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LONG-TERM PERFORMANCE OF 4 K GIFFORD-McMAHON REFRIGERATORS ON THE BIMA ARRAY

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ABSTRACT

Eight radio telescopes in the Berkeley-Illinois-Maryland Array (BIMA) are outfitted with 4 K Gifford-McMahon refrigerators. The refrigerators cool superconducting detectors (SIS mixers) on the radio receivers; the heat load at 4 K is 10 to 20 mW. The refrigerators were constructed by welding third stages onto standard CTI model 1020 cryocoolers; Er_3Ni or ErNi spheres are used as the low temperature regenerators. The refrigerators are operated almost continuously; one has been in service for 4 years. Maintenance consists of disassembling the cold heads every 1 to 2 years to clean out water and dust.

On the telescopes the refrigerators' third stage temperatures range from 2.7 to ~5 K. Often these temperatures are stable within ± 0.1 K for weeks, even while the refrigerators are tipped from 0 to 90 degrees as the telescopes track radio sources. Sometimes, however, the temperature creeps up by > 1 K over a period of days or weeks, then jumps back to its original value following a power interruption or "defrost" cycle. Contaminants within the cold head may possibly cause this behavior. With active temperature regulation, the SIS mixer temperatures can be stabilized to ±0.01 K despite the refrigerator fluctuations.

INTRODUCTION

Three-stage Gifford-McMahon refrigerators are used to cool SIS (superconductor–insulator-superconductor) mixers on the Berkeley-Illinois-Maryland array (BIMA), an aperture synthesis instrument consisting of 10 radio telescopes[1]. Each BIMA dewar accommodates up to 4 SIS mixers, cooled by a single refrigerator. The heat loads on the refrigerators' first, second, and third stages are estimated to be 6 watts (from the 50 K outer radiation shield), 0.5 watts (from the 12 K inner radiation shield and I.F. amplifiers), and 10 to 20 milliwatts (from conduction losses and SIS mixer bias circuits), respectively.

The BIMA cryocooler design has been described previously[2,3]. We machine the end plug off a standard CTI model 1020 cryocooler, then weld on a 1.27 cm I.D. × 15 cm long third stage cylinder. The third stage displacer consists of a stainless steel tube, with an 0.5 mm thick plastic[4] sleeve epoxied to the outside to serve as a bearing surface. Spheres[5] of Er_3Ni or ErNi, diameter range 180–450 μm, are used as the third stage regenerator. The third stage swept volume is 4 cm^3, while the regenerator volume is 10 to 12 cm^3. A key difference from most cryocoolers is that the third stage seal[6]

Table 1. Lab test results for all cryocoolers.

Serial Number	Regenerator	T (0 mW)	T (50 mW)
5093	53.0 g Er_3Ni	2.50 K	3.80 K
5747	68.8 g Er_3Ni	2.50 K	3.73 K
6154	70 g Er_3Ni	2.60 K	3.62 K
5746	68.5 g Er_3Ni	2.40 K	3.64 K
6418	67.3 g Er_3Ni	2.56 K	3.77 K
6584	50.5 g Er_3Ni	3.28 K	4.00 K
6585	60.7 g ErNi	2.62 K	3.70 K
5346	60.6 g Er_3Ni	2.71 K	3.71 K
7528	60.6 g ErNi	2.65 K	3.67 K

is clamped to the warm end of the cylinder, not mounted on the displacer, so that it shrinks more tightly onto the displacer when cold. A digital power inverter controls the refrigerator's cycle frequency, which must be reduced below the normal value of 72 rpm in order to achieve third stage temperatures below ∼4.5 K. On the telescopes the refrigerators normally operate at 31 rpm.

As of June 1997 we have built 9 such cryocoolers (the first of the series, #5093, differs from the rest in that it uses a conventional split seal mounted on the displacer). As indicated in Table 1, all performed comparably in a laboratory test dewar, where we measured the third stage temperatures with applied heat loads of 0 and 50 mW; cryocoolers with larger regenerators reached slightly lower temperatures.

