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Cryogenic Temperature Stabilization of the Daikin 308 Cryocooler

Michael J Smith
Harvard University
Cambridge, MA, USA 02138

Jeff Jennings, PE
Equilibar, LLC
Fletcher, NC, USA 28732

ABSTRACT

We report on a scheme developed at the Harvard-Smithsonian Center for Astrophysics to stabilize longer term cryogenic temperature variations in equipment used for high frequency radio telescope receivers. Cryogenic temperature variations of the 30 minute time scale are reduced an average of 55 percent by controlling the helium pressure flowing through the cryostat. Applications in the field of cryogenic radio astronomy will benefit from this resulting reduction of power fluctuations and corresponding reductions in observation time on source. An Equilibar® back pressure regulator was used to allow helium from the compressor to bypass the cryostat, thereby providing a very stable pressure control system. Manually set reference port pressure regulates the helium bypass and deviates less than 6.2 x $10^{\wedge-4}$ MPa for the 30 minute time period while power output deviations of the heterodyne receiver are reduced as a result of the increase in pressure stability an average of 46%.

Keywords: Cryogenic, pressure control, heterodyne.

I. Introduction

The Sumitomo/Daikin 308, GM/JT helium 4 cryocooler is in wide spread use for numerous applications including the Submillimeter Array (SMA) operated by the Smithsonian Astrophysical Observatory. The array consists of eight 6-meter radio telescope dishes, each housing a cryostat which, currently contain four cryogenic receiver inserts connected to a central cold head. Utilizing available cooling capacity as a result of the helium within the cold head passing through a Joule-Thomson valve each cryostat is cooled to 4.2 Kelvin. Upon each receiver insert resides an SIS (superconductor, insulator, superconductor) detector that is thermally coupled to the cryocooler by means of high purity, multilayer copper foil with electron beam welded terminal blocks. It is this SIS detector which must be stabilized thermally in order to improve system performance and decrease observation time. Resistivity within the copper is minimal with losses less than 0.1K over a length of 28cm. Figure 1 depicts the correlation between thermal deviations of the cryocooler and receiver output power fluctuation before implementation of the Equilibar back pressure regulator (BPR). Instabilities such as this result in longer required integration times and decreased sensitivity in the detection of astronomical objects [1]. Reviews of previous literature turn up little work in the area of cryogenic stabilization at the level needed and length of time required to reduce astronomical observation time. Although laboratory testing looked promising, field implementation and operation of an internal helium pot [1] proved difficult in a multi element array and was not pursued.

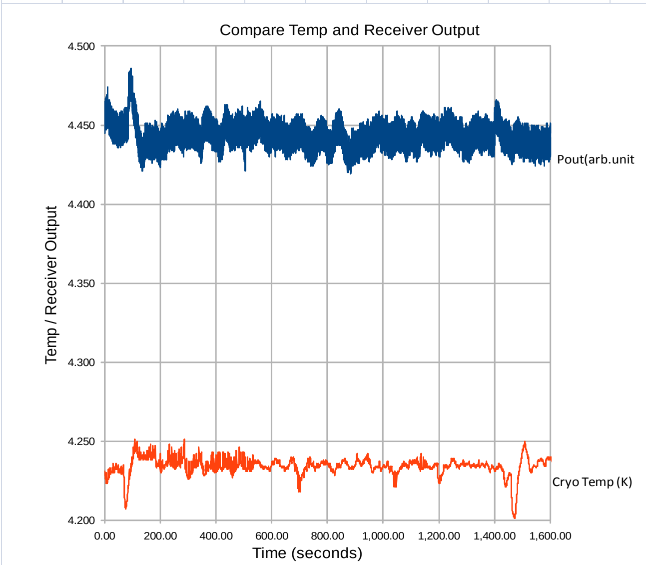

Fig. 1 Correlation Between Temperature and Power

In the 4.2 K operating range, variations of up to 64 mK in the Daikin 308 cryocooler result in instability of array's high frequency (200-600 GHz) radio telescope receivers. Reductions in absolute power are less detrimental to the astrophysical interferometer than the temperature variations (drifting & noise) of the receiver. An examination of temperature fluctuations before installation of the BPR in Figure 2 show temperature deviations of 64 mK during the test with the minimum of 4.190 K occurring at the 1 second mark and the maximum of 4.254 K occurring at the conclusion of the 3600 second test period. The data show a significant drift of the average temperature during the 3600 second time period ranging from 4.217 K at the beginning of the test to 4.235 K at the test conclusion. Both peak to peak fluctuations and drift of the average cryocooler temperature must be addressed in a thermal stability solution.

