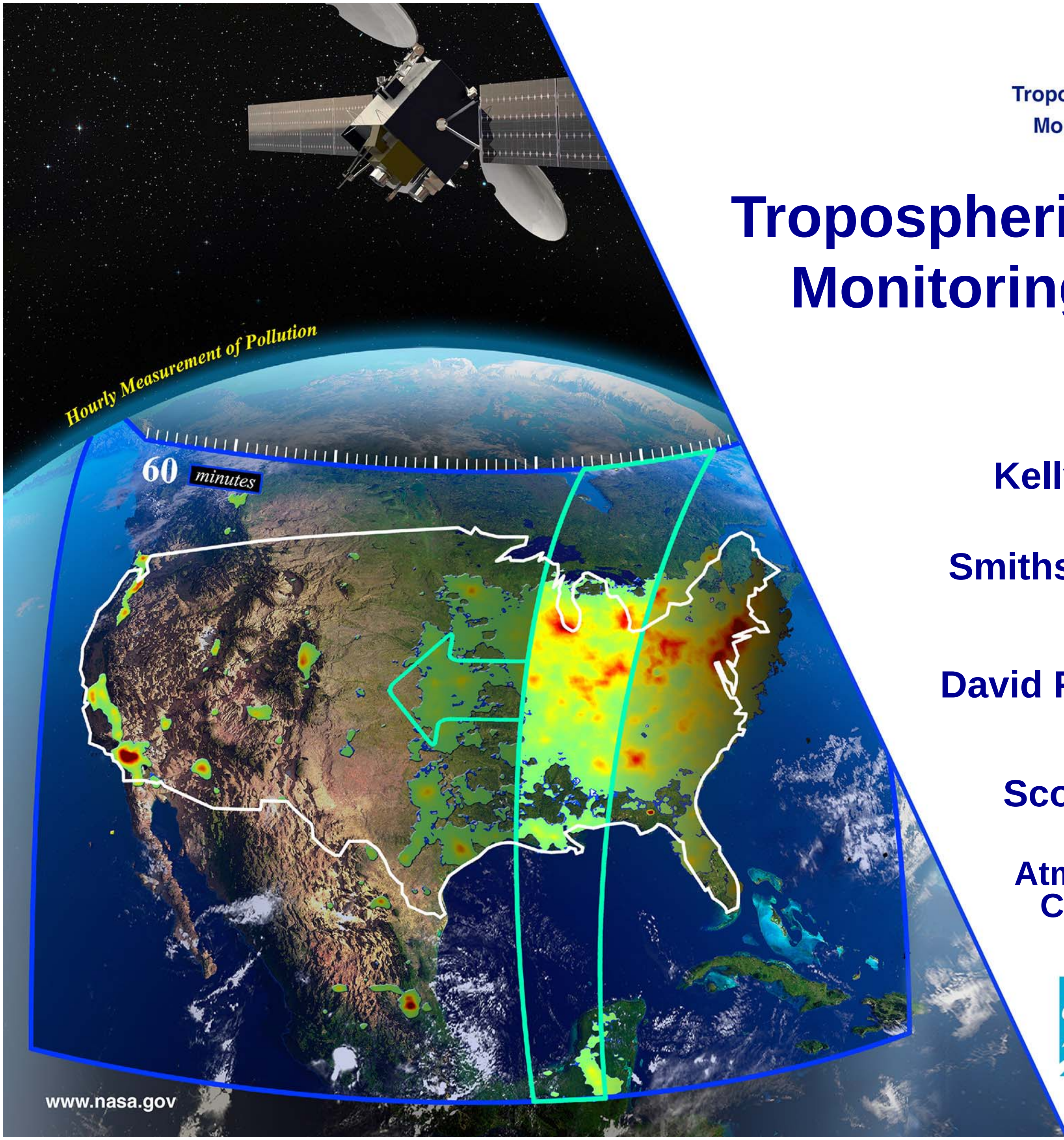
Tropospheric Emissions:
Monitoring of Pollution



