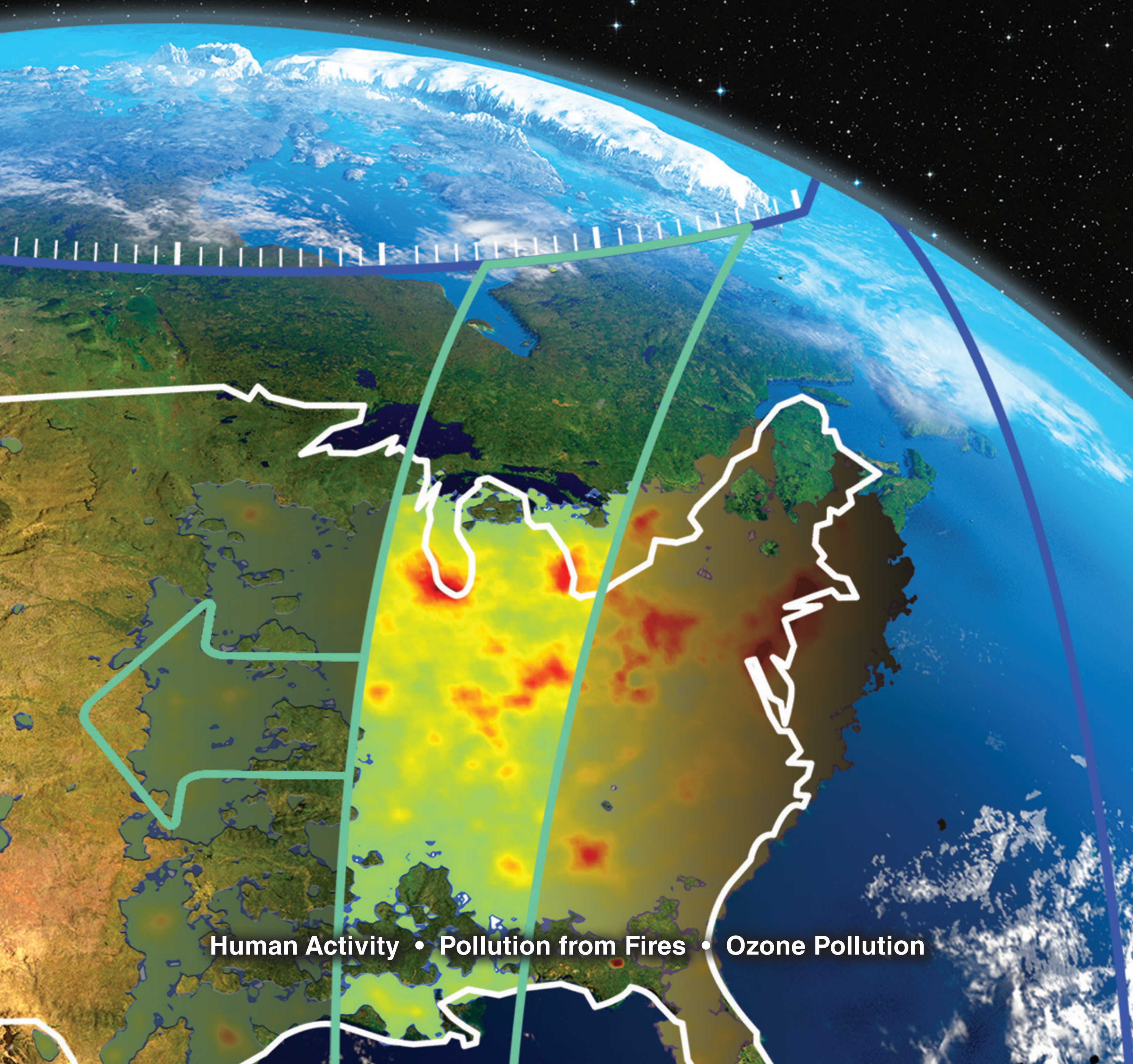
National Aeronautics and Space Administration

TEMPO

Tropospheric Emissions: Monitoring of Pollution



Human Activity • Pollution from Fires • Ozone Pollution

TEMPO will provide first-ever hourly daytime observation of atmospheric pollution at high spatial resolution over North America from a geostationary orbit.

Acknowledgments

TEMPO Website
http://tempo.si.edu

TEMPO would not be possible without the work of prior NASA concept studies and more recently, the GeoCAPE Decadal Survey Recommendations.

The TEMPO Science Team is a collaboration of scientists from multiple U.S. and international organizations with extensive experience in measuring the components of air quality from space. Members of the TEMPO Team include:

Principal Investigator: Kelly Chance, Smithsonian Astrophysical Observatory
Project Management: NASA's Langley Research Center
Instrument Development: Ball Corporation
Satellite Hosts: Maxar, Intelsat
Other Institutions: NASA's Goddard Space Flight Center, National Oceanic and Atmospheric Administration, Environmental Protection Agency, National Center for Atmospheric Research, Harvard University, University of California at Berkeley, St. Louis University, University of Alabama Huntsville, University of Nebraska, RT Solutions, Carr Astronautics
International Collaboration: Korea, Europe, Canada, Mexico
Content: TEMPO Project Team (NASA, SAO and the Science Directorate Communications Team)
Design: Kevin Miller

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North America's Air Pollution

Air pollution is created by numerous sources including automobiles, trucks, power plants, wildfires, and cargo ships, to name a few. These pollutants undergo rapid chemical reactions as they are transported down wind. This has meant that comprehensive observations of the transport and transformation of air pollution has been out of reach. But, with hourly data from NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission comes new possibilities.

TEMPO will be able to observe hourly air quality conditions as they unfold across North America.

For decades, satellite-based instruments have provided insights into the physical and chemical processes that govern the Earth's atmosphere. The current generation of air quality satellites only makes an observation near mid-day. This has prevented researchers from answering some of the most pressing questions relating to air quality, including when and how much pollution is being emitted and how it varies over time. This information is vital to effectively combat atmospheric pollution and its harmful consequences to human health and ecosystems worldwide.

To address this problem, TEMPO will scan and track pollution hourly as it moves across North America. An international team of scientists will analyze these in-depth measurements of North American pollution.

"TEMPO will measure atmospheric pollution from Mexico City, Puerto Rico, Cuba, and the Bahamas, to the Canadian oil sands in Alberta; and from the Atlantic to the Pacific," ~ Dr. Kelly Chance, TEMPO Principal Investigator

