NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

ELECTRONICS DIVISION INTERNAL REPORT NO. 322

Evaluation of a Stirling-cycle Refrigerator

R. Norrod

September 9, 2008

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1 Introduction

This document reports on operational tests of a Sunpower, Inc. model GT refrigerator. The GT is a Stirling cycle one-stage cryocooler, and may be of interest for some radio astronomy applications because of its relatively small size, claimed reliability, low power consumption, and lack of an external compressor. A similar refrigerator (another manufacturer) is used in the current Allen Telescope Array receivers, but NRAO has no documented experience with such devices. We recently purchased one GT unit for evaluation. Here is described experiences with the refrigerator and controller operating characteristics, measured performance, load tests, cooldown curves, and temperature stability. Included in the Appendix is a report on refrigerator vibration tests done shortly after receipt of the refrigerator.

The Sunpower free-piston Stirling cryocoolers have an internal supply of gas and require no external compressor. They use gas bearings and a linear alternator with no contacting seals, and do not require routine maintenance.

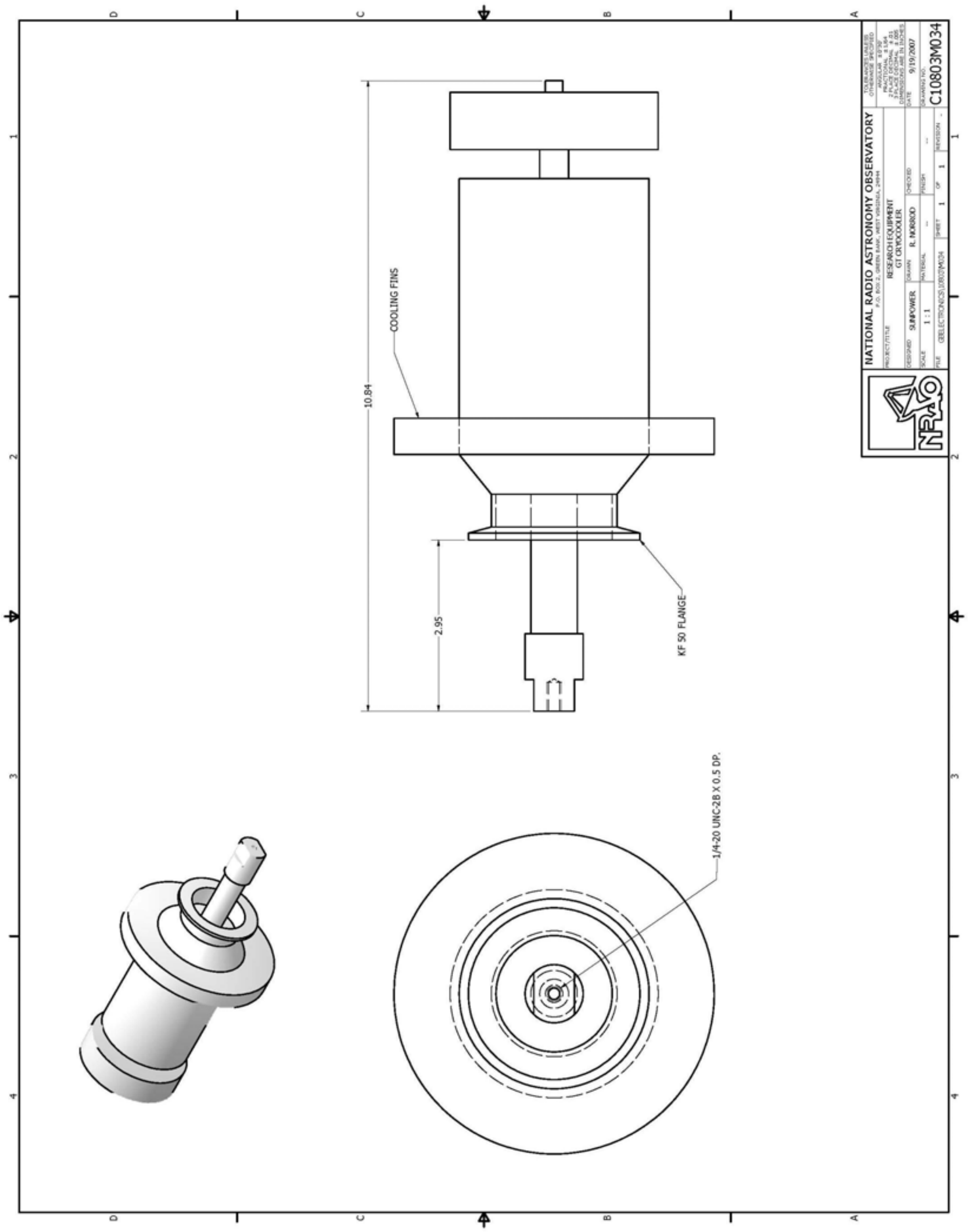
2 Refrigerator Facts

2.1 General

The refrigerator was purchased from the manufacturer, Sunpower Inc., 182 Mill Street, Athens, OH 45701, (740)594-2221, http://www.sunpower.com/ in late 2007. The GT is the most powerful Stirling cooler currently sold by Sunpower and several configuration options are available. We selected a welded KF50 flange for mounting, air fins for cooling, and the standard passive vibration damper. The vibration damper is a flat spiral spring assembly attached to the end of the refrigerator case, tuned at the factory to minimize vibration. When operating, the damper deflects about ½ inch so clearance around the end of the refrigerator must be provided. Tests were done to compare the vibration characteristics with a CTI 1020 refrigerator, and a report on those tests are included in Appendix A.

Figure 1 shows a simplified outline drawing of the GT with dimensions, and Figure 2 is a photograph of the refrigerator. For testing we fabricated a small test cryostat, and Figure 3 shows the cryostat with GT mounted. Note the fan to the side of the cooling fins. After some experimentation, this arrangement proved unsatisfactory for removing heat from the refrigerator, and a shroud was added around the refrigerator case and fins with the fan mounted below the vibration damper, pulling air through the shroud as shown in Figure 4. During cooldown and operation under load, the refrigerator requires 250-300 W of input power, and it is necessary to efficiently remove this heat for best performance.

One disappointment is that the operating manual received with our unit (in January 2008) was for the model CT rather than for a GT. Our Sunpower contact stated that a GT manual was not yet available but the CT manual applies except for a few minor points. We found that to generally be true but still a bit confusing.



COOLING FINS
10.84
2.95
KF 50 FLANGE
1/4-20 UNC-2B X 0.5 DP.
NATIONAL RADIO ASTRONOMY OBSERVATORY
P.O. BOX 2, GREEN BANK, WEST VIRGINIA, 24944
PROJECT/TITLE
RESEARCH EQUIPMENT
GT CRYOCOOLER
DESIGNED SUNPOWER
DRAWN R. NORROD
CHECKED
SCALE 1 : 1
MATERIAL --
FINISH --
SHEET 1 OF 1
REVISION -
TOLERANCES UNLESS OTHERWISE SPECIFIED
ANGULAR ±0°30'
FRACTIONAL ±1/64
2 PLACE DECIMAL ±.01
3 PLACE DECIMAL ±.005
DIMENSIONS ARE IN INCHES
DATE 9/19/2007
DRAWING NO.
C10803M034

Figure 2: The GT cryocooler. The cold finger is to the left and the vibration damper is to the right. The unit weighs 8 lb., 14 oz.

Figure 3: The GT refrigerator mounted to the test cryostat.

Figure 4: An air shroud installed around the refrigerator case and fins. A 100cfm fan is located below the shroud, pulling air downward.

2.2 Controller

The GT is shipped with a controller module which requires a 48VDC input voltage. Sunpower recommends a DC power supply capable of 10 amps – we used a Bravo model PSP-500-48 switching power supply. Sunpower supplies a temperature sensor to be mounted on the cold-finger, and the controller adjusts the refrigerator power to maintain a target cold temperature, as long as the target and heat load are within the heat lift capability of the refrigerator. The controller has a RS232 port allowing monitor and control of the refrigerator. The GT can be driven with a 60Hz AC voltage, and we tested this using a laboratory Variac, although that means of operation is not recommended by Sunpower. Because the coldhead piston stroke length increases with voltage, it is possible to damage the coldhead if too high a voltage is applied. The Sunpower controller and the 48V power supply are shown in Figure 5.

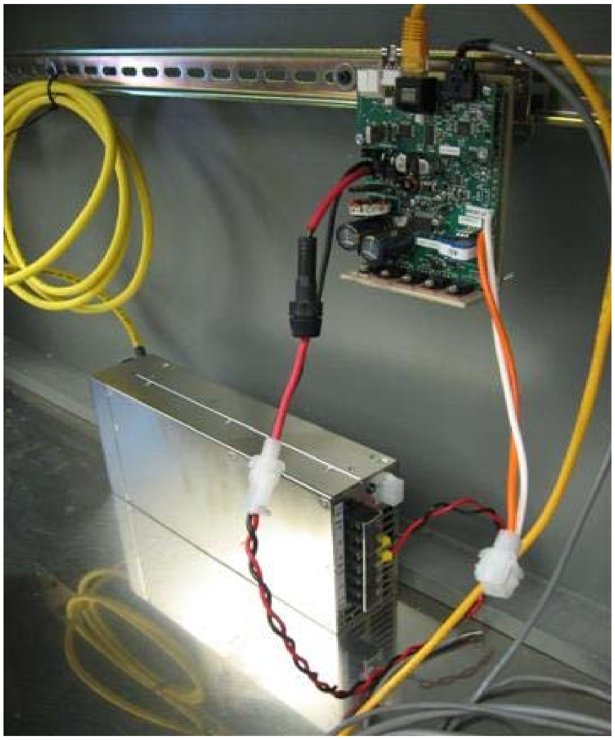


Figure 5: The Sunpower controller (upper unit) and 48V DC power supply. The controller is 3.2 X 5.6 X 1.5 inches. The red/black fused connection is the controller DC input, the orange/white cable is refrigerator power output. Connector jacks for the RS232 port and the temperature sensor input are at the top.

The Sunpower controller appears to drive the refrigerator by a pulse-width-modulated chop of the 48VDC voltage, as shown in Figure 6. Overlaid on the PWM voltage is the Variac drive voltage we found to operate the GT smoothly at room temperature (maximum voltage that gave no knocking sound).

A USB-RS232 converter and cable to connect a PC to the controller were received with the system, along with instructions for communication via ASCII sequences. User settable parameters are stored in non-volatile memory in the controller. We used the terminal program Hyperterm for communication. Upon application of 48VDC power, the controller initiates a start-up sequence taking about 10 seconds and then the refrigerator begins cooling. The default control mode is such that the controller uses PID servo control to achieve and maintain a temperature setpoint (value settable by the command “SET TTARGET=XX.X”). The controller adjusts the refrigerator piston stroke via PWM, increasing the stroke at several points during a cooldown. A query command “E” yields a response of three stroke magnitudes in mm: MAX, MIN, ACTUAL. The minimum stroke MIN is always 4.0, and MAX varies with the coldhead temperature, e.g. 4.69 at 290K and 7.0 at temperatures less than 200K. ACTUAL is the current commanded stroke – during a cooldown this is equal to MAX and will lie somewhere between MIN and MAX once TTARGET is achieved. Of course, depending on the system heat loading, it is possible to set a TTARGET that lies outside the refrigerator control range, either below the achievable temperature with the maximum stroke, or above the temperature at the minimum stroke of 4mm. Another useful query command is "TC" which responds with the current coldhead temperature in Kelvin. The controllable temperature range depends on the refrigerator heat load.

A second control mode is available in which servo control is disabled. The user commands the refrigerator to a specific stroke, but we did little experimentation with this mode. Strangely, there is nothing like an "OFF/ON" command – we found no way to tell the refrigerator to stop running via the serial port.

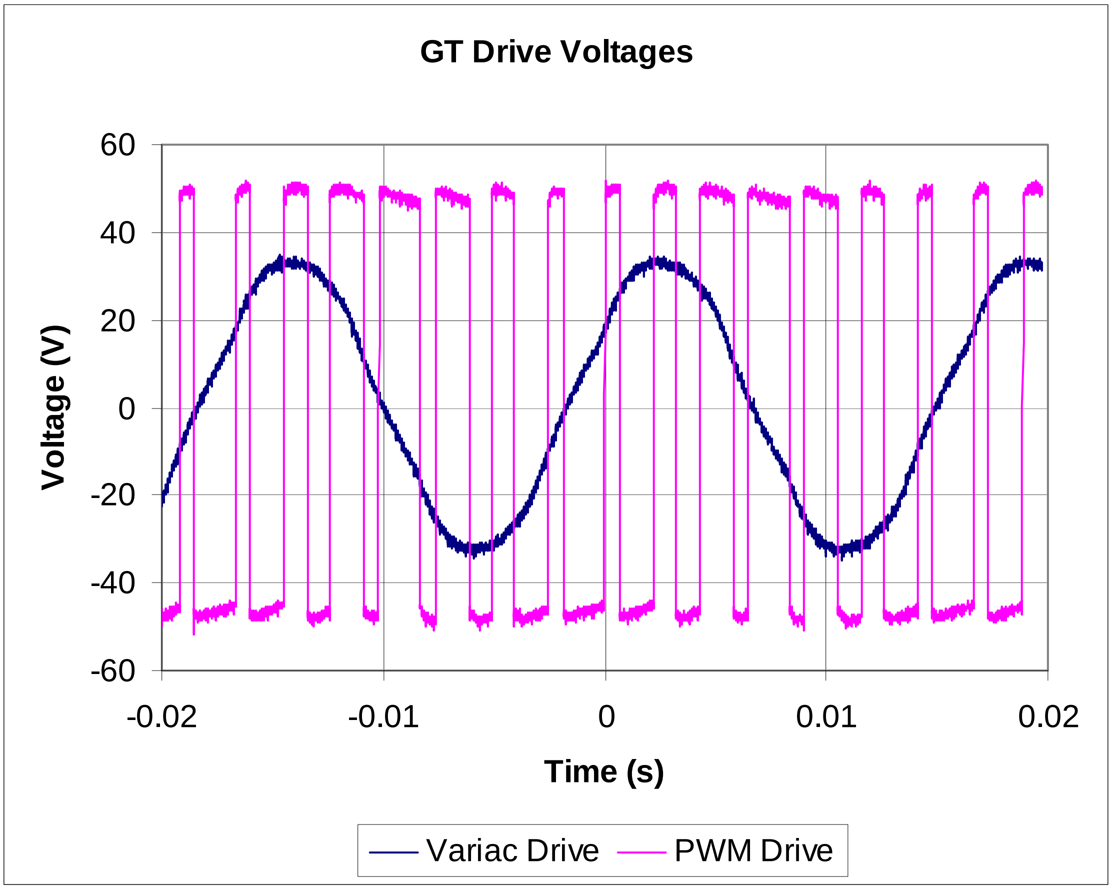


Figure 6: Refrigerator drive voltage. The pulse-width modulated waveform is typical of that supplied by the Sunpower controller. The sinusoid is an example of a 60Hz drive voltage that will also operate the refrigerator.