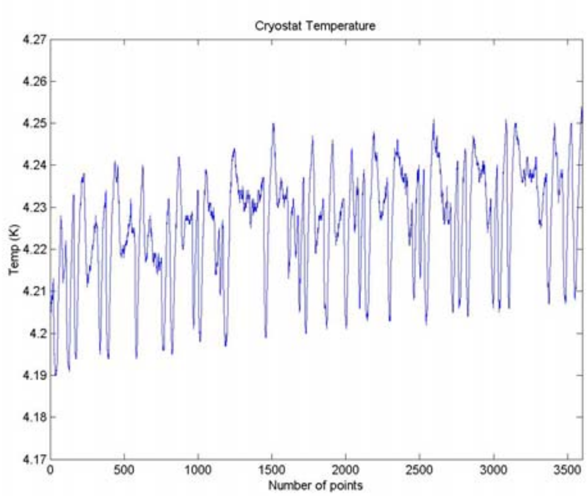

Fig. 2 Temperature Deviation Before BPR Installation

II. Experimental Setup

Figure 3 depicts the helium circulation system that provides the stable temperature for the cryostat. Each element of the array has its own cryostat and closed loop helium compressor. The Equilibar back pressure regulator provides a flow bypass around the cryostat in order to control its pressure.

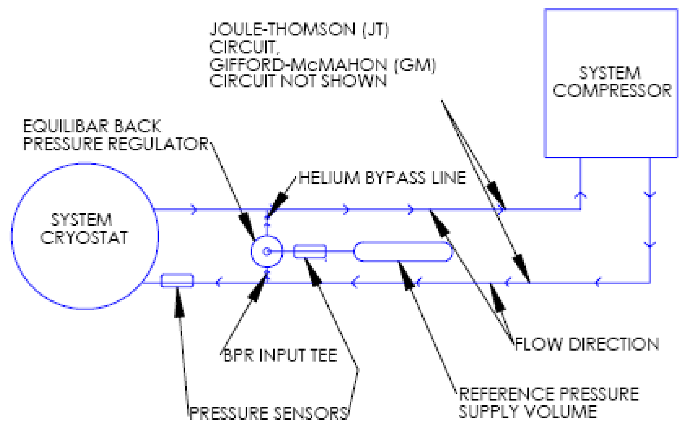

Fig. 3 Cryostat System Schematic

Figure 4 depicts a monitoring station to investigate cryostat compressor pressure variations and cryostat cold head temperature fluctuations. Temperature monitoring of the 4 K cold head stage of the cryostat is achieved using the Lakeshore DT-470 Silicon Diode and is monitored with the Lakeshore 218 Temperature Monitor outputted directly to a laptop computer and recorded using the Matlab interface.

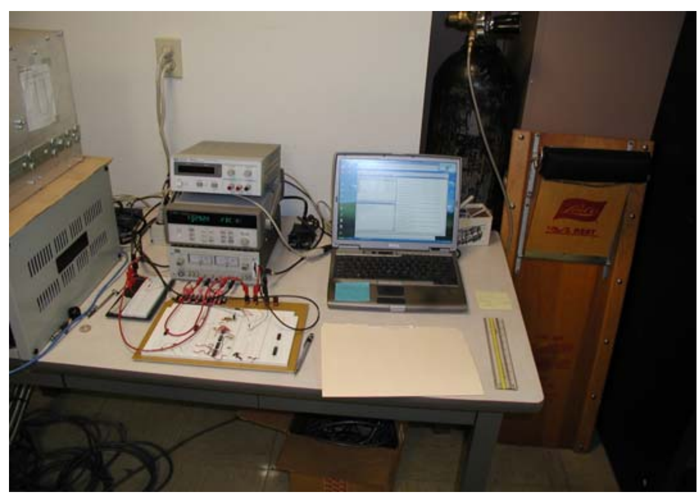

Fig. 4 Cryogenics Monitoring Station

Compressor pressure is detected in line near the compressor input and output connections using the AST model 4000 pressure sensors shown in Figure 5 (note the temperature sensor wire on the near pressure sensor body). The signal is fed into the HP Agilent 3497A Data Acquisition System then fed into the laptop computer and recorded using the Matlab interface.

