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Testing the GP-B telescope readout electronics on a flight quality telescope

S. Wang*, D.-H. Gwo*, K.A. Bower*, L.W. Huff*, R.K. Kirschman*,**, J.A. Lipa*, M. Jhabvala***, S. Babu**** and N. Das*****

** Hansen Experimental Physics Laboratory, Stanford University, Stanford, California, U.S.A.*
*** Consulting Physicist, Mountain View, California, U.S.A.*
**** NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.*
***** Ball Aerospace and Technologies Corp., Boulder, Colorado, U.S.A.*
****** Hughes/STX, Lanham, Maryland, U.S.A.*

Abstract. Integrated photodiodes and silicon JFET preamps are used for the optical readout of the Gravity Probe B cryogenic star tracking telescope. The heated circuit assembly is mounted on a thermal isolator so that it can be heated to around 80 K while the telescope remains at its operating temperature of 2.8 K. We present test results of the readout with a flight quality telescope.

1. INTRODUCTION

Gravity Probe B (GP-B) is a NASA flight program which will measure the geodetic and frame dragging precessions of gyroscopes in earth orbit. Both effects are predicted[1] by the theory of general relativity with the former being 6.6 arc sec/year and the latter between 33 and 42 marc sec/year depending on the gyro spin axis orientation. The GP-B earth orbiting satellite is expected to measure the geodetic effect to a precision of 0.01% and frame dragging effect to 1%. To achieve such precision, a reliable inertial reference system is required. This system consists of a star-tracking telescope with a pointing servo and a guide star with low proper motion.

The telescope is rigidly attached to a fused quartz block which houses the gyroscopes; both are in a high vacuum at approximately 2.8 K. The telescope is of a Schmidt-Cassagranian design with a tertiary mirror. To ensure minimal cryogenic distortion, all the optical components are made from specially annealed Herasil 1-top fused quartz from the same boule. The telescope has an effective focal length of 3.8 m, an aperture of 14.4 cm diameter and a central obscuration of 7.1 cm diameter. The focused star beam goes through a beam splitter and each split beam is bisected by a roof prism configured to provide orthogonal readout axes. Each bisected beam is refocused by a pair of field lenses onto a silicon PIN photodiode. The pair of bisected beams is imaged so that they focus on a pair of photodiodes on the same Si die separated by 2 mm. In addition, two sets of detectors are used for each readout axis to provide redundancy.

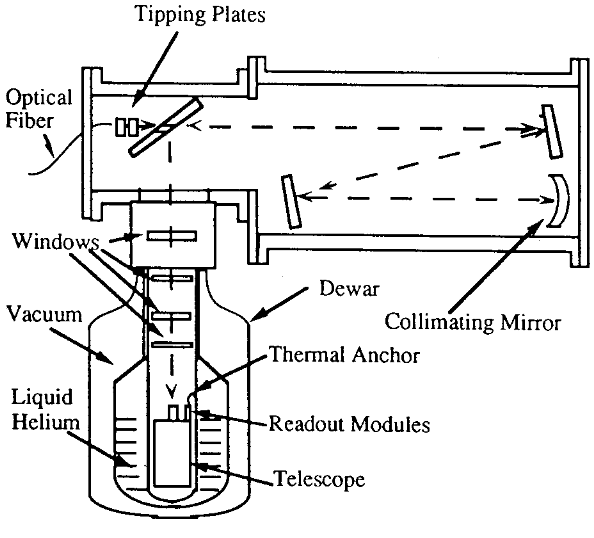

Figure 1: Telescope Test Configuration

To achieve the lowest noise performance, custom Si JFETs are used as preamps in the cryogenic environment. These Si JFETs were designed and fabricated specifically for cryogenic operation by the Solid State Device Development Branch of NASA Goddard Space Flight Center. The current from each photodiode is fed into a two-stage JFET preamp that is part of a capacitive-feedback loop. The nominal operating temperature of the telescope is 2.8 K. Since the Si JFETs need to operate at a higher temperature, the photodiodes and Si JFETs are mounted on a heated sapphire platform which is thermally isolated from the telescope main body by polyimide films. Metallized traces on the films provide electrical connections. To reduce the stability requirements on the supply voltages, the JFET preamps are configured to provide current outputs. The details of the design and fabrication of the readout assembly are discussed by Demroff, et al in these proceedings.

2. TEST CONFIGURATION

The tests were conducted with an artificial star which provides a low intensity 15-cm diameter collimated beam. A single-mode fiber-pigtailed laser diode with a wavelength of 685 nm is used as the light source with the fiber output end located at the focal point of the artificial star. The direction of the output beam can be steered in two orthogonal directions in steps of 1 milli-arcsec by means of a pair of tipping plates near the light source. The entire optical system is suspended inside a vacuum chamber to reduce thermal effects. Fig. 1 shows a schematic view of the general configuration. The vacuum chamber is anchored in four sand buckets which in turn are suspended by air mounts to minimize the effects of floor noise.

The cryogenic telescope probe and dewar system is attached to the light output end of the star. The probe consists of a vacuum tube with four optical windows to reduce transmission of thermal radiation into the telescope. It has an optical aperture of 15 cm. The telescope is mounted at the bottom of the probe with the detector assemblies mounted on top of the Schmidt corrector plate. Each detector assembly is thermally anchored to the probe with a copper wire which conducts the heat away allowing the telescope to remain at 2.8 K.

Room temperature electronics provides the bias for the FETs, the reset signal for the circuit and readout of the output. It is connected to the low temperature part of the circuit via sets of 0.13 mm diameter phosphor bronze wires through low temperature vacuum feedthroughs. The details of the circuit are also described in the paper by Demroff, et al.

3. RESULTS AND DISCUSSION

3.1 Test of Readout Detectors on the Telescope

A constant photon flux on the photodiode generates a ramping voltage across the feedback capacitor in the preamp.circuit. This voltage is reset to zero every 0.1 seconds. The voltage ramp is measured with an A/D card with a sampling rate of 2500 samples/sec. Since the photo current is given by $I = C\ (dV/dt)$, where C is the capacitance of the feedback capacitor, a section of the voltage ramp data from 20 msec to 80 msec after the reset, where the effects of reset transient are negligible, is used for a least-squares fit. The product of the slope of the fit and the feedback capacitance gives the photo current. We characterize the noise of such a system by examining the noise of temporal ensemble of the photo current. In the case of zero photon flux, the noise reflects that due to the electronics alone. For the prototype of such a readout system, the best noise performance was 17 aA/rtHz [2]. For the engineering model, we measured the noise as a function of temperature in the range from 40 to 90 K. Preliminary data shown in fig. 2 indicates that the optimal operating temperature range lies between 60 and 70 K. More data averaging is necessary to improve the precision of this measurement.

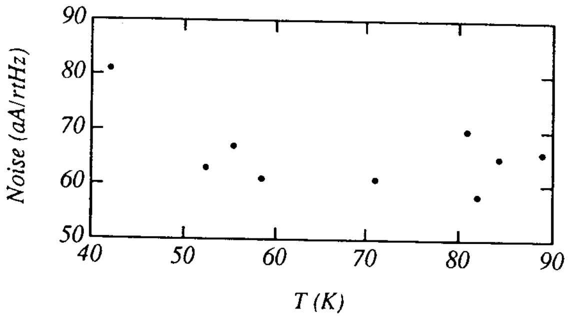

Figure 2: Readout Noise as a Function of Temperature with Zero Photon Flux

During the test it was found that the temperature of the top of the telescope was at 6 K while the bottom was at 4 K. This indicates that the thermal anchoring of the detectors was not as effective as needed. Subsequently, the thermal isolator has been redesigned to use thinner polyimide films and fewer support posts to reduce the amount of heat needed to elevate the platform temperature to a given value.

3.2 Test of the Telescope Optics with the Low-Temperature Readout

For a collimated monochromatic light beam entering the telescope, the intensity profile at the focal point is given by the formula:

$$I(v) = I_0 (1 - \varepsilon^2)^2 [2J_1(v)/v - 2\varepsilon^2 J_1(\varepsilon v)/ \varepsilon v]^2$$

where v is a scaled angle from optical axis and ε is the obscuration ratio. If we write the above expression in Cartesian coordinates with x and y axis representing the angles in two orthogonal directions, the integration of the above function from a given x to infinity is the total light power on one of the detectors on x axis. The integration from minus infinity to x is the total light power on the complementary detector. The difference of the above integrals is the difference in output signal from the complementary detectors when the incident angle is x from the optical axis along x direction.

Data was obtained by rotating the tipping plate so that the incident angle of the light beam with respect to the optical axis of the telescope changes from - 5 arc sec to + 5 arc sec in steps of 0.1 arc sec. At every step, ten voltage ramps were measured and fitted as described in section 3.1 and then averaged. The data are normalized to unity at ± 5 arc sec. Such sweeps were performed in two orthogonal axes both at room temperature and at 4.2 K. Fig. 3 shows the data along one of the axes. The solid line shows the theoretical calculation for a perfect optical system; the crosses are room temperature data and circles are 4.2 K data.

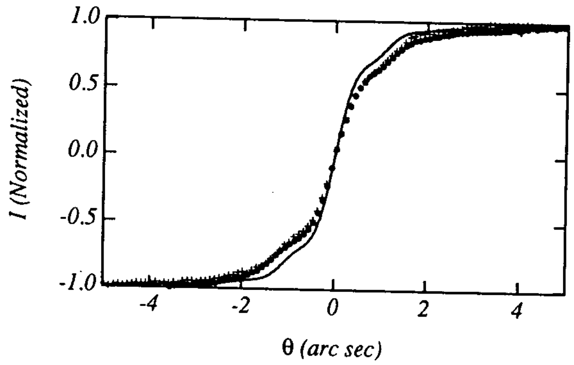

Figure 3: GP-B Telescope Optical Test Data

For the prototype GP-B telescope, we found a 5 cm focal position change upon cooling down to 4.2 K[3]. The material used for the prototype was random selected Corning 7940 fused silica. Due to small mismatches in coefficient of thermal expansion (CTE), the focal length of the telescope changed upon cooling. We have chosen Herasil 1-top fused quartz from a single boule to make the flight quality telescope. Such material has proven to have CTE mismatches of less than 0.3 ppb/K within a single boule. The data shown in fig. 3 demonstrate that there is no observable focal position change from room temperature to 4.2 K. The small deviations of the data from the theoretical curve can be attributed to the wavefront distortions of the telescope, the artificial star and the windows. The calculations with the wavefront errors included showed (not included in the figure) good agreement with the data.

4. CONCLUSION

The engineering model of the photodiode-JFET preamp assembly has been tested with a flight quality GP-B telescope. The noise meets the GP-B requirement of 100 aA/rtHz. Preliminary data was collected for the noise as a function of temperature. More measurements are necessary to improve the precision of the noise values. For the flight detectors, the thermal isolators have been improved to require less heating power. The improved design of the telescope with the material Herasil 1-top showed no detectable cryogenic focal shift to within 0.5 mm. The ultimate flight telescope itself is currently being tested.

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