TES on the Aura Mission: Scientific Objectives, Measurements, and Analysis Overview

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***Abstract*—The Tropospheric Emission Spectrometer (TES) is a high-resolution infrared imaging Fourier transform spectrometer specifically aimed at determining the chemical state of the Earth's lower atmosphere (the *troposphere*). In particular, TES produces vertical profiles 0–32 km of important pollutant and greenhouse gases such as carbon monoxide, ozone, methane, and water vapor on a global scale every other day.**

***Index Terms*—Chemistry, Fourier spectroscopy, infrared spectroscopy, ozone, remote sensing, terrestrial atmosphere.**

I. Introduction

THE Tropospheric Emission Spectrometer (TES) on the Earth Observing System (EOS) Aura mission provides a global view of several species in the troposphere (the lowest region of the atmosphere, extending from the surface to about 10–15 km altitude). While other satellite experiments such as the Global Ozone Monitoring Experiment (GOME) [1], [2], the Measurements of Pollution in the Troposphere (MOPITT) [3]–[5], and the Interferometric Measurements of Greenhouse Gases (IMG) [6] have provided global measurements of some species (e.g., carbon monoxide), the TES investigation is especially focused on mapping the global distribution of tropospheric ozone and on understanding the factors that control ozone concentrations.

Ozone is produced in the troposphere by photochemical oxidation of carbon monoxide (CO) and hydrocarbons in the presence of nitrogen oxides (NO_x) and water vapor. These ozone precursors have both natural and anthropogenic sources. The chemistry of ozone is complex and tightly coupled to the atmospheric transport of both ozone and the precursors.

Tropospheric ozone has the following three major environmental impacts.

1) *As an air pollutant*. Ozone in surface air is toxic to humans, animals, and vegetation. It is the principal harmful component of smog.
2) *As a cleansing agent*. Photolysis of ozone in the presence of water vapor is the primary source of the hydroxyl radical (OH), which is the main oxidant in the atmosphere. Reactions with OH in the lower and middle troposphere are the principal sink for a large number of environmentally important species including air pollutants (carbon monoxide), greenhouse gases (methane), and gases depleting the stratospheric ozone layer (HCFCs, methyl halides).
3) *As a greenhouse gas*. Ozone in the middle and upper troposphere is an efficient greenhouse gas. Perturbation of ozone in this region of the atmosphere results in spatially and seasonally variable radiative forcing with complicated implications for climate.

The troposphere contains only about 10% of the total ozone in the atmosphere—the bulk is in the stratosphere. The environmental implications of tropospheric ozone are very different from those of stratospheric ozone. The ozone layer in the stratosphere shields the Earth's surface from solar UV-B radiation, and thinning of this layer as a result of human activities is a matter of grave concern. Tropospheric ozone, by contrast, has increased as a consequence of human activity (primarily because of combustion processes). Whether this increase in tropospheric ozone is beneficial (cleansing agent) or harmful (air pollutant, greenhouse gas) depends to a large extent on its altitude. It is very important, therefore, to map the global three-dimensional distribution of tropospheric ozone and its precursors in order to improve our understanding of the factors controlling ozone in different regions of the troposphere.

The specific Standard Products that TES produces are global-scale vertical concentration profiles (0–$\sim$33 km) of ozone, water vapor, carbon monoxide, methane, nitrogen dioxide, and nitric acid (the last two in the mid and upper troposphere only). Essential by-products of the analysis are atmospheric temperature profiles and surface temperature and emissivity. In addition, since TES is a spectrometer with near-continuous coverage of the spectrum, we will search for localized species such as hydrogen cyanide, ammonia, and vibrationally excited carbon monoxide from biomass burning and sulfur dioxide from volcanoes.

II. Instrument Characteristics

TES is an infrared, high-resolution, Fourier transform spectrometer covering the spectral range 650–3050 cm^{-1} (3.3–15.4 μm) at a spectral resolution of 0.1 cm^{-1} (nadir viewing) or 0.025 cm^{-1} (limb viewing). The two observation modes are essential because many of the spectral features that TES observes are very weak (especially the nitrogen oxides) and limb-viewing markedly enhances their measurability due to the long path through the atmosphere (but with the deficiency that cloud interference is much more likely than in nadir viewing, where TES has relatively good spatial resolution). That is, at the limb, height discrimination is determined by

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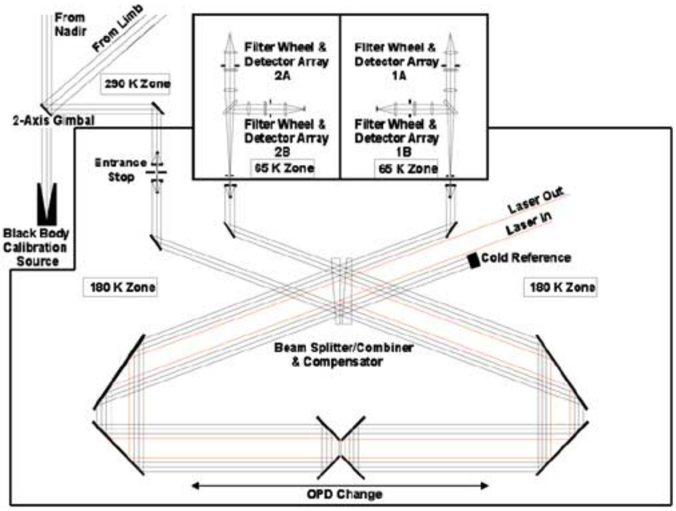

Fig. 1. Schematic of the TES optical system.

