AIRS Pulse Tube Coolers Performance Update – Six Years in Space

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) instrument pulse tube cryocoolers began operation 39 days after launch of the NASA EOS/AQUA on May 4, 2002. Designed with redundant cryocoolers (a primary and a backup), the instrument began operation using a single cooler to bear the load of both the detector and the non-operating, backup cooler. During the early months of the mission, contamination of the cryogenic surfaces led to increased cryocooler loads and the need for periodic decontamination cycles. A change in operating strategy was made in November 2002 to run both coolers simultaneously to both overcome the increased cryogenic contamination load and to allow operation at a much reduced compressor stroke level. This change led to the successful continuous operation of the coolers since November 2002 and the non-interruption of science data collection from the AIRS instrument.

After a brief review of the AIRS instrument cryogenic design, this paper presents detailed data on the highly successful continuous operation of the AIRS pulse tube cryocoolers and instrument thermal design over the past six years since the original turn-on in 2002. The data show that the cryogenic contamination reached an equilibrium level after a year of space operation and the cooler stroke required for constant-temperature operation has only increased by 2% since that time. This high level of operational stability not only indicates that the cooler contamination load has not increased, but also that the cryocoolers have maintained near-constant efficiency and that the instrument's thermal design has presented a near-constant heat rejection and parasitic-load environment. At this time AIRS maintains continuous operation in space providing important scientific data on Earth's atmospheric parameters.

INTRODUCTION

Launched in May 2002 aboard the NASA Aqua spacecraft, the AIRS instrument was designed to provide high-accuracy global air temperature data for application to climate studies and weather prediction. Fundamental to its operation is a precisely calibrated, high spectral resolution grating spectrometer operating between 3.7 to 15.4 μm. The cryogenically cooled spectrometer, shown in Fig. 1, uses a pair of TRW (now Northrup Grumman Space Technologies) 55 K pulse tube cryocoolers to cool the HgCdTe focal plane to 58 K.[1] Also shown is the ambient portion

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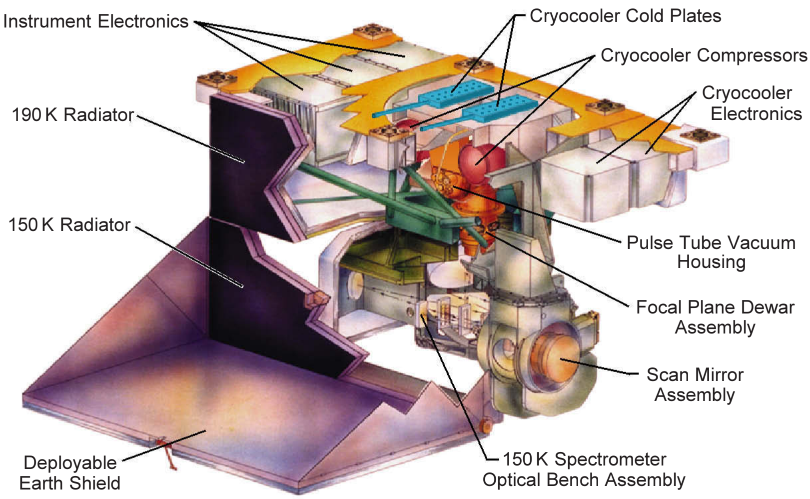

Figure 1. Overall AIRS instrument.

of the instrument, which contains the high power components including the instrument electronics and the cryocooler compressors and their electronics. The waste heat from these assemblies is removed by means of a spacecraft-provided heat rejection system (HRS) that utilizes variable conductance heat pipes and space-viewing radiators.

The cryogenic portions of the instrument are schematically illustrated in Fig. 2. At the top of the figure is the optical bench assembly (OBA) that houses the instrument's spectrometer optics and supports the focal plane dewar. The OBA is passively cooled to ~155 K using the 150 K/190 K two-stage cryogenic radiator shown in Fig. 1. The OBA is surrounded by multilayer insulation (MLI) blankets and a 195 K thermal radiation shield that is tied to the 190 K stage of the 2-stage radiator. Below the optical bench is the cryocooler pulse tube housing that supports the pulse tubes of the primary and redundant coolers. This housing is heat sunk to the spacecraft HRS and operates around 320 K when the coolers are operating, and 308 K when they are off.

Extensive characterization of the AIRS cryocooler performance was carried out during the cooler development and qualification testing phases at TRW and JPL.[2] This was followed by extensive characterization of the integrated cooler system at both the instrument and spacecraft level.[3]

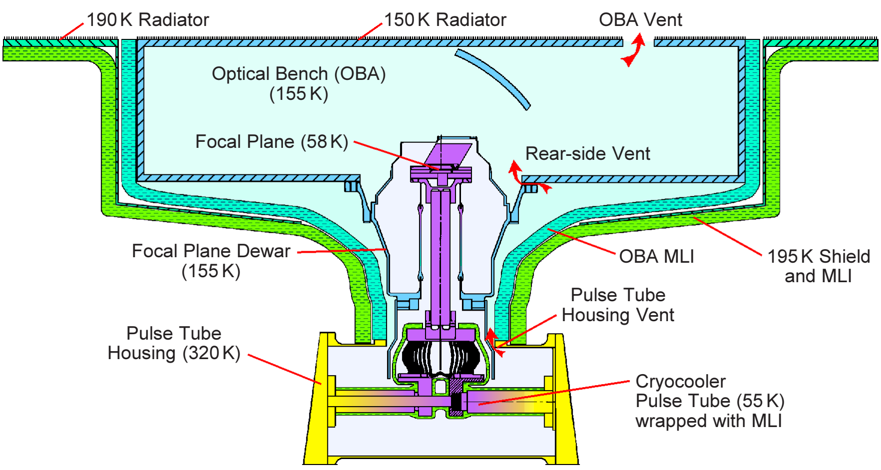

Figure 2. AIRS instrument cryogenic assemblies.

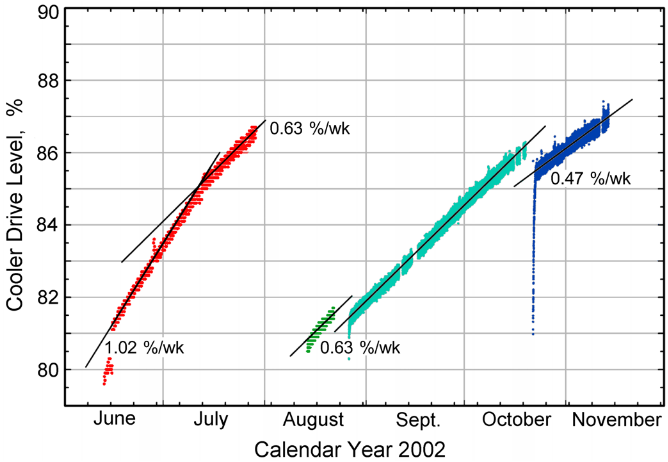

Figure 3. AIRS cryocooler drive increase during initial operation in 2002.

AIRS INITIAL IN-SPACE PERFORMANCE

The EOS Aqua spacecraft carrying AIRS was successfully launched on May 4, 2002 aboard a Delta II launch vehicle from Vandenberg Air Force Base, California. Following launch, the AIRS instrument was subjected to a 36 day decontamination period to allow time for the high residual moisture in the surrounding spacecraft structure and MLI to dissipate substantially from its as-launched condition. On day 39, both the primary and redundant (backup) coolers were operated sequentially to verify their health, and the measured cryogenic load was found to be within 25 mW of ground-test predictions.[3]

However, soon after, the load began to increase as shown in Fig. 3 due to contaminants adsorbing onto the instrument's optics and low emittance cryogenic surfaces. Prior to launch it was recognized that periodic decontamination cycles would be required over the life of the mission, and that this need would decrease with time.[4] Once instrument operation began, ice buildup was monitored daily by using the instrument itself to track the loss of IR transmissivity of the instrument's optics within the broad absorption features of water at 4.2 and 10.4 μm. Although IR transmission losses up to 50% can be tolerated in the science data, the cooler drive level was also increasing at a rate near 1%/week as shown in Fig. 3. At initial turn-on, the cooler's drive level was approximately 81%, and the maximum drive limit was conservatively set at 90% to achieve a long operating life. By day 70, the drive level had increased to 85%, with indications that the 90% limit would be reached by day 130.

AIRS Deicing Experience

As shown in Fig. 3, three deicing cycles were performed on the AIRS instrument over the summer and fall of 2002. During this time, ice formed in three regions: 1) on the optical surfaces within the OBA, 2) on the rear (outer surfaces) of the OBA, and 3) on the cryogenic pulse tube (PT) surfaces (~55 K) and MLI within the pulse tube housing. The rate of ice accumulation was driven by the relative water vapor pressures within these volumes coming from the instrument's composite structures and MLI. Discussion of the gettering rates and efficiency of the various deicing approaches is detailed in earlier papers.[4,5] Given the likely need for decontamination processes every few months in the future, and the high stress that these posed to the AIRS instrument, a decision was made to thoroughly examine alternative operating procedures that would increase the AIRS instrument science availability and minimize the thermal-cycle stressing of the focal plane and OBA.[5,6]

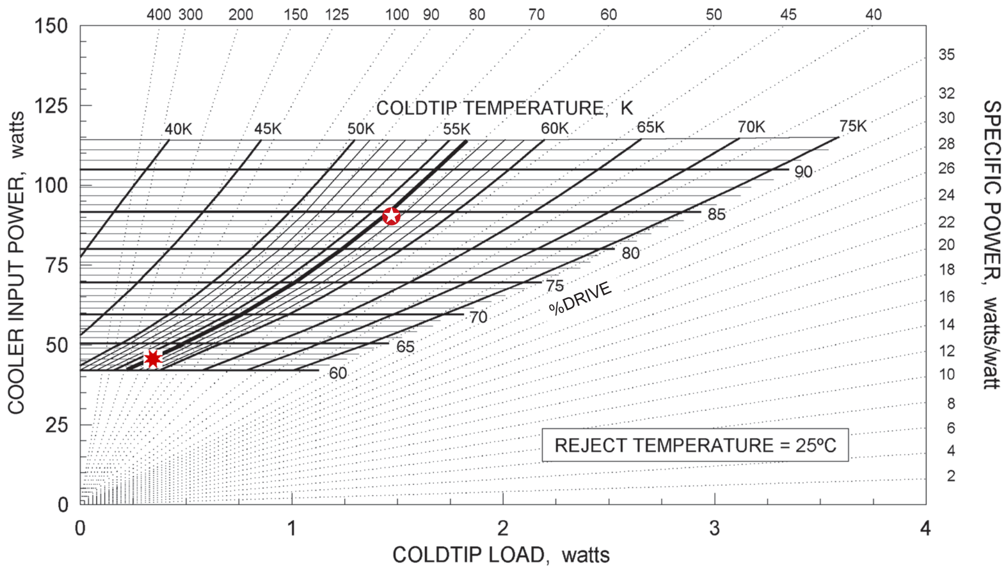

Figure 4. Cryocooler operating point in the AIRS instrument with single cooler operating ✪ and with load shared by two coolers in active redundancy mode ✷.

Implementing a Two-Cooler Operational strategy

Based on a through analysis of cooler and system reliability tradeoffs[6], a decision was made to run both coolers (the primary and the backup) simultaneously. This had two very positive attributes: 1) The increased capacity of two coolers could accommodate a higher level of icing and thereby lengthen the interval between required decontaminations, and 2) lengthening the deicing interval would cut down on thermal cycling of the instrument and focal planes, thus greatly reducing life-limiting stress on the instrument's critical subsystems.

From a spacecraft power perspective, the impact of two-cooler operation was determined to be minimal because nearly 50% of the AIRS cooler load is the parasitic load of the non-operating redundant cooler. When the second cooler is turned on, the total cooling load will drop in half and be shared by the two coolers. Thus, with two-cooler operation, each of the operating coolers will only be carrying one quarter of the cryogenic load, and only require a ~62% drive level. This is shown in Fig. 4. When the required spacecraft bus power is computed for the two-cooler operating mode, it is found to be comparable to that for a single cooler.

Based on the above considerations and with the agreement of the Aqua project, a two-cooler operational strategy was implemented on a trial basis on November 21, 2002 (day 201). Immediately upon switching to two-cooler operation, the drive levels dropped to 61% and 64% for coolers A and B, respectively. Over the next eight months after the switch to two-cooler operation, the drive level increased less than 2 percent, thus requiring no further deicing warm-ups. Based on this excellent performance trend, the two-cooler operational strategy was permanently adopted as the baseline for the instrument and has remained so ever since.

COOLER PERFORMANCE OVER THE TOTAL MISSION DURATION

Over the past 5½ years since two-cooler operation began in November 2002, the AIRS instrument has performed beyond expectations, with flawless cooler performance. This is graphically shown in Fig. 5, which indicates that the cooler drive level has only increased 2% over the past 5 years. And, most of that increase occurred back in 2003 due to a small level of continued icing at that point in time.

Cooler drive level is of course dependent on a large number of parameters including cryocooler icing load, cooler state of health (possible wearout), cooler heatsink temperature, and

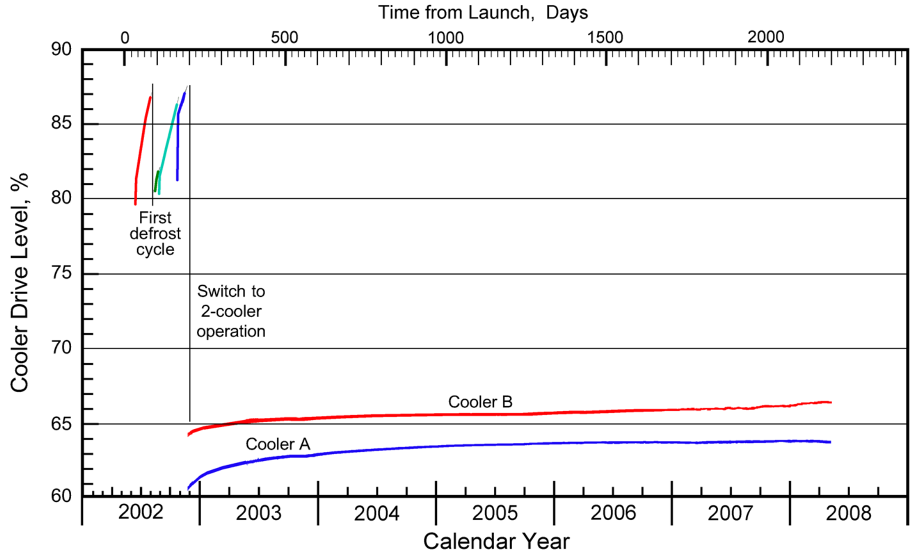

Figure 5. AIRS cryocooler drive level over the complete 6-year mission to date.

optical bench temperature. Maintaining the near-constant drive level shown in Fig. 5 not only implies that the cooler icing load stabilized out, but also that: 1) the cryocooler shows no visible signs of wear-out-related efficiency decrease, 2) the cooler's heatsink has not increased in temperature due to possible degradation of the spacecraft-provided VCHP/radiator system, and 3) the 155 K cryoradiator has not warmed and created a higher background radiation temperature for the FP coldlink assembly.

Let's examine these one at a time starting with cryocooler wearout.

Looking for Possible Cryocooler Wearout versus Time

In general, we have no direct means of assessing cryocooler wearout other than cooler drive current and drive level in the absence of any increased loads. However, as a likely independent indicator of the cooler's wearout health, one can also examine the relative level of cooler-generated vibration over the mission duration; it should be noted that the cooler's closed-loop vibration reduction system has been turned off during the entire flight. Compressor drive current and generated vibration are shown in Figs. 6 and 7. The transient behavior noted in late October 2003 was caused by a total instrument shutdown and recalibration associated with protection against a large solar flare event at that time. Because both compressors are bolted to a common structure, the vibration shown is essentially the sum for the two compressors. Note that the cooler current

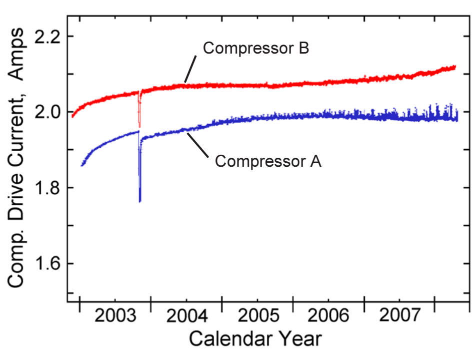

Figure 6. Cryocooler input current for compressors A and B over the course of the mission to date.

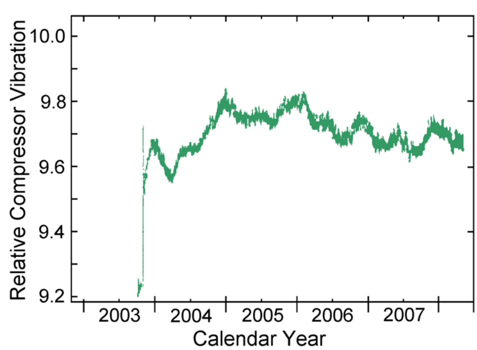

Figure 7. Relative level of vibration generated by AIRS cryocoolers over the mission to date.

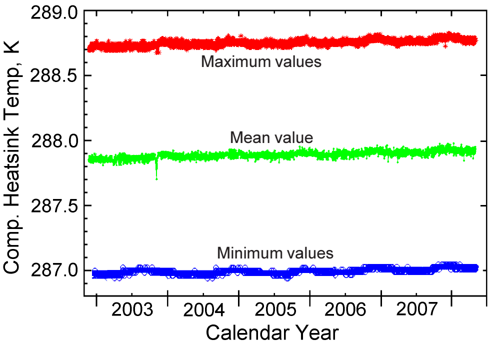

Figure 8. Long-term temperature stability of the AIRS cryocooler compressor heatsink.

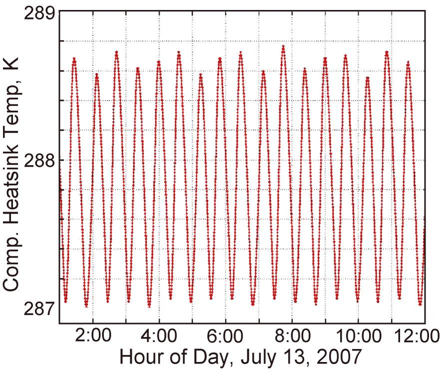

Figure 9. Short-term temperature fluctuation of the AIRS cryocooler compressor heatsink.

and self-induced vibration have maintained a near constant level over the total mission duration. Thus, there is essentially no indication of cooler wearout present after 6 years.

Cryocooler Temperature Stability

With respect to the cryocooler compressor's heat rejection system, Fig. 8 shows that the HRS has maintained an extremely stable long-term heatsink temperature for the coolers, with the mean varying less than 0.1°C over the six-year mission. On a shorter term, the HRS temperature control algorithm gives rise to a sinusoidal heatsink temperature swing of about 1.7°C peak-peak as shown in Fig. 9. The envelop of this fluctuation is also displayed in Fig. 8 as the maximum and minimum curves.

The influence of this heatsink-temperature ripple on the cryocooler's coldtip temperature is taken out by the cryocooler's closed-loop temperature control system. The resulting excellent stability of the focal plane temperature is shown in Fig. 10. Note that the average FP temperature has only increased about 10 mK over the past 4 years. This long-term drift is well within the long-term stability of the temperature sensors. The cryocooler coldtip temperature is controlled from its own temperature sensor, and thus shows no change over the course of the mission.

Cryoradiator Temperature Stability

A key driver for the cryocooler's coldlink assembly cryogenic loads is the ~155 K background radiation temperature of the optical bench assembly (OBA). Having stable cryogenic loads implies that the OBA temperature also had to be highly stable over the AIRS mission. This is confirmed in Fig. 11, which shows that the mean temperature of the 150 K radiator has been

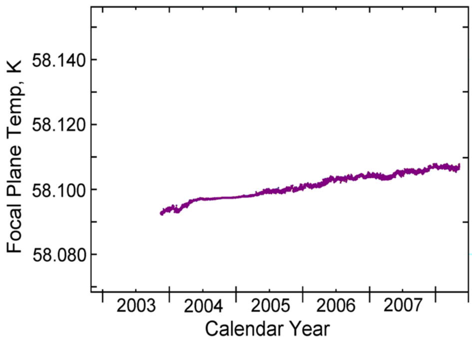

Figure 10. AIRS mean focal plane temperature as a function of time over mission duration.

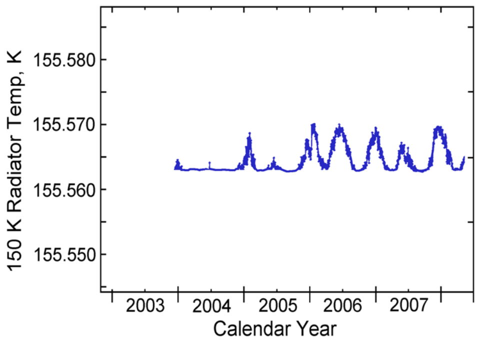

Figure 11. Long-term temperature stability of the AIRS 150 K radiator and OBA.

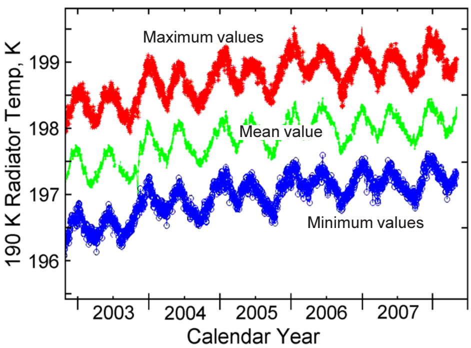

Figure 12. Long-term temperature stability of AIRS 190 K radiator.

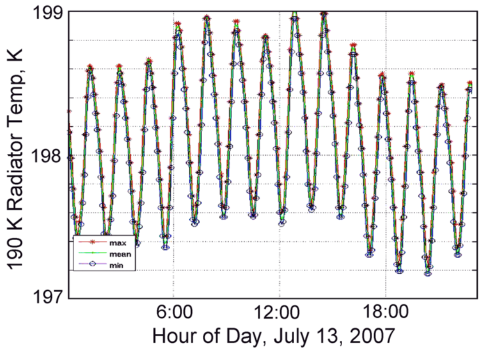

Figure 13. Short-term temperature fluctuations of AIRS 190 K radiator.

constant over the mission to within 5 mK; even the peak-to-peak temperature fluctuation was only 25 mK. What variation there is appears to be mostly driven by seasonal orbit variations, not by long-term aging.

Similarly, the 190 K first-stage radiator stayed very constant — in this case varying by about 1K over the mission duration as shown in Fig. 12. The 190 K radiator also prominently displays the seasonal environmental variations noted to a lesser degree in the 150 K radiator. Figure 13 presents a 24-hour example of the short-term influence of AIRS's Earth orbit on the 190 K radiator; the envelope of these fluctuations shows up as the max and min curves in Fig. 12.

SUMMARY

Over the past six years the AIRS instrument has performed beyond expectations, with flawless cooler performance since the start of two-cooler operation in November 2002. Also, valuable data have been acquired in the area of on-orbit contamination and the long-term stability of AIRS's various thermal control systems. With respect to the level of icing, it slowed and eventually reached equilibrium after about a year in orbit. Over the past five years, the stroke level of the cryocoolers has only increased by one percent. Some of this slowing may be saturation of the effect of the ice on surface emittances, and some due to the fall-off in water vapor as the spacecraft and instrument reduce their outgassing. For reference, no decontamination warm-up of the AIRS instrument has occurred since the thorough August 2002 deicing procedure was conducted.

On a larger scale, this superb instrument performance speaks extremely well for the robustness of the TRW pulse tube cryocoolers and the thermal control systems of the AIRS instrument and NASA Aqua spacecraft. As a result, the AIRS instrument maintains continuous operation in space providing important scientific data on Earth's atmospheric parameters, and it is expected to do so for the foreseeable future.

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