AIRS Pulse Tube Coolers Performance Update – Twenty 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. It has now completed over twenty years of successful operation using a pair of Northrop Grumman pulse tube cryocoolers to cool its IR detectors. 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 nonoperating, backup cooler. However, 6 months after launch, a change in operating strategy was made to run both coolers simultaneously. This change led to the successful continuous 24/7 operation of both coolers over the past 19½ years.

After a brief review of the AIRS instrument cryogenic design, detailed data are presented on the highly successful continuous operation of the AIRS pulse tube cryocoolers and instrument thermal design. A valuable feature has been the extremely stable temperatures provided to the instrument over its lifetime. This high level of operational stability not only indicates that the cryocoolers and thermal design have maintained near-constant efficiency, but the stability has also provided enormous benefits to the science data in terms of tracking long-term global changes.

During its 20-year lifetime, the instrument itself has evolved in its mission scope and expanded its data gathering well beyond its original role as just a temperature sounder measuring global daily air temperature. It now generates a wealth of data not only on global air temperatures, but also on global and local greenhouse gas distributions. For example, AIRS can detect carbon monoxide emissions from large forest fires and can follow their giant plumes as the gas moves across the planet. At this time the cryocoolers continue in 24/7 operation and the AIRS instrument continues to generate daily scientific data on Earth’s atmospheric parameters.

AIRS CRYOGENIC INSTRUMENT DESIGN

The core of AIRS's scientific operation is a precisely calibrated, high spectral resolution grating spectrometer operating between 3.7 to 15.4 μm. By resolving the spectra of light reflected from different parts of the Earth's atmosphere, AIRS is able to determine the temperature of the atmospheric air as a function of height above the ground over the entire surface of the globe twice daily. By looking at different spectral signatures, AIRS data can also be used to create global, three-dimensional maps of atmospheric humidity, cloud amounts and heights, greenhouse gas concentrations, and many other atmospheric phenomena.

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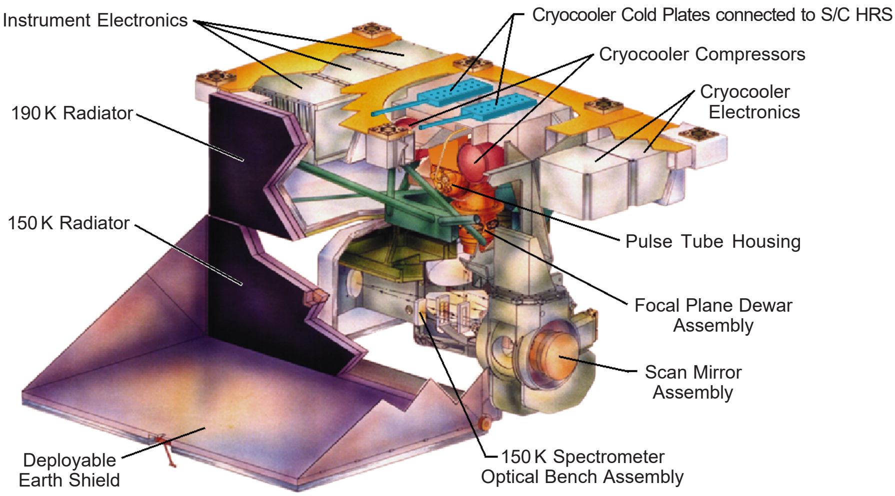

Figure 1. Overall AIRS instrument.

Figure 1 provides an overview of the overall instrument design including its optical bench mounted spectrometer, which runs at 150 K, the 150 K and 190 K two-stage radiators used to cool the optical bench, the focal plane dewar that contains the HgCdTe focal plane that is cooled to 58 K by a pair of 55 K pulse tube cryocoolers, and the room-temperature electronics platform, which is temperature-controlled by a spacecraft-provided heat rejection system (HRS) that utilizes variable conductance heat pipes connected to space-viewing radiators.[1]

The integration of the pair of TRW (now Northrop Grumman Space Systems—NGSS) 55 K pulse tube cryocoolers with the optical bench and focal-plane dewar assembly is schematically illustrated in Fig. 2. At the bottom of the figure is the 155 K optical bench assembly (OBA) that houses the instrument's spectrometer optics and supports the focal plane dewar. The OBA is

