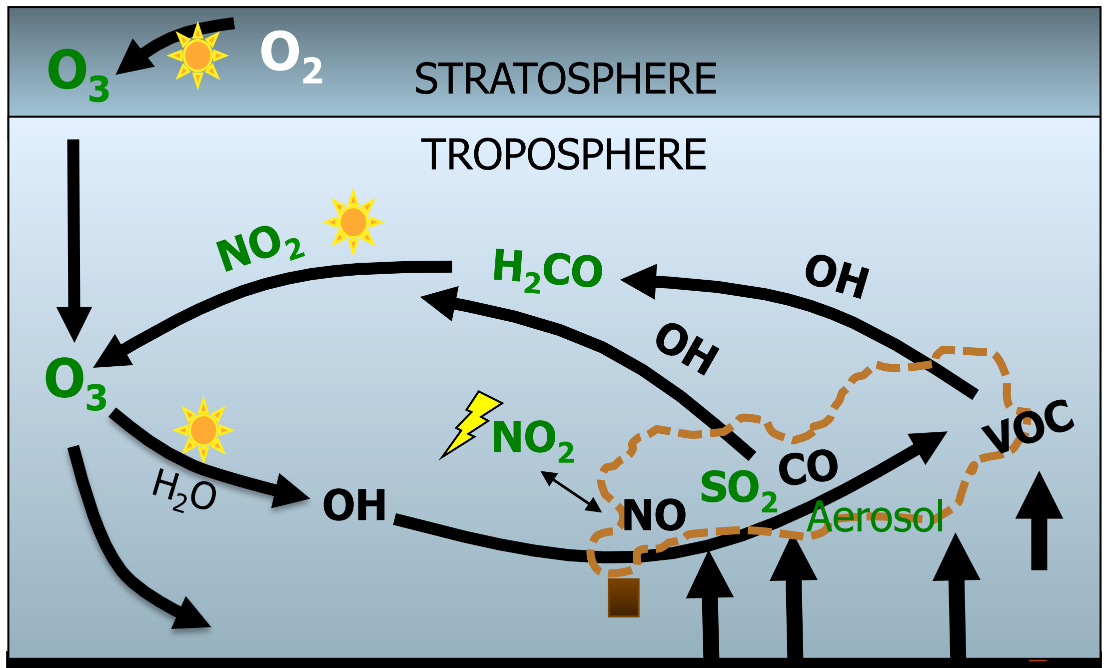
TEMPO Science Questions

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?
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?

TEMPO science measurements

- **Violations of US National Ambient Air Quality Standards are primarily related to ozone (O_3) and particulate matter (aerosol)**
  - O_3 adversely impacts health and agriculture and is a greenhouse gas
  - Aerosol adversely impacts health, reduces visibility, and influences climate
  - Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are also regulated
- **TEMPO measures O_3, key proxies for O_3 precursors (H_2CO and $C_2H_2O_2$ for hydrocarbons and NO_2 for nitrogen oxides), SO_2, and aerosol**

By simultaneously measuring O_3 and the precursors from which it is produced, TEMPO provides understanding of all key phases of air quality: **emissions, photochemistry, and long range transport**



O_3 is created in the troposphere by photochemical cycles dependent on hydrocarbons and nitrogen oxides

TEMPO instrument concept

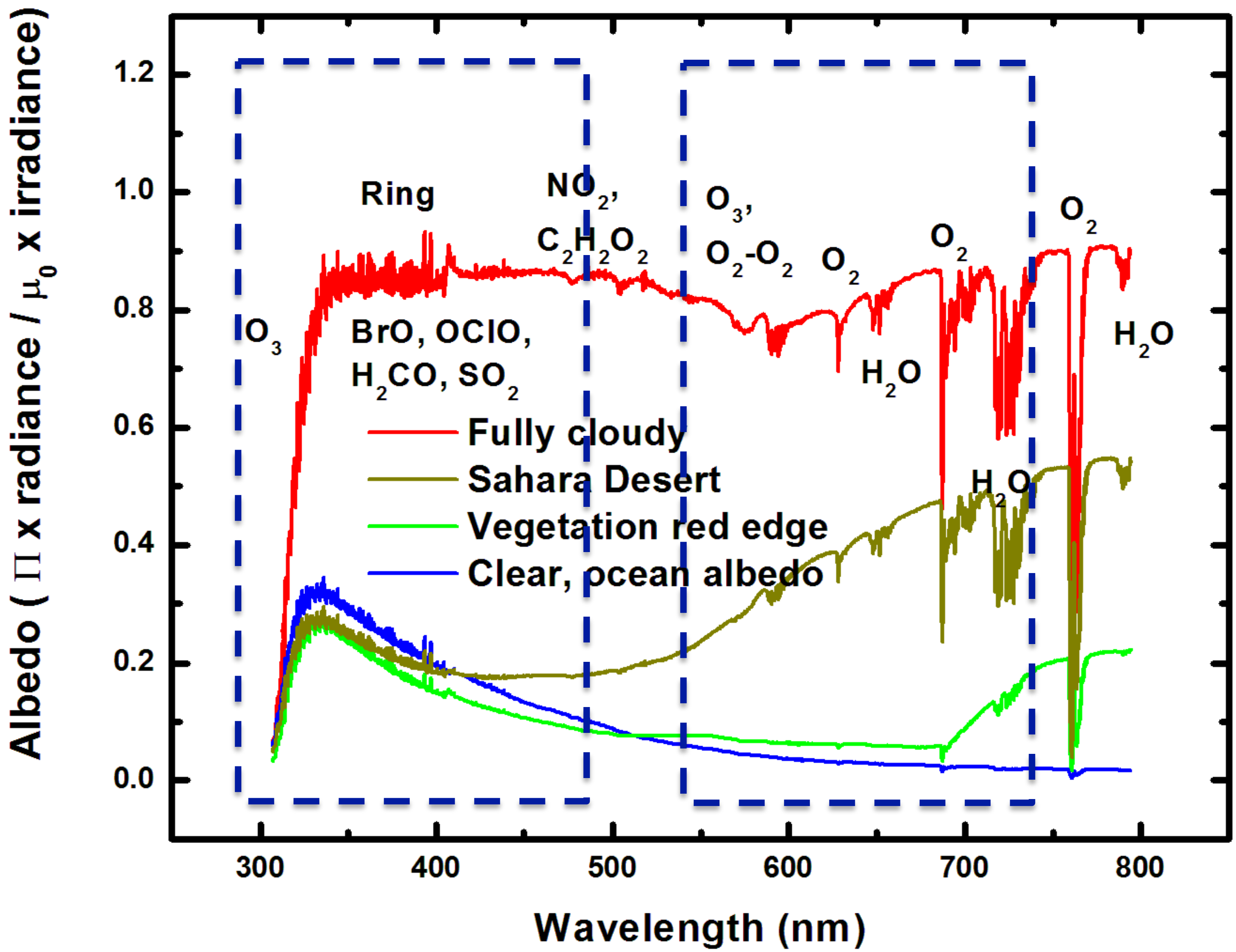
- **Measurement technique**
  - Imaging grating spectrometer measuring solar backscattered Earth radiance
  - Spectral band & resolution: 290-490 + 540-740 nm @ 0.6 nm FWHM, 0.2 nm sampling
  - 2 2-D, 2k×1k, detectors image the full spectral range for each geospatial scene
- **Field of Regard (FOR) and duty cycle**
  - Mexico City/Yucatan Peninsula to the Canadian tar/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) for selected areas
  - 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