Tropospheric Emissions: Monitoring of Pollution Overview

Kelly Chance, Xiong Liu, Raid M. Suleiman, Smithsonian Astrophysical Observatory

David Flittner, Jay Al-Saadi, NASA LaRC

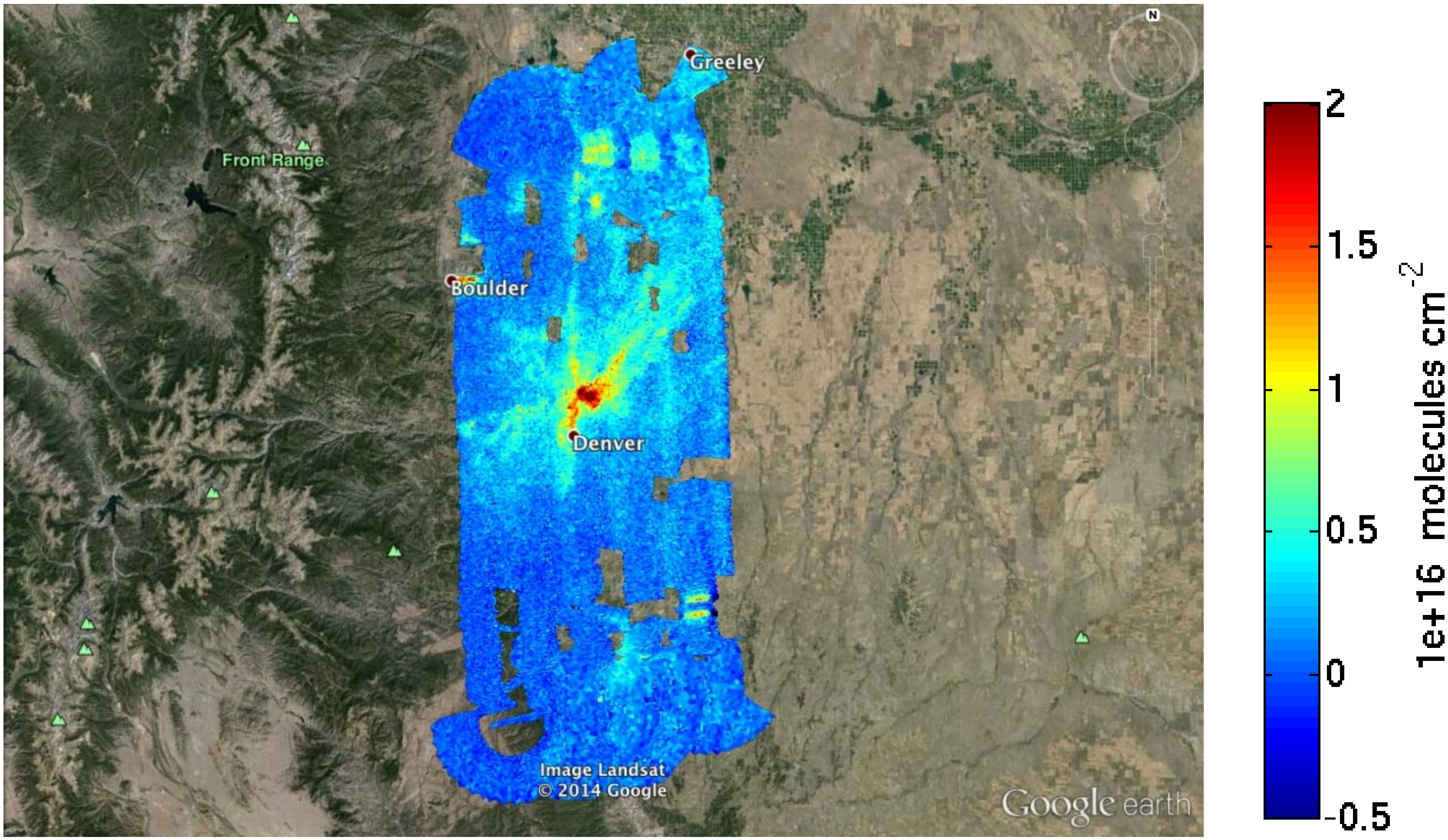
Scott Janz, NASA GSFC

Atmospheric Composition Constellation Meeting 11
April 29, 2015

Smithsonian

TEMPO measurements will capture the diurnal cycle of pollutant emissions

GeoTASO NO_2 Slant Column, 02 August 2014 Morning

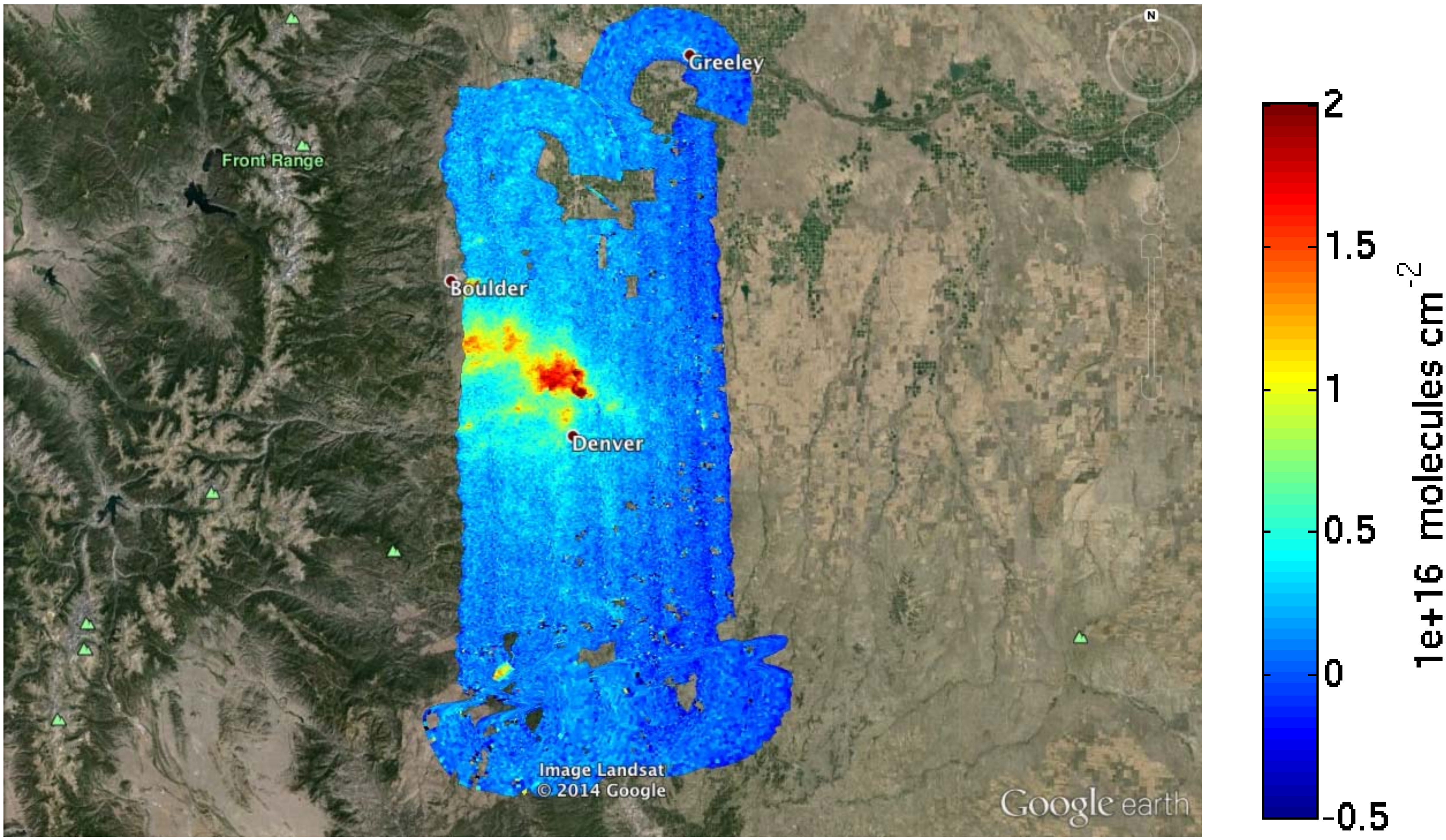


Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

GeoTASO NO_2 Slant Column, 02 August 2014 Afternoon



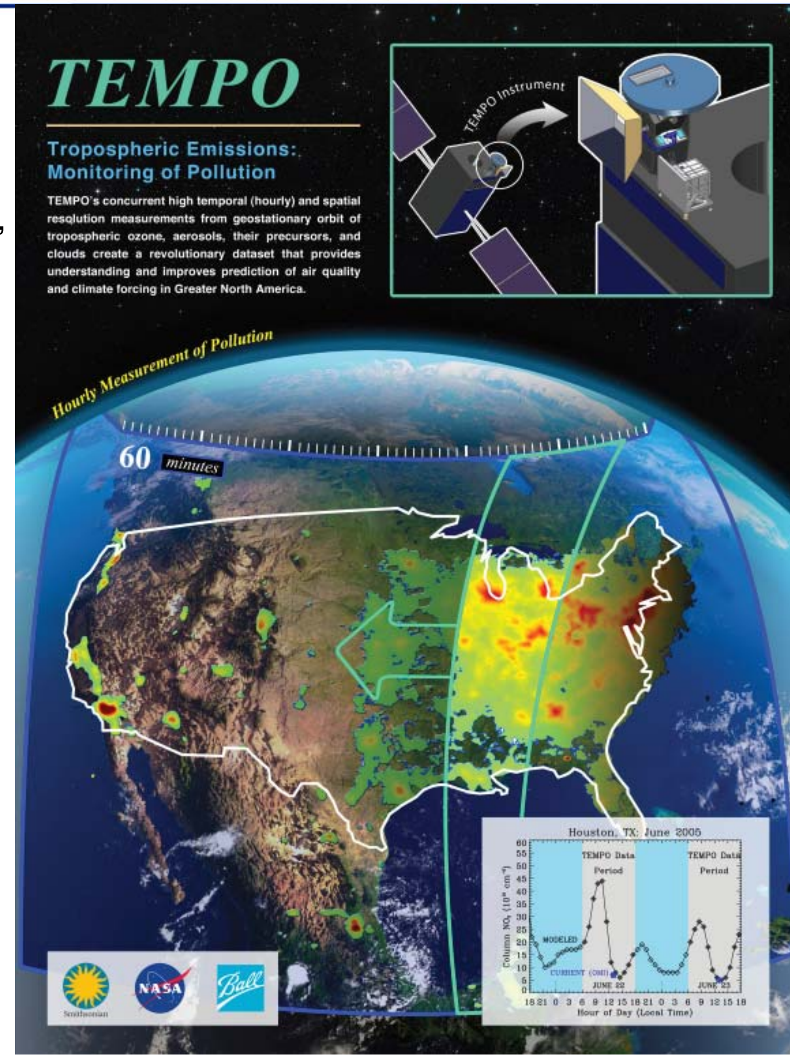
Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

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, U.K., ESA, Canada, Mexico



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

- Instrument being implemented, 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 instrument project detailed organization structure

TEMPO Instrument
Principal Investigator: Kelly Chance
Deputy Principal Investigator: Xiong Liu
Program Administrator: Joseph Webber

Investigation Advisory Panel
SAO, LaRC, Ball Senior Management

Science Advisory Panel
Geo Constellation/CEOS

Science Team

Project Management
Project Manager: Wendy Pennington
Project Scientist: David Flittner
Deputy Project Scientist: Jay Al-Saadi
Deputy PM: Craig Jones, COR
Deputy PP&C: Don Shick

Management Support
Schedules: Barbara Guilmette
Configuration Manager: Donna Lewis
Communications: Jonathan Behun/Katie Bethea

Systems Engineering
Project CE: David Rosenbaum
SE: Mark Andraschko

Safety & Mission Assurance
Mission Assurance Manager: Jose Caraballo

Instrument
PM Dennis Nicks
Chief SE: Laura Hale
Instrument Performance: Brian Baker

