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EMERGING EARTH REMOTE SENSING INSTRUMENT FOR TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO)

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ABSTRACT

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) program was selected by NASA for the Earth Venture Instruments 2012 Announcement of Opportunity. TEMPO is an innovative use of a well-proven remote sensing technique for air quality measurements and Ball Aerospace is the instrument developer. Low Earth Orbit (LEO) remote sensing techniques have made measurements of photochemical species, precursors and oxidation products relative to air quality. These include NO_2, O_3, SO_2, $C_2H_2O_2$, CH_2O and atmospheric aerosol. The TEMPO instrument combines a high spatial resolution spectrometer with a geostationary orbit to achieve unprecedented spatial and temporal measurement resolution. These new measurements will allow for hourly observations of air quality of Greater North America with urban-regional spatial scales (<60 km^2). Hourly daytime observations will allow for measurements of the complex diurnal cycle of pollution driven by photochemistry. These measurements will contribute to better understanding of regional air quality and improved air quality forecasts. The TEMPO mission will be hosted on a yet to be announced commercial communications satellite with a launch date no earlier than 2020. In this paper, we discuss the mission and instrument design, as well as the opportunities and challenges involved in a hosted payload.

AIR POLLUTION – A GLOBAL ISSUE

The air we breathe is the ultimate shared resource. It is necessary for life, the production of food and other crops and directly impacts human health. Yet, this same air knows no boundaries, whether it be geopolitical borders, oceans or continents. A recent World Health Organization (WHO) report indicates that 92% of the world's population is living in areas where air pollution is at unsafe levels[1]. The greatest numbers of these people live in the WHO defined South-East Asia and Western Pacific regions. These regions include China, Cambodia, Bangladesh, Bhutan, India, Indonesia, Thailand, and Nepal. These unsafe levels of air pollution contribute to respiratory ailments, cardiovascular disease, lung cancer and stroke. The WHO estimates that up to 6.5 million premature deaths are related to a combination of indoor and outdoor air pollution. Significant sources of this air pollution include use of inefficient energy sources for home cooking and heating, agricultural practices, industrial activities, burning of trash and inefficient sources of power and transportation. Developed nations with existing emissions and air pollution regulations are not immune from the social costs of air pollution. A recent study estimates that the annual social costs of air pollution related to energy production in the United States is as high at \$175 billion[2]. Frequent, wide-spread measurements of pollution levels will help inform air pollution and emission regulations and help policy makers balance social and economic costs[3].

An emerging constellation of geostationary pollution monitors is being developed. The Tropospheric Emissions: Monitoring of Pollution (TEMPO), the Geostationary Environment Monitoring Spectrometer (GEMS) and the Sentinel 4 (S4) instruments are being developed by the United States, Republic of Korea and the European Union, respectively. These sensors will cover a vast geographical area including the Contiguous Continental United States (CONUS) and parts of Canada and Mexico (greater North America), The South Korean Peninsula, Japan and the Asia Pacific and greater Asian Continent, and the European Continent. This paper focuses on the TEMPO instrument and mission, as part of this greater constellation.

TEMPO MISSION

The TEMPO program was selected by NASA as the first Earth Venture Instrument (EVI) in 2012. The EVI program is part of the NASA Earth System Science pathfinder (ESSP) Program portfolio. EVI programs are "missions of opportunity" in that they are pure instrument programs where a host spacecraft will be identified during the development of the instrument. The TEMPO team includes the Principle Investigator, Prof. Kelly Chance, of the Smithsonian Astrophysical Observatory (SAO), NASA Langley Research Center (LaRC) providing Project Management, Ball Aerospace as the Instrument Developer, and SAO as the Ground System and Science Data Processing team.

The primary mission of TEMPO is to make the first trace gas measurements of Earth's atmosphere from geostationary orbit. TEMPO addresses the trace gas and aerosol measurement objectives of the GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission[4]. The GEO-CAPE mission was recommended by the 2007 National Research Council (NRC) Earth Science Decadal Survey[5]. The UV/Vis TEMPO instrument will make measurements of trace gases critical to the understanding of ground level ozone and aerosol pollution. These include NO_2, O_3, SO_2, $C_2H_2O_2$, CH_2O and atmospheric aerosol. While these measurements have been made by multiple instruments in a low Earth orbit (LEO), the measurement from a geostationary orbit will provide unprecedented spatial and temporal coverage. This high temporal and spatial resolution is critical to observing and better understanding the complex and dynamic air pollution levels and chemistry.