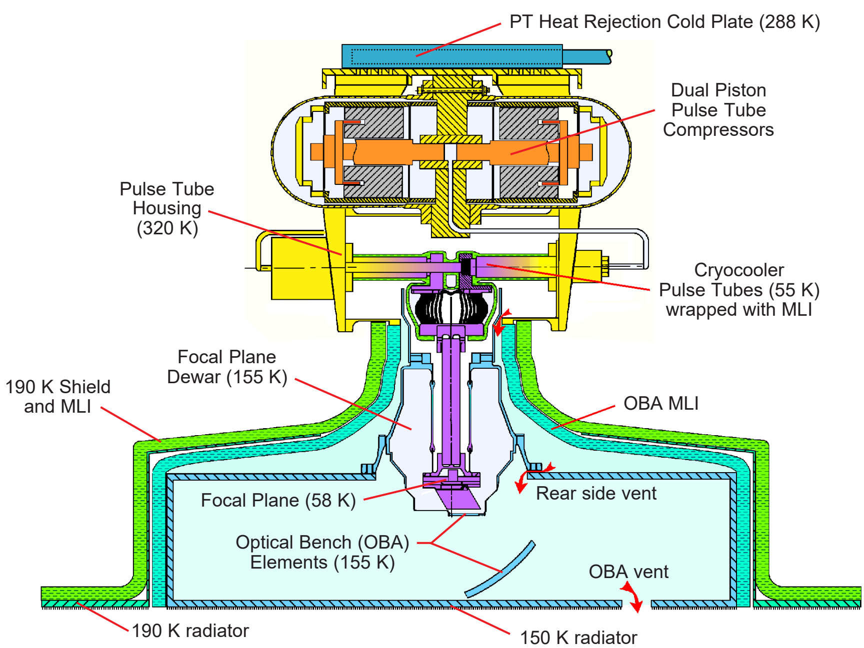

Figure 2. Schematic of AIRS instrument cryogenic assemblies.

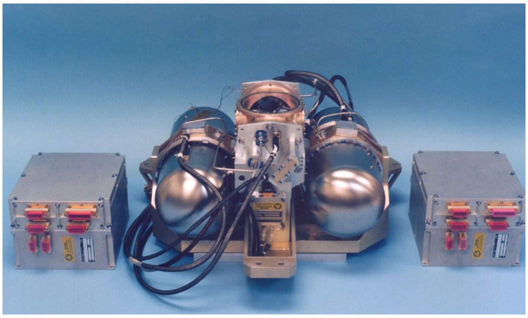

Figure 3. AIRS flight cryocoolers and electronics.

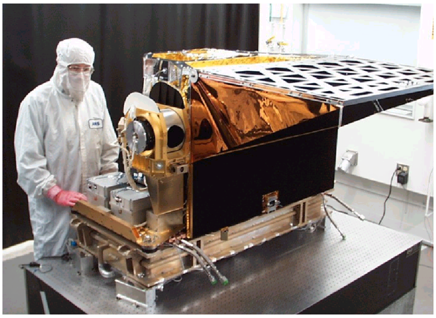

Figure 4. AIRS flight instrument.

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 overall cryocooler frame structure, shown in Fig. 3, which is temperature controlled by the spacecraft HRS and operates around 320 K. Figure 4 provides an overview of the overall flight AIRS instrument during its final assembly and integration.

INITIAL IN-SPACE THERMAL & CRYOGENIC PERFORMANCE

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

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. 5 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. 5. This required

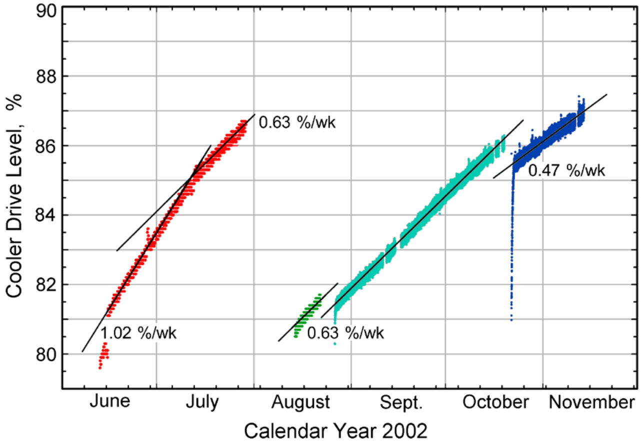

Figure 5. AIRS cryocooler drive increase during initial operation in 2002.