Ground Systems
Raid M. Suleiman

Instrument Operations
John E. Davis

Science Data Processing System
John Houck

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

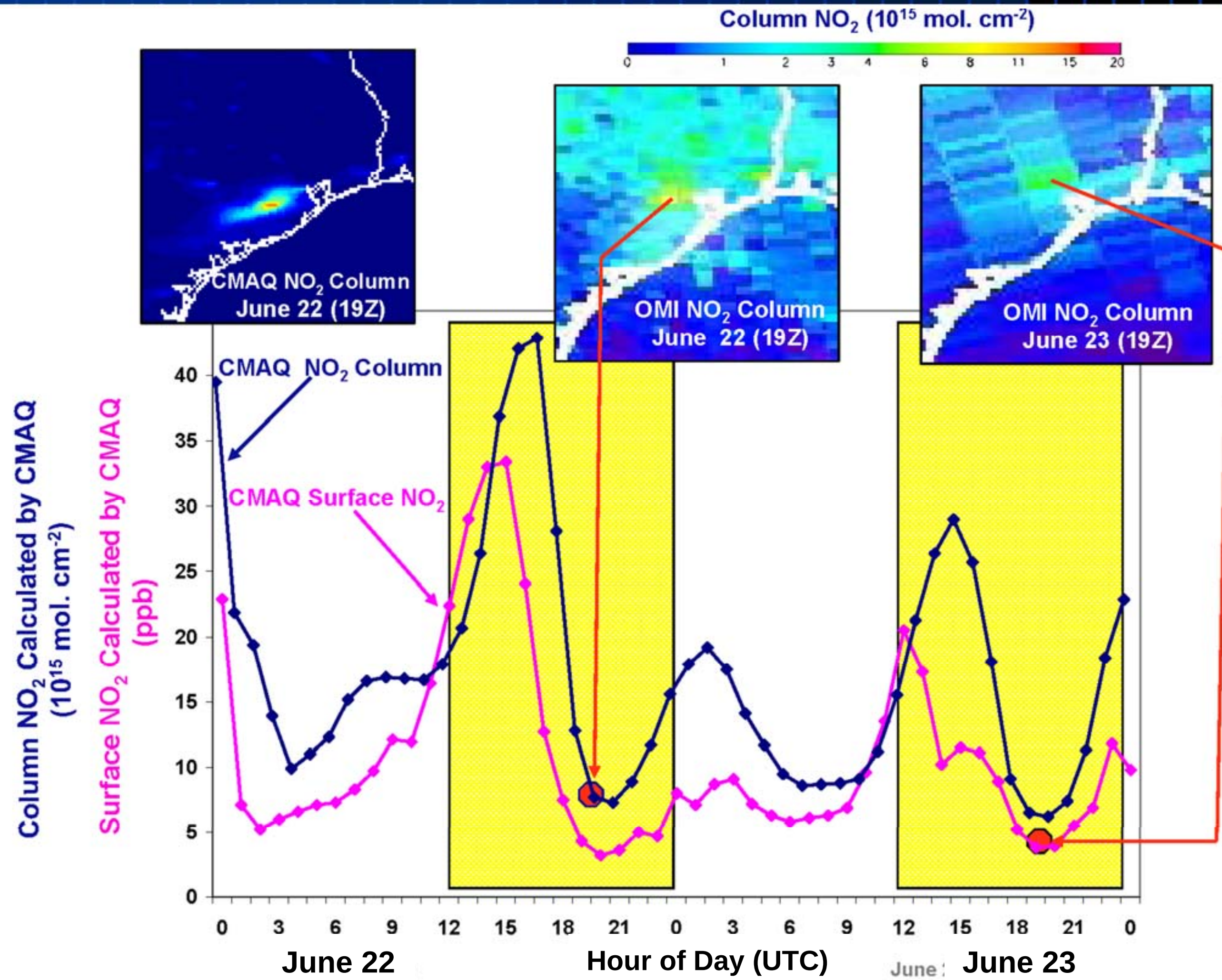
TEMPO Science Team, non-U.S.

Team Member	Institution	Role	Responsibility
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
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
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

The view from GEO

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

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

Baseline#* Trace gas column densities (10^{15} cm^{-2}) hourly @ 8.9 km x 5.2 km

Species	Precision	Band	Signal to Noise: Required	Signal to Noise: Predicted
O_3: 0-2 km	10 ppbv	O_3:Vis (540-650 nm) / O_3: UV (290-345 nm)	≥1413 / ≥1032	1765 / 1247
O_3: FT	10 ppbv			
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: Required	Signal to Noise: Predicted
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

Physical Parameters	Parameter	Required	Predicted
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

Physical Parameters	Parameter	Required	Predicted
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

Physical Parameters	Parameter	Required	Predicted
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

Baseline and threshold data products

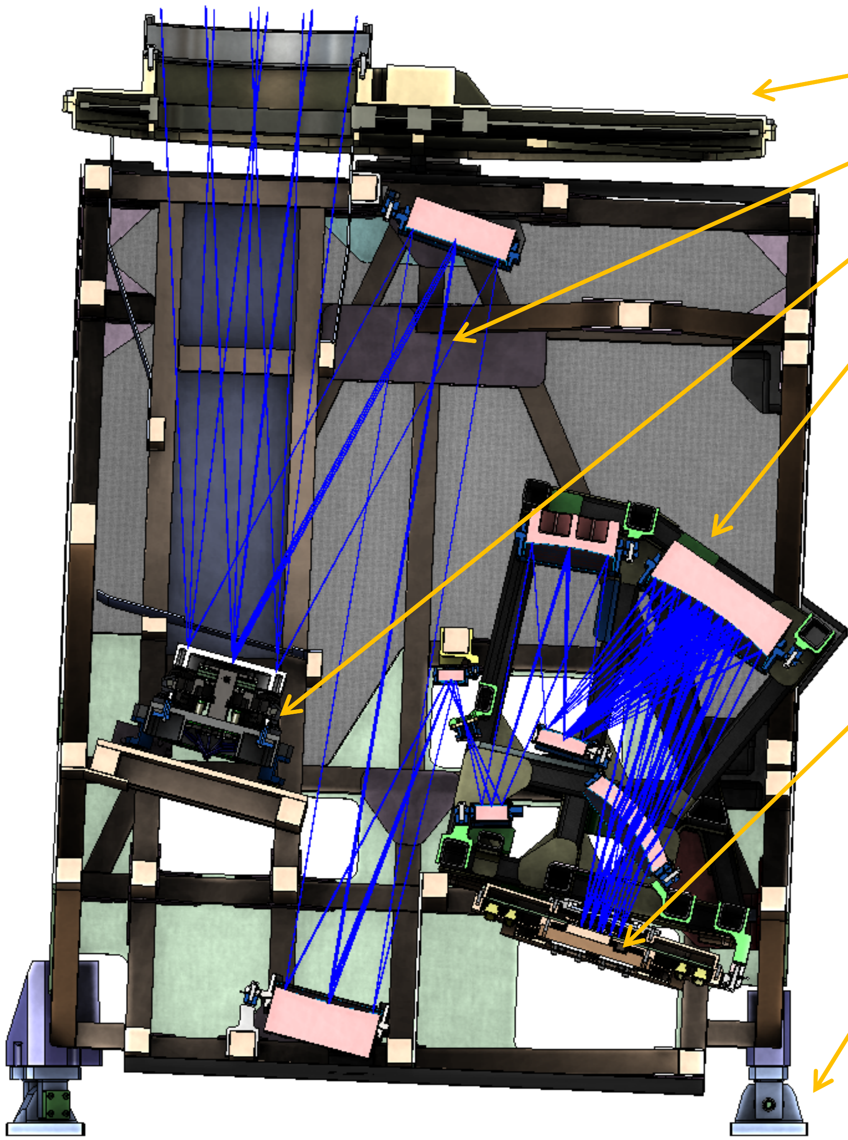
Species/Products	Required Precision	Temporal Revisit
0-2 km O_3 (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric SO_2	1.0×10^{16} 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 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