TEMPO mission concept

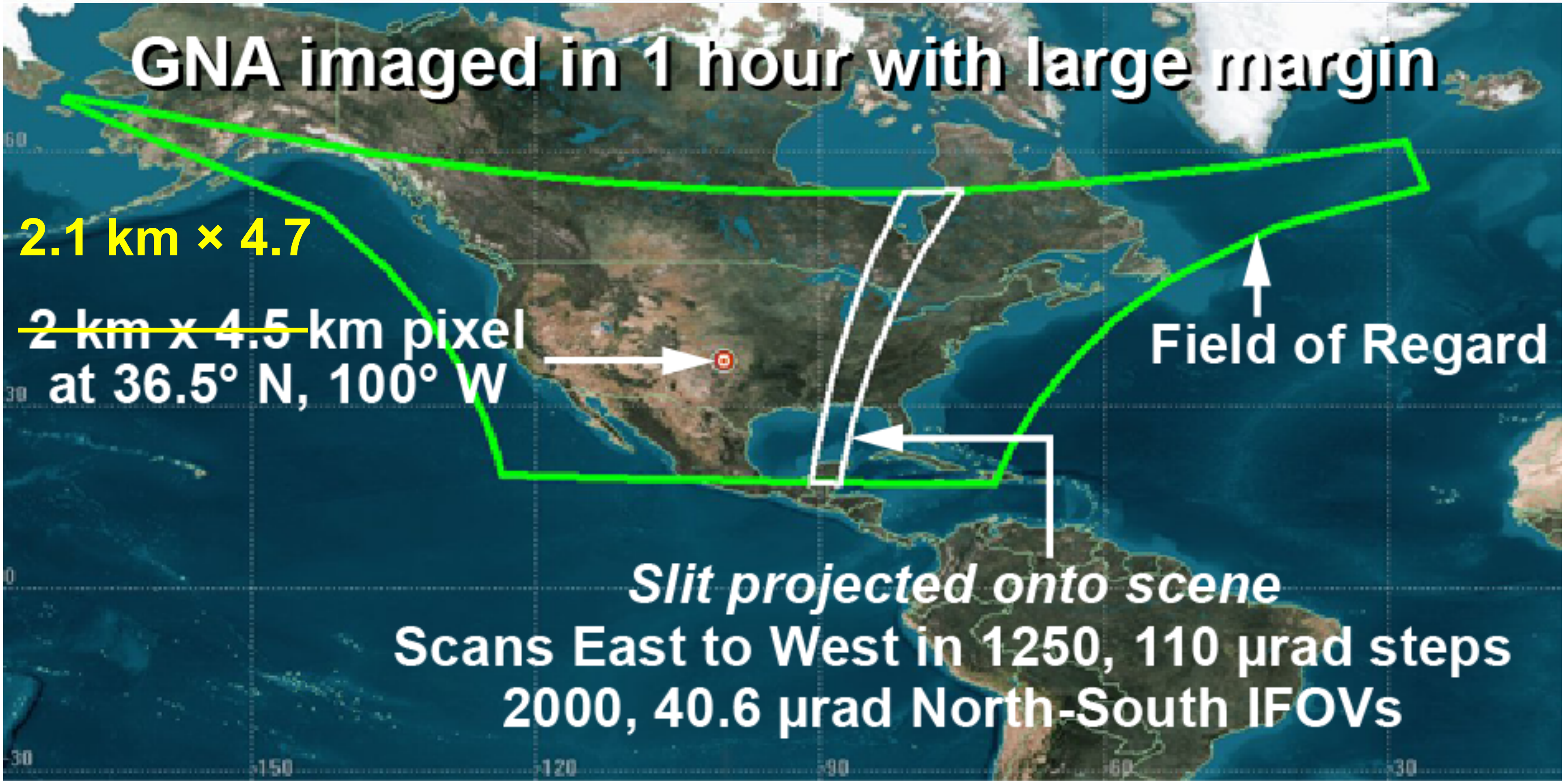
- **Geostationary orbit, operating on a commercial telecom satellite**
  - NASA will arrange launch and hosting services (per Earth Venture Instrument scope)
    - 80-115^{o} W
    - Specifying satellite environment, accommodation
  - Hourly measurement and telemetry duty cycle for at least ≤70^{o} SZA
    - **Hope to measure up to 20 hours/day**
- **TEMPO is low risk with significant space heritage**
  - All proposed TEMPO measurements have been made from low Earth orbit satellite instruments to the required precisions
  - 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
    - 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:** eXceL profile O_3 for broad regions; BrO from AMF-normalized cross sections; height-resolved SO_2; additional cloud/aerosol products; vegetation products

