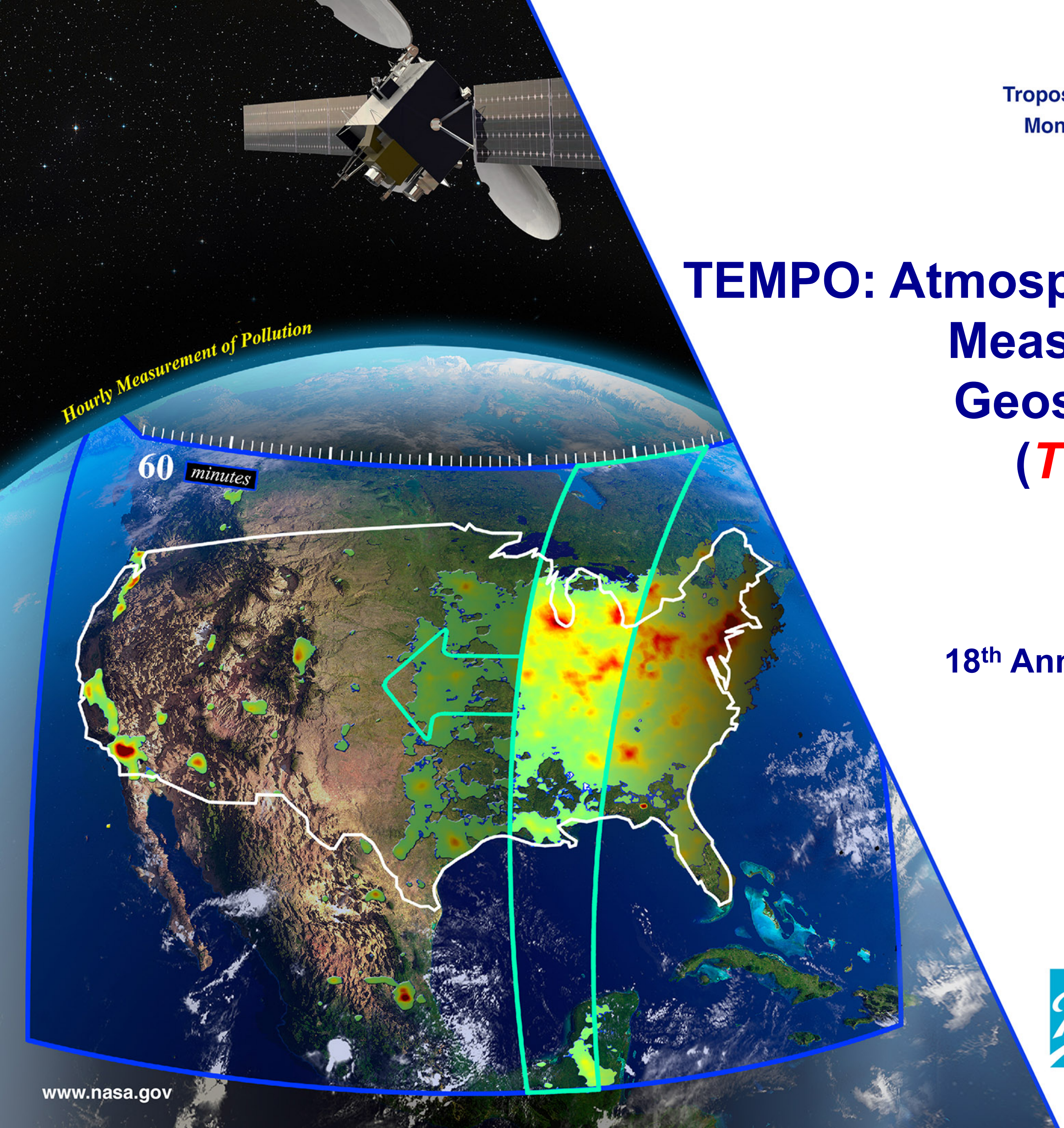
Tropospheric Emissions:
Monitoring of Pollution



TEMPO: Atmospheric Pollution Measurements from Geostationary Orbit (*TEMPO.SI.EDU!*)

Kelly Chance

18th Annual CMAS Conference
UNC Chapel Hill
October 21, 2019

Smithsonian

TEMPO

Hourly atmospheric pollution from geostationary Earth orbit

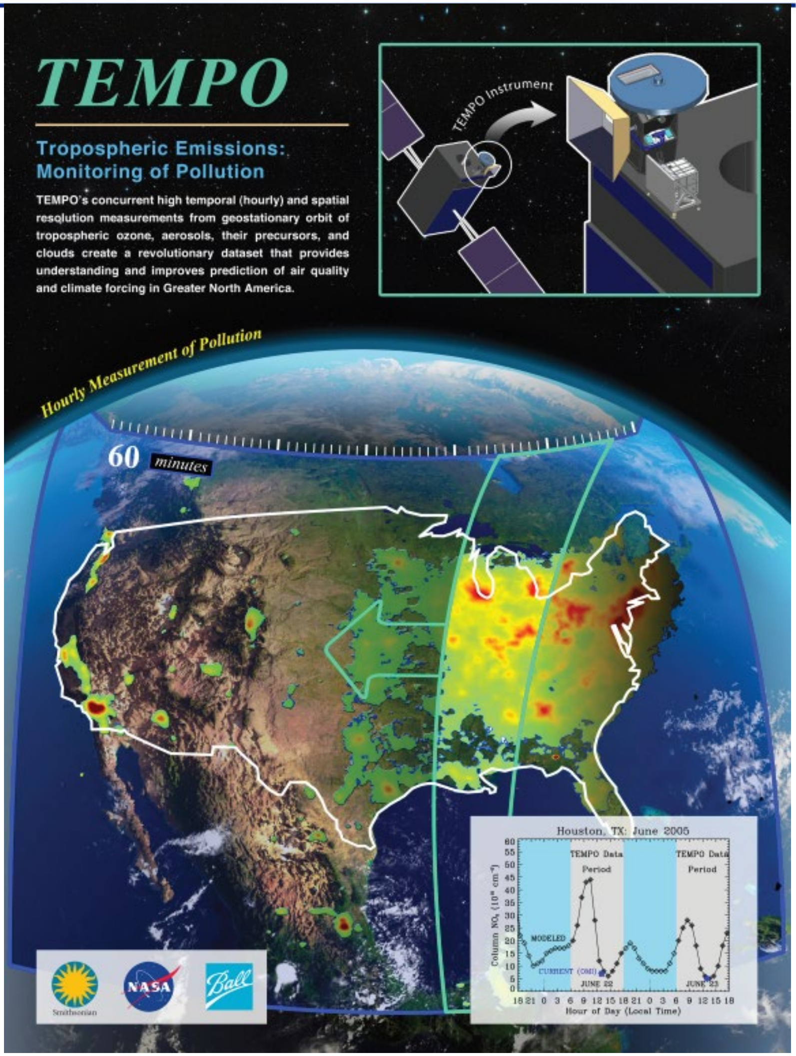
PI: Kelly Chance, Smithsonian Astrophysical Observatory
Deputy PI: Xiong Liu, Smithsonian Astrophysical Observatory
Instrument Development: Ball Aerospace
Project Management: NASA LaRC
Other Institutions: NASA GSFC, NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, U.K., ESA, Spain

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

- Instrument delivery 2018
- NASA has arranged hosting on a commercial geostationary communications satellite with launch expected 2/2022

Provides hourly daylight observations to capture rapidly varying emissions & chemistry important for air quality

- Distinguishes boundary layer from free tropospheric & stratospheric ozone



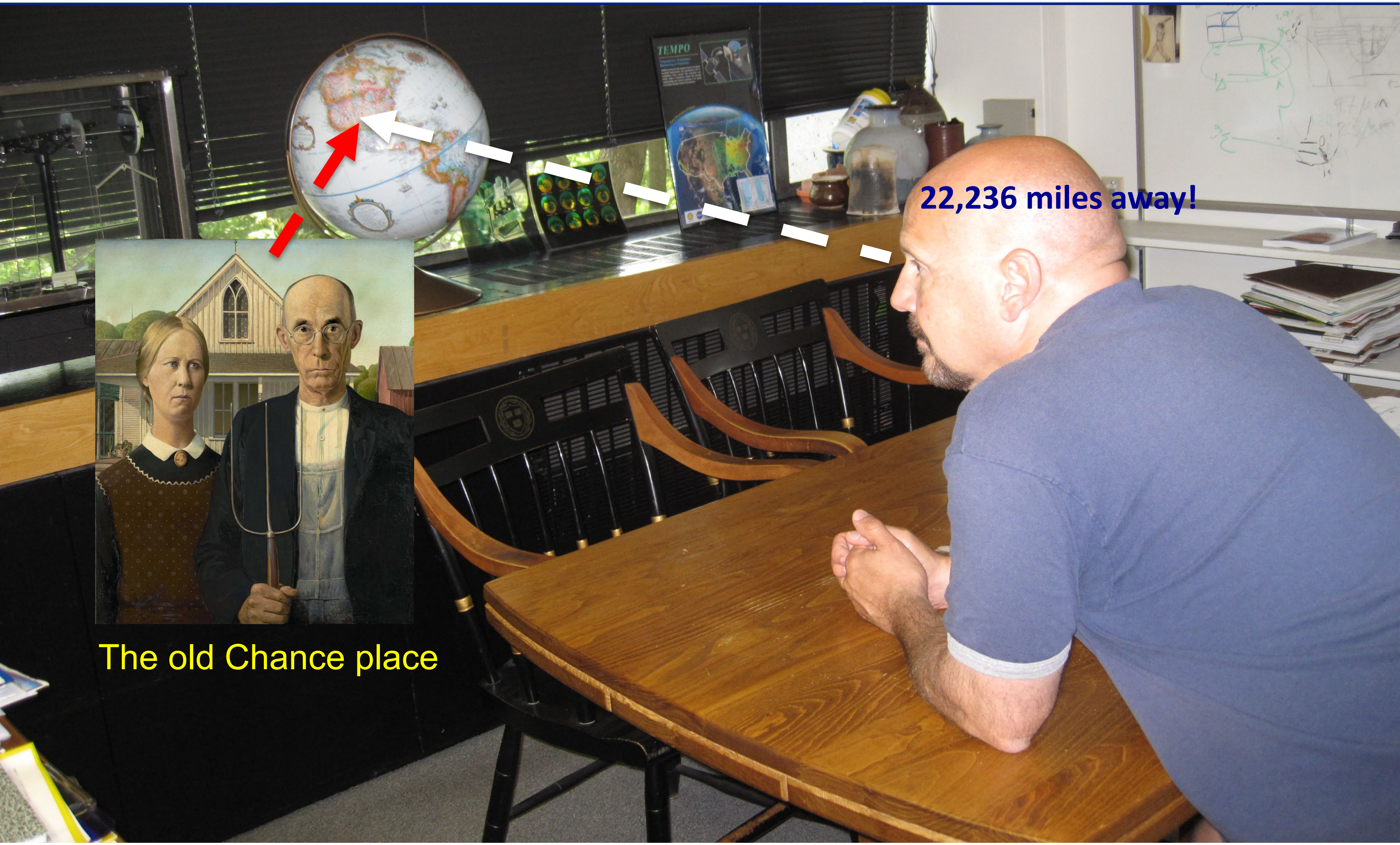
TEMPO

Tropospheric Emissions: Monitoring of Pollution

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

North American component of an international constellation for air quality observations