Instrument layout



Calibration Mechanism Assembly

Telescope Assembly

Scan Mechanism Assembly

Spectrometer Assembly

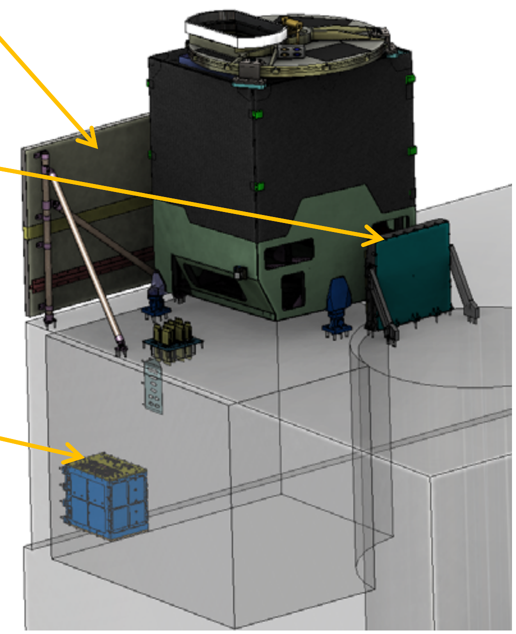
Radiator Assembly

Focal Plane Electronics

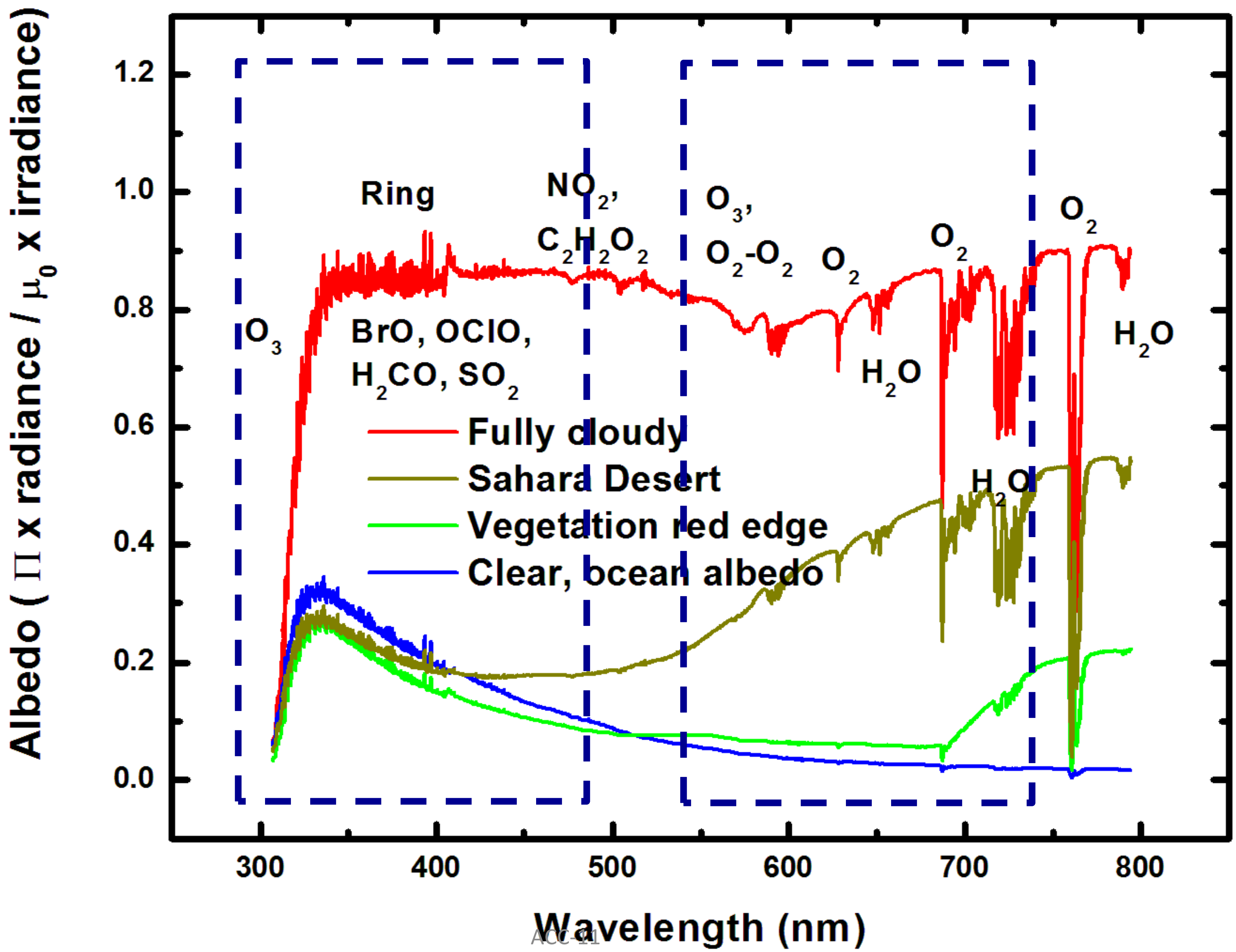
Focal Plane Assembly

Instrument Control Electronics

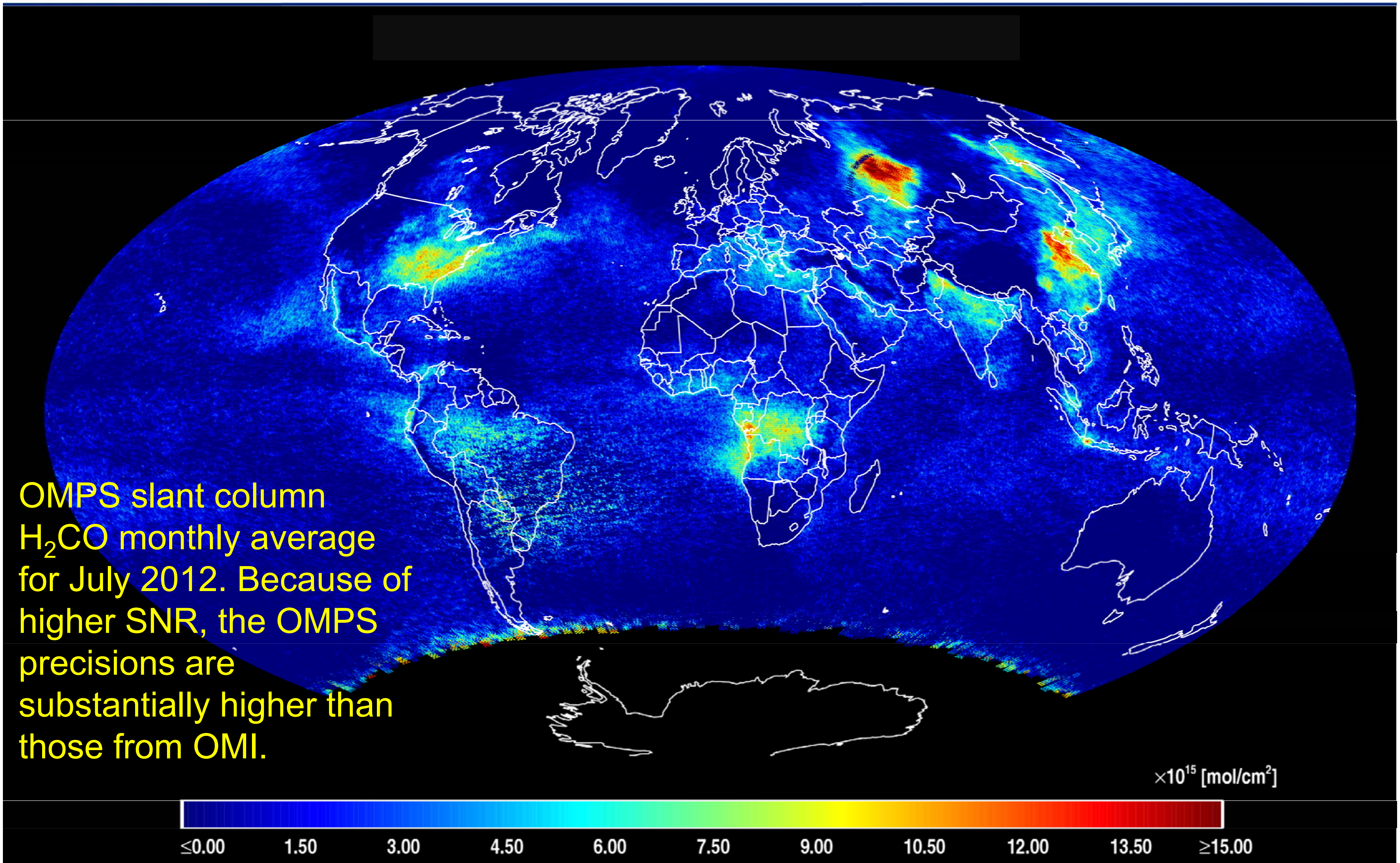
Instrument Support Assembly



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

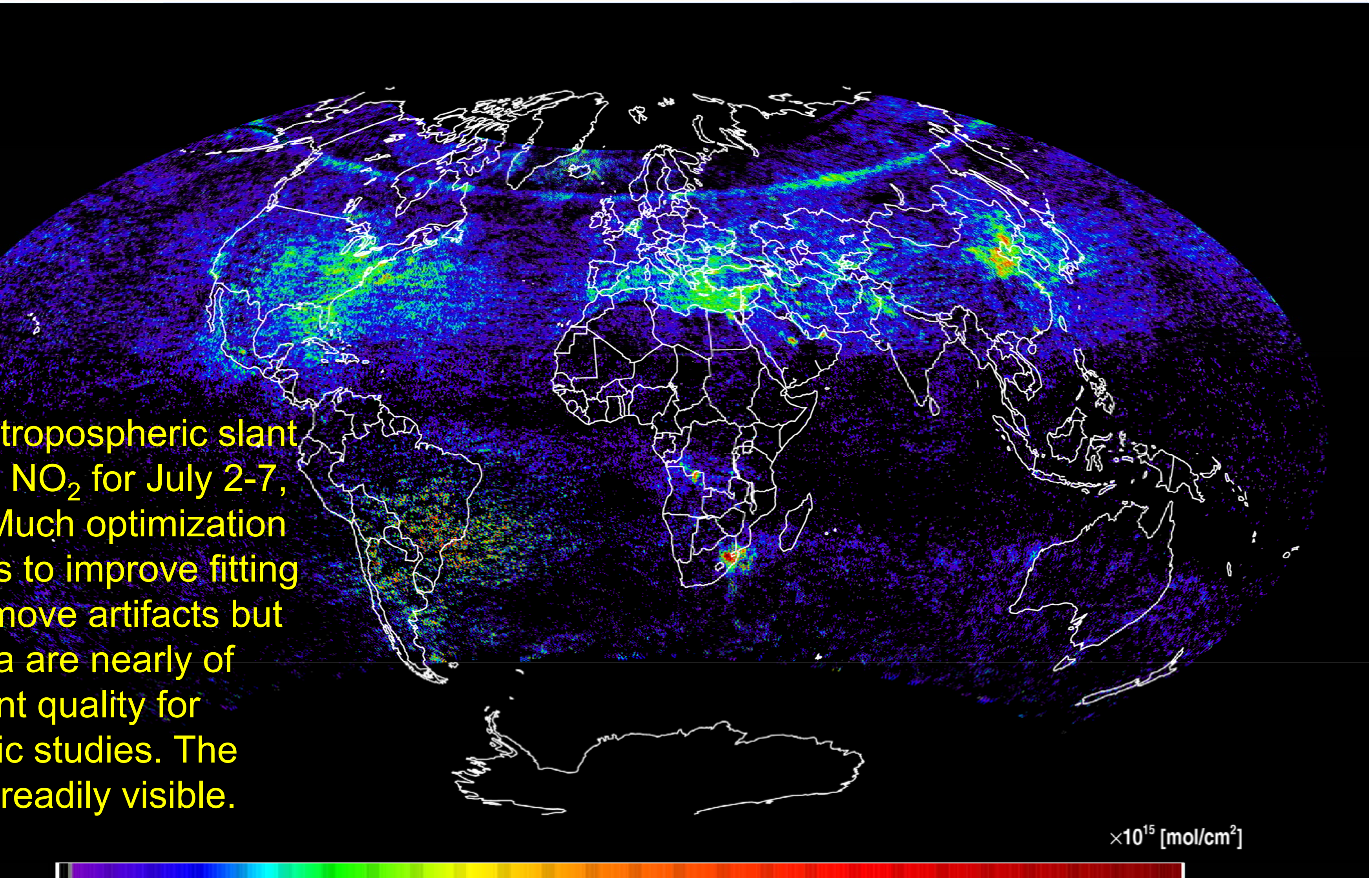


Algorithm testing: OMPS H_2CO



OMPS slant column H_2CO monthly average for July 2012. Because of higher SNR, the OMPS precisions are substantially higher than those from OMI.