three deicing cycles to be performed over the summer and fall of 2002 to maintain the coolers below their 90% stroke flight-allowable limit. 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 this thermal cycling imposed on the instruments focal plane arrays and OBA, a decision was made to thoroughly examine alternative operating procedures that would increase the AIRS instrument science availability and minimize the thermal-cycle stressing.[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 to accommodate a higher level of icing, lengthen the interval between required decontaminations, and greatly reduce the thermal cycling of the instrument's critical subsystems. The impact on the instrument power of two-cooler operation was determined to be minimal because nearly 50% of the AIRS cooler load is the parasitic load of the nonoperating redundant cooler. When the second cooler is turned on, the total cooling load drops in half and is shared by both coolers. Thus, with two-cooler operation, each of the operating coolers is only carrying one quarter of the cryogenic load, and only requires a very low drive level. Based on these considerations, two-cooler operation was implemented on a trial basis on November 21, 2002 (day 201) and was permanently adopted as the baseline for the instrument a few months later.

COOLER PERFORMANCE OVER THE TOTAL MISSION DURATION

Figure 6 notes that, immediately upon switching to two-cooler operation, the drive levels of the two coolers dropped to 61% and 64%, respectively. Also shown in Fig. 6 are the present drive levels of the coolers after 20 years operation in space —only marginally higher than the levels in November 2002. Figure 7 plots the actual year-by-year cooler drive levels over the total AIRS mission. Note that no further deicing warm-ups were ever required.

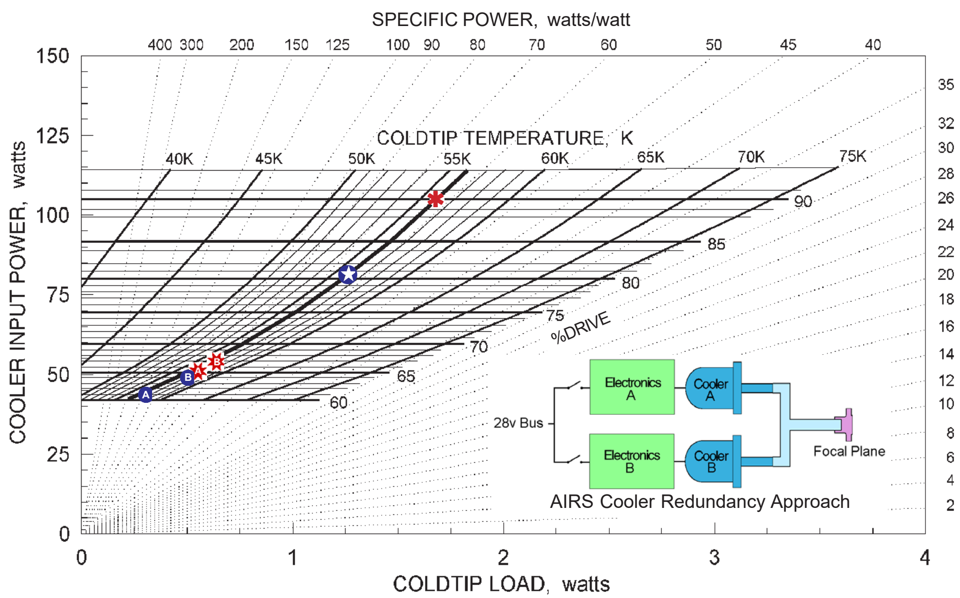

Figure 6. Cryocooler operating points on cooler performance diagram: ✪ = Beginning of life operating point with one cooler operating; ✱=Maximum stroke safe operating limit; Ⓐ Ⓑ = Cooler A and B initial operating points after switching to two-cooler operation in November 2002; A, B = Cooler A and B present operating points in May 2022, after running 24/7 in orbit for ~20 years.