The view from GEO

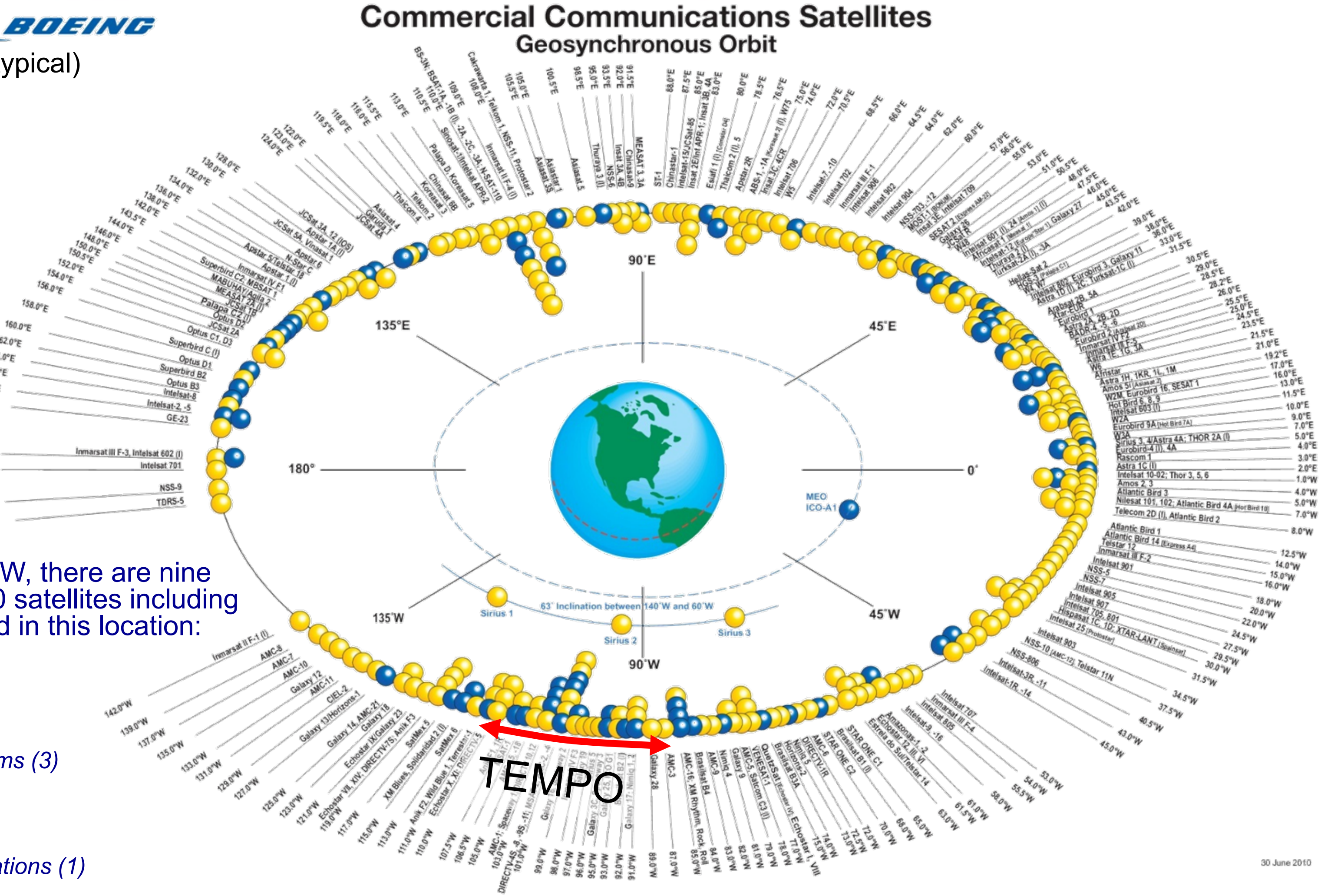


22,236 miles away!

The old Chance place

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:

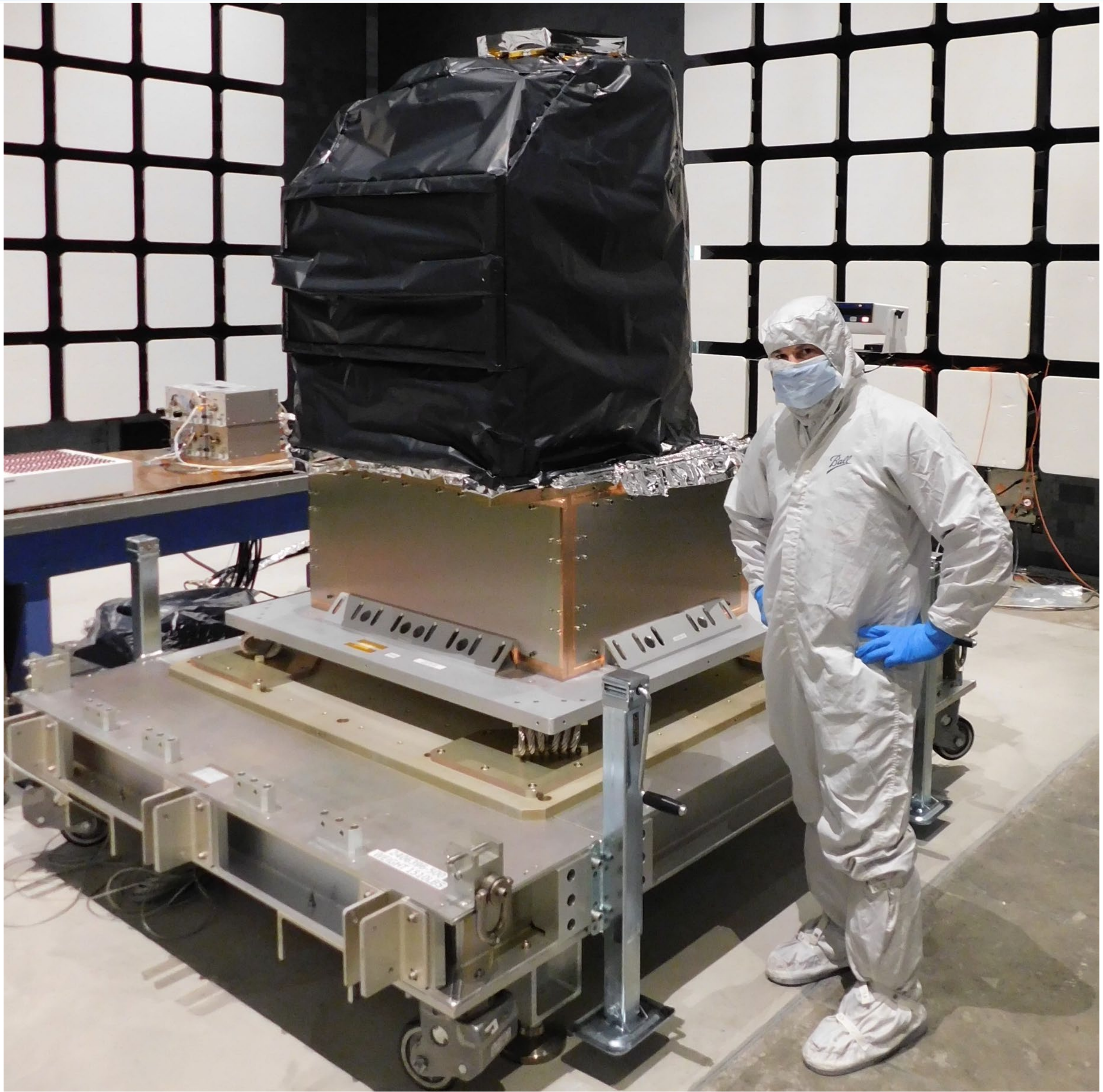
- *Direct TV Group (7)*
- *AGS (5)*
- *Intelsat (5)*
- *Telesat (4)*
- *Hughes Network Systems (3)*
- *Echostar (2)*
- *SkyTerra (2)*
- *Inmarsat (1)*
- *ICO Global Communications (1)*

TEMPO will be located at 91° West

TEMPO status

- Instrument completed, accepted, delivered, now in storage
- Commercial geostationary satellite host selected for launch in February 2022 to 91^{o}W

Ready for storage



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)
  - Measurement requirements met up to 50^o for SO_2, 70^o SZA for other products

TEMPO science questions

1. What are the temporal and spatial variations of **emissions of gases and aerosols important for air quality** and climate?
2. What are the physical, chemical, and dynamical **processes that transform 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?

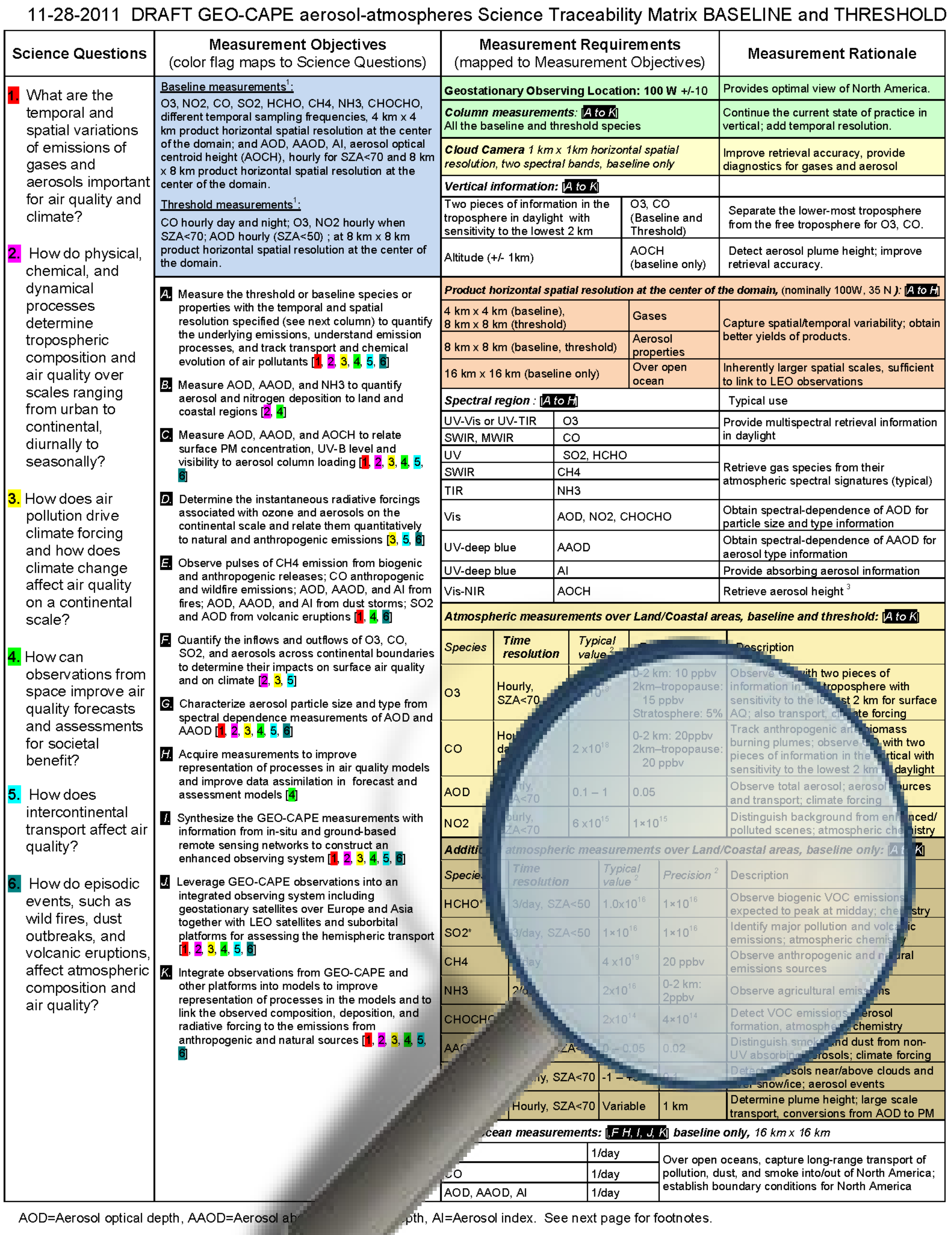
TEMPO Science Team, U.S.