Algorithm testing: OMPS NO_2



tropospheric slant
NO_2 for July 2-7,
Much optimization
s to improve fitting
move artifacts but
a are nearly of
nt quality for
ic studies. The
readily visible.

TEMPO mission concept

stationary 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

- **Hope to measure up to 20 hours/day**

PO 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

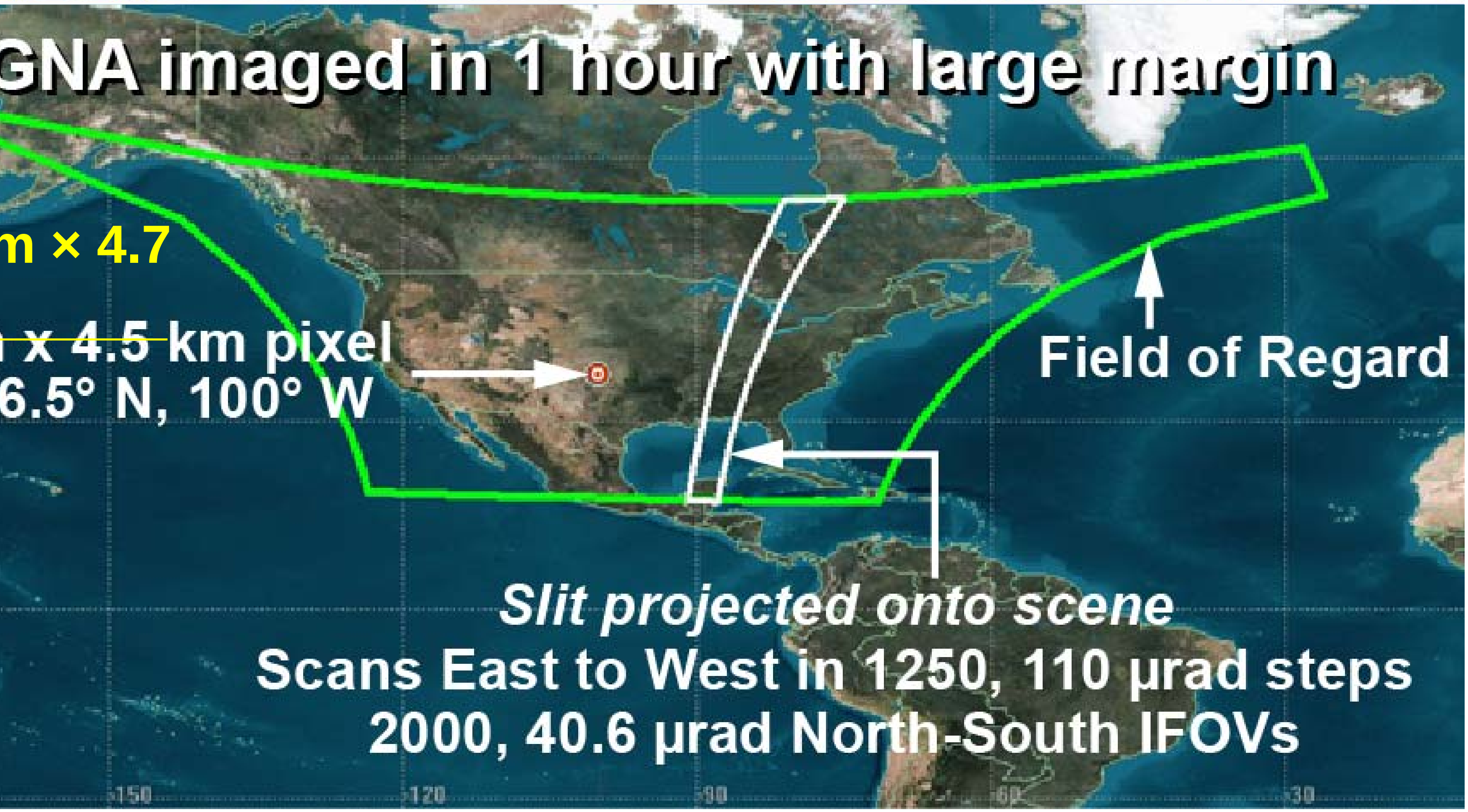
- NASA TOMS-type O_3
- SO_2, NO_2, H_2CO, $C_2H_2O_2$ from fitting with AMF-weighted cross sections
- Absorbing Aerosol Index, UV aerosol, Rotational Raman scattering cloud
- eXceL profile/tropospheric/PBL O_3 for selected geographic targets

