Tropospheric Emissions: Monitoring of Pollution Overview

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NASA LaRC

Scott Janz, NASA GSFC

GEO-CAPE 2015 Open Community Workshop
August 31, 2015
**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**
The view from GEO
Why geostationary? High temporal and spatial resolution

Hourly NO₂ surface concentration and integrated column calculated by CMAQ air quality model: Houston, TX, June 22-23, 2005

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\textsubscript{2} Slant Column, 02 August 2014 Morning

Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

4/29/15

ACC-11
TEMPO measurements will capture the diurnal cycle of pollutant emissions

GeoTASO NO$_2$ Slant Column, 02 August 2014 Afternoon

Co-added to approx. 500m x 450m

Morning vs. Afternoon

Preliminary data, C. Nowlan, SAO

4/29/15 ACC-11
<table>
<thead>
<tr>
<th>Science Questions</th>
<th>Science Objective</th>
<th>Science Measurement Requirement</th>
<th>Instrument Function Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>What are the temporal and spatial variations of emissions of gases and aerosols important for AQ and climate?</td>
<td>High temporal resolution measurements to capture changes in pollutant gas distributions.</td>
<td>Baseline* Trace gas column densities (10$^{16}$ cm$^{-2}$) hourly @ 8.9 km x 5.2 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spatially imaged &amp; spectrally resolved, solar backscattered earth radiance, spanning spectral windows suitable for retrievals of O$_3$, NO$_2$, H$_2$CO, SO$_2$, and C$_2$H$_5$O$_2$.</td>
<td>Species: O$_3$ (540-650 nm), O$_3$: UV (290-345 nm), Required: ≥1413, Predicted: 1765</td>
</tr>
<tr>
<td>Q2</td>
<td>How do physical, chemical, and dynamical processes determine tropospheric composition and AQ over scales ranging from urban to continental, diurnally to seasonally?</td>
<td>High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas.</td>
<td>Baseline* Aerosol/Cloud properties hourly @ 8.9 km x 5.2 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurements at spatial scales comparable to regional atmospheric chemistry models.</td>
<td>Property: AOD, AOD (0.1), COCP (0.05), Multispectral data in suitable O$_3$ absorption bands to provide vertical distribution information.</td>
</tr>
<tr>
<td>Q3</td>
<td>How do episodic events affect atmospheric composition and AQ?</td>
<td>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.</td>
<td>Spectral Imaging Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectral radiances measurements with suitable quality (SNR) to provide multiple measurements over daylight hours (solar zenith angle &lt; 70°) at precisions to distinguish pollutants from background levels.</td>
<td>Relevant absorption bands for trace gases &amp; windows for aerosols</td>
</tr>
<tr>
<td>Q4</td>
<td>How does AQ drive climate forcing and climate change affect AQ on a continental scale?</td>
<td>Observe aerosol optical properties with high temporal and spatial resolution for quantifying and tracking evolution of aerosol loading.</td>
<td>Radiometric Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determination of instantaneous radiative forcings associated with O$_3$ and aerosols on the continental scale.</td>
<td>Solar irradiance and Earth backscattered radiance spectrally resolved over spectral range</td>
</tr>
<tr>
<td>Q5</td>
<td>How can observations from space improve AQ forecasts and assessments for societal benefit?</td>
<td>Integrate observations from TEMPO and other platforms into models to improve representation of processes in the models and construct an enhanced observing system.</td>
<td>Spatial Imaging Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles &lt;70°.</td>
<td>Observations at relevant urban to synoptic scales and multiple times during daylight</td>
</tr>
</tbody>
</table>

**TEMPO science traceability matrix**

**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

<table>
<thead>
<tr>
<th>Species/Products</th>
<th>Required Precision</th>
<th>Temporal Revisit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2 km $O_3$ (Selected Scenes)</td>
<td>10 ppbv</td>
<td>2 hour</td>
</tr>
<tr>
<td><strong>Baseline only</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric $O_3$</td>
<td>10 ppbv</td>
<td>1 hour</td>
</tr>
<tr>
<td>Total $O_3$</td>
<td>3%</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric $NO_2$</td>
<td>$1.0 \times 10^{15}$ molecules cm$^{-2}$</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric $H_2CO$</td>
<td>$1.0 \times 10^{16}$ molecules cm$^{-2}$</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric $SO_2$</td>
<td>$1.0 \times 10^{16}$ molecules cm$^{-2}$</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric $C_2H_2O_2$</td>
<td>$4.0 \times 10^{14}$ molecules cm$^{-2}$</td>
<td>3 hour</td>
</tr>
<tr>
<td>Aerosol Optical Depth</td>
<td>0.10</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