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. Iowa	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)

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]10^18	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe [illegible] with two pieces of information in [illegible] troposphere with sensitivity to the lo[illegible]st 2 km for surface AQ; also transport, c[illegible]ate forcing
CO	Ho[illegible] da[illegible]	2×10^{18}	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic an[illegible]iomass burning plumes; observe [illegible] with two pieces of information in the [illegible]rtical with sensitivity to the lowest 2 km [illegible] daylight
AOD	[illegible]rly, [illegible]A<70	0.1 – 1	0.05	Observe total aerosol; aerosol [illegible]urces and transport; climate forcing
NO2	[illegible]ourly, [illegible]ZA<70	6×10^{15}	1×10^{15}	Distinguish background from en[illegible]nced/ polluted scenes; atmospheric che[illegible]istry

Additi[illegible] atmospheric measurements over Land/Coastal areas, baseline only: [A t[illegible]K]

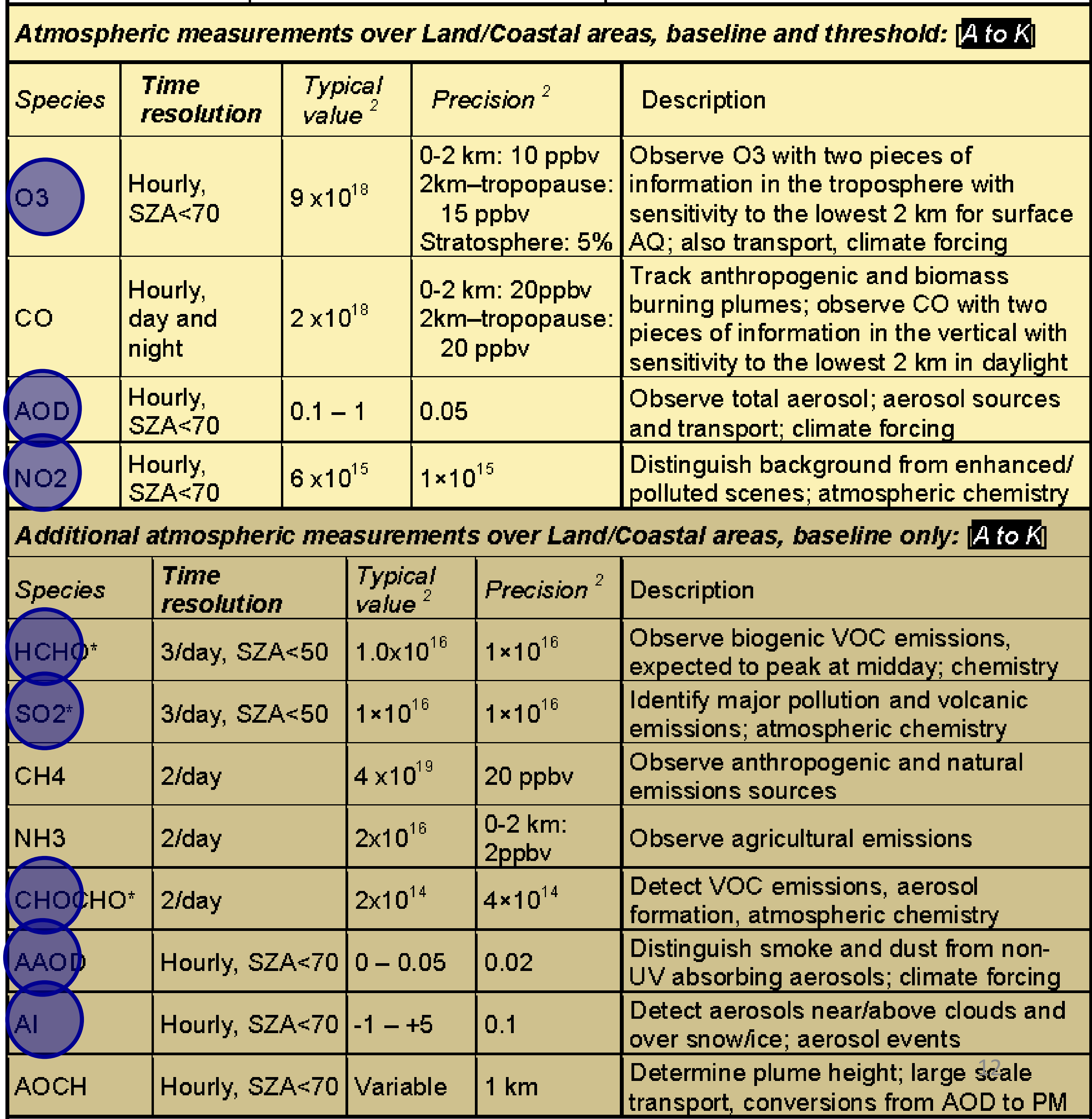
Specie[illegible]	*Time resolution*	*Typical value* [2]	*Precision* [2]	Description
HCHO*	3/day, SZA<50	1.0×10^{16}	1×10^{16}	Observe biogenic VOC emissions expected to peak at midday; che[illegible]stry
SO2*	3/day, SZA<50	1×10^{16}	1×10^{16}	Identify major pollution and volca[illegible]ic emissions; atmospheric chemis[illegible]y
CH4	[illegible]day	4×10^{19}	20 ppbv	Observe anthropogenic and n[illegible]ural emissions sources
NH3	2/[illegible]	2×10^{16}	0-2 km: 2ppbv	Observe agricultural emiss[illegible]ns
CHOCH[illegible]	[illegible]	2×10^{14}	4×10^{14}	Detect VOC emissions, [illegible]erosol formation, atmosphe[illegible] chemistry
AA[illegible]	[illegible]ZA<[illegible]	0 – 0.05	0.02	Distinguish smok[illegible]nd dust from non-UV absorbin[illegible]erosols; climate forcing
[illegible]	[illegible]ly, SZA<70	-1 – +[illegible]	[illegible]	Detect [illegible]osols near/above clouds and [illegible]ver 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.

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



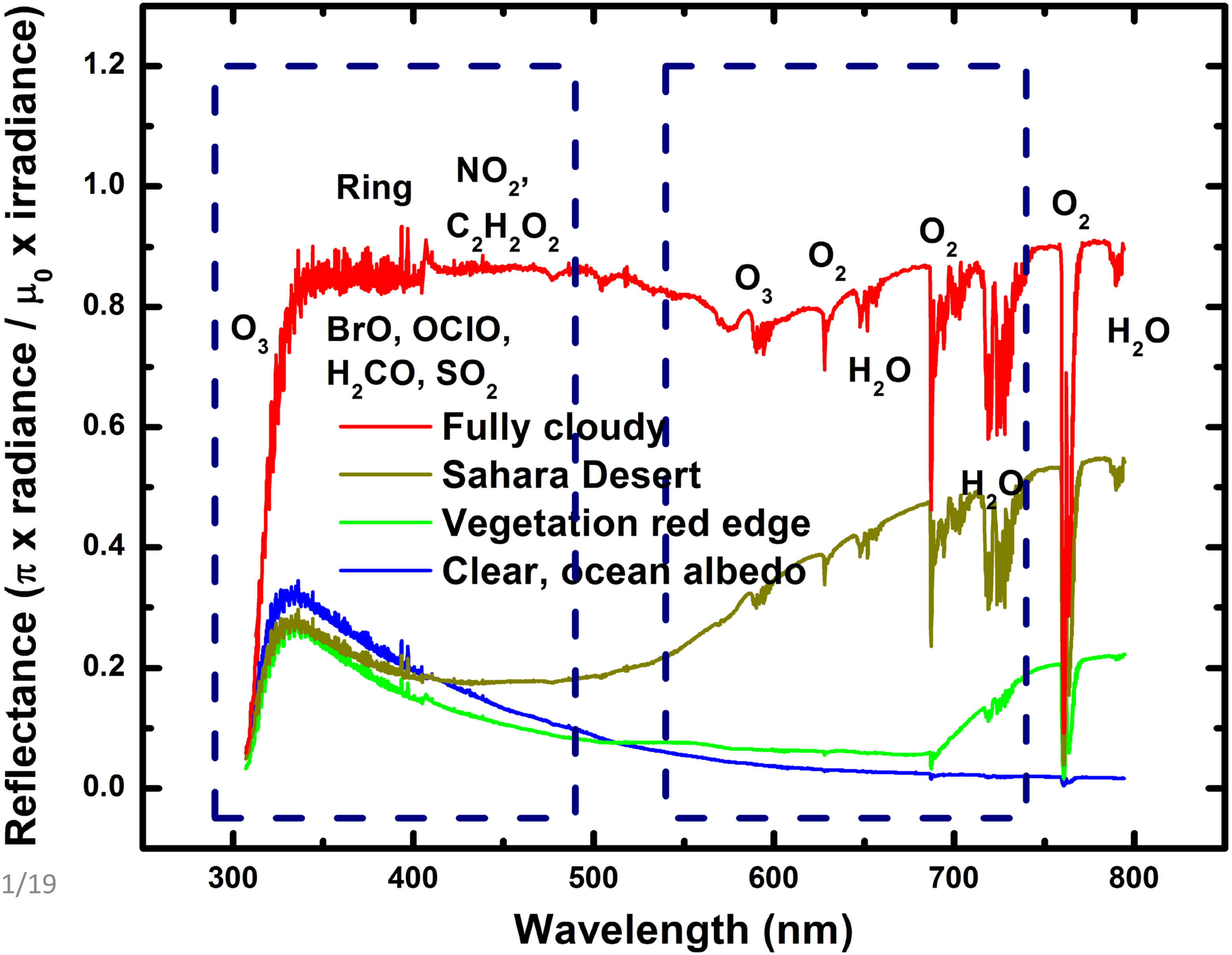
Atmospheric measurements over Land/Coastal areas, baseline and threshold: A to K

Species	Time resolution	Typical value [2]	Precision [2]	Description
O3	Hourly, SZA<70	9 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)



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

More than 10 billion measurements of spectra!

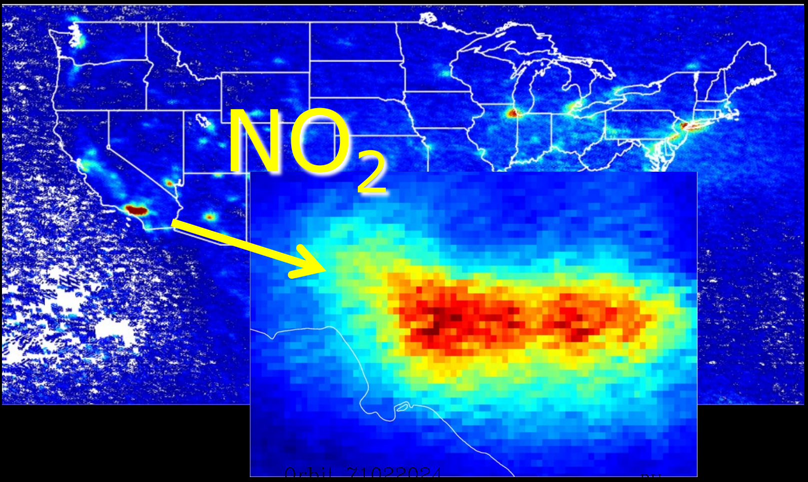
Previous experience (since 1985 at SAO and MPI)

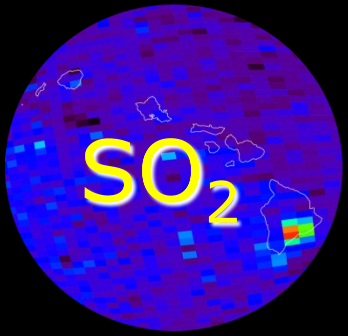
Scientific and operational measurements of pollutants O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$ (& CO, CH_4, BrO, OClO, ClO, IO, H_2O, O_2-O_2, Raman, aerosol, ….)

LEO measurement capability

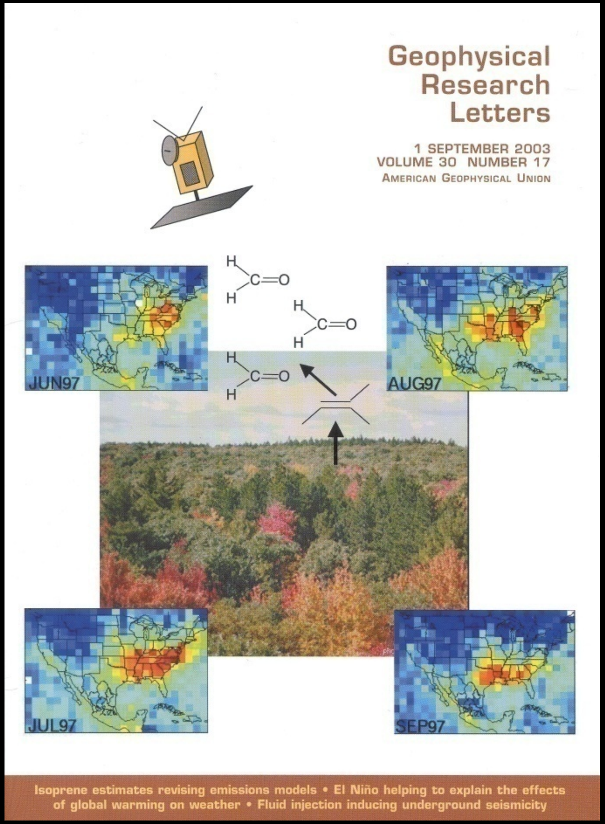
A full, minimally-redundant, set of polluting gases, plus aerosols and clouds is now measured to very high precision from satellites. Ultraviolet and visible spectroscopy of backscattered radiation provides O_3 (including profiles and tropospheric O_3), NO_2 (for NO_x), H_2CO and $C_2H_2O_2$ (for VOCs), SO_2, H_2O, O_2, O_2-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.