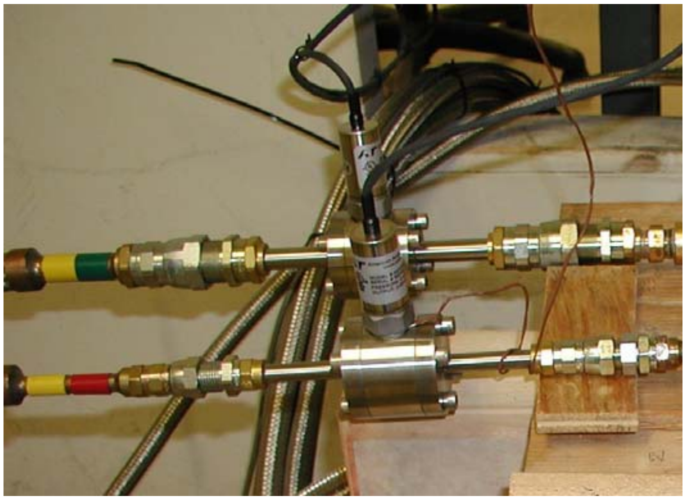

Fig. 5 AST Model 4000 Pressure Sensors

III. System Testing

An examination of the compressor characteristics before BPR implementation during thermal equilibrium are shown in Figure 6 and reveal normalized temperature fluctuations follow normalized pressure deviations of the discharge line (high pressure). These deviations are a result of pressure inconsistencies in the multi stage pump arrangement of the Daikin compressor in combination with cold head displacer valve orientation. Suction line (low pressure) pressure variations showed poor correlation to the temperature deviations.

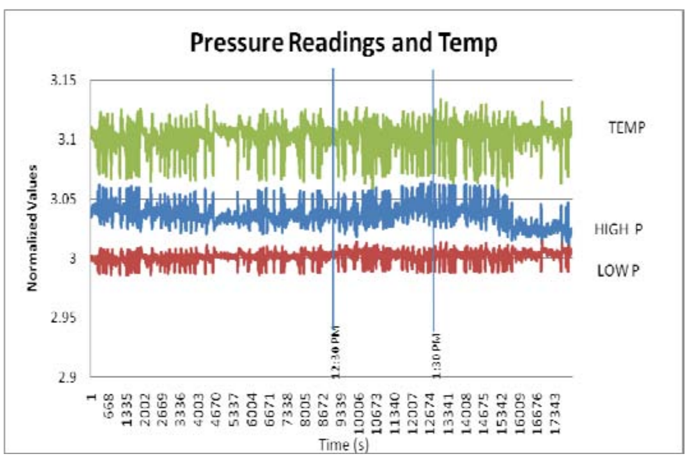

Fig. 6 Cryostat High And Low Pressure Readings

The trend in the normalized data shows a substantial decrease in temperature with the pressure increase which occurs in the high pressure output of the system. This trend is most evident later in the data set starting around the 11,000 second area where the normalized average high pressure reading is 3.040 with a corresponding normalized average temperature of 3.104. High pressure average then rises to 3.0489 (a change of 0.0089 in the normalized pressure value) with a corresponding average temperature decrease to 3.095 at the 12,288 second mark (a change of 0.009 in the normalized temperature value) with a return back to normal temperatures and pressures around the 15,000 second area. At this time the low pressure side shows a change in average normalized value of 0.003. The most compelling temperature correlation with the high pressure output occurs toward the end of the data run beginning at the 15,000 second area and continues through the completion of the data gathering run. In this instance a noticeable drop in the high pressure side of the compressor from 3.045 to 3.023 (a decrease of 0.022) in average normalized value corresponds directly with a rise in average cryogenic temperature from 3.100 to 3.112, an increase in 0.012 in the normalized average value. The low pressure side of the system shows a reduction in amplitude of the data point deviations during this time but the average normalized pressure only rises 0.003.