The TEMPO instrument has a field of view that spans from Mexico City to the Canadian oil sands in the North/South direction, but is narrow (~5 km) in the East/West direction. The TEMPO instrument utilizes a step-stare approach, moving from East to West, to assemble a complete UV/Vis hyperspectral image of greater North America every hour. Multiple images from each step position are co-added on board the instrument and then sent to the science data processing facility. The hyperspectral image data gathered at each step are then merged on the ground to form an image hypercuberepresenting that hour's measurements. A graphical representation of the TEMPO operations is shown in Figure 1.

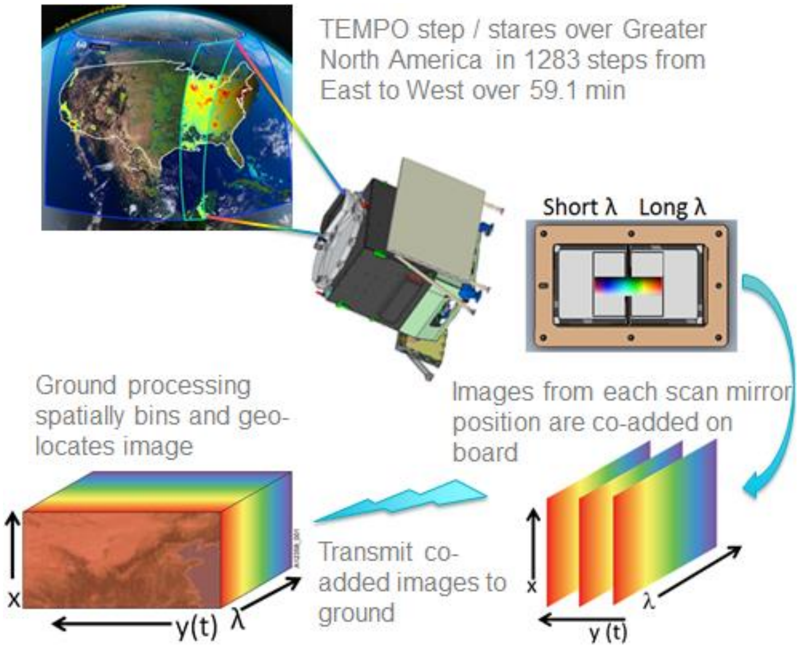


Figure 1 The TEMPO instrument combines over 1200 narrow spectral images of Greater North America as it scans from East to West. The end result is a hyperspectral image cube for retrieving hourly pollution levels.

As an EVI mission, TEMPO is a hosted payload. NASA LaRC is utilizing the US Air Force Hosted Payload Solution (HoPS) contract to select a commercial communications satellite provider who will host TEMPO as a secondary payload on a planned mission. NASA is currently working on a draft request for proposal (RFP) for this opportunity, with a final RFP planned for mid-2017.