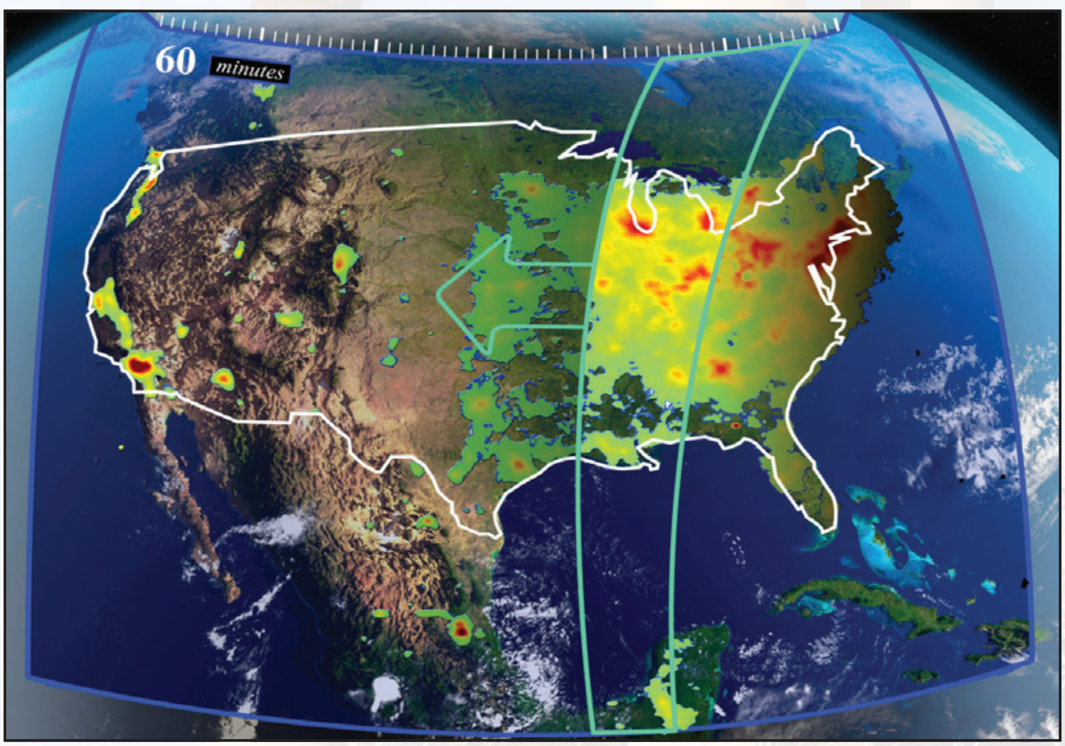


Photo credit: NASA.

TEMPO's hourly measurements from geostationary orbit will create a dataset that improves prediction of air quality and climate forcing.

HUMAN ACTIVITY

Human activity contributes to air pollution and transportation is one of the most significant sources of pollution that humans create. However, because traffic varies widely throughout the day, once per day satellite observations are insufficient to account for its impact.

Emissions of a particular group of polluting chemicals, called nitrogen oxides, can escape from crop farms under certain conditions, polluting the atmosphere as well as wasting large amounts of fertilizer. TEMPO will make measurements of croplands to follow the evolution of nitrogen oxide emissions.

TEMPO will measure nitrogen dioxide variations of pollution from transportation at the sub-urban scale.

POLLUTION FROM FIRES

As climate change accelerates, wildfires are becoming an increasing concern for many communities worldwide. TEMPO will provide crucial insights into these disasters, which can produce massiveamounts of pollution that can be transported to. TEMPO will document wildfire fire emissions, as well as their production of formaldehyde and potentially ozone as the smoke is transported downwind.

Wildland fires—uncontrolled fires that occur in areas of combustible vegetation—are an essential process that connects terrestrial systems to the atmosphere and climate. But their effects can also be disastrous to the communities in their path, in both the short and long-term.

OZONE POLLUTION

High up in the atmosphere, in the stratosphere, ozone protects us from the Sun's harmful ultraviolet radiation. However, ozone at ground level is a gaseous pollutant as it is damaging to animals and plants. TEMPO will measure stratospheric ozone and aims to provide additional information about the amount of ozone in the troposphere, the lowest layer of the atmosphere where we live and breathe. TEMPO will also measure key ozone precursors (e.g., nitrogen dioxide, formaldehyde) to understand the distribution and evolution of ozone pollution.

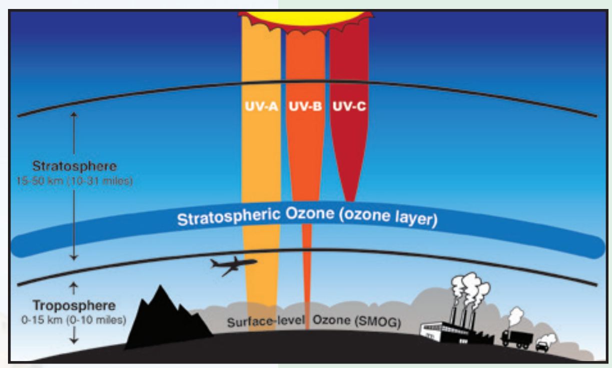


Image credit: NASA

Ozone in the upper layers of the atmosphere is beneficial because it absorbs all of the most energetic ultraviolet radiation (UV-C), most of the UV-B radiation, and some of the least energetic UV radiation (UV-A). But ozone in lower layers is a pollutant associated with the formation of smog, irritation of human lungs and damage to plants.

"We will take measurements at peaks in vehicle traffic to capture the variability in emissions from mobile sources," ~ Dr. Kelly Chance, TEMPO Principal Investigator

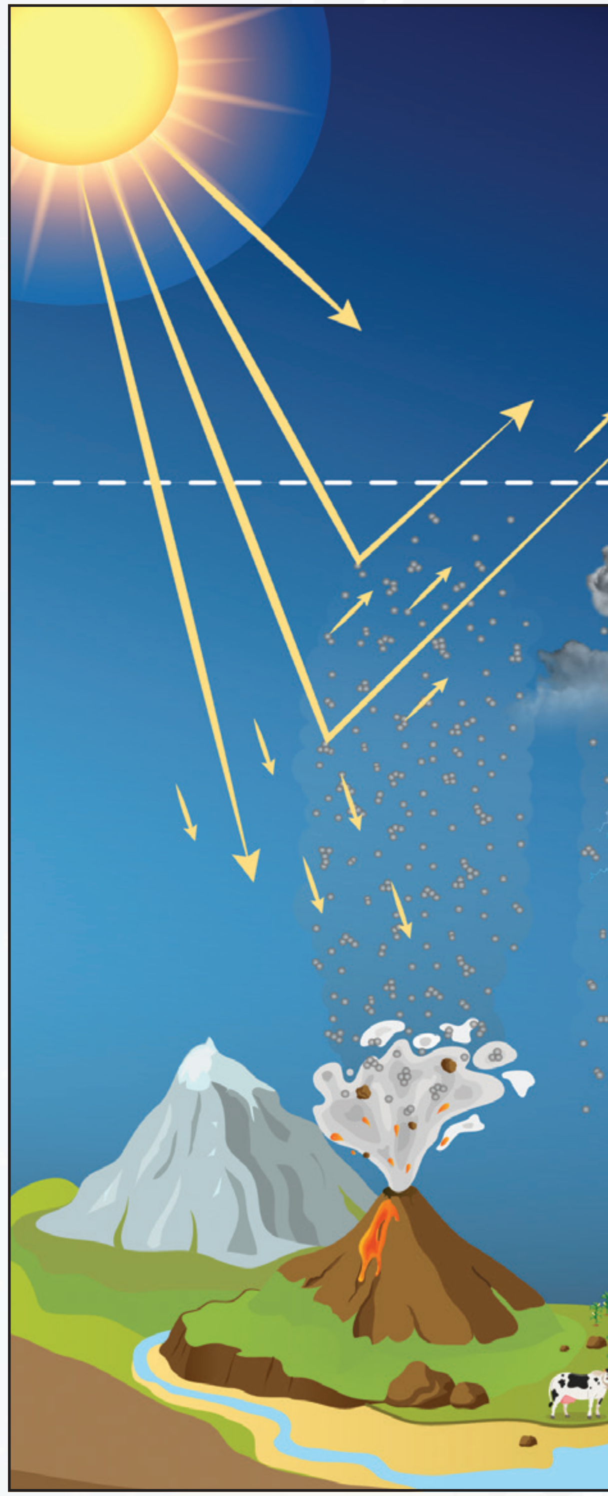
Tropospheric Emissions: Monitoring of Pollution