GOME, SCIAMACHY, and OMI examples





Kilauea activity, source of the VOG event in Honolulu on 9 November 2004



Geophysical Research Letters

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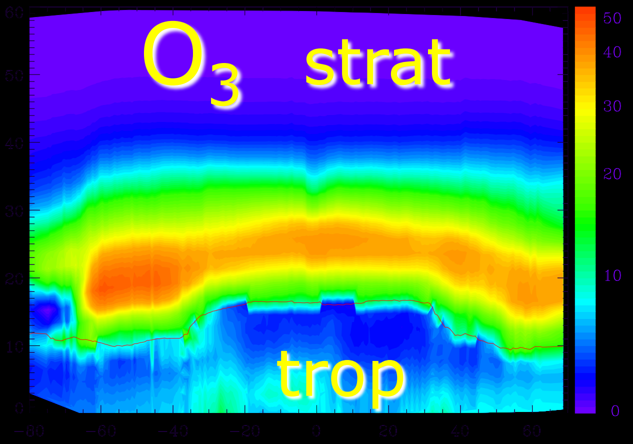
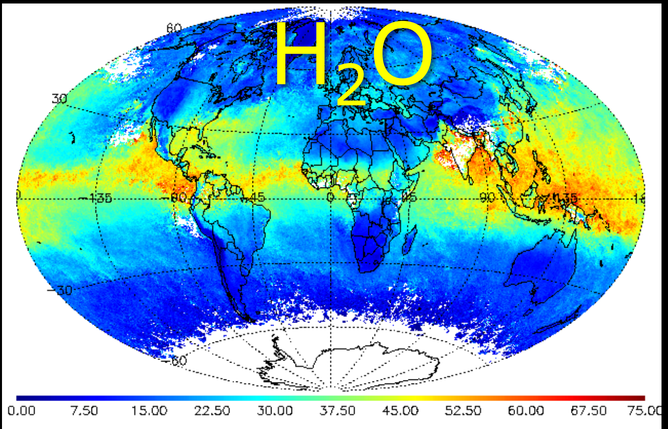
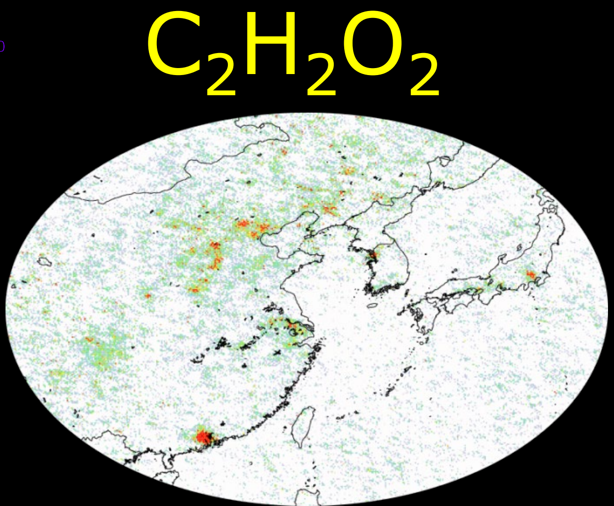
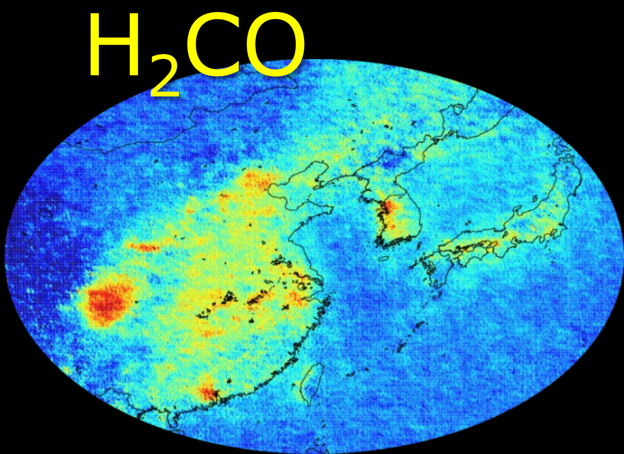
AMERICAN GEOPHYSICAL UNION

Isoprene estimates revising emissions models • El Niño helping to explain the effects of global warming on weather • Fluid injection inducing underground seismicity







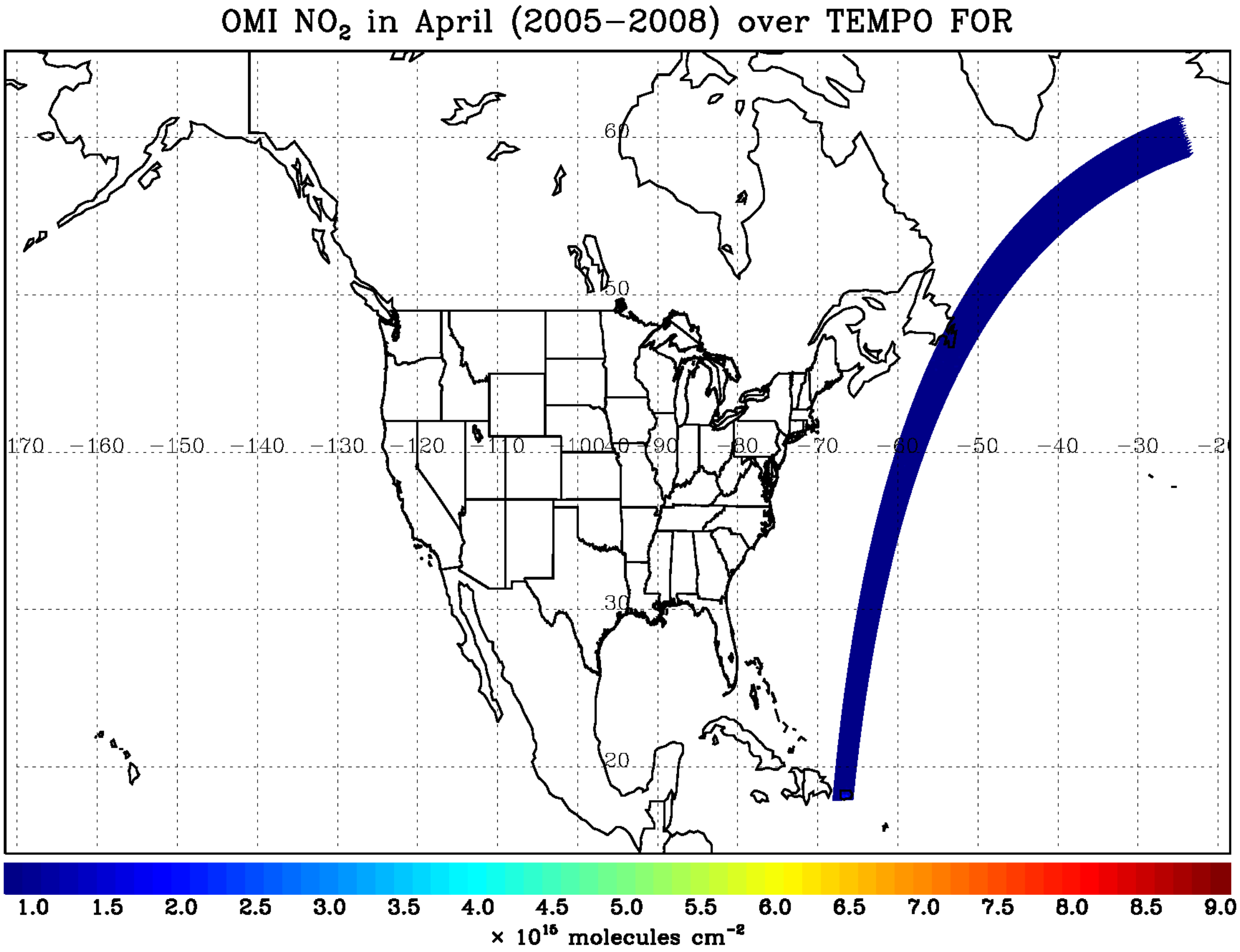


Baseline and threshold data products

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**
- **Geolocation uncertainty of less than 4 km**
- **Mission duration, subject to instrument availability**
  - **Baseline 20 months**
  - **Threshold 12 months**

TEMPO hourly NO_2 sweep (GEO @92.85W)



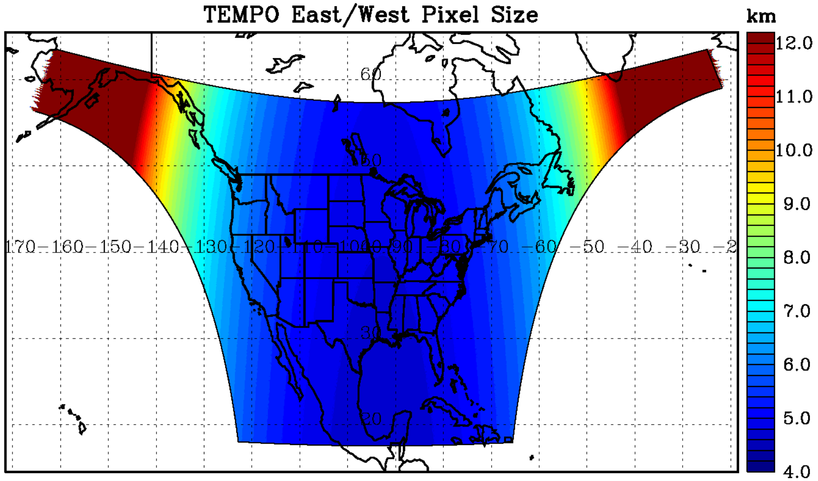
Boresight: 34N, 91W
~ 2034 good N/S pixels

- **~ 1282 scans/hr**
- **~ 2.6 M pixels/hr**
- **Data rate: ~31.2 Mbs (~20 times of OMI data, comparable to TROPOMI)**
- **Scanning partial FOV at ≤ 10 min allowed up to 25% of time**

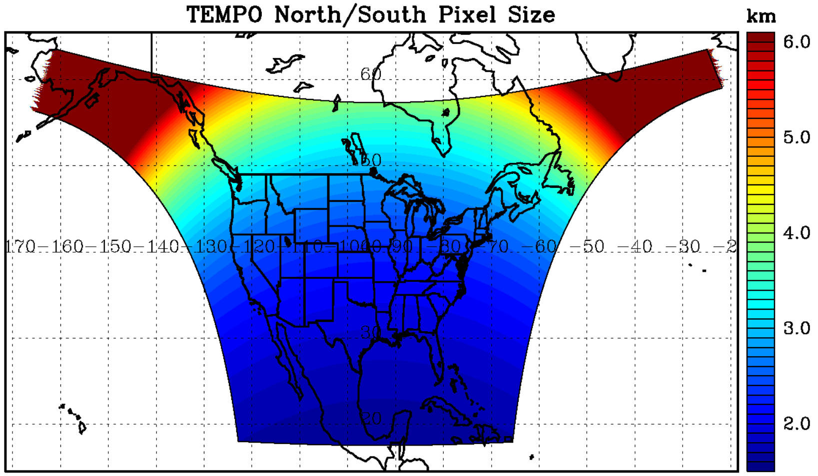
TEMPO footprint (GEO @91° W)

