

TES CRYOCOOLER SYSTEM DESIGN AND DEVELOPMENT

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ABSTRACT

JPL's Tropospheric Emission Spectrometer (TES) instrument is typical of recent NASA cryogenic instruments that take advantage of mechanical cryocoolers to enable the acquisition of important science data using cryogenic focal plane arrays. TES is a high-resolution infrared imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 microns and is under development at JPL for flight on NASA's EOS-Aura spacecraft in the 2003 timeframe.

The instrument contains four focal plane arrays in two separate housings that are cooled to 65 K by a pair of TRW pulse tube cryocoolers. The instrument also includes a two-stage passive radiator to cool the optical bench to 180 K. The cryocooler system design is tightly coupled with the overall thermal control design to maximize performance of the TES instrument.

This paper describes the cryogenic system design including the cryogenic loads, thermal performance margins, and performance properties for the cryocoolers. Test results are presented from recent integration activities that focused on the critical interface between the cryocoolers and the focal plane subsystem.

INTRODUCTION

The objective of the Tropospheric Emission Spectrometer (TES) instrument is to measure the three-dimensional distribution of ozone and its chemical precursors in the lower atmosphere on a global scale. The instrument is a high-resolution infrared imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 microns at a spectral resolution of 0.1 cm^{-1} (nadir view) or 0.025 cm^{-1} (limb view).

FIG 1 illustrates the overall instrument construction and highlights the key assemblies. Physically, the instrument is approximately 1.8 m x 1.3 m x 1.0 m in size, with a mass allocation of 385 kg and an input power of 335 watts. The foundation of the instrument is the interferometer and its optical bench assembly that is passively cooled to 180 K by the instrument's two-stage 180 K/230 K passive radiator. The ambient portion of the instrument contains the high power dissipation components including the instrument electronics and the cryocoolers and their electronics. These high-power-dissipation components reject their heat to instrument-mounted nadir-facing radiators via a system of loop heat pipes.

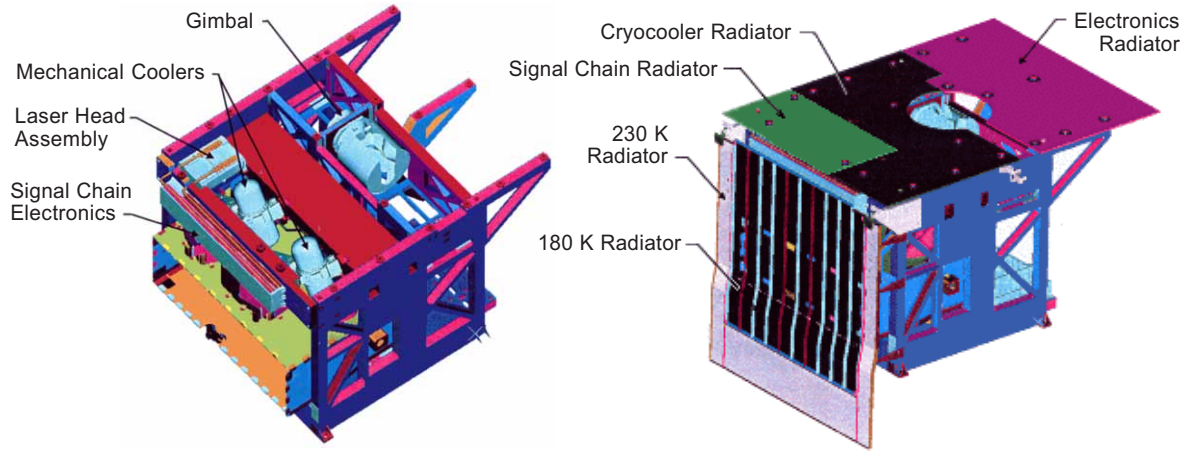


FIGURE 1 Layout of key functional elements of the TES instrument including cryocoolers and radiators.

The core of the TES instrument is the four HgCdTe focal plane arrays with somewhat overlapping capabilities that reside in two separate Focal Plane Optical Mechanical Assemblies (FPOMA). The FPOMAs (FIG 2) were designed and developed by Utah State University Space Dynamics Lab and each contain a number of cryogenic elements including 150 K, 180 K and 230 K radiation shields, MLI insulation, and optical elements such as filter wheels and the focal planes themselves. The FPOMAs are hard-mounted to the 180 K interferometer optical bench, and the internal focal-plane elements are connected to the 65 K pulse tube cryocoolers via an S-link flexible thermal conductor. The various thermal shields and MLI of the FPOMA are visible in FIG 3, which highlights the buildup of an engineering model assembly and integration with the EM cryocooler during thermal balance testing at JPL. FIG 4 illustrates the coupling between the cryocooler and the FPOMA.

TES CRYOSYSTEM DESIGN AND THERMAL INTERFACE ATTRIBUTES

TABLE 1 provides a breakdown of the overall cryocooler beginning-of-life (BOL) refrigeration loads predicted for the TES instrument, and projections of representative end-of-life (EOL) properties. A key determiner of these BOL/EOL loads is the BOL/EOL temperature of the 180 K radiator and the effective emittance of the MLI. These were assumed to be 176 K/180 K and $\epsilon = 0.04/0.06$, respectively.

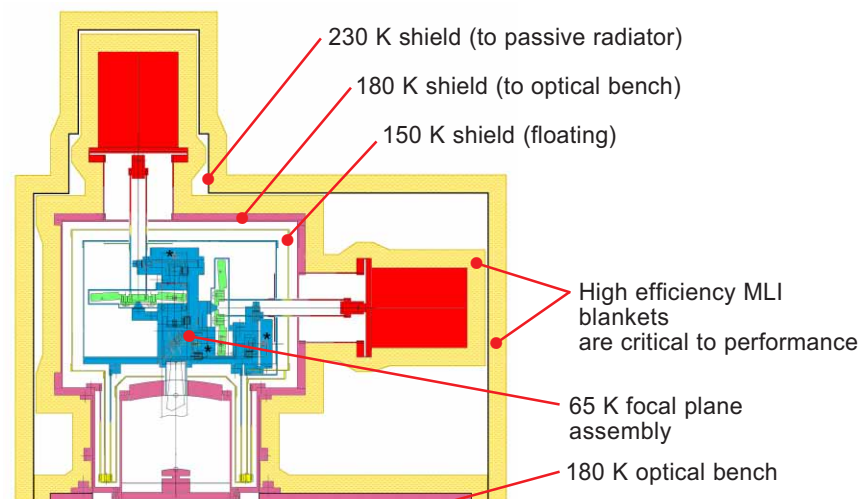


FIGURE 2 Focal Plane Optical Mechanical Assembly (FPOMA) construction details.

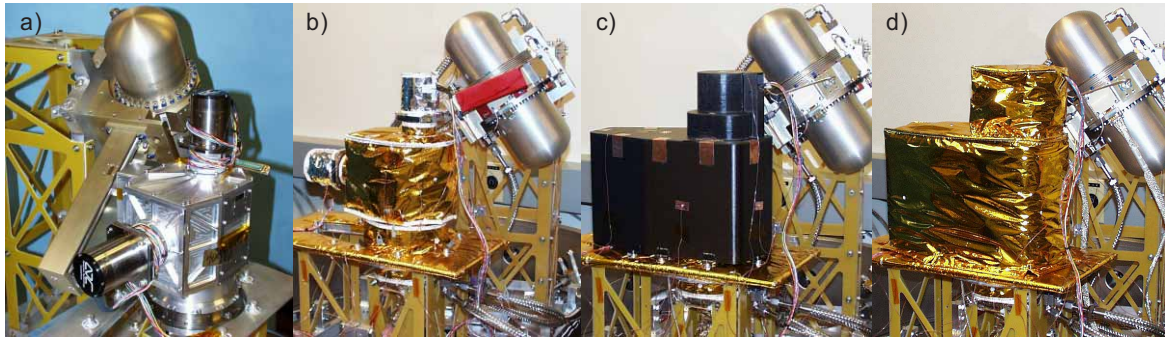


FIGURE 3 Focal Plane Optical Mechanical Assembly (FPOMA) construction details: a) bare FPOMA, b) with added inner MLI, c) with 230K shield added, and d) complete with outer MLI.

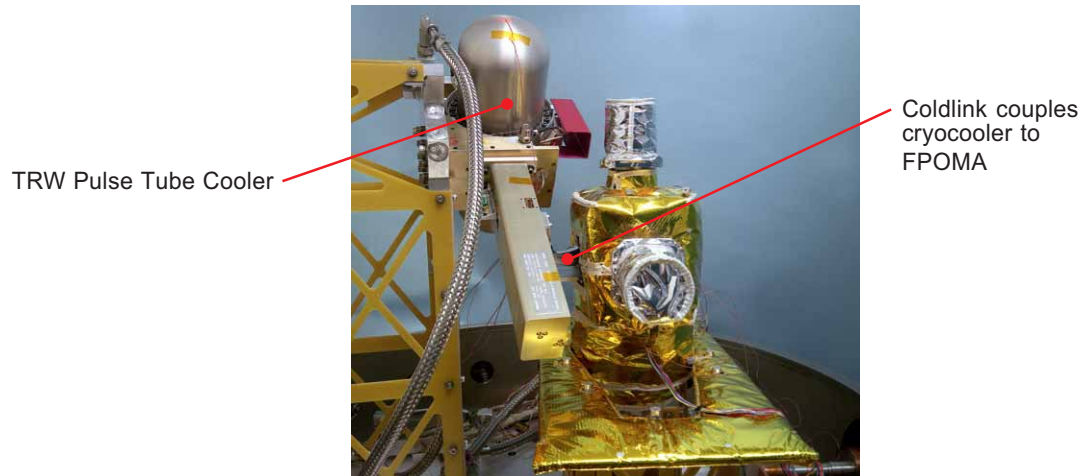


FIGURE 4 Flight-like integration of the FPOMA and the TES pulse tube cryocooler.

TABLE 1 Predicted FPOMA thermal loads for beginning-of-life (BOL) and end-of-life (EOL) conditions.

| | BOL | EOL |
|------------------------|-------------------|-------------------|
| Optical Bench | 176 K | 180 K |
| | $\epsilon = 0.04$ | $\epsilon = 0.06$ |
| Detector Dissipation | 40 mW | 60 mW |
| Detector Leads | 53 mW | 55 mW |
| Structural Support | 170 mW | 176 mW |
| Housing Radiation | 101 mW | 136 mW |
| Filter Wheel Radiation | 107 mW | 115 mW |
| Cold Link Radiation | 33 mW | 45 mW |
| Subtotal | 504 mW | 587 mW |
| Margin (40%) | 201 mW | 233 mW |
| Total Heat Load | 705 mW | 820 mW |

Focal Plane Optical Mechanical Assembly (FPOMA) Thermal Balance Test

To validate the predicted cryocooler loads in TABLE 1, a subsystem-level thermal balance test was conducted using the Engineering Model pulse tube cryocooler and a thermal mock-up of the FPOMA as illustrated in FIGS 3 and 4. During this test the cryocooler input power was measured for a variety of thermal loading conditions representative of the

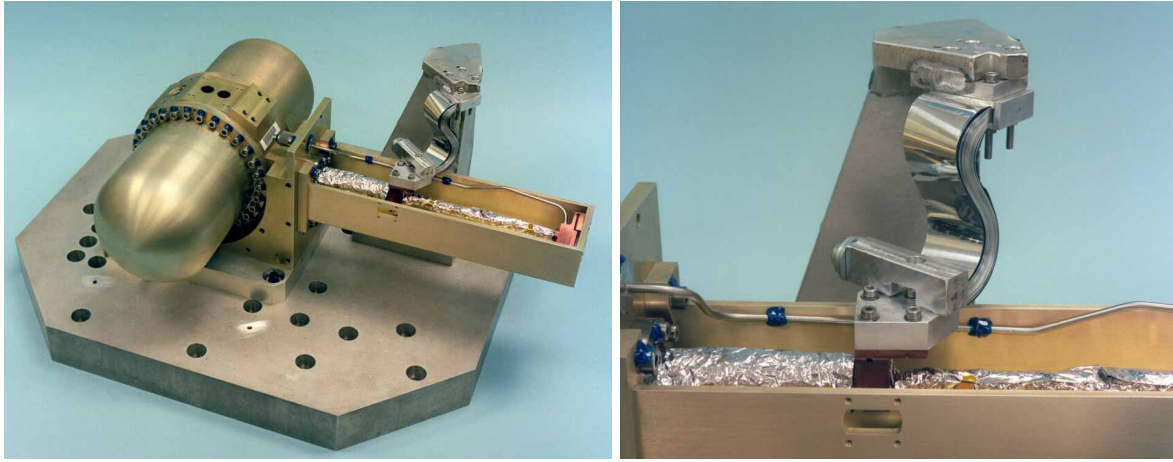


FIGURE 5 Details of the S-link used to connect between the FPOMA and the cryocooler as seen during dynamic testing of dynamic-mockups of the S-link and the TRW TES pulse tube cooler.

expected flight conditions, including focal plane dissipation and passive radiator temperature. For the test the passive radiator was simulated with a GM cryocooler that was used to set the FPOMA shields to known parametric temperatures of interest.

For a representative set of BOL test conditions the measured cryocooler input power was 30 W, in contrast to a predicted value of 33 W, and a maximum power allocation of 44 W. Thus, the thermal balance test verified the cryo/thermal performance of the fully integrated cryogenic system.

Cooler Flexlink Performance

The cryocooler flexlink assembly is required to accommodate motion between the cooler and the FPOMA while also minimizing thermal conduction losses between the two. Another important consideration is the structural loads imparted into the FPOMA and pulse tube during launch vibration as determined by the units mass and vibration damping attributes. The TES S-link unit was designed and fabricated by the Utah State University Space Dynamics Lab and consists of 250 layers of 1100-series aluminum foil with swaged terminations, a length of 129 mm, and a mass of 99 grams. To accurately characterize the S-links thermal and structural properties, a representative unit was included in both the FPOMA thermal balance tests described above, and in a special dynamic vibration test (FIG 5) designed to characterize the units vibration damping attributes.

In these tests the flexlink thermal impedance was determined to be < 3.4 K/W and the vibration amplification at the pulse tube coldblock (ratio of coldblock acceleration to shaker input acceleration) was found to be around 20. The flexlink itself was qualified with a 32 Grms shake test.

TES CRYOCOOLER DEVELOPMENT AND PERFORMANCE

Cooler Sizing Calculations

In order to provide an accurate understanding of the needed beginning-of-life (BOL) and end-of-life (EOL) cryocooler system performance, a sensitivity analysis of the cryocooler/load system was conducted using the BOL and EOL estimates given previously in TABLE 1. This sizing analysis is summarized in TABLE 2. In this table, the column labeled "BOL Performance" presents the predicted performance for the 705 mW nominal BOL cryogenic load noted in TABLE 1, together with BOL estimates of the cryocooler heat rejection temperature, assuming BOL cryocooler performance extrapolated from that of the