TEMPO Mission Overview

TEMPO was selected as NASA's first Earth Venture Instrument (EVI) in 2012 and is led by Principal Investigator Dr. Kelly Chance of the Smithsonian Astrophysical Observatory (SAO). The TEMPO Science Team includes members from NASA's Langley Research Center, NASA's Goddard Space Flight Center, the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA). The TEMPO instrument is an ultraviolet and visible grating spectrometer that collects spectra to measure major pollutants including ozone, nitrogen dioxide, formaldehyde, sulfur dioxide, and aerosols.

Operating in geostationary orbit on a commercial communications satellite Intelsat 40e (IS-40e) approximately 22,000 miles (35,785 kilometers) above Earth's equator at 91 degrees west longitude, TEMPO will be able to collect pollution data covering Mexico, the United States, and Canada at an hourly rate during daytime. This is a major improvement in the current capabilities in which data can only be collected once a day from a Low Earth Orbit (LEO). TEMPO will examine a large region that is home to a diverse array of communities, species, and environments.

TEMPO aims to improve our understanding of important air quality emissions over greater North America. TEMPO's hourly measurements allow better understanding of the complex chemistry and dynamics that drive air quality on short timescales.



Once in orbit, TEMPO will measure major pollutants in the troposphere including, ozone, nitrogen dioxide, formaldehyde, sulfur dioxide, and aerosols.

"From its position in geostationary orbit, TEMPO will be able to 'sweep' from coast to coast once every hour – picking up incredibly small details," said TEMPO Project Scientist Dave Flittner. "With TEMPO data, scientists and air quality managers and policy makers will examine a wide range of pollution-related issues."

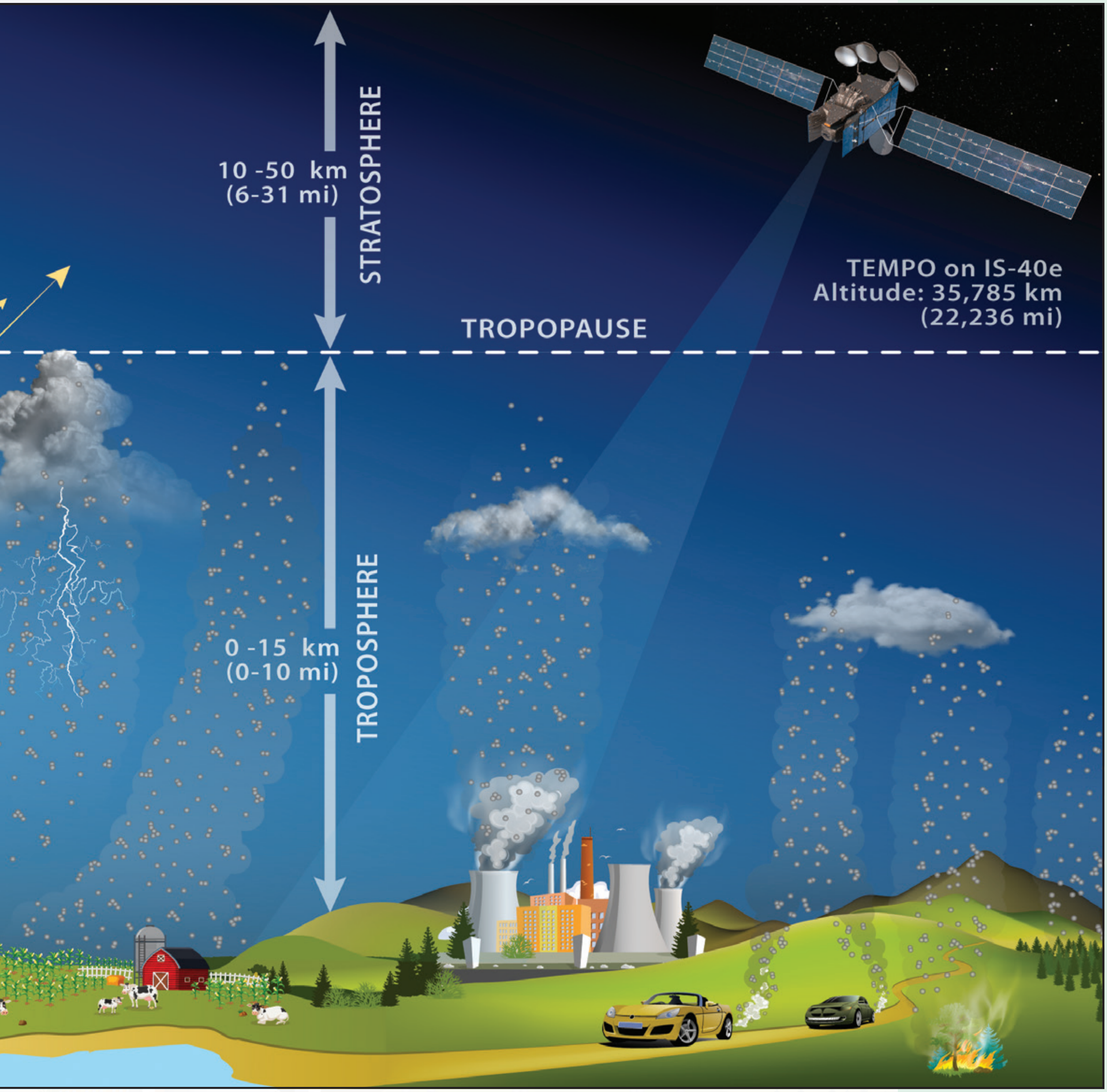


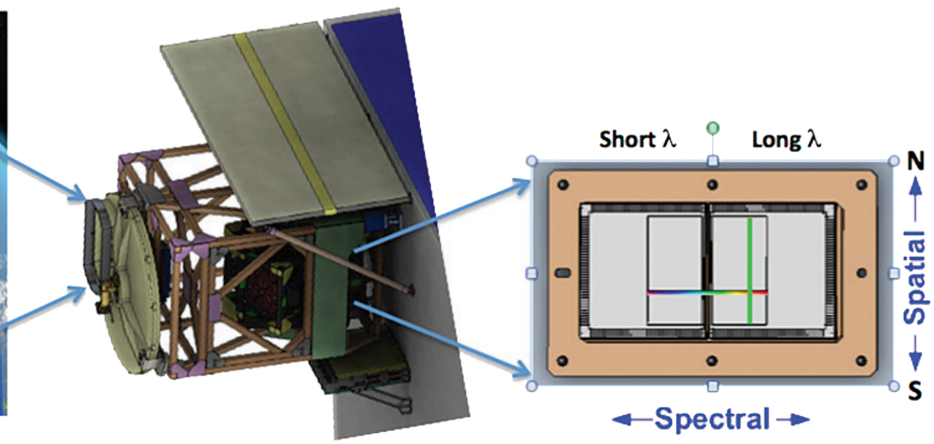
Image credit: NASA

Instrument Overview

The TEMPO instrument, built by Ball Aerospace, is a grating spectrometer, sensitive to ultraviolet and visible wavelengths of light, which will be attached to the Earth-facing side of the Intelsat IS-40e commercial communications satellite in geostationary orbit. This allows TEMPO to maintain a constant view of North America so the instrument's light-collecting mirror can make a complete East-to-West scan of the "field of regard" every hour of the daytime. By measuring sunlight reflected and scattered from the Earth's surface and atmosphere back to the instrument's detectors, TEMPO's ultraviolet and visible light sensors will provide the spectra of various trace gases that are important for understanding air quality, including nitrogen dioxide, formaldehyde, and ozone.

