Gravity Probe B Relativity Mission

SRE Temperature Coefficient Investigation Report

S0618 Rev –

1 October 2002

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ITAR Control Required? ☐Yes ☒No

Revision History

Ver	Date	Summary of Changes
-	1 Oct 2002	Initial draft
	8 Jan 2003	Post space vehicle thermal vacuum update prior to initial release.

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1. Summary

The results of detailed temperature coefficient measurement tests made at the box and space vehicle level indicate that the SRE (SQUID Readout Electronics) system meets its thermal bias drift requirement (§3.2.3.1.3.3) and (§3.2.3.1.1.3) as detailed in the SRE specification.

Note: the SRE does not have an excessive temperature coefficient problem as originally measured in the the October, 2001 SRE box acceptance thermal/vacuum test. The excessively large temperature coefficient has been attributed to the test setup and is not a feature of the SRE.

2. Background

The SRE system is a set of four electronics boxes which operate the four SQUIDs used to measure the orientation of the gyroscopes by measuring the time rate of change of magnetic coupling between the gyroscope pickup loop and the London Moment field generated by the spinning gyroscope rotor. Commercial SQUID electronics have been seen to be particularly sensitive to ambient temperature changes, therefore the GP-B SRE system has been designed to minimize its sensitivity to temperature changes while meeting the requirements of the mission.

To this end, the SRE specification was written to ensure the necessary performance (ref: SRE Specification, P480136 Rev. D)

> §3.2.3.1.3.3:Thermal Bias Drift. The thermal-induced bias drift shall be less than 20 PPM of full scale per K for FLL (Flux Locked Loop) ranges 1 and 2.
>
> § 3.2.3.1.1.3: Bias Variation The unit shall provide a 0.1 marcsec equivalent 1 year linear or orbital frequency variation, a 0.4 marcsec equivalent maximum frequency variation at roll, calibration, or dither frequencies for SRE sensitivity ranges 1 and 2.

These requirements were levied to address the primary source of temperature sensitivity in commercial electronics packages: the Flux Locked Loop. In this implementation, this requirement translates to 0.4 mV/K for a ±10 V full scale range. This temperature sensitivity can be measured in the lab and this report gives upper bounds for this result

While this document focuses primarily on the results of a box-level thermal vacuum test performed from December 2001 and January 2002, additional tests performed at the space vehicle level during integrated vehicle thermal vacuum testing in November-December 2002 show that the SRE meets its thermal bias drift requirements in the on-orbit environment.

The net thermal sensitivity for the SRE can be split into two components:

1) The intrinsic thermal sensitivity of the base electronics system. This effect is independent of the frequency of thermal excitation in the range of expected space vehicle roll rates, 1 to 3 minute period.
2) The transfer function or thermal attenuation factor between the enclosure walls and the base electronics. This is believed to be very sensitive to the frequency of thermal excitation.

The product of these two effects determine the overall thermal sensitivity of the SRE system. The thermal attenuation factor is a combination of both active and passive thermal control of the sensitive electronics. The driving term in this function is temperature variation at space vehicle roll rate at the SRE enclosure walls in the flight configuration on orbit.

2.1 Expected thermal variations on orbit

Prior to increasing the FEE skin thickness to from 0.010 inch to 0.050 inch (PCB 549), the predicted on-orbit thermal variation on the SRE box wall in the flight configuration was estimated to be ±7.5 mK at a 3 minute roll rate. The thermal model did not have adequate fidelity to provide an estimate of the of the improved on orbit thermal variation resulting from this skin thickness change.

Space vehicle level thermal vacuum testing which the thickened skin, however, showed a measured ±1.5 mK thermal variation at the 3 minute roll period. This test was done using simulated solar radiation from high intensity lamps in the thermal vacuum chamber. The lamps were arrayed around the space vehicle and were turned on and off in sequence to simulate the roll of the spacecraft in direct sunlight. This is the best physical test we have to date to indicate what the on orbit temperature variations will be with the actual spacecraft hardware.

3. The Initial Temperature Coefficient Test

In October, 2001, during the SRE box-level thermal/vacuum (TVAC) acceptance tests, a subset of tests were performed to measure the thermal sensitivity of the SRE to verify the above requirement.

3.1 Test Results

An analysis of this data indicated that the box temperature coefficient in SRE Range 1 was roughly 35 times the value required by the SRE specification.

This raised serious concerns about the performance of the SRE system.

3.2 Data and Test Setup Concerns.

This data, upon review by the GP-B team however, did not appear to be “physical” in a number of cases. For instance:

1. The measured temperature coefficient from box wall to SQUID output appeared to be roughly constant regardless of the frequency of the thermal inputs. From the physics of the setup, the thermal capacity of the box itself should act as a low pass filter at the thermal frequencies of interest and thus one would expect a significant reduction in box temperature-to-output response as the frequency of the thermal input was increased.
2. The SQUID simulator used as part of this test is significantly noisier than an actual SQUID, is sensitive to temperature, and was not in a tightly controlled thermal environment during the test.
3. The SRE was being heated/cooled by conduction to the thermal chamber’s cold plate, not via radiative heat exchange the way it will operate on orbit. This heating scheme raises questions about off-nominal thermal gradients that may effect the electronics.
4. The temperature coefficients were of very large magnitude – on the order of 10 mV/K. A result of this magnitude is difficult to understand given the quality of the components and construction of the electronics package. Generally, circuits that are to be used as thermometers have temperature variation as large as this.
5. Test results from run to run were inconsistent. For essentially equivalent tests, the observed thermal sensitivity varied by up to a factor of 10 run to run.

