Cryogen-free dilution refrigerator for ACTPOL polarization-sensitive receiver

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Abstract. We present a new cryogenic receiver for the Atacama Cosmology Telescope (ACT), a six-meter diameter off-axis Gregorian telescope located at an altitude of 5,200 meters (17,000 ft.) on Cerro Toco, in Northern Chile. The focal plane contains 3000 polarization-sensitive transition edge sensor (TES) bolometers, and is cooled to below 100 mK with a removable pulse-tube based customised JDry-100 dilution refrigerator insert. The optical tubes and the rest of the receiver are cooled with a dedicated pulse tube to below 3 K. Details of the receiver-to-telescope integration and first season on-site operation are described, including detector base temperature stability in vertical and tilted position as well as remote operation via Ethernet link.

1. Introduction
The Atacama Cosmology Telescope (ACT) is a six-meter off-axis Gregorian telescope [1] (Figure 1) dedicated to investigating the formation and evolution of structure in the early universe, including the study of dark matter and dark energy. It accomplishes this by directly observing the Cosmic Microwave Background (CMB) radiation with arcminute resolution through limited atmospheric opacity from its unique high and dry location in the mountains of Chile’s Atacama Desert.

ACT’s new microwave receiver ACTPol (Figure 2), designed and built in collaboration between the ACTPol team and Janis Research Company, consists of three optical tubes containing silicon reimaging optics, filters, and polarization-sensitive detector array package modules (dual 150 GHz, and one multi-chroic 90/150 GHz). Many of the optical tube components require cooling to 1 K in order to reduce their thermal emission and insure good performance of the cold detector readout electronics. The TES detector packages must be cooled to a stable temperature below 100 mK in order to maximize detector yield.

2. Design
The receiver “dewar” consists of a cylindrical outer vacuum can (OVC) of about 1 meter diameter, sealed with top and bottom flanges, all made of 6061 aluminum. The top flange has a removable hatch with three anti-reflection coated ultra-high molecular weight polypropylene windows transparent to microwaves, and serves as a mechanical support for the internal structure.
The receiver cross-section is shown in Figure 2. The 50 K and 4 K aluminum plates with corresponding removable shields are supported with two thin-wall G-10 drums. The shields are cooled by a dedicated PT-410 pulse-tube cryocooler [2], via a combination of flexible and rigid OFHC copper links. The detectors are cooled below 100 mK by a customized cryogen-free $^3$He-$^4$He dilution refrigerator JDry-100-ACTPol insert (DR, Figure 3), equipped with a PT-407 pulse-tube cryocooler [2]. The insert pre-cooling from room temperature is done via a manually operated mechanical heat-switch connected to the PT-407 2nd stage. The automated gas handling system GHS4 is positioned next to the receiver in the temperature-controlled receiver cabin attached to the telescope and is remotely operated via Ethernet computer interface during all phases of the experiment. Its air cooling system for the electronics and solenoid valves, as well as the XDS 35i scroll and High Pace 300 turbo pumps [3] inside GHS4 allow for continuous operation at an atmospheric pressure near 500 mbar.

![Telescope components arrangement on the left and receiver position inside the cabin on the right.](image)

**Figure 1.** Telescope components arrangement on the left and receiver position inside the cabin on the right.

Pulse tube cryo-cooler, as well as DR stage performance degrades when operated in tilted position. To avoid the degradation or system shut-down in ACTPol, which scans in elevation from 32 to 60 degrees from horizon, both PT’s are mounted on top ports at about 30 degree angle to its optical axis (see Figure 1).
3. Results

Initial tests were performed at the Janis lab with the DR insert enclosed in a small test vacuum shroud. The mixing chamber reached a base temperature near 10 mK and had 120 µW of available cooling power at 100 mK (as shown in Figure 4), exceeding the specification of 100 µW. After that, the system was integrated with the ACTPol receiver without the optical tubes installed and all windows blanked. Subsequent tests showed that although the pre-cooling time from 300 K to 6 K had increased due to additional loading from the larger “dewar”, overall DR performance had not changed.

During the spring of 2013, the first 150 GHz kilo-TES polarimeter array package (PA1) was assembled and installed in the ACTPol receiver\textsuperscript{1}, along with high-purity copper heat-straps that connect the 1K optical tubes and the sub-100 mK focal plane to the DR insert. Upon completion, pre-cooling was observed to take longer (just under 6 days – see Figure 5-Figure 8) than during prior tests due to the additional thermal-mass of the new optical tube components attached to the still and mixing chambers of the dilution refrigerator.

\textsuperscript{1} One additional 150 GHz array (PA2) is currently in the process of being deployed while a third 90/150 GHz multi-chroic array (PA3) is slated for early 2015
Once everything had finished pre-cooling, the mechanical heat switch was manually disconnected and $^3$He-$^4$He mixture condensation was initiated, taking approximately 2 hours to complete. This was followed by mixture phase separation, with the system reaching base temperature in just over one hour thereafter. Following several hours of biasing and tuning the TES bolometers, the instrument achieved first-light with PA1 on the night of July 18th, 2013 with a test observation of the planet Saturn.

After several weeks of testing, calibrating, and focusing of the telescope optics, first observations of the CMB began on September 11th, 2013 and lasted until December 14th, 2013, when weather conditions became unfavorable. During this period, several patches of the sky were observed while they were rising and setting by scanning the telescope back and forth in azimuth at a fixed elevation.

In order to maximize the time spent on each patch (and thereby maximize the total signal-to-noise of the data), the telescope often tracked patches as they moved across the sky by changing its elevation.

Aside from a few brief interruptions due to system maintenance and testing activities (~ 3.7% of total time), the DR mixing chamber maintained a relatively stable base temperature throughout the entire season. The longest continuous stretch at base lasted just over 24 days and is shown in Figure 10 (for comparison, the temperature variation of the 4 K cold plate during the same period is also shown in Figure 9).

Although diurnal oscillations caused by air-cooled PT cryo-coolers were a major source of variation, their amplitude was not large enough to adversely affect the detector data, with the array...
package maintaining a stable temperature of 77.3 ± 1.0 mK. Changes in the tilting angle of the DR insert that were essential to executing the aforementioned observing strategy had no significant impact on the temperature stability of the detector array (Figure 12), even though temperatures for some of the warmer components attached to the pulse-tube cooler show a clear dependence on elevation (Figure 11).

![4 K Cold Plate](image1)

**Figure 11.** 4 K cold plate temperature variation with change in tilting angle

![Array Package](image2)

**Figure 12.** Array package temperature variation with change in tilting angle

4. Summary

We have designed, built and tested a new polarization-sensitive receiver using a $^3\text{He}^4\text{He}$ dilution refrigerator as opposed to the more conventionally used ADR system. The DR’s large cryogenic cooling capacity permits the detector arrays to reach an operating base temperature below 100 mK despite numerous sources of thermal loading from higher temperature components. This feature, in combination with the system’s thermal stability over time and across a large range of tilting angles, resulted in consistent collection of high quality scientific data. Furthermore, continuous operation and remote access via Ethernet allowed for uninterrupted day and night-time observations of the CMB, making the DR an important reason for the success of the experiment.

References

[1] arXiv:astro-ph/0402234v1
[2] Cryomech, Inc., 113 Falso Drive, Syracuse, NY 13211 USA
[3] Edwards Vacuum, Inc., 88700 Expedite Way, Chicago, IL 60695 USA, and Pfeiffer Vacuum, 24 Trafalgar Square, Nashua, NH 03063-1988 USA, correspondingly.