The Actual data graph for the 18,000 point (second) gathering run is shown in Figure 7. Average pressure at the 15,000 second mark is 2.434 MPa and falls to 2.428 MPa at the end of the run resulting in a total average pressure change of 0.006 MPa. This pressure decrease corresponds to a temperature increase from 4.148 K to 4.160 K for the same time period. As a result of analysis on this early test data, further testing focused on control of the high pressure side of the system with the expected result of cryogenic temperature variation minimization.

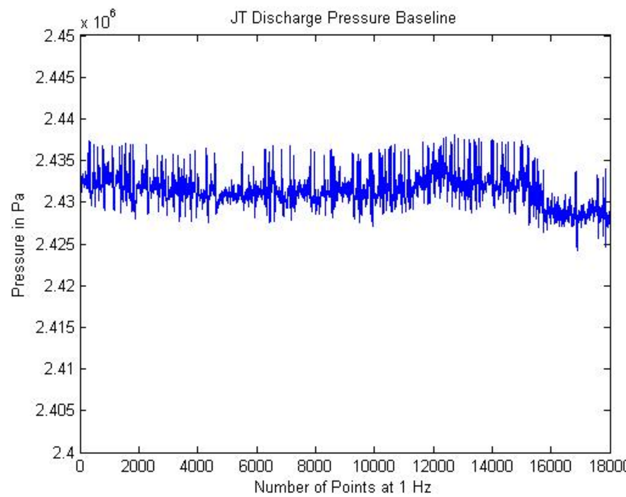

Fig. 7 Discharge Pressure Before BPR Installation

In addition to the close correlation of the high pressure side of the compressor to the cryogenic temperature deviations, the effect of the environmental temperature variation became evident from this data set. Referring back to figure 6, the high pressure side of the compressor shows a pressure increase from a normalized value of 3.035 to a normalized value of 3.049 between 12:30 PM and 1:30 PM. This correlates to the time when the lab personnel have lunch (shown as 12:30 PM in Fig 6). The door to the compressor enclosure is closed around this time for acoustical purposes and the room begins to heat up from 24 C to 35 C. This temperature change (normalized) is evident in the graph of compressor discharge temps vs. time shown in Fig 8.

Although the room housing the cryogenic compressor and experimental setup heat up during the time when the door is closed the data set showing the temperature of the compressor discharge line shows an inverse temperature fluctuation, it drops from 33.2 C to 31 C as shown in Figure 8 (Figure temps have been normalized). The reason for this inverse temperature fluctuation becomes evident from an examination of Figure 9. When the cryogenic compressor is in operation, a vent fan exhausts heat from the immediate environment. When the compressor room door is closed, the air is then forcibly drawn through the helium line openings in the compressor room wall.

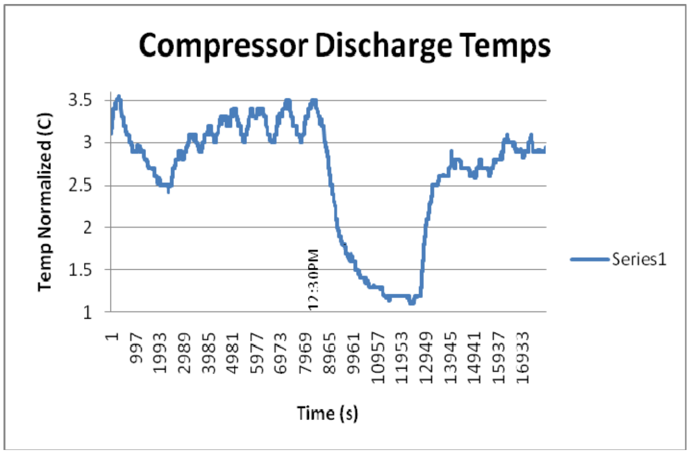

Fig. 8 Compressor Discharge Line Temperatures Impacted By Room Temperature Variations

The Fluke temperature sensor wire is seen in Figure 9 as a wire wrapping around the pressure sensor flange in the foreground then, touching the top surface of the pressure sensor itself. As the air conditioned laboratory air is drawn through the nearby opening, the immediate area near the temperature probe is affected by the cooler air while the room itself and the cryogenic compressor within it, heat up.