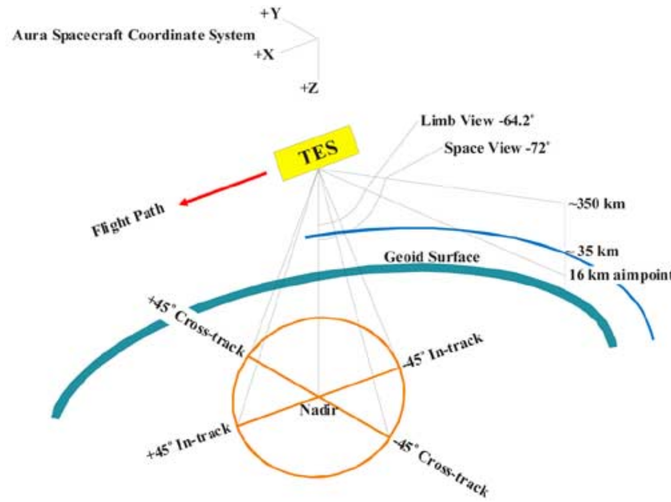

Fig. 2. Diagram of the TES viewing geometry. Downlooking view: TES can target locations anywhere within 45° of nadir (e.g., volcanoes). However, most observations are made along the in-track direction. Limb view: the detector arrays are positioned so that their centers are aimed at 16 km above the geoid. Calibration view: the detectors are aimed alternately at an onboard 340-K blackbody calibration source and at cold space (approximately 350 km above the geoid).

the instrument geometry whereas in the nadir, height discrimination depends on spectral resolution, which can separate the broadened wings of spectral features formed in the lower atmosphere (pressure broadening) from the sharper line cores formed at high altitude where the pressure is low.

In order to improve signal-to-noise ratio and collection efficiency, TES is, except for its pointing system, radiatively cooled to ∼180 K, and it divides the spectral range into four subregions, each observed with a separate 1 × 16 array of detectors (identified as 1A, 1B, 2A, and 2B) actively cooled to 65 K. The bandwidth is further restricted to $\sim 250\,\mathrm{cm}^{-1}$ by interchangeable filters. With these arrays, 16 altitudes in the troposphere and lower stratosphere are observed simultaneously with a height separation of 2.3 km or, alternatively, 16 contiguous areas (each 0.5 × 5 km) are observed on the ground. A complete description of TES can be found in [7], but Fig. 1 shows a schematic of the optical system and Fig. 2 the viewing geometries.

III. Operating Modes

TES was launched into a polar sun-synchronous orbit (13:38 local mean solar time ascending node) on July 15, 2004. The orbit repeats its ground track every 16 days (233 orbits), allowing global mapping of the troposphere on a reproducible grid.

Standard Products are produced from *Global Surveys*. Global Surveys consist of a sequence of observations: a view of cold space followed by a view of the internal 340-K black body (both calibrations at 0.1-cm^{-1} resolution) followed by two 0.1-cm^{-1} resolution nadir scans and three 0.025-cm^{-1} resolution limb scans. Each such sequence occupies about 82 s and is repeated continuously for 16 orbits (just over one day). The dataset is preceded and followed by two orbits of calibration. After intervals of nine or ten orbits (used for *Special Observations* such as validation campaigns, biomass burning, and volcano measurements), the whole cycle begins again at the beginning of the next 16-day period. The coverage during a typical Global Survey is shown in Fig. 3.

The most commonly used Special Observation mode is called "step-and-stare" where TES is pointed at nadir for 4 s (plus

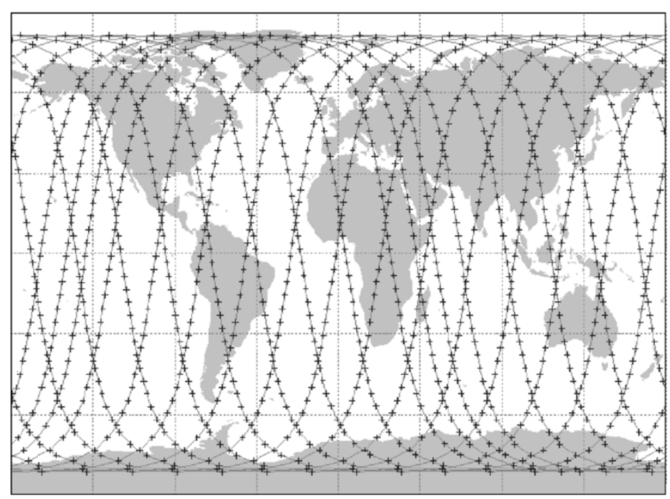

Fig. 3. Coverage during a typical 16-orbit Global Survey (crosses). There are eight such surveys undertaken during the 16-day repeat period of the orbit. Each successive Global Survey is shifted eastward in longitude by about 2° at the equator.

