The Tropospheric Emission Spectrometer: From Discovery Mission to Earth System Sounding

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Abstract: The Tropospheric Emission Spectrometer (TES) was launched aboard the Aura spacecraft in 2004 and decommissioned in February 2018. Over more than a decade of observations, TES has shown the potential of high-resolution Fourier Transform Spectrometer (FTS) measurements to alter our understanding of atmospheric composition and its relationship to the Earth System. We survey some of the major contributions TES has made to understanding air quality, chemistry-climate interactions, atmospheric hydrology, and carbon cycle science. We then show how innovations in retrieval methods pioneered by the TES team are now being applied to multi-spectral, multi-instrument records, establishing a new paradigm for composition measurements into the future.

OCIS codes: 000.0000, 999.9999.

TES as an Earth System Sounder

The Tropospheric Emission Spectrometer (TES) was launched on July 15, 2004 aboard the Aura Earth Observing System (EOS) satellite. 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) using a 16 pixel array with a nadir ground track of 0.5×5 km.

When the TES instrument was proposed in 1988, one of the primary scientific concerns at NASA was the ozone "hole". Nevertheless, atmospheric composition was increasingly understood as an integral part of a broader Earth System There was increased urgency to understand this system as the awareness of anthropogenic climate change increased both within the scientific community and the general public [1]. While TES was designed to quantify tropospheric ozone and its precursors, the broad, high-resolution spectral range afforded the opportunity to a observe a wide range of species that provided information beyond atmospheric chemistry to include global hydrology, carbon cycle, and climate. In order to infer the global distribution, considerable focus was put on the development of optimal estimation techniques, which both characterize the retrieval and provide the elements for observation operators needed for data assimilation [2, 3]. Based upon this framework, TES data was used to show that roughly half of the expected reduction in Western US tropospheric ozone were offset by increases in Chinese emissions [4]. Changes in ozone also impact the Earth's radiative balance. TES pioneered the use of observational instantaneous radiative kernels (IRK), which represent the sensitivity of outgoing longwave flux to the vertical distribution of a trace gas [5]. These kernels were combined with chemical transport adjoint modeling techniques to attribute direct ozone radiative forcing (RF) to NO_x and CO emissions at large urban spatial scales [6]. They were furthermore used to constrain preindustrial to present day ozone RF through an emergent constraint from chemistry-climate models, resulting in a 30% reduction in uncertainty [7] . However, the ozone greenhouse gas effect is radiative coupled to water vapor—and therefore changes in the hydrological cycle [8].

TES provided a new window into the hydrological cycle through new retrievals of HDO, which is sensitive to the evaporation and condensation history of an air parcel, providing insights such as the contribution of tropical rainfall evaporation to lower tropospheric humidity [9]. Over the Amazon, these data showed that the tropical forests play an important role in initiating their own rainy season [10]. However, these forests are vulnerable to climate variability and disturbances, such as wildfire. Linking CH_4 and CO, the once-in-a-century biomass burning in 2010 was shown to be driven by reduced drought-fire biomass combustion rates [11]. However, global biomass burning has been declining, which was used with TES CH_4 and other data to show that the recent increase in methane is related to increases in fossil fuel and biogenic emissions [12].

The OE techniques developed on TES were readily adapted to focus on a new frontier for remote sensing of atmospheric composition: combining multiple spectra from multiple instruments to produce enhanced composition retrievals. These techniques showed the potential of near-surface ozone sensitivity with IR and UV measurements [13], and high spatial resolution near-surface CO from meteorological sounders and NIR instruments [14]. These can serve as part of a broader constellation of composition measurements (including geostationary) that will advance our understanding of changes in atmospheric composition and their impact on the broader Earth System [15].

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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