LONG TERM PERFORMANCE ON THE TELESCOPES

As of June 1997, 8 BIMA telescopes were outfitted with 4 K cryocoolers, for a total accumulation of 12 cryocooler-years operation; one refrigerator has been in service since March 1993. Over the past 3 years only one cryocooler suffered a catastrophic failure – a shorted motor winding, possibly caused by voltage spikes from the digital power inverter. Maintenance is done once per year: we take apart each cold head, wipe dirt and water off the displacer and cylinder, then reassemble and purge the unit. Thus far it has not been necessary to replace any of the third stage seals.

The cryocoolers are tipped over an elevation angle range of 0–150 degrees as the telescopes track radio sources. The cold tip points straight up at elevation 90 degrees. Typically, as shown in Figure 1, the third stage temperature varies by less than 0.1–0.2 K

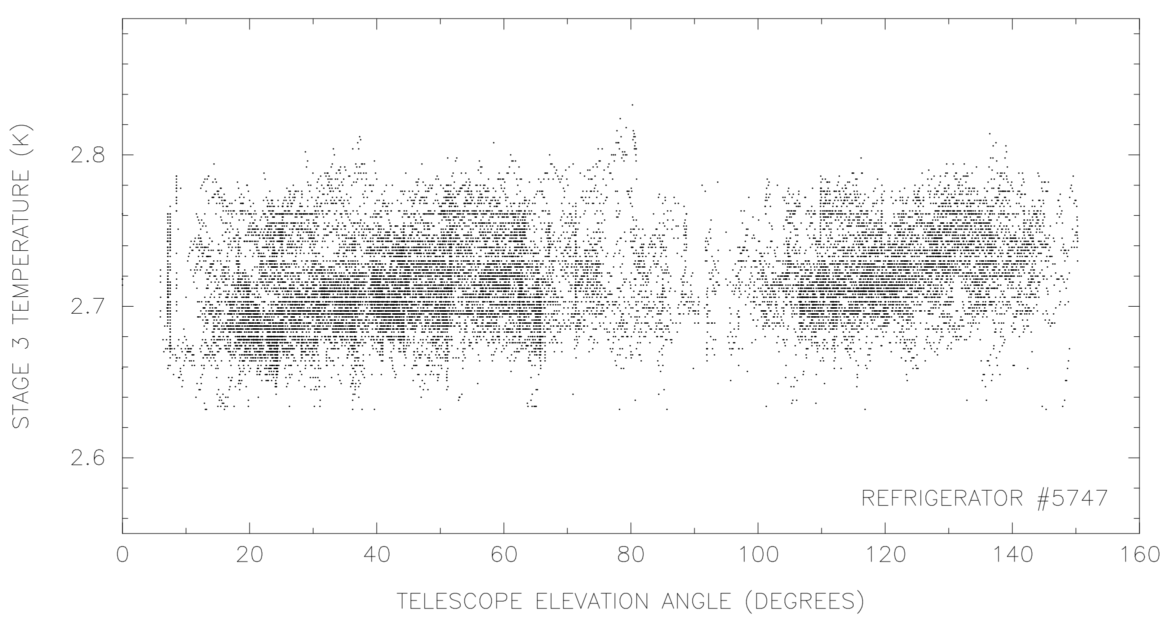

Figure 1. Cryocooler third stage temperature as a function of telescope elevation angle. At 90 degrees, the cryocooler's cold end is up. Data were measured every 1 minute over an 18 day period.