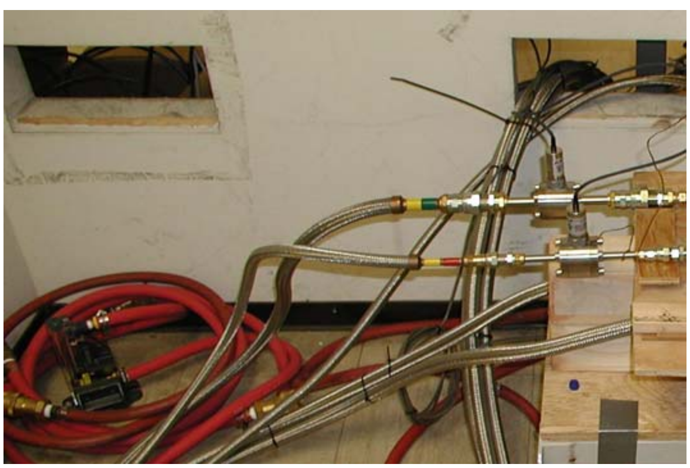

Fig. 9 Wall Openings Affecting Sensor Temperature

An initial test system shown in Figure 10 was devised for back pressure regulation at the compressor location. An EB1LF1 Equilibar back pressure regulator with 1/8" NPT ports, circled near the center of the photo, is connected to the output line of the cryogenic compressor and provides a bypass flow of helium around the cryostat. The Equilibar back pressure regulator is a dome-loaded variety, and will control fluid pressure at its inlet port equal to the pressure connected to its reference port. The reference pressure (approximately 2.425 MPa) was provided by a separate helium tank and regulator. Once set, a valve downstream of the regulator is shut and pressure maintained in the small gas bottle. A 3 meter stainless steel hose is shown in the photo connecting the reference gas bottle to the reference port of the Equilibar. Reference pressure using this method proved to be too difficult to control as wide temperature swings in the closed environment had large effects on the pressure.

Fig. 10 Initial Equilibar Test System

Because both environmental temperature fluctuations and cyclic pressure deviations of the compressor result in cryogenic temperature instability in the system, a solution to the instability must encompass both aspects of the problem. A closed loop, helium bypass arrangement for cryostat base mounting is fabricated with the Equilibar back pressure regulator for control of the pressure variations and, is shown in Figure 11. A lecture size bottle of high purity helium provides the reference pressure for the regulator in very close proximity to the port opening. The size of the reference gas reservoir was chosen to minimize the environmental temperature effects governed by the theoretical P*V = M*R*T while still allowing for ease of installation and movement of the final assembly.

Fig. 11 BPR Ready For Cryostat Base Installation

This effect of environmental temperature underscored the need to control thermal effects during both testing and operation of the system. As a result, the testing equipment was moved to the main laboratory floor close to the base of the cryostat as seen in Figure 12. The BPR, Pressure Sensors, Surge Bottle and Reference Pressure Bottle are shown unwrapped for visual clarity. In normal testing mode the components are wrapped in insulation to minimize the effects of the laboratory air conditioning system on the hardware.

Fig. 12 BPR Final Installation

In addition to hardware placement changes the Equilibar back pressure regulator was upgraded to a virgin PTFE diaphragm to eliminate a slight leak of helium around the sealing ring.

