# AIRS Pulse Tube Coolers Performance Update – Twelve Years in Space

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## ABSTRACT

The Atmospheric Infrared Sounder (AIRS) instrument began operation 39 days after its May 4, 2002 launch into Earth orbit. 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 a change in operating strategy 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, with minimal interruption of science data collection from the AIRS instrument over the past 11½ years.

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 twelve years. The data show that early cryogenic contamination reached an equilibrium level after a year of space operation and that the cooler stroke required for constant-temperature operation has only increased a few percent since that time. This high level of operational stability not only indicates that the cryocoolers have maintained near-constant efficiency, but also 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 climate studies and weather prediction. Since that time AIRS has expanded its data gathering to include creating global, three-dimensional maps of atmospheric temperature and humidity, cloud amounts and heights, greenhouse gas concentrations, and many other atmospheric phenomena.

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 Northrop Grumman Aerospace Systems—NGAS) 55 K pulse tube cryocoolers to cool the HgCdTe focal plane to 58 K.[1] Also shown is the ambient portion of the instrument, which contains the high power components including the instrument electronics and the

*Cryocoolers 18,* edited by S.D. Miller and R.G. Ross, Jr.

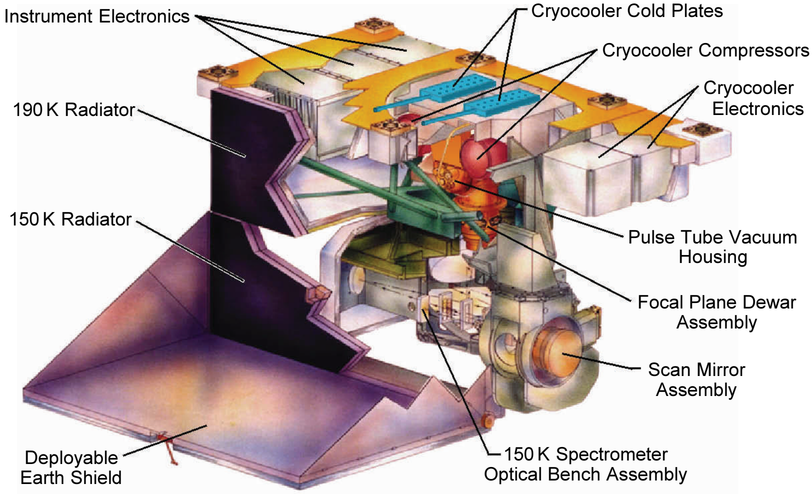


**Figure 1.** Overall AIRS instrument.

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 connected to space-viewing radiators.

The cryogenic portions of the instrument are schematically illustrated in Fig. 2. At the bottom 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. Above 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.