[Above] The light from one vertical stripe on the Earth's surface enters the TEMPO spectrometer instrument and is projected onto a detector that measures reflected and scattered sunlight revealing aspects of ozone and nitrogen dioxide separately.

Image credit: NASA/BATC/CfA



Schematic of TEMPO Spectrometer.

TEMPO Characteristics	
Spectral Range	293–493 nm, 537–741 nm (UV, VIS)
Spectral Sampling	0.2 nm
Spectral Resolution	0.6 nm
Spatial Resolution	2.0 km/pixel North/South, 4.7 km/pixel East/West at center of Field of Regard
Scan Frequency	1 hour during daylight
Max Data Rate	66 Mbps
Mass	137 kg
Volume	1.4m x 1.1m x 1.2m
Average Power	132 W

The instrument's optical system resolves a few square miles per pixel, so that pollution can be tracked at sub-urban scales. TEMPO's dataset will show diurnal variations in the concentrations of pollutants, thereby providing researchers, air quality managers, and policy makers improved observations of the changing "chemical weather" locally, regionally, and across the continent.

The TEMPO instrument has two major components: the instrument control electronics, which are installed within the host spacecraft and provide the communication link to the sensor, and the nadir deck subsystem, which is mounted on the Earth-facing side of the spacecraft. The nadir deck subsystem includes the sensor, the telescope assembly, the focal plane assembly, the sensor heat sink, and the focal plane electronics. The light reflected and scattered from Earth is focused down onto a diffraction grating where the light is dispersed into spectra before being detected by a CCD chip on the focal plane.

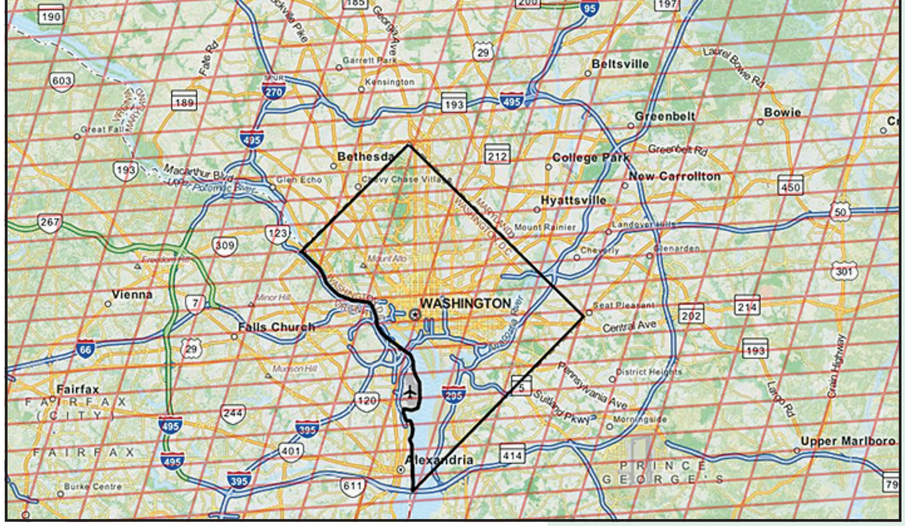
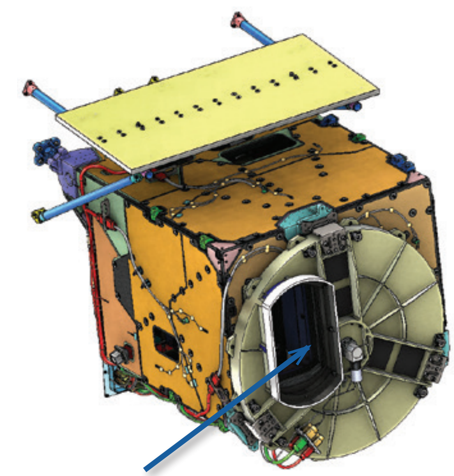


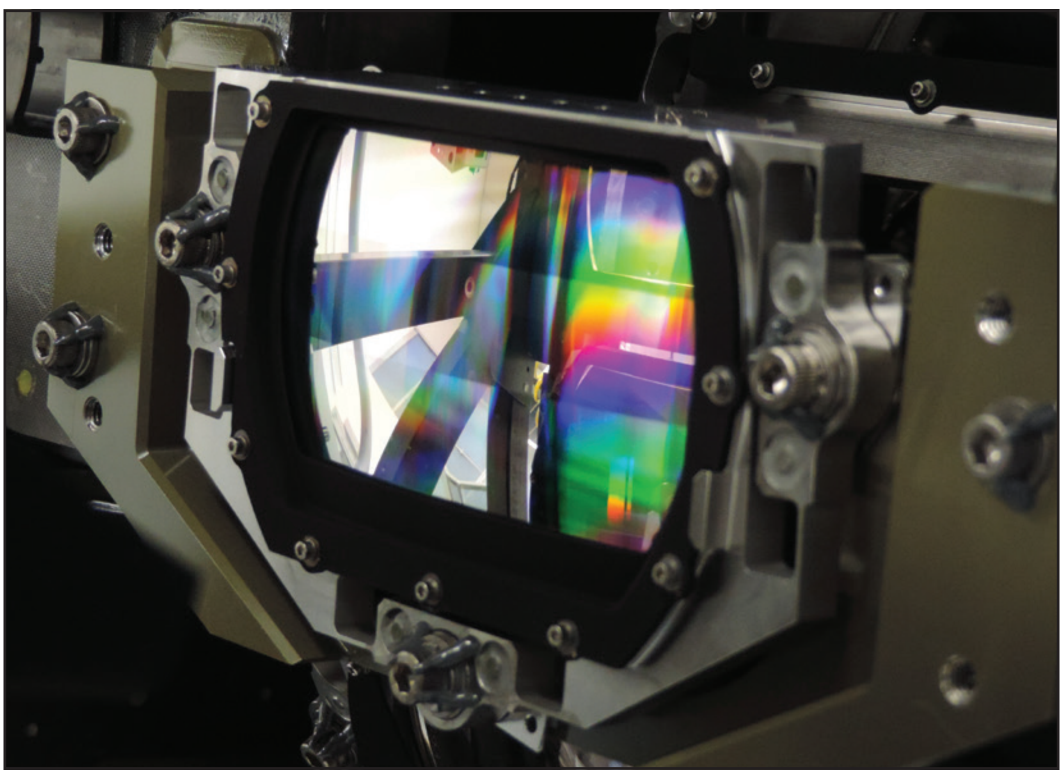
Image credit: © OpenStreetMap contributors/CfA.