3 Results

3.1 Unloaded Performance

In order to evaluate the refrigerator as it might be used in a radio astronomy receiver, a small cryostat was constructed. The initial goal was to do cooldown and capacity tests with minimal mass and heat loading on the refrigerator. A small OFHC copper bracket assembly was constructed with heaters, thermostat, the Sunpower supplied temperature sensor (Lakeshore XPT-111-45), and a second sensor for temperature logging (Lakeshore DT-471-DI). This assembly weighs 8 oz. The conducted heatload to the bracket assembly is dominated by the heater wires, two 7X38 AWG stranded, silver-plated copper wires with teflon insulation. Using NIST thermal conductivity data for OFHC copper, the heat load for these two wires (38cm long, 300K to 40K) is calculated to be 15 mW. The conducted heat load of each phosphor-bronze solid 36 AWG wire to the Lakeshore sensors is estimated to be 0.5 mW based on Lakeshore thermal conductivity data, so the six wires' total contribution is approximately 3 mW. The bracket assembly was mounted to the GT cold finger using a single bolt with indium foil at the interface. To reduce radiation loading, the bracket was wrapped with five layers of aluminized mylar superinsulation with spacer layers of polyester mesh.

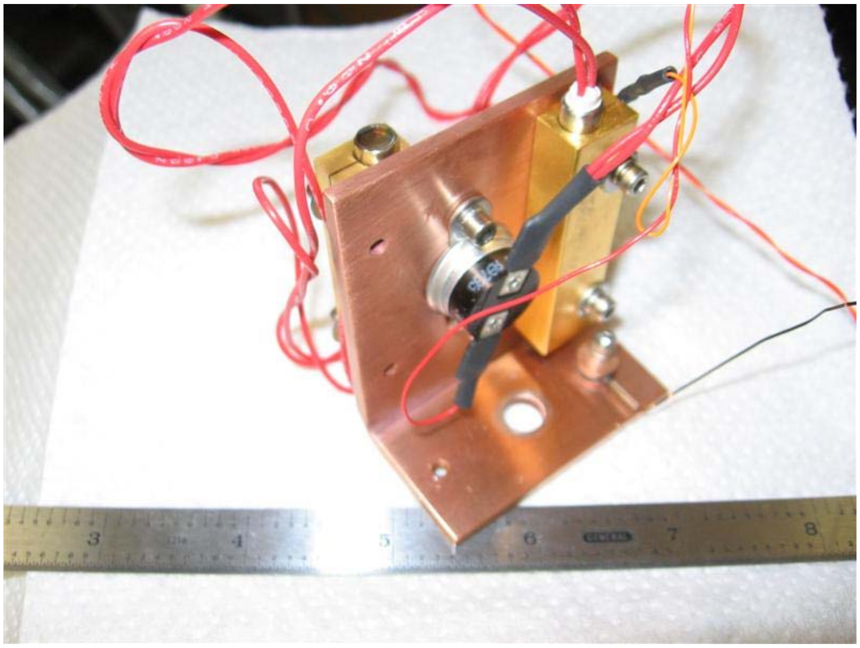


Figure 7: The heater and sensor assembly ready to be mounted on the cold finger.

Figure 8 is a log of the GT cooldown with the minimal mass and load as described above. With this configuration, the temperature reaches the controller target temperature of 40K and stabilizes in less than 20 minutes. The case temperature is obtained by mounting a Lakeshore sensor to the refrigerator case near the heatsink fins. By reducing the target temperature after the cooldown, we found that the minimum achievable temperature with this configuration is 37K.

Figure 9 shows the result of a capacity test of this configuration. Heat is applied with DC current through the heaters mounted on the coldhead bracket, the sensor temperature is allowed to stabilize, and then temperatures are recorded. The Sunpower controller is able to maintain the target temperature (40 K) until loading reaches about 3W at which point the stroke reaches the maximum 7mm, and then the temperature begins to increase.

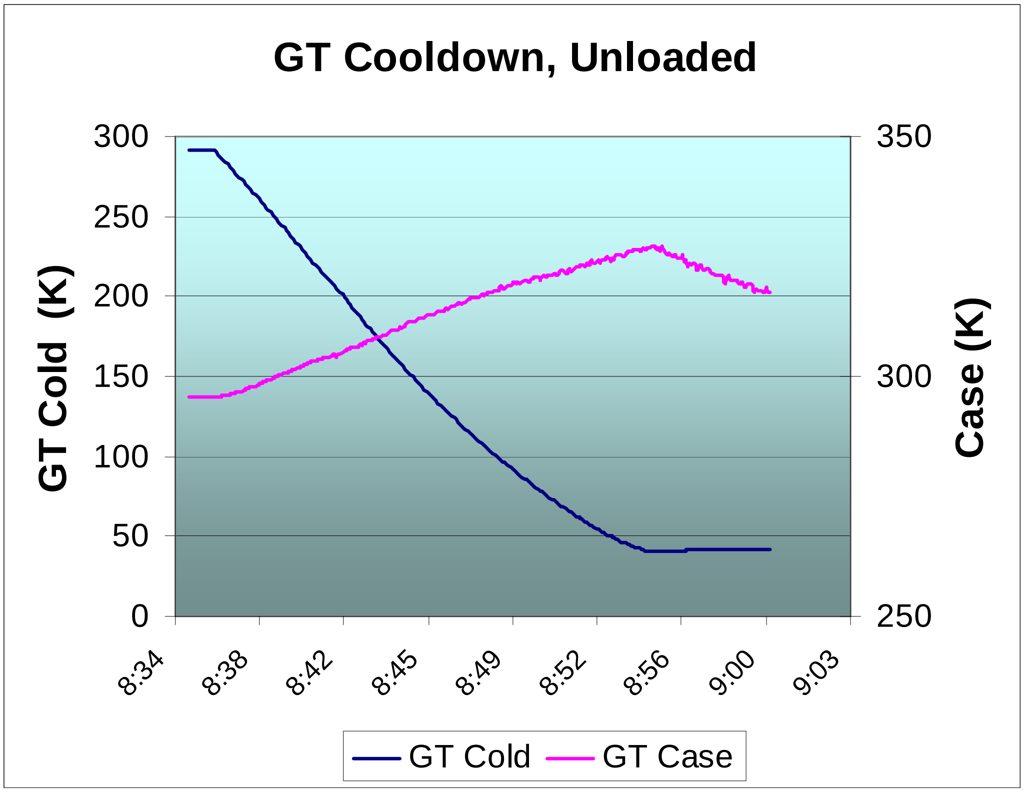


Figure 8: Cooldown of the "unloaded" GT with 40K target temperature. The horizontal axis is time.

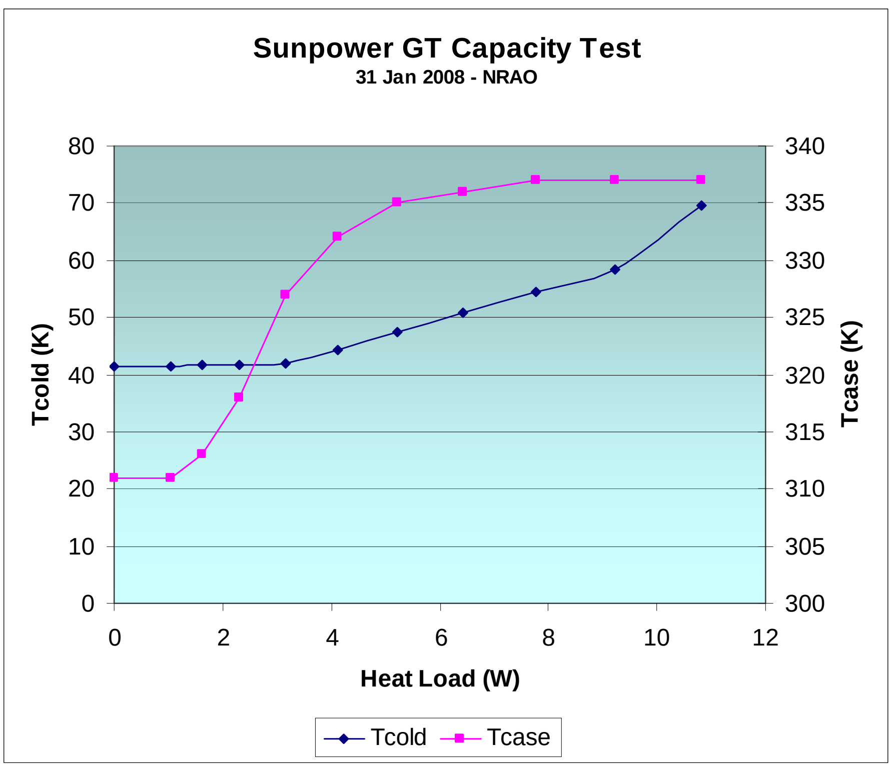


Figure 9: Capacity test of the "unloaded" GT system. The controller target temperature was 40K throughout. The controller temperature sensor and the Tcold sensor have about 1K offset.

3.2 Loaded Performance

To demonstrate the refrigerator performance under conditions similar to those that might be present during use in a radio astronomy receiver, an additional 5 lb. mass was mounted on the cold finger. Initially, a floating radiation shield, a cylinder of 0.032 aluminum polished on interior and exterior surfaces mounted on fiberglass standoffs, was installed around the cold mass shown in Figure 10. With this configuration, the shield was cooled to 262 K, but the minimum cold finger temperature was 46 K. We then changed the configuration so that the polished aluminum cylinder was attached to the cold finger, and wrapped it in five layers of superinsulation (Cryolam, available from MPI Technologies, Winchester, MA. http://www.mpirelease.com). With this configuration, Figure 11, the minimum temperature is just under 40 K.

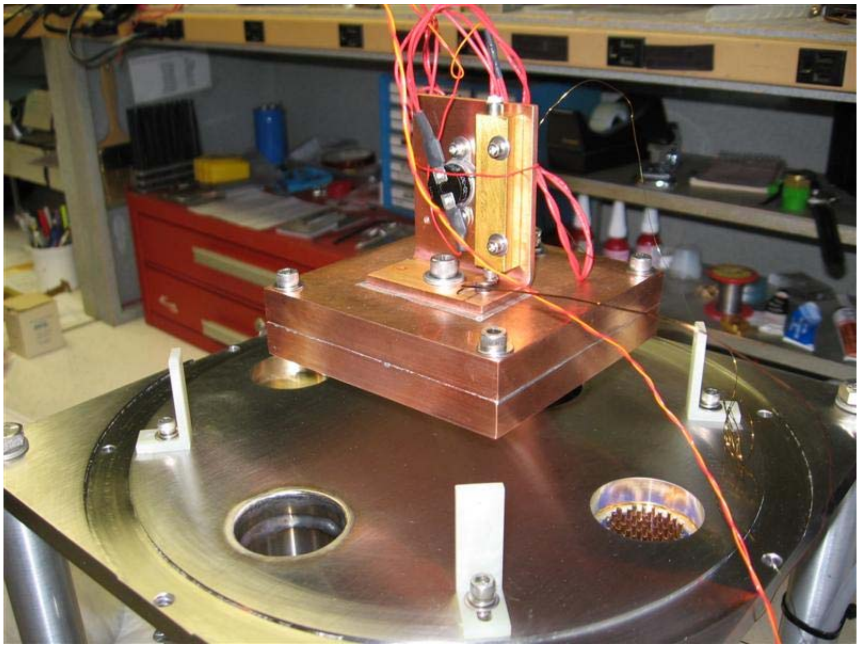


Figure 10: Mass added to the cold finger to simulate receiver cold mass. The total weight is 5.5 lbs, mostly OFHC copper.

Figure 12 is a plot of the GT cooldown configured as shown in Figure 10 and Figure 11. The discontinuities in the case temperature curve indicate the several points during the cooldown when the controller increases the refrigerator stroke, and then reduces it as the temperature reaches the target temperature and stabilizes.

