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THE GRAVITY PROBE-B STAR-TRACKING TELESCOPE

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ABSTRACT

We describe the design, development, and testing of a cryogenic star-tracking telescope that provides the inertial pointing reference for the Gravity Probe-B gyroscopes, as established by a distant guide star. The telescope has a modified Cassegrainian configuration with an aperture of 14.4 cm and an effective focal length of 3.8 m, and operates at 2.5 K. It consists of high-grade fused-quartz components silicated together to maximize strength and dimensional stability. The star image is split at the focal plane to provide quadrant pointing information for subtraction from the gyro readout signal and for spacecraft attitude control. We also briefly describe the status of the telescope readout electronics and the guide star selection. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

INTRODUCTION

The Gravity Probe-B Relativity Mission (GP-B) will measure the general relativistic changes in the spin axis orientation of a set of gyroscopes in polar orbit around the earth. The GP-B telescope, when locked on the guide star, will provide the inertial reference for these angular measurements with an accuracy approaching 0.1 milli-arc-sec (mas) per year. The changes in the gyro pointing angles relative to inertial space are then obtained through simple subtraction of the telescope readout signal from the gyro signals after appropriate gain adjustment. To minimize errors in this process, the mechanical interface between the telescope and the gyros must be extremely stable. This is achieved by connecting the two subsystems with a massive block of fused-quartz and operating the assembly at close to 2.5 K. Long term drift errors are further reduced by rolling the spacecraft about the line of sight to the star. Although the cryogenic requirement presents several challenges in design, fabrication and testing, it gives rise to some significant advantages, such as enhanced thermal stability and low electronic noise background. Other major requirements are: the linearity error of the telescope pointing signal must not exceed 3 mas within a ± 60 mas range about the null-pointing direction; the pointing error must be < 0.1 mas at the spacecraft roll frequency when averaged over the duration of science mission; and the noise in the telescope readout must be small enough to allow the spacecraft pointing system to keep the telescope aligned within 20 mas rms of the guide star direction. The operational approach is to null the telescope error signal and use the gyro readout signals to observe the relativity effects (geodetic drift ~ 6.6 arc-sec/year; frame dragging drift ~ 43 mas/year), the aberration of starlight, and the guide star proper motion.

DESIGN OVERVIEW

The telescope consists of three sub-assemblies: the basic optics, which collects the guide star photon flux

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and focuses it into a nearly diffraction-limited image, the image dividing assembly (IDA) near the focal-plane, and a pair of photon detector/pre-amp assemblies. The basic optics has a modified Cassegrainian design (Everitt *et al.*, 1986), as shown in Turneaure *et al.* (2003, fig. 4). In addition to the usual primary and secondary spherical reflectors, it has a tertiary reflector embedded at the center of the primary. The focal plane is located a short distance outside a corrector plate, which forms the entrance pupil of the telescope. The central region of the corrector plate supports the IDA which splits the image and transports the resulting photon fluxes to detectors mounted near the rim. The telescope aperture has a 14.4 cm outer and 7.1 cm inner diameter, with the latter defined by the obscuration due to the IDA. The effective focal length of the telescope is approximately 3.8 m, and the diffraction-limited image is 30-40 μm in diameter. A 50/50 beam-splitter is located a short distance in front of the focal plane creating two images which are split by roof-edge prisms. The image dividing axes of the prisms are orthogonal when projected onto the original focal plane creating two images which are split by roof-edge prisms. The image dividing axes of the prisms are orthogonal when projected onto the original focal plane, allowing us to extract the differential pointing signal in two axes.

Overall, the telescope is 50.5 cm long and 18.4 cm in diameter. Its components are all cut from a single fused-quartz boule specially heat-treated to improve the uniformity of its thermal expansion coefficient and refractive index. Similar material was shown to have a linearized differential thermal expansion coefficient as low as 1 ppb/K-cm (Jacobs, 1995). The use of fused-quartz as the material for a cryogenic telescope results in unique fabrication challenges. Of major importance is the component bonding technique. In an early prototype, joints were formed by optical contacting. This technique proved to be somewhat unreliable and therefore unsuitable for a flight instrument. Silicate bonding was chosen as the component joining technique for the telescope currently in fabrication. This method shows superior strength and reliability. For example, shearing a silicated interface typically results in fractures of the bulk material, instead of fairly clean cleavage in the case of an optical contact. The bond survives thermal shocks to 4 K and causes negligible optical distortion over the range 300 to 4 K, as verified by Fizeau interferometry. The thinnest interface is essentially unresolvable with a scanning electron microscope having nanometer resolution.. This implies that any interface wedging has negligible impact on critical alignments.