[Above] TEMPO will be able to resolve pollution at sub-urban or neighborhood scales. Each red rectangle represents the footprint of a single pixel.



[Left] The TEMPO instrument is a UV-visible spectrometer.

Image credit: Ball Corporation



[Left] Diffraction grating within the TEMPO instrument separates the light into different wavelengths to discern the unique patterns of the various pollutants.

Photo credit: Ball Corporation

Geostationary Constellation

TEMPO will be collecting data during a timeframe when two other geostationary pollution-monitoring satellites from Asia (GEMS on GEO- KOMPSAT-2B) and Europe (Sentinel-4 on MTG-S) will also be in operation. Together the three instruments will form a geostationary air quality (Geo-AQ) constellation. The combination of Geo-AQ and existing instruments in Low Earth Orbit (LEO) making global, but less frequent observations, creates an atmospheric composition 'virtual constellation' (AC-VC) able to track pollution transport between neighborhoods and between continents.

The Geostationary Environment Monitoring Spectrometer (GEMS) was launched by the Korea Aerospace Research Institute (KARI) on February 18, 2020. Like the TEMPO Instrument, the GEMS Instrument was also built by Ball Aerospace in Boulder, CO, and the two instruments share many design elements. The GEMS spectrometer observes the ultraviolet and visible parts of the spectrum.

The Copernicus Sentinel-4 instrument is hosted on the European Space Agency (ESA) Meteosat Third Generation Sounder (MTG-S) spacecraft. The Sentinel-4 spectrometer will observe the ultraviolet, visible, and near-infrared portions of the spectrum.

The AC-VC will measure pollutants—including ozone, nitrogen dioxide, formaldehyde, and tiny atmospheric particles called aerosols—in unprecedented detail and frequency. Air pollution can be damaging to the human respiratory and cardiovascular systems, and to the environment. Data products from the constellation will significantly improve air quality forecasting around the most densely populated areas of the Northern Hemisphere. These data can also help inform decisions by policymakers aimed at improving air quality.

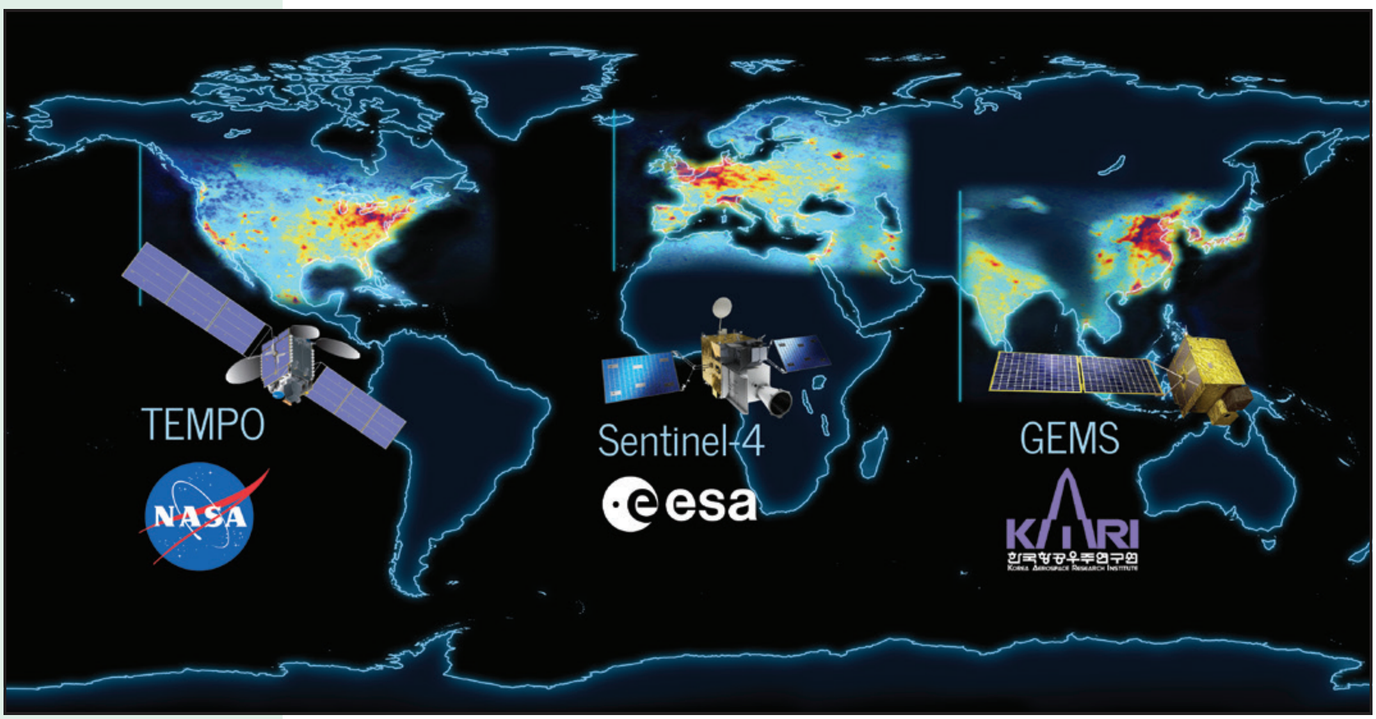


Image Credit: NASA/Tim Marvel

Pollution-monitoring instruments from NASA, the European Space Agency (ESA), and the Korea Aerospace Research Institute (KARI) will together form a geostationary air quality (Geo-AQ) constellation.

Getting to Space

As a hosted payload, the TEMPO instrument will fly as part of the Intelsat IS-40e spacecraft. The IS-40e is a commercial communication satellite designed to connect a world-on-the-go with 40+ Gbps of internet connectivity directly over North and Central America, providing Intelsat's commercial aviation customers with high throughput "coast-to-coast" internet coverage in the U.S. TEMPO is a unique collaboration between NASA, a spacecraft manufacturer, and a commercial satellite operator.

The satellite, manufactured by Maxar in Palo Alto, California, is based on the Maxar 1300-class spacecraft platform. After integration with IS-40e, the entire spacecraft underwent a rigorous environmental test campaign conducted by Maxar to verify the satellite—including the TEMPO instrument—will survive all of the challenges related to launch, as well as sustained operations in geostationary orbit.

The spacecraft will be shipped from Maxar to the Cape Canaveral Space Force Station in Florida and launch on a Falcon 9 rocket—a two-stage launch vehicle powered by liquid oxygen and rocket-grade kerosene with a 17-foot (5.2-meter) diameter payload fairing.

Once launched, the satellite will be in a geostationary orbit 22,236 miles (35,785 kilometers) above the Earth's equator, traveling just under 7,000 mph (11,300 kph). By matching the rotation of the Earth, the satellite will remain above the same point on the equator at all times, providing a unique vantage point to continuously observe North America. The IS-40e is designed for an operational lifetime of 15 years.