The results of all these studies cast doubt on the validity of the data; the effect measured may not be attributable to the SRE electronics, but due to GSE and/or cabling issues.

4. Anomaly Investigation and Resolution Plan

A team of SQUID and electronics experts from Stanford and Lockheed-Martin was formed to investigate the source of these discrepant measurements and recommend/implement solutions to the problem. The plan of action to is outlined in the following block diagram, Figure 1. This plan investigates all aspects of the problem and potential corrective actions that may be able to be used to minimize the overall thermal sensitivity of the system.

The sections which follow summarize the results of these individual investigations represented by the individual blocks in this diagram. The numbers at the upper left corner of the block correspond to the subsection number herein for ease of reference:

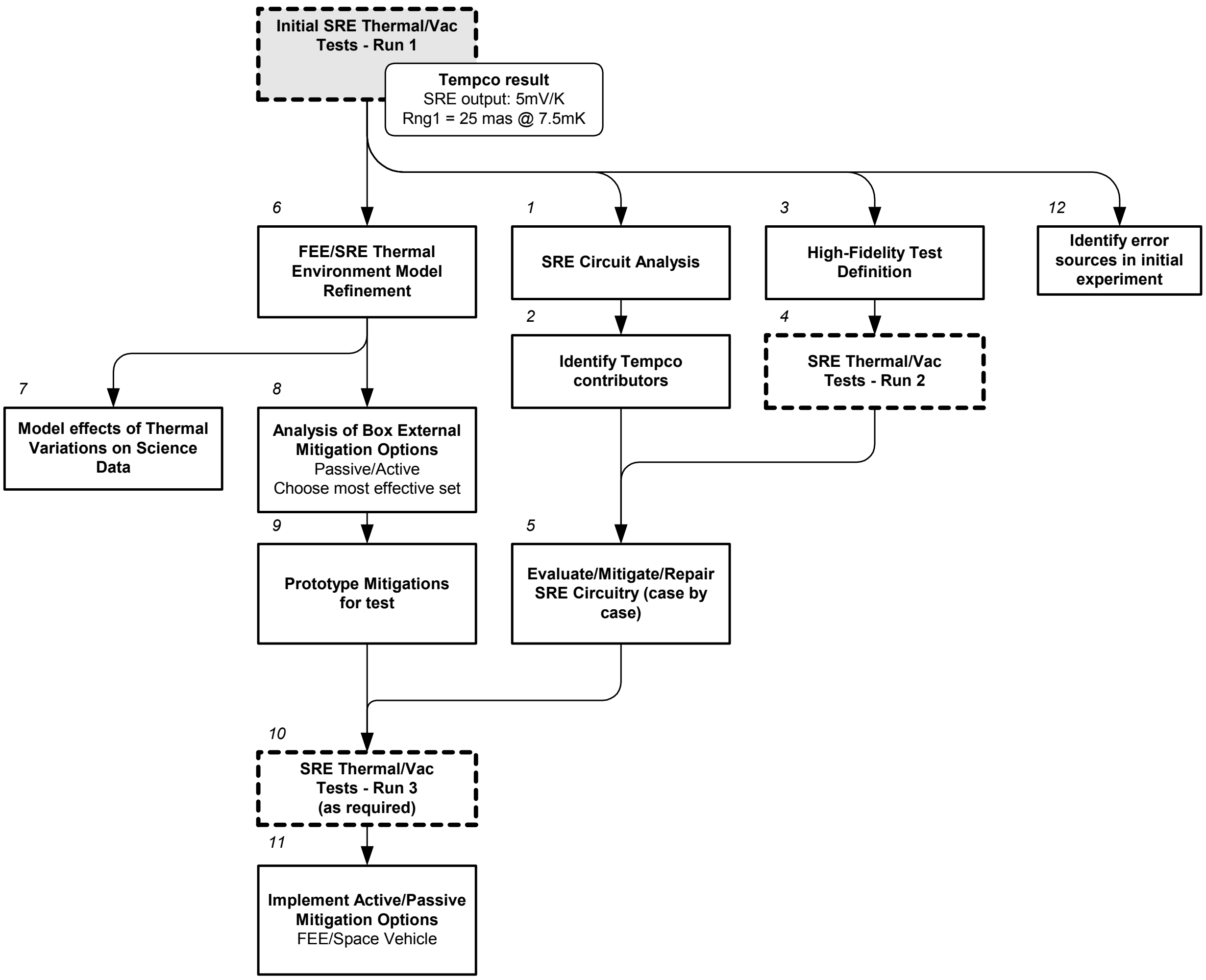


Figure 1: Anomaly Investigation Flow Block Diagram

4.1 SRE circuit temperature sensitivity analysis (Block 1, Figure 1)

An in-depth circuit analysis was performed by a team of electrical engineers (T. McGinnis, B. Farley) to identify which components were particularly temperature sensitive and could give rise to the problems seen. No clear offender was found; all parts in the system were of high quality and of low intrinsic temperature coefficient.

4.2 On-board thermal control performance study (Block 2, Figure 1)

The SRE system was designed with active board-level temperature control for the three critical subsystems in the SRE architecture: 1) Flux-locked loop (FLL) circuitry, 2) Digital-to-Analog conversion (DAC) circuitry, and 3) the Analog-to-Digital conversion (DAC) circuitry. These analog control loops' set point is digitally controlled, and were designed to compensate for the larger orbital-rate and annual-rate temperature swings of the box. (2 K and 10 K respectively)

These loops were designed and implemented properly and function as expected in the orbital and annual thermal frequency ranges.