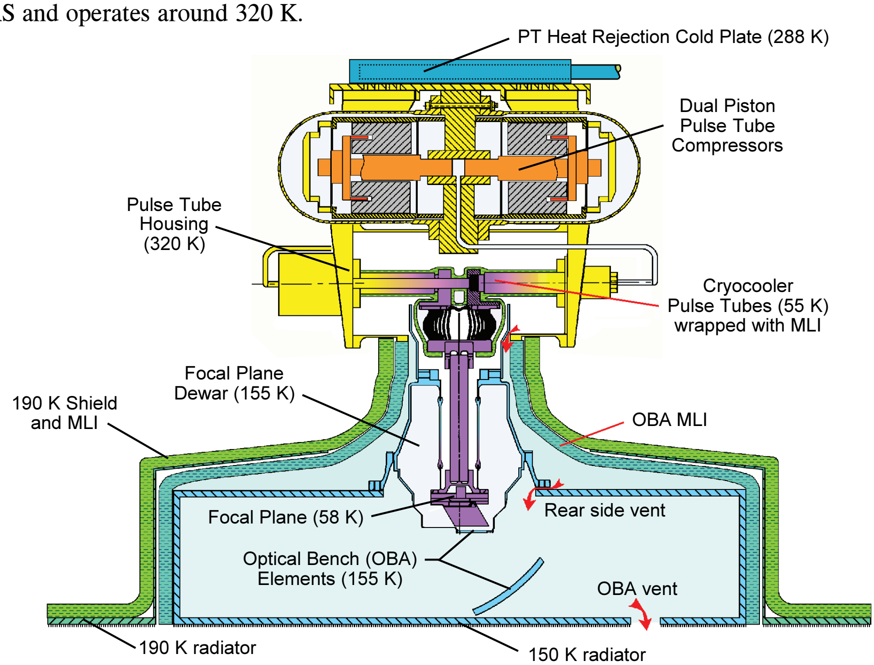


**Figure 2.** Schematic of AIRS instrument cryogenic assemblies.

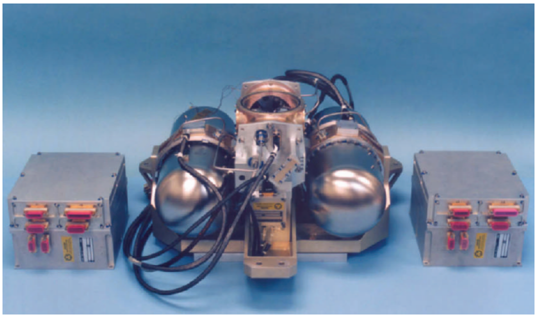

**Figure 3.** AIRS flight cryocoolers and electronics.

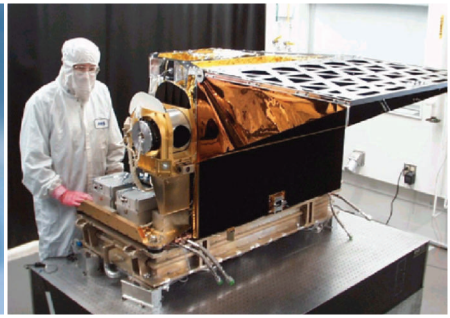

**Figure 4.** AIRS flight instrument.

Extensive performance characterization of the AIRS flight cryocoolers (shown in Fig. 3) was carried out during the cooler development and qualification testing phases at TRW (now NGAS) and at JPL.[2] This was followed by extensive characterization of the integrated cooler system at both the instrument (shown in Fig. 4) and at the spacecraft level.[3]

Figure 5 presents a performance map of the measured cooler performance. Positioned on the map are predictions of the Beginning of Life (BOL) operating point of the operating AIRS cooler in orbit and the maximum operating-power point that defines a conservative "not to be exceeded" safe drive level of 90%. The combination of these two points provided for a 35% growth in the cooling load from BOL to the EOL. Before the EOL point is reached, a load reduction decontamination event would have to be carried out. Prior to launch it was recognized that periodic decontamination cycles would be required over the life of the mission to remove high-emissivity deposits (principally water ice) from the pulse tubes and critical coldlink surfaces.[4]

## 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

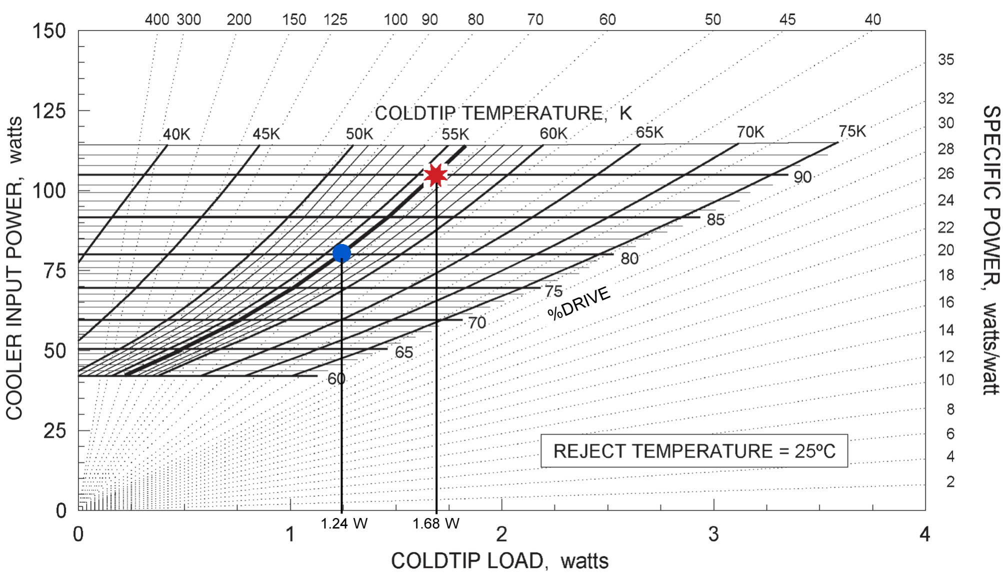


**Figure 5.** AIRS Cryocooler Performance map with 80%-drive nominal Beginning of Life (BOL) operating point (●) and 90%-drive nominal End of Life (EOL) maximum operating limit (✱) noted.