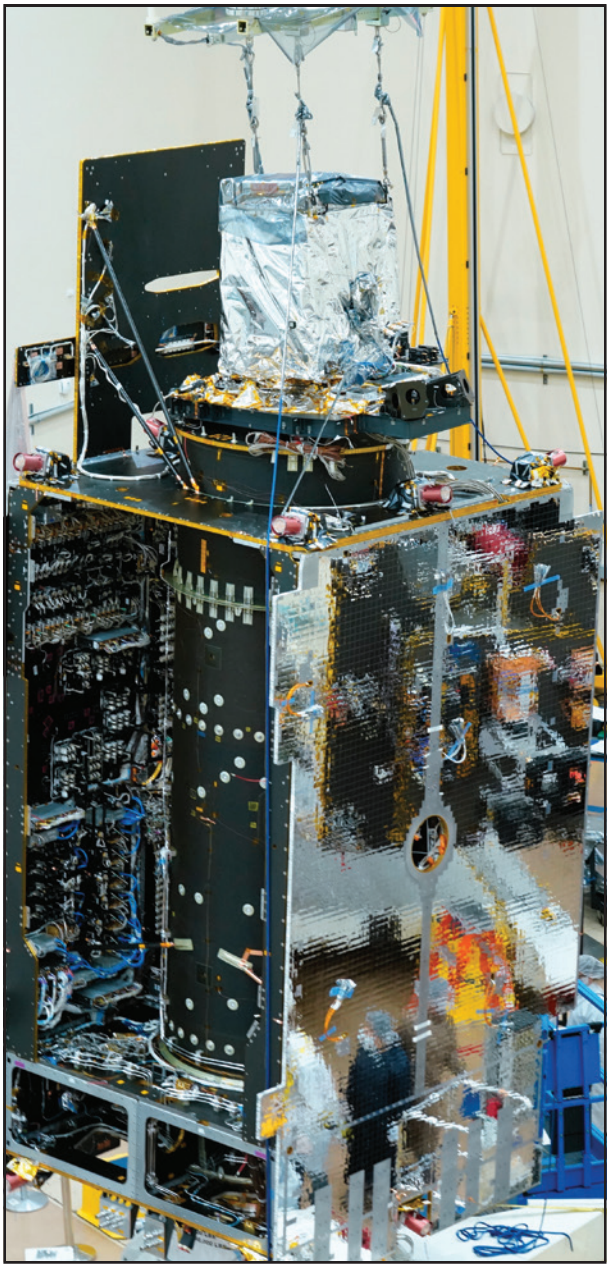


Photo credit: Maxar

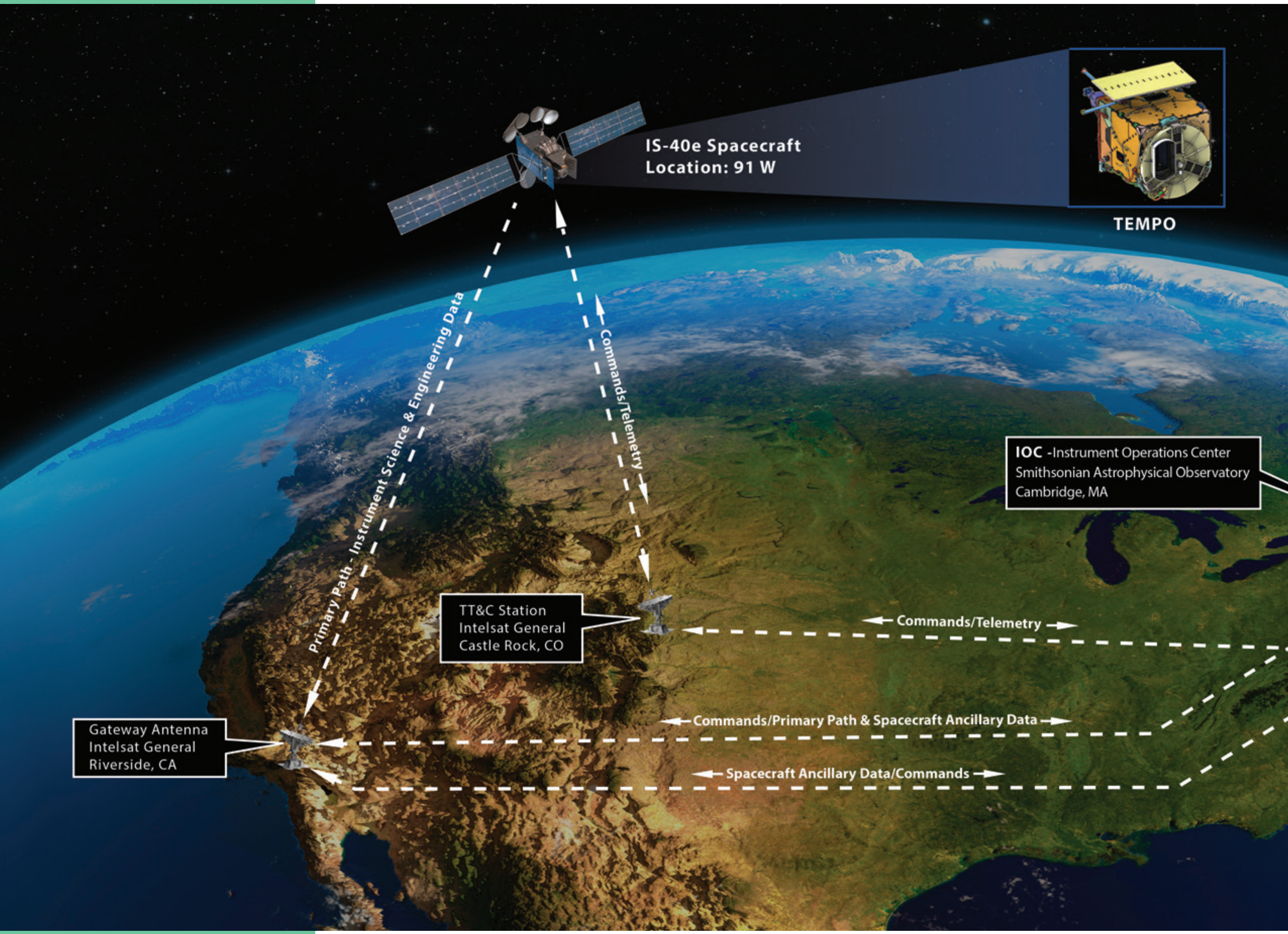
The TEMPO instrument rest atop Maxar's Intelsat 40e in Palo Alto, California.

"Maxar and Intelsat have collaborated with NASA on this groundbreaking mission to provide a lower-cost solution for getting to space. Both companies bring a lot of expertise and infrastructure that will be instrumental to the success of the TEMPO mission."

~ Kevin Daugherty, TEMPO Project Manager

Ground System and Science Data

Once in space, commands will be issued to TEMPO through the Instrument Operations Center (IOC), which is based at the Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachusetts. The IOC will have the capability to send real-time commands to the instrument, allowing TEMPO to monitor sudden environmental events such as wildfires or volcanic eruptions.



In orbit, data collected by TEMPO will be relayed to the Science Data Processing Facility, located at the Smithsonian Astrophysical Observatory (SAO). Commands will be issued to TEMPO through the Instrument Operations Center (IOC) at SAO.

Raw data collected by TEMPO will be relayed to the Science Data Processing Facility, also located at the SAO, and will be processed there into data products.