Figure 13 shows a capacity test after this cooldown. Comparing this data with Figure 9, it appears the capacity is 2-3 watts lower; the difference should be due to increased radiation loading because of the larger cold surface area. This factor is discussed further in section 3.3.

Figure 11: A cylindrical heat shield wrapped in superinsulation added to the cold finger.

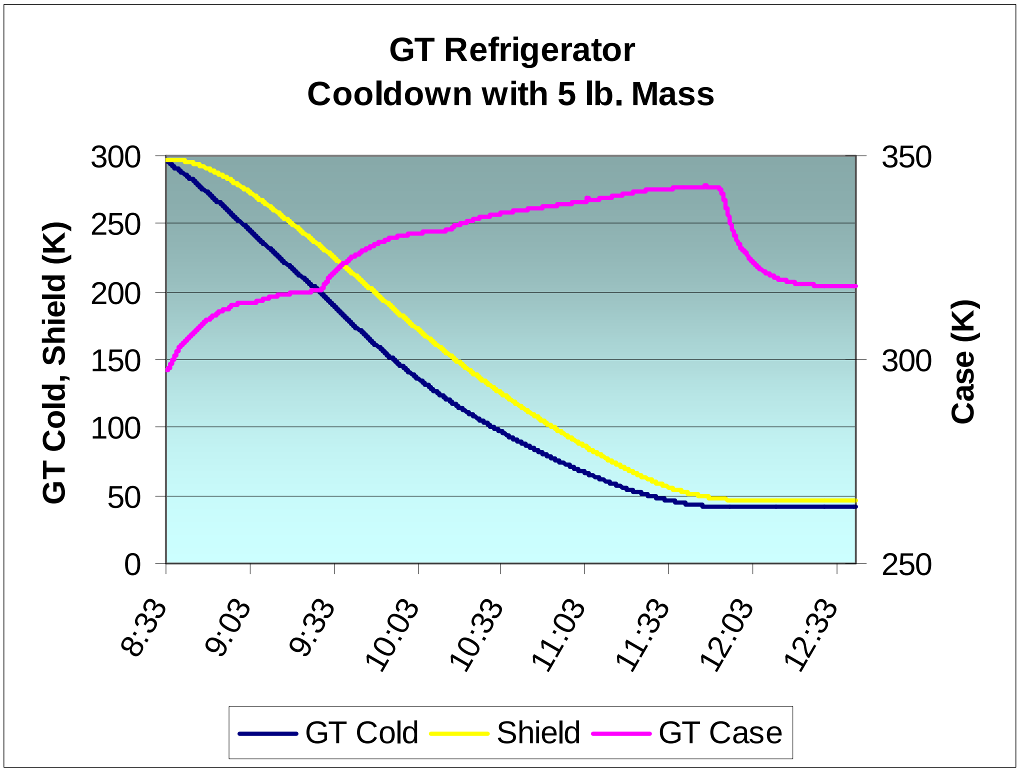


Figure 12: Cooldown of the GT with 5.5 lb. mass, and radiation shielding as shown in the previous figure. The controller target temperature was set to 40 K.

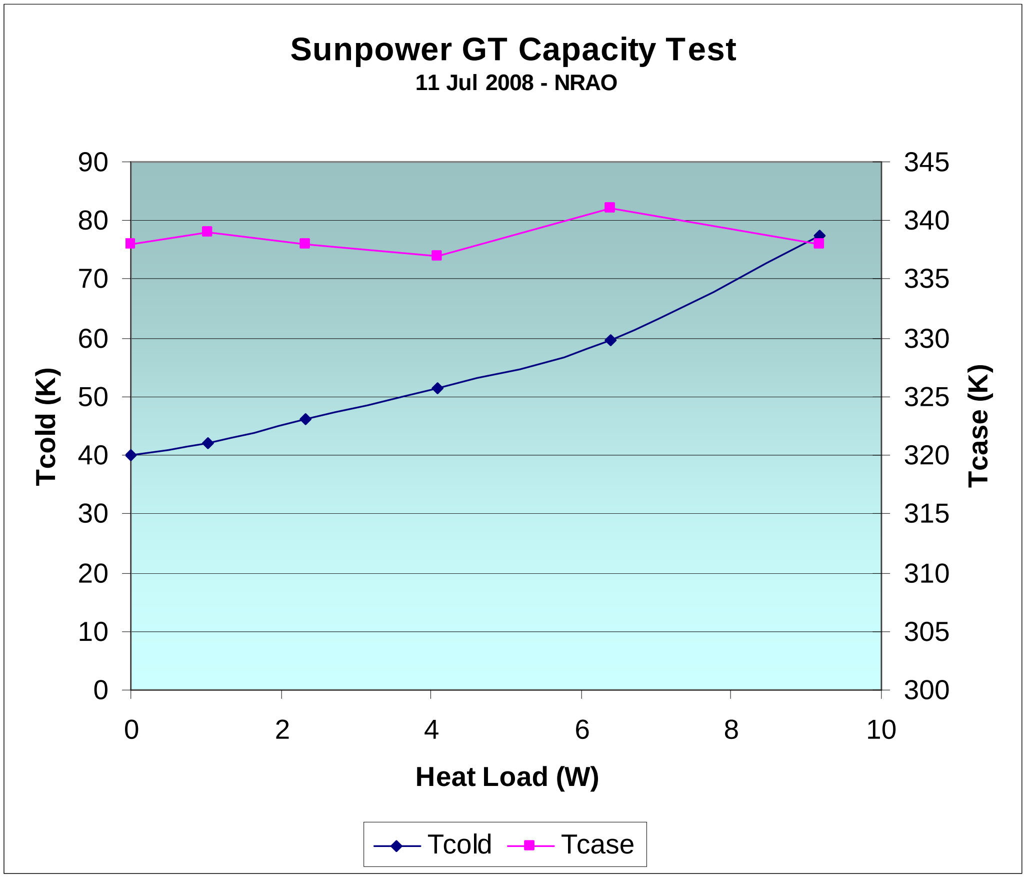


Figure 13: Capacity test following the cooldown of Figure 12. The target temperature was set to 35 K so that the refrigerator stroke was at the maximum throughout the capacity test.

As a final illustration of the GT performance, Figure 14 shows a cooldown with the 5.5 lb. mass and 4 watts of additional heat load applied through the heaters. The target temperature was set at 55 K to allow some capacity margin under these conditions. Table 1 illustrates how the power to the refrigerator controller changes as the system cools. This power is measured at the input to the controller, delivered by the 48 VDC supply.

Table 1

Tc, K	Pdc, W
292	53
192	196
136	236
82	262
55	215

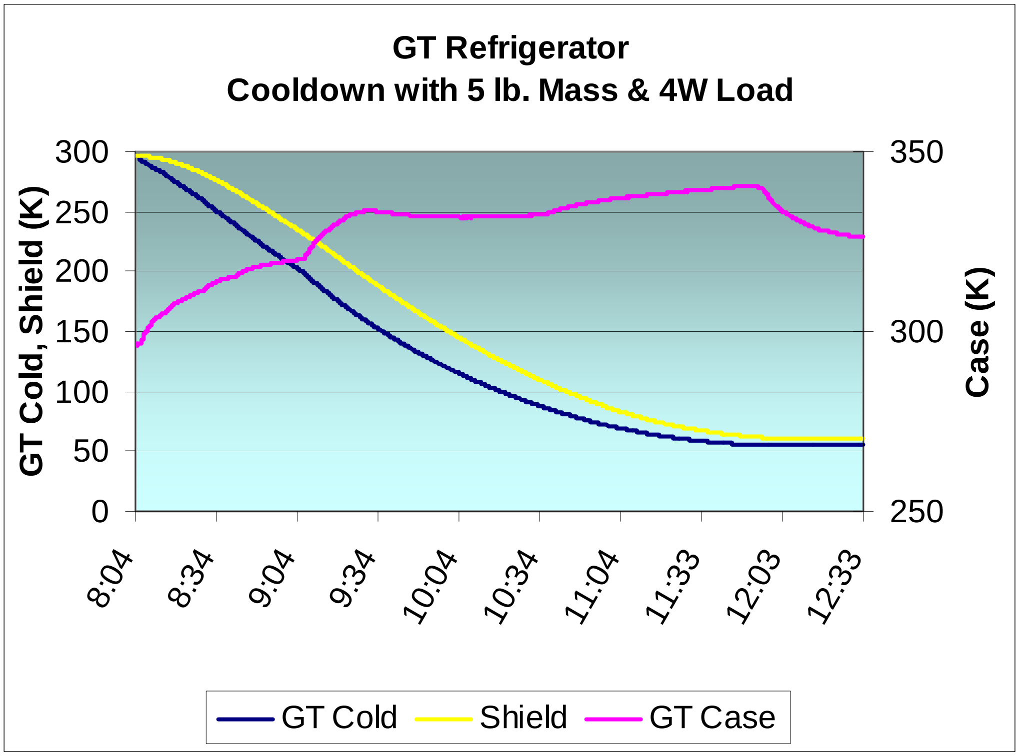


Figure 14: Cooldown with 5.5 lb. mass and 4 W additional heat load. The controller target temperature was 55 K.

3.3 Estimate of Radiation Loading

The heat transfer by radiation between long coaxial cylinders or concentric spheres is given by[1]:

$$Q_o = \frac{A_1\sigma(T_2^4 - T_1^4)}{1/\epsilon_1 + (A_1/A_2)*(1/\epsilon_2 - 1)} \qquad \text{Watts} \qquad (1)$$

where A_1, T_1, ϵ_1 are the area, temperature, and emissivity of the inner surface, and A_2, T_2, ϵ_2 apply to the outer surface. The Stefan-Boltzmann constant is: $\sigma = 5.67X10^{-8}W/(m^2K^4)$. In this case, the dimensions of the cylindrical radiation shield and the inner surface of the cryostat shell give $A_1 = 0.131m^2$ and $A_2 = 0.228m^2$. For temperatures of 40 K and 300 K, and assuming $\epsilon_1 = \epsilon_2 = 0.1$, equation 1 gives $Q_o = 4.0W$. For $\epsilon_1 = \epsilon_2 = 0.05$, $Q_o = 2.0W$. Comparing the capacity tests of Figure 9 and Figure 13, we can estimate that the effective emissivity of the test system configuration shown in Figure 11, including the effect of the superinsulation, is 0.05 to 0.1. (This estimate relies on the assumption that the radiation load of the "unloaded" configuration is negligable compared with that of the much larger area of the cylindrical radiation shield.)

3.4 Temperature Stability

The temperature stability of the GT over several hours is illustrated in Figure 15 and Figure 16. The Sunpower controller clearly provides good stability when operating in the servo control mode. It is not known why the temperatures fluctuated with the 60 Hz voltage drive. The unit

[1] ***Heat Transfer,*** by M. Necati Ozisik, p. 655, McGraw-Hill.

was operating in the laboratory unattended, so there was no significant variations in the external environment that should affect the refrigerator loading. Line voltage variations are a possibility, but that was not monitored during the test.

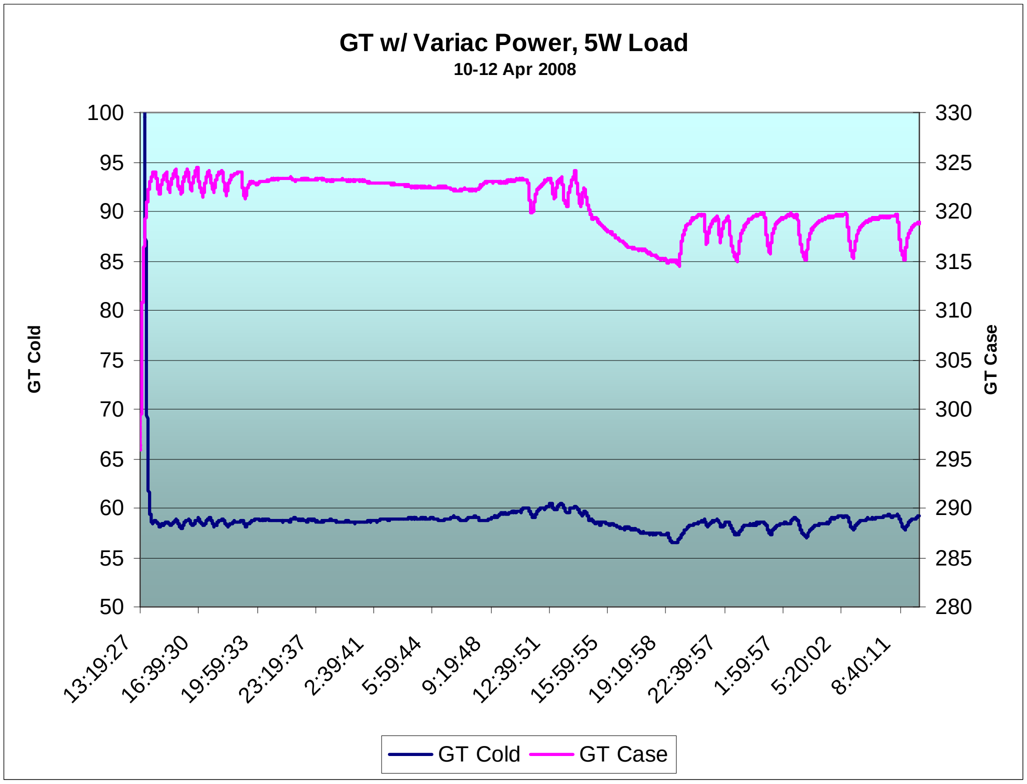


Figure 15: Temperature log of the GT when driven by 60 Hz AC voltage taken from a variable transformer. Mass on the cold finger was 1/2 lb. and 5 W electrical load was added.

