A terahertz superconducting receiver instrumented on a low power space cryocooler

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Abstract—**In order to realize affordable, long-duration missions utilizing superconducting receivers, we investigate the use of an active cooler to achieve the bath temperatures required to operate detectors instead of using a liquid helium-filled cryostat. Although past large missions such as Herschel and Spitzer have successfully used liquid helium-cooled instruments during their mission lifetimes, they owed their longevity to their chosen orbit: in low-Earth orbit or a suborbital environment the thermal environment severely constrains the lifetime of a liquid helium-cooled cryostat. On the other hand, power consumption of a commercially available 4 K-class cooler can easily exhaust resources of a balloon gondola or spacecraft. For our application we require highly specialized, low power coolers. We describe the operation of a THz receiver instrumented on a Lockheed Martin four-stage pulse tube refrigerator, which was developed under NASA's Advanced Cryocooler Technology Development Program (ACTDP). The cooler's demonstrated performance margin will allow us to implement array receivers for long-duration (>0.5 yr) suborbital and orbital missions.**

I. Introduction

Studies of the interstellar medium using Herschel's heterodyne instrument HIFI have established the utility of far-infrared fine structure lines to further our understanding of how diffuse hydrogen gas turns into natal environment where stars are born. The Stratospheric Terahertz Observatory, a small suborbital mission, will continue this work by mapping a portion of the sky in three THz spectral lines. A comprehensive study of the interstellar medium using THz lines will allow bigger questions to be addressed about how our Galaxy was formed and shaped, what transport of energy and mass occur to regions outside the Milky Way, and how to interpret emission from extragalactic sources across the history of the Universe. Indeed, the proposed GUSTO mission will work towards this goal by mapping a much larger area of the Milky Way. Given a fixed size for the detector array, the practical limit to sky coverage is determined by the lifetime of the cryogenic system, where liquid helium-cooled (<4.2 K) cryostats are used. These systems typically limit mission duration to about 3 months in low-Earth orbit and suborbital environments. In order to be able to extend the mission lifetime and hence the science return, we wish to consider low-power mechanical refrigerators, which can run continuously for years.

The NASA Advanced Cryocooler Technology Development Program (ACTDP) solicited the development of mechanical refrigerators for future missions, one of which evolved into the James Webb Space Telescope. JWST is now in the development phase with Northrup Grumman having been chosen to provide the cryogenic subsystem. The basic ACTDP requirements were simultaneous heat lift of 20 mW at 6 K and 150 mW at 18 K, an overall system power consumption of 200 W, mass of 40 kg, and a lifetime of 10 years continuous operation [1]. These specifications match quite well with what a straightforward ~20 pixel NbN superconducting heterodyne receiver system would require, and the resources are relatively easily managed by existing gondolas and low-cost spacecraft buses. Similar performance has been demonstrated by a cryocooler system built by Sumitomo [2]. Fortuitously, under the ACTDP program Lockheed Martin delivered to JPL a fully functional, well-characterized four-stage pulse tube refrigerator [3] that met (or exceeded) the original program requirements. We have housed the cryocooler in a practical vacuum housing, assembled the required electronic controller, begun to assess and analyze the performance of the cooler, and are currently modifying the system to incorporate a single-pixel THz mixer.

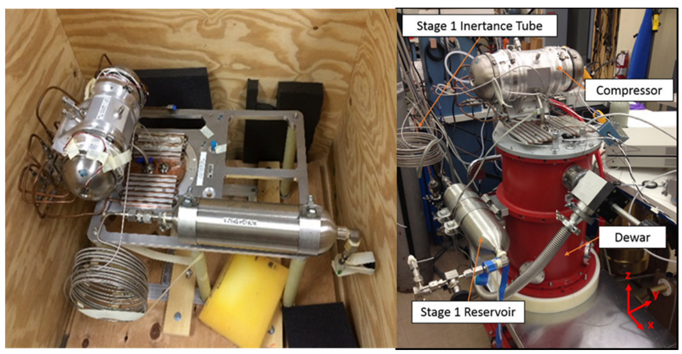

Figure 1. As-delivered configuration of the Lockheed Martin pulse tube refrigerator (left). The assembly was designed to be tested entirely in vacuum. Details are in reference [3]. The current configuration of the refrigerator housed in a vacuum jacket (right).

II. Cryocooler Performance

The Lockheed Martin refrigerator is a 4-stage pulse tube cryocooler with a single compressor module. During final testing at Lockheed Martin, the refrigerator was reconfigured to maximize cooling power at 6 K. The fridge was then modified to operate in a 77 K radiative environment and to eliminate cooling power at the 18 K stage. The refrigerator was shipped to JPL in this configuration (Figure 1, left).