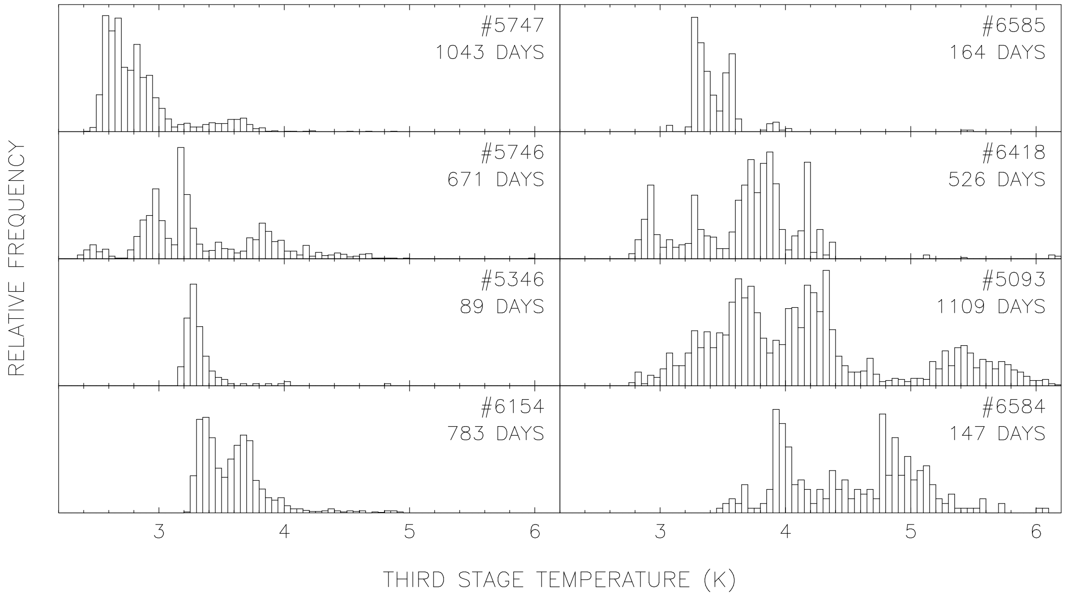

Figure 2. Temperature behavior of all cryocoolers from January 1994 to June 1997, based on measurements made every 12 hours. Histograms show the relative number of data points in each 0.05 K temperature interval; the time accumulated on a telescope is indicated for each cryocooler.

over the full range of elevation angles.

The refrigerator temperatures are recorded twice per day, averaged over 20 second intervals to smooth over temperature variations caused by the 1.92 second refrigerator cycle. Histograms of these data are shown in Figure 2. The third stage temperature is most erratic on refrigerator #5093, which uses a conventional split seal on the displacer.

Figure 3 shows the time series of temperatures for two of the oldest cryocoolers. Typically, the third stage temperature is stable to ± 0.1 K for weeks or months, then drifts upward over a period of days or weeks, sometimes becoming erratic. Then, following a power interruption, it jumps back to its original value. Brief power interruptions are rarely apparent in the long term record because the refrigerators recool in minutes. However, they are guaranteed to occur about every 2 months, when the telescopes are unplugged for a few minutes in order to move them to new locations.

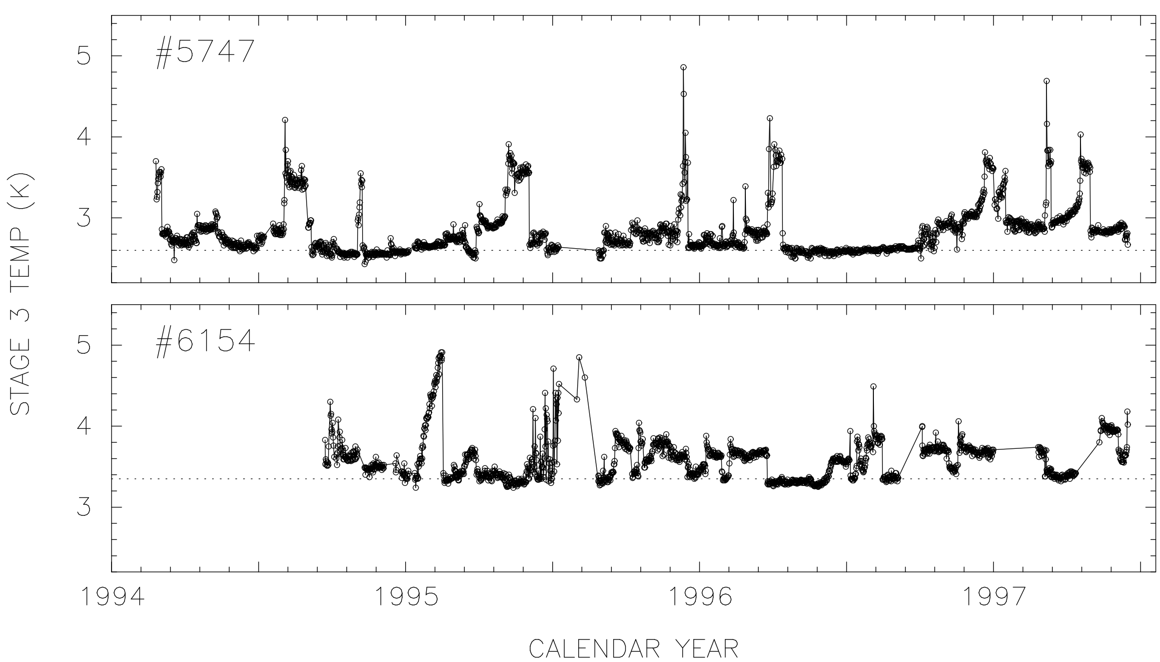

Figure 3. Third stage temperatures sampled twice per day over 3.3 years for cryocoolers #5747 and #6154.

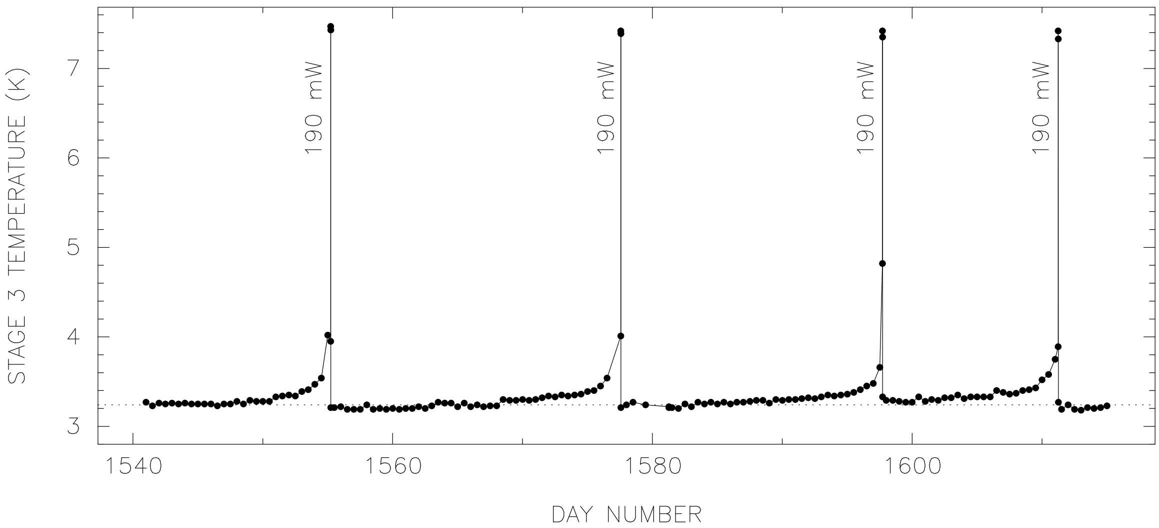

Figure 4. Temperature history of refrigerator #5346 over a 3 month period. The stage 3 temperature drifts upward gradually, but is driven back to its original value with the "defrost" cycle.

Instead of turning off the refrigerator, one often can succeed in driving the third stage temperature back to a lower value using a "defrost" cycle. One allows the refrigerator to run normally, but uses a heater resistor to apply about 200 mW to the third stage, raising its temperature to 7 or 8 K. After 15 minutes the heater is turned off and the third stage temperature drops back to its original value in a few minutes. An example of this behavior is shown in Figure 4.

Although the cause of the upward temperature drift is uncertain, 3 possibilities suggest themselves:

1. Gas leakage past the third stage seal. We are doubtful about this possibility – it isn't clear how the "defrost" cycle could restore the seal's original performance.
2. Development of flow channels within the regenerator. As a cryocooler's exhaust valve opens and the helium pressure drops from 18 to 6 atmospheres, gas rushes out of the third stage expansion space through the regenerator. Below 6 K, the helium density changes little from 18 to 6 atmospheres, so the mass flow and pressure drop through the regenerator is small. Perhaps this allows the gradual development of preferred flow channels through the regenerator, which degrade its performance. Figure 5 shows that the pressure drop rises rapidly above 6 K, perhaps explaining how the "defrost" cycle could disrupt the flow channels and drive the cryocooler back to its original temperature.

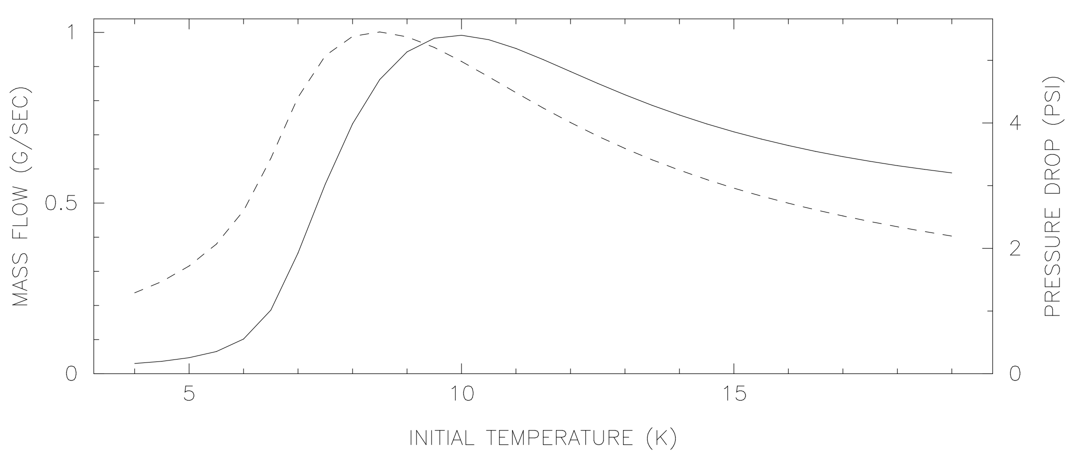

Figure 5. Calculated mass flow (dashed line) and pressure drop through a 1 cm long section of regenerator as a cryocooler's exhaust valve opens. The computation assumes that helium from a 4 cm^3 working volume flows through the regenerator in 0.3 seconds; the regenerator, filled with 0.018 cm diameter spheres with a packing factor of 0.6, has a cross section of 0.71 cm^2.

3. Buildup of contaminants within the third stage might increase friction between the displacer and cylinder wall. Since the "defrost" cycle raises the temperature only to 7 K, hydrogen is the most plausible contaminant.

ACTIVE TEMPERATURE REGULATION

The conversion gain of an SIS mixer is a sensitive function of the DC bias voltage applied to the superconducting junction. Normally one sets the bias voltage to maximize the output power from the receiver. As the physical temperature of the junction increases, the superconductor energy gap decreases and so does the optimum bias point, as shown in Figure 6. Thus, to obtain stable, well calibrated performance from the mixer, one must stabilize its temperature within a few milliKelvin over periods of hours. This requires active temperature regulation.

A calibrated silicon diode sensor and a heater resistor are attached to each mixer block in the BIMA dewars. The mixers are attached to the third stage heat station with flexible copper straps. Typically the thermal resistance from the mixer to the cold station is 0.15 K/mW, so one may regulate the mixer temperature over a range of ~0.5 K with just a few milliwatts of heater power; such a small heat load has little effect on the cryocooler's third stage temperature. Each mixer temperature is measured every 0.32 seconds by a control computer, which averages groups of 6 samples to compute the mean temperature over the past refrigerator cycle, then adjusts the heater power as follows:

$$P = G_p \times (T - T_{set}) + G_i \times \int_0^t (T - T_{set})\, dt'.$$

Here P is the heater power, T_{set} is the desired setpoint, and G_p and G_i are the proportional and integral gains, which are optimized empirically. Figure 7 shows that this technique succeeds in stabilizing the cycle-averaged mixer temperature to 1.8 mK r.m.s. – a peak-to-peak variation of 15 to 20 mK.

While the temperature regulation scheme described above works adequately, it does not remove the 10 to 20 mK swing within each refrigerator cycle. As shown in Figure 8, this causes the receiver's output power to vary by a few percent, which is

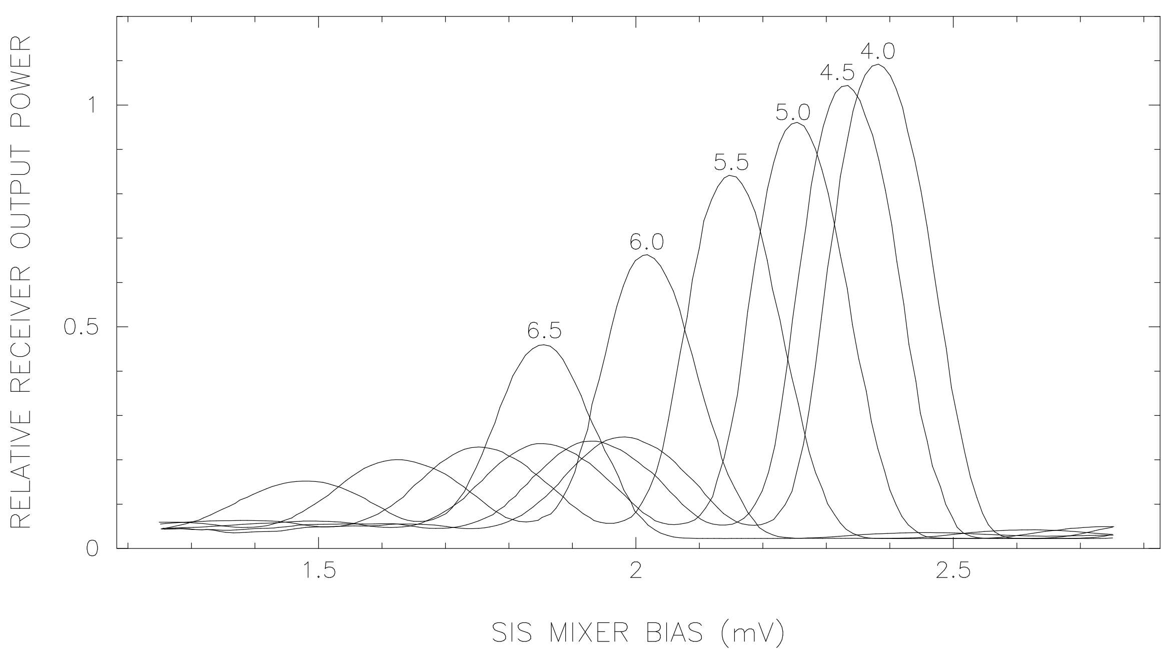

Figure 6. Receiver output power vs. DC bias voltage applied to a Nb/AlOx/Nb SIS junction, with the junction held at 5 temperatures. The local oscillator frequency is 107 GHz in this example. Generally the bias voltage is adjusted to maximize the output power. The optimum bias is a sensitive function of temperature.

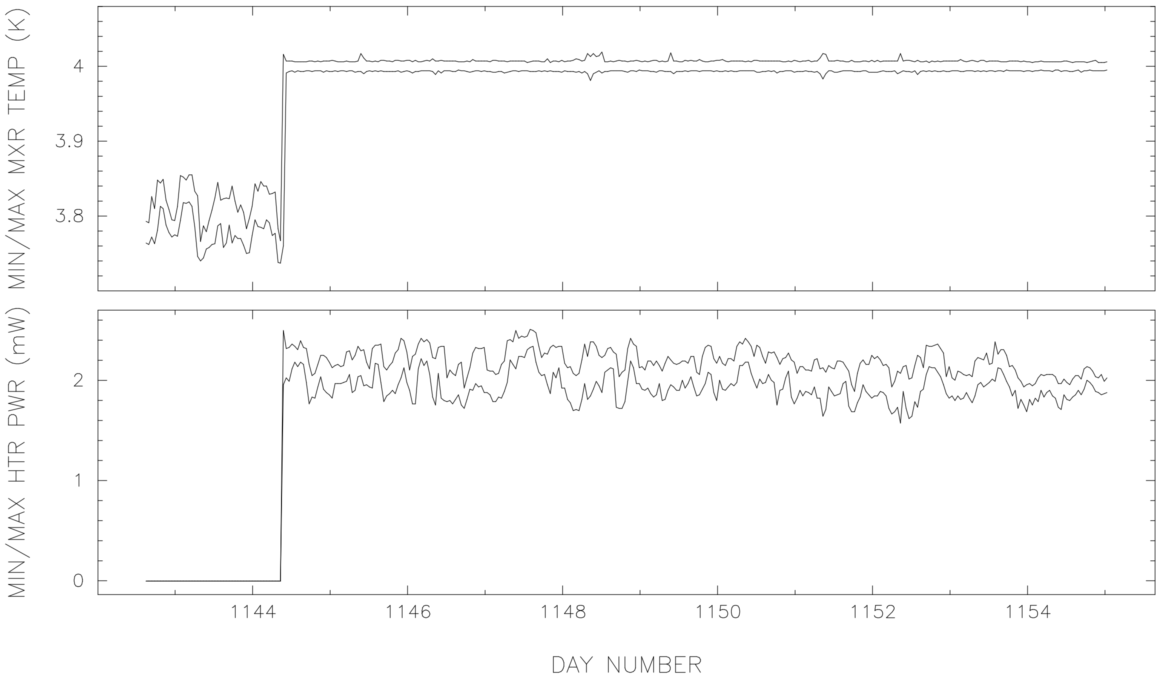

Figure 7. SIS mixer block temperature monitored over a 12 day period, showing the effect of temperature regulation. The top panel shows the minimum and maximum mixer temperatures (averaged over the 1.92 sec refrigerator cycle) measured in 53-minute intervals. The bottom panel shows the minimum and maximum heater powers in the corresponding intervals. Temperature regulation lowers the peak-to-peak mixer temperature fluctuations from 100 mK to <20 mK.

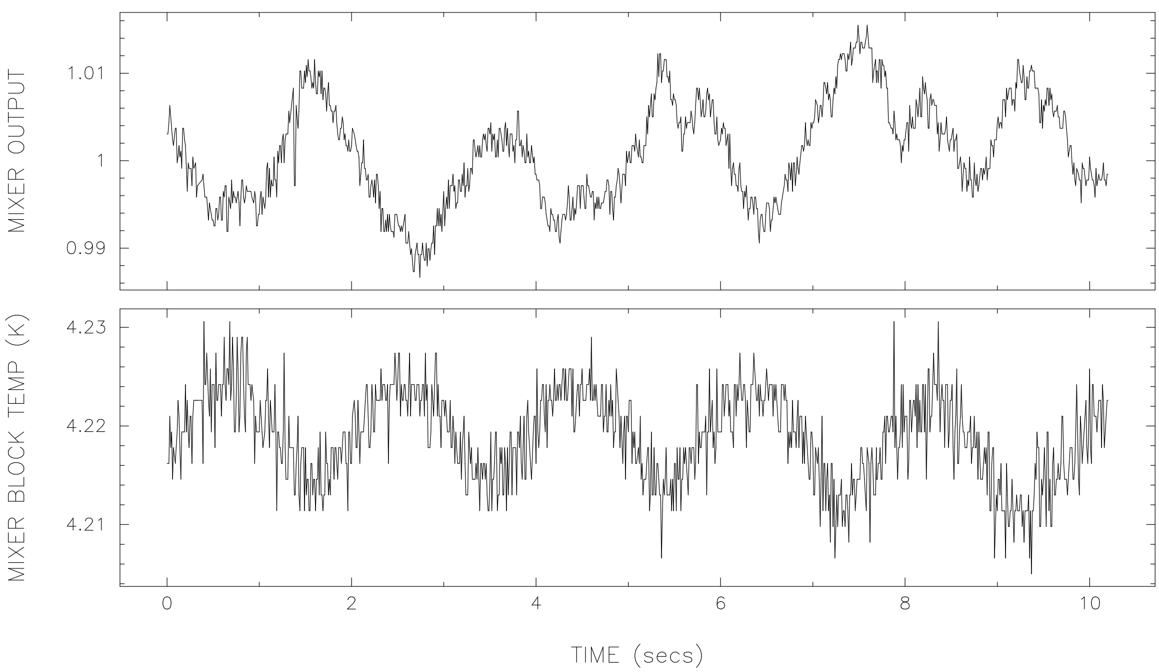

Figure 8. Mixer block temperature and receiver output power monitored every 0.01 sec for 10 seconds. The mixer block temperature varies by 10 mK with each refrigerator cycle. This causes the receiver output power to vary by 1.5%.

not generally serious. If necessary, the mixer block temperature can be controlled more tightly by pulsing the heater power within each refrigerator cycle. Lab tests, shown in Figure 9, demonstrate that this can reduce the mixer's peak-to-peak temperature swing to < 2 mK.

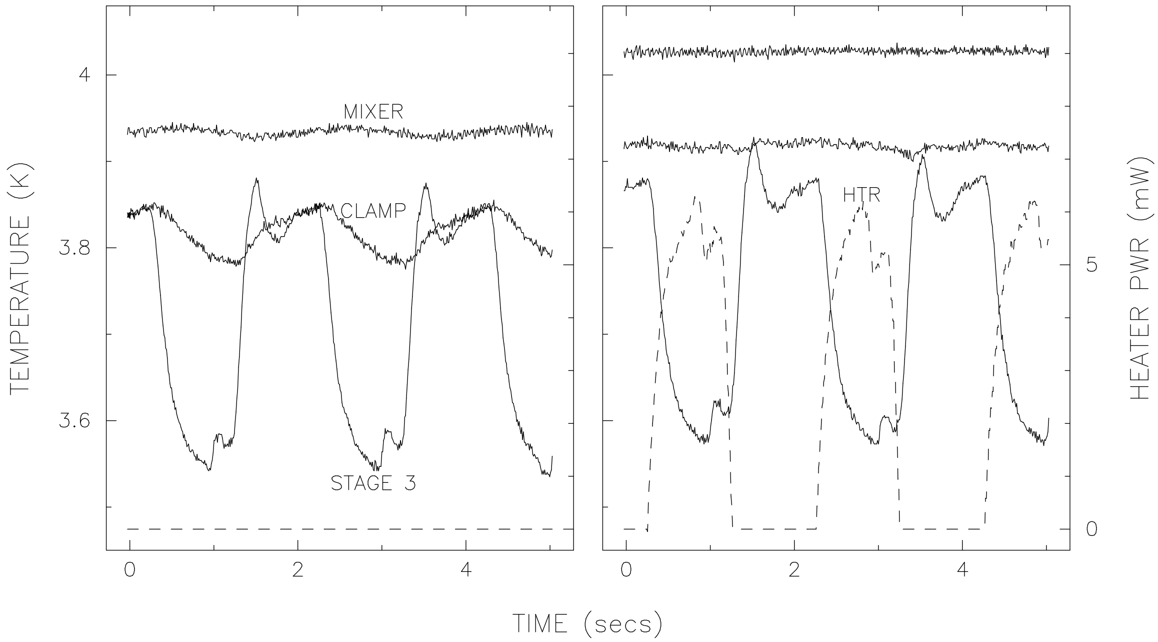

Figure 9. The left panel shows the stage 3, mixer clamp ring, and mixer temperatures with no heater current applied. The right panel shows the same temperatures with the heater pulsed to smooth out the cyclical temperature variations. The peak-to-peak temperature swing on the mixer is reduced from 15 mK to less than 2 mK. In this test the heater was mounted on the clamp ring, not the mixer block.

CONCLUSIONS

Gifford-McMahon cryocoolers operating at ∼4 K have performed reliably on radio telescopes in the BIMA array for several years with no long-term degradation. The third stage temperatures are insensitive to the refrigerator orientation, and typically are stable to ± 0.1 K for periods of weeks. Over time the third stage temperatures tend to drift upward, but often can be caused to jump back to their original values using a 15-minute "defrost" cycle. SIS mixers attached to the cryocoolers can be temperature stabilized to a few milliKelvin r.m.s. with a straightforward regulation scheme.

ACKNOWLEDGEMENTS

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REFERENCES

1. Welch, W.J., et al., The Berkeley-Illinois-Maryland-Association millimeter array, Publications of the Astronomical Society of the Pacific, 108:93 (1996).
2. Plambeck, R., Thatte, N., and Sykes, P., A 4 K Gifford-McMahon refrigerator for radio astronomy, in "Proc. 7th International Cryocooler Conf.," Phillips Laboratory report PL-CP–93-1001, Kirtland AFB, NM (1993), p. 401.
3. Plambeck, R.L., Improved seal for a 4 K Gifford-McMahon cryocooler, in: "Cryocoolers 8," R.G. Ross, Jr., ed., Plenum Press, New York (1995), p. 795.
4. Vespel SP-21, DuPont Engineering Polymers, Newark, DE.
5. Purchased from Toshiba America Electronics, Westboro, MA.
6. Part number R310MB-014-SP31, Bal Seal Engineering Co., Santa Ana, CA.