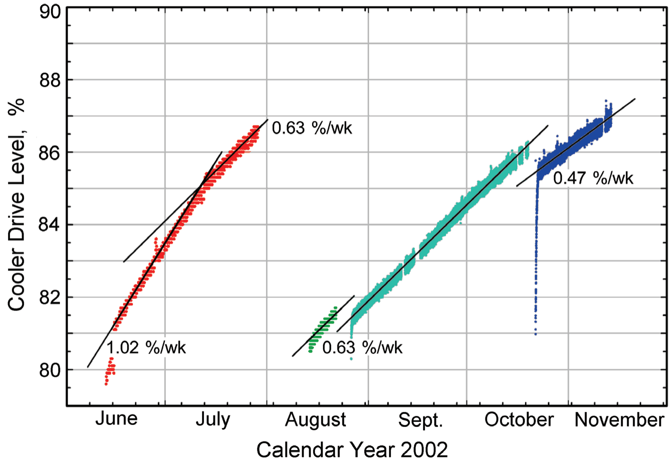


**Figure 6.** AIRS cryocooler drive increase during initial operation in 2002.

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. 6 due to contaminants adsorbing onto the instrument's optics and low emittance cryogenic surfaces. 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. 6. At initial turn-on, the cooler's drive level was approximately 81%, closely matching the predictions shown earlier in Fig. 5. However, 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. 6, 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]

## Implementing a Two-Cooler Operational strategy

Based on a thorough 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.

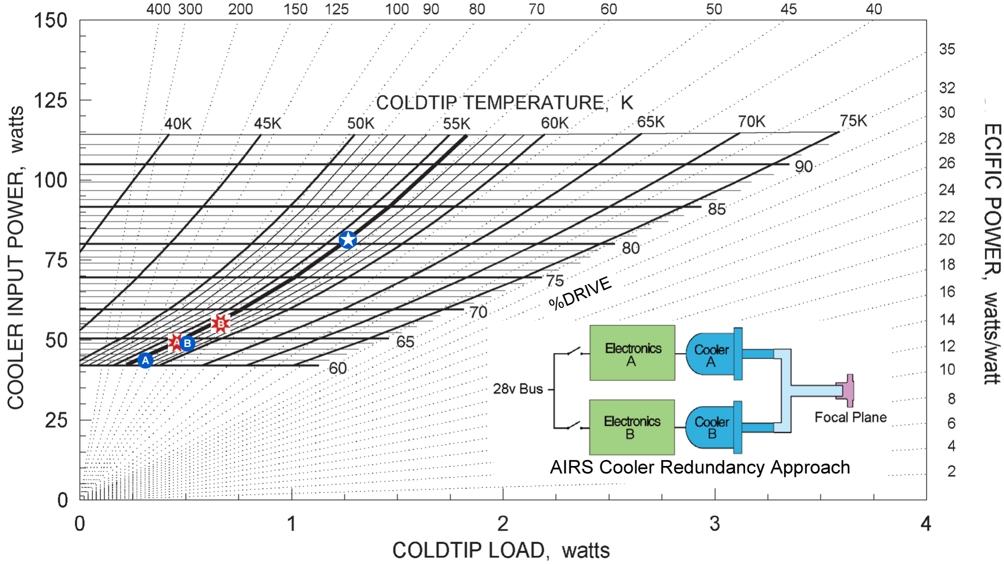


**Figure 7.** Cryocooler operating points on cooler performance diagram: ✪ = Beginning of life operating point with one cooler operating; Ⓐ,Ⓑ = Cooler A and B initial operating points after switching to two-cooler operation in November 2002; A,B = Cooler A and B present operating points in May 2014, after running 24/7 in orbit for 12 years.