- **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
• **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 km²)
  - Co-add/cloud clear as needed for specific data products

• **Standard data products and sampling rates**
  - Most sampled hourly, including eXceL O₃ (troposphere, PBL) for selected areas
  - H₂CO, C₂H₂O₂, SO₂ 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° for SO₂, 70° SZA for other products

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

- BrO, OCIO, H₂CO, SO₂
- O₃
- Fully cloudy
- Sahara Desert
- Vegetation red edge
- Clear, ocean albedo
Algorithm testing: OMPS H$_2$CO

OMPS slant column H$_2$CO monthly average for July 2012. Because of higher SNR, the OMPS precisions are substantially higher than those from OMI.
OMPS tropospheric slant column NO$_2$ for July 2-7, 2012. Much optimization remains to improve fitting and remove artifacts but the data are nearly of sufficient quality for scientific studies. The SAA is readily visible.
• **Geostationary orbit, operating on a commercial telecom satellite**
  o NASA will arrange launch and hosting services (per Earth Venture Instrument scope)
    - 80-115° W acceptable latitude
    - Specifying satellite environment, accommodation
  o Hourly measurement and telemetry duty cycle for at least ≤70° SZA
    - **Hope to measure up to 20 hours/day**
• **TEMPO is low risk with significant space heritage**
  o All proposed TEMPO measurements have been made from low Earth orbit satellite instruments to the required precisions
  o All TEMPO launch algorithms are implementations of currently operational algorithms
    - NASA TOMS-type O₃
    - SO₂, NO₂, H₂CO, C₂H₂O₂ from fitting with AMF-weighted cross sections
    - Absorbing Aerosol Index, UV aerosol, Rotational Raman scattering cloud
    - eXceL profile/tropospheric/PBL O₃ 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**
  o **Example research products:** eXceL profile O₃ for broad regions; BrO from AMF-normalized cross sections; height-resolved SO₂; additional cloud/aerosol products; vegetation products; H₂O
TEMPO footprint, ground sample distance and field of regard

GNA imaged in 1 hour with large margin

2.1 km × 4.7

2 km × 4.5 km pixel at 36.5° N, 100° W

Field of Regard

Slit projected onto scene
Scans East to West in 1250, 110 μrad steps
2000, 40.6 μrad North-South IFOVs

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
OMI NO$_2$ in April (2005–2008) over TEMPO FOR
Bay Area coverage

Every hour!
¡Cada hora!
Global pollution monitoring constellation

Policy-relevant science and environmental services enabled by common observations