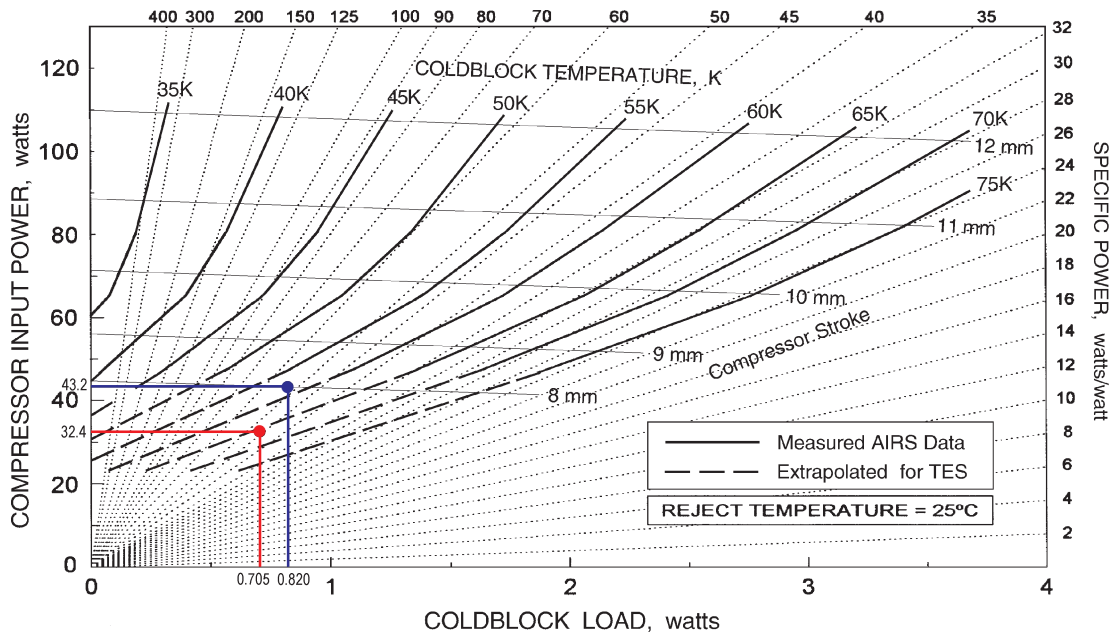
TABLE 2 Cryocooler sizing analysis for beginning-of-life (BOL) and end-of-life (EOL) conditions.

| Parameter | Units | BOL Perform. | EOL Perform. |
|--------------------------------------------|-------|--------------|--------------|
| Detector Temperature | K | 65 | 65 |
| Coldblock Load | mW | 705 | 820 |
| Coldblock ΔT to Detector | K | 2.6 | 3.0 |
| Coldblock Temperature (T_C) | K | 62.4 | 62.0 |
| Cooler Reject Temp (T_R) | K | 280 | 292 |
| T_C Correction for $T_R \neq 298$ K | K | 3.6 | 1.2 |
| T_C Correction for Cooler Wearout | K | 0 | -5.0 |
| Total Coldblock Temp Correction | K | 3.6 | -3.8 |
| Effective 298K Coldblock Temp (T_{EC}) | K | 66.0 | 58.2 |
| Cooler Specific Power at T_{EC} | W/W | 46 | 53 |
| Cooler Input Power (P) | W | 32.4 | 43.2 |
| Total Input Power (P/0.8 + 6) | W | 46.5 | 60.0 |

AIRS cryocooler presented in FIG 6 for 298 K heat rejection temperature. For heat rejection temperatures different from 25°C (298 K), the coldtip temperature for a given load and input power rises approximately 1 K for each 5 K increase in heat rejection temperature [1,2]. Note that this correction is included in the line " T_C Correction for $T_R \neq 298$ K."

The right most column of TABLE 2 represents the projected EOL performance of the TES cryocooler system. Note that the estimated difference between EOL and BOL performance is fairly significant. In this EOL projection, the end-of-life performance of the cryocooler due to wearout is modeled as a 5 K shift in the cryocooler load line, i.e. the EOL input power at 65 K is the same as the BOL input power at 60 K for the same cryogenic load. Based on lifetest experience to date, this 5 K degradation of performance at EOL appears to be a conservative, yet reasonable assumption.