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. 7. 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, as shown in Fig. 7. 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 11½ 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 Figs. 7 and 8, which indicate that the cooler drive level has only increased 2-3% over the past 11 years. And, much of that increase occurred back in 2003 due to a small level of continued icing at that point in time. As noted in Fig. 8, the drive level of cooler B has increased a bit more than that of cooler A, which hasn't increased at all in the last nine years.

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 optical bench temperature. Maintaining the near-constant drive level shown in Fig. 8 not only implies that the cooler icing load stabilized out, but also that: 1) the cryocoolers show minimal 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

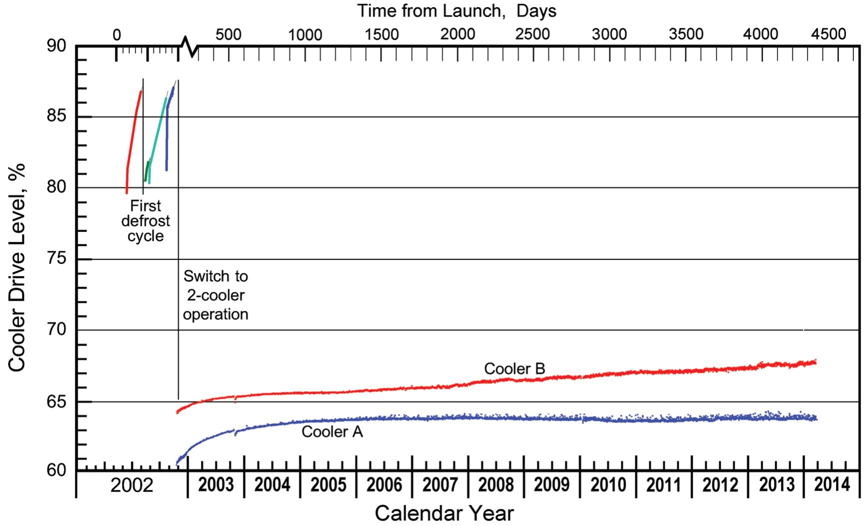


**Figure 8.** AIRS cryocooler drive level over the complete 12-year mission to date.

155 K cryoradiator has not warmed and created a higher background radiation temperature for the focal-plane coldlink assembly. Each of these possibilities is now examined 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. Compressor drive current and generated vibration ($mG_{rms}$ in dB re preamp 0-dB level) are shown in Figs. 9 and 10. When both coolers are in standby mode (zero stroke), the measured vibration level is -2 dB due to residual instrument and spacecraft vibration sources. It should be noted that the cooler's closed-loop vibration reduction system has been turned off during the entire mission (i.e. for the data in Fig 10).

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 same for the two compressors. Note that the cooler drive current and self-induced vibration have only increased slightly (0.5 dB) over the total mission duration, corresponding to the slight stroke increase of cooler B. These are quite small considering the 12 years of 24/7 operation.