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support United Nations Convention on Long Range Transboundary Air Pollution
TEMPO will use the EPA’s Remote Sensing Information Gateway (RSIG) for subsetting, visualization, and product distribution – to make TEMPO YOUR instrument
• Currently on-schedule and on-budget
  • Passed PDR July, 2014
  • Converted instrument to firm fixed price March 2015
  • Now in Phase C: Passed KDP-C April, 2015
  • Addressing detector issues to ensure PBL O₃
  • Ground systems development at SAO on schedule
• Passed instrument CDR June 2015
  • Reassessing operational data product list
  • Separate Ground Systems CDR March 2016
• Select satellite host probably in 2017
  • TEMPO operating longitude and launch date are not known until after host selection
• Instrument delivery 05/2017 for launch 11/2018 or later
  • Could be as late as 2021 but we hope not
<table>
<thead>
<tr>
<th>Team Member</th>
<th>Institution</th>
<th>Role</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>K. Chance</td>
<td>SAO</td>
<td>PI</td>
<td>Overall science development; <strong>Level 1b, H₂CO, C₂H₂O₂</strong></td>
</tr>
<tr>
<td>X. Liu</td>
<td>SAO</td>
<td>Deputy PI</td>
<td>Science development, data processing; <strong>O₃ profile, tropospheric O₃</strong></td>
</tr>
<tr>
<td>J. Al-Saadi</td>
<td>LaRC</td>
<td>Deputy PS</td>
<td>Project science development</td>
</tr>
<tr>
<td>J. Carr</td>
<td>Carr Astronautics</td>
<td>Co-I</td>
<td><strong>INR Modeling and algorithm</strong></td>
</tr>
<tr>
<td>M. Chin</td>
<td>GSFC</td>
<td>Co-I</td>
<td>Aerosol science</td>
</tr>
<tr>
<td>R. Cohen</td>
<td>U.C. Berkeley</td>
<td>Co-I</td>
<td>NO₂ validation, atmospheric chemistry modeling, process studies</td>
</tr>
<tr>
<td>D. Edwards</td>
<td>NCAR</td>
<td>Co-I</td>
<td>VOC science, synergy with carbon monoxide measurements</td>
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<tr>
<td>J. Fishman</td>
<td>St. Louis U.</td>
<td>Co-I</td>
<td>AQ impact on agriculture and the biosphere</td>
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<tr>
<td>D. Flittner</td>
<td>LaRC</td>
<td>Project Scientist</td>
<td>Overall project development; STM; instrument cal./char.</td>
</tr>
<tr>
<td>J. Herman</td>
<td>UMBC</td>
<td>Co-I</td>
<td>Validation (PANDORA measurements)</td>
</tr>
<tr>
<td>D. Jacob</td>
<td>Harvard</td>
<td>Co-I</td>
<td>Science requirements, atmospheric modeling, process studies</td>
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<tr>
<td>S. Janz</td>
<td>GSFC</td>
<td>Co-I</td>
<td>Instrument calibration and characterization</td>
</tr>
<tr>
<td>J. Joiner</td>
<td>GSFC</td>
<td>Co-I</td>
<td><strong>Cloud, total O₃, TOA shortwave flux research product</strong></td>
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<tr>
<td>N. Krotkov</td>
<td>GSFC</td>
<td>Co-I</td>
<td><strong>NO₂, SO₂, UVB</strong></td>
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<tr>
<td>M. Newchurch</td>
<td>U. Alabama Huntsville</td>
<td>Co-I</td>
<td>Validation (O₃ sondes, O₃ lidar)</td>
</tr>
<tr>
<td>R.B. Pierce</td>
<td>NOAA/NESDIS</td>
<td>Co-I</td>
<td>AQ modeling, data assimilation</td>
</tr>
<tr>
<td>R. Spurr</td>
<td>RT Solutions, Inc.</td>
<td>Co-I</td>
<td><strong>Radiative transfer modeling for algorithm development</strong></td>
</tr>
<tr>
<td>R. Suleiman</td>
<td>SAO</td>
<td>Co-I, Data Mgr.</td>
<td>Managing science data processing, <strong>BrO, H₂O, and L3 products</strong></td>
</tr>
<tr>
<td>J. Szykman</td>
<td>EPA</td>
<td>Co-I</td>
<td>AIRNow AQI development, validation (PANDORA measurements)</td>
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<tr>
<td>O. Torres</td>
<td>GSFC</td>
<td>Co-I</td>
<td><strong>UV aerosol product, Al</strong></td>
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<tr>
<td>J. Wang</td>
<td>U. Nebraska</td>
<td>Co-I</td>
<td>Synergy w/GOES-R ABI, <strong>aerosol research products</strong></td>
</tr>
<tr>
<td>J. Leitch</td>
<td>Ball Aerospace</td>
<td>Collaborator</td>
<td>Aircraft validation, instrument calibration and characterization</td>
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<tr>
<td>D. Neil</td>
<td>LaRC</td>
<td>Collaborator</td>
<td>GEO-CAPE mission design team member</td>
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<tr>
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<td>R. Martin</td>
<td>Dalhousie U.</td>
<td>Collaborator</td>
<td>Atmospheric modeling, air mass factors, AQI development</td>
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<tr>
<td>Chris McLinden</td>
<td>Environment Canada</td>
<td>Collaborator</td>
<td>Canadian air quality coordination</td>
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<tr>
<td>Michel Grutter de la Mora</td>
<td>UNAM, Mexico</td>
<td>Collaborator</td>
<td>Mexican air quality coordination</td>
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<tr>
<td>Gabriel Vazquez</td>
<td>UNAM, Mexico</td>
<td>Collaborator</td>
<td>Mexican air quality, algorithm physics</td>
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<tr>
<td>Amparo Martinez</td>
<td>INECC, Mexico</td>
<td>Collaborator</td>
<td>Mexican environmental pollution and health</td>
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<td>J. Victor Hugo Paramo Figueiroa</td>
<td>INECC, Mexico</td>
<td>Collaborator</td>
<td>Mexican environmental pollution and health</td>
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<tr>
<td>Brian Kerridge</td>
<td>Rutherford Appleton Laboratory, UK</td>
<td>Collaborator</td>
<td>Ozone profiling studies, algorithm development</td>
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<tr>
<td>Paul Palmer</td>
<td>Edinburgh U., UK</td>
<td>Collaborator</td>
<td>Atmospheric modeling, process studies</td>
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<tr>
<td>J. Kim</td>
<td>Yonsei U.</td>
<td>Collaborators, Science Advisory Panel</td>
<td>Korean GEMS, CEOS constellation of GEO pollution monitoring</td>
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<tr>
<td>C.T. McElroy</td>
<td>York U. Canada</td>
<td></td>
<td>CSA PHEOS, CEOS constellation of GEO pollution monitoring</td>
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<tr>
<td>B. Veihelmann</td>
<td>ESA</td>
<td></td>
<td>ESA Sentinel-4, CEOS constellation of GEO pollution monitoring</td>
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</table>
TEMPO Mission Project
March 2015 Host Award, Nov. 2018 Launch (NET)