There are two electronic detector-preamp packages mounted near the rim of the corrector plate, which receive photon fluxes from the roof prisms. The light from both sides of a roof prism enters the aperture of a single package and falls on two silicon PIN diodes mounted close together on a thermally isolated sapphire platform. This configuration allows the readout circuit to be operated at a controlled temperature within the range of 50 to 80 K to minimize the noise of the silicon JFET differential-input preamps. The co-location of the diodes minimizes the effect of thermal gradients on readout bias variations. These diodes typically have a quantum efficiency of 60% from the visible to near-infrared. The preamplifiers are operated in a charge integration mode with resets every 100 ms and a dead time of 3 ms. The photo-electron current in each detector is determined from the slope of the corresponding integration ramp. To reduce the risks of single-point failure, each package is doubly redundant in electronics. Basically the two beams impinging on a package are each split into two beams to match the electronic redundancy. There are two sapphire platforms in each package independently feeding complete sets of single-axis readout information to later stages of electronics to generate the pointing error signal.

TELESCOPE ASSEMBLY

To maximize the pointing stability, the basic optics and the IDA are bonded with no built-in adjustment capability. Since the silicate bonding technique is essentially irreversible, and the amount of material available from a given boule is severely limited, special techniques are used in the assembly of the telescope. Probably the most critical step is to set the spacing between the primary/tertiary mirror assembly and the secondary/corrector plate assembly so that the focal point falls on the roof-edges at the operating temperature. In the prototype model (Everitt *et al.*, 1986) this was done by setting up the optics on a bench in front of a wide-aperture autocollimator and determining the location of the focal point. The metering tube, which holds and separates the mirror assemblies, was then cut to length and contacted into place. The IDA was then built piece-by-piece on the corrector plate, with the roof-edges placed exactly at the focus. Unfortunately, the focal point shifted by about 5 cm when this instrument was cooled to 4 K, severely decreasing its sensitivity (Wang *et al.*, 1996). The main cause of this shift was traced to slight differences in the expansion coefficient of randomly selected samples of fused-quartz. For the engineering model, currently in the final stages of assembly, a different approach is being used. First, all material was taken from a specially annealed boule using a cutting scheme that preserved the approximate relative location of the individual components. Next, a trial assembly was performed using very thin plastic shims at the ends of the metering tube. At this stage the IDA was left off the telescope. The position of the focal point was first determined with Fizeau interferometry, and then with a quad-cell detector in the IDA location, at both 300 and 4 K. From this information, the desired length of the metering tube was determined. In this test cycle we saw no significant focal shift at 4 K, indicating that the fused-quartz is extremely homogeneous. Care is needed in determining the length of the metering tube because of the factor of sixty amplification between its length and the focal position. Also, the tubes constitute the major portion of a boule, so spares are hard to come by. The next steps are to bond the metering tube in place, verify the low temperature focal position, and attach the IDA using a quartz shim of appropriate thickness. This shim is the final spacer element locating the roof-edges along the optic axis. Finally, the detector packages can be attached to the corrector plate.

TESTING AND VERIFICATION

The basic approach to testing a completed telescope is to use a device called an artificial star (AS) to scan a simulated star image across the roof edges. The beam of light from the AS is wide enough to simulate the near-perfect spatial coherence of starlight. The prototype telescope, mentioned above, was tested with an AS lacking vibration isolation and pointing stabilization. Data acquisition relied heavily on a software scheme to compensate in real time for low frequency thermal drift in the beam angle with a control bandwidth approximately of 10 Hz. During an image scan across a roof edge, the intensity difference on the two sides was monitored. From the angle-dependence of this difference signal, we were able to determine the telescope linearity. Through extensive signal averaging, we were able to verify at room temperature that the linearity error within a ± 60 mas range about the line of sight was less than 0.5 mas, well within the requirement of 3 mas. Unfortunately, due to the defocus problem, no useful results were obtained at low temperatures.

A new AS has been built, incorporating many improvements. Preliminary measurements have been made with this device on the partially assembled engineering telescope. So far, we have operated with a quad-cell at the focus, instead of the IDA. The observed Strehl ratio of the image appears to be at least 50%, both at 300 and 4 K. This may be limited by edge effects in the quad-cell elements. For low temperature operations the telescope must look through an optical window system designed to minimize the heat load into the cryogenic area. Some degradation in performance is expected due to inