

On-Orbit Thermal Performance of the TES Instrument – Three Years in Space

Jose I. Rodriguez, Arthur Na-Nakornpanom, Jose G. Rivera,
Virgil Mireles and Howard Tseng

Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

The Tropospheric Emission Spectrometer (TES), launched on NASA's Earth Observing System Aura spacecraft on July 15, 2004 has successfully completed over three years in space and has captured a number of important lessons. The instrument primary science objective is the investigation and quantification of global climate change. TES measures the three-dimensional distribution of ozone and its precursors in the lower atmosphere on a global scale. It is an infrared (IR) high resolution, imaging Fourier Transform Spectrometer (FTS) with a 3.3 to 15.4 μm spectral coverage required for space-based measurements to profile essentially all infrared-active molecules present in the Earth's lower atmosphere. The nominal on-orbit mission lifetime is 5 years. The Aura spacecraft flies in a sun-synchronous near-circular polar orbit with 1:38 pm ascending node.

The instrument uses four focal plane arrays in two separate housings cooled to 65 K by a pair of Northrop Grumman Space Technology (NGST) pulse tube cryocoolers. It includes a two-stage passive cooler to cool the interferometer to 180 K. The electronics including the cryocooler compressors transport their waste heat via loop heat pipes (LHPs) and constant conductance heat pipes (CCHPs) to room temperature nadir facing radiators for rejection to space.

After cooling the optical bench and focal planes to their operating temperatures for the first time, a decontamination cycle was required only 14 days later due to ice contamination of the focal planes. The signal throughput from one of the eight channels decreased by 40%. The 2B1 channel with a 600-900 cm^{-1} filter showed strong evidence of the presence of water ice. Ice buildup of cryogenic surfaces also led to increased cryocooler heat loads.

After six months of successful science operations, plans were developed to increase the optics temperature to near 187 K to improve the interferometer optical alignment and obtain higher quality science data. The optics temperature was increased successfully on November 29, 2005 with results showing significant improvement in the science data quality. This paper

provides a general overview of the thermal and cryogenic system design and reviews the on-orbit performance over the three years.

INTRODUCTION

Launched from Vandenberg Air Force Base in California, the Aura spacecraft was placed in a sun-synchronous near-circular polar orbit with an inclination of 98.2 degrees, mean altitude of 705 km, and a 98.7 minute orbit period. The overall science objective of the TES instrument is the investigation and quantification of global climate change, both natural and anthropogenic. TES measurements have already been used to determine local atmospheric temperature and humidity profiles, local surface temperatures, and local surface reflectance and emittance. TES observations are also being used to study volcanic emissions for hazard mitigation, indications of the chemical state of the magma, eruption prediction, and quantification of the role of volcanoes as sources of atmospheric aerosols. The satellite's orbit was selected to permit measurements at all latitudes with complete coverage of the entire globe in 16 days. A detailed description of TES and its science capabilities is found elsewhere (Refs. 1-3). The Aura spacecraft on top of the Boeing Delta II launch vehicle at lift-off is shown in Fig. 1. The Aura spacecraft forms part of NASA's Earth Observing System (EOS) afternoon Constellation (A-Train), see Fig. 2. The Aura observatory flies at the tail end of the A-Train, just behind the PARASOL satellite along with OCO, Aqua, CloudSat, and CALIPSO satellites (Ref. 4). TES integrated on the Aura spacecraft at NGST, formerly TRW, is shown on Fig. 3.

TES was developed with significant subcontractor support building critical hardware such as the composite optical bench and support structure, two-stage passive cooler with Earth shade, pulse tube cryocoolers, LHPs, CCHPs, pointing and interferometer control subsystems and beryllium optics.

The thermal control system makes use of passive and active elements to maintain the instrument within allowable flight temperature (AFIT) limits. The passive thermal control includes multilayer insulation (MLI)

blankets, thermal straps, and surface coatings to manage the transfer of waste energy from sources through structures and ultimately to radiators. Active thermal control employs CCHPs, LHPs and both open-loop and close-loop heater control systems. Operational and replacement heaters are used in science mode and survival heaters are used in safe and survival modes.