IV. Results

With a stabilized test system, pressure regulation measurements resumed. The back pressure regulator was in operation during the first 2,200 points (seconds) of the final data run with pressure readings shown in figures 13, 14 and 15. It was turned off just beyond the 2,200 point mark and a noticeable increase in discharge pressure deviation amplitude; temperature deviation amplitude and output power deviation amplitude are seen as a result. Figure 13 permits overall qualitative comparison of pressure fluctuation before and after the BPR is used and, comparison to the reference pressure. It should be noted that during the testing time period, the reference pressure shown at the bottom of the graph ranged from a minimum of 2.380 to a maximum of 2.381 MPa. A 10 minute snapshot of pressure deviations during BPR operation just prior to termination (1,550 to 2150s) as seen in Figure 14 shows pressure ranging from 2.422 to 2.425 MPa, a pressure fluctuation amplitude of 2.975 KPa. A contrasting 10 minute snapshot of pressure after the BPR has been turned off (2250 to 2850s) as seen in Figure 15 shows pressure ranging from 2.430 to 2.438 MPa, a pressure fluctuation amplitude of 7.697 KPa.

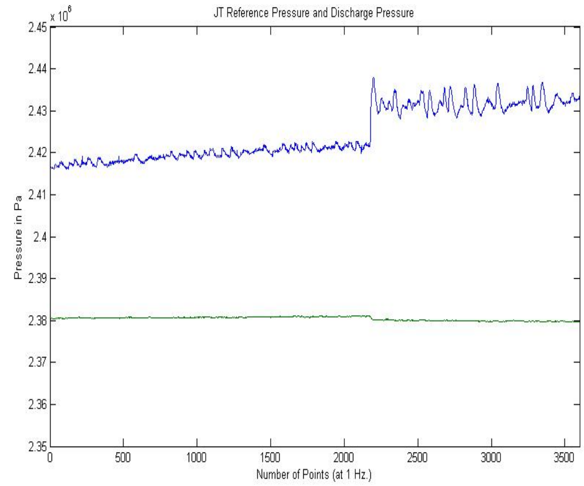

Fig. 13 Pressure Contrast With BPR Operation

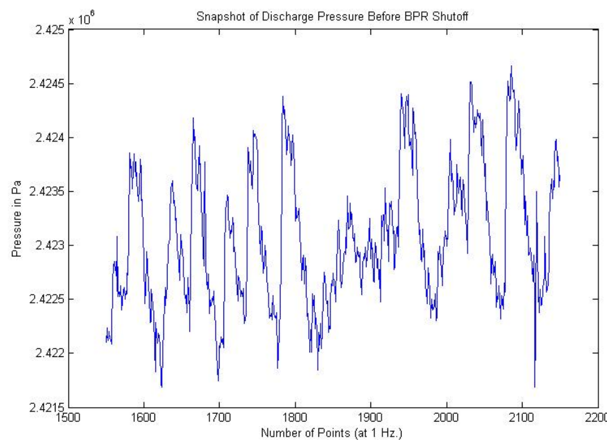

Fig. 14 Discharge Pressure Before BPR Shutoff

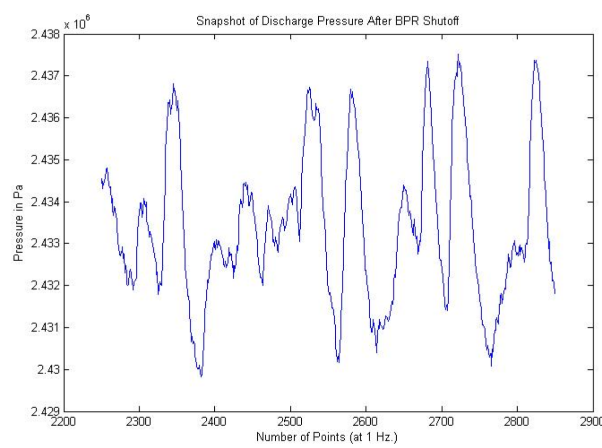

Fig. 15 Discharge Pressure After BPR Shutoff

During this same period of time with the Equilibar back pressure regulator in operation the cryostat temperature showed a minimum value of 4.277 K and a maximum value of 4.300 K, a total change in the amplitude of the temperature fluctuations of 0.023 K. In contrast, during the entire period after the 2,200 point (second) mark when the back pressure regulator was turned off, the pressure fluctuation amplitude was 8.653 KPa. During this same unregulated period the temperature fluctuations went from a minimum of 4.183 K to a maximum of