- **Boresight at 33.76°N, 92.85°W**

TEMPO East/West Pixel Size

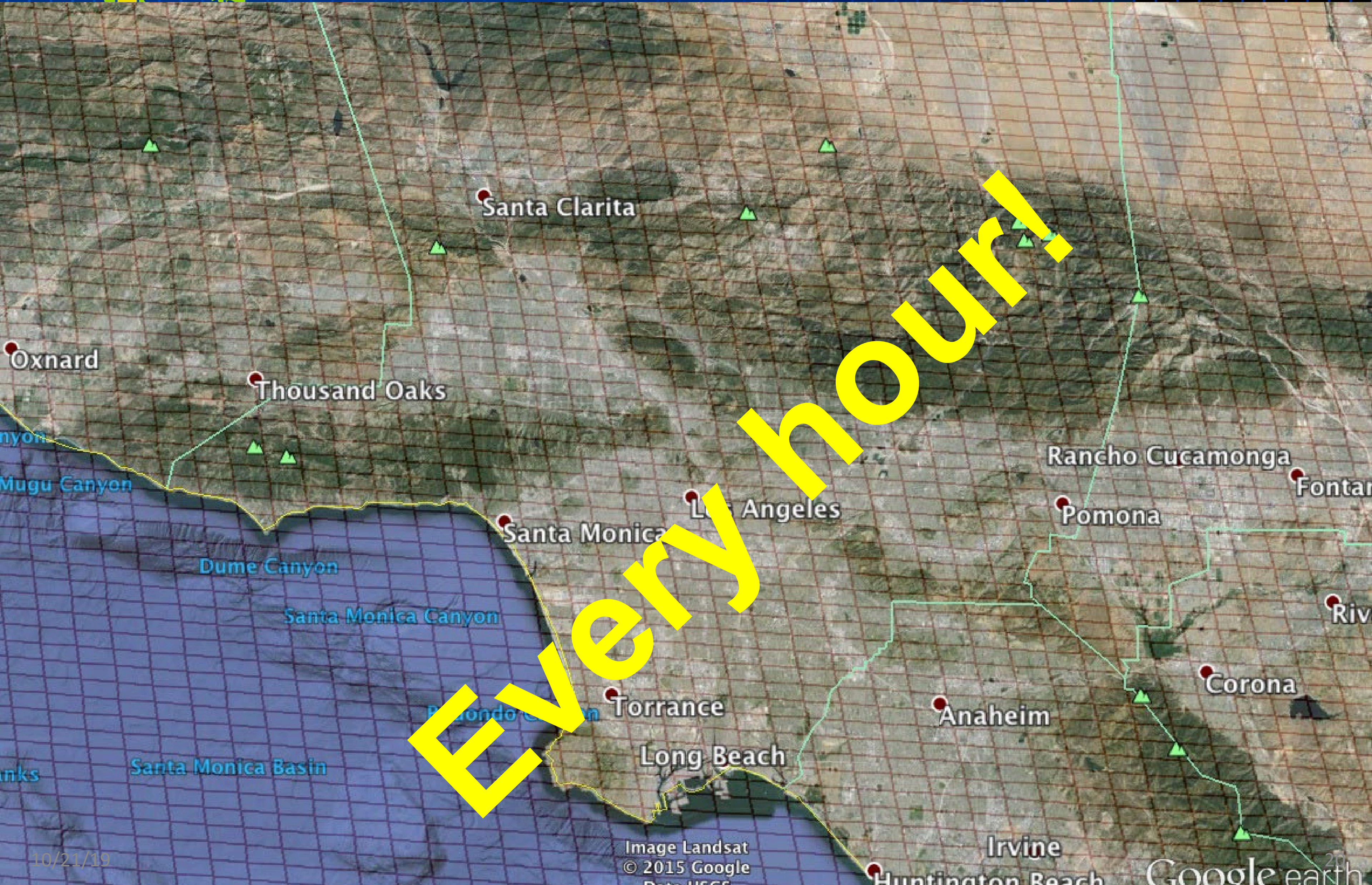


TEMPO North/South Pixel Size



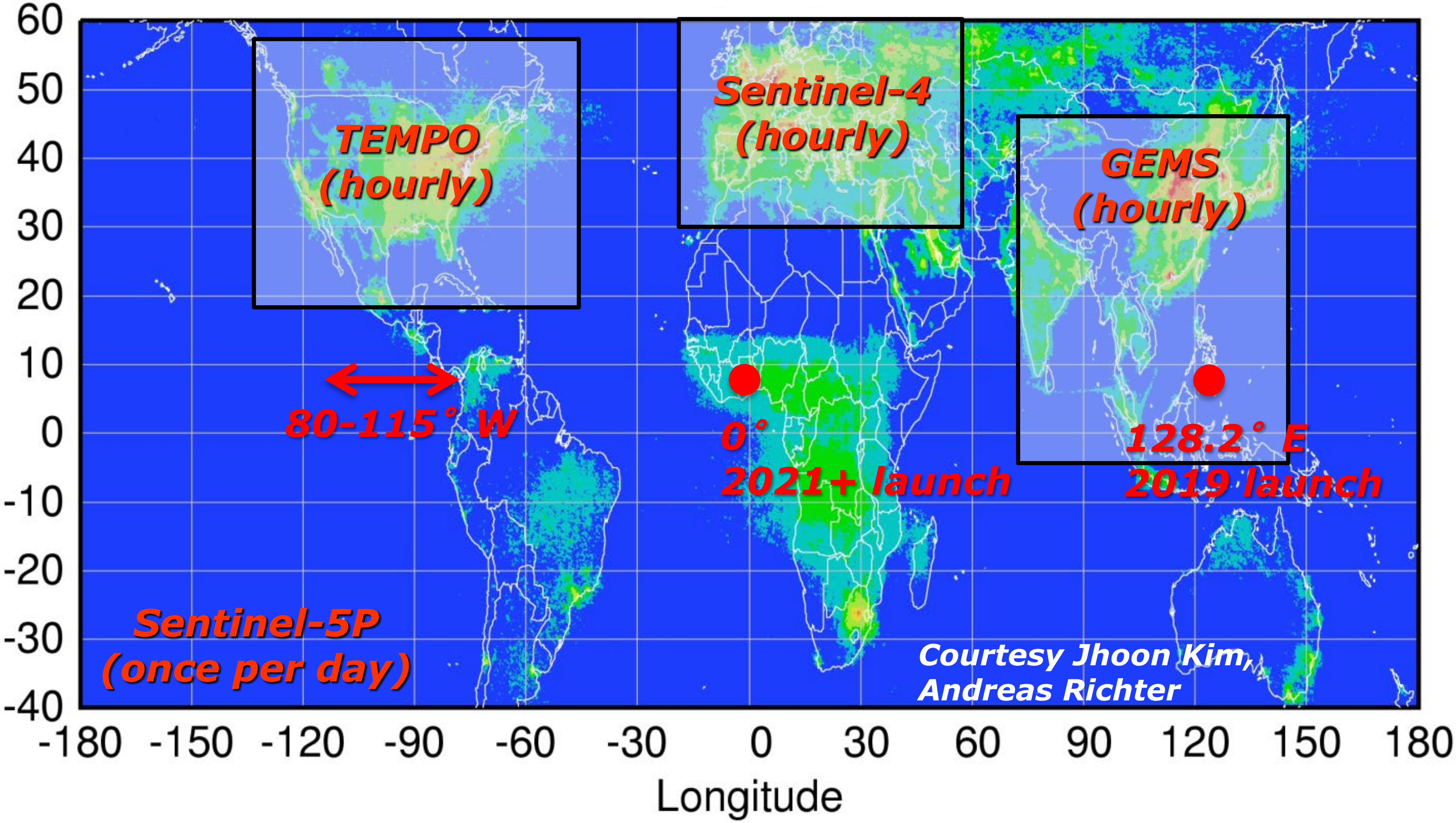
Location	N/S (km)	E/W (km)	GSA (km²)	VZA (°)
Boresight	2.0	4.8	9.5	39.3
36.5°N, 100°W	2.1	4.8	10.1	42.4
Washington, DC	2.3	5.1	11.3	48.0
Seattle	3.2	6.2	16.8	61.7
Los Angeles	2.1	5.6	11.3	48.0
Boston	2.5	5.5	13.0	53.7
Miami	1.8	4.9	8.6	33.2
San Juan	1.7	5.6	9.2	37.4
Mexico City	1.6	4.7	7.7	23.9
Can. tar sands	4.1	5.6	20.8	67.0
Juneau	6.1	9.1	33.3	75.3

Los Angeles coverage



Every hour!

Global pollution monitoring constellation



Courtesy Jhoon Kim, Andreas Richter

TEMPO

The TEMPO Green Paper

Smithsonian NASA

Chemistry, physics, and meteorology experiments with the Tropospheric Emissions: Monitoring of Pollution instrument

Now at: https://www.cfa.harvard.edu/atmosphere/publications.html

K. Chance[a], X. Liu [a], C. Chan Miller[a], G. González Abad [a], G. Huang[b], C. Nowlan [a], A. Souri [a], R. Suleiman [a], K. Sun[c], H. Wang [a], L. Zhu [a], P. Zoogman [a], J. Al-Saadi[d], J.-C. Antuña-Marrero[e], J. Carr[f], R. Chatfield[g], M. Chin[h], R. Cohen[i], D. Edwards[j], J. Fishman[k], D. Flittner[d], J. Geddes[l], M. Grutter[m], J.R. Herman[n], D.J. Jacob[o], S. Janz[h] J. Joiner[h], J. Kim[p], N.A. Krotkov[h], B. Lefer[q], R.V. Martin,[a,r,s], O.L. Mayol-Bracero[t], A. Naeger[u], M. Newchurch[u], G.G. Pfister[j], K. Pickering[v], R.B. Pierce[w], C. Rivera Cárdenas[m], A. Saiz-Lopez[x], W. Simpson[y], E. Spinei[z], R.J.D. Spurr[aa], J.J. Szykman[bb], O. Torres[h], J. Wang[cc]

NORMAL TIME RESOLUTION STUDIES

- Air quality and health
- Ultraviolet exposure
- Biomass burning
- Synergistic GOES-16/17 Products
- Advanced aerosol products
- Soil NO_x after fertilizer application and after rainfall
- Solar-induced fluorescence from chlorophyll
- Foliage studies
- Mapping NO_2 and SO_2 dry deposition at high resolution
- Crop and forest damage from ground-level ozone
- Halogen oxide studies in coastal and lake regions
- Air pollution from oil and gas fields
- Night light measurements resolving lighting type
- Ship tracks, drilling platform plumes, and other concentrated sources.
- Water vapor studies
- Volcanoes
- Socio-economic studies
- National pollution inventories
- Regional and local transport of pollutants
- Sea breeze studies for Florida and Cuba
- Transboundary pollution gradients
- Transatlantic dust transport

HIGH TIME RESOLUTION EXPERIMENTS

- Lightning NO_x
- Morning and evening higher-frequency scans
- Dwell-time studies and temporal selection to improve detection limits
- Exploring the value of TEMPO in assessing pollution transport during upslope flows
- Tidal effects on estuarine circulation and outflow plumes
- Air quality responses to sudden changes in emissions
- Cloud field correlation with pollution
- Agricultural soil NO_x emissions and air quality

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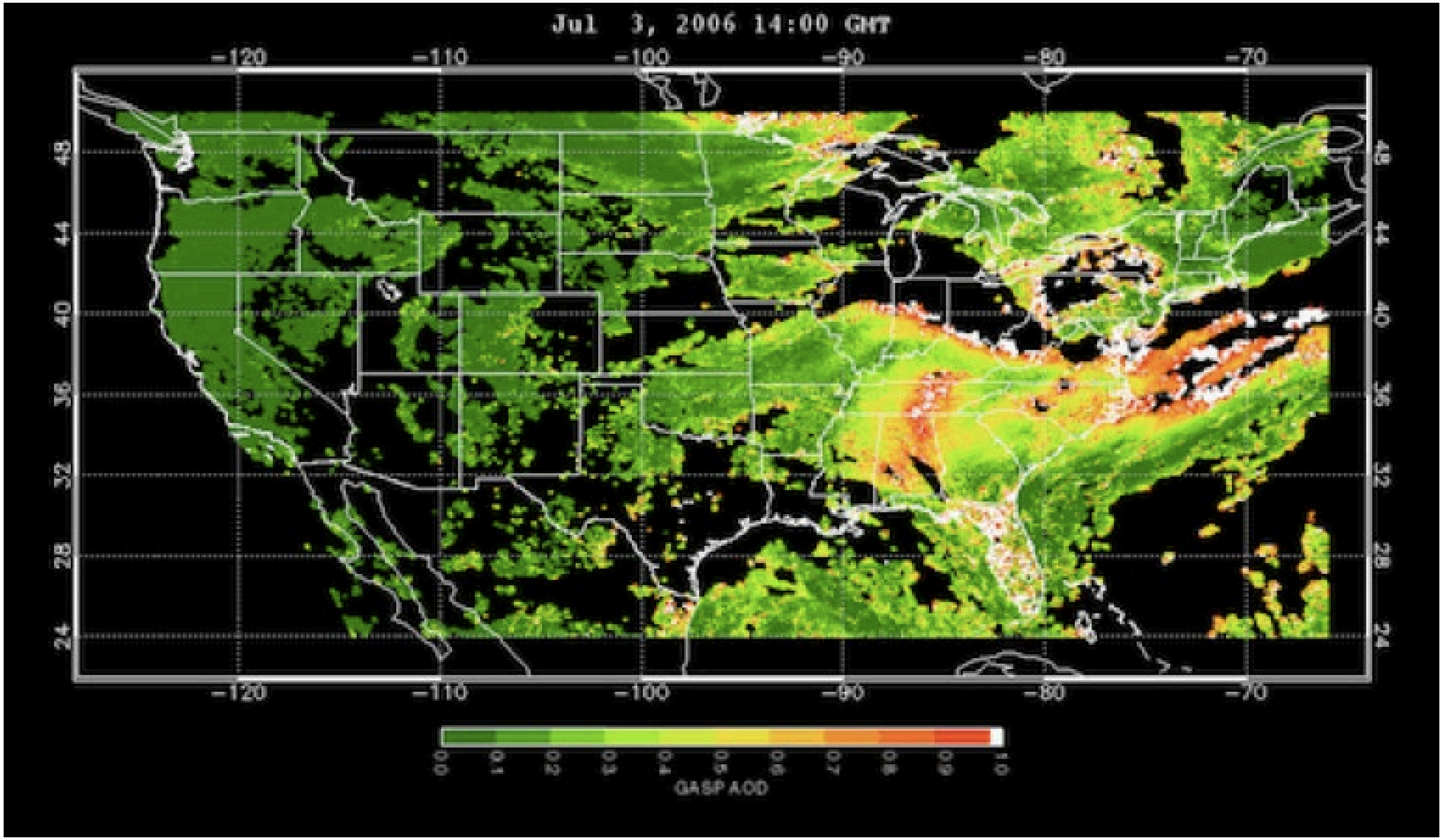
Ship tracks, drilling platform plumes, and other concentrated sources.	**Cloud field correlation with pollution**
Water vapor studies	**Agricultural soil NO_x emissions and air quality**

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*



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).