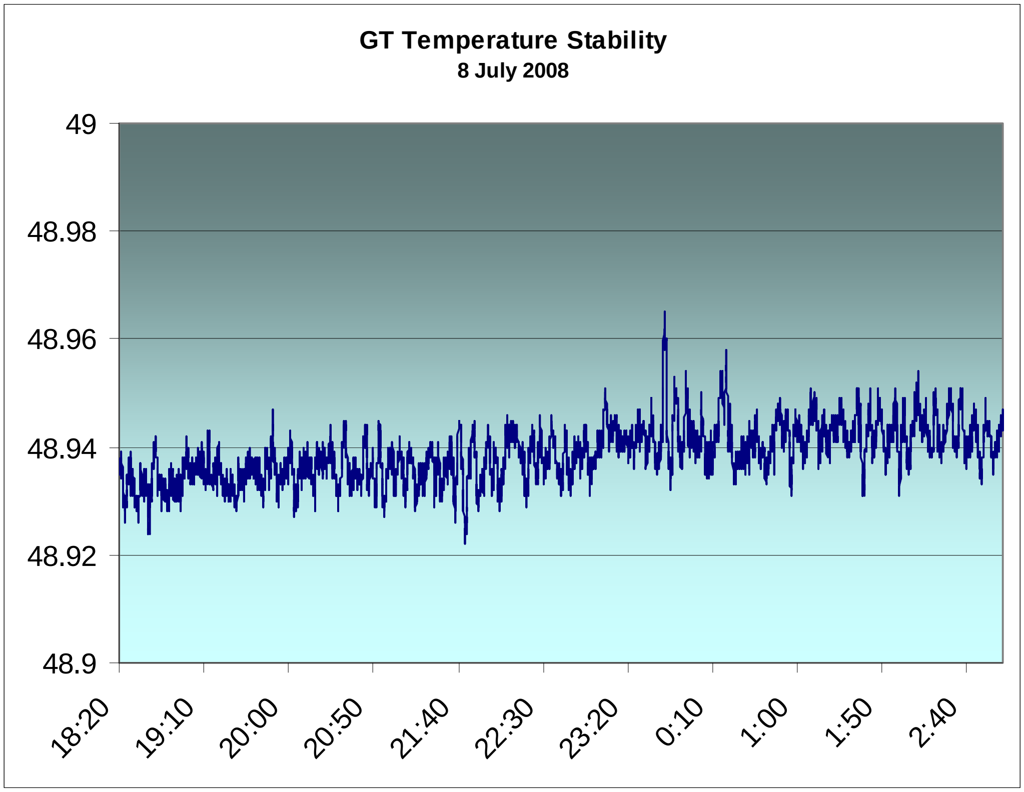


Figure 16: Temperature log of the GT driven by the Sunpower controller. Mass on the cold finger was 5.5 lbs. The controller temperature target was 48 K.

4 Summary

The refrigerator performed approximately as advertised, although we were not able to achieve 15W of cooling at 77K as Sunpower claims. However, that capacity is specified when the refrigerator case is kept below 35C (308K); we were not able to achieve this with our air-cooled arrangement – the case ran up to 67C (340K). With a more powerful fan, water cooling, or otherwise better cooling design, higher cooling capacity than achieved in these tests should be possible.

If using a single-stage refrigerator such as the GT, the receiver designer will need to take particular care with radiation loading. There is no powerful intermediate refrigerator stage to which radiation loads can be dumped, but the results we achieved with polished surfaces and superinsulation in these tests indicates that the problem is managable. The vibration spectrum of the GT and similar refrigerators are very different than that of the more common GM refrigerators that pulse at 1 or 2 Hz, but the GT vibration does not seem to be an extreme problem.

Although no RFI tests were done, it is almost certain that it will be necessary to add RFI shielding and filters around the PWM refrigerator controller and motor leads when operating in a radio astronomy receiver. Driving the motor with a 60 Hz AC voltage would be much more simple and produce less RFI, but the adaptive drive and superior temperature stability provided by the Sunpower controller is attractive.

The principal limitation of the refrigerator for radio astronomy applications is the minimum temperature achievable. The “no-load” minimum temperature is about 37K, and under typical receiver loads, the operating temperature will be 45-60K or higher. Because most NRAO centimeter receivers are currently cooled to 15-20K, there will be some predictable penalty in receiver noise temperature due to the higher operating temperature. For example, 2007 tests on the GBT 4-6 GHz receiver showed that the receiver noise temperature increased from 9 K at operating temperature of 11 K to 18 K at 53 K. The difference is due to a combination of higher LNA noise temperature and increased contributions from ohmic input losses in the OMT, isolator, calibration coupler, and so forth.

The GT seems to be a relatively powerful yet efficient cooler, and its properties could be quite attractive in some radio astronomy applications. The small size and weight should enable compact and light receiver designs, and the lack of a need for periodic maintenance due to seal wear or contamination should result in operational savings. Elimination of the need for a compressor could also result in significant savings, doing away with helium lines, compressor power consumption and maintenance costs, and the extra weight involved.

5 Acknowledgements

My thanks go to Rick Fisher and Steve White for encouragement and resources needed to purchase and evaluate the refrigerator. Ken Ward did most of the wiring and assembly of the cryostat and test system.

Appendix A
Vibration Test Results

January 18, 2008

Vibration Tests of a Sunpower GT Refrigerator

R. Norrod

1 Summary

This document reports initial operational and vibration tests of a Sunpower, Inc. model GT refrigerator. The GT is a stirling cycle, one-stage cryocooler, which may be of interest for some radio astronomy applications because of its relatively small size, claimed reliability, low power consumption, and lack of an external compressor. A similar refrigerator (another manufacturer) is used in the Allen Telescope Array receivers, but NRAO has no experience with such devices. We recently purchased one GT unit to test and evaluate. Here we describe measurements of the GT drive voltage, average current, and results of vibration tests using an accelerometer. For comparison, vibration tests were also done on a CTI 1020 refrigerator.

2 Setup

All the tests described here were done with the refrigerators on the bench, open to the atmosphere. The GT is shipped with controller module which requires a 48VDC input voltage. Sunpower recommends a DC power supply capable of 10 amps. The Sunpower controller accepts input from a temperature sensor mounted on the cold-finger, and will control the refrigerator power to maintain a set-point cold temperature, within the load capability of the refrigerator. It also has a RS232 port allowing remote monitor and control of the refrigerator. The GT can also be driven with a 60Hz AC voltage, and we tested this mode using a laboratory Variac.

The GT cools to 215K in 10 minutes in this setup, so to prevent significant cooling or frosting of the accelerometer PCB, data was taken as quickly as possible and the refrigerator was turned off and allowed to warm-up when necessary.

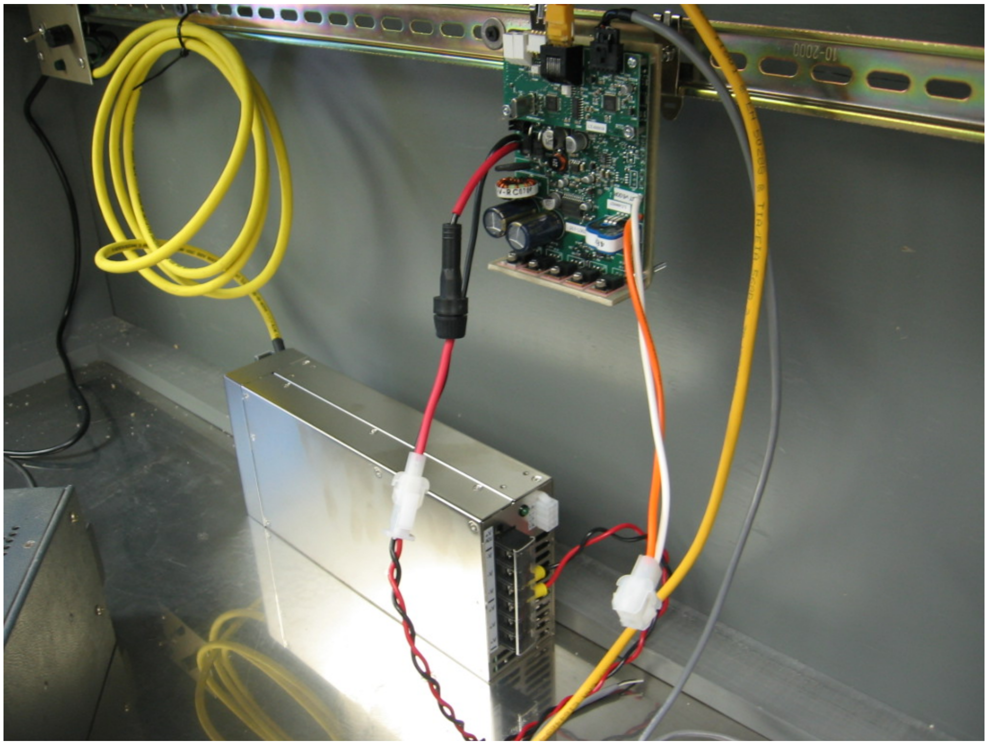


Figure 1: Sunpower controller (top) and 48VDC supply.

The vibration tests were done using a Silicon Designs 1221J-002 accelerometer mounted on a NRAO circuit board (developed for the GBT PTCS project). The single-axis accelerometer was oriented to measure the force parallel to the cold-finger/displacer axis. We input the accelerometer board output voltage both to a Tektronix TDS3012, 100 MHz bandwidth, 1.25Gsps oscilloscope for time-domain measurements and to a HP 3561A Dynamic Signal Analyzer for display of the frequency domain results. During vibration testing, the refrigerators were kept horizontal to eliminate gravity bias on the accelerometer.

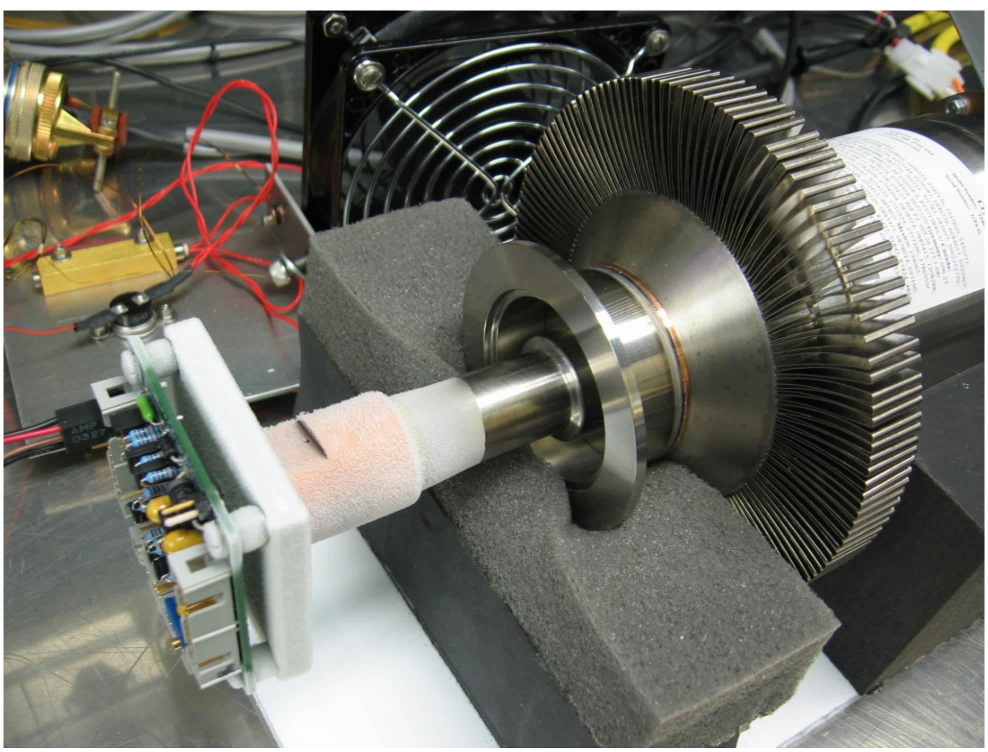


Figure 2: Accelerometer board mounted on the GT cold-finger.

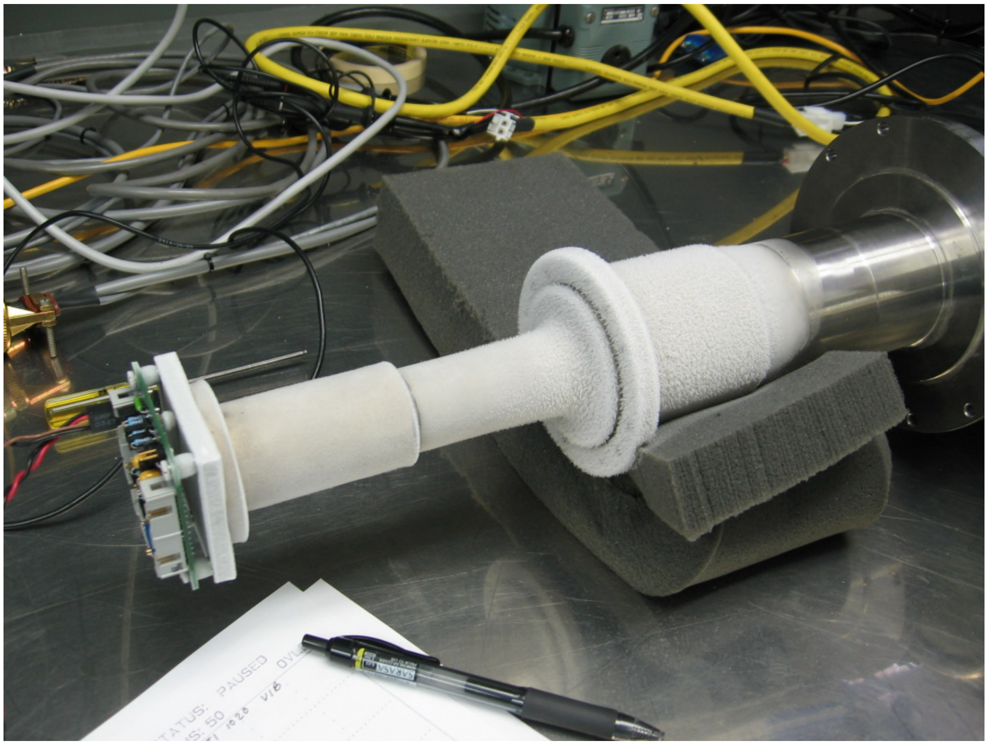


Figure 3: Accelerometer board mounted on the CTI 1020 cold-finger.

