North American pollution measurements from geostationary orbit with Tropospheric Emissions: Monitoring of Pollution (TEMPO, tempo.si.edu)

Kelly Chance
Smithsonian Astrophysical Observatory

CEOS AC-VC
May 3, 2018
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 2018
- NASA will arrange hosting on commercial geostationary communications satellite with launch expected NET 11/2019

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
Air quality requirements from the GEO-CAPE Science Traceability Matrix
### Ultraviolet/visible species (GOME, SCIA, OMI, OMPS, TEMPO, etc.)

- **Species**: O3, CO, AOD, NO2
- **Infrared species**: CO

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Time resolution</th>
<th>Typical value</th>
<th>Precision</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3</td>
<td>Hourly, SZA&lt;70</td>
<td>9x10^18</td>
<td>0-2 km: 10 ppbv, 2km-tropopause: 15 ppbv, Stratosphere: 5%</td>
<td>Observe O3 with two pieces of information in the troposphere with sensitivity to the lowest 2 km for surface AQ; also transport, climate forcing</td>
</tr>
<tr>
<td>CO</td>
<td>Hourly, day and night</td>
<td>2x10^18</td>
<td>0-2 km: 20 ppbv, 2km-tropopause: 20 ppbv</td>
<td>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</td>
</tr>
<tr>
<td>AOD</td>
<td>Hourly, SZA&lt;70</td>
<td>0.1 – 1</td>
<td>0.05</td>
<td>Observe total aerosol; aerosol sources and transport; climate forcing</td>
</tr>
<tr>
<td>NO2</td>
<td>Hourly, SZA&lt;70</td>
<td>6x10^16</td>
<td>1x10^15</td>
<td>Distinguish background from enhanced/polluted scenes; atmospheric chemistry</td>
</tr>
</tbody>
</table>

### Additional atmospheric measurements over Land/Coastal areas, baseline only: (A to K)

<table>
<thead>
<tr>
<th>Species</th>
<th>Time resolution</th>
<th>Typical value</th>
<th>Precision</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCHO</td>
<td>3/day, SZA&lt;50</td>
<td>1.0x10^16</td>
<td>1x10^16</td>
<td>Observe biogenic VOC emissions, expected to peak at midday; chemistry</td>
</tr>
<tr>
<td>SO2</td>
<td>3/day, SZA&lt;50</td>
<td>1.0x10^16</td>
<td>1x10^16</td>
<td>Identify major pollution and volcanic emissions; atmospheric chemistry</td>
</tr>
<tr>
<td>CH4</td>
<td>2/day</td>
<td>4x10^19</td>
<td>20 ppbv</td>
<td>Observe anthropogenic and natural emissions sources</td>
</tr>
<tr>
<td>NH3</td>
<td>2/day</td>
<td>2x10^16</td>
<td>0-2 km: 2ppbv</td>
<td>Observe agricultural emissions</td>
</tr>
<tr>
<td>CHOCH2</td>
<td>2/day</td>
<td>2x10^14</td>
<td>4x10^14</td>
<td>Detect VOC emissions, aerosol formation, atmospheric chemistry</td>
</tr>
<tr>
<td>AAOD</td>
<td>Hourly, SZA&lt;70</td>
<td>0 – 0.05</td>
<td>0.02</td>
<td>Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing</td>
</tr>
<tr>
<td>Al</td>
<td>Hourly, SZA&lt;70</td>
<td>-1 – +5</td>
<td>0.1</td>
<td>Detect aerosols near/above clouds and over snow/ice; aerosol events</td>
</tr>
<tr>
<td>AOCH</td>
<td>Hourly, SZA&lt;70</td>
<td>Variable</td>
<td>1 km</td>
<td>Determine plume height; large scale transport, conversions from AOD to PM</td>
</tr>
</tbody>
</table>