Experimental opportunities

The TEMPO Green Paper living document is at http://tempo.si.edu/publications. Please feel free to contribute

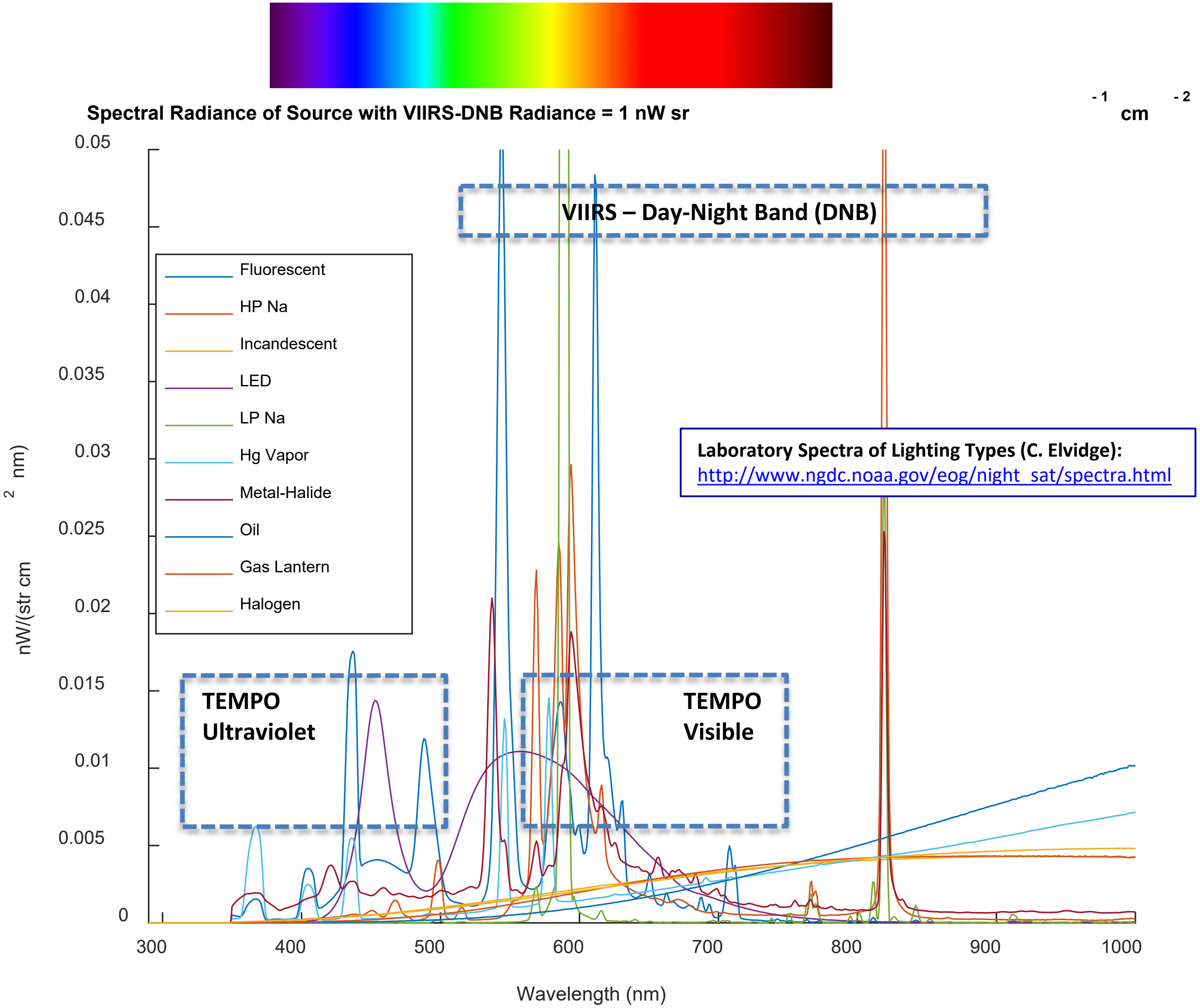
1. **Up to 25% of observing time can be devoted to non-standard operations: Time resolution higher, E/W spatial coverage less**
2. **Two types of studies under regular or non-standard operations**
    1. **Events (*e.g.*, eruptions, fires, dust storms, etc.)**
    2. **Experiments (*e.g.*, agriculture, forestry, NO_x, ….)**
3. **TEMPO team will work with experimenters concerning Image Navigation and Registration (*i.e.*, pointing resolution and accuracy)**
4. **Experiments could occur during commissioning phase**
5. **Hope to include SO_2, aerosol, H_2O, and $C_2H_2O_2$ as operational products**
6. **Can initiate a non-standard, pre-loaded scan pattern within several hours**
7. **Send your ideas into a TEMPO team member**

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.

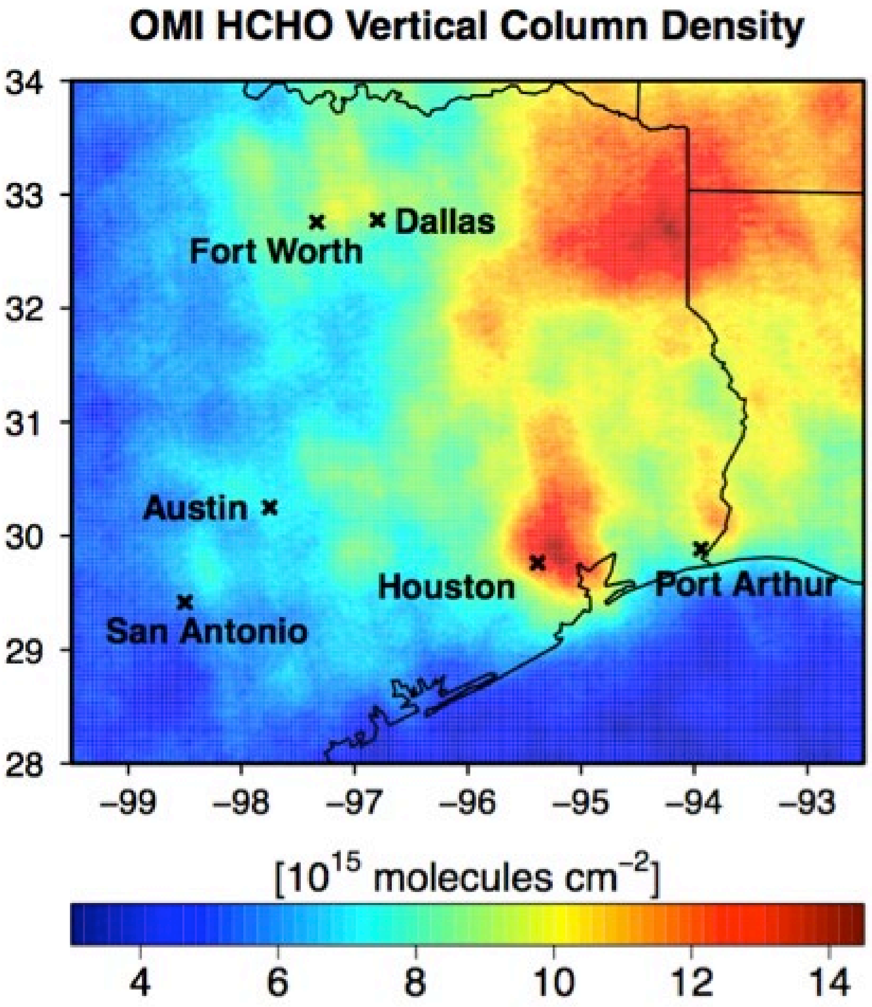
Biomass burning The unexplained variability in ozone production from fires is of particular interest. The suite of NO_2, H_2CO, $C_2H_2O_2$, H_2O, O_3, and aerosol measurements from TEMPO is well suited to investigating how the chemical processing of primary fire emissions effects the secondary formation of VOCs and ozone. For particularly important fires it is possible to command special TEMPO observations at even shorter than hourly revisit time, as short as 10 minutes.

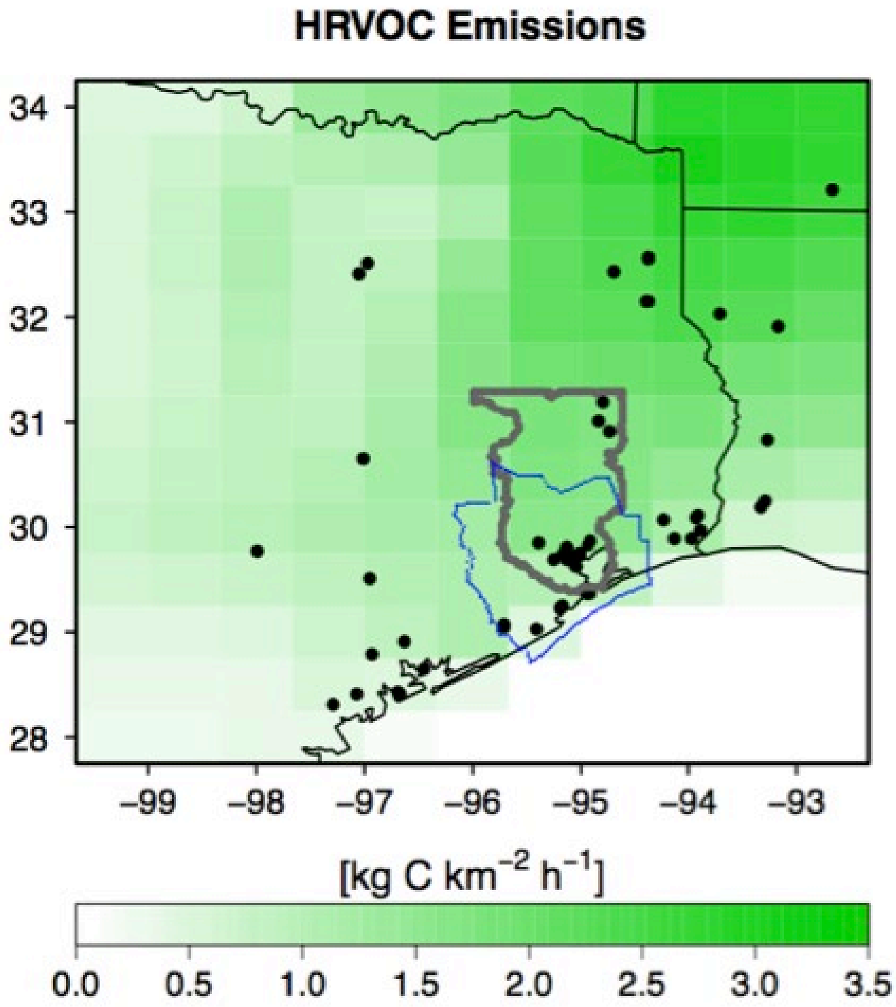
City lights spectroscopic signatures



Laboratory Spectra of Lighting Types (C. Elvidge):
http://www.ngdc.noaa.gov/eog/night_sat/spectra.html

Oversampling
Lei Zhu *et al.*, 2014





TEMPO

The end!

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

Smithsonian

NASA

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA

UAH
THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY

SAINT LOUIS
UNIVERSITY

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OF IOWA

YORK
UNIVERSITÉ
UNIVERSITY

THE UNIVERSITY OF EDINBURGH

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INSTITUTE

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ASTRONAUTICS
Science at work

RTS

NCAR

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Environment and
Climate Change Canada

Environnement et
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Backups

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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
Per Veritatem Vis
1853

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
1868

UAH
THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY
MODELING GROUP

YONSEI UNIVERSITY
1885
연 세 대 학 교

AD MAJOREM DEI GLORIAM
1818
IHS
SAINT LOUIS
UNIVERSITY

THE UNIVERSITY
OF IOWA

UNIVERSITY OF MARYLAND BALTIMORE COUNTY
UMBC
1966

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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 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}).

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-16** 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.

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.