These loops, however, were not designed to reject roll-rate thermal variations. This decision was made by the SRE design team based on some engineering thermal sensitivity data taken a number of years ago on an earlier engineering unit SRE. It was found that the temperature coefficient around roll rate was sufficiently small that roll-rate temperature control is unnecessary.

The roll-rate thermal sensitivity data is anecdotal; no records of this test could be located by the SRE team.

4.3 High-fidelity temperature coefficient test: (Block 3, Figure 1)

Driven by the concerns raised in Section 3.2, the tiger team formulated a high-fidelity thermal vacuum test to carefully measure the thermal sensitivity of the SRE in as much of a flight-like environment as possible. The key components of this test are:

A. The SRE box is to be mounted using flight-equivalent titanium brackets with a TRE mass simulator.

B. SRE is to be radiatively heated/cooled in a flight-prototypical manner.

C. SRE is to run an actual SQUID, not a simulator, to reduce the background noise level.

4.3.1 Test Configuration

This test is to be run in the SRE development lab at (LMCO B/203) using a small Stanford-owned thermal vacuum chamber. This configuration gives the investigation team the greatest flexibility and control over the experiment.

A diagram of this test configuration is given below in Figure 2. Photos of the actual test configuration are presented in the appendix.

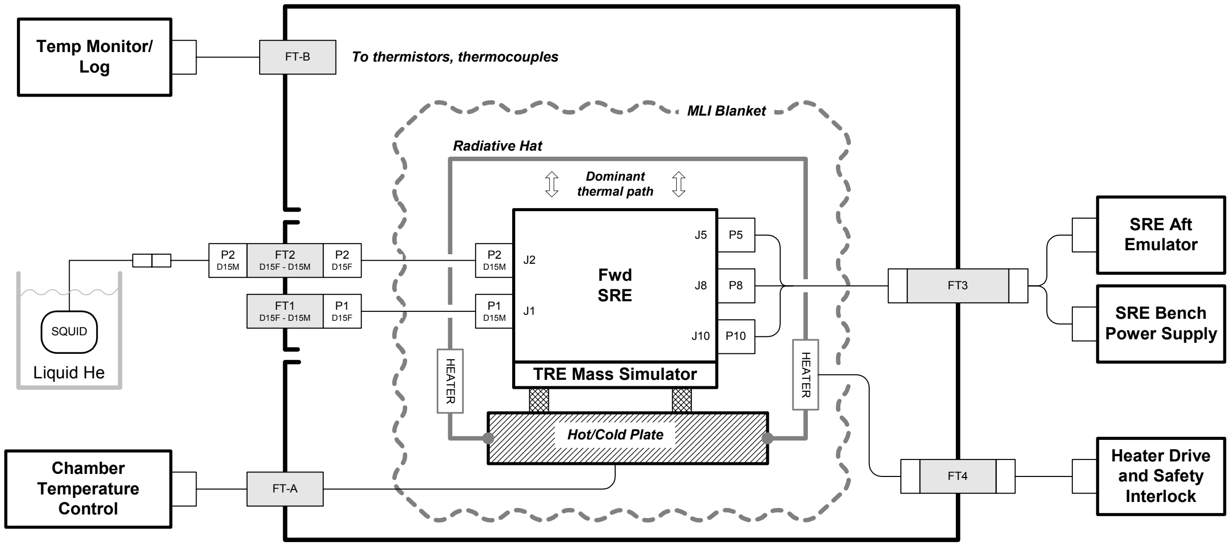


Figure 2: High Fidelity Thermal Vacuum Test Configuration

4.3.2 Test Plan

The following summarizes the tests planned for this configuration. The detailed test plan is documented in LMCO operations order SRE-208.

These tests were designed to measure the overall temperature of the box at various frequencies as well as selectively stimulate subsections of the box (where internal heaters are available) to probe for thermally sensitive components.

A. Box-wide large temperature swings (~ 5 K); Measure overall low frequency sensitivity of box.
   - Modulate heat input at 1 hour period (30 min on/30 min off) for 6 hours.
   - Calibration signal off.
   - No closed loop temperature control.
   - SRE range 1/ post gain 64.

B. Box-wide small temperature swings (~ 0.5 K-pp) at roll frequencies; Measure overall roll rate frequency sensitivity of box at roll-like frequencies
   - Modulate heat input at 5 and 1 minute periods.
   - Calibration signal off.
   - No closed loop temperature control.
   - SRE range 1/ post gain 64; range 2/ post gain 128.

C. Cycle board level heaters (~ 0.5 K-pp) at 60 minute period; Measure individual board temperature coefficients and determine if one particular board is the dominant contributor
   - Modulate FLL, DAS, DAC board level heaters at 60 minute period
   - Calibration signal off.
   - No closed loop temperature control.
   - SRE range 1/ post gain 64

4.4 High fidelity temperature coefficient test results. (Block 4, Figure 1)

The tests described above were executed between 15 December, 2001 and 21 January, 2002. Forward SRE box data was taken through the Aft SRE emulator at a 2200 Hz sample rate and stored to disk. An auxiliary data acquisition system was used to measure the temperatures of 1) the SRE skin, 2) the TRE simulator, and 3) the chamber cold plate at a sample rate of approximately 10 Hz.

The chamber was evacuated to better than 10^{-5} torr to eliminate any convective heat exchange between the box and the surrounding environment

The chamber cold plate was cooled to approximately 160 K (-120° C) to act as a heat sink for the system. The "hot hat" heater power was adjusted to bring the forward SRE box into its predicted on-orbit operating temperature range prior to any heater modulation.