4.235 K, a fluctuation amplitude of 0.052 K as shown in Figure 16.

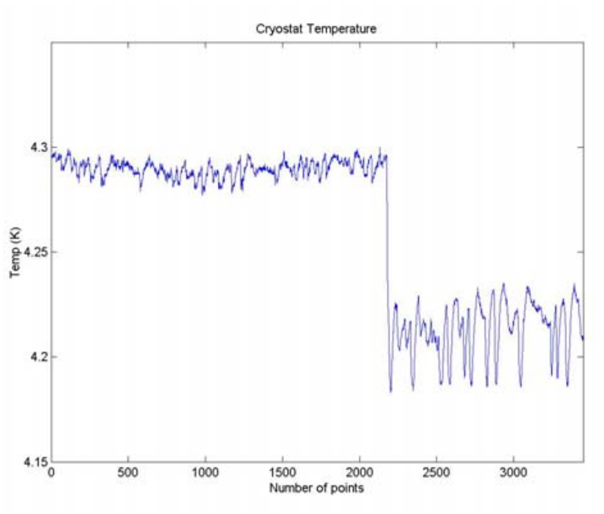

Fig. 16 Temperature Contrast With BPR Operation

With the ultimate goal of cryogenic temperature variation minimization the corresponding power fluctuations of the test instrument are now shown in Figure 17. During the time of pressure regulator operation, power deviations were a minimum of 0.573 and a maximum of 0.579. Thus, the amplitude of the power fluctuation has a peak to peak range of 0.006 W. The contrasting data shown after the 2,200 point location show an increase in power deviations with a minimum of 0.587 and a maximum of 0.598, a peak to peak power fluctuation amplitude of 0.011 W.

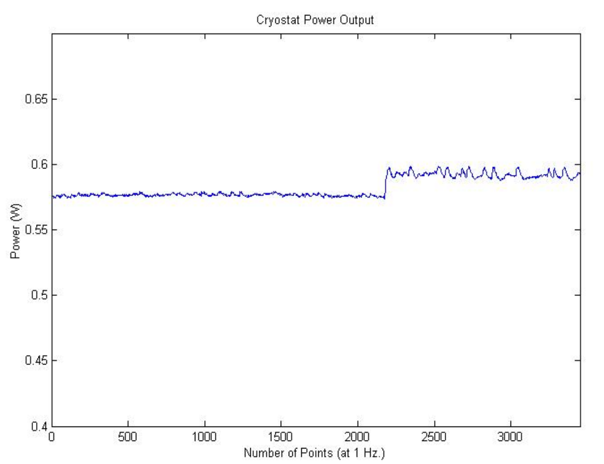

Fig. 17 Power Contrast With BPR Operation

V. Conclusion

From the experimental data gathered, the Daikin 308 Cryocooler temperature deviations are minimized an average of 55% as a result of implementation of the Equilibar back pressure regulator and a custom fabricated, closed loop helium bypass system. These temperature deviations stem from pressure variation in the Joule-Thomson effect at the throttling valve of the cold head.

Cryogenic temperature variations within the system are minimized by “clipping” the amplitude of the pressure deviations while bypassing a small helium volume through the Equilibar orifice. Corresponding system power variations are reduced approximately 50% as a result of this temperature stabilization. Applications in the field of cryogenic radio astronomy will benefit from this reduction of power fluctuation with a corresponding reduction in observation time on source. Further field testing and implementation are indicated based on these preliminary laboratory results with expected improvement in system sensitivity and reduction in observation time required.

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REFERENCES

[1] Smith, M.J., Blundell R., 2009 “A Cryogenic Stabilization Scheme for Radio Astronomy Applications,” Paper no. IMECE2009-11193, ASME 2009 International Mechanical Engineering Congress and Exposition (IMECE2009), Lake Buena Vista, Florida, USA pp.549-552

[2] Rui Li, Atsushi Onishi, Toshimi Satoh, and Yoshiaki Kanazawa, “Temperature Stabilization on Cold Stage of 4 K G-M Cryocooler,” *Cryocoolers 9* pp.765-770, 1997.