3 Results

3.1 Voltage and Current

The Sunpower controller appears to drive the refrigerator by a pulse-width-modulated chop of the 48VDC voltage, as shown in Figure 4. Upon application of power, the controller initiates a start-up sequence taking about 10 seconds and then the refrigerator begins cooling. According to the documentation, the start-up sequence centers the refrigerator piston. Overlaid on the PWM voltage is the Variac drive voltage which operated the GT smoothly as well (voltage amplitude tuned "by ear"). Additional testing will be needed to evaluate the refrigerator capacity and other measures using each drive method. The average Variac output current, measured using a clamp-on RMS ammeter, was 4.0 A at room temperature, increasing to 4.5 A at about 270K. Measurements at colder temperatures have not yet been done.

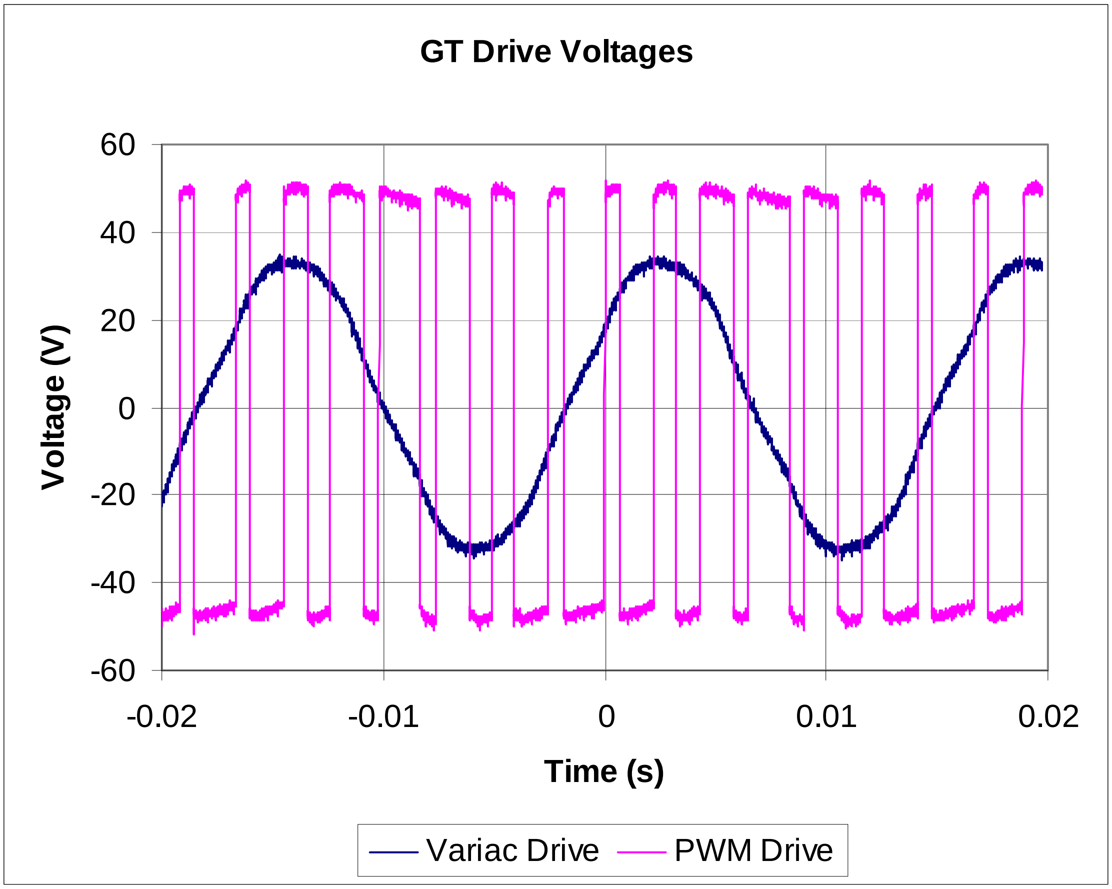


Figure 4: GT drive voltages as measured by the Tek TDS3012.

3.2 Vibration

3.2.1 Time Domain Data

Figure 5 and Figure 6 show typical accelerometer data for the GT using the Sunpower control module and the Variac, respectively. As can be seen, the acceleration peaks at about 2.2 g in both cases, but not surprisingly exhibits higher frequency characteristics when the Sunpower controller is used. The accelerometer scale was calibrated using the local gravity, by noting the voltage with the chip horizontal; linearity is assumed.

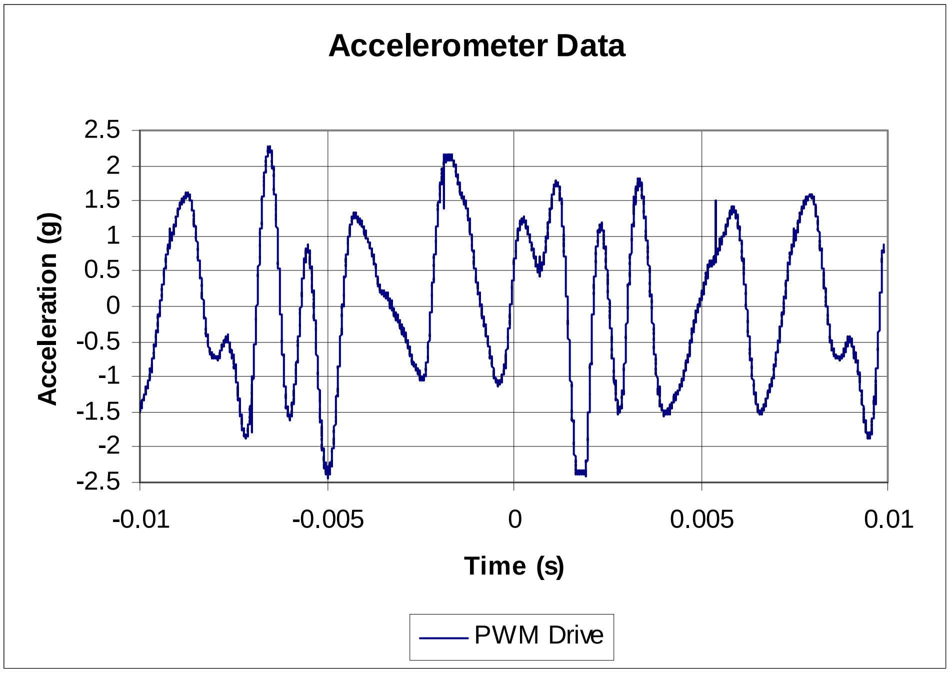


Figure 5: GT acceleration using PWM drive voltage.

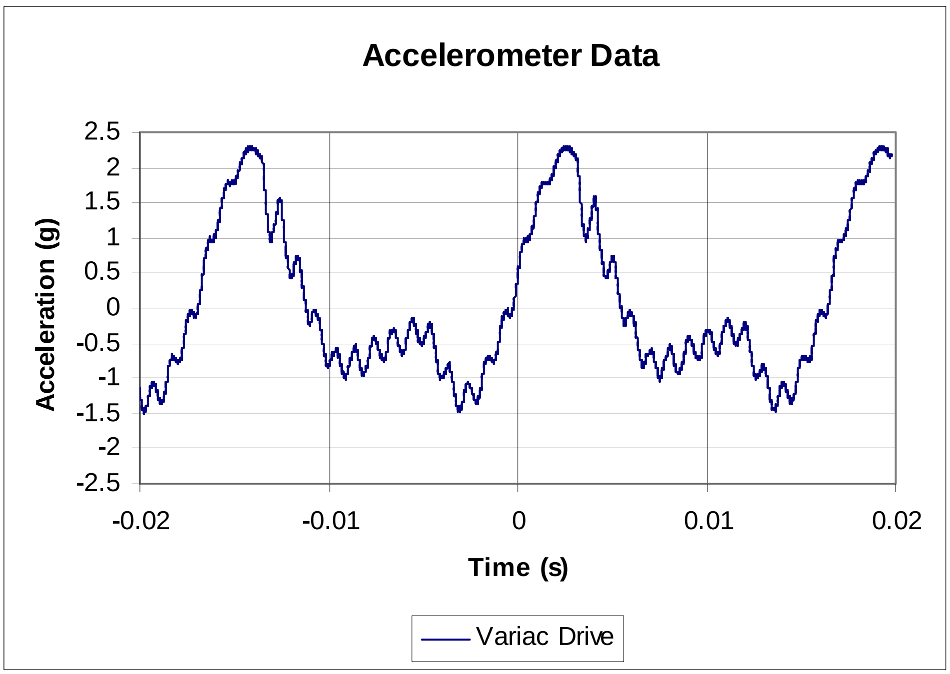


Figure 6: GT acceleration using Variac sine-wave drive.

For comparison, the vibration of a CTI 1020 refrigerator was measured using the same equipment and methods. The 1020 displacer cycles at a period of 1.2 seconds and the vibration shows a ~1g pulse at that rate, with lower level vibrations between, as shown in Figure 7. Figure 8 is a detail of the short pulse.

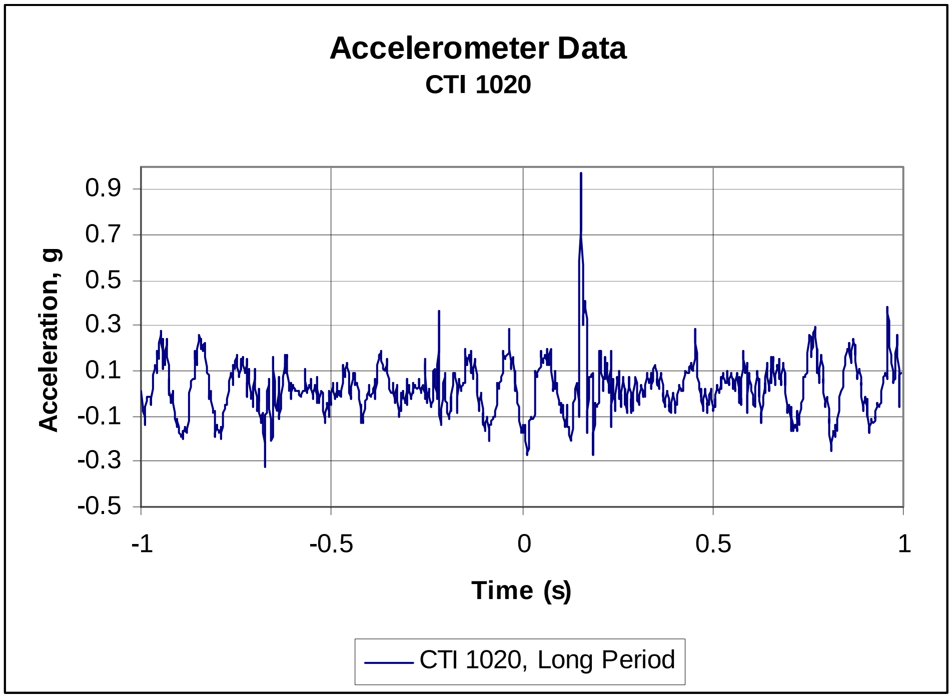


Figure 7: CTI 1020 acceleration.

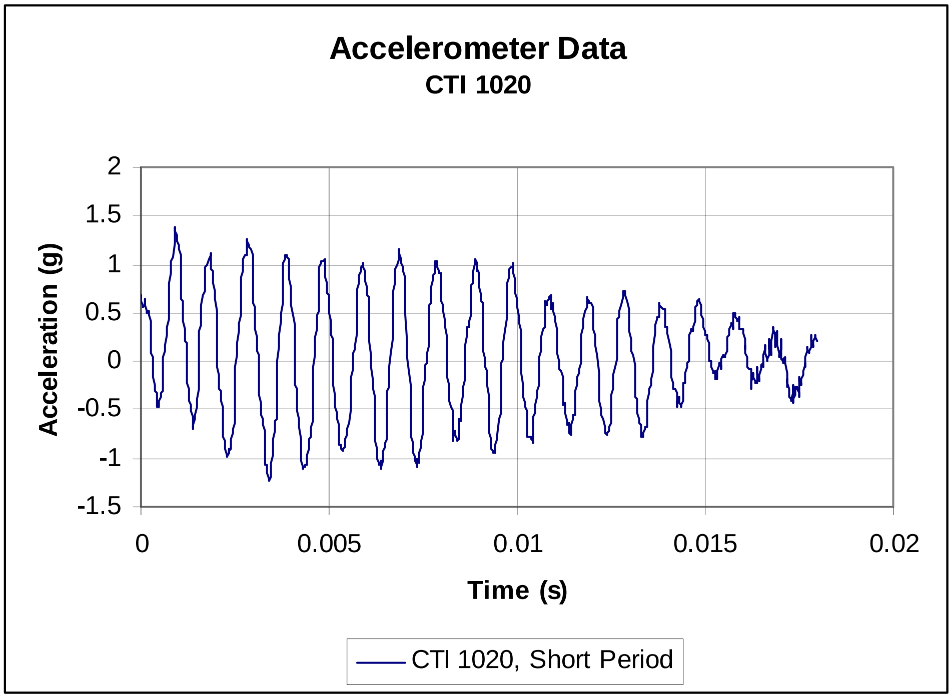


Figure 8: Detail of the main 1020 vibration pulse.

3.2.2 Frequency Domain Data

Figure 9 through Figure 12 display the GT vibration spectral information, for both drive modes and for two frequency spans. As might be expected from the time domain data, the PWM drive results in more vibrational power at higher frequencies. Harmonics of the 60Hz fundamental are visible above the noise floor to more than 3 kHz.

Figure 13 and Figure 14 provide similar information about the CTI 1020 spectrum. Here, the vibrations are both weaker, and fall-off much faster with frequency.

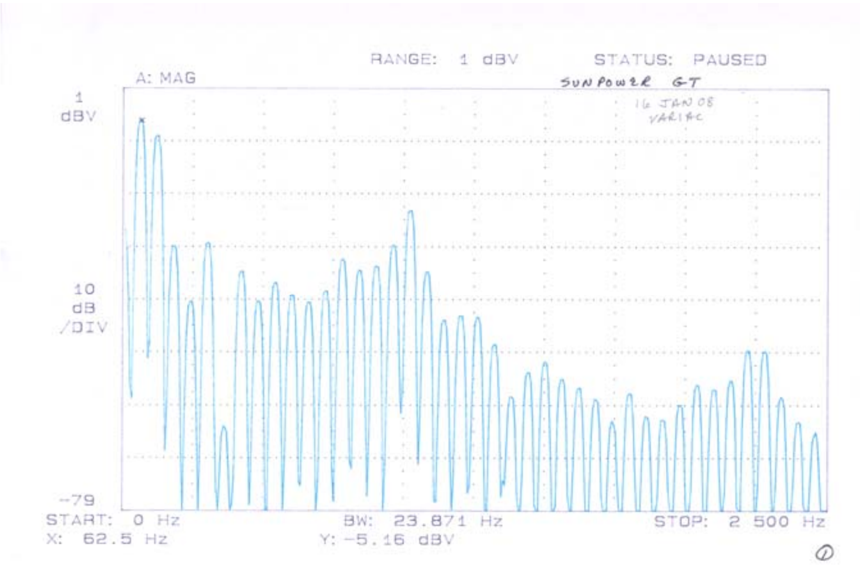


Figure 9: GT vibration, Variac drive, 0-2.5kHz.

Figure 10: GT, PWM drive, 0-2.5kHz.

Figure 11: GT, Variac drive, 0-500Hz.

Figure 12: GT, PWM drive, 0-500Hz.

Figure 13: CTI 1020, 0-500Hz.

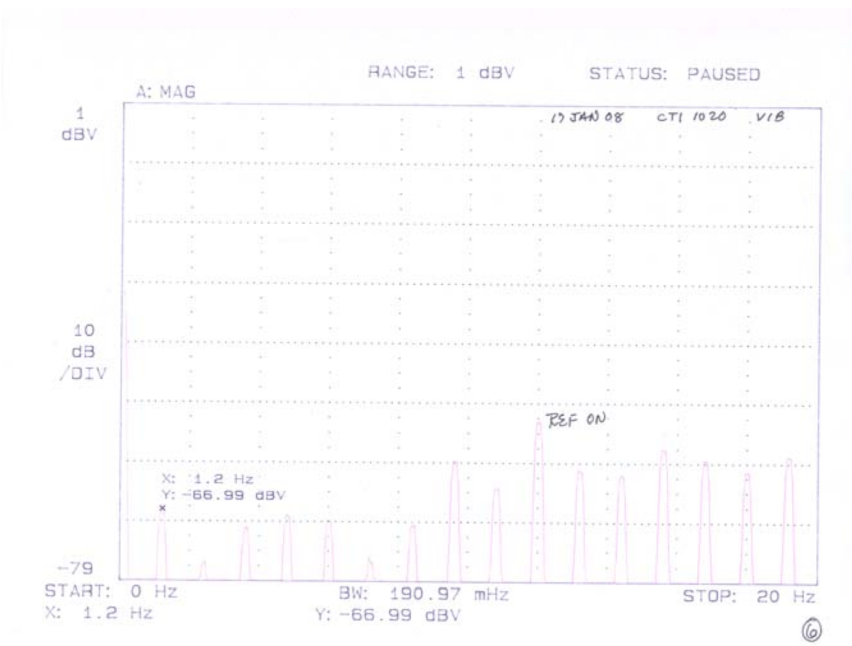
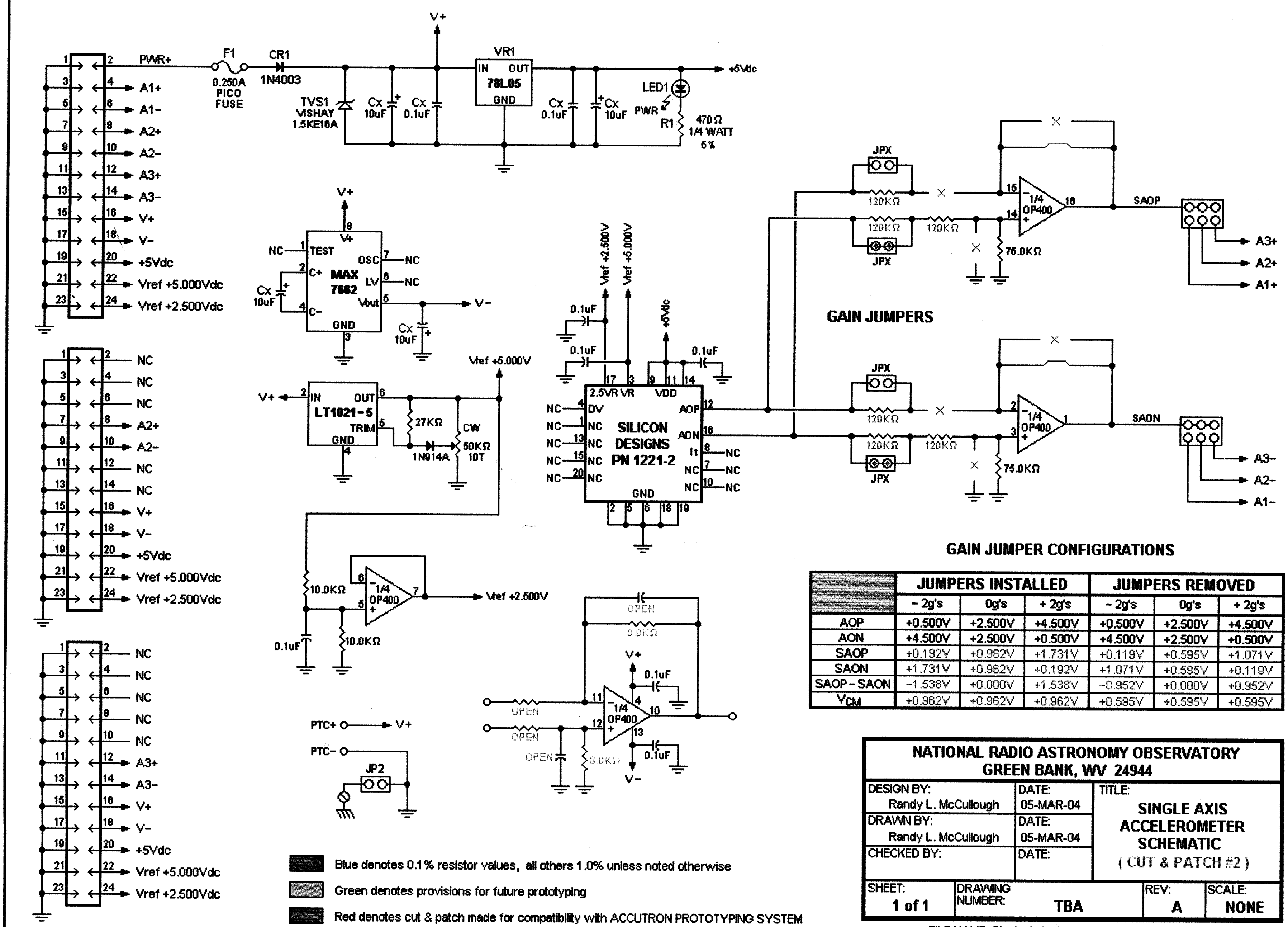


Figure 14: CTI 1020, 0-20Hz.

Accelerometer Schematic and Data Sheet



GAIN JUMPER CONFIGURATIONS

	JUMPERS INSTALLED			JUMPERS REMOVED		
	− 2g's	0g's	+ 2g's	− 2g's	0g's	+ 2g's
AOP	+0.500V	+2.500V	+4.500V	+0.500V	+2.500V	+4.500V
AON	+4.500V	+2.500V	+0.500V	+4.500V	+2.500V	+0.500V
SAOP	+0.192V	+0.962V	+1.731V	+0.119V	+0.595V	+1.071V
SAON	+1.731V	+0.962V	+0.192V	+1.071V	+0.595V	+0.119V
SAOP - SAON	−1.538V	+0.000V	+1.538V	−0.952V	+0.000V	+0.952V
V_{CM}	+0.962V	+0.962V	+0.962V	+0.595V	+0.595V	+0.595V

NATIONAL RADIO ASTRONOMY OBSERVATORY GREEN BANK, WV 24944			
DESIGN BY: Randy L. McCullough	DATE: 05-MAR-04	TITLE: SINGLE AXIS ACCELEROMETER SCHEMATIC (CUT & PATCH #2)	
DRAWN BY: Randy L. McCullough	DATE: 05-MAR-04		
CHECKED BY:	DATE:		
SHEET: 1 of 1	DRAWING NUMBER: TBA	REV: A	SCALE: NONE

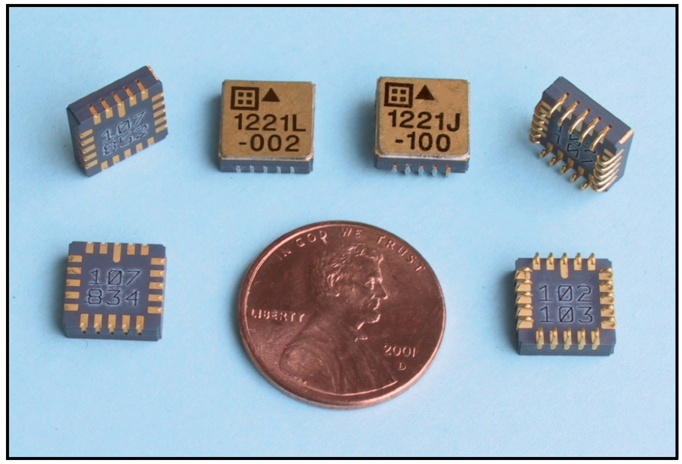
FILE NAME: Single Axis Accelerometer Schematic revA C&P#2.bmp

SILICON DESIGNS, INC

Model 1221

LOW NOISE ANALOG ACCELEROMETER

- **SENSOR:** Capacitive Micromachined
  Nitrogen Damped
  Hermetically Sealed
- **Low Noise: 5 µg/√Hz typical for 2g Full Scale Version**
- **Internal Temperature Sensor**
- **±4V Differential Output or 0.5V to 4.5V Single Ended Output**
- **Fully Calibrated**
- **Responds to DC & AC Acceleration**
- **-55 to +125 °C Operation**
- **+5 VDC, 8 mA Power (typical)**
- **Non-Standard g Ranges Available**
- **Integrated Sensor & Amplifier**
- **LCC or J-Lead Surface Mount Package**
- **Serialized for Traceability**
- **Pin Compatible with Model 1210**
- **RoHS Compliant**



ORDERING INFORMATION

Full Scale Acceleration	Hermetic Packages	
	20 pin LCC	20 pin JLCC
±2 g	1221L-002	1221J-002
±5 g	1221L-005	1221J-005
±10 g	1221L-010	1221J-010
±25 g	1221L-025	1221J-025
±50 g	1221L-050	1221J-050
±100 g	1221L-100	1221J-100
±200 g	1221L-200	1221J-200
±400 g	1221L-400	1221J-400

DESCRIPTION

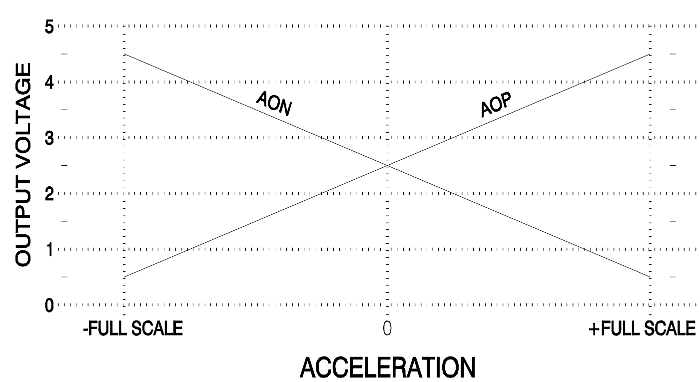
The Model 1221 is a low-cost, integrated accelerometer for use in zero to medium frequency instrumentation applications that require extremely low noise. The 2g version is ideally suited for seismic applications. Each miniature, hermetically sealed package combines a micro-machined capacitive sense element and a custom integrated circuit that includes a sense amplifier and differential output stage. It is relatively insensitive to temperature changes and gradients. Each device is marked with a serial number on its bottom surface for traceability. An optional calibration test sheet (1221-TST) is also available which lists the measured bias, scale factor, linearity, operating current and frequency response.

OPERATION

The Model 1221 produces two analog output voltages which vary with acceleration as shown in the figure below. The outputs can be used either in differential or single ended mode referenced to +2.5 volts. Two reference voltages, +5.0 and +2.5 volts (nominal), are required; the output scale factor is ratiometric to the +5 volt reference voltage, and both outputs at zero acceleration are equal to the +2.5 volt reference. The sensitive axis is perpendicular to the bottom of the package, with positive acceleration defined as a force pushing on the bottom of the package.

APPLICATIONS

- Seismic Monitoring
- Earthquake Detection
- Security Systems
- Machine Control
- Modal Analysis
- Instrumentation
- Appliances
- Robotics
- Crash Testing
- Vibration Monitoring
- Vibration Analysis
- Vehicle Dynamics



SIGNAL DESCRIPTIONS

V_{DD} and GND (power): Pins (9,11,14) and (2,5,6,18,19) respectively. Power (+5 Volts DC) and ground.

AOP and AON (output): Pins 12 and 16 respectively. Analog output voltages proportional to acceleration. The AOP voltage increases (AON decreases) with positive acceleration; at zero acceleration both outputs are nominally equal to the +2.5 volt reference. The device experiences positive (+1g) acceleration with its lid facing up in the earth's gravitational field. Either output can be used individually or the two outputs can be used differentially but differential mode is recommended for both lowest noise and highest accuracy operation. Voltages can be measured ratiometrically to VR for good accuracy without requiring a precision reference voltage. (See plot.)

DV (input): Pin 4. Deflection Voltage. Normally left open. A test input that applies an electrostatic force to the sense element, simulating a positive acceleration. The nominal voltage at this pin is ½ V_{DD}. DV voltages higher than required to bring the output to positive full scale may cause device damage.

VR (input): Pin 3. Voltage Reference. Tie directly to V_{DD} for ratiometric measurements or to a +5V reference for better absolute accuracy. A 0.1µF bypass capacitor is recommended at this pin.

2.5 Volt (input): Pin 17. Voltage Reference. Tie to a resistive voltage divider from +5 volts or to a +2.5 volt reference voltage.

I_T (output): Pin 8. Temperature dependent current source. (May be tied to V_{DD}; see full description on page 5).

PERFORMANCE - by Model: V_{DD}=V_R=5.0 VDC, T_C=25°C.

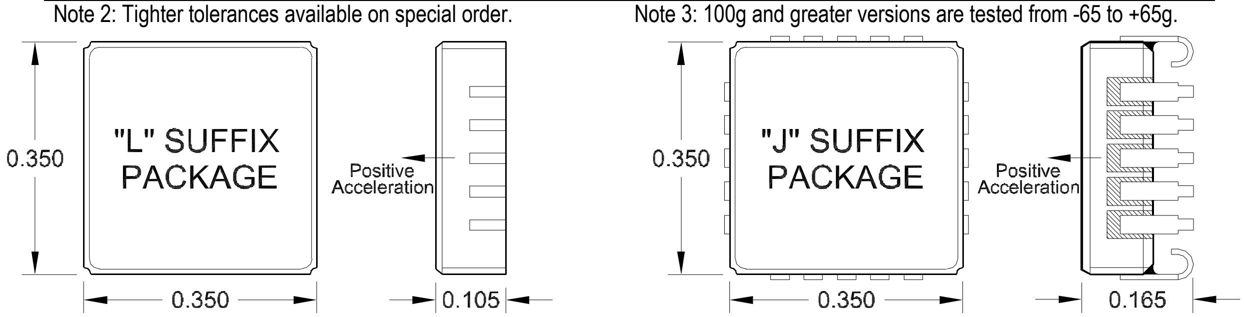
MODEL NUMBER	1221x-002	1221x-005	1221x-010	1221x-025	1221x-050	1221x-100	1221x-200	1221x-400	UNITS
Input Range	±2	±5	±10	±25	±50	±100	±200	±400	g
Frequency Response (Nominal, 3 dB)	0 - 400	0 - 600	0 - 1000	0 - 1500	0 - 2000	0 - 2500	0 - 3500	0 - 4000	Hz
Sensitivity (Differential) [1]	2000	800	400	160	80	40	20	10	mV/g
Output Noise (Differential, RMS, typical)	5	7	10	25	50	100	200	400	µg/(root Hz)
Max. Mechanical Shock (0.1 ms)	2000		5000						g

Note 1: Single ended sensitivity is half of values shown.

PERFORMANCE - all Models: Unless otherwise specified V_{DD}=V_R=5.0 VDC, T_C=25°C, Differential Mode.

PARAMETER		MIN	TYP	MAX	UNITS
Cross Axis Sensitivity			2	3	%
Bias Calibration Error [2]	-002		2	4	% of span
	-005 thru -200		1	2	
Bias Temperature Shift (T_C= -55 to +125°C) [2]	-002		100	300	(ppm of span)/°C
	-005 thru -200		50	200	
Scale Factor Calibration Error [2, 3]			1	2	%
Scale Factor Temperature Shift (T_C= -55 to +125°C) [2]		-250		250	ppm/°C
Non-Linearity (-90 to +90% of Full Scale) [2, 3]	-002 thru -050		0.15	0.5	% of span
	-100		0.25	1.0	
	-200		0.4	1.5	
	-400		0.7	2.0	
Power Supply Rejection Ratio			25		dB
Output Impedance			90		Ohms
Operating Voltage		4.75	5.0	5.25	Volts
Operating Current (I_{DD}+I_{VR}) [2]			8	10	mA
Mass: 'L' package (add 0.06 grams for 'J' package)			0.62		grams

Note 2: Tighter tolerances available on special order. Note 3: 100g and greater versions are tested from -65 to +65g.



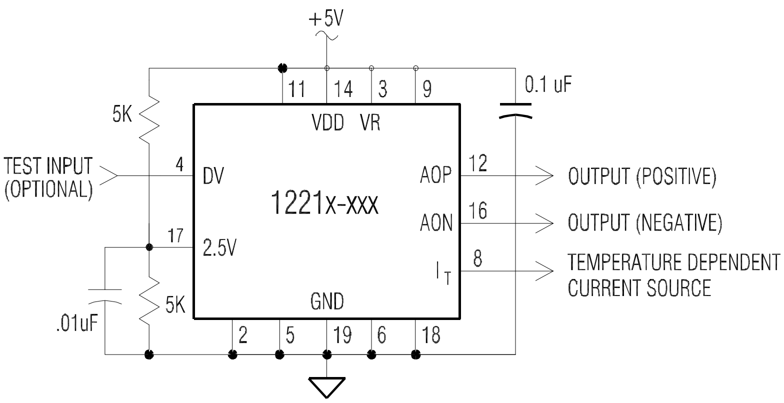
SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

ABSOLUTE MAXIMUM RATINGS *

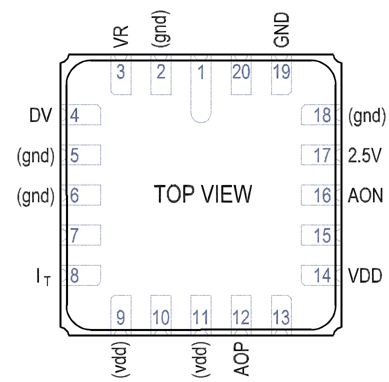
Case Operating Temperature	-55 to +125°C
Storage Temperature	-55 to +125°C
Acceleration Over-range	2000g for 0.1 ms
Voltage on V_{DD} to GND	-0.5V to 6.5V
Voltage on Any Pin (except DV) to GND [4]	-0.5V to V_{DD}+0.5V
Voltage on DV to GND [5]	±15V
Power Dissipation	50 mW

Note 4: Voltages on pins other than DV, GND or V_{DD} may exceed 0.5 volt above or below the supply voltages provided the current is limited to 1 mA..
Note 5: The application of DV voltages higher than required to bring the output to positive full scale may cause device damage.

****NOTICE:*** *Stresses greater than those listed above may cause permanent damage to the device. These are stress ratings only. Functional operation of the device at or above these conditions is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.*



RECOMMENDED CONNECTIONS



PINOUT
(LCC & JLCC PACKAGES)

The 2.5V reference input (pin 17) may be driven from either a precision voltage source or by the capacitively bypassed resistive divider shown above.

DEFLECTION VOLTAGE (DV) TEST INPUT: This test input applies an electrostatic force to the sense element, simulating a positive acceleration. It has a nominal input impedance of 32 kΩ and a nominal open circuit voltage of **½ V_{DD}**. For best accuracy during normal operation, this input should be left unconnected or connected to a voltage source equal to ½ of the **V_{DD}** supply. The change in differential output voltage (**AOP** - **AON**) is proportional to the square of the difference between the voltage applied to the **DV** input (**V_{DV}**) and **½ V_{DD}**. Only positive shifts in the output voltage may be generated by applying voltage to the **DV** input. When voltage is applied to the **DV** input, it should be applied gradually. The application of **DV** voltages greater than required to bring the output to positive full scale may cause device damage. The proportionality constant (k) varies for each device and is not characterized.

$$\Delta(AOP - AON) \approx k\left(V_{DV} - \tfrac{1}{2}V_{DD}\right)^2$$

ESD and LATCH-UP CONSIDERATIONS: The model 1221 accelerometer is a CMOS device subject to damage from large electrostatic discharges. Diode protection is provided on the inputs and outputs but care should be exercised during handling to assure that the device is placed only on a grounded conductive surface. Individuals and tools should be grounded before coming in contact with the device. Do not insert the model 1221 into (or remove it from) a powered socket.

INTERNAL TEMPERATURE SENSING

The model 1221 accelerometer contains a temperature dependent current source that is output on pin 8. This signal is useful for measuring the internal temperature of the accelerometer so that any previously characterized bias and scale factor temperature dependence, for a particular accelerometer, can be corrected. The nominal output current at 25°C is ≈500 µA and the nominal sensitivity is 1.5 µA/°C. It is up to the user to characterize each device's exact output current versus temperature over the range it is to be used. Fluctuations in V_{DD} & V_R have little effect on the temperature reading. A reduction of 0.10 V to both V_{DD} & V_R will reduce the current about 1 µA which corresponds to less than a 1°C change in reading.

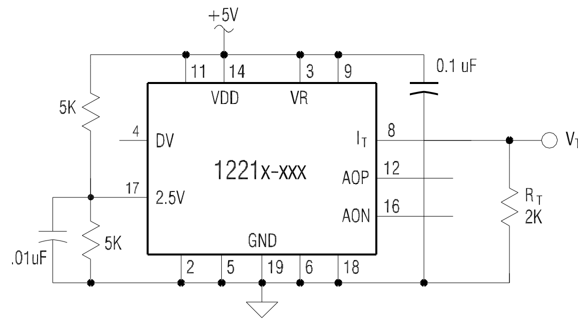


FIGURE 1

With a single resistor R_T = 2K between I_T (pin 8) and GND, as shown in Figure 1, the output voltage V_T will vary between +0.76 and +1.3 volts from -55 to +125°C, which equates to a sensitivity of ≈+3 mV/°C.

$$V_T \approx R_T\left[(500\mu A) + \left[(1.5\mu A)(T-25)\right]\right] \qquad \frac{\Delta V_T}{\Delta T} = R_T(1.5\mu A)$$

If a greater voltage change versus temperature or a lower signal source impedance is needed, the circuit in Figure 2 can be used. With offset voltage V_{OFF} = -5V, gain resistor R_G = 15.0K and offset resistor R_{OFF} = 7.32K, the output voltage V_T will vary between +4.5 and +0.5 Volts from -55 to +125°C, which equates to a sensitivity of ≈ -29 mV/°C.

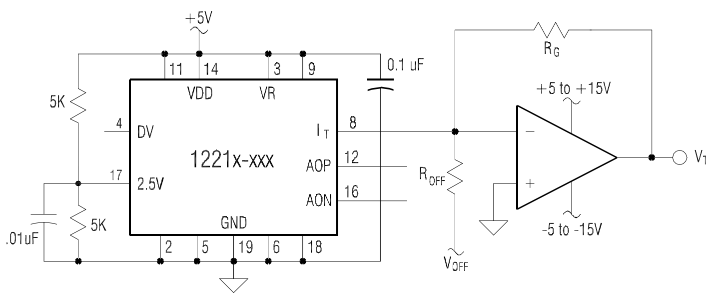


FIGURE 2

$$V_T \approx -R_G\left[\frac{V_{OFF}}{R_{OFF}} + (500\mu A) + \left[(1.5\mu A)(T-25)\right]\right]$$

$$R_{OFF} = \frac{-V_{OFF}}{\left(V_T/R_G\right) + (500\mu A) + \left[(1.5\mu A)(T-25)\right]}$$

$$R_G = \frac{-\Delta V_T}{(1.5\mu A)(\Delta T)}$$

$$\frac{\Delta V_T}{\Delta T} = -R_G(1.5\mu A)$$

FIGURE 3: TYPICAL I_T OUTPUT CURRENT vs VOLTAGE at +25C

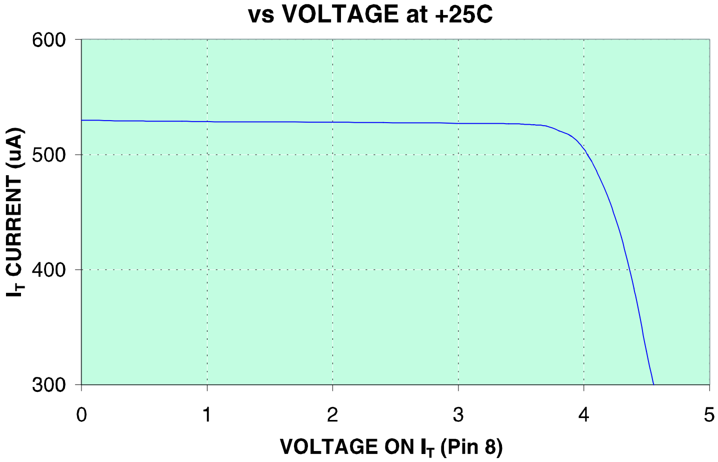
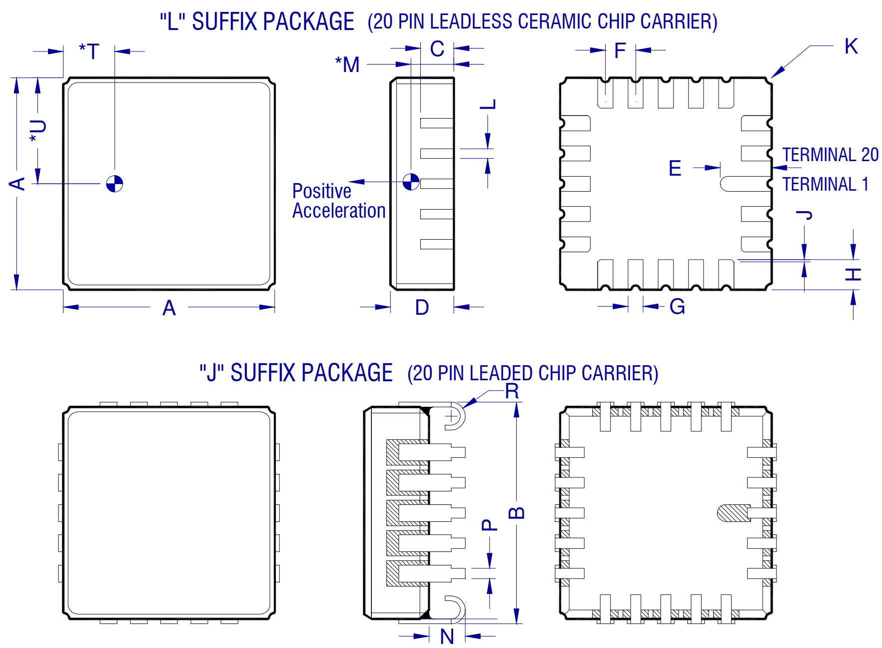


Figure 3 shows the voltage compliance of the temperature dependent current source (**I_T**) at room temperature. The voltage at pin 8 must be kept in the 0 to +3V range in order to achieve proper temperature readings.

BIAS STABILITY CONSIDERATIONS

Bias temperature hysteresis can be minimized by temperature cycling your model 1221 accelerometer after it has been soldered to your circuit board. If possible, the assembled device should be exposed to ten cycles from -40 to +85 °C minimum (-55 to +125 °C recommended). The orientation to the Earth's gravitational field during temperature cycling should preferably be in the same orientation as it will be in the final application. The accelerometer does not need to have power applied during this temperature cycling.

PACKAGE DIMENSIONS



DIM	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	0.342	0.358	8.69	9.09
B	0.346	0.378	8.79	9.60
C	0.055 TYP		1.40 TYP	
D	0.095	0.115	2.41	2.92
E	0.085 TYP		2.16 TYP	
F	0.050 BSC		1.27 BSC	
G	0.025 TYP		0.64 TYP	
H	0.050 TYP		1.27 TYP	
J	0.004 x 45°		0.10 x 45°	
K	0.010 R TYP		0.25 R TYP	
L	0.016 TYP		0.41 TYP	
* M	0.048 TYP		1.23 TYP	
N	0.050	0.070	1.27	1.78
P	0.017 TYP		0.43 TYP	
R	0.023 R TYP		0.58 R TYP	
* T	0.085 TYP		2.16 TYP	
* U	0.175 TYP		4.45 TYP	

NOTES: 1. * DIMENSIONS 'M', 'T' & 'U' LOCATE ACCELERATION SENSING ELEMENT'S CENTER OF MASS .
2. LID IS ELECTRICALLY TIED TO TERMINAL 19 (GND).
3. CONTROLLING DIMENSION: INCH.
4. TERMINALS ARE PLATED WITH 60 MICRO-INCHES MIN GOLD OVER 80 MICRO-INCHES MIN NICKEL. (THIS PLATING SPECIFICATION DOES NOT APPLY TO THE METALLIZED PIN-1 IDENTIFIER MARK ON THE BOTTOM OF THE J-LEAD VERSION OF THE PACKAGE).
5. PACKAGE: 90% MINIMUM ALUMINA (BLACK), LID: SOLDER SEALED KOVAR.

SOLDERING RECOMMENDATIONS:

RoHS Compliance: The model 1221 does not contain elemental lead and is RoHS compliant.

WARNING: If no-lead solder is to be used to attach the device, we do not recommend the use of reflow soldering methods such as vapor phase, solder wave or hot plate. These methods impart too much heat for too long of a period of time and may cause excessive bias shifts. For no-lead soldering, we only recommend the manual "Solder Iron Attach" method (listed on the next page of this data sheet). We also do not recommend the use of ultrasonic bath cleaners because these models contain internal gold wires that are thermo sonically bonded.

SOLDERING RECOMMENDATIONS (continued):

Reflow of Sn62 or Sn63 type solder using a hotplate is the preferred method for assembling the model 1221 surface mount accelerometer to your Printed circuit board. Hand soldering using a fine tipped soldering iron is possible but difficult without a steady hand and some form of visual magnification due to the small size of the connections. When using the hand solder iron method, it's best to purchase the J-Leaded version (1221J) for easier visual inspection of the finished solder joints.

Pre-Tinning of Accelerometer Leads is Recommended: To prevent gold migration embrittlement of the solder joints, it is best to pre-tin the accelerometer leads. We recommend tinning one lead at a time, to prevent excessive heating of the accelerometer, using a fine-tipped solder iron and solder wire. The solder bath method of pre-tinning is not recommended due to the high degree of heat the interior of the device gets subjected to which may cause permanent shifts in the bias and/or scale factor.

Hotplate Attach Method using Solder Paste or Solder Wire: Apply solder to the circuit board's pads using Sn62 or Sn63 solder paste or pre-tin the pads using solder and a fine tipped soldering iron. If pre-tinning with an iron, apply flux to the tinned pads prior to placing the components. Place the accelerometer in its proper position onto the pasted or tinned pads then place the entire assembly onto a hotplate that has been pre-heated to 250°C. Leave on hotplate only long enough for the solder to flow on all pads **(DO NOT OVERHEAT!)**

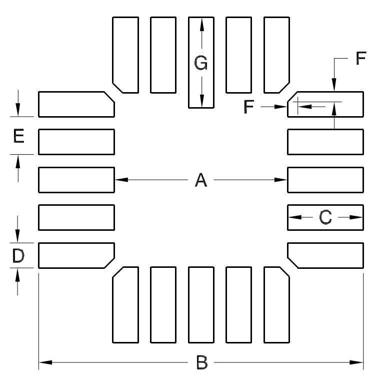
Solder Iron Attach Method using Solder Paste: Apply solder paste to the circuit board's pads where the accelerometer will be attached. Place the accelerometer in its proper position onto the pasted pads. Press gently on the top of the accelerometer with an appropriate tool to keep it from moving and heat one of the corner pads, then an opposite corner pad with the soldering iron. Make sure the accelerometer is positioned so all 20 of its connections are centered on the board's pads. Once the two opposite corner pads are soldered, the part is secure to the board and you can work your way around soldering the remaining 18 connections. Allow the accelerometer to cool in between soldering each pin to prevent overheating.

Solder Iron Attach Method using Solder Wire: Solder pre-tin two opposite corner pads on the circuit board where the accelerometer will be attached. Place the accelerometer in its proper position onto the board. Press gently on the top of the accelerometer and heat one of the corner pads that was tinned and the part will drop down through the solder and seat on the board. Do the same at the opposite corner pad that was tinned. Make sure the accelerometer is positioned so all 20 of its connections are centered on the board's pads. Once the two opposite corner pads are soldered, the part is secure to the board and you can work your way around soldering the remaining 18 connections. Allow the accelerometer to cool in between soldering each pin to prevent overheating.

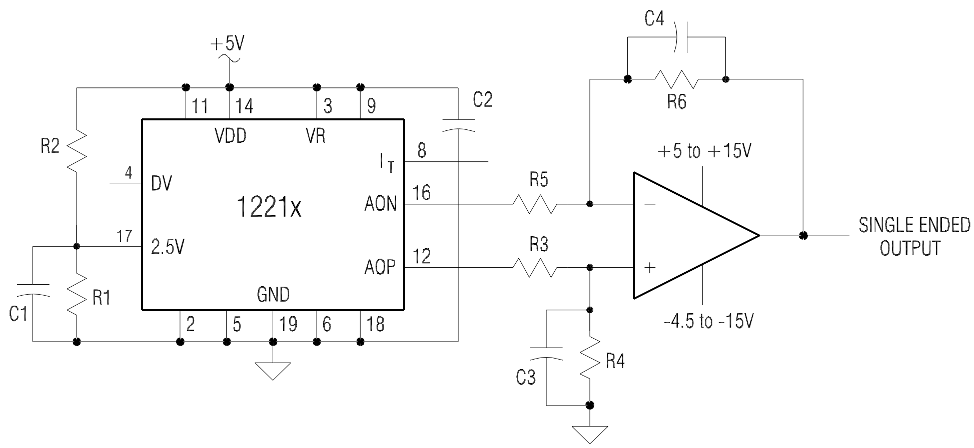
LCC & JLCC Solder Contact Plating Information: The plating composition and thickness for the solder pads and castellations on the "L" suffix (LCC) package are 60 to 225 micro-inches thick of gold (Au) over 80 to 350 micro-inches thick of nickel (Ni) over a minimum of 5 micro-inches thick of moly-manganese or tungsten refractory material. The leads for the "J" suffix (JLCC) package are made of an Iron-Nickel sealing alloy and have the same gold over nickel plating thicknesses as for the LCC pads.

Recommended Solder Pad Pattern: The recommended solder pad size and shape for both the LCC and J-LCC packages is shown in the diagram and table below. These dimensions are recommendations only and may or may not be optimum for your particular soldering process.

DIM	inch	mm
A	.230	5.84
B	.430	10.92
C	.100	2.54
D	.033	0.84
E	.050	1.27
F	.013	0.33
G	.120	3.05



ADDING A SINGLE ENDED OUTPUT TO THE MODEL 1221 DIFFERENTIAL OUTPUT ACCELEROMETER



R1 = R2 = 5.00K ±0.5% for precision 2.50V ref.	R3, R4, R5 & R6 = 20kΩ to 50kΩ R3 = R5 to within 0.1% for common mode rejection R4 = R6 to within 0.1% for common mode rejection R4 / R3 ratio accurate to within 0.1% for gain control R6 / R5 ratio accurate to within 0.1% for gain control
C1 = C2 (See below for value calculation)	

To achieve the highest resolution and lowest noise performance from your model 1221 accelerometer module, it should be connected to your voltage measurement instrument in a differential configuration using both the **AOP** and **AON** output signals. If your measurement instrument lacks differential input capability or you desire to use a differential input capable instrument in single ended mode, then the circuit above can be used to preserve the low noise performance of the model 1221 while using a single ended type connection.

This circuit converts the ± 4 Volt differential output of the model 1221 accelerometer, centered at +2.5 Volts, to a single ended output centered about ground (0.0 Volts). It provides the advantage of low common mode noise by preventing the accelerometer's ground current from causing an error in the voltage reading.

The op-amp should be located as close as possible to your voltage monitoring equipment so that the majority of the signal path is differential. Any noise present along the differential path will affect both wires to the same degree and the op-amp will reject this noise because it is a common mode signal. The op-amp type is not critical; a µA741 or ¼ of a LM124 can be used. Both plus and minus supplies are needed for the op-amp to accommodate the positive and negative swings of the single ended output. The same +5V supply can be used for both the op-amp and the 1221 or a higher voltage positive supply can be used for the op-amp if you need a larger single ended output swing.

For this design, always set $R_4 = R_6$, $R_3 = R_5$ and $C_3 = C_4$. The gain of the circuit is then determined by the ratio R_4/R_3. When $R_4 = R_3 = R_6 = R_5$, the gain equals 1 and the output swing will be ± 4 Volts single ended with respect to ground. To obtain a ± 5 Volt single ended output, set $R_4/R_3 = R_6/R_5 = 5/4 = 1.25$. The single ended output of the op-amp will be centered at ground if R_4 and C_3 are tied to ground; using some other fixed voltage for this reference will shift the output. The value of the optional capacitors C_3 and C_4 ($C_3 = C_4$) can be selected to roll off the frequency response to the frequency range of interest. The cutoff frequency f_0 (-3 dB frequency) for this single order low pass filter is given by:

$$f_0 = \frac{1}{2\pi R_4 C_3}$$