Figure 1. Launch of the EOS Aura spacecraft from Vandenberg Air Force Base in California

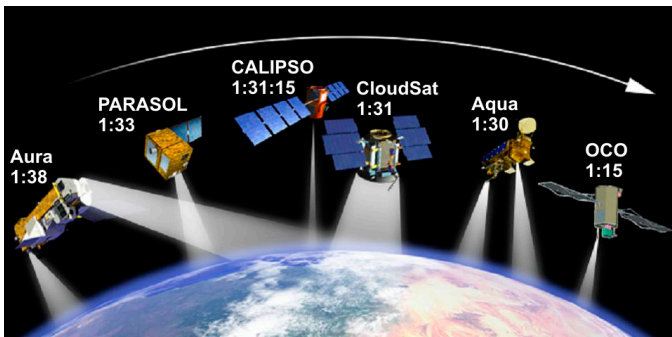


Figure 2. NASA's EOS A-Train Constellation on orbit

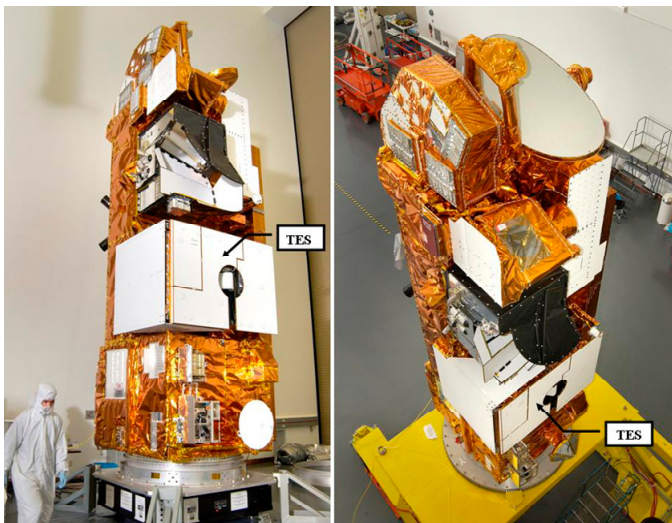


Figure 3. TES instrument integrated on the Aura spacecraft at NGST.

The Aura spacecraft carrying TES was successfully launched on July 15, 2004 at 3:02 am PDT aboard a Delta II vehicle from the Western Test Range of Vandenberg Air Force Base and achieved operational orbit two weeks later. TES was powered on July 17, 2004 and remains operational to date. Two hours after launch, the instrument survival bus power was turned on

and the instrument transitioned to survival mode as planned with all five LHPs off. Two days later, the instrument electronics and signal chain were powered on and the two LHPs for these boxes started operating. After four weeks of outgassing, the optical bench and focal planes were cooled to their operating temperatures in preparation for acquiring science data.

INSTRUMENT DESCRIPTION

The TES instrument is a high-resolution IR imaging FTS with spectral coverage of 3.3 to 15.4 μm at a spectral resolution of 0.1 cm^{-1} in nadir view or 0.025 cm^{-1} in limb view. TES contains four optically-conjugated 1x16 pixel Mercury Cadmium Telluride (HgCdTe) detector arrays housed in two separate focal plane opto-mechanical assemblies (FPOMAs). The focal plane arrays are cooled by separate long-life, low vibration, pulse tube cryocoolers with coldtip at 63 K. Refs. 5-9 provide a chronological account of the development efforts for the TES cryocoolers. A two-stage passive cooler with a deployable Earth shade provides cooling for the interferometer optics operating near 180 K. The optics and translator housing contain all the interferometer optics including the retro-reflector. The retro-reflector is a double cube corner that is mounted on a translator carriage that traverses back and forth, continuously changing the optical path length. The passive cooler first-stage, at 230 K, intercepts parasitic heat leaks from the surrounding environment and provides cold surroundings for the optics bench.

TES has capability to make both nadir and limb observations. In the limb mode, it has a height resolution of 2.3 km, with coverage from 0 to 34 km. In the nadir modes, it has a spatial resolution of 0.53 by 5.3 km with a swath of 5.3 by 8.5 km. The pointing mirror is mounted on a gimbal which provides access to any target within 45 degrees of local vertical, or can produce regional transects up to 885 km length without any gaps in coverage. The instrument makes use of both the natural emission of the surface and atmosphere and reflected sunlight, thereby providing day-night coverage around the globe.

The Aura spacecraft low altitude sun-synchronous orbit results in significant Earth IR and albedo heat flux loading on the nadir side of the spacecraft. The two-stage passive cooler requires an Earth shade to block incoming thermal radiation. To protect against direct solar loading on both radiator stages, the cold radiators face the anti-sun side of the spacecraft. However, direct solar radiation does impinge on the tip of the inside surface of the Earth shade for a short period (~12 min) during the 98 minute orbit. To limit the amount of back scattering solar radiation on the cold radiators, the Earth shade inside surface is a highly specular vapor deposited aluminum surface. Both radiators have black painted open-cell aluminum honeycomb bonded to the external surface to enhance their heat rejection capability.

The instrument structure is built primarily from advanced composite materials, as is the passive cooler Earth shade. The instrument is approximately 1.0 m x 1.3 m x 1.4 m in size, with a 385 kg mass and average power of 235 Watts. The heart of the instrument is the interferometer passively cooled to 180 K by the instrument's passive cooler and the two focal plane arrays cooled to 65 K by the pulse tube cryocoolers. The heat load from the interferometer to the second stage radiator of the passive cooler is ~22 Watts at 180 K. The cryocooler beginning-of-life (BOL) total heat load is approximately 650 mW at 65 K for each cryocooler.

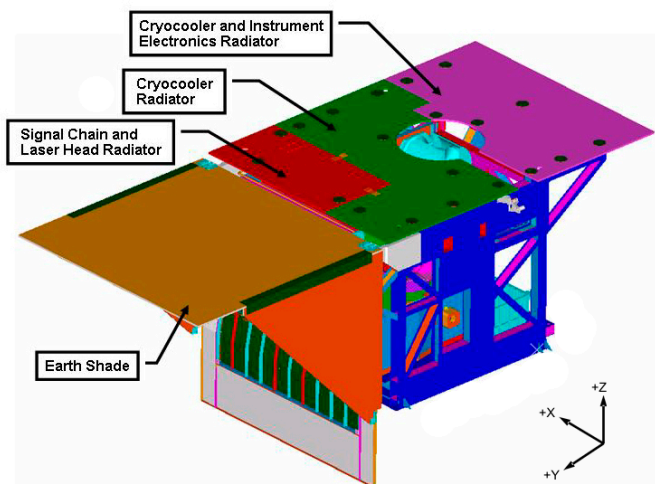


Figure 4. Instrument configuration with key assemblies and cryocoolers with loop heat pipes and radiator

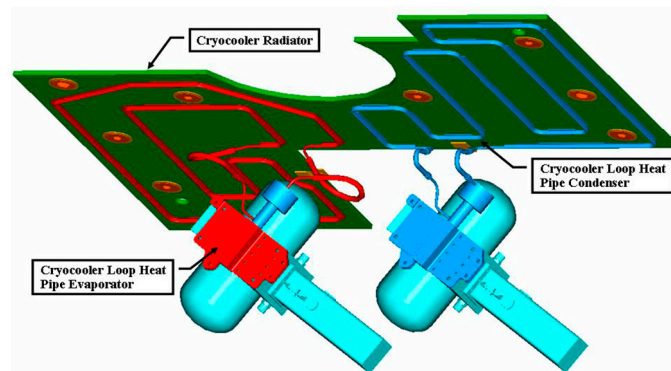


Figure 6. Cryocooler compressors with loop heat pipes and radiator

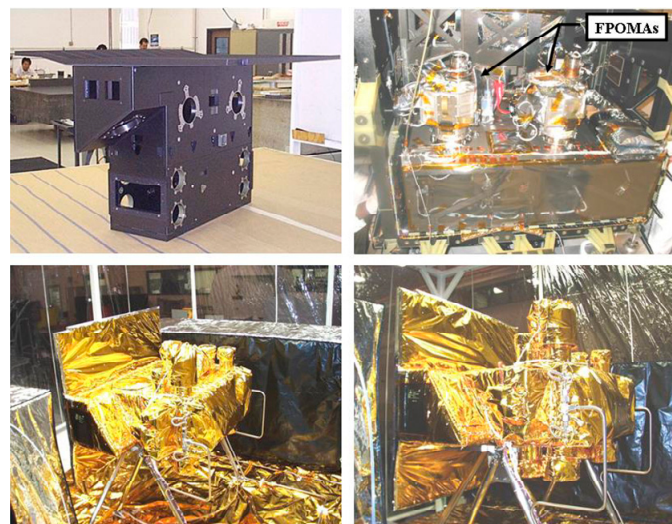


Figure 7. Instrument optical bench with the passive cooler second-stage radiator and external MLI blankets

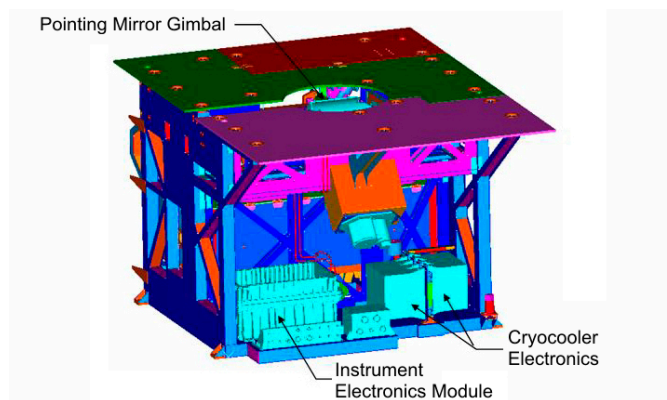


Figure 5. Instrument configuration with key assemblies and cryocoolers with loop heat pipes and radiator

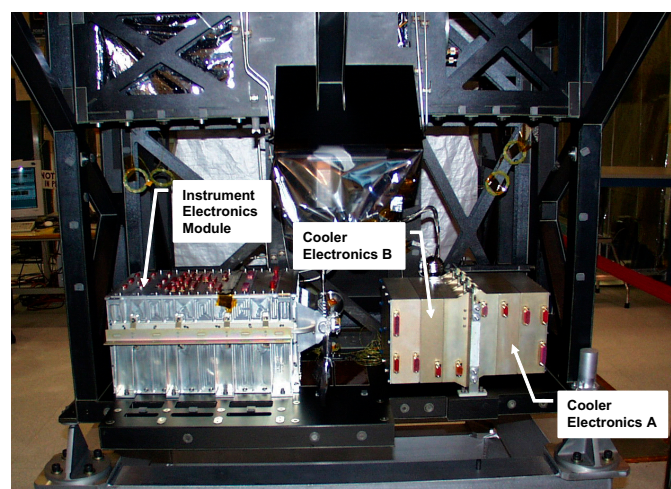


Figure 8. Instrument and cryocooler electronics

The high power dissipating room temperature components including the cryocooler compressor, cryocooler electronics and instrument electronics reject their waste heat to the instrument-mounted nadir-facing radiators by means of the LHPs and CCHPs. Figs. 4-6 illustrate solid CAD models of the overall instrument and highlights the key assemblies. Fig. 4 shows the instrument coordinate system with +Z pointing nadir in science mode. A detailed description of the thermal design of the instrument is found in Ref. 6.

Electronics assemblies are mounted to the base structure and the +X side panel of the instrument. Figs. 7-8 show the optical bench and electronics assemblies. The radiometric and spatial calibrators are mounted to composite beams spanning the structure near the pointing mirror. The pointing mirror mounts to a

gimbal assembly in the +Z side of the support structure. The field of view is 45° for cross-track and +45° to -72° along-track. Figs. 9-10 show views of the instrument with the Earth shade stowed and deployed.