5/3/18
### 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><strong>0-2 km O\textsubscript{3}</strong></td>
<td>10 ppbv</td>
<td>2 hour</td>
</tr>
<tr>
<td>(Selected Scenes) <strong>Baseline only</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric O\textsubscript{3}</td>
<td>10 ppbv</td>
<td>1 hour</td>
</tr>
<tr>
<td>Total O\textsubscript{3}</td>
<td>3%</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric NO\textsubscript{2}</td>
<td>$1.0 \times 10^{15}$ molecules cm\textsuperscript{-2}</td>
<td>1 hour</td>
</tr>
<tr>
<td>Tropospheric H\textsubscript{2}CO</td>
<td>$1.0 \times 10^{16}$ molecules cm\textsuperscript{-2}</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric SO\textsubscript{2}</td>
<td>$1.0 \times 10^{16}$ molecules cm\textsuperscript{-2}</td>
<td>3 hour</td>
</tr>
<tr>
<td>Tropospheric C\textsubscript{2}H\textsubscript{2}O\textsubscript{2}</td>
<td>$4.0 \times 10^{14}$ molecules cm\textsuperscript{-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\textsuperscript{2} at center of Field Of Regard (FOR)
  - Threshold ≤ 300 km\textsuperscript{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
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 km² (native) at center of FOR (36.5°N, 100°W)
  - Full resolution for NO₂, HCHO, total O₃ products
  - Co-add 4 N/S pixels for O₃ profile product: 8.4 km N/S × 4.7 km E/W

~ 1/300 of GOME-2
~ 1/30 of OMI
Global pollution monitoring constellation

Tempo (hourly)

Sentinel-4 (hourly)

Gems (hourly)

80-115°W

0°

128.2°E

2021+ launch

2019 launch

Sentinel-5P (once per day)

Courtesy Jhoon Kim, Andreas Richter

Longitude
<table>
<thead>
<tr>
<th>Team Member</th>
<th>Institution</th>
<th>Role</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randall Martin</td>
<td>Dalhousie U.</td>
<td>Collaborator</td>
<td>Atmospheric modeling, air mass factors, AQI development</td>
</tr>
<tr>
<td>Chris McLinden</td>
<td>Environment Canada</td>
<td>Collaborator</td>
<td>Canadian air quality coordination</td>
</tr>
<tr>
<td>Michel Grutter de la Mora</td>
<td>UNAM, Mexico</td>
<td>Collaborator</td>
<td>Mexican air quality coordination</td>
</tr>
<tr>
<td>Gabriel Vazquez</td>
<td>UNAM, Mexico</td>
<td>Collaborator</td>
<td>Mexican air quality, algorithm physics</td>
</tr>
<tr>
<td>Amparo Martinez</td>
<td>INECC, Mexico</td>
<td>Collaborator</td>
<td>Mexican environmental pollution and health</td>
</tr>
<tr>
<td>J. Victor Hugo Paramo Figeuroa</td>
<td>INECC, Mexico</td>
<td>Collaborator</td>
<td>Mexican environmental pollution and health</td>
</tr>
<tr>
<td>Brian Kerridge</td>
<td>Rutherford Appleton Laboratory, UK</td>
<td>Collaborator</td>
<td>Ozone profiling studies, algorithm development</td>
</tr>
<tr>
<td>Paul Palmer</td>
<td>Edinburgh U., UK</td>
<td>Collaborator</td>
<td>Atmospheric modeling, process studies</td>
</tr>
<tr>
<td>Alfonso Saiz-Lopez</td>
<td>CSIC, Spain</td>
<td>Collaborator</td>
<td>Atmospheric modeling, process studies</td>
</tr>
<tr>
<td>Juan Carlos Antuña Marrero</td>
<td>GOAC, Cuba</td>
<td>Collaborator</td>
<td>Cuban Science team lead, Cuban air quality</td>
</tr>
<tr>
<td>Osvaldo Cuesta</td>
<td>GOAC, Cuba</td>
<td>Collaborator</td>
<td>TEMPO validation, Cuban air quality</td>
</tr>
<tr>
<td>René Estevan Arredondo</td>
<td>GOAC, Cuba</td>
<td>Collaborator</td>
<td>TEMPO validation, Cuban air quality</td>
</tr>
<tr>
<td>J. Kim</td>
<td>Yonsei U.</td>
<td>Collaborator</td>
<td>Korean GEMS, CEOS constellation of GEO pollution monitoring</td>
</tr>
<tr>
<td>C.T. McElroy</td>
<td>York U. Canada</td>
<td>Collaborator</td>
<td>CSA PHEOS, CEOS constellation of GEO pollution monitoring</td>
</tr>
<tr>
<td>B. Veihelmann</td>
<td>ESA</td>
<td>Collaborator, Science Advisory Panel</td>
<td>ESA Sentinel-4, CEOS constellation of GEO pollution monitoring</td>
</tr>
<tr>
<td>J.P. Veefkind</td>
<td>KNMI</td>
<td></td>
<td>ESA Sentinel-5P (TROPOMI)</td>
</tr>
</tbody>
</table>
• Currently on-budget and close to on-schedule