Throughout the mission, data products will be transferred continuously to NASA's Atmospheric Science Data Center (ASDC) in Hampton, Virginia, for archival and public distribution. Standard tools and services at ASDC can be used to search, visualize, and subset TEMPO data. In addition, TEMPO data can also be directly accessed for easy and quick visualization and subsetting from the Environmental Protection Agency's Remote Sensing Information Gateway (RSIG3D) application. The TEMPO Early Adopters Program will closely coordinate with ASDC to ensure that user needs in terms of data file formats, tools, and visualizations of TEMPO data are well documented.

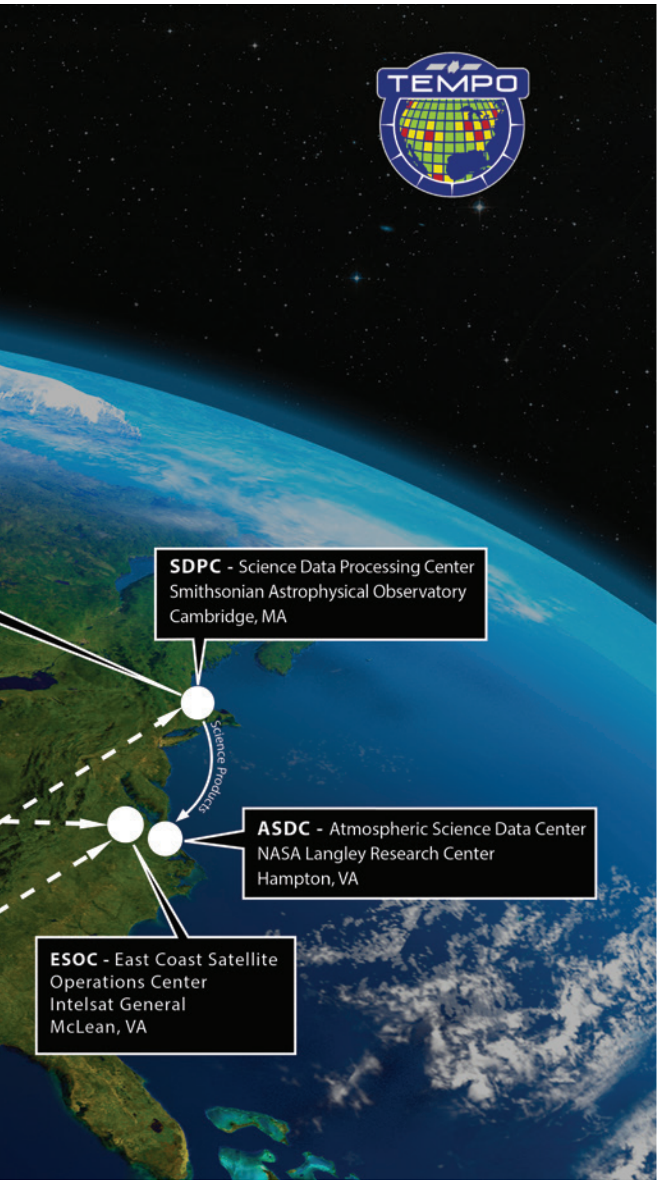


Image credit: NASA

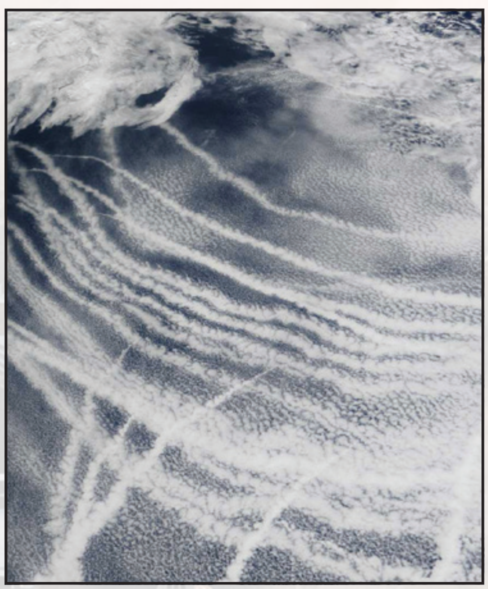
TEMPO DATA PRODUCTS

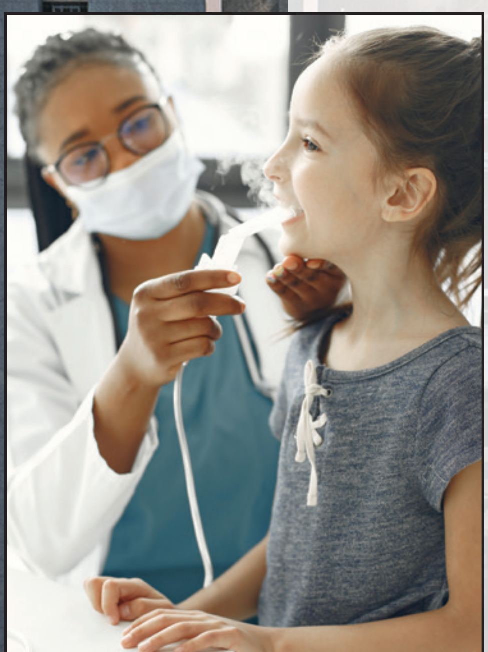
Level	Product	Major Outputs	Resolution (km^2)	Frequency/ Size
L0	Digital counts	Reconstructed digital counts	2.0 × 4.7	Daily/hourly
L1	Irradiance	Calibrated & quality flags		Daily
L1B	Radiance	Geolocated, calibrated solar backscattered radiances	2.0 × 4.7	Hourly, Granule
L2	Cloud	Cloud fraction, cloud pressure	2.0 × 4.7	
	O_3 (ozone) profile	Total, Stratospheric, Tropospheric, & 0-2 km column	8.0 × 4.7	
	Total O_3	Total column, Aerosol Index	2.0 × 4.7	
	NO_2 (nitrogen dioxide)	Stratospheric & Tropospheric Vertical Column Densities (VCD)	2.0 × 4.7	
	HCHO (formaldehyde)	Total Vertical Column Densities (VCD)	2.0 × 4.7	
	$C_2H_2O_2$ (glyoxal)			
	H_2O (water vapor)			
	BrO (bromine monoxide)			
	SO_2 (sulfur dioxide)			
	Aerosol	• Absorbing Aerosol Index • UV & Visible Aerosol Optical Depth • UV Single Scattering Albedo, Aerosol • Optical Centroid Height	8.0 × 4.7	
	TEMPO/GOES-R Synergistic	Radiance, aerosol, cloud & mask, fire/hotspot, lightning, snow/ice, etc.	2.0 × 4.7	
L3	Gridded L2	same products at L2	2.0 × 2.0	Hourly, Scan
L4	UVB	UV irradiance, erythemal irradiance, UV Index	2.0 × 4.7	

Applications and Benefits to Society

Planning is underway to combine TEMPO data with regional air quality models to improve Environmental Protection Agency (EPA) air quality indices and directly supply the public with near real-time pollution reports and forecasts through website and mobile applications. The ability to observe and attribute air pollution events over the entire TEMPO field of view offers promising policy and societal benefits.

