Status of the cryogenic inertial reference system for the Gravity Probe B mission

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ABSTRACT

We describe the status of the development and testing program for the inertial reference system for the Gravity Probe B gyroscopes. The gyroscope housings are attached to a cryogenic telescope with a 14 cm aperture that continuously points at a guide star. The star image is split to provide quadrant pointing information which is used to steer the spacecraft. This data is also combined with the gyro readout data to provide an absolute precession measurement. Motion of the guide star is independently checked by reference to background galaxies. Room temperature testing of a prototype telescope has been completed and preparations are being made for low temperature tests.

INTRODUCTION

For some time now, the hardware to perform a new test of General Relativity has been under development[1] at Stanford. The experiment, called Gravity Probe B, consists of measuring the precession of gyroscopes in earth orbit relative to inertial space, as established by a distant reference frame, the 'fixed' stars[2]. Two precession effects are predicted: the larger is due to the orbital motion of the gyroscope about the central mass, and for a 650 km altitude orbit is expected to be about 6.6 arc sec per year in the orbit plane; while the smaller is due to the earth's rotation and is about 0.042 arc sec per year in the equatorial plane, for a gyroscope in a polar orbit. The goal of the experiment is to measure both effects and to resolve the smaller to about 1%, implying a detection capability of about 3×10^{-4} arc-sec per year.

The inertial reference frame is locally established in the experiment package by means of a star tracking telescope bore-sighted on a reference star, which is currently Rigel. To achieve the desired level of stability in the reference direction, the telescope is mounted directly onto the gyro support assembly. This approach places a number of constraints on the star tracker design, primarily because of the operating temperature of the gyros which is about 2 K. In return, we gain a significant advantage because of the enhanced stability and low thermal expansion coefficient of materials at such temperatures. Other constraints are imposed by the mission lifetime and the spacecraft pointing requirements. The basic design of the telescope has been described elsewhere[3] and is touched on only briefly here. In this paper we concentrate on test results from the prototype telescope, progress with a solid state, low temperature readout scheme, and plans for the future.

TELESCOPE REQUIREMENTS AND DESIGN

As mentioned above, the design requirements placed on the telescope mainly result from the co-location of the gyroscope and telescope sub-systems and overall mission constraints. These requirements are summarized in Table 1 where they are split into primary and secondary requirements, which are major and minor design drivers respectively.

Primary:		
	Mechanical and Readout Null Stability:	< 0.1 marcs over roll period
	Linear Range:	± 60 marcs
	Linearity:	< 3 marcs peak to peak
	Sensitivity:	<3 marcs / √ Hz
Secondary:		
	Orthogonality of Readout Axes:	< 1 arc min
	Scale Factor Calibration (preflight):	30%
	Field of View:	± 2 arc min
	Alignment to Gyro Axes:	< 5 arc sec
	Stray Light in Field of View :	< 0.1%

Table 1: Telescope requirements

The basic pointing stability requirement is on the alignment between the gyro readout axis and the telescope boresight. This requirement can be broken into two parts: long term effects on time scales of days or longer, and higher frequency effects. Because the spacecraft rolls once per 10 mins, low frequency effects cause the reference line to move in a small cone about the boresight. The only effect of this is to slightly increase the linear range requirement on the gyro readout system. If the cone angle is held below 5 arc sec, this is not a significant problem. Slow variations of up to this magnitude have been shown to have little impact on the science return from the mission[4]. This level of dimensional stability can be achieved by good design, and in our case three additional factors make it more easily attained. First, the telescope can be fabricated entirely of fused quartz except of course for the reflective coatings. This material has been shown to have exceptionally good dimensional stability even at room temperature[5]. Second, by operating at low temperatures, the effect of thermal gradients is substantially reduced, virtually eliminating potential errors from this source. This is because thermal expansion coefficients approach zero below 10 K, and thermal fluxes generally tend to be less in low temperature situations. Third, in our application the telescope structure can be very symmetric, leading to a high degree of cancellation of possible errors. All these factors plus spacecraft roll give us a high degree of confidence that low frequency boresight drift will not be a problem for the current experiment. At frequencies closer to the roll rate boresight disturbances can be treated as additional noise in the telescope output. This again is well averaged , except for a very narrow frequency band centered on the roll rate. The most likely sources of disturbance at this rate are environmental, for example stray light scattered into the field of view, or external thermal effects on the telescope electronics. Even for these effects further annual averaging will likely occur. These considerations give rise to the stray light requirement listed in the table, and other requirements on the electronics which are not listed.

Because of the limitations of the spacecraft pointing control system, the telescope readout needs to be linear over some finite operating range. Recent models of the control system indicate that the operating range can be held to ±20 marcs, but for safety we require the telescope to perform well up to ±60 marcs. Simulation of the control system and its effect on the science data has shown that over this range we require linearity to within 5% peak to peak. Sensitivity is again primarily a control system issue, with the requirement set at 3 marcs in a 1 Hz bandwidth.

The basic optics for the telescope have been described elsewhere[3]. Briefly, the system is a folded Cassegrainian design with three spherical reflectors and a Schmidt corrector plate. All components are made from quartz and bonded by the optical contacting technique. The effective focal length is 380 cm and the aperture is 14 cm. A cross-section of the telescope is shown in figure 1. The primary focus is located at a pair of

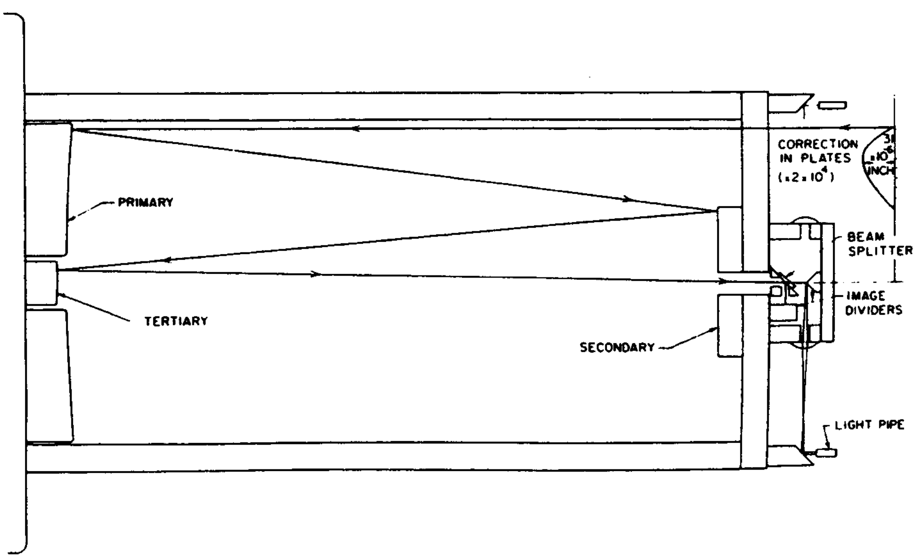


Figure 1: Schematic view of telescope optics.

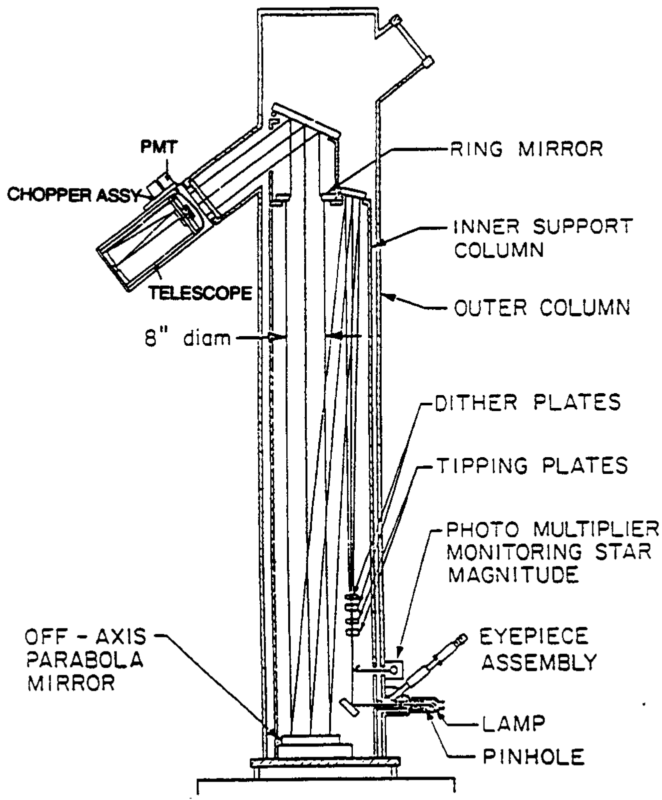
roof prisms mounted at 90° after a beam splitter in a box on the back of the secondary mirror. When the star is boresighted, both images from the beam splitter are bisected by the apex of one of the prisms. This configuration allows us to easily obtain differential readout information in two axes without having to worry about linearity issues near the center of a quadrant divider.

Beyond the focal plane, two alternative readout configurations are being developed. The first option is to transfer the four partial images to fiber-optic bundles which extend from the telescope out of the dewar to room temperature photomultipliers and light choppers. The second is to re-image the divided starlight at four locations on the rim of the telescope and use low temperature semiconductor photo-diodes for intensity readout. This latter approach has the advantages of giving a better conversion efficiency and more stable gain parameters, but may suffer from noise problems if a guide star much fainter than Rigel is chosen. A final decision on these issues is expected to be made in about a year.

TESTING

One of the most important requirements on the telescope is its linearity over the inner region of the star image. Early measurements[3] of this parameter were encouraging, but were not of sufficient resolution to give useful quantitative results.

The linearity measurements are made by using a star simulator, a schematic view of which is shown in figure 2. This device collimates a beam of light passing through a small pinhole and aims it at the telescope aperture. The direction of the output beam can be varied in steps as small as 1 marc using a tipping plate near the pinhole, allowing the user to scan the image across the telescope roof prisms. We upgraded this image scanning system and the telescope readout system to allow automated data collection over many scans with a high degree of repeatability. We found that thermal effects in the star simulator and telescope support structure caused significant image drift over short time periods, but if the assembly was thermally lagged by a six inch layer of styrofoam the problem was manageable. Some results obtained during a period of high stability are shown in figures 3 and 4. Wide range data in figure 3 can be used to get an idea of the image size for comparison with the theoretical diffraction limited spot convolved with the finite pinhole. We find good agreement to within the 10% uncertainty of the measurement. To obtain data with a resolution of a few marcs, we must average over a number of scans and adjust for the drift of the center of the image. A sample of data collected in this way plotted as deviations from the best fit linear behavior is shown in figure 4a. it can be seen that the linearity requirement in table 1 is easily met in the test configuration. It was also found that the details of the deviations from the best fit tended to vary somewhat on the time scale of hours, possibly due to thermal effects in the imaging system. However the magnitude of the departures was rarely much larger than



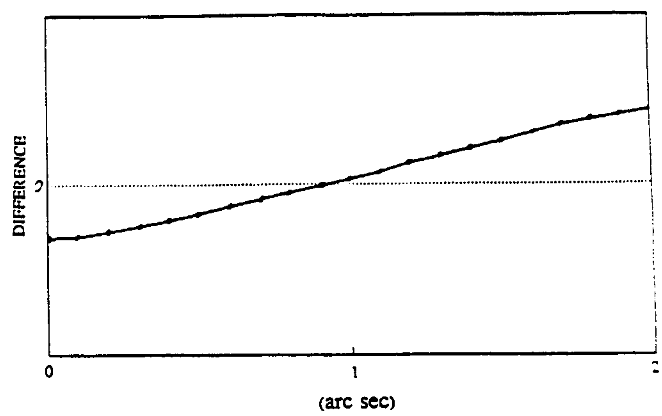
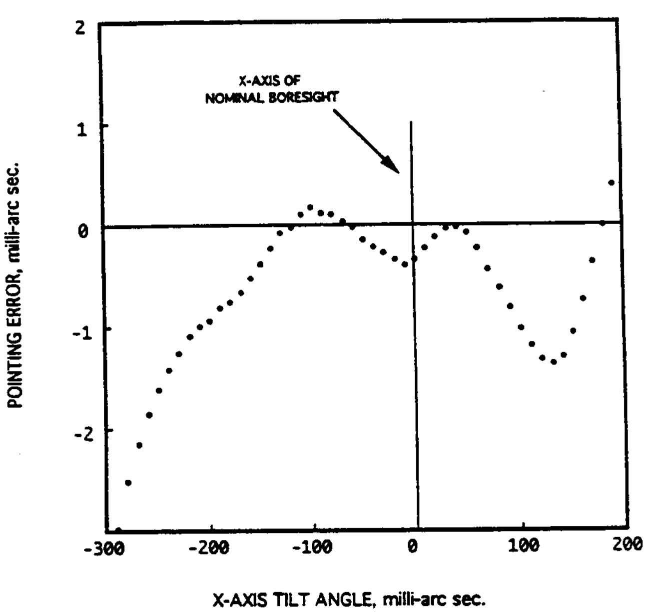


Figure 3: Telescope error signal vs incident angle of starlight. (vertical scale in arbitrary units)

Figure 2: Schematic view of room temperature telescope test facility.



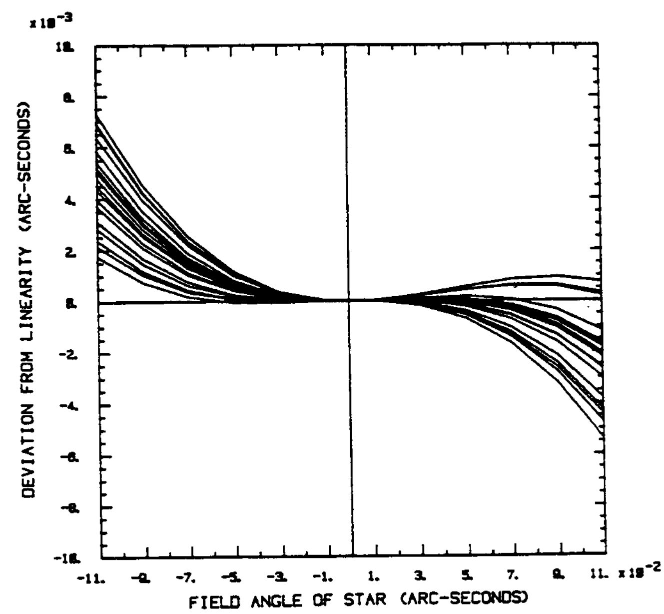


Figure 4a: Deviations from linear response in central portion of star image vs incident angle of starlight.

Figure 4b: Computed sample linearity deviations for optics with $\lambda/20$ rms surface errors.

those shown in the figure. For comparison, typical departures from linearity expected[6] with optics having $\lambda/20$ surface finishing errors are shown in figure 4b.

To date, all telescope testing has been performed at room temperature. While the instrument has been fully engineered for operation at 2 K, it is still an open question as to what special problems will be encountered by operating in this temperature regime. The only known issues are the effect of cryo-deposits and the slight change in focal position due to the contraction of the quartz. Optically contacted joints have already been operated at low temperatures on a number of occasions. A secondary but important aspect of low temperature operation in the flight experiment is the need to view the guide star through a number of windows at intermediate temperatures. These windows attenuate the flow of heat into the low temperature region from the earth's albedo and the sunshade, and allow the gyro area to be sealed off to attain ultra high vacuum. Design analysis performed at Lockheed Palo Alto has shown the need for high thermal conductivity material in the windows, and the material of choice is currently calcium fluoride.

To determine the effects of low temperatures on the star tracker performance in a comprehensive way we are constructing a new star simulator facility designed to give improved flexibility and to be integrated with a low temperature telescope assembly. A cross-section of the new facility is shown in figure 5. It generates a primary beam similar to that in the earlier simulator, plus a secondary beam that reflects off a small mirror mounted on the front of the telescope to form an autocollimator system. This arrangement will be used to keep

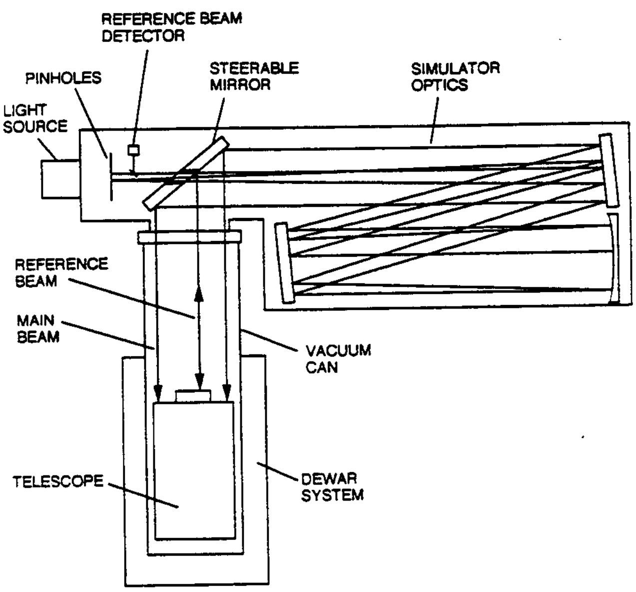


Figure 5: Schematic view of star simulator with low temperature test facility.

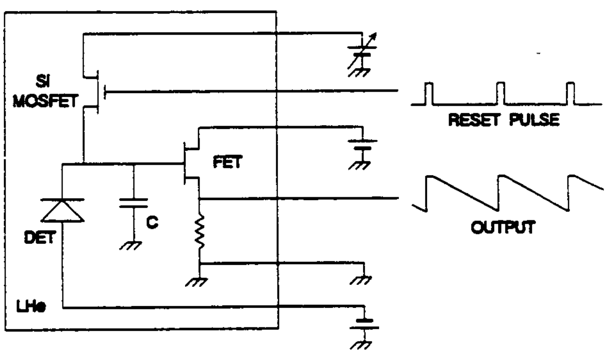


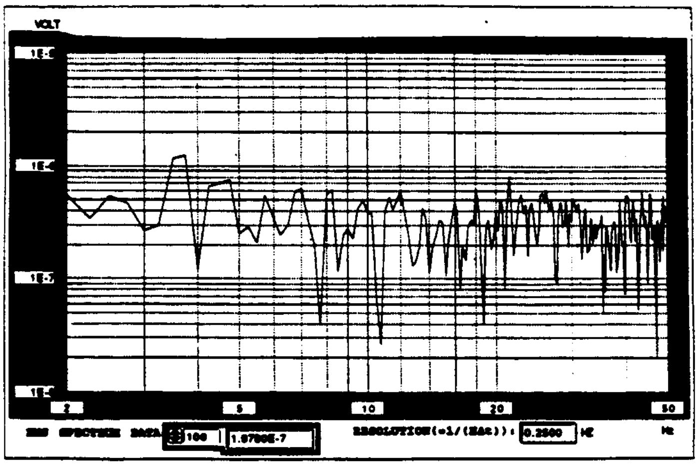
Figure 6: Circuit diagram for low temperature readout electronics. Wave forms have a 100 Hz repetition rate.

the telescope pointed at the reference beam while the primary beam can be moved relative to it in small increments using tipping plates. This approach is expected to provide enhanced stability to allow sub-arc second work with part of the system at low temperatures and the rest at room temperature. Near the light sources, extreme stability is required to minimize relative drift between the two beams. All critical parts are made of Invar and the whole assembly operates in a vacuum which promotes thermal stability. The exterior of the simulator is made of extra thick aluminum to minimize thermal gradients and rates. The optics assembly is hung inside the vacuum can from flexures designed to minimize stress on the mirror support frame. All couplings to the beam adjustment mechanisms are soft and all motors are external to the vacuum. The major source of thermal dissipation is the white light source which is also mounted externally. Beam steering is achieved by tilting the large 45° mirror using piezoelectric transducers. For larger adjustments and initial alignment the dewar and telescope assembly can be tilted separately using lead screws and stepper motors. The star simulator is also provided with extensive vibration isolation to minimize the effects of ground motion.

READOUT DEVELOPMENT

In the hope of reducing complexity and improving both performance and reliability, we have been developing a low temperature readout system to replace the photo-multiplier/chopper wheel system currently baselined. It is well known that at least some silicon-based photodiodes operate well at low temperatures with quantum efficiencies comparable to those observed at room temperature. However no suitable amplifier system capable of working near 2 K with the desired levels of stability and noise could be identified. Silicon devices generally suffer from some form of pathological behavior when operated below about 30 K, and GaAs devices were of too high power consumption for the present application.

Since GaAs in principle should work well at 2 K we have started a program to evaluate both commercial and foundry chips that could potentially have low noise in the frequency band 1 -1000 Hz when operated at very low power. A progress report on our findings has been published[7]. We have found that low power operation does not appear to be a problem, at least to the level of 10 μW per amplifier unit. Also the grounded and open gate noise voltage spectra indicated that at least for a star as bright as Rigel photon noise-limited performance could be reached. Unfortunately in our application the photodiodes have an extremely high resistance and significant capacitance, so low frequency current noise is also a significant issue. The open gate measurements indicated that this might not be a real problem but it appeared highly desirable to obtain noise data with a realistic circuit configuration. Recently we set up a breadboard readout circuit as shown in figure 6 using a small photodiode and a GaAs FET. The node capacitance is about 5 pf, somewhat higher than that expected on the flight instrument. The assembly was operated at 4 K in nominally dark conditions. A preliminary noise spectrum is shown in figure 7a. For comparison, in figure 7b we show earlier measurements of



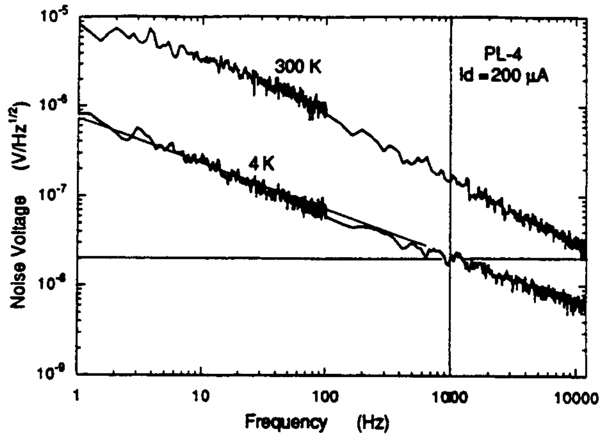


Figure 7a: Noise spectrum with prototype readout circuit operating at 4K.

Figure 7b: Grounded gate noise spectra of preamplifier chip vs temperature

the grounded gate noise at room temperature and 4K using the same type of FET, the Plessey P35-1101. While the breadboard measurements are very preliminary, it can be seen that over the frequency range of interest the total noise of the circuit is comparable to that of the FET alone. For reference, the expected photon noise for Rigel is about 8 microvolts with a 100 Hz sampling rate.

In parallel with the noise studies we are procuring a set of custom GaAs FETs with a wide variety of gate configurations, in the hope of developing even lower noise devices. If this venture is successful we will be able to substantially expand the choice of guide stars for the mission while simultaneously achieving a high reliability readout system.

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