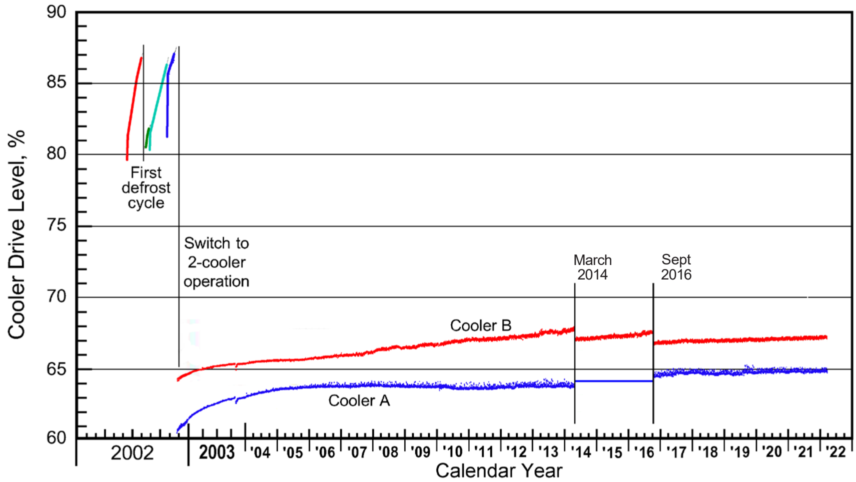

Figure 7. AIRS cryocooler drive level over the complete 20-year mission to date.

Over the past 19½ years since two-cooler operation began, the AIRS instrument has performed beyond expectations, with near flawless performance, except for the anomalous period from March 2014 to September 2016 as noted in Fig. 7. On March 22, 2014 an electronic event (SEU) took place that tripped out Cooler A. Although the cooler was restarted successfully, digital communication between Cooler A and the instrument was found to be inoperative a few days later. Both coolers continued to operate with normal cooling levels, but cooler A was essentially operating blind in a fixed-stroke operating mode. This required that cooler B manage the focal plane temperature control, which it did. After lengthy deliberations and some failed attempts at commanding the cooler, it was decided to allow the coolers to proceed in this mode, as the focal plane temperature was nominal and there were currently no adverse effects on AIRS's science data quality. On September 27, 2016, after a couple of years of operating in this mode, another electronic event tripped out the coolers and provided an opportunity to safely power-cycle Cooler A. Like with many electronic devices, power cycling solved the communication issue, and both cooler's electronics have been functioning normally ever since.

Figure 7 shows that despite this electronics anomaly, the mechanical coolers have continued to operate flawlessly with the cooler drive level required to maintain the focal plane temperature at 55 K only increasing 2-3% over the past 19 years. And, much of that increase occurred back in 2003 due to a small level of continued icing at that point in the mission. As noted in Fig. 7, the drive level of cooler B initially increased a bit more than that of cooler A, but both have been remarkably stable in recent years.

Operational Tripouts and Electronic Glitches

Before further examining the excellent long-term thermal performance of the pulse tube coolers, it is useful to also address the long-term electrical stability of this first-generation TRW cryocooler system drive electronics. This was an all-new design developed specifically for the AIRS cryocoolers, and lacked many robustness features and input-current ripple suppression features added to more recent versions of the Northrop Grumman cooler drive electronics.[7, 8]

One weakness that surfaced early in this electronics was a sensitivity to single event upsets (SEUs) in some of the safety protection circuits (over current and stroke), when exposed to heightened radiation levels, such as when passing through the South Atlantic Anomaly. This led to one or more instances of cooler safety-system tripouts due to noise induced out-of-bound parameter values. In each instance, the electronics was safely reset and cryocooler operation continued stably for a few years until a another glitch occurred. The most prominent glitch was the 2014 to 2016 loss of Cooler A communication between March 2014 and September 2016.

In the end, the glitches have been a periodic aggravation, but had no lasting impact on the science quality. However, they did surface important design weaknesses that lead to thoughtful design improvements to the follow-on generations of Northrop Grumman cooler electronics.[7, 8]

EXAMINING THE LONG-TERM PERFORMANCE TRENDS OF THE COOLERS

Looking for Possible Cryocooler Wearout versus Time

Cooler drive level, as shown in Fig. 7, is essentially a measure of commanded piston stroke level, and it is selected by the cooler's drive electronics to maintain the cooler's cryogenic-load setpoint temperature near 55 K. Thus, it is directly affected by the cryo thermal load on the cooler, any changes in cryocooler efficiency as affected by wearout or changes in cooler heatsink temperatures, and any changes in thermal parasitic loads as driven by, for example, the optical bench temperature. Thus, it is dependent on a large number of parameters. Maintaining the near-constant drive level shown in Fig. 7 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 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.