The view from GEO

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

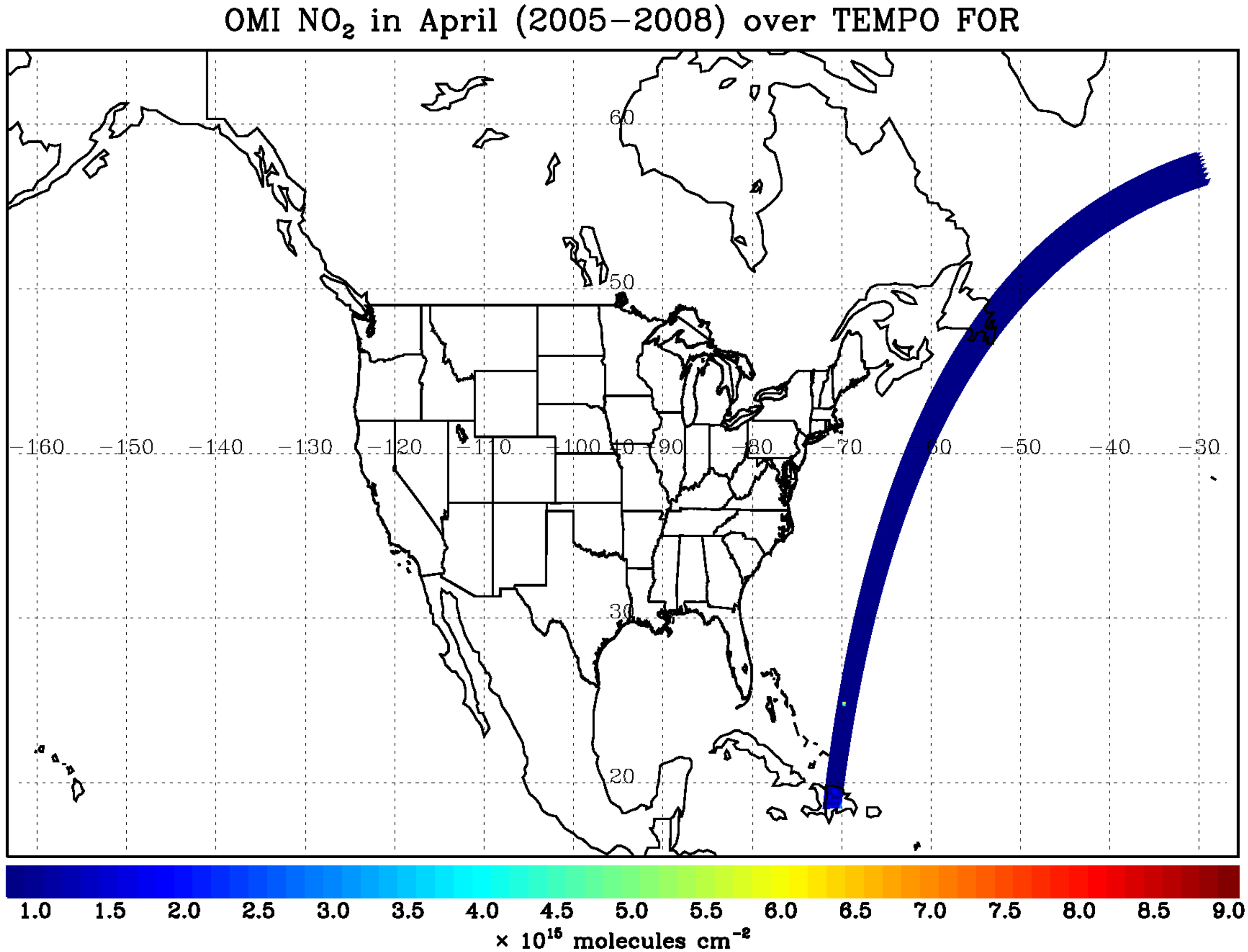


TEMPO footprint, ground sample distance and field of regard

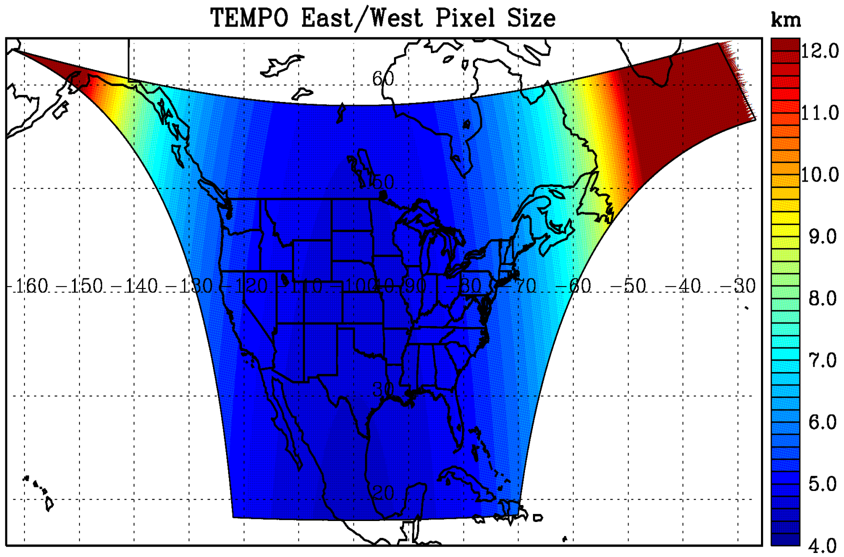


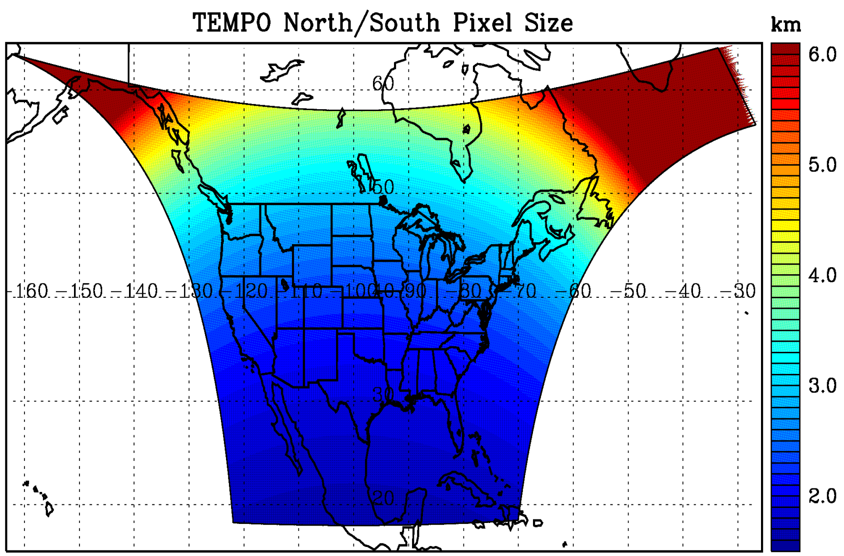
Each 2.1 km × 4.7 km pixel is a 2K element spectrum from 290-740 nm
GEO platform selected by NASA for viewing Greater North America

TEMPO hourly NO_2 sweep



TEMPO footprint (GEO at 100° W)





Location	N/S (km)	E/W (km)	GSA (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.

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.