TEMPO INSTRUMENT

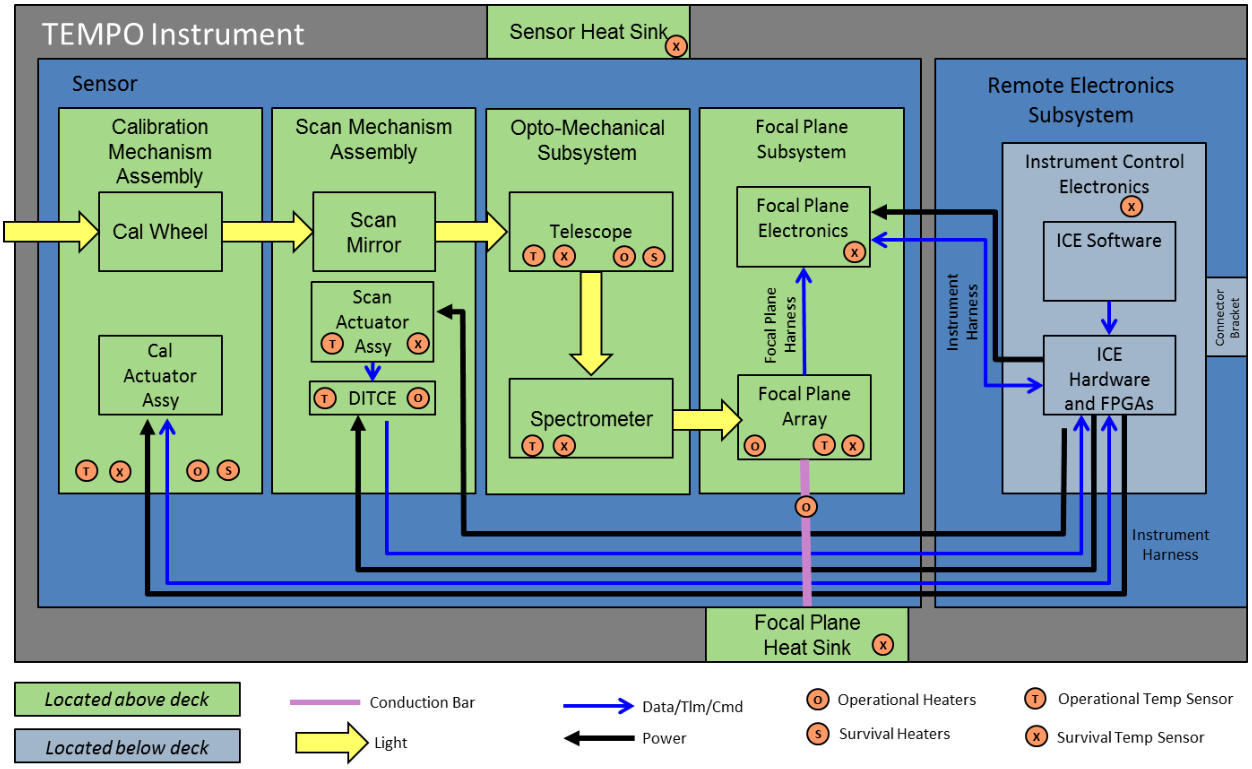
The TEMPO and GEMS instruments are being designed and built by Ball Aerospace in Boulder, CO as part of a co-development. A block diagram of the TEMPO instrument and the key technical parameters is shown in Figure 2. The yellow arrows in the figure show the light path through the instrument. Each major subsystem is described below:

The Calibration Mechanism Assembly (CMA) consists of a rotating wheel that controls the instrument aperture. The wheel contains four selectable positions: Open, closed, working solar diffuser and reference solar diffuser. The ground UV-grade fused silica diffusers allow for solar irradiance measurements that are used for calibration. The working solar diffuser is used daily and the reference solar diffuser used periodically (nominally every 3 months) to trend any radiation or contamination degradation of the working solar diffuser over the instrument lifetime. Dark image data is taken twice a day, when the calibration mechanism is in the closed position.

The Scan Mechanism Assembly (SMA) is the first reflective optic within the Schmidt form telescope. The SMA consists a silicon carbide (SiC) mirror gimballed to a 2-axis fast steering mirror. The SMA projects the TEMPO slit image (or TEMPO field of view) from East to West across the TEMPO field of regard. The SMA uses inertial data from a gyroscope to reject unwanted spacecraft motion[6,7]. The mechanism actuators consist of voice coils and magnets which are controlled inductively. Position is determined using differential impedance transducers (DITs) which are read by the DIT conditioning electronics (DITCE).

An Offner spectrometer was chosen for its compact design and excellent re-imaging performance. It is similar to the spectrometer design of the Ozone Mapping Profiler Suite (OMPS) nadir spectrometer. Optical dispersion is achieved using a mechanically ruled diffraction grating with a peak efficiency at 325 nm. The optical bench consists of a truss-type structure with square composite tubes and titanium fittings. The athermal optomechanical design is actively temperature controlled for excellent spectral stability over changing diurnal and seasonal thermal conditions.

The spectrometer reimages the spatial and spectral data onto the focal plane array (FPA). The FPA consist of two separate 1K x 2K pixel, full frame transfer charge coupled devices (CCDs). The two CCDs are precisely mounted and co-registered on a single focal plane. Each device has 2K spatial pixels and 1K spectral pixels. One device captures spectral data from 290 – 490 nm and the other from 540 – 740 nm. The FPA and focal plane electronics (FPE) comprise the focal plane subsystem (FPS). Optical windows over each detector are coated to transmit the proper spectral range, while blocking out-of-band stray light. The CCDs are back-thinned to optimize the quantum efficiency in the UV and cooled to -20°C to reduce dark signal.