• Select commercial geostationary satellite host 2018+
  • Probably Jan-Feb 2019
  • TEMPO operating longitude and launch date are not known until after host selection

• Instrument delivery 2018 for launch 2019 or later, most likely in 2020 or 2021
As of April 11
Instrument flow includes 21 weekends which provides schedule flexibility.
TEMPO template

tempo.si.edu

TEMPO green paper on science studies

TEMPO Presentations

- Draft TEMPO Green Paper
- TEMPO Fact Sheet
- North American pollution measurements from geostationary orbit with Tropospheric Emissions: Monitoring of Pollution (TEMPO) PowerPoint
- Strategies for Stratosphere-Troposphere Separation of Nitrogen Dioxide Columns from the TEMPO Geostationary Instrument. AGU Fall 2016.pdf
- TEMPO System Test Readiness Review, August 2016.pdf
- Medición de contaminantes atmosféricos desde plataformas satelitales (principalmente TEMPO), Encuentro Nacional de Respuestas al Cambio Climático: Calidad del Aire, Mitigación y Adaptación, El Instituto Nacional de Ecología y Cambio Climático, Mexico, 2016.pdf
- Tropospheric Emissions: Monitoring of Pollution (TEMPO) - status and potential science studies, ESA Living Planet Symposium, 2016.pdf
- Status of Tropospheric Emissions: Monitoring of Pollution, AGU Fall 2015.pptx
- Converting Paper into Hardware: A Status of the TEMPO Instrument Design and Manufacturing, AGU Fall 2015.pptx
- Overview of TEMPO for the 11th meeting of the Atmospheric Composition Constellation of the Committee on Earth Observation Satellites, April 2015.pptx
- A TEMPO for the Middle East, 11th Conference of the Arab Union for Astronomy and Space Sciences (AUASS), December 2014.pdf
- Implementation of Tropospheric Emissions: Monitoring of Pollution (TEMPO), Korean GEMS Science Team Meeting, October 2014.pptx
- Tropospheric Emissions: Monitoring of Pollution (TEMPO) Status, June 2014.pdf
- Status of the first NASA EV-I Project, Tropospheric Emissions: Monitoring of Pollution (TEMPO), AGU Fall 2013.pptx
- TEMPO overview.pptx

Science Team Meetings

May-June 2017
June 2016
May 2015
May 2014
July 2013

Applications Workshop
July 2016

Validation Workshop
April 2017
Artistic conception of MethaneSAT (Environmental Defense Fund)

The Environmental Defense Fund has partnered with the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) and the Smithsonian Astrophysical Observatory (SAO) to develop and launch MethaneSAT into orbit in 2020 or 2021. MethaneSAT is a part of TED’s new Audacious Project for supporting world-changing ideas.

While much of the attention on greenhouse warming has properly focused on carbon dioxide (CO₂) emissions, methane (CH₄) emissions cause about a quarter of the global warming. Much of the CH₄ emissions come from leakage and other practices by the oil and natural gas industries. Reducing these emissions will have substantial economic as well as environmental benefit.