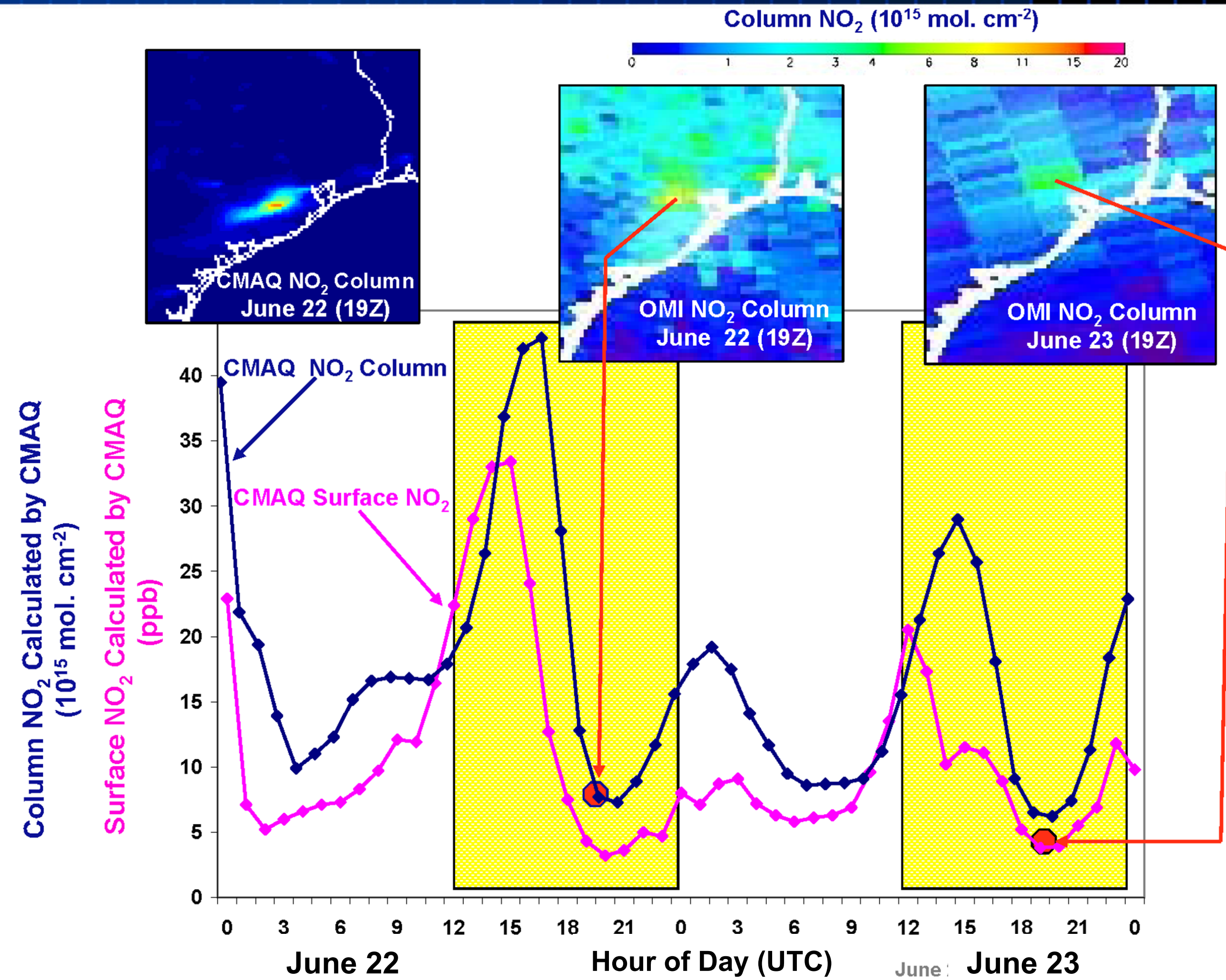
Species/Products		Typical value[2]	Required Precision	Expected Precision[3]	
				Worst	Nominal
O_3 Profile	0-2 km (ppb)	40	10	9.15	9.00
	FT (ppb) [4]	50	10	5.03	4.95
	SOC [4]	8×10^3	5%	0.81%	0.76%
Total O_3		9×10^3	3%	1.54%	1.47%
NO_2*		6	1.00	0.65	0.45
H_2CO* (3/day)		10	10.0	2.30	1.95
SO_2* (3/day)		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

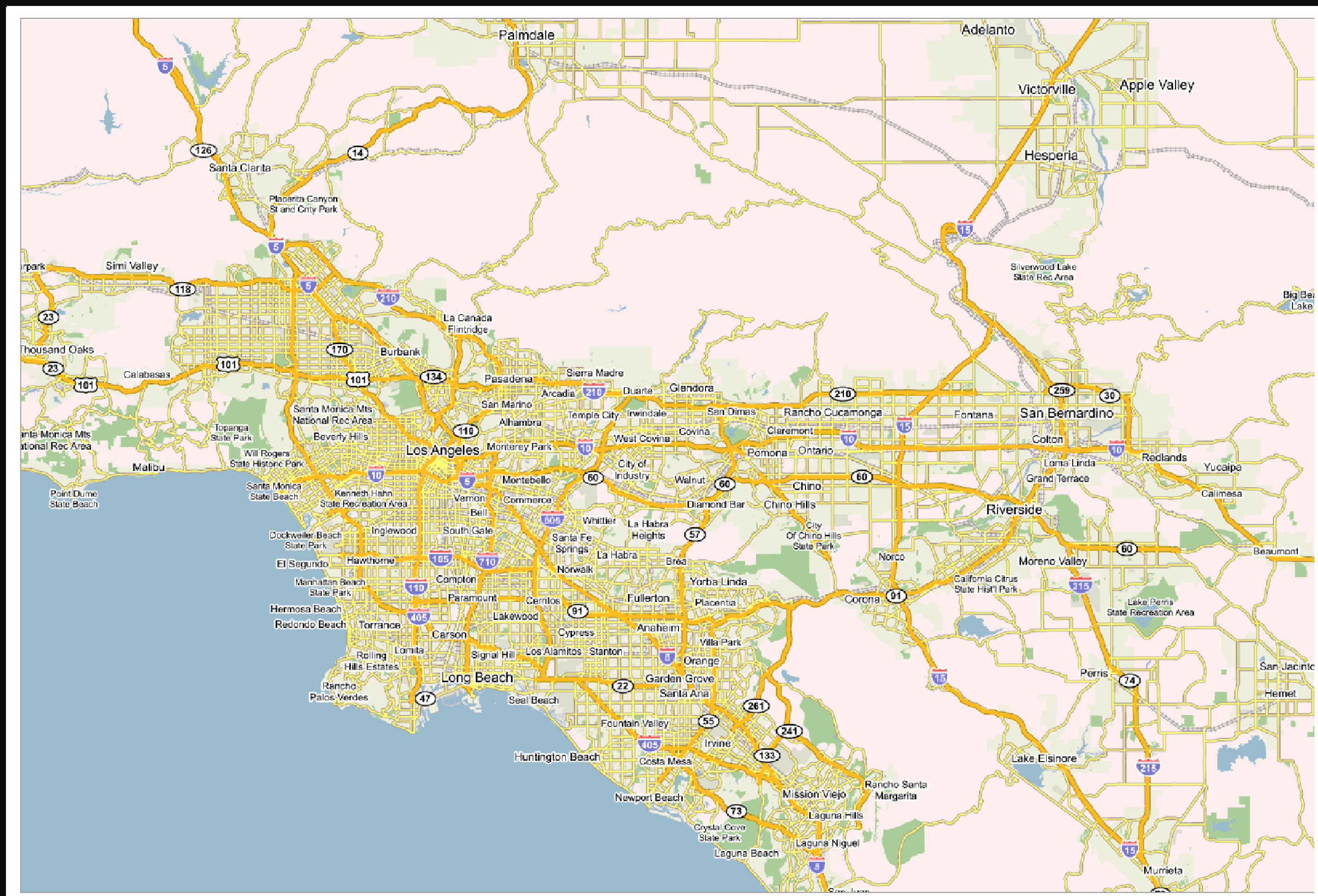
Hourly NO_2 surface concentration and integrated column calculated by CMAQ air quality model: Houston, TX, June 22-23, 2005



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

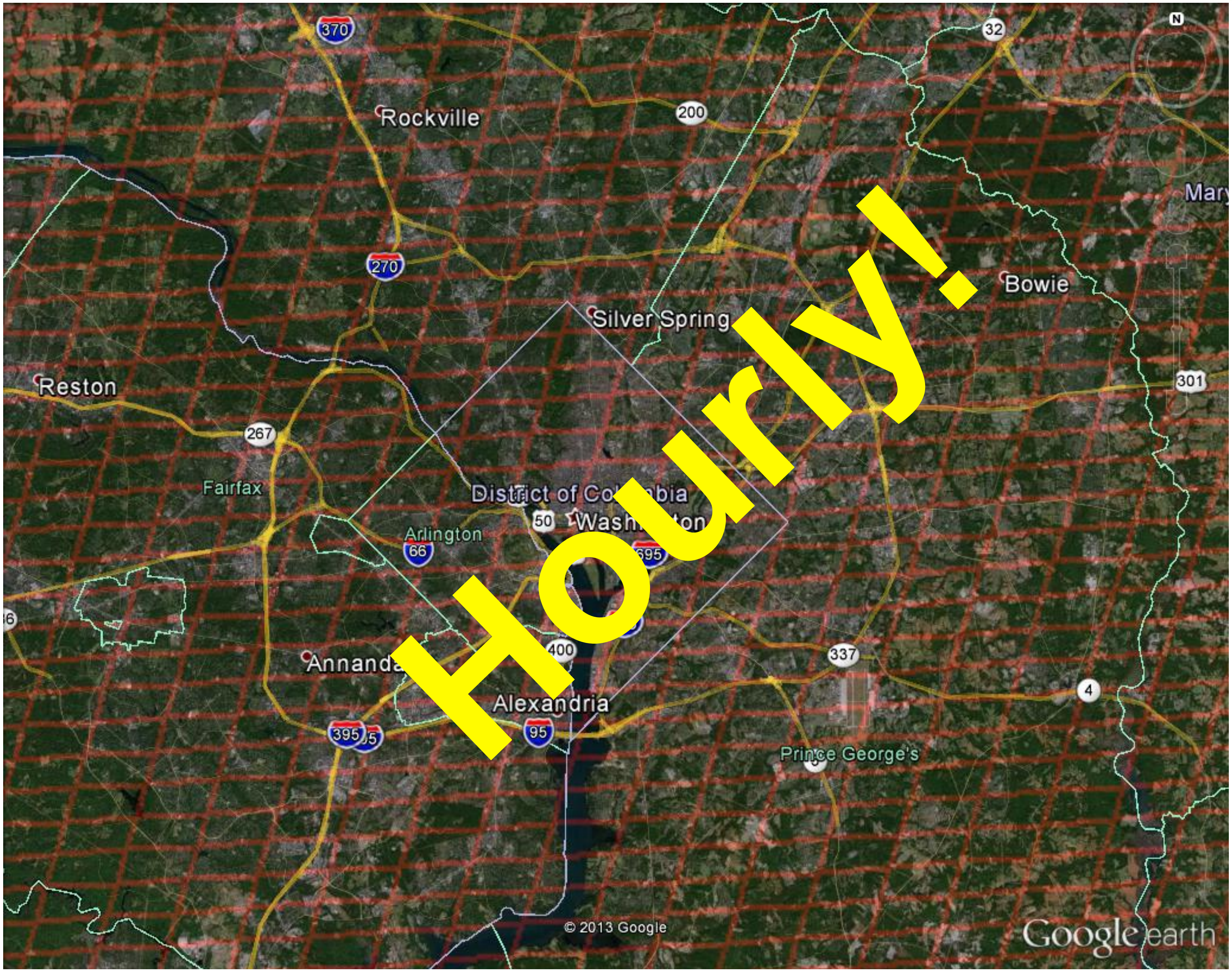
GEO will provide observations at temporal and spatial scales highly relevant to air quality processes

NO_2 over Los Angeles

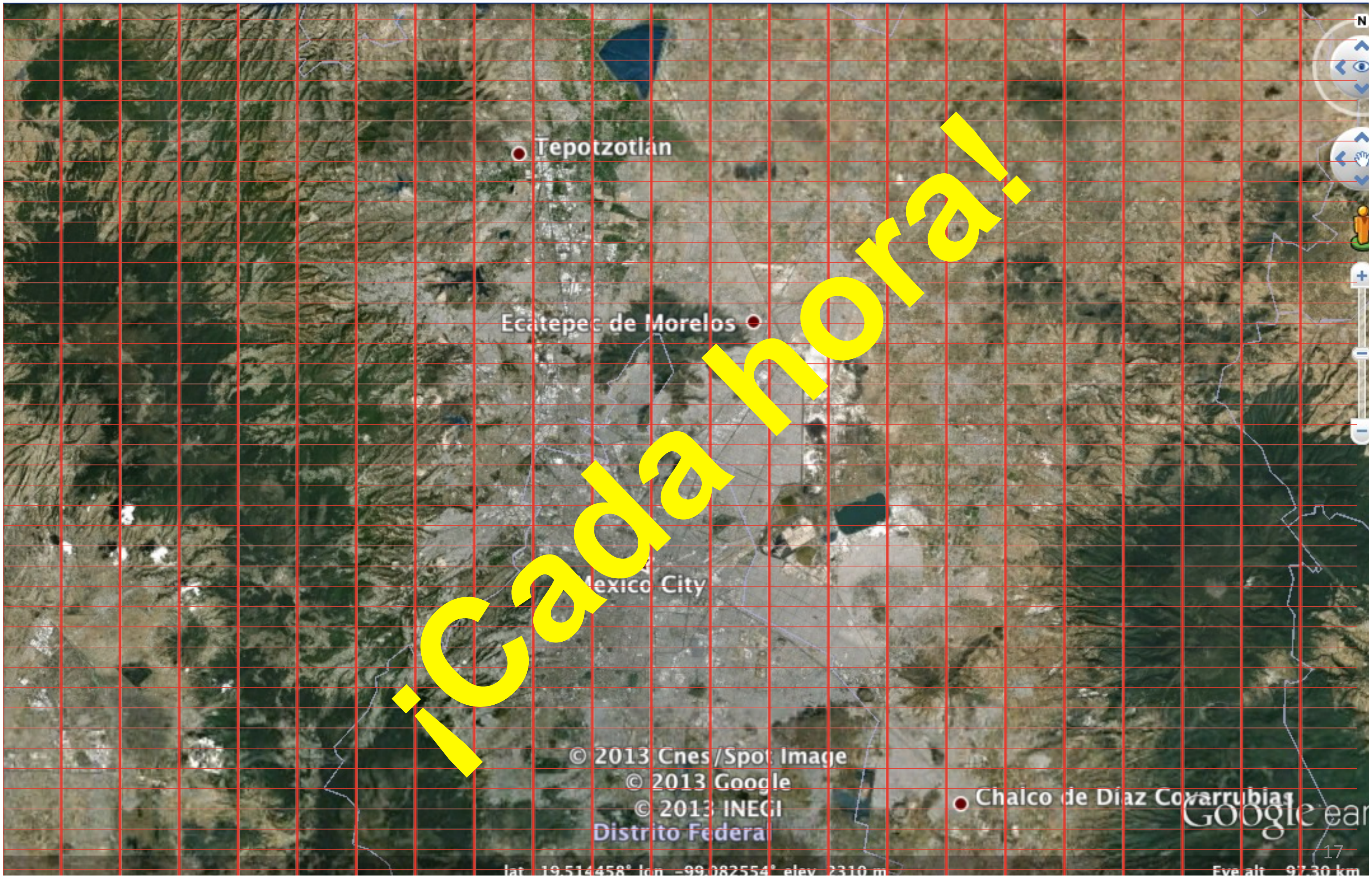


Courtesy T. Kurosu

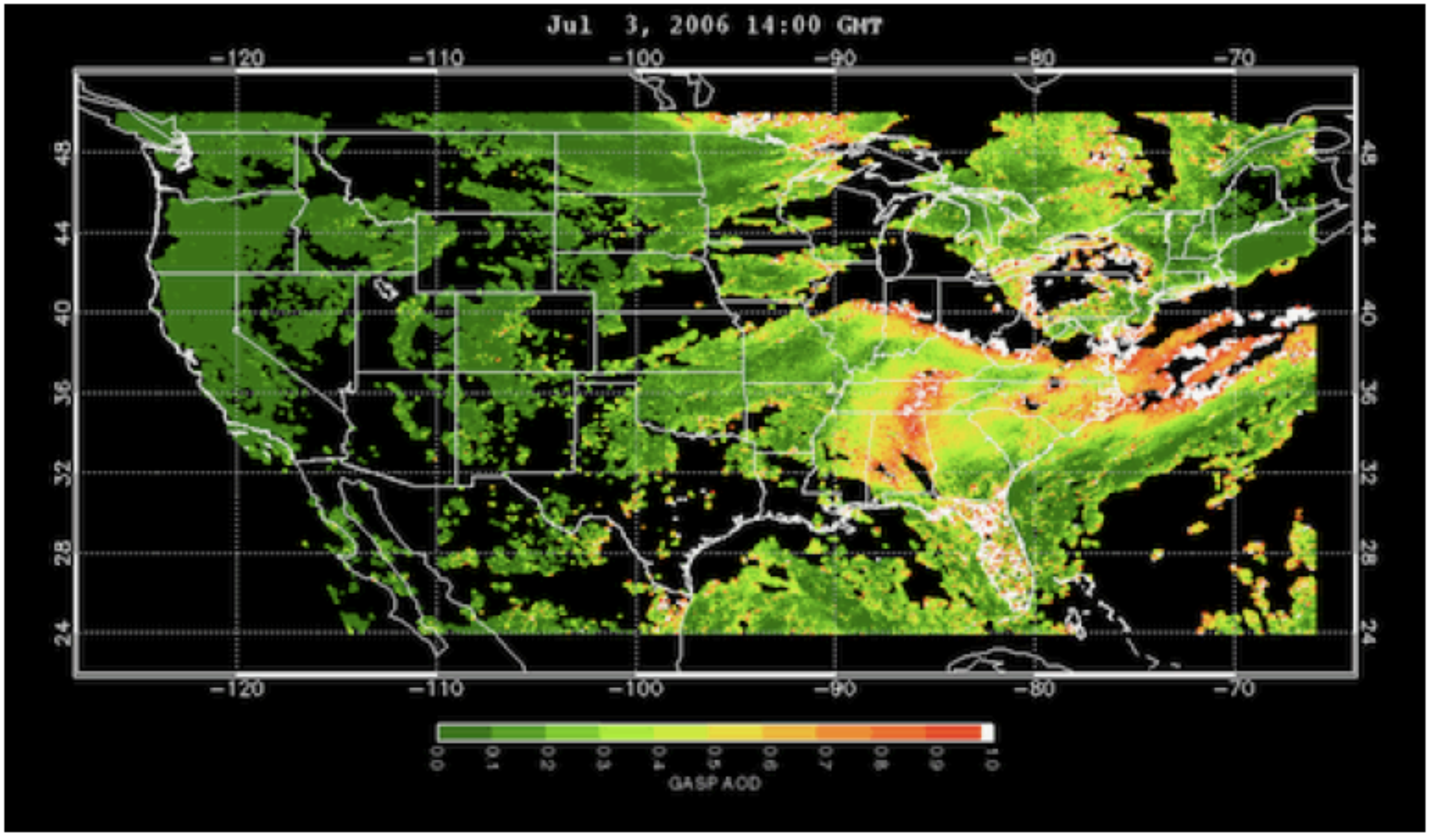
Washington, DC coverage



Mexico City coverage



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



TEMPO spectroscopic needs

- H_2O cross-section versus temperature in UV/visible
  - v7 vibrational polyad @ 440-450 nm, e.g., is ideal for H_2O monitoring from space (now operational on OMI with SAO algorithm)
  - Other bands needed for correction of interference and also possible monitoring
  - Line parameters are incomplete and will likely remain so for some time into the future
- Liquid H_2O absorption, H_2O-leaving radiance in visible, to correct for interference
- Comprehensive UV/visible O_3 spectra with temperature dependence
  - Brion, Daumont, Malicet are excellent but incomplete in temperature dependence
  - Could be extended into Wulf band
- SO_2 still incomplete in P^3 reference spectra

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!

Backups

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

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

Ball

SAINT LOUIS UNIVERSITY

NCAR

THE UNIVERSITY OF CALIFORNIA 1868

UAH

HARVARD UNIVERSITY ATMOSPHERIC CHEMISTRY MODELING GROUP

UNIVERSITY OF MARYLAND BALTIMORE COUNTY UMBC 1966

UNIVERSITY OF Nebraska Lincoln

CARR ASTRONAUTICS Science at work

RTS

The Rules

1. **Don't define your algorithm in advance**
   - *Test all steps for utility and applicability*
   - *Let the physics guide you*
2. **No black boxes**
   - *You must have and understand all source code, and be able to modify it as necessary*
   - *You must test all assumptions*
3. **Fitters must go to bedrock: (Occam's taser): If you didn't do it yourself, it isn't done (and you have to do it down to bedrock and also understand and publish all the reasons why you did it that way)**
4. **Reference data *as used* must be peer-reviewed, published, and publicly-available (*P*^{3})**
   - *no unexplained shifts in cross sections, for example*

TEMPO Science Traceability Matrix

Science Questions	Science Objective	Science Measurement Requirement: Observables	Investigation Requirements
Q1. What are the temporal and spatial variations of emissions of gases and aerosols important for AQ and climate?	**A.** High temporal resolution measurements to capture changes in pollutant gas distributions. [Q1, Q2, Q3, Q4, Q5, Q6]	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]	Mission lifetime: 1-yr (Threshold), 20-mon (Baseline), 10-yr (Goal)
Q2. How do physical, chemical, and dynamical processes determine tropospheric composition and AQ over scales ranging from urban to continental, diurnally to seasonally?	**B.** High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas. [Q1, Q2, Q3, Q5, Q6]	Measurements at spatial scales comparable to regional atmospheric chemistry models. [A, B, C, D, F, G]	Orbit Longitude °W: 90-110 (Preferred), 75-137 (Acceptable)
Q3. How do episodic events affect atmospheric composition and AQ?	**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]	Multispectral data in suitable O_3 absorption bands to provide vertical distribution information. [A, B, C, E, F, G]	GEO Bus Pointing: Control <0.1° Knowledge <0.04°
Q4. How does AQ drive climate forcing and climate change affect AQ on a continental scale?	**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]	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]	On-orbit Calibration, Validation, Verification
Q5. How can observations from space improve AQ forecasts and assessments for societal benefit?	**E.** Determine the instantaneous radiative forcings associated with O_3 and aerosols on the continental scale. [Q3, Q4, Q6]	Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles <70°. [B, D, E, F, G]	FOR encompasses CONUS and adjacent areas
Q6. How does trans-boundary transport affect AQ?	**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]		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
	G. Quantify the flow of pollutants across boundaries (physical & political); Join a global observing system. [Q2, Q3, Q4, Q5, Q6]		Distribute and archive TEMPO science data products

Physical Parameters		Instrument Function Requirements: 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

Refinement of instrument SNR requirements

- **Sensitivity studies quantify variation of trace gas performance with respect to variables including SZA, time, location, cloudiness, aerosol loading, terrain height, etc.**
- **Synthetic dataset developed from state-of-the-art (GEOS-Chem) model fields**
  - Hourly over TEMPO field of regard for 12 days (1 day/month) up to SZA 80° → ~90000 simulations
  - O_3, NO_2, H_2CO, SO_2, $C_2H_2O_2$, H_2O, BrO, OClO, O_2, O_4
  - 6 types of aerosols, water/ice clouds, pixel independent approximation
  - Koelemeijer GOME surface albedo database with linear interpolation
  - Actual viewing geometry for a geostationary satellite (e.g., 100°W)
- **RTM Calculation and Sensitivity Calculation**
  - 270-800 nm at 0.6 nm FWHM, 0.2 nm sampling
  - Include additional weighting functions with respect to AOD, ASSA, COD, cloud fraction
  - State vector includes AOD, ASSA, COD, cloud fraction additionally
  - TEMPO SNR model: account for optical transmission and grating efficiency, including shot, dark current, RTN, readout, quantization, smear, CTE noise terms

SNR requirements and instrument performance

The current TEMPO design meets SNR requirements for nominal radiances with >20% EOL margin.

Species	Spectral range (nm)	Nominal radiance phot s^{-1} cm^{-2} nm^{-1} sr^{-1}	Req'd. SNR	Actual SNR	EOL margin
O_3	290-300	6.74×10^{10}	48.2	64.2	33.3%
O_3	300-345	7.07×10^{12}	1134	1512	33.3%
O_3	540-650	1.19×10^{13}	1327	1769	33.3%
SO_2	305-345	7.93×10^{12}	1399	1683	20.3%
H_2CO	327-356	1.25×10^{13}	763	2277	198%
Cloud	346-354	1.26×10^{13}	1200	2265	88.8%*
AOD	354-388	1.25×10^{13}	1414	2213	56.5%**
NO_2	423-451	1.65×10^{13}	963	2609	171%
$C_2H_2O_2$	420-465	1.74×10^{13}	1897	2629	38.6%
Vegetation	700-740	1.36×10^{13}		923	
* SNR of 600 is needed at native resolution of ~2.2×5.1 km^2					
** SNR of 1000 is needed at native resolution using OMI UV aerosol algorithm (354+388 nm)					

Measurement requirements

Species	Required precision	Sensitivity driver
Trop O_3	10 ppbv	Hourly for SZA ≤ 70º
Free trop O_3	10 ppbv	Hourly for SZA ≤ 70º
0-2 km O_3	10 ppbv	Hourly for SZA ≤ 70º
Total O_3	3%	Hourly for SZA ≤ 70º
NO_2	1.0×10^{15}	Hourly for SZA ≤ 70º
H_2CO	1.0×10^{16} 1.73×10^{16}	3/day for SZA ≤ 70º or Hourly for SZA ≤ 70º
SO_2	1.0×10^{16} 1.73×10^{16}	3/day for SZA ≤ 50º or Hourly for SZA ≤ 50º
$C_2H_2O_2$	4.0×10^{14} 6.98×10^{14}	3/day for SZA ≤ 70º or Hourly for SZA ≤ 70º
AOD	0.10	Hourly for SZA ≤ 70º

- Spatial Resolution: ~8.84×5.11 km^2 or better at the center of the field of regard
- Aerosol: requires smaller native pixels for cloud clearing.
- NO_2, H_2CO, $C_2H_2O_2$, SO_2 are in vertical column densities (VCDs; molecules cm^{-2})

- TEMPO STM: from GEO-CAPE STM with modifications:
  - H_2CO, SO_2, $C_2H_2O_2$: scale precision from 3 times/day to hourly
  - SZA req. for H_2CO & $C_2H_2O_2$ is changed to 70º. Still 50º for SO_2.
- STM measurement requirements → Instrument requirements.

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**

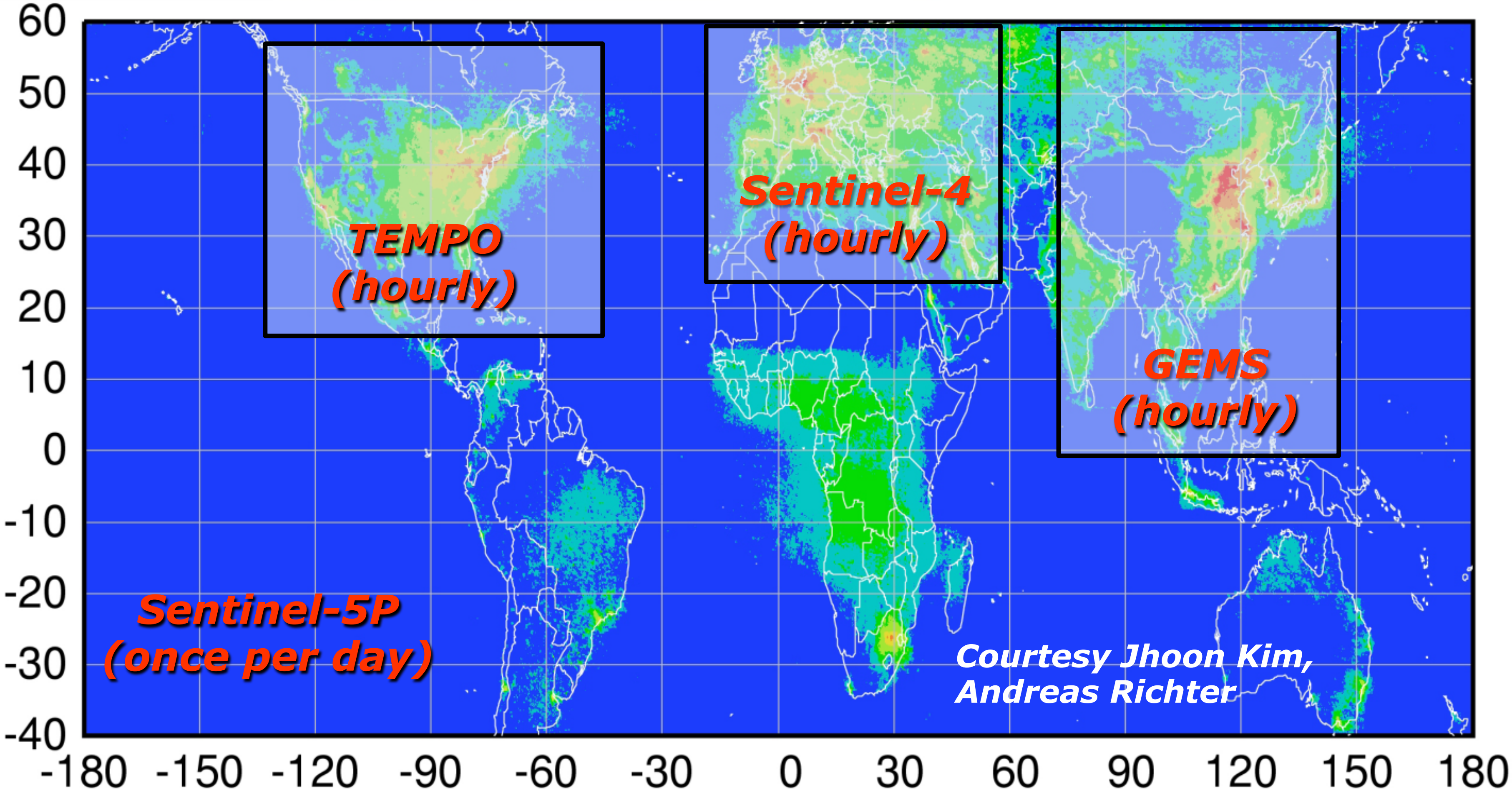
- **Minimal set of products sufficient for constraining air quality**
- **Field of Regard (FOR) is Greater North America, depending on host satellite selected:**
  - **At least 19°N to 57.5°N near 100°W**
  - **At least 67°W to 125°W near 42°N**
- **Data products at urban-regional spatial scales**
  - **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**

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.

Science summary

- The TEMPO mission addresses NASA's Strategic Plan:
  - Strategic Goal 2: Expand scientific understanding of the Earth and the universe in which we live
    - Advance Earth system science to meet the challenges of climate and environmental change
- The science objectives of the mission lead to specific mission, measurement, and instrument requirements
- The existing TEMPO mission meets these Level 1 requirements
- Have defined Baseline and Threshold science requirements
- The project science team, instrument team, mission team and PI are working closely together to have a successful mission.