mple higher-level products: Near-real-time pollution/AQ indices, UV index

PO 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

TEMPO footprint, ground sample distance and field of regard

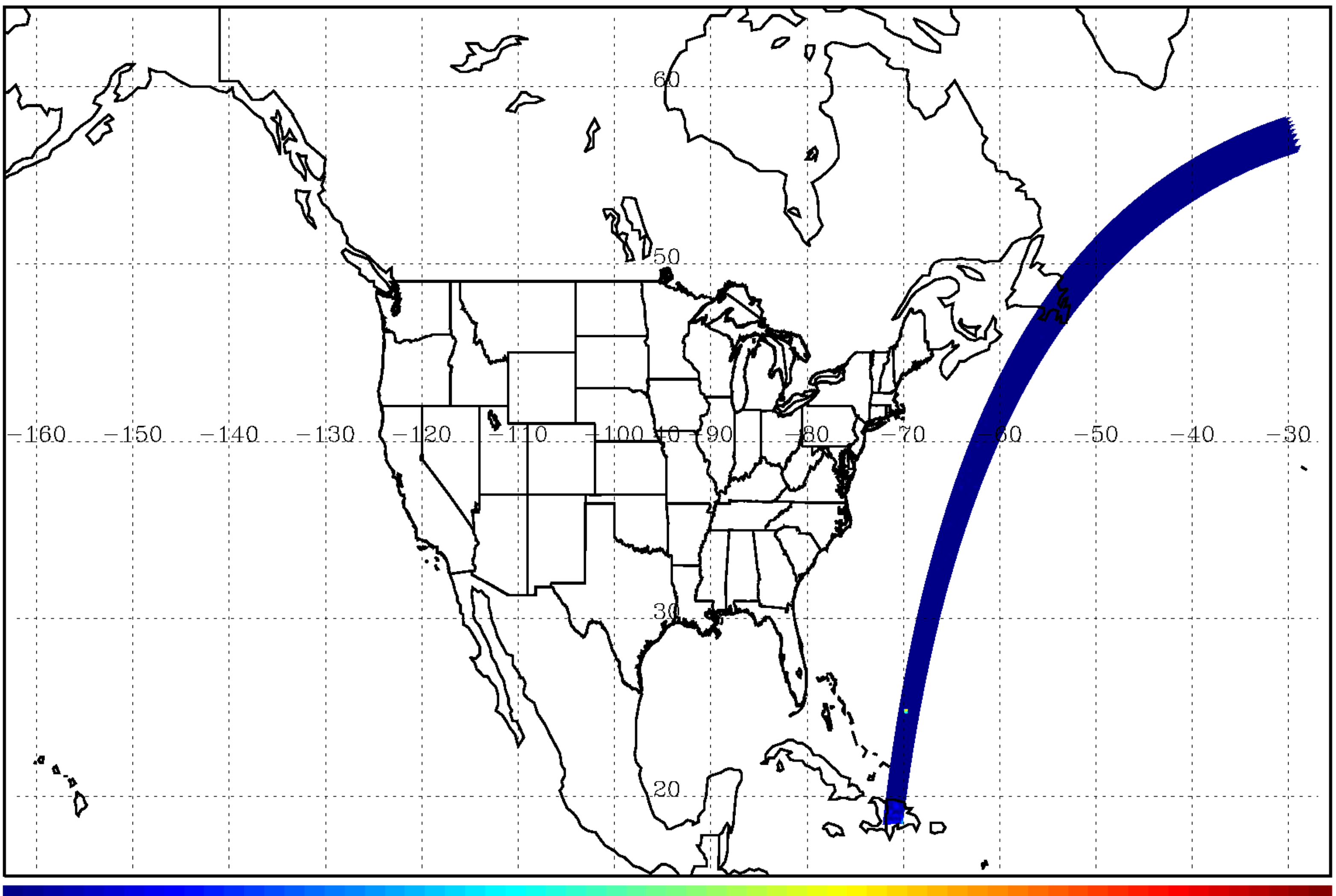


h 2.1 km × 4.7 km pixel is a 2K element spectrum from 290-740 nm

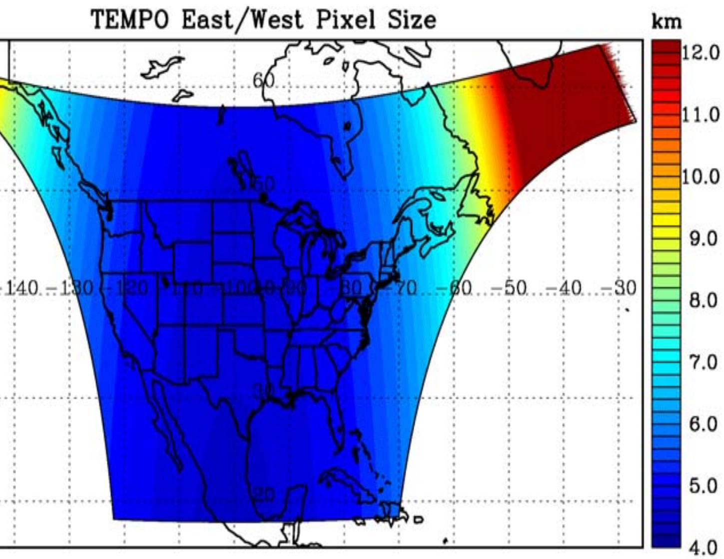
EO platform selected by NASA for viewing Greater North America

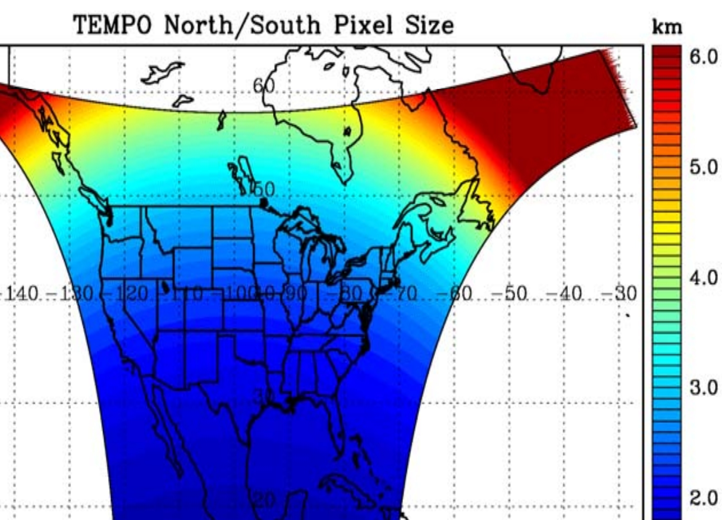
TEMPO hourly NO_2 sweep

OMI NO_2 in April (2005–2008) over TEMPO FOR



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 80ºW, pixel size at

TEMPO baseline products

PO has a
mally-redundant
surement set for air
ity.

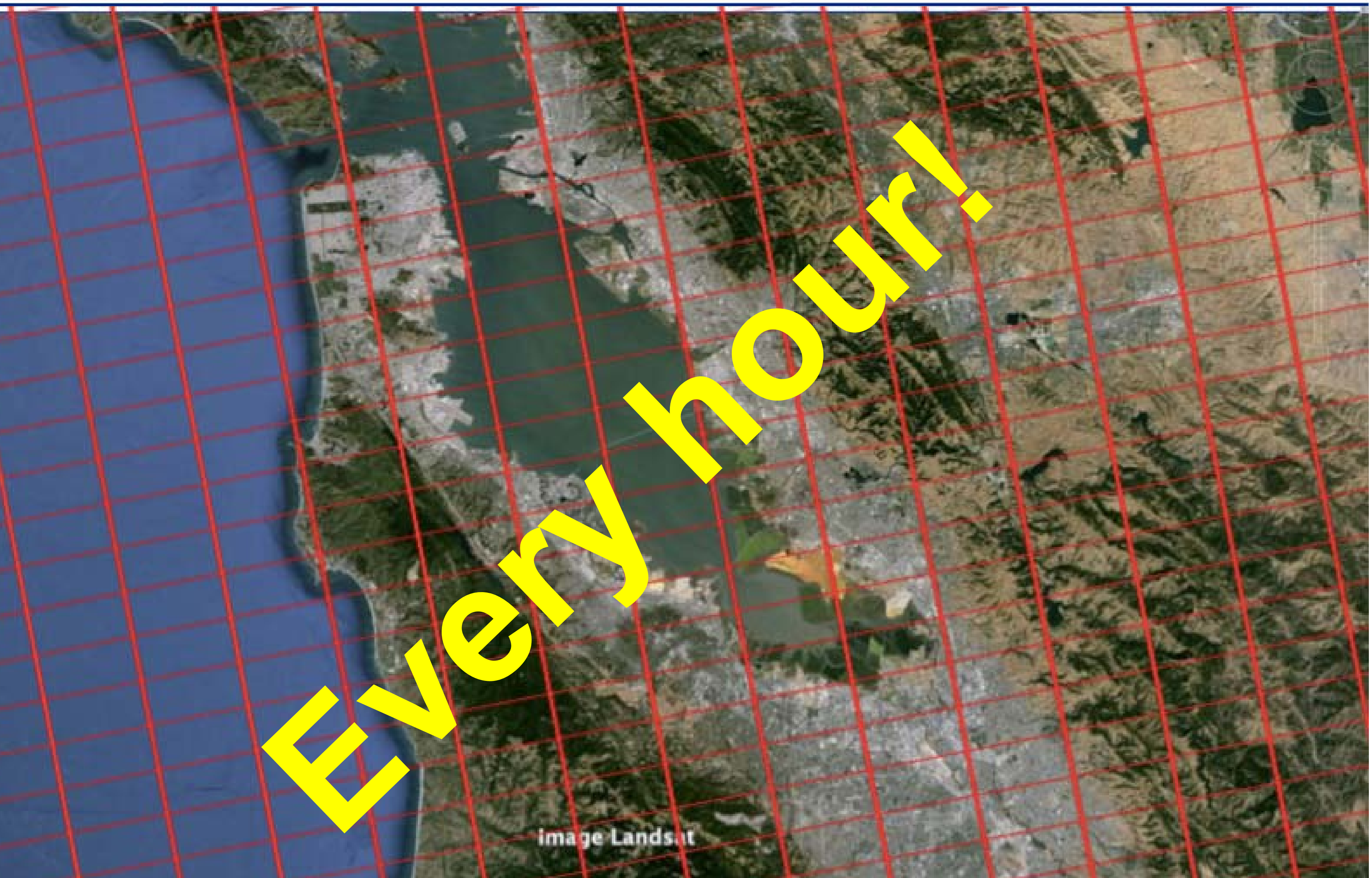
r-real time products
allow for pollution
s, chemical
ther, app-based
 air quality.