MethaneSAT will measure CH₄ from oil and gas fields of up to 200 kilometer cross-orbit size globally from space at 1 kilometer resolution. Fields accounting for more than 80% of global oil and gas productions will be monitored on a weekly basis or better. MethaneSAT will additionally measure CH₄ from feedlots, landfills, cities, and natural sources.

MethaneSAT spectroscopic measurements will be processed into CH₄ abundances at the SAO, piggybacking on the ground systems developed for the Smithsonian/NASA space mission Tropospheric Emissions: Monitoring of Pollution (TEMPO; tempo.si.edu). Harvard SEAS scientists will perform the inversions necessary to precisely determine source emissions and apportionment from these abundances. Data will be freely, publicly available to the industry, scientists, governments, and any other interested users.
The end!

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

The University of Alabama in Huntsville

The University of Iowa

Harvard University

Yonsei University

United States Environmental Protection Agency

UMBC

CSIC

Ramón y Cajal Science Center

The University of Edinburgh

Environment and Climate Change Canada

Environnement et Changement climatique Canada

Dalhousie University

Saint Louis University

Dalhousie University

Dalhousie University

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Dalhousie University
Backups

- INECC
- NOAA
- Ball
- University of Alabama in Huntsville
- Harvard University
- Yonsei University
- SAINT LOUIS UNIVERSITY
- United States Environmental Protection Agency
- University of California
- University of Iowa
- UMBC
- CSIC
- Finnish Meteorological Institute
- Environment and Climate Change Canada
- Environnement et Changement climatique Canada
- NCAR
- KNMI
Spectroscopy and radiative transfer are rapidly growing fields within atmospheric and planetary science with implications for weather, climate, biogeochemical cycles, air quality on Earth, as well as the physics and evolution of planetary atmospheres in our solar system and beyond. Remote sensing and modeling atmospheric composition of the Earth, of other planets in our solar system, or of planets orbiting other stars requires detailed knowledge of how radiation and matter interact in planetary atmospheres. This includes knowledge of how stellar or thermal radiation propagates through atmospheres, how that propagation affects radiative forcing of climate, how atmospheric pollutants and greenhouse gases produce unique spectroscopic signatures, how the properties of atmospheres may be quantitatively measured, and how those measurements relate to physical properties. This book provides readers with fundamental knowledge, enabling them to performing quantitative research on atmospheres.

The book is intended for graduate students or for advanced undergraduates. It spans across principles through applications, with sufficient background for students without prior experience in either spectroscopy or radiative transfer. Courses based on this book are intended to be accompanied by the development of increasing sophisticated atmospheric and spectroscopic modeling capability (ideally, the student develops a computer model for simulation of atmospheric spectra from microwave through ultraviolet).

Kelly Chance is a Senior Physicist at the Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics, and the Principle Investigator for the NASA/Smithsonian Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument.

Randall V. Martin is Professor and Arthur B. McDonald Chair of Research Excellence at Dalhousie University and Research Associate at the Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics.
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).
What is an AQ index?”

“The Canadian Air Quality Health Index is a multipollutant index based on the sum of PM2.5, NO₂, and O₃, weighted by their contribution to mortality in daily time-series study across Canadian cities.” [Cooper et al., 2012]

Cooper et al., for example, propose a satellite-based multipollutant index using the WHO Air Quality Guidelines (AQP):

\[
\text{SATMPI} = \frac{\text{PM}_{2.5}}{\text{AQG}_{\text{PM}_{2.5}}} \left[ 1 + \frac{\text{NO}_2}{\text{AQG}_{\text{NO}_2}} \right]
\]

• Can we define different indices as appropriate to locations, seasons, times?
• Might they be formulated using RSIG?
• Might assimilation be included?

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.