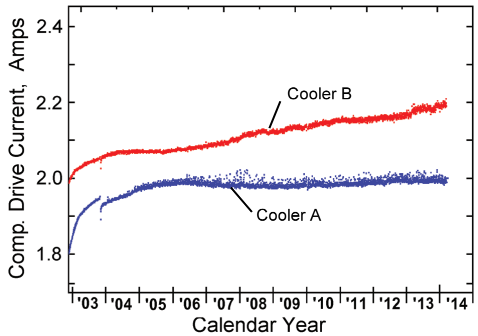


**Figure 9.** Cryocooler input current for compressors A and B over the course of the mission to date.

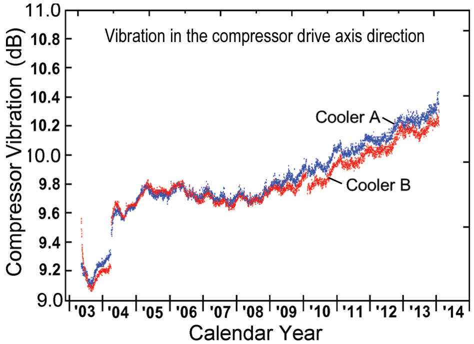


**Figure 10.** Compressor accelerometer output level over the mission to date (scaled mV).

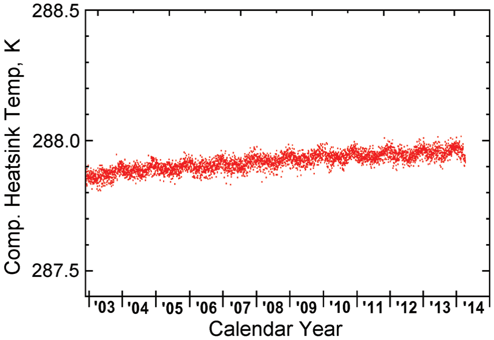


**Figure 11.** Long-term average temperature of the AIRS cryocooler compressor heatsink.

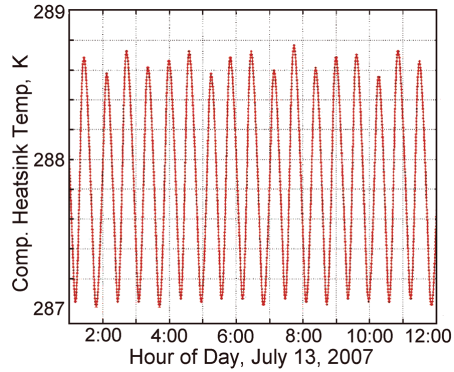


**Figure 12.** Short-term temperature fluctuation of the AIRS cryocooler compressor heatsink.

## Cryocooler Temperature Stability

With respect to the cryocooler compressor's heat rejection system, Fig. 11 shows that the HRS has maintained an extremely stable long-term heatsink temperature for the coolers, with the mean varying less than 0.1 K over the 12-year mission to date. On a shorter term, the HRS's response to orbital heat load variations gives rise to a sub- hourly sinusoidal heatsink temperature swing of about 1.7 K peak-peak as shown in Fig. 12.

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. 13. Note that the average FP temperature has been highly stable, with just a 10 mK increase from 2003 to 2009. Remarkably, the focal-plane temperature returned to its original level after a 10-day instrument shutdown in January 2010 to resolve an instrument-heater-circuit SEU event. Although, this response is indicative of shedding of a built-up FP-to-cooler load during the shutdown, this is difficult to justify given that the cooler remained ON, maintaining an FPA temperature of 65 K during this 2010 event.

## Cryocooler Electronics Temperature Stability

Although the cryocooler's cold-tip temperature is pretty much independent of the cooler's electronics temperature, it is useful to examine the electronics temperature stability in terms of the overall temperature stability of the AIRS instrument. As noted in Fig. 14, the electronics has also been subjected to a very stable thermal environment with long-term variations of less than 0.25°C. This is quite similar to the compressor heatsink temperature stability noted in Fig. 11.