The raw data was decimated to a 10 Hz rate in post processing and then run through a set of spectral analysis routines written by the GP-B science group (A. Silbergleit, M. Heifetz) to look for signals at/around the frequency of excitation (60 min., 30 min., 5 min., 1 min., depending on the test). This analysis provides the following key pieces of data. This data is summarized in the table that follows.

A. Temperature coefficient of the SRE output (SQUID signal) with respect to temperature variations on the FLL card, DAC card, and DAS card. This measurement is used to evaluate the SRE output variation due to changes in temperature of individual boards. This is not a conclusive metric, however. It implicitly assumes that all the output variation is due to the variation on that particular board. In the case where the output variation is large and the board temperature variation is low (good thermal isolation), this metric will indicate a large sensitivity, even if all the variation is due to some other, independent part of the circuit.

   From program history it has been observed that the FLL circuit has dominated the thermal sensitivity of the box.

B. Passive thermal attenuation between box wall and circuit boards. The box and boards act as a thermal low pass filter from the outside environment to the internal circuitry, thus reducing the sensitivity of the internal electronics to external variations. The attenuation should increase with thermal excitation frequency.

C. These data may be combined (or directly derived from the source data) to find the effective temperature coefficient of the SRE from the box wall to the SQUID output. This macroscopic parameter is a straightforward handle on the performance of the box with temperature.

   These data is summarized in the following table in the effective box temperature coefficient and flight variation columns. The SRE output in V/K is converted to equivalent angle using the conversion factors in Section 2; the flight variation column predicts the SRE thermal variation given the predicted 7.5 mK and 1.5 mK box temperature variation.

Date	Test	SRE Rng	Pd *(min)*	Temp Variation *K (Location)*	FLL to SQUID (2) *Tempco* *Pass. Atten*	DAC to SQUID (2) *Tempco* *Pass. Atten*	DAS to SQUID (2) *Tempco* *Pass. Atten*	Offset Voltage (OV) *Tempco*	Bias Voltage (BV) *Tempco*	Effective box tempco *mas/K*	Flight variation *mas at 7.5 mK (at 1.5 mK)*	Notes
18-Dec-01	SQUID noise baseline test	1	DC	0.8 K (box)	90 mV/K NA	90 mV/K NA	60 mV/K NA	-	-	61,200 mas/K	459 mas (92 mas)	Cold start, direct connection to SQUID; in 1ATM ambient temp.
20-Dec-01	Radiative heating	1	60	4.5 K-pp (box)	< 1.9 mV/K 2.5	< 1.5 mV/K 2.3	< 2.9 mV/K 4.5	-	-	466 mas/K	3.5 mas (0.7 mas)	Passive attenuation is FLL/box, DAC/box, DAS/box
21-Dec-01	Radiative heating	1	60	4.5 K-pp (box)	< 1.9 mV/K 2.5	< 1.5 mV/K 2.0	< 2.9 mV/K 4.0	-	-	507 mas/K	3.8 mas (0.76 mas)	Passive attenuation is FLL/box, DAC/box, DAS/box
18-Jan-02	Radiative heating	2	30	0.9 K-pp (box)	< 1.2 mV/K 3.1	< 0.7 mV/K 1.9	< 2.6 mV/K 11.5	-	-	655 mas/K	4.9 mas (0.98 mas)	Passive attenuation is FLL/box, DAC/box, DAS/box
20-Dec-01	Radiative heating	1	5	0.6 K-pp (box)	NES 200	NES 63	NES > 200	-	-	17 mas/K	**0.13 mas** **(0.026 mas)**	Passive thermal attenuation is FLL/box, DAC/box, DAS/box [Note 1]
20-Dec-01	Radiative heating	1	1	15 mK-pp (box)	Noise lim Noise lim	Noise lim Noise lim	Noise lim Noise lim	-	-	<17 mas/K	**<0.13 mas** **(0.026 mas)**	Noise limited measurements [Note 2]
4-Jan-02	Heater Pulsing, FLL	1	DC	7 K Δ (FLL bd)	0.3 mV/K 1	- 17	- 500	NES	NES	-	-	Passive thermal attenuation is DAC/FLL, DAS/FLL, OV/ FLL, BV/ FLL
7-Jan-02	Heater Pulsing, DAC	1	DC	4.5K Δ (DAC bd)	- 13	0.6 mV/K 1	- 50	NES	NES	-	-	Passive thermal attenuation is FLL/DAC, DAS/DAC, OV/ DAC, BV/ DAC
8-Jan-02	Heater Pulsing, DAS	1	DC	6.5K Δ (DAS bd)	- 250	- 250	0.12 mV/K 1	0.1 mV/K	0.05 mV/K	-	-	Passive thermal attenuation is FLL/DAS, DAC/DAS, OV/DAS, BV/DAS
4-Jan-02	Heater Pulsing, FLL	1	60	7K Δ (FLL bd)	0.5 mV/K 1	- 14	- 167	NES	NES	-	-	Passive thermal attenuation is DAC/FLL, DAS/FLL, OV/ FLL, BV/ FLL
7-Jan-02	Heater Pulsing, DAC	1	60	4.5K Δ (DAC bd)	- 6.7	0.7 mV/K 1	- 50	NES	NES	-	-	Passive thermal attenuation is FLL/DAC, DAS/DAC, OV/ DAC, BV/ DAC
8-Jan-02	Heater Pulsing, DAS	1	60	6.5K Δ (DAS bd)	- 333	- 333	0.4 mV/K 1	0.08 mV/K	0.05 mV/K	-	-	Passive thermal attenuation is FLL/DAS, DAC/DAS, OV/DAS, BV/DAS

4.4.1 Key to data table:

The sample table and notes below show how to read this data table format. Each test is represented by an individual row in the table. Shaded rows indicated the expected on-orbit conditions.

Date	Test	SRE Rng	Pd *(min)*	Temp Variation	FLL to SQUID (2)	DAC to SQUID (2)	DAS to SQUID (2)	Offset Voltage (OV)	Bias Voltage (BV)	Effective box tempco	Flight variation	Notes
				K (Location)	*Tempco* / *Pass. Atten*	*Tempco* / *Pass. Atten*	*Tempco* / *Pass. Atten*	*Tempco*	*Tempco*	*mas/K*	*mas* *at 7.5 mK (at 1.5 mK)*	
Test Date	*Example **A***	1 **B**	60 **C**	1 K-pp (box) **D**	1 mv/K **E** / 10 **F**	2 mV/K **E** / 15 **F**	3 mV/K **E** / 5 **F**	**G**	**H**	189 mas/K **I**	14.2 mas (2.8 mas) **J**	Passive attenuation is FLL/box, DAC/box, DAS/box

A. Test type: radiative heating of the box or heater pulse on an individual function card (FLL, DAC, DAS)

B. SRE range: 1 or 2, depending on the test. Note the conversion factor from flux quanta to SRE output voltage to equivalent angle in the table below.

SRE Range	Flux quanta /volt	Angle/flux quanta	Net angle/volt
Range 1	0.17 Φ_o/V	4.0 x 10^6 marcsec/Φ_o	6.8 x 10^5 marcsec/V
Range 2	0.50 Φ_o/V		2.0 x 10^6 marcsec/V
Range 3	1.2		4.8 x 10^6 marcsec/V
Range 4	10		40.0 x 10^6 marcsec/V

C. Period of heater modulation, in minutes.

D. As-measured temperature variation. Either box skin peak-peak temperature variations for radiative heating or thermal control zone temperature variations on a PWA for individual heater pulse tests.

E. SRE output variation (in mV) divided by the temperature variation on an individual PWA (FLL, DAS, DAC). Implicitly assumes that all the measured sensitivity is due to variations on that particular PWA. For PWA heater sensitivity tests, this tempco is given for only the PWA on which the heater was modulated. Note, in some test cases, the variations were too small to measure, and thus are noted with a “No Effect Seen (NES)” label. In other test cases, the background noise of the measurement was too large to observe the signal of interest, and these cases are noted with "noise lim" label. A less-than symbol (<) indicates that the signal was generally less than the value given and the maximum value was taken as a worst case for this calculation.

F. Attenuation of box wall temperature to PWA temperature for the DAS, DAC, FLL cards. (i.e a thermal attenuation factor of 10 would indicate a 1 K variation at the noted period would cause a variation on the PWA of 0.1 K) This attenuation is factor is a strong function of thermal excitation frequency. In some test cases, the background noise of the measurement was too large to observe the signal of interest, and these cases are noted with "noise lim" label. For the heater pulse cases, the attenuation factor for the PWA on which the heater is activated is 1 (no attenuation); of interest, however, is the attenuation (or coupling) factor to the other PWAs in the set. This data is given in the table as well.

G. Tempco of the offset voltage signal in the SRE. In some test cases, the SRE offset voltage was measured by the data system and an effective box wall to output tempco was calculated

H. Tempco of the bias voltage signal in the SRE. In some test cases, the SRE bias voltage was measured the data system and an effective box wall to output tempco was calculated

I. The effective box tempco was calculated by combining the individual temperature sensitivities and thermal attenuations to generate a net box thermal sensitivity in the following manner:

$$\text{Net T/C} = \frac{1}{3}\left(\text{Squid Range Factor}\right)\left(\frac{\text{FLL tempco}}{\text{FLL pass atten}} + \frac{\text{DAC tempco}}{\text{DAC pass atten}} + \frac{\text{DAS tempco}}{\text{DAS pass atten}}\right)$$

J. The effective on orbit variation is given for the 7.5 mK SRE wall temperature oscillation predicted by the 3-minute roll model (the first number) and the measured 1.5 mK oscillation measured in space vehicle thermal vacuum testing (the second number in parentheses)

4.4.2 Notes [1] and [2] from the table:

At these high thermal frequencies (periods of 1 and 5 minutes), the measurements became noise-limited so a direct computation of the effective box wall temperature to SRE output is not possible. However, for the 5 minute period, good measurements of the thermal attenuation were possible. Therefore, the following assumptions were made:

A. An upper bound of roughly 3 mV/K can be established, as seen from the data from the 30 and 60 minute runs, and is assumed to remain constant at higher thermal frequencies. (conservative upper bound)

B. The measured thermal attenuation from box wall to the DAS, DAC, and FLL PWAs for the 5 minute run on 20-Dec-02 will remain constant at higher frequencies (conservative assumption; the attenuation is expected to increase at 3 and 1 minute roll periods)

The product of these two numbers gives the thermal sensitivity at the 5 minute period. (0.03 mV/K). We have no useable data at the one minute period (noise dominated) but assume performance will be better than the 5 minute runs.

4.4.3 Summary of the results:

Based on the data summarized in the table above, the following results can be reported.

A. For the 1 and 5 minute roll periods , the effective thermal variation is slightly above spec using the conservative bounds in the previous section and the predicted 7.5 mK thermal variation. The requirement is 0.1 marcsec at roll; upper bound estimate given here is 0.13 marcsec at roll rate. However, using the measured 1.5 mK thermal variation from space vehicle thermal vacuum testing, the net variation is better than 0.026 mas and is within specification.

B. The bias variation is also satisfied by this test for the 1.5 mK thermal variation at roll. The predominant disturbance a roll frequency is the thermal variation, other frequencies of interest are at higher frequencies still. The 0.026 measured thermal variation satisfies the 0.4 marcsec bias variation requirement.

C. The effective passive attenuation between the box walls and the circuitry in the SRE is better than 60, in some cases much better and seen in the table above.

D. There does not seem to be a single standout contributor to the overall box temperature coefficient.

These thermal vacuum test results directly verify thermal bias drift requirement of the SRE system:

> §3.2.3.1.3.3 Thermal Bias Drift. The thermal-induced bias drift shall be less than 20 PPM of full scale per K for FLL (Flux Locked Loop) ranges 1 and 2.
>
> §3.2.3.1.1.3 Bias Variation: The unit shall provide a 0.1 marcsec equivalent 1 year linear or orbital frequency variation, a 0.4 marcsec equivalent maximum frequency variation at roll, calibration, or dither frequencies for SRE sensitivity ranges 1 and 2.

SRE circuitry modifications and mitigating actions. (Block 5, Figure 1)

Based on the satisfactory test results from the previous section, no mitigations or changes to the SRE electronics are recommended at this time.

4.5 Enhanced SRE/FEE thermal model (Block 6, Figure 1)

The LMCO thermal engineering team (K. Burns/LMCO) reviewed the thermal model for the forward SREs in the FEE looking to see if any further improvements in the FEE thermal model could be made based on current understanding of the GP-B spacecraft. The overall system model had changed little, so no improvement in the thermal variation estimate of ±7.5 mK at roll could be made. Test data however demonstrates a ±1.5 mK roll rate variation with the thickened FEE skins.

4.6 Model effects of thermal variations on science data. (Block 7, Figure 1)

Because the SRE is meeting its specifications based on this test data, there is no anticipated adverse effects on science data, and no additional modeling is necessary.

4.7 Review of box external thermal mitigation options. (Block 8, Figure 1)

A number of proposals were put forth to attenuate further the ±7.5 mK roll rate box thermal variation. The following is a brief list of the proposals and surrounding issues which affect the proposal's feasibility and effectiveness.

4.7.1 Active control of box skin temperature. This approach requires heaters, temperature sensors, and a controller. There are no unused channels in the spacecraft or payload to implement this control system, so a new box or interface in existing hardware would be required. In addition, insuring that the solution will improve the situation is difficult or impossible to do prior to operations on orbit. *Judged high risk, expensive, time consuming. No plan in place*.

4.7.2 Roll rate heating of FEE skin. Apply heaters to FEE skin to smooth the differential heat input to the FEE skin (one half is in sunlight, the other is in shade). This could be done open loop, but would require heaters and an actuator. Difficult to get enough heat into FEE to make a significant difference. *Judged moderately difficult, somewhat effective*. *No plan in place*.

4.7.3 Additional passive isolation around SRE. Additionally decoupling the SRE from the FEE thermal radiation source/sink and tying it to the dewar shell has the potential to lessen the roll-rate variations of the SRE box. New, highly conductive mounting brackets would need to be designed (aluminum rather than titanium) and installed, additional insulation around the SRE and TRE would need to be added. Separately or in addition, the FEE skin can be thickened to lessen the thermal variations the boxes see by providing a better path of thermal conduction around the FEE structure. *This later modification was judged easy and low risk, and was implemented per Stanford PCB 549. The FEE skin was thickened from 0.010 inch to 0.050 inch to improve the thermal situation*

4.7.4 Removal of the thermal effect in data processing. It does appear possible to characterize the thermal effects and to some degree remove them in post processing of the data on the ground during the mission. *However, this is highly undesirable and has been judged as an approach of last resort. No plan in place*.

4.8 Prototype Mitigation

No hardware or system modifications are recommended at this time.

4.9 Additional thermal/vacuum testing

Additional engineering tests have been performed as part of the space vehicle thermal vacuum testing in November/December 2002 and exposed the SRE forward boxes to flight-like roll rate thermal inputs. Here, the flight hardware is mounted on the vehicle with surrounding payload electronics packages and cables and FEE enclosure in place. The SREs will be connected to the flight SQUIDs, which offer significantly lower noise and better thermal stability than their lab counterparts.

In this test all four flight SQUIDs can be tested (versus only one EU SQUID during the box level test program) and relative as well as absolute performance can be measured.

Results from heater pulse tests on the individual PWAs are summarized in the data table below, and can be compared with the tests run at the box level on SRE channel 2.

4.9.1 Space Vehicle thermal vacuum test results (heater pulsing tests)

Date	Test	SRE Rng	Pd *(min)*	Temp Variation *K (Location)*	FLL to SQUID (2) *Tempco*	DAC to SQUID (2) *Tempco*	DAS to SQUID (2) *Tempco*	Bias Voltage (BV) *Tempco*	Effective box tempco *mas/K*	Notes
10-Dec-02	Heater Pulse, FLL1	1	30	2.5K Δ @ 20.5 C (FLL bd)	0.091 mV/K 1	-	-	-0.20 mV/K	-	SQUID1/FLL1 – SV thermal vacuum test, cold
	Heater Pulse, FLL2	1	30	2.5K Δ @ 20.5 C (FLL bd)	0.19 mV/K 1	-	-	-0.67 mV/K	-	SQUID2/FLL2 – SV thermal vacuum test, cold
	Heater Pulse, FLL3	1	30	2.5K Δ @ 20.5 C (FLL bd)	**2.57 mV/K** 1	-	-	**-18.3 mV/K**	-	SQUID3/FLL3 – SV thermal vacuum test, cold
	Heater Pulse, FLL4	1	30	2.5K Δ @ 20.5 C (FLL bd)	0.42 mV/K 1	-	-	-0.31 mV/K	-	SQUID43/FLL4 – SV thermal vacuum test, cold
10-Dec-02	Heater Pulse, FLL1	1	30	2.5K Δ @ 30 C (FLL bd)	0.03 mV/K 1	-	-		-	SQUID1/FLL1 – SV thermal vacuum test, hot
	Heater Pulse, FLL2	1	30	2.5K Δ @ 30 C (FLL bd)	0.15 mV/K 1	-	-		-	SQUID2/FLL2 – SV thermal vacuum test, hot
	Heater Pulse, FLL3	1	30	2.5K Δ @ 30 C (FLL bd)	**2.57 mV/K** 1	-	-		-	SQUID3/FLL3 – SV thermal vacuum test, hot
	Heater Pulse, FLL4	1	30	2.5K Δ @ 30 C (FLL bd)	0.40 mV/K 1	-	-	-	-	SQUID4/FLL4 – SV thermal vacuum test, hot

4.9.2 Space Vehicle thermal vacuum test results (heater pulsing tests, continued)

Date	Test	SRE Rng	Pd *(min)*	Temp Variation	FLL to SQUID (2)	DAC to SQUID (2)	DAS to SQUID (2)	Bias Voltage (BV)	Effective box tempco	Notes
				K (Location)	*Tempco*	*Tempco*	*Tempco*	*Tempco*	*mas/K*	
10-Dec-02	Heater Pulse, DAC1	1	30	1.5K Δ @ 27.5 C (DAC bd)	-	0.005 mV/K 1	-	-	-	SQUID1/DAC1 – SV thermal vacuum test, hot
	Heater Pulse, DAC2	1	30	1.5K Δ @ 27.5 C (DAC bd)	-	0.012 mV/K 1	-	-	-	SQUID2/DAC2 – SV thermal vacuum test, hot
	Heater Pulse, DAC3	1	30	1.5K Δ @ 27.5 C (DAC bd)	-	-0.396 mV/K 1	-	-	-	SQUID3/DAC3 – SV thermal vacuum test, hot
	Heater Pulse, DAC4	1	30	1.5K Δ @ 27.5 C (DAC bd)	-	0.006 mV/K 1	-	-	-	SQUID4/DAC4 – SV thermal vacuum test, hot
10-Dec-02	Heater Pulse, DAS1	1	30	2.0K Δ @ 34 C (DAS bd)	-	-	-0.014mV/K 1	-	-	SQUID1/DAS1 – SV thermal vacuum test, hot
	Heater Pulse, DAS2	1	30	2.0K Δ @ 34 C (DAS bd)	-	-	0.009 mV/K 1	-	-	SQUID2/DAS2 – SV thermal vacuum test, hot
	Heater Pulse, DAS3	1	30	2.0K Δ @ 34 C (DAS bd)	-	-	0.092 mV/K 1	-	-	SQUID3/DAS3 – SV thermal vacuum test, hot
	Heater Pulse, DAS4	1	30	2.0K Δ @ 34 C (DAS bd)	-	-	-0.007 mV/K 1	-	-	SQUID4/DAS4 – SV thermal vacuum test, hot

4.10 Implementation of Mitigations

No hardware mitigations identified so no implementations are needed.

4.11 Source of Initial Anomalous Temperature Coefficient Measurements

There are many possible sources of error for the large temperature coefficient measured in the October, 2001 temperature coefficient test. Leading candidates include:

1) Thermal variation of the SQUID simulator. A SQUID simulator is used as a test load for the SRE in lieu of a cold SQUID for test convenience (no liquid helium is required). This unit was neither designed to be temperature insensitive nor kept in a controlled thermal environment during the test.

2) Non-flight thermal configuration. For ease of thermal testing, the SREs were mounted directly to the cold plate in the thermal vacuum chamber, providing a good thermally conductive path through the box walls and internal ribs. Heat exchange on orbit is dominated by radiation. In this test configuration, a thermal shunt path may exist that is not present in the flight configuration that could give rise to an apparently higher temperature coefficient.

3) External/EMI sources. The SRE box level thermal vacuum tests are designed to thermally stress the box, not to perform sensitive measurements. To this end, the test laboratory is not particularly quiet from an EMI standpoint; this may contribute to the overall measurement.