sed PLRA has O_3,

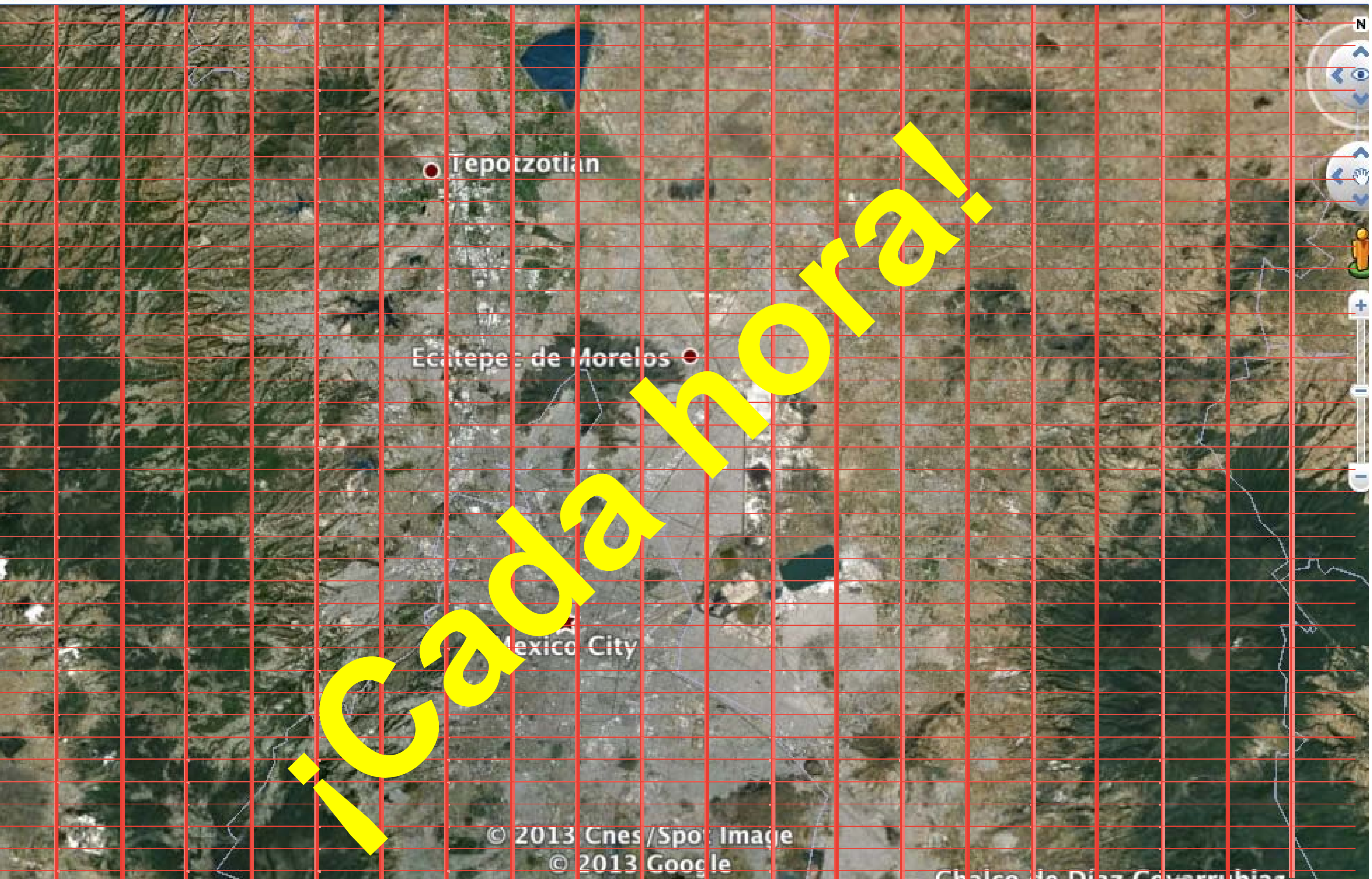
Species/Products		Typical value[2]	Required Precision	Expected Precision[3]	
				Worst	Nominal
O_3 Profile	0-2 km (ppb)	40	10	9.15	9.00
	FT (ppb) [4]	50	10	5.03	4.95
	SOC [4]	8×10^3	5%	0.81%	0.76%
Total O_3		9×10^3	3%	1.54%	1.47%
NO_2*		6	1.00	0.65	0.45
H_2CO* (3/day)		10	10.0	2.30	1.95
SO_2* (3/day)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

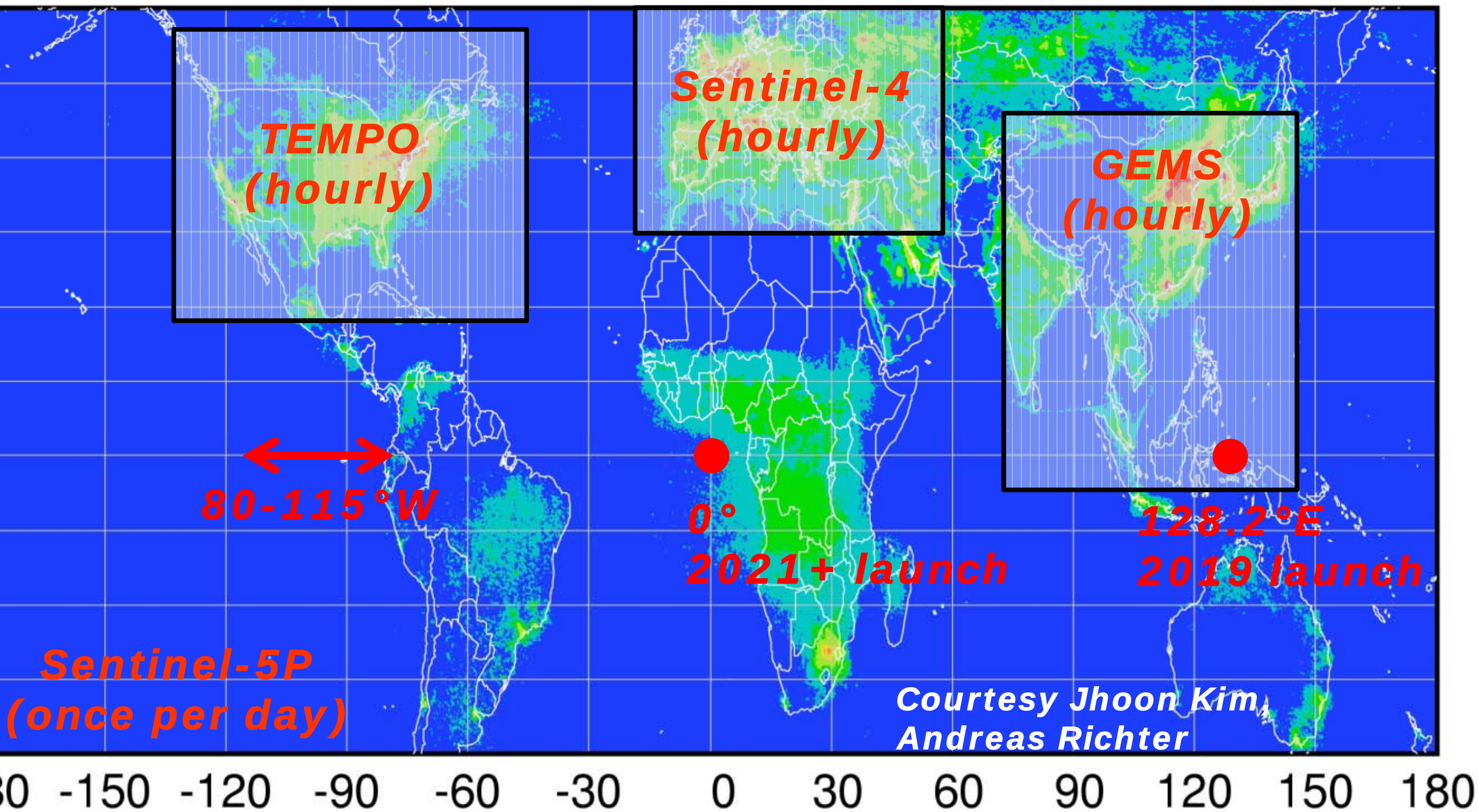
Bay Area coverage



Mexico City coverage



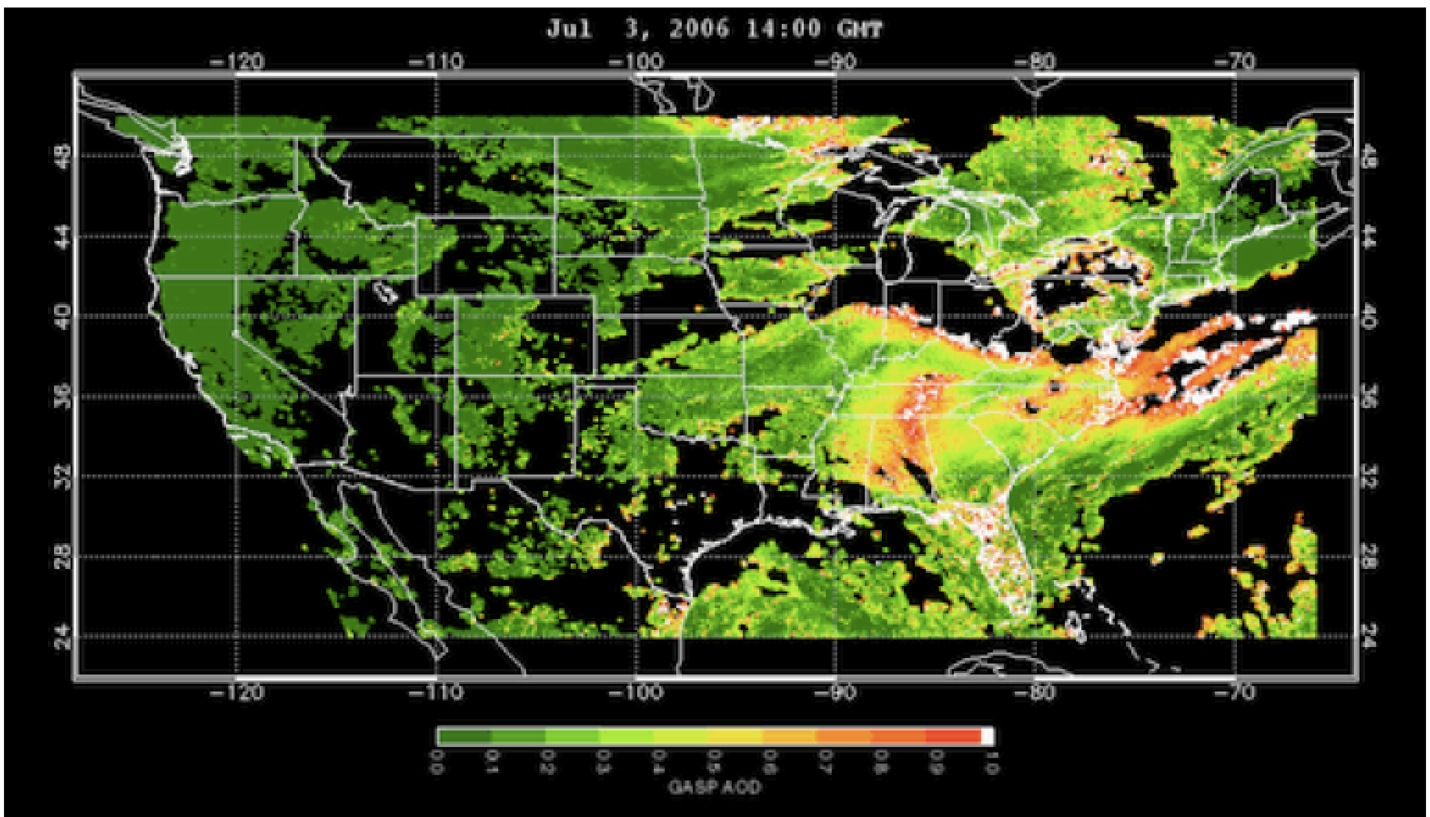
Global pollution monitoring constellation