Parameter	TEMPO
Mass	148kg
Volume	1.4 x 1.1 x 1.2m (x, y, z)
Average Operational Power	134 W
Field of Regard (FOR)	4.76° N/S x 8.95° E/W
Ground Sample Distance (GSD)	2.21 x 4.97 km (N/S x E/W)
Spectral Range	290 – 490nm, 540-740 nm
Spectral Bandwidth	0.6 nm

Figure 2: TEMPO instrument block diagram and key technical parameters

The TEMPO instrument is currently in production and test. The spectrometer is aligned separately and then integrated with the FPS. This spectrometer subassembly is then tested and spectrometer requirements are verified. The spectrometer is integrated into the telescope, where the spectrometer slit is precisely aligned to the telescope (boresight, clocking, and focus). The instrument harnesses, close-out panels and CMA are then integrated and the instrument undergoes spatial testing. Figure 3 shows images of the major subsystem hardware for TEMPO.

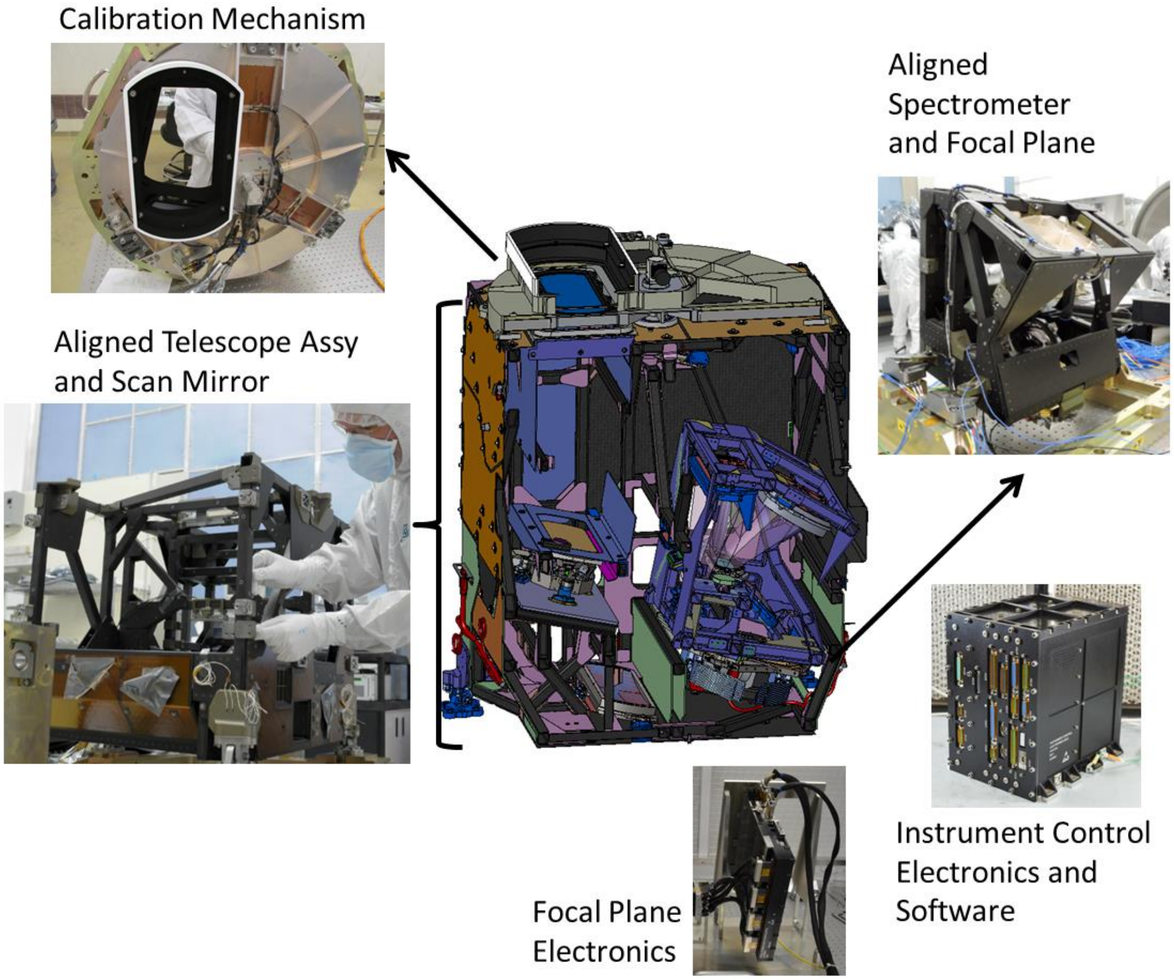


Figure 3: Major subsystem components of TEMPO are complete, or in final alignment and test.