TABLE 2 provides estimates of the needed power handling capacity of the TES cooler to meet the requirements of the instrument over its total life cycle, including representative end-of-life degradation. With the assumed end-of-life degradation, the performance of an

**FIGURE 6.** Projected thermal performance of the TES cooler based on extrapolating measured performance of the AIRS cooler [2] to lower power levels.

AIRS-like cooler easily satisfies the focal plane cooling requirement, and remains well within the nominal operating range of its compressor.

Cryocooler Development History

Based on a competitive solicitation and the predicted cryogenic loads as described above, TRW, Inc. of Redondo Beach, CA was contracted to develop the TES cryocoolers starting in April 1997. The TES cooler design was based heavily on TRW's pulse tube coolers delivered previously for JPL's AIRS instrument [2,3,4]. The primary difference is that the AIRS coolers are in a split configuration with the pulse tubes separate from the compressors, whereas the TES cooler has the pulse tube integrally mounted to the compressor similar to the TRW 6020 cooler [5] developed for the Air Force and flown on MTI. The TES pulse tube itself, and the compressor, are essentially identical to those of the AIRS cooler.

Following their successful development and testing at TRW [6], the TES flight coolers were delivered to JPL in November 1999 and have undergone extensive EMI testing, electrical integration testing, and system-level thermal performance testing as described below.

Cryocooler Thermal Performance

One of the key attributes of the AIRS and TES pulse tube cryocoolers is their excellent system-level thermal performance. FIGURE 7 illustrates the thermal-vacuum test setup used to characterize the thermal performance of the TES cryocoolers plus their drive electronics. The measured performance is presented in FIG 8 for a cooler heat rejection temperature of 25°C. Note that the flight coolers achieve approximately 38 W/W at 65 K, and 60 W/W at 55 K. This is about 5 W/W better than the AIRS coolers [2], probably due to the TES cooler's integral configuration (no transfer pipe) and lower ΔT between the pulse tube heat exchanger and the cooler's heat rejection interface. With the AIRS cooler, the pulse tube heat exchanger is widely separated from the coldplate interface and leads to the pulse tube running as much as 15°C above the cooler reject temperature [2].

Cryocooler Electronics Performance

Included in the performance data of FIG 8 is the efficiency performance of the TES cryocooler drive electronics. These electronics, top-center in FIG 7, are a key part of the overall TES cryocooler system and play a critical role in the overall cooler performance.



FIGURE 7. TES coolers and electronics during performance characterization testing at JPL.