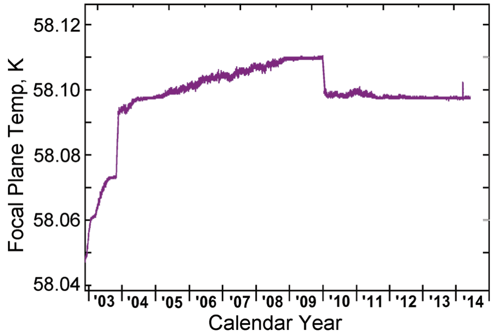


**Figure 13.** AIRS mean focal plane temperature as a function of time over mission duration.

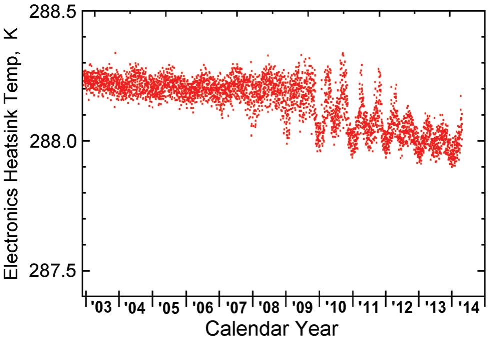


**Figure 14.** Long-term temperature stability of the AIRS cooler electronics heatsink.

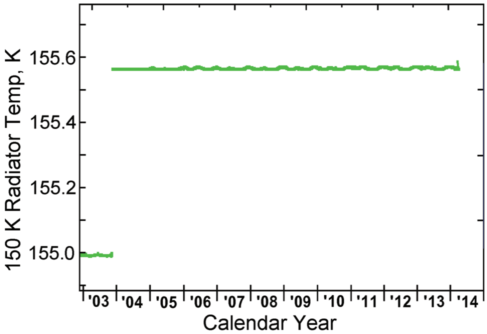


**Figure 15.** Long-term temperature stability of the AIRS 150 K radiator and OBA.

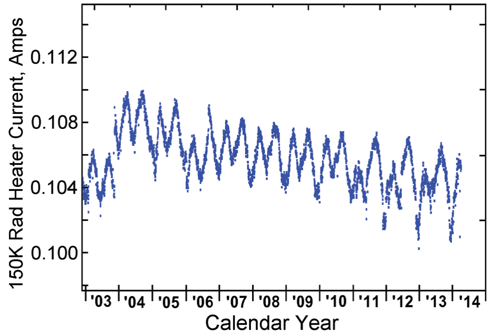


**Figure 16.** Long-term stability of the AIRS 150K radiator temperature-control heater current

## 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. 15, which shows that the mean temperature of the 150 K radiator has been constant over the mission to within 5 mK. It should be noted, however, that credit for this temperature stability goes to the active heater-control of the AIRS 150 K radiator temperature. The long-term drive current for this heater control, shown in Fig. 16, suggests that the temperature control is mostly driven by seasonal orbit variations, not by long-term aging.

Similarly, the 190 K first-stage radiator temperature has stayed very constant over the mission — in this case varying by about 1K over the mission duration as shown in Fig. 17. The 190 K radiator also prominently displays the seasonal environmental variations noted to a lesser degree in the 150 K radiator. Figure 18 presents a 24-hour example of the short-term influence of AIRS's Earth orbit on the 190 K radiator; these are superimposed on the long-term average temperature shown in Fig. 17.

## SUMMARY

Over the past twelve 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 11 years, the stroke level of the cryocoolers has only increased by 1-2 percent. Some of this slowing may be saturation of

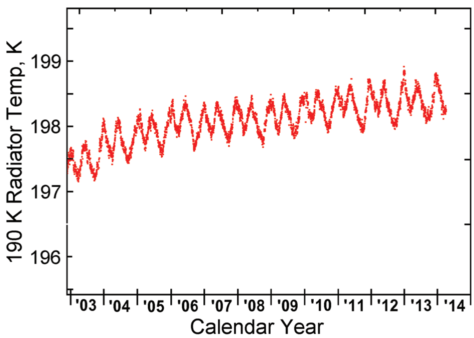


**Figure 17.** Long-term average temperature of AIRS 190 K radiator.

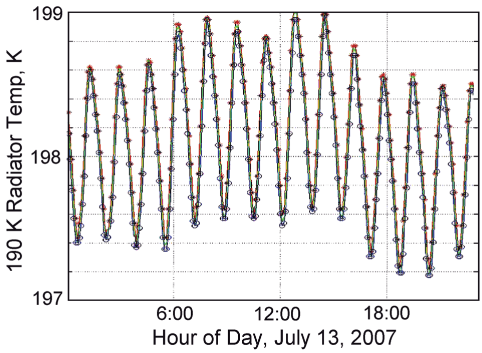


**Figure 18.** Short-term temperature fluctuations of AIRS 190 K radiator.

the effect of the ice on surface emittances, and some may be 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. Most recently, in March 2014, another single event upset occurred in the cooler's electronics when passing through the South Atlantic Anomaly. This caused the cooler to be shut down for approximately 7 days. However, upon restarting the coolers, the coolers and instrument returned to their nominal operating point for the past few years.

On a larger scale, this superb instrument performance speaks extremely well for the robustness of the TRW (NGAS) 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.[7]

## ACKNOWLEDGMENT

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology; it was sponsored by the NASA EOS AIRS Project through an agreement with the National Aeronautics and Space Administration.

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7. See the AIRS instrument web site for up-to-date descriptions of the science returns from the AIRS instrument and its science team members: http://www-airs.jpl.nasa.gov/