CHALLENGES OF BEING A HOSTED PAYLOAD

TEMPO is the first NASA EVI and the first to go through the process of finding a host spacecraft. The primary challenge for a hosted payload developer is the lack of a host with whom to discuss and negotiate interface requirements. To assist payload developers with this challenge, NASA has developed a set of Common Instrument Interfaces (CII) guidelines. The CII guidelines were developed by using a compilation of interface and environmental requirements. The guidelines are helpful in that they inform payload suppliers with the wide range of potential requirements. For instance, the launch loads contained in the CII envelope many potential spacecraft buses and launch vehicles. Using the loads indicated in the CII would cause a payload developer to over-specify and over-design a payload from a structural point of view. This potential issue can be mitigated with an early selection of a host spacecraft provider. In the absence of an early selection, it is recommended that the CII guidelines be tailored based on the probability of each spacecraft and launch vehicle combination. This approach helps to identify low-probability combinations of spacecraft and launch vehicle that may be driving requirements (and cost) of the hosted payload. The TEMPO mission team at NASA LaRC in charge of the selection of the TEMPO host has been working closely with the TEMPO instrument team to help minimize any risks of over-design and over-test.

The TEMPO mission requires precise pointing and stability for imaging. Undesirable jitter and drift can cause degradation of the TEMPO data. In a dedicated Earth remote sensing mission, the spacecraft and instrument would be designed such that the system would meet these pointing stability requirements. Commercial communication satellites have stability requirements to carry out radio frequency (RF) communications missions. While RF communication missions require good pointing, they can accommodate some level of drift. These levels of drift would significantly impact an optical remote sensing mission such as TEMPO. To mitigate this issue, the TEMPO instrument includes a high precision scan mirror. The scan mirror uses position feedback from an inertial sensor (3-axis gyroscope). The scan mirror controller uses closed-loop control to take out spacecraft jitter and drift, while scanning the instrument's narrow East-West field of view, over the wide-area field of regard. The TEMPO scan mechanism assembly could provide this capability to other hosted payloads that require similar high-precision pointing (Figure 4).

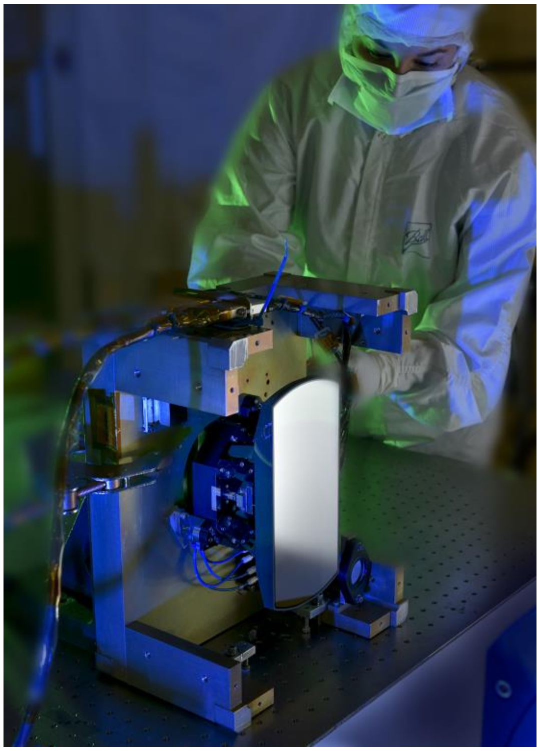


Figure 4: TEMPO Scan Mechanism Assembly enables precise optical remote sensing missions on commercial spacecraft.

SUMMARY

The TEMPO instrument leverages decades of UV/Vis hyperspectral measurements of Earth's atmosphere in low Earth orbit to make the first trace gas measurements from geostationary orbit. The resulting high spatial and temporal resolution data will provide hourly measurements of trace gases important to understanding air pollution emissions and transport, and photochemical production of groud-level ozone. This new dataset will enable new public health and epidemiological studies of the affects of air pollution on humans as well as impacts to agricultural production. Policymakers can introduce thoughtful regulations based on broad atmospheric measurements that balance the impacts of air pollution with the costs of emissions reductions.

TEMPO will join GEMS and Sentinal 4 as a constellation of geostationary pollution monitors. This network will provide data to scientists who study global atmospheric chemistry and the fate and transport of pollutants. As an EVI program, TEMPO will be hosted on a commercial communications satellite. NASA is in the process of selecting a host spacecraft with a target date for selection in late 2017. While the TEMPO instrument duration is only 20 months, the technology developed can easily be applied to future operational systems, greatly reducing the cost, schedule and technical risk of deployment and long-term operations.

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