Figure 9. TES instrument with Earth shade stowed

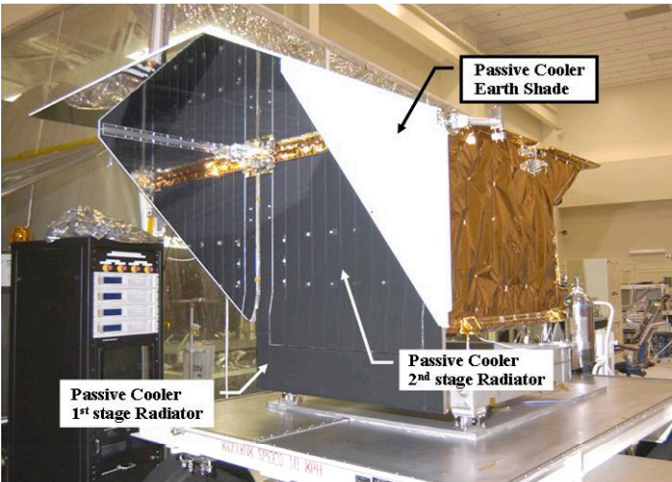


Figure 10. TES instrument with Earth shade deployed

OBSERVATORY ENVIRONMENT

Key thermal design drivers for the instrument are as follows:

- Orbit parameters: sun-synchronous, circular orbit, 705 km altitude, 1:38 pm ascending node, 98.21 degree orbit inclination,
- Spacecraft interface temperatures: 0/+30°C for science and safe mode, -20/+50°C for survival mode,
- Heat transfer to spacecraft limited to 15.5 W/m², including radiation and conduction heat transfer,
- Spacecraft accommodations maximum backload of 3 W/m² heat flux to passive cooler radiators,

- Survival heater power limited to 30% of allocated operational mode average power.

The parameters and conditions of each spacecraft state defining the hot and cold mission environments, safe hold and survival spacecraft attitudes and the solar vector to orbit plane (beta) angle are shown in Table 1. The environmental constants are defined in Table 2. Fig. 11 defines the science and survival orbits.

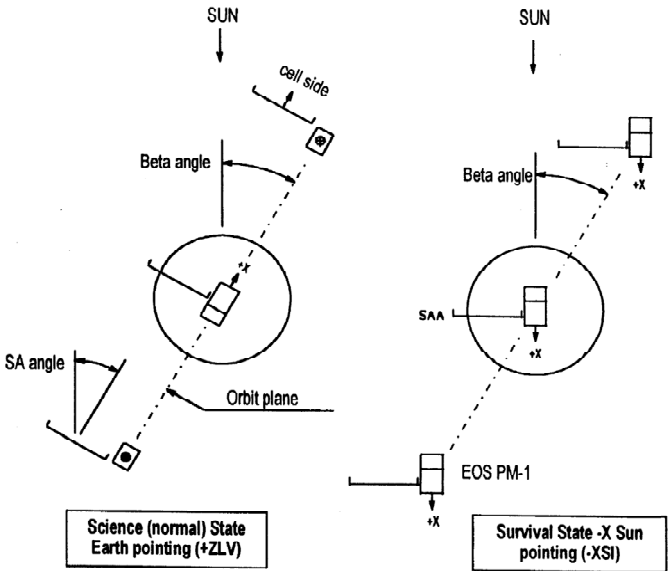


Figure 11. Aura spacecraft science and survival orbit definitions

S/C state	Beta angle (degrees)		S/C Attitude	Description
	hot	cold		
Launch	varies	varies	varies	Includes ascent, coast, orbit insertion to power on. Stowed config.
Science	16	36	+Z local vertical (nadir pointing)	Earth shade deployed
Safe	16	36	+Z local vertical (nadir pointing)	Earth shade deployed
Survival	NA	16	-X solar inertial (sun pointing). S/C rolls about X-axis at 2 ± 0.2 rev/orbit	Earth shade deployed

Table 1. Aura spacecraft states

Parameter	Cold Case	Hot Case
Solar Flux	1290 W/m ²	1420 W/m ²
Albedo	0.275	0.375
Earth IR	222 W/m ²	243 W/m ²

Table 2. Mission environment parameters

Spacecraft thermal isolation requirements dictated that the instrument thermal control be independent of the observatory. This led to the use of MLI blankets and titanium mounts to provide the required thermal isolation. Passive nadir pointing radiators were required to reject the instrument power dissipation. To provide