-relevant science and environmental services enabled by common observations

- proved emissions, at common confidence levels, over industrialized Northern Hemisphere
- proved air quality forecasts and assimilation systems

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



TEMPO summary

urrently on-schedule and on-budget

- Passed System Requirements Review and Mission Definition Review in November 2013
- Passed KDP-B April 2014
- Most technical issues solved at the preliminary design level, following technical interchange meeting at Ball, April 2014
- Passed PDR on July 31, 2014
- In Phase C: KDP-C April 10, 2015!
- Detectors in-house, grating and optical bench ordered
- Ground systems development at SAO on schedule

strument CDR summer 2015, select satellite host 2017+

- TEMPO operating longitude and launch date are not known until after host selection

strument delivery 05/2017 for launch 11/2018 or later

The end!

Smithsonian

NASA

NOAA

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE

Ball

SAINT LOUIS UNIVERSITY

NCAR

HARVARD UNIVERSITY

ATMOSPHERIC CHEMISTRY MODELING GROUP

THE UNIVERSITY OF CALIFORNIA 1868

UAH

UMBC

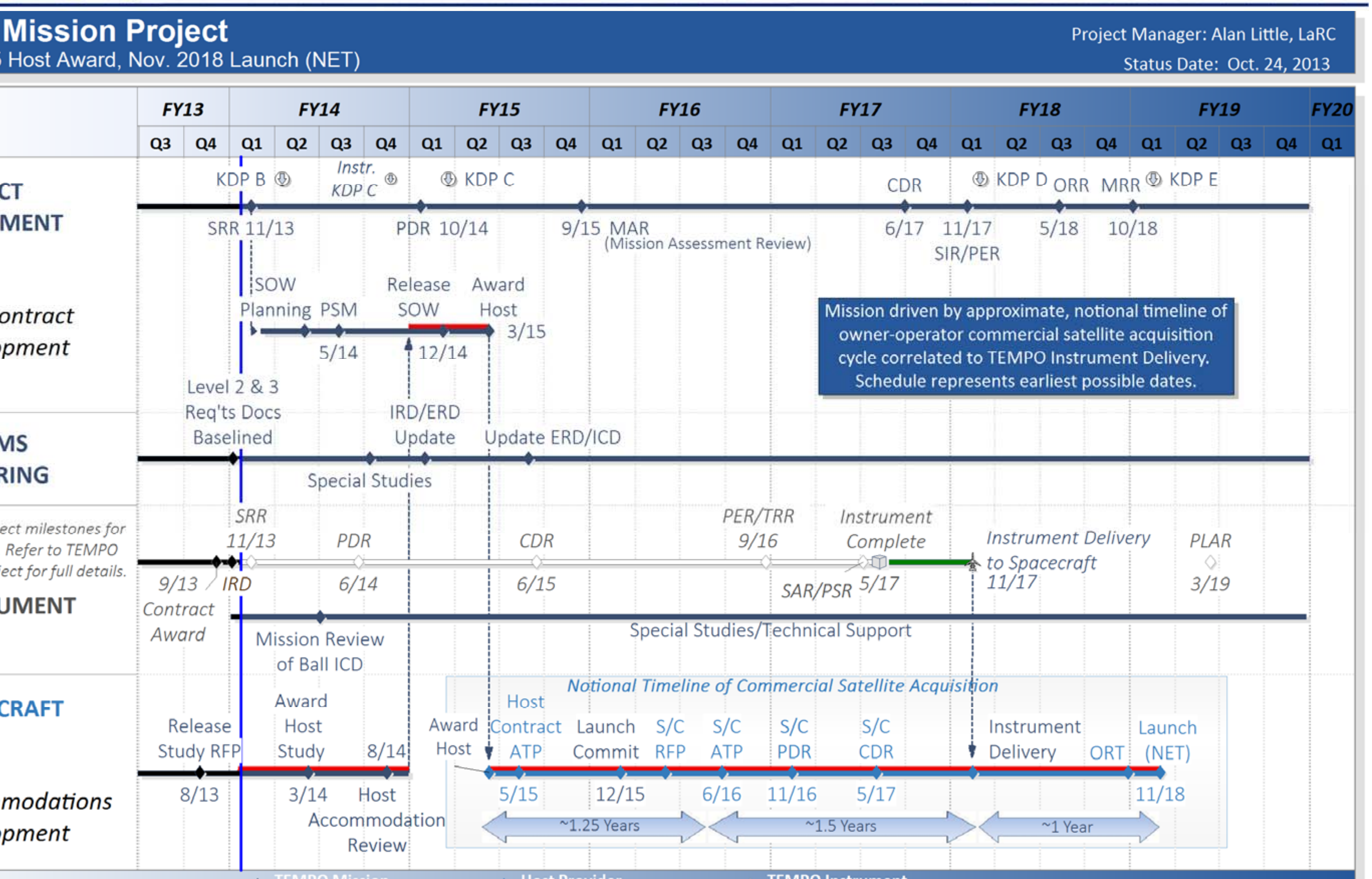
UNIVERSITY OF Nebraska Lincoln

CARR ASTRONAUTICS

Science at work

Backups

TEMPO mission project integrated master schedule



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[†]
	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO
	Derived Gridded Geophysical Data Products	6 months	1 month after completion of data accumulation required for individual geophysical products

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

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

Instrument progress since KDP-B

@ Ball in April plus follow-on studies:

- **N now meets reqs. with high margin (engineering & retrieval studies)**
- **avelength stability accepted, will use cross-correlation algorithm solution**
- **larization sensitivity modeled to be acceptable with high margin**
- **eld of regard (instrument plus mission jitter budget) resolved by changing cceptable range, still including Mexico City, Canadian oil sands**
- **S modulation transfer function (MTF) issue resolved by analysis**
  - May reduce MTF requirements to threshold near slit edge, beyond CONUS
- **ray light modeled to be well within acceptable levels**
  - Stray light instrument specifications now accepted
  - Stray light knowledge and levels are nominal for this type of instrument (GOME, SCIA, OMI, OMPS)
  - Normal stray light correction is in 0-1 algorithm, as planned. Low risk of additional resources being required
  - Developing details of verification/characterization/calibration/testing is normal planned engineering work

EMPO instrument design is capable of meeting Baseline Level 1 science

UV/Visible/IR satellite array spectrometers

Instrument	Wavelength (nm)	Viewing Geometry	Gases	Launch Year
OME (GOME-2)	240-790	Nadir	O_3, NO_2, BrO, OClO, SO_2, HCHO, H_2O	1995 (2006, 2012)
SIRIS/ODIN	280-800	Limb	O_3, NO_2, BrO, OClO, SO_2, HCHO, H_2O	2001
AGE III	280-1040	occultation (limb)	O_3, NO_2, BrO, OClO, H_2O	2001
OMOS/Envisat	250-952	stellar occultation	O_3, NO_2, H_2O, NO_3	2002
CIAMACHY/Envisat	240-2380	nadir/limb/ occultation	O_3, NO_2, BrO, OClO, SO_2, HCHO, CHO-CHO, H_2O, NO_3, N_2O, CH_4, CO, CO_2	2002
IAESTRO/ACE	285-1030	occultation	O_3, NO_2, BrO, OClO, SO_2, HCHO, H_2O	2003
MI/AURA	270-500	nadir	O_3, NO_2, BrO, OClO, SO_2, HCHO, CHO-CHO	2004
PUS/GCOM	306-420	nadir	O_3, NO_2, BrO, OClO, SO_2, HCHO	2006
MPS/NPOESS	250-1000	nadir/limb	O_3, NO_2, BrO, OClO, SO_2, HCHO, H_2O	2011