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. 8 and 9. 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 9).

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 very similar for the two compressors. Note that the cooler drive current and self-induced vibration have minimal change (<0.5 dB) over the total mission duration. These are quite small considering the 20 years of 24/7 operation, and suggest that no significant cooler wear-out is occurring.

Cryocooler Temperature Stability

With respect to the cryocooler compressor's heat rejection system, Fig. 10 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 20-year mission to date. On a shorter term, the HRS's

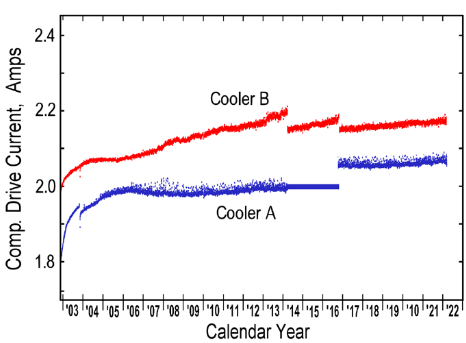

Figure 8. Cryocooler input current for compressors A and B over the course of the mission to date.

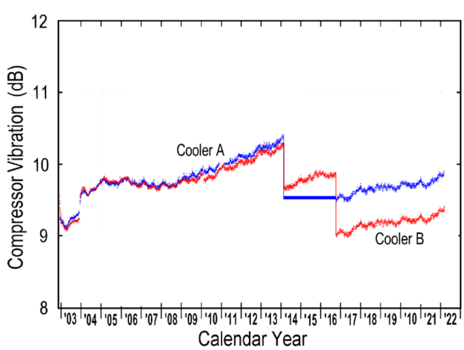

Figure 9. Compressor accelerometer output level over the mission to date.

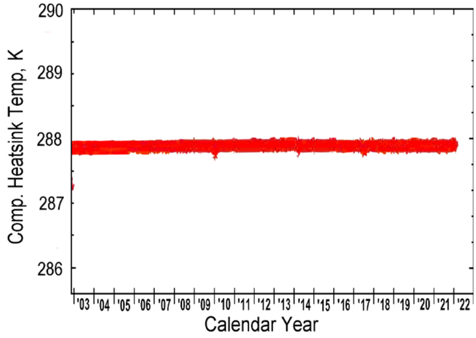

Figure 10. Long-term average temperature of the AIRS cryocooler compressor heatsink.

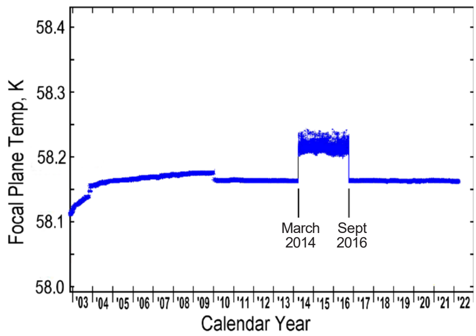

Figure 11. AIRS mean focal plane temperature as a function of time over mission duration.

response to orbital heat load variations gives rise to a sub-hourly sinusoidal heatsink temperature swing of about 1.7 K peak-peak that is superimposed on this average.[9,10]

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. 11. Note that the average FP temperature has been highly stable, with just a 0.1 K shift during the 2014-2016 anomaly when the temperature control loop of cooler A was inoperative. After that anomalous event, the focal-plane temperature returned to its original level and has been stable ever since.

Cryocooler Electronics Temperature Stability

Although the cryocooler's cold-block 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. 12, the electronics has also benefitted from a very stable thermal environment with long-term variations of less than 0.25 K. This is quite similar to the compressor heatsink temperature stability noted in Fig. 10 and is very desirable from the point-of-view of minimizing long-term electronic part thermal-cycle fatigue or parameter value drift with temperature.