For testing at JPL the cold head is housed in a vacuum jacket, with the heat rejection plate used as the vacuum bulkhead (Figures 1 & 2). For the drive electronics we use a commercial function generator followed by a water-cooled class D audio amplifier to excite the compressor coils at ~30 Hz. The refrigerator's heat rejection plate, compressor and amplifier are cooled, for the time being, with a laboratory circulating chiller.

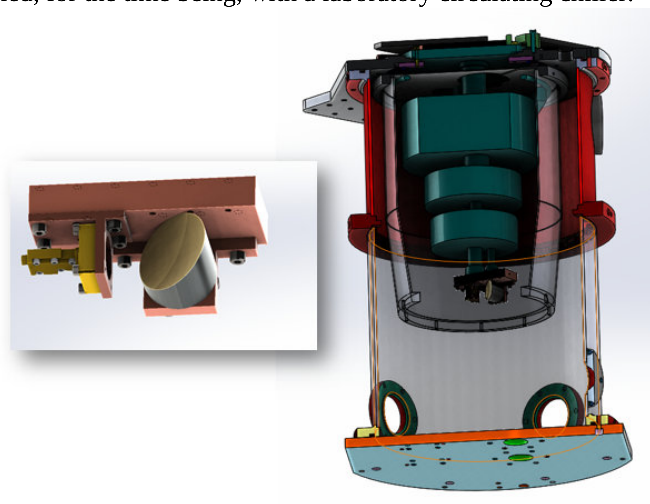

Figure 2. A cartoon rendering of the cryocooler cold head enclosed in the vacuum jacket (right) showing how a mixer assembly (with integrated amplifier) might be attached to the 6 K cold finger. For single pixel operation, this is the simplest configuration; for multiple-pixel operation, the amplifiers would be placed on the 3rd or even the 2nd stage.

After setting up the cryocooler at JPL, the first stage inertance tube was shortened to restore the cooling power necessary to operate the fridge in a room temperature environment; inertance tubes on the third stage have been left unmodified for the current set of tests. With this modification we expect to observe reduced cooling capacity on the 18 K stage. In addition we use ^{4}He as the refrigerant instead of ^{3}He as originally intended, which further reduces the cooling power. Radiation shields have been installed, thermally anchored to the first and second stages. Currently, the no-load minimum temperatures we observe with the fridge are 96 K, 32 K, 17 K, and 4.5 K at the first, second, third and fourth stages, respectively.

The cooling capacity in its current configuration is sufficient to begin work integrating a receiver into the refrigerator: with 200 W delivered to the compressor, the fridge can lift 20 mW at 6 K with no load on the 18 K stage, or 11 mW with 50 mW applied on the 18 K stage. Figure 3 shows the heat lift as a function of the 6 K (fourth) stage temperature with no power applied to the third stage. The highest temperature our NbN mixers can operate is 8.5 K, and the heat lift on the fourth stage at this temperature is ~45 mW. Prior to installing the mixer, the cooler will need modifications that include opening an optical access to the 4th stage and adding a coaxial cable to convey the signal to the outside. The estimated heat load from one low-noise amplifier and coaxial cable path is <10 mW. Thus, even its current configuration, the fridge has sufficient cooling power and margin to accommodate 4 mixers, or may be run with just 100 W of compressor power to provide sufficient heat lift to operate one mixer. In the future, to accommodate a greater number of pixels, the first-stage amplifiers would be mounted on the third or possibly the second stage. We would also need to optimize the cryocooler's performance by modifying the third stage inertance tube, similar to what we did for the first stage.

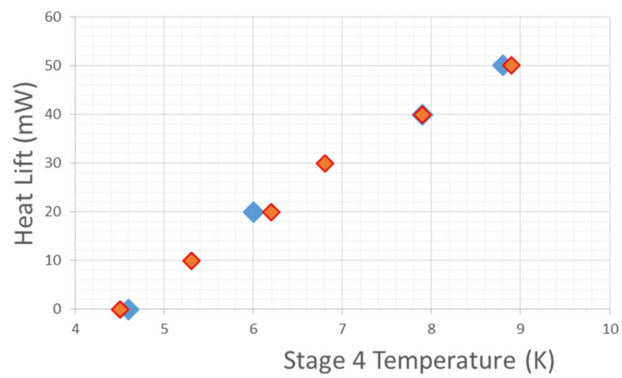

Figure 3. Measurement of the 4th stage heat lift with no power applied to the 3rd stage with 200 W of compressor power. The maximum temperature before significant noise degradation occurs at 8.5 K. The two plot colors show measurements made on successive cool-downs.

ACKNOWLEDGMENT

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