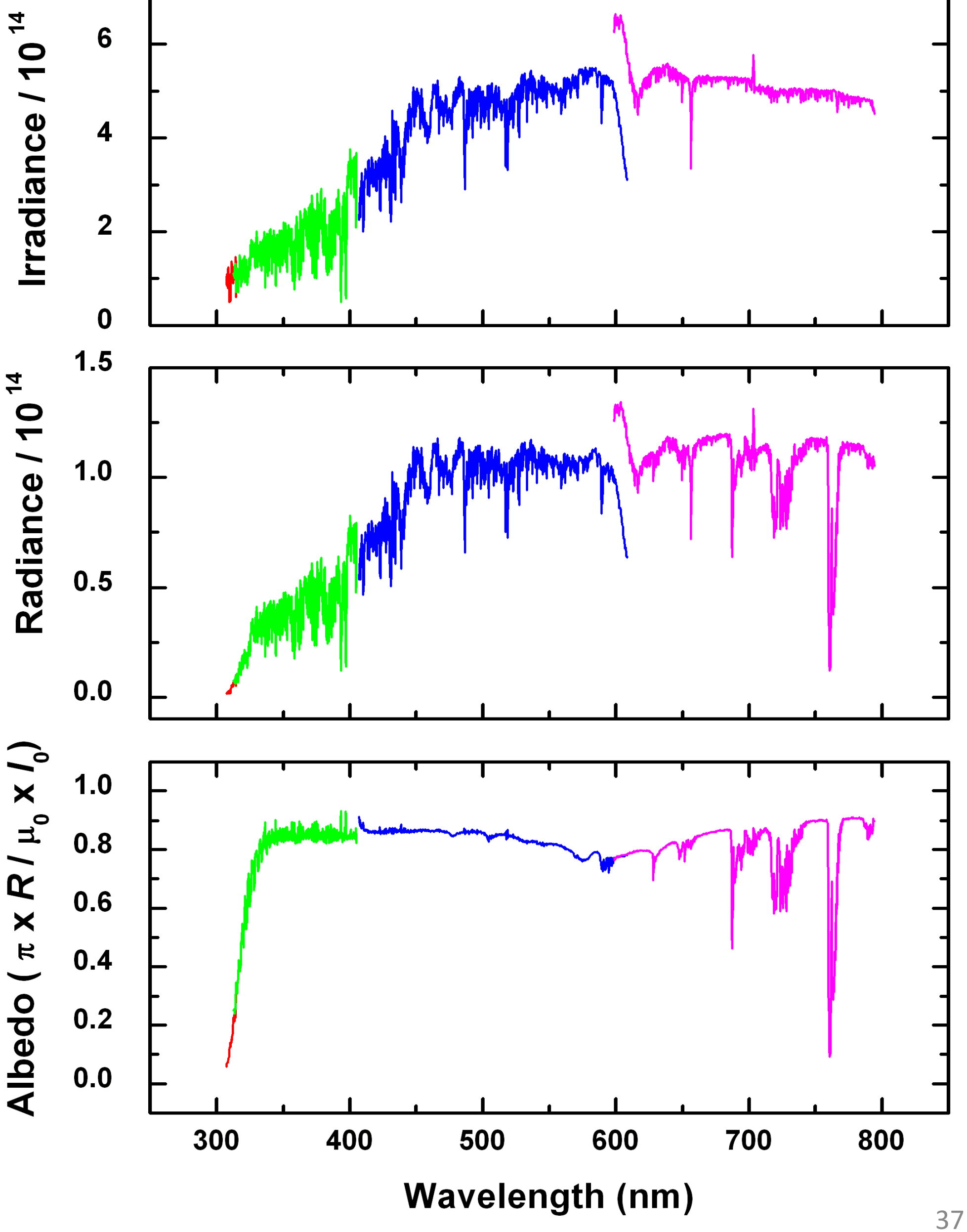
TEMPO also performs **hourly measurements one of the world's largest salt lakes: the Great Salt Lake in Utah**. Measurements over Salt Lake City show the highest concentrations of BrO over the globe. Hourly measurement at a high spatial resolution can improve understanding of BrO production in salt lakes.

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 except eXceL O_3 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; city lights

What do we measure?

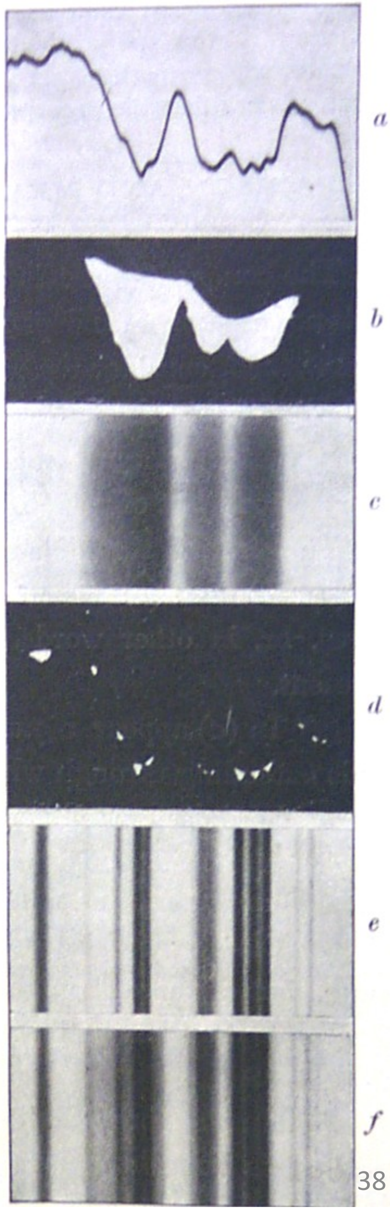
GOME irradiance, radiance, and reflectance spectrum for high-albedo (fully cloudy) ground pixel



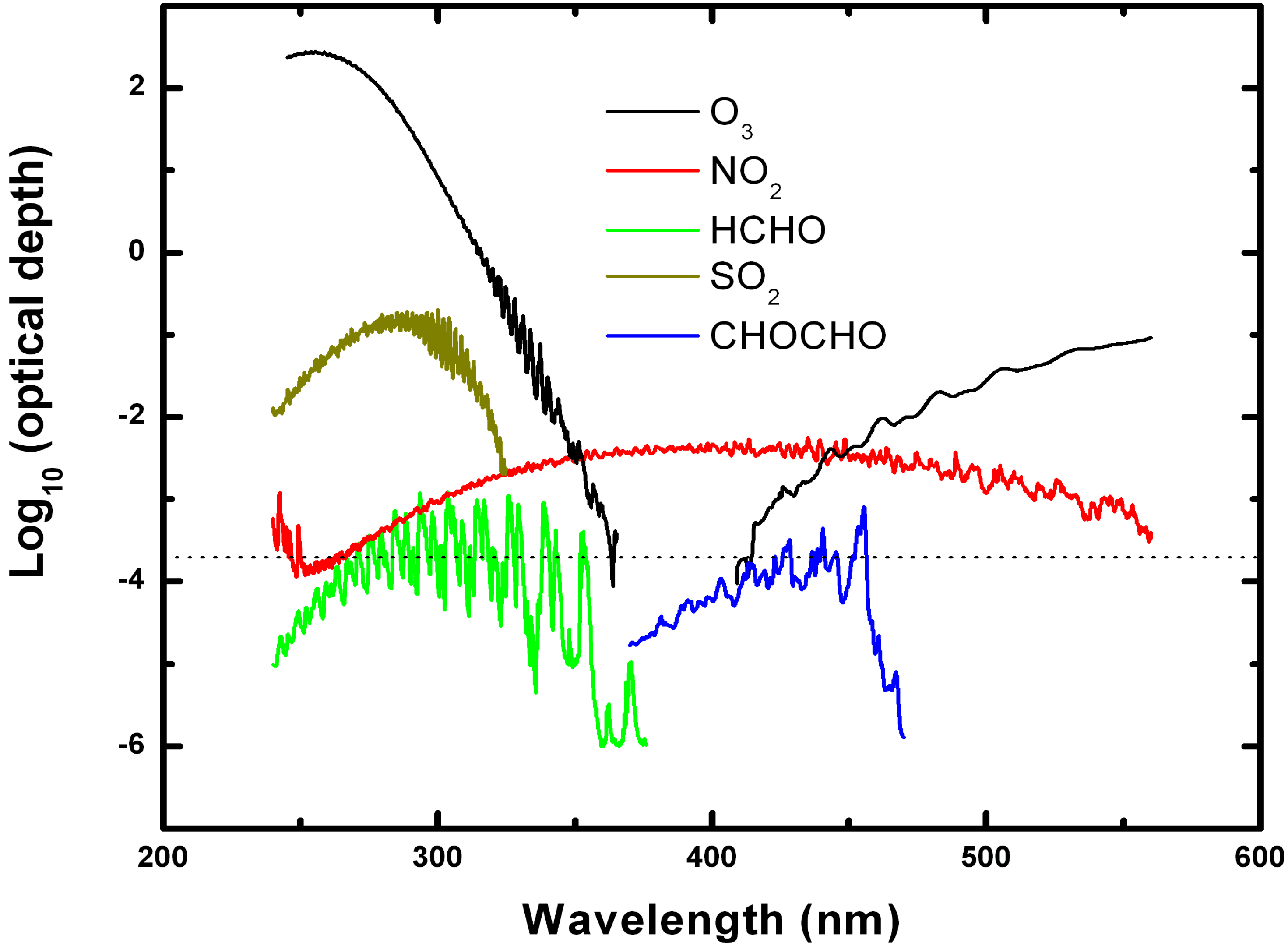
Why the Smithsonian?

Langley, S.P., and C.G. Abbot, *Annals of the Astrophysical Observatory of the Smithsonian Institution, Volume 1* (1900).

Langley's recently invented bolometer was used to make measurements from the infrared through the near ultraviolet in order to determine the mean value of the solar constant and its variation. Langley and Abbot also developed substantial new experimental techniques (such as an early chart recorder) and various analysis techniques (*e.g.*, the "Langley plot"), including photographic techniques for high and low pass filtering to produce line spectra from "bolographs" (spectra), illustrated, foreshadowing the high pass filtering used today by researchers employing the DOAS technique for analyzing atmospheric spectra.



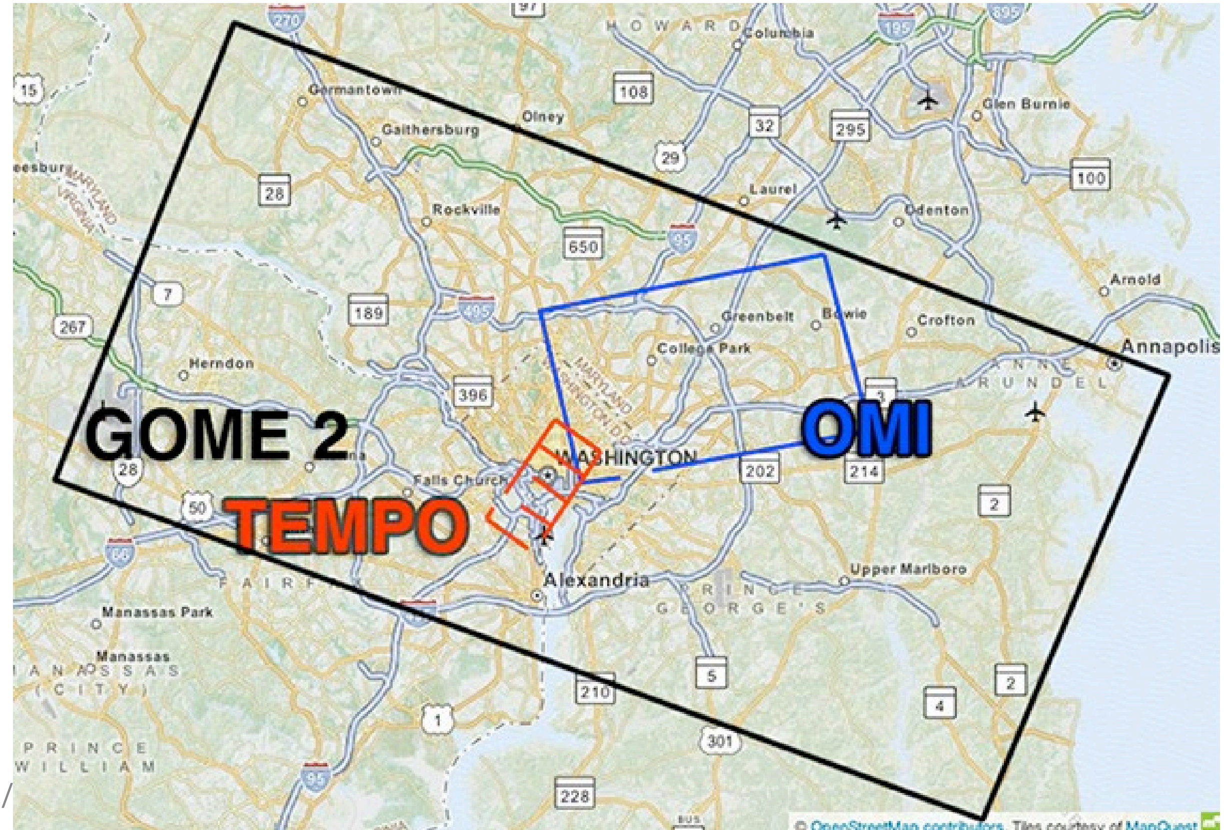
Optical Depths for Typical GEO Measurement Geometry