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. 13, which shows that the mean temperature of the 150 K radiator has been

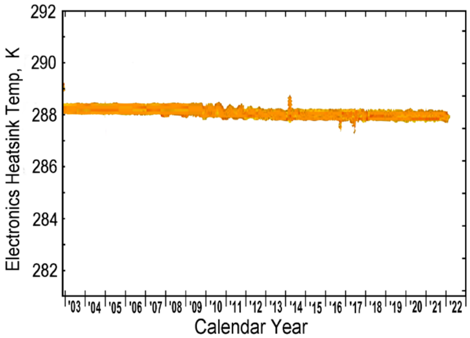

Figure 12. Long-term temperature stability of the AIRS cooler electronics heatsink.

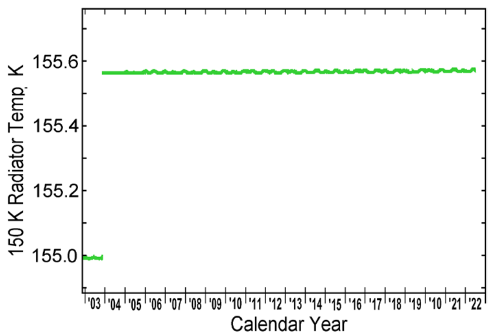

Figure 13. Long-term temperature stability of the AIRS 150 K radiator and OBA.

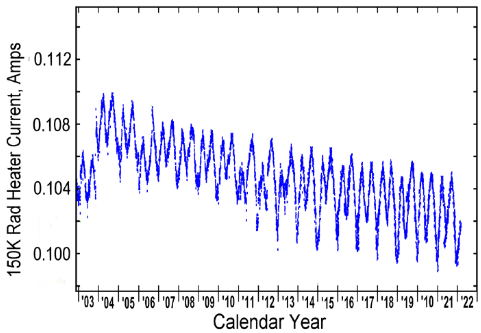

Figure 14. Long-term stability of the AIRS 150K radiator temperature-control heater current.

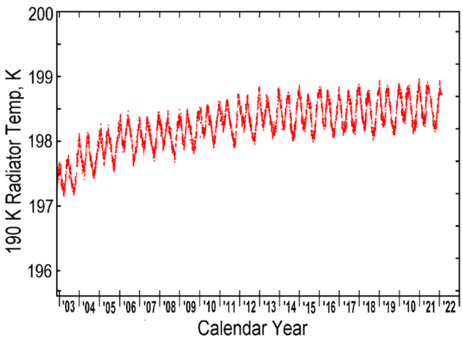

Figure 15. Long-term average temperature of AIRS 190K radiator.

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 150K radiator temperature. The long-term drive current for this heater control, shown in Fig. 14, suggests that the temperature control is mostly driven by seasonal orbit variations, not by long-term aging.

Similarly, the 190K first-stage radiator temperature has also stayed very constant over the mission — in this case varying by about 1 K over the mission duration as shown in Fig. 15. In addition to the seasonal oscillation displayed in Fig. 15, the 190K radiator also has a short-term orbital oscillation of around 1.5 K peak to peak that is superimposed on the long-term average temperature.[9,10]

SUMMARY

Over the past twenty 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 19 years, the stroke level of the cryocoolers has only increased by 1-2 percent. Some of this slowing may be saturation of 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.

On a larger scale, the superb performance and unprecedented stability of the AIRS instrument speaks extremely well for the robustness of the TRW (now Northrop Grumman) pulse tube cryocoolers and the thermal control systems of the AIRS instrument and Aqua spacecraft. At this point, the AIRS cryocoolers are among a dozen other long-life cryocoolers with over 20 years operational time in space—a combination of both pulse tube and Stirling Oxford-style coolers.[11] From a scientific products point-of-view, the AIRS instrument's data calibration stability has been particularly important to the discernment of long-term trends of Earth's atmospheric parameters that is extremely difficult to achieve from multiple instruments over different time spans. At this time in 2022, AIRS has orbited the Earth over 100,000 times and produced one of the longest near-continuous records of Earth observation data ever assembled. This includes over 20 billion measured spectra of our planet's atmosphere and over 1200 formal publications of the scientific findings drawn from the data.[12]

Given its continued excellent performance, the AIRS instrument is planning continuous operation in space as long as the Aqua spacecraft remains operational. At this point, the satellite is expected to have sufficient power to operate into 2026, after which its future is uncertain. Even with the end of the active mission, the two decades of data already accumulated from AIRS will provide unrealized possibilities for numerous further investigations and scientific findings.

ACKNOWLEDGMENT

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