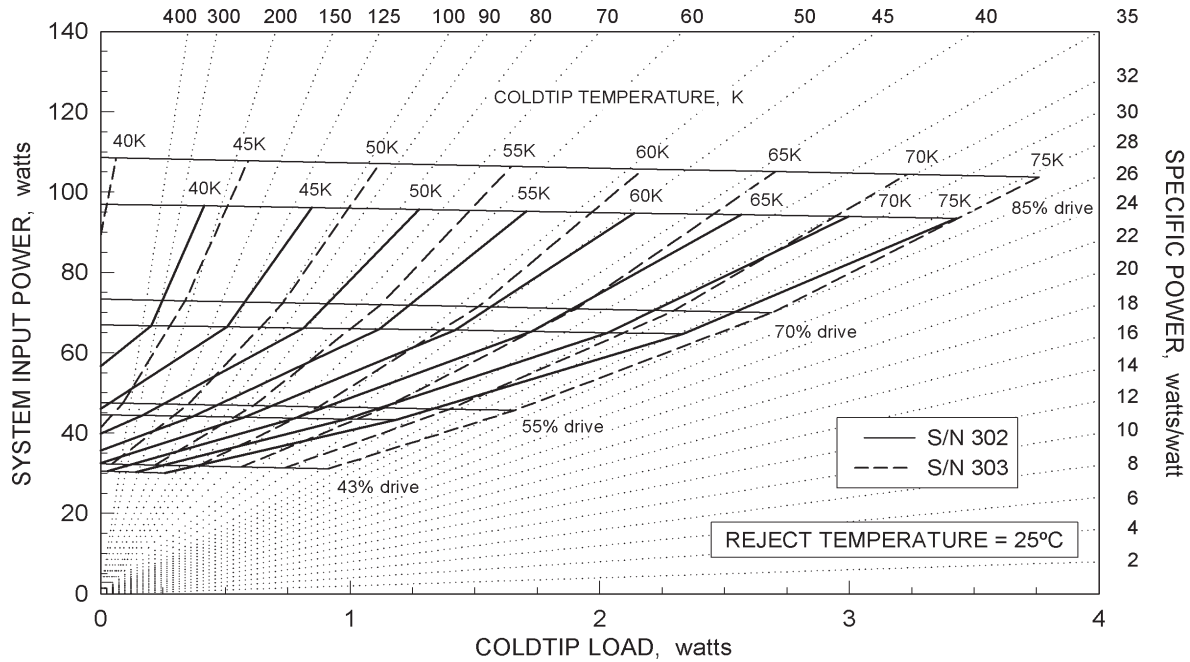


FIGURE 8. Measured performance of the TES flight cryocoolers with electronics.

In addition to being required to drive the compressors with high electrical efficiency, the cryocooler electronics are also required to perform a number of vital control, noise suppression, and data acquisition functions. These additional design attributes include:

- Full (dc-dc) transformer isolation from the input 29 Vdc power bus
- Built-in shorting relays to suppress cooler piston motion during launch
- Coolers synchronized in frequency at 44.643 Hz, and 90° phase shifted to allow input current leveling
- Very high degrees of EMI shielding, consistent with MIL-STD-461C
- Advanced feedforward vibration suppression system with accelerometer-based closed-loop nulling of the first 16 cooler vibration harmonics
- Closed-loop cooler coldblock temperature control (± 10 mK) via piston stroke control
- Built-in monitoring of cooler operational variables and performance data
- Built-in low-frequency stiction test drive waveform

Electromagnetic Interference

An important attribute of both the TES mechanical cooler and its electronics is generated EMI, particularly AC magnetic fields, radiated electric fields, and AC ripple current fed onto the 29 Vdc power bus. From an EMI point-of-view, the TES cooler design is nearly identical to that of the AIRS cooler as described in Ref 7. This includes the incorporation of special external mu-metal magnetic shielding to suppress AC magnetic fields from the mechanical compressor drive motors, and special EMI-suppression packaging of the electronics to control radiated electric fields. With these provisions and an external input filter, the TES cooler meets all EMI requirements including AC ripple currents on the input power bus. Excessive ripple current is a particularly demanding issue for linear coolers of the Oxford type because the motor drive current varies sinusoidally at the relatively low operating frequency of the cooler — 44.643 Hz for the TES cooler. For TES, the ripple current solution involves operation of the two coolers synchronously and 90° out of phase so that the peak ripple currents of one cooler fill in the troughs of the other cooler.

Cryocooler System Mass

In the final flight-hardware configuration, the mass of each TES mechanical cooler is 11.3 kg including 0.7 kg of added external mu-metal magnetic shields, and each electronics unit has a mass of 6.7 kg including a 0.4 kg contribution from the external input filter.

SUMMARY AND CONCLUSIONS

The TES cryocooler system development activity is a key part of the TES instrument development and focuses on developing and integrating the cryocoolers so as to maximize the performance of the overall instrument; it is a highly collaborative effort involving development contracts with Utah State University Space Dynamics Lab and TRW, and extensive characterization testing at JPL. To date, the overall cryocooler integration approach has been developed and refined, and the state-of-the-art TRW pulse tube cooler has demonstrated excellent thermal performance.

Results have been presented detailing the cryogenic loads on the cooler, and the overall cryocooler thermal performance margins achieved. Mass properties of the cryocooler system, and thermal properties of the developed coldlink assembly have also been presented.

ACKNOWLEDGMENT

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