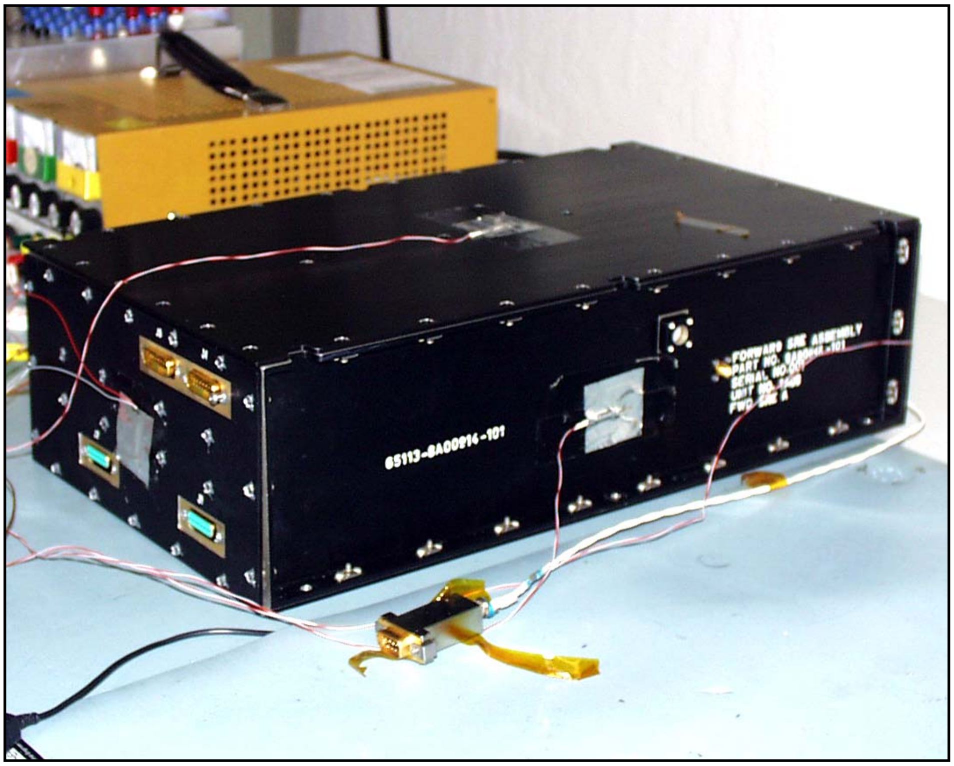
To date, the source of this error has not been isolated. The carefully designed and executed tests described in this document, however, have given the GP-B team the confidence that the SRE system will perform as required on orbit and that the test data we have taken as part of the temperature coefficient investigation is sound and consistent with expected on-orbit performance. With this in mind, we have judged that any additional investigation into the root cause of the initial large temperature coefficient measurement would not be a productive use of limited program resources; GP-B's efforts have been directed to confirming the performance of the system as outlined earlier in this document. No additional investigations into the root cause of the anomalous SRE temperature coefficient measurement are recommended at this time.

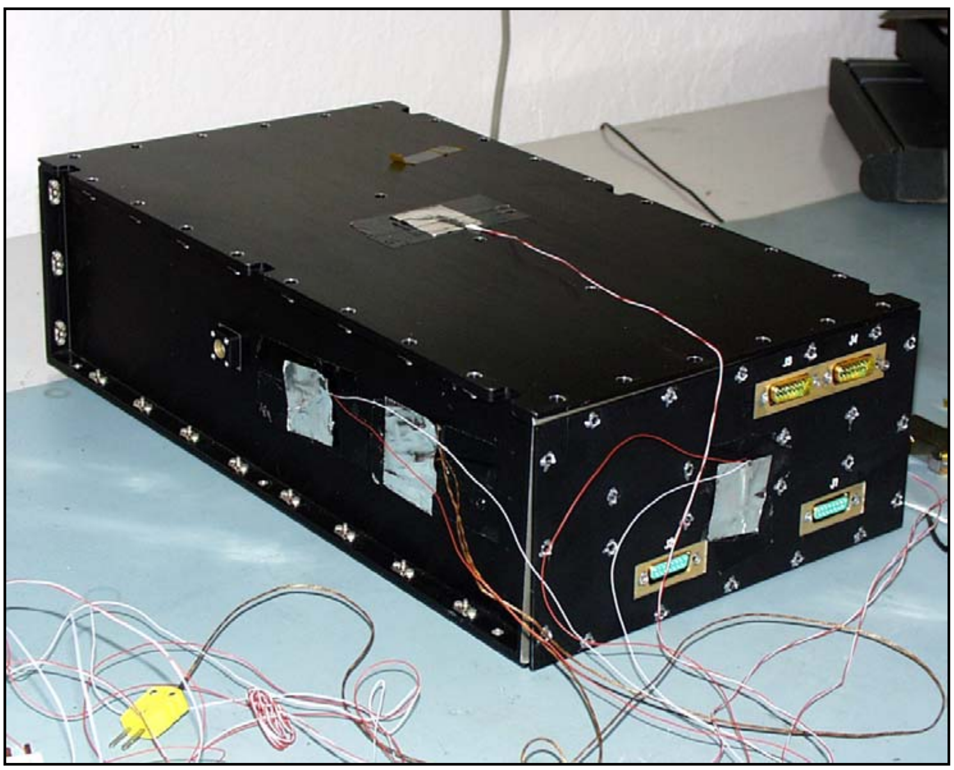
APPENDIX A. Photographs of test setup.

A.1 Thermal-vacuum camber open; MLI blanket covers SRE under test. Liquid He dewar with SQUID can be seen at the right of the photo

A.2 Hot hat, heater and thermistors can be seen in this photo. Inside wall of hot hat coated with black kapton tape for high thermal emissivity. The hot hat is the primary thermal interface to the SRE; very little heat leaves the SRE/TRE system by conduction across the titanium flight-like brackets.

A.3 SRE (black box) mounted on TRE mass simulator (plate) on flight-equivalent titanium brackets. Feedthroughs for the SQUID leave the chamber at the bottom of the photo. Bundle of wires under SRE are the interconnect wires for the thermometry system. SRE aft/forward connections are made at the top of the unit.





A.4 Photos of SRE showing location of thermistors for box wall temperature measurement