1.2 s for instrument reset and turnaround). During this time, the spacecraft has moved about 35 km, and another nadir view is acquired. Such a cycle can be repeated indefinitely but is usually limited to 40° of orbital latitude. A similar mode can be employed at the limb.

However, because TES is a targetable instrument, Special Observations can also be conducted either using transects wherein the successive footprints are "stacked" end-to-end for as much as 800 km or by staring at a specific location (e.g., a volcano) for as much as 240 s.

IV. Data Analysis

Data analysis proceeds through the following several levels.

Level 0 is the raw serial bit-stream from the spacecraft.

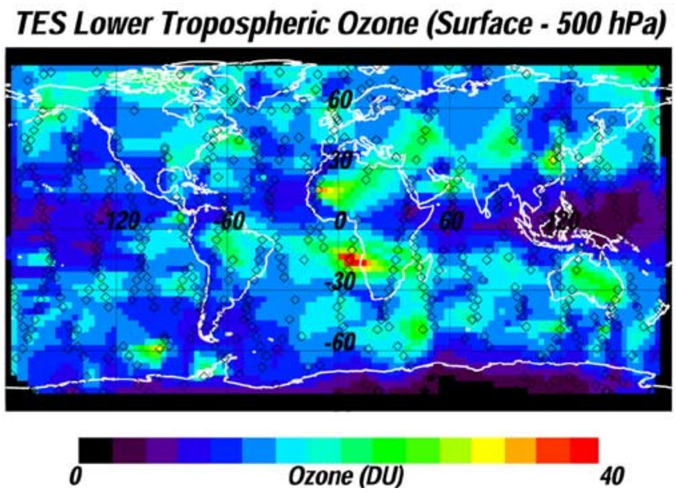

Fig. 4. Example of the global distribution of ozone in the lower troposphere on September 20, 2004. Diamonds indicate the locations of observation—the map has been interpolated for clarity. Notes: 1 Dobson Unit (DU) = a column of 2.686×10^{16} molecules/cm^2; 500 hPa is the pressure at *approximately* 5.6 km above mean sea level.

Level 1A takes this bit-stream and reconstructs the original interferograms—one for each of the 64 pixels. The geolocation of the observation is also computed at this time.

Level 1B converts the interferograms into spectra and, when appropriate, applies radiometric calibration to the data. Spectral radiances from Global Surveys will be openly available from the Atmospheric Sciences Data Center at the NASA Langley Research Center in Hampton, VA. The paper by Worden *et al.* [8] in this issue describes the algorithms used for this process.

Level 2 extracts the vertical abundance profiles from the calibrated spectra. The general approach is to construct a "forward model" using an initial guess at the state of the atmosphere and, via an equation of radiative transfer, to compute the expected radiance spectrum. This computed spectrum is compared to the observation and, using appropriate rules and constraints, the initial guess is modified until the model and the observation are indistinguishable. The resultant constituent profiles and associated error covariances from Global Surveys are available at the Langley Research Center Atmospheric Sciences Data Center.

The papers by Clough *et al.* [9], Bowman *et al.* [10], and Kulawik *et al.* [11], [12] in this issue discuss the specific algorithms and associated error analysis used by TES. Elsewhere, Lampel *et al.* [13] discuss the problem of species retrieval in the presence of clouds, and Rodgers [14] provides a general background to the many methods that have been developed to address the inversion problem.

In addition, the papers by Chu *et al.* [15] and Paradise *et al.* [16] describe the ground data system and associated software which execute the aforementioned algorithms.

Level 3 takes the retrieved profiles and puts them onto global maps at predetermined pressure levels. This is primarily a browse product. An example of such a map is shown in Fig. 4, where the enhanced ozone off the west cost of Africa due to Southern Hemisphere biomass burning is clearly evident, as is the expected very low ozone concentration in the intertropical convergence zone to the east of Indonesia.

Level 4, still under development, will take the profiles and error analysis and through a process of data assimilation, drive global chemical transport models to provide, among other things, a "chemistry forecast."

V. Conclusion

The Tropospheric Emission Spectrometer is in excellent health and operating normally on the EOS Aura platform. We have every expectation that significant advances in our knowledge of global tropospheric chemistry will ensue over the next few years.

Since the foregoing was written, concerns about instrument lifetime have required a modification to the Global Survey strategy. Routine limb observations have been eliminated (but are still occasionally available as Special Observations) and a third nadir observation added.

Acknowledgment

An instrument system as complex as TES could not have been realized without the dedicated efforts of almost 200 individuals over a period of several years. The author wishes to thank them all but with a specific acknowledgment of the Project Manager, T. A. Glavich, for almost 16 years of effort above and beyond the call of duty.

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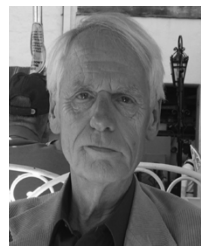

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