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 may be used together with the advanced baseline imager (ABI) instruments on the NOAA GOES-16 and GOES-17 satellites, particularly the 1.37μm bands, for aerosol retrievals, reducing AOD and fine mode AOD uncertainties from 30% to 10% and from 40% to 20%. 
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 NO₂, H₂CO, C₂H₂O₂, O₃, H₂O, 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.
**Lightning NO\textsubscript{x}** Interpretation of satellite measurements of tropospheric NO\textsubscript{2} and O\textsubscript{3}, and upper tropospheric HNO\textsubscript{3} lead to an overall estimate of 6 ± 2 Tg N y\textsuperscript{-1} from lightning [Martin et al., 2007]. TEMPO measurements, including tropospheric NO\textsubscript{2} and O\textsubscript{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\textsubscript{x}** Jaeglé et al. [2005] estimate 2.5 - 4.5 TgN y\textsuperscript{-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\textsuperscript{-1}. For Central America it is 1.5 ± 1.6 TgN y\textsuperscript{-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\textsubscript{x} emissions may also improve estimated of lightning NO\textsubscript{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 the 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 products are the downward spectral irradiance at the ground (in W m$^{-2}$ nm$^{-1}$) and the erythemally weighted irradiance (in W m$^{-2}$).
<table>
<thead>
<tr>
<th>BUID Milestone</th>
<th>Milestone / Task</th>
<th>Estimated Completion Date as of 3/16/18</th>
<th>Current Estimated Completion Date</th>
<th>Actual Completion Date</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 835            | Spectrometer Install & Alignment Iteration No. 1 | 3/9/18 | 3/9/18 | Integration began - 11/17/17  
Alignment began - 12/14/17  
HAR investigation began - 12/27/17  
Alignment complete - 3/9/18 |
|                | Troubleshoot Alignment HAR | | 2/14/18 | HAR investigation started 12/27/17  
1. Inspect spectrometer for mechanical interference - complete 1/9/18  
2. Perform telescope optics push-pull test - complete 1/10/18  
3. Optical modeling iterations to simulate the observed optical behavior - complete 1/15/18  
4. DIT Electronics analysis, modeling, and resolution - complete 2/14/18 |
| 840            | Spectrometer Install & Alignment Iteration No. 2 & Gravity Flip | 3/26/18 | 3/27/18 | Alignment process extended due to anomaly resolution requiring DITCE mapping |
| 847            | Pre-Staking Review | 3/27/18 | 3/28/18 | |
| 845            | Stake Spectrometer, Baffle Install & Maintenance Clean | 4/6/18 | 4/6/18 | |
| 13881          | Pre-Harness MLI & Thermal Installs | 4/16/18 | 4/10/18 | |
| 13488          | Install Conduction Bar & Stake Fasteners | 4/27/18 | 4/17/18 | |
| 13482          | Perform Pre-Vibe Functional/Optical Testing and Data Analysis | 5/3/18 | 4/23/18 | |
| 13494          | Setup for Vibe Testing | 5/14/18 | 4/30/18 | |
| 893            | Perform Vibe Testing | 5/22/18 | 5/5/18 | |
| 892            | Perform Post Vibe Alignment and Functional Verification Testing | 6/1/18 | 5/15/18 | |
| 13487          | Deconfigure Test Setup & Inspection | 6/13/18 | 5/25/18 | |
| 5866           | Setup for TVAC Testing | 6/29/18 | 6/13/18 | |
| 890            | Perform TVAC Testing | 7/28/18 | 7/12/18 | |
| 13497          | Post TVAC Testing and Setup for EMI/EMC Testing | 8/7/18 | 7/23/18 | |
| 886            | Perform EMI/EMC Testing | 8/12/18 | 7/28/18 | |
| 859            | Prep for Storage | 8/21/18 | 8/7/18 | |
| 3628           | Instrument Acceptance | 9/21/18 | 9/21/18 | |
City lights spectroscopic signatures

Spectral Radiance of Source with VIIRS-DNB Radiance = 1 nW sr\(^{-1}\) cm\(^{-2}\)

- Fluorescent
- HP Na
- Incandescent
- LED
- LP Na
- Hg Vapor
- Metal-Halide
- Oil
- Gas Lantern
- Halogen

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

5/3/18
OMI NO$_2$ in April (2005–2008) over TEMPO FOR

N.B. special operations give 10-minute resolution for selected longitude regions
For GEO at 80°W, pixel size at 36.5°N, 100°W is 2.2 km × 5.2 km.
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.