<table>
<thead>
<tr>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
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<tbody>
<tr>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td>KDP B</td>
<td>Instr. KDP C</td>
<td>KDP C</td>
<td>CDR</td>
<td>KDP D ORR</td>
<td>MRR</td>
<td>KDP E</td>
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<tr>
<td>Levels 2 &amp; 3 Reqts Docs Baselined</td>
<td>5/14</td>
<td>12/14</td>
<td>Host</td>
<td>3/15</td>
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<tr>
<td>Update</td>
<td>Update ERD/ICD</td>
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</tbody>
</table>

01 PROJECT MANAGEMENT

Host Contract Development

02 SYSTEMS ENGINEERING

Instrument Project milestones for reference only. Refer to TEMPO Instrument Project for full details.

05 INSTRUMENT

Mission Review of Ball ICD

06 SPACECRAFT

Host Accommodations Development

Mission driven by approximate, notional timeline of owner-operator commercial satellite acquisition cycle correlated to TEMPO Instrument Delivery. Schedule represents earliest possible dates.

Notional Timeline of Commercial Satellite Acquisition

Host Contract Award

TEMPO Mission Funded

Host Provider Activity (Notional)

TEMPO Instrument Funded

Reserve

Critical Path

Project Manager: Alan Little, LaRC
Status Date: Oct. 24, 2013

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## Data product definitions and details

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

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.
TIM @ Ball in April plus follow-on studies:

- S/N now meets reqs. with high margin (engineering & retrieval studies)
- Wavelength stability accepted, will use cross-correlation algorithm solution
- Polarization sensitivity modeled to be acceptable with high margin
- Field of regard (instrument plus mission jitter budget) resolved by changing acceptable range, still including Mexico City, Canadian oil sands
- N/S modulation transfer function (MTF) issue resolved by analysis
  - May reduce MTF requirements to threshold near slit edge, beyond CONUS
- Stray 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

The TEMPO instrument design is capable of meeting Baseline Level 1 science requirements
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
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength (nm)</th>
<th>Viewing Geometry</th>
<th>Gases</th>
<th>Launch Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSIRIS/ODIN</td>
<td>280-800</td>
<td>Limb</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO, H₂O</td>
<td>2001</td>
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<tr>
<td>SAGE III</td>
<td>280-1040</td>
<td>occultation</td>
<td>O₃, NO₂, BrO, OCIO, H₂O</td>
<td>2001</td>
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<tr>
<td>GOMOS/Envisat</td>
<td>250-952</td>
<td>stellar occultation</td>
<td>O₃, NO₂, H₂O, NO₃</td>
<td>2002</td>
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<tr>
<td>SCIAMACHY/Envisat</td>
<td>240-2380</td>
<td>nadir/limb/occultation</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO, CHO-CHO, H₂O, N₂O, N₂O, CH₄, CO, CO₂</td>
<td>2002</td>
</tr>
<tr>
<td>MAESTRO/ACE</td>
<td>285-1030</td>
<td>occultation</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO, H₂O</td>
<td>2003</td>
</tr>
<tr>
<td>OMI/AURA</td>
<td>270-500</td>
<td>nadir</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO, CHO-CHO</td>
<td>2004</td>
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<tr>
<td>OPUS/GCOM</td>
<td>306-420</td>
<td>nadir</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO</td>
<td>2006</td>
</tr>
<tr>
<td>OMPS/NPOESS</td>
<td>250-1000</td>
<td>nadir/limb</td>
<td>O₃, NO₂, BrO, OCIO, SO₂, HCHO, H₂O</td>
<td>2011</td>
</tr>
</tbody>
</table>
Footprint comparison
For GEO at 80°W, pixel size at 36.5°N, 100°W is 2.2 km × 5.2 km.

<table>
<thead>
<tr>
<th>Location</th>
<th>N/S (km)</th>
<th>E/W (km)</th>
<th>GSA (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.5°N, 100°W</td>
<td>2.11</td>
<td>4.65</td>
<td>9.8</td>
</tr>
<tr>
<td>Washington, DC</td>
<td>2.37</td>
<td>5.36</td>
<td>11.9</td>
</tr>
<tr>
<td>Seattle</td>
<td>2.99</td>
<td>5.46</td>
<td>14.9</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>2.09</td>
<td>5.04</td>
<td>10.2</td>
</tr>
<tr>
<td>Boston</td>
<td>2.71</td>
<td>5.90</td>
<td>14.1</td>
</tr>
<tr>
<td>Miami</td>
<td>1.83</td>
<td>5.04</td>
<td>9.0</td>
</tr>
<tr>
<td>Mexico City</td>
<td>1.65</td>
<td>4.54</td>
<td>7.5</td>
</tr>
<tr>
<td>Canadian tar sands</td>
<td>3.94</td>
<td>5.05</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Assumes 2000 N/S pixels
SAO L2 OMI H$_2$O product
SAO L3 OMI H₂O product
Three changes were made to the TEMPO PLRA soon after KDP-B

1. Reduce the number of operational data products to focus on the most fundamental tropospheric air pollution chemistry;
2. Relax the field of regard slightly, but still covering CONUS, Mexico City and the Canadian oil sands;
3. Revise the acceptable longitude range for GEO hosts to 80°W to 115°W to be consistent with baseline science (a range demonstrated to include suitable candidates).

With these changes:

- Key science measurements remain intact.
- Ball has a complete set of requirements that can be met at an acceptable level of risk.
- Savings in science budget of $1.25M.
As a result of SAO/LaRC/Ball technical interchange meetings and follow-on studies:

- Detectors can produce PLRA baseline products (engineering & retrieval studies)
  - Assumptions included current predicted worst-case dark current
  - The largest impact of dark current is on the ozone retrieval products
  - The Science Team has quantified the degradation in ozone retrieval performance and believes PLRA baseline can be met with the current design, albeit with no margin remaining

- Wavelength stability accepted, will use cross-correlation algorithm solution
- Polarization sensitivity modeled to be acceptable with high margin
- Field of regard (instrument plus mission jitter budget) resolved by changing acceptable range, still including Mexico City, Canadian oil sands
- N/S modulation transfer function (MTF) issue resolved by analysis
- Stray light modeled to be well within acceptable levels
Adjusting the field of regard (FOR) requirement from 18°N – 58°N to 19°N – 57.5°N (baseline) still allows, with the current BATC preliminary optical design, the measurement of both Mexico City and the Canadian oil sands, even if the maximum spacecraft pointing error permitted by the IHIRD is realized. The threshold is adjusted from 18°N – 55°N to 19°N – 55°N.

- This change avoids cost risk on the Mission side by accepting the maximum allowed pointing error from the IHIRD rather than finding a way to mitigate it

- This change may avoid risk on the Instrument side if the error budget independent of the IHIRD exceeds the specifications, thus requiring resources to improve instrument pointing

- If the spacecraft pointing error is lower than the IHIRD maximum, the guaranteed field of regard will increase
Revising the acceptable longitude range for GEO hosts from 175°W – 137°W to 80°W – 115°W improves the ground footprint and improves diurnal coverage.

- The proposed range has been demonstrated to include many suitable candidates
- New orbital longitude range to 120° W is being analyzed for feasibility by the Instrument contractor to open the host opportunities
US air quality standards continue to become more stringent to better protect human health

New and transient pollution sources (e.g., vehicular traffic, oil & gas development, trans-boundary pollution) are growing in importance yet are very difficult to monitor from ground networks

Many areas that are not currently monitored are expected to violate proposed ozone standards

TEMPO measurements will provide data to help solve this national challenge

US EPA ozone 8-hour design projections to 2020

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?