Puerto Rico coverage

Coverage comparisons

- Spatial resolution: allows tracking pollution at sub-urban scale
  - GEO at 100°W: 2.1 km N/S × 4.7 km E/W = 9.8 km^2 (native) at center of FOR (36.5°N, 100°W)
  - Full resolution for NO_2, HCHO, total O_3 products
  - Co-add 4 N/S pixels for O_3 profile product: 8.4 km N/S × 4.7 km E/W

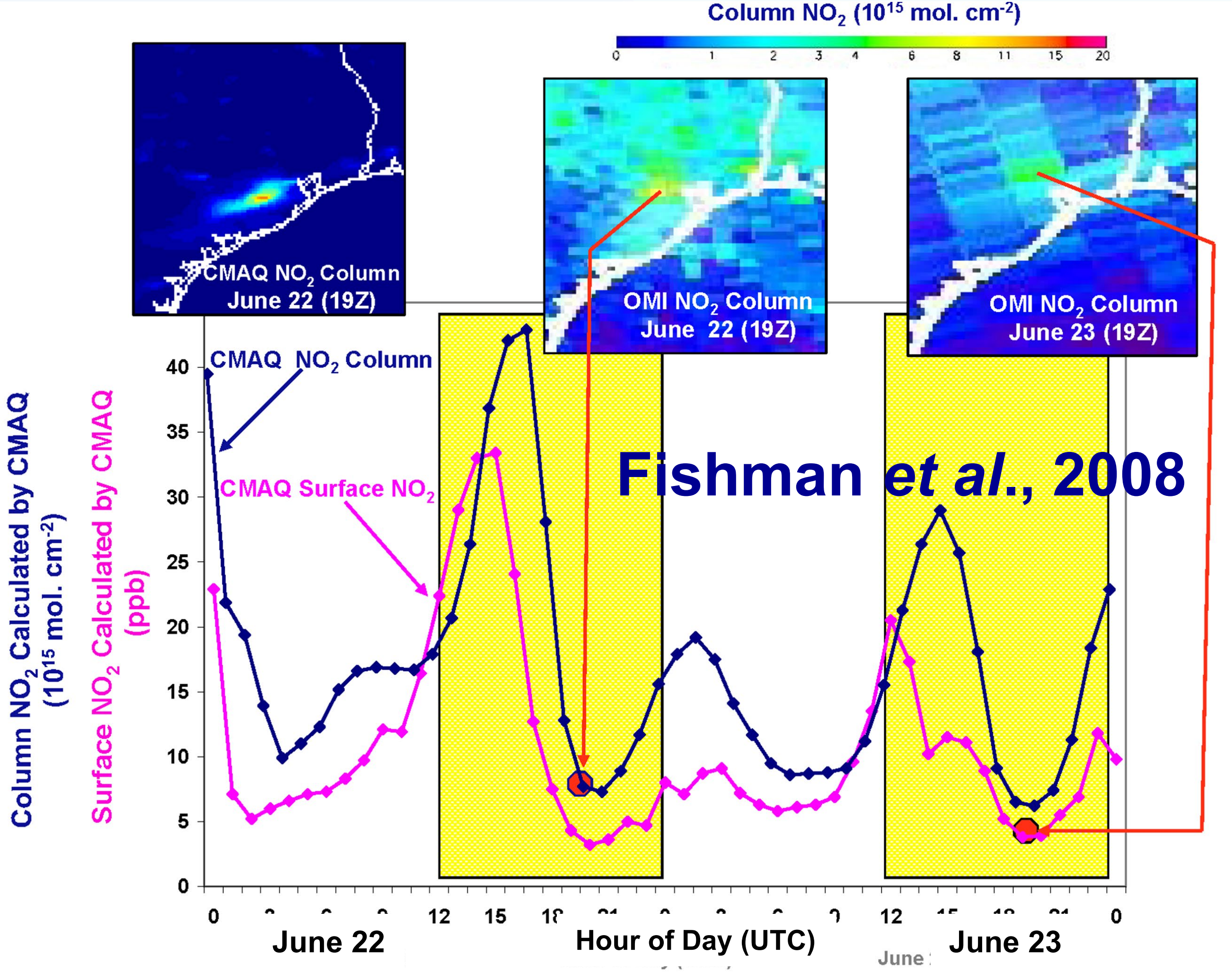


~ 1/300 of GOME-2

~ 1/30 of OMI

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



Fishman *et al.*, 2008

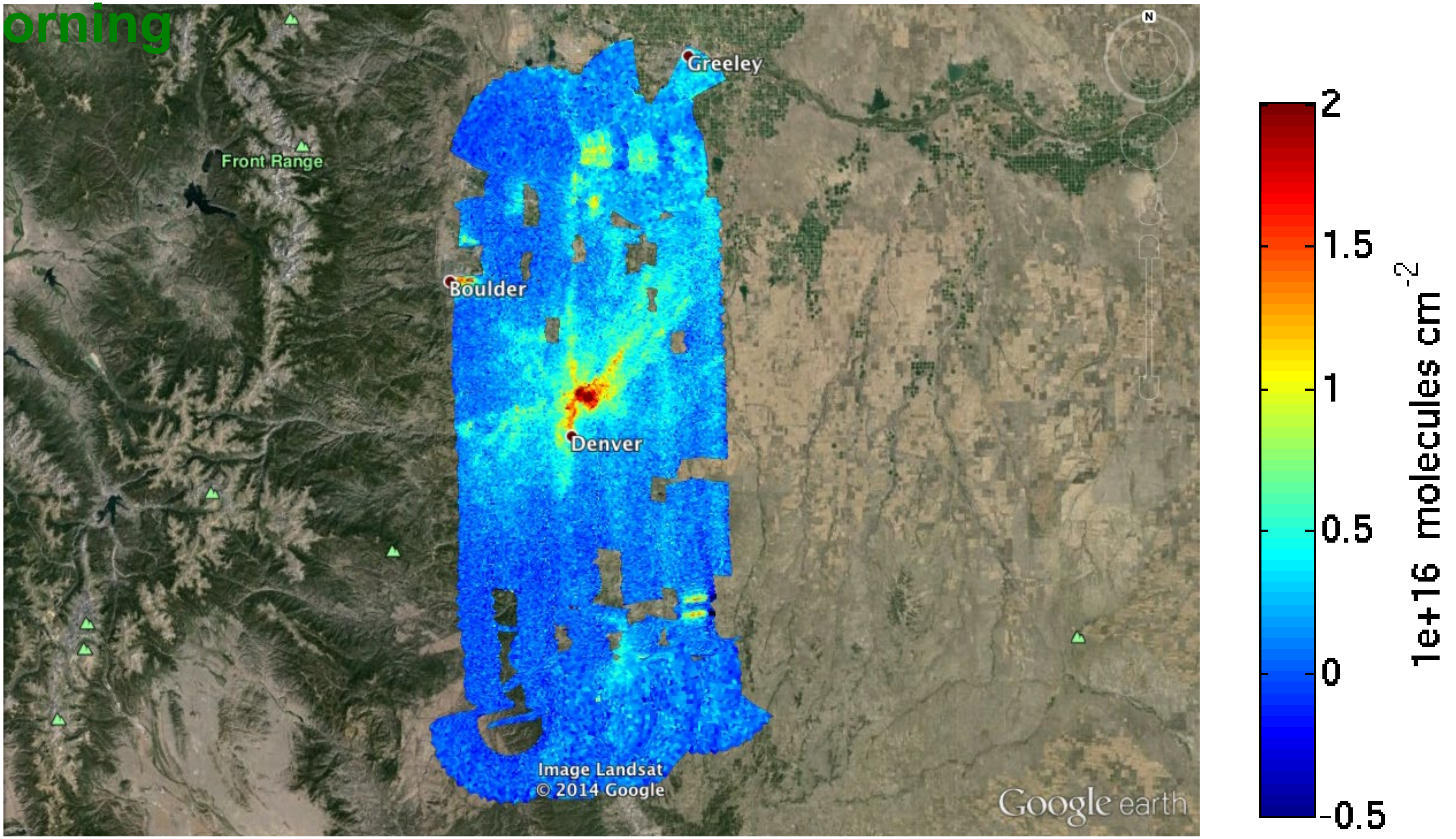
LEO observations provide limited information on rapidly varying emissions, chemistry, & transport

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

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

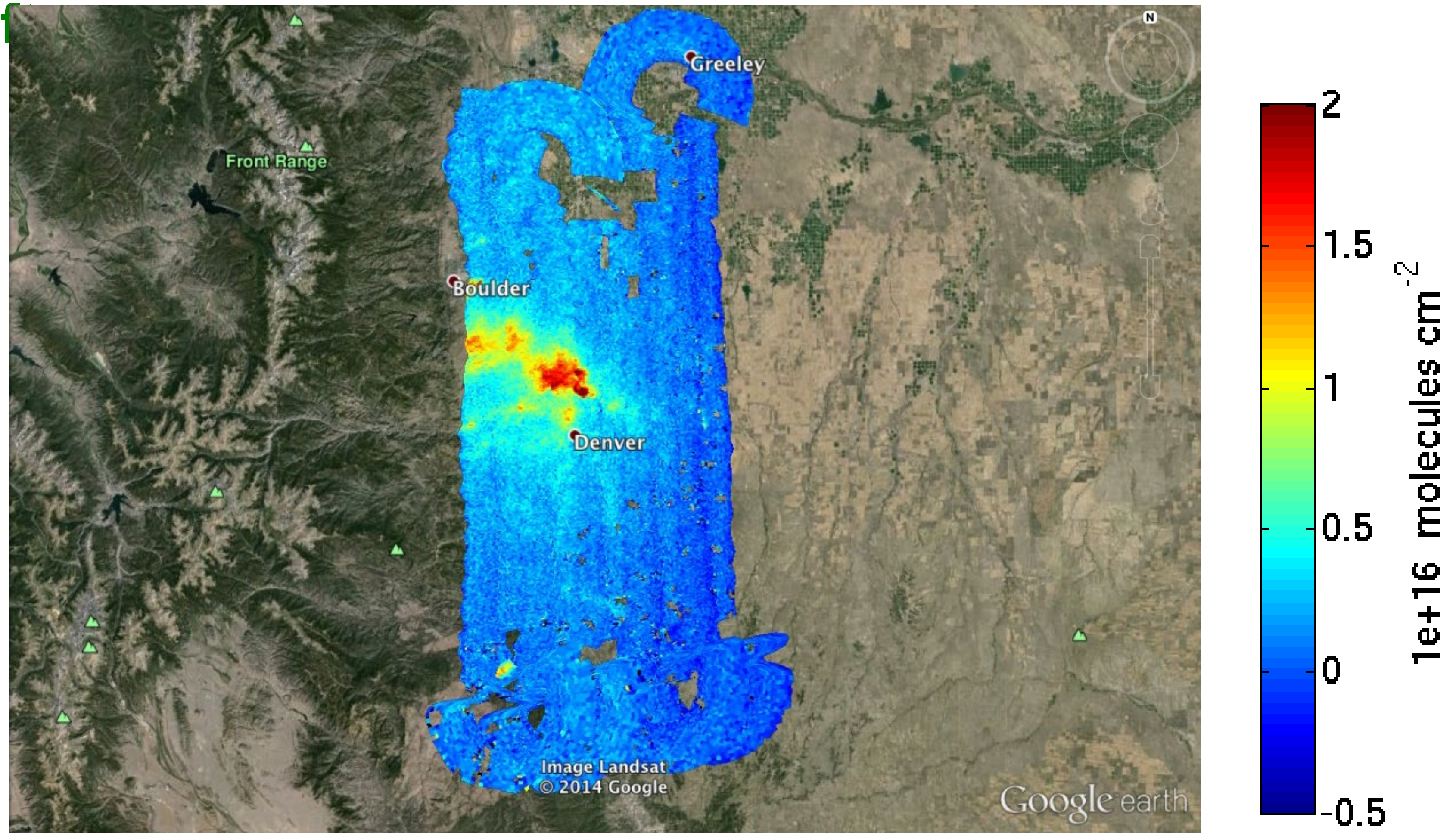
Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

TEMPO measurements will capture the diurnal cycle of pollutant emissions

GeoTASO NO_2 Slant Column, 02 August 2014

Af



Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO