TEMPO Overview and Status

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and the TEMPO Team

1. SAO  2. NASA LaRc
3. Carr Astronautics  4. BATC  5 BU

OMI Science Team Meeting
NASA GSFC
September 14, 2017
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:** Mexico, Canada, Cuba, Korea, U.K., ESA, Spain

Selected Nov. 2012 as NASA’s first Earth Venture Instrument  
- Instrument delivery March 2018  
- NASA will arrange hosting on commercial geostationary communications satellite with launch expected NET 2019

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  
- 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
Global pollution monitoring constellation

TEMPO (hourly)

Sentinel-4 (hourly)

GEMS (hourly)

80-115°W
2019-2021 launch

0°
2021+ launch

128.2°E
2019 launch

Sentinel-5P (once per day), OMPS, GOMÉ-2

Courtesy Jhoon Kim, Andreas Richter
Currently on-budget and close to on-schedule

- SRR/MDR in November 2013
- KDP-B in April 2014, PDR in July 2014
- Converted instrument to firm fixed price in March 2015
- Now in Phase C: Passed KDP-C in April 2015
- Passed instrument CDR in June 2015 & GS CDR in May 2016
- PER/TRR in August 2016
- Currently undergoing assembly, integration, and testing

Instrument delivery in March 2018.


IOC and SDPC software testing (L0-L3) to be completed by late-2018, ready 6 months before launch

- V1 L0-1 processor: ~March 2018
- V2 L0-1 processor: ~December, 2018
Imaging grating spectrometer measuring solar backscattered Earth radiance
- 0.6 nm FWHM, 0.2 nm sampling
- 290-490 + 540-740 nm, 2 channels (1 focal plane but with 2 2-D 2 k x 1k detectors)

Geostationary, operating on commercial communication satellite as a hosted payload, with acceptable longitude range 115°W-80°W
- Great North America: Mexico City to Canadian tar sands, Atlantic to Pacific
- Instrument slit aligned N/S and sweep across the Field of Regard (FOR) in the E/W in 1 hour at ~2.1x4.5 km² (center of FOR) with ~2.5M spatial pixels/hr
• Calibration wheel with transmissive diffusers for daily solar calibration
• Step/stare 2-axis scan mechanism
• Detectors operating at -20°C
• Instrument Control Electronics (ICE) mounted below spacecraft deck
• Volume: 1.4 m x 1.1 m x 1.2 m Mass: 148 kg Avg. Power: 134W
TEMPO Telescope with optics, scan mechanism and thermal installs completed.

TEMPO Spectrometer subsystem complete and ready for vibe test
TEMPO hourly NO$_2$ sweep

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

~ 1283 steps/hr
~ 2.6 M pixels/hr
N.B. special operations give 10-minute resolution for selected longitude Regions

Courtesy of L. Lamsal & N. Krotkov
TEMPO footprint (GEO at 100° W)

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 oil sands</td>
<td>3.94</td>
<td>5.05</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Assumes 2000 N/S pixels
Table 1. Key TEMPO instrument parameters based on the latest design as of February 2016 for a geostationary satellite at 100°W. The signal to noise ratio is the average value over the specific retrieval windows for the nominal radiance spectrum. IFOV is Instantaneous Field of View at 36.5°N, 100°W. MTF is Modulation Transfer Function at Nyquist.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>148 kg</td>
<td>Spectral range</td>
<td>290–490 nm, 540–740 nm</td>
</tr>
<tr>
<td>Volume</td>
<td>1.4 × 1.1 × 1.2 m</td>
<td>Spectral resolution &amp; sampling</td>
<td>0.57 nm, 0.2 nm</td>
</tr>
<tr>
<td>Avg. operational power</td>
<td>163 W</td>
<td>Albedo calibration uncertainty</td>
<td>2.0% λ-independent, 0.8% λ-dependent</td>
</tr>
<tr>
<td>Average Signal to Noise [hourly @ 8.4 km x 4.4 km]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O$_3$:Vis (540–650 nm)</td>
<td>1436</td>
<td>Spectral uncertainty</td>
<td>&lt; 0.1 nm</td>
</tr>
<tr>
<td>O$_3$: UV (300–345 nm)</td>
<td>1610</td>
<td>Polarization factor</td>
<td>≤ 2% UV, &lt; 10% Vis</td>
</tr>
<tr>
<td>NO$_2$: 423–451 nm</td>
<td>1771</td>
<td>Revisit time</td>
<td>1 h</td>
</tr>
<tr>
<td>H$_2$CO: 327–356 nm</td>
<td>2503</td>
<td>Field of regard: N/ S × E/W</td>
<td>4.82° × 8.38° (greater North America)</td>
</tr>
<tr>
<td>SO$_2$: 305–345 nm</td>
<td>1797</td>
<td>Geo-location Uncertainty</td>
<td>2.8 km</td>
</tr>
<tr>
<td>C$_2$H$_2$O$_2$: 420–480 nm</td>
<td>1679</td>
<td>IFOV: N/S × E/W</td>
<td>2.1 km × 4.4 km</td>
</tr>
<tr>
<td>Aerosol: 354, 388 nm</td>
<td>2313</td>
<td>E/W oversampling</td>
<td>5%</td>
</tr>
<tr>
<td>Clouds: 346–354 nm</td>
<td>2492</td>
<td>MTF of IFOV: N/S × E/W</td>
<td>0.19 × 0.36</td>
</tr>
</tbody>
</table>

* SNR are for 4 pixels coadded as requirements are derived from coadding 4 pixels at 8.4 x 4.5 km$^2$!
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 O₃ (Selected Scenes)</td>
<td>10 ppbv</td>
<td>2 hour</td>
</tr>
<tr>
<td>(Baseline only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric O₃</td>
<td>10 ppbv</td>
<td>1 hour</td>
</tr>
<tr>
<td>Total O₃</td>
<td>3%</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric NO₂</td>
<td>$1.0 \times 10^{15}$ molecules cm⁻²</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric H₂CO</td>
<td>$1.0 \times 10^{16}$ molecules cm⁻²</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric SO₂</td>
<td>$1.0 \times 10^{16}$ molecules cm⁻²</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric C₂H₂O₂</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 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 km² at center of Field Of Regard (FOR)
  - Threshold ≤ 300 km² 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

4/10/17
• Aerosols, SO$_2$, C$_2$H$_2$O$_2$ were removed from the baseline products during KDPC
  ➢ Will use reserve to bring it back during the gap period

• TEMPO research products will greatly extend science and applications
  ➢ H$_2$O, BrO, OCIO, IO, volcanic (SO$_2$ plume height and VCD), and more species (e.g., HONO?)
  ➢ Additional cloud with O$_2$-O$_2$ bands or O$_2$-B bands
  ➢ Additional aerosol products from hyperspectral spectra, and TEMPO + GOES-R synergy at @U Iowa, GSFC, NOAA
  ➢ UVB
  ➢ Vegetation products (SIF)
  ➢ Diurnal out-going shortwave radiation and cloud forcing
  ➢ City lights

• Higher-level products: Near-real-time pollution/AQ indices, UV index
TEMPO Launch Algorithms

NO$_2$, H$_2$CO, SO$_2$, C$_2$H$_2$O$_2$ vertical columns
Direct fitting to TEMPO radiances (e.g., OMHCHO)
AMF-corrected reference spectra, Ring effect, etc.
NO$_2$ strat/trop separation (STS) adapted from OMI
Research products could include H$_2$O, BrO, OCIO, IO

O$_3$ profiles and tropospheric O$_3$
SAO OE-based ozone profile method developed for GOME and OMI
Add visible to improve retrieval sensitivity in the lower troposphere
May be extended to SO$_2$, especially volcanic SO$_2$

TOMS-type total ozone retrieval (OMTO3) included for heritage

Aerosol products based on OMAERUV: AOD, AAOD, Aerosol Index
Advanced/improved products likely developed @ GSFC, U. Iowa

Cloud Products from OMCLDRR: CF, CTP
Advanced/improved products likely developed at GSFC

UVB research product based on OMI heritage (FMI, GSFC)
Nighttime research products include city lights (Carr Astronautics)

4/10/17
Retrieval averaging kernels based on iterative nonlinear retrievals from synthetic TEMPO radiances with the signal to noise ratio (SNR) estimated using the TEMPO SNR model at instrument critical design review in June 2015 for (a) UV (290-345 nm) retrievals and (b) UV/Visible (290-345 nm, 540-650 nm) retrievals for clear-sky condition and vegetation surface with solar zenith angle 25°, viewing zenith angle 45° and relative azimuthal angle 86°. DFS is degrees of freedom for signal, the trace of the averaging kernel matrix, which is an indicator of the number of pieces of independent information in the solution.
J. Geddes and R. Martin adapted OMI NO$_2$ STS algorithm to TEMPO and found small errors of $\sim$2.0E14 molecules at the edge. It is being implemented by our software engineers.
Spectroscopic Signatures

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

Observing Nightlights from Space with TEMPO

James Carr¹, Xiong Liu², Brian Baker³, Kelly Chance²

¹Carr Astronautics Corp., Greenbelt, MD, USA
²Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
³Ball Aerospace and Technologies Corp., Boulder, CO, USA
TEMPO Ground Systems Overview

TEMPO Instrument Project

Class C

TEMPO Mission Project

Ground Systems Overview

Spacecraft Operation Center

Commands

Raw Science & Ancillary Data

Externally Obtained Ancillary Science Data

Instrument Operations Center (IOC)

Science Data Processing Center (SDPC)

SAO

Level 0 Science & Ancillary Data

L0-L3 Science Data Products & Ancillary Data

DAAC

User Community

TEMPO Ground Systems: Instrument Operations Center (IOC)
• Prototype to production iterative development
• L1/L2 science data formats specified. netCDF4/HDF-5 I/O & error libraries were built.
• Cloud, total ozone, & trace gas code adapted and tested with TEMPO I/O and errors.
• Ozone profile (UV) adapted.
• L0-L1 algorithm is being developed
Heritages from: OMI, TROPOMI, OMPS, GOME/GOME-2, GEOTASO

- TEMPO specifics
  - INR (geo-location) by Carr Astronautics
  - T-dependent dark current correction
  - Polarization correction

Requirements from SDPCRD [TEMPO-09-0003] labeled as 4.X.X
INR System Block Diagram

- **L0_inrprep**: add spacecraft position & scan mirror orientation
- **L0_inr**: provide geo-location coordinates to all spatial pixels by transferring GOES geo-location accuracy to TEMPO, calculate viewing geometry

**INR Quality**

- Tie points between TEMPO and GOES imagery serve as pointing truth rather than stars or landmarks.

**SDPC – L0-to-L1 Processing**

- Combine Earth orientation and spacecraft tracking to align tie points in the GOES imagery with TEMPO data
- Two-pass Kalman filter
- Archive tie points
- Provide scan tailoring parameters

**Image Navigation and Registration (INR)**

**L0_inrprep, L0_inr**

- GOES-R Imagery
- Tie Points
- Topo
- Propagate
- Update
- Geolocate
- Smooth
- Kalman Filter/Smoother
- Scan Tailoring
- L1-to-L2
- Real Time
- INR Quality

**INR System Block Diagram**

- Host & Instrument
  - Optics
  - Gyro
  - Control Inputs
  - Tracking Ephemeris
- Imagery
  - EW Scan
  - NS Tilt
  - Two-Axis Orientation
- Scan Tailoring
- GOES-R Imagery (or GOES-NOP)
GEOS-5 Truth Atmosphere

Surface Ozone - 20130715 - 13:00 EST

“G5NR” - GEOS-Chem coupled to the GEOS-5 GCM run globally at ~12x12 km² resolution

Courtesy of Christoph Keller
Synthetic radiance simulation

Simulation Details

- Absorption by all TEMPO target molecules with p/T dependence where possible
- Topography correction based on GMTED2010
- Scan geolocation from Carr Astronautics instrument pointing model
- Aerosols (GEOS-Chem types) with RH dependence
- Plant fluorescence (GOME-2 downscaled by MODIS NDVI)
- Ring effect (parameterization following Wagner et al. (2009))
- Scattering clouds with generated with stochastic downscaling algorithm follow MRAN assumption (right)
- Surface reflection: MODIS BRDF w/ USGS+ASTER PC fit (land) or Cox-Monks kernel (ocean)
Synthetic data will be used to test L0-L3 algorithms and verify retrieval performance.
The TEMPO Green Paper is a living community document – see http://tempo.si.edu/presentations.html. Please make additions and corrections.

Scientific studies using high temporal resolution special observations:
- Lightning NOx/Soil NOx
- Traffic/urban pollution: Morning and evening higher-frequency scans
- Biomass burning
- Atmospheric chemistry of halogen oxides over the ocean, and in particular in coastal regions
- Fluorescence and other spectral indicators
- Assessing pollution transport during upslope flows
- Tidal effects on estuarine circulation and outflow plumes
- Cloud field correlation with pollution
• TEMPO Science Team Meeting: Cambridge, May 31-June 1, the theme of this year is early adopters

• TEMPO Validation Workshop: April 26-27, UC Berkley, organized by Ron Cohen. Discussions focused on experimental strategies that will
  - Give confidence in the TEMPO data, especially with respect to its unique features—hourly with spatial resolution of ~10km²
  - Emphasize observations that could identify systematic errors in retrievals.
  - The evolving Pandora network within TEMPO FOR through NASA & EPA efforts is key to validate TEMPO, but not solely sufficient. Need surface networks, TOLNet, GeoTASO/GCAS, profiling aircraft etc.

• TEMPO Aerosol Workshop: September 11, NOAA, organized by Omar and Shoba
  - Individual TEMPO/GEMS, ABI(AMI), MAIC algorithms
  - TEMPO(GEMS)/ABI(AMI) synergy: cloud clearing, multi-view, combine UV aerosol absorption to ABI
TEMPO will use the EPA’s Remote Sensing Information Gateway (RSIG) for subsetting, visualization, and product distribution – to make TEMPO YOUR instrument

There will be a TEMPO data distribution workshop this winter in Ft. Collins, CO, sponsored by the Western States Air Resources Council
Summary

- TEMPO will provide hourly atmospheric pollution at high spatial resolution (≈10 km$^2$ at center of FOR) over North America from the GEO orbit.
- TEMPO currently on budget and close to on schedule.

See Zoogman et al. (2017), JQSRT for more detail.
The end!

Thanks to NASA, ESA, Ball Aerospace & Technologies Corp., The Boeing Company

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Instituto Nacional de Ecología y Cambio Climático

United States Environmental Protection Agency

National Oceanic and Atmospheric Administration

Ball Aerospace & Technologies Corp.

The Boeing Company

Dalhousie University

Saint Louis University

University of Alabama in Huntsville

Harvard University

Yonsei University

University of Maryland Baltimore County

CSIC - Consejo Superior de Investigaciones Científicas

The University of Iowa

York University

NCAR

FINNISH METEOROLOGICAL INSTITUTE

Environment and Climate Change Canada

Environnement et Changement climatique Canada

KNMI