TEMPO is targeted at improving the observation, assessment, and chemical understanding of air quality over North America. TEMPO's hourly measurements will allow for better understanding of the complex chemistry and dynamics that drive air quality on short timescales. The density of TEMPO data is ideally suited for assimilation into chemical models for both air quality forecasting and better constraints on emissions that lead to air quality exceedances. The high spatial and temporal resolution of TEMPO observations will provide new insight into the identity and timing of the emission sources and atmospheric drivers of air pollution inequality at intra-urban scales. TEMPO data will improve the ability to not only describe inequalities, but also to mitigate them through air quality policy making.

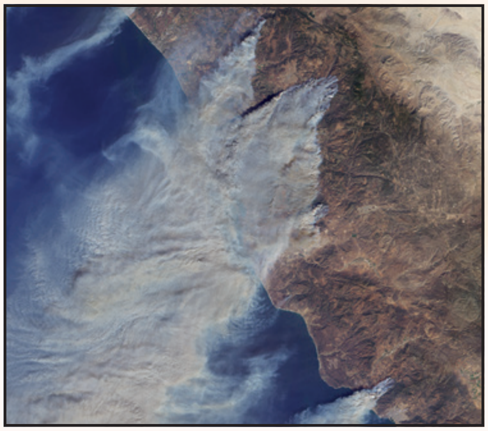




TEMPO measurements will be a powerful tool for observing and assessing pollution's impact on human health. Hourly estimates of gaseous air pollutants from TEMPO will be included as inputs for air pollution exposure calculations needed to understand the health effects of air pollution. Harmful air pollution levels may lead to notifications or prompts for specific patients to avoid physical exertion or to stay indoors when possible. It can also underscore the importance of effective disease management, whereby individuals who live in areas with chronically higher levels of air pollution can be encouraged to see their doctor for a medical checkup.

Experimental Opportunities

The TEMPO mission plans to use as much as 25% of the observing time for non-standard operations known as 'special.' A focus of the 'special' operations will be disaster events, such as wildfires, dust storms, volcanic eruptions, and industrial accidents, along with unique chemistry experiments aimed at further enhancing our understanding of rapidly varying emissions and air pollutants in complex environments. These operations can be performed in the first four months after launch during the commissioning phase of the mission when instrument testing and calibration are conducted. The 'special' scan mode can be easily initiated a couple of days after notice of an impending or occurring event with the potential to initiate in about one-hour after notification of the event. There is also considerable flexibility in the specifications of temporal frequency (e.g., ≤ 10 minutes) and swath width with the 'special' scans.



To maximize the value of both standard (hourly) and 'special' observations from TEMPO, planning and coordination activities commenced during the pre-launch era of the mission. Early Adopters can have an impactful role in the planning activities by submitting experiment requests for the standard and 'special' observations from TEMPO. Descriptions of experiment requests can be found in the TEMPO Green Paper living document, which is being routinely updated with new experiments from the community. Input from early adopters from a wide spectrum of science applications is key in the development of a comprehensive TEMPO Green Paper that will enhance mission planning activities and use of TEMPO data for societal benefit after launch.

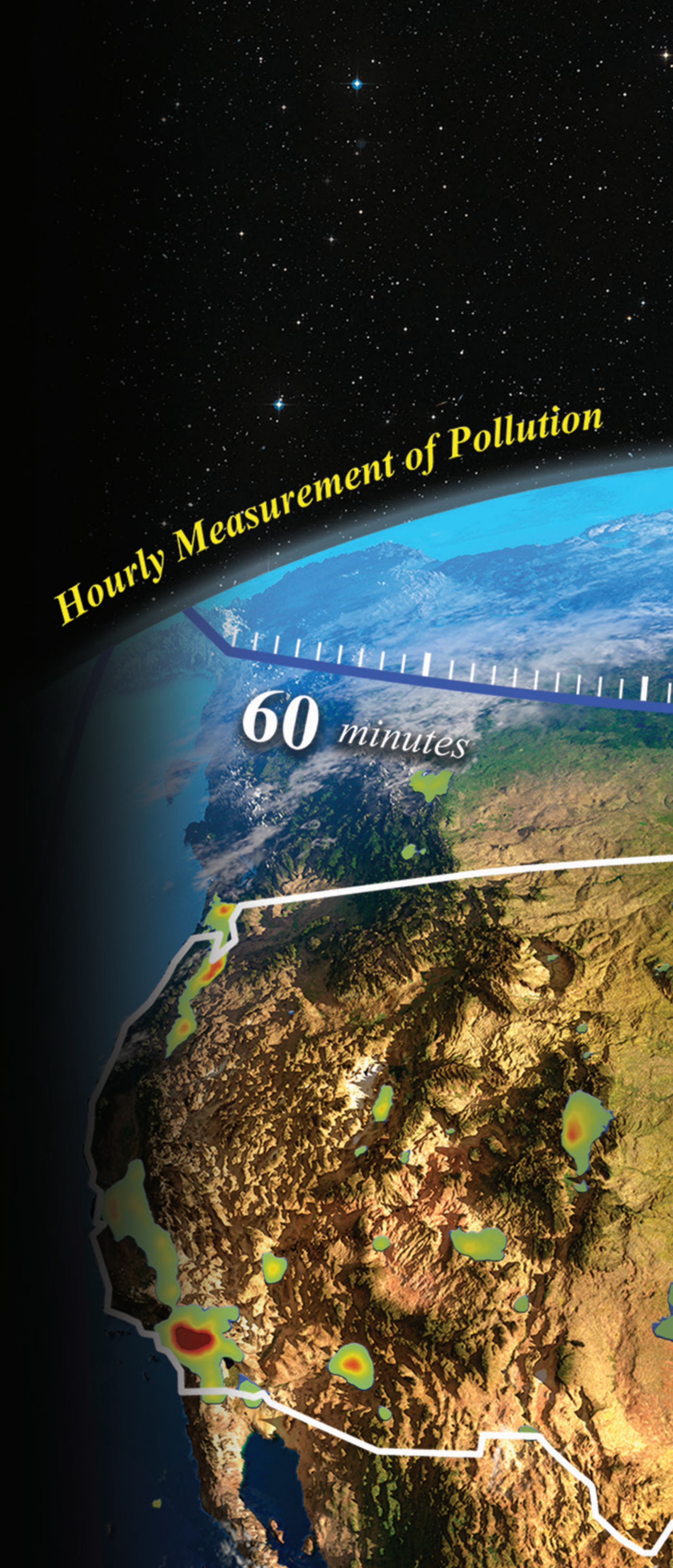
https://weather.msfc.nasa.gov/tempo/green_paper.html

Early Adopters

The TEMPO Early Adopters Program actively engages diverse individuals and organizations to expand their knowledge and abilities in using TEMPO data for applied research. Through these engagement activities, the program aims to maximize and accelerate the value of TEMPO data for societal benefit, with special attention on health and air quality applications.

The high spatiotemporal air pollutant data from TEMPO are ideally suited for enhancing the following application areas:

- ***Air Quality Modeling & Forecasting***
- ***Regulatory Science***
- ***Air Pollution Emissions & Monitoring***
- ***Vegetation & Ocean Monitoring***
- ***Public Health***
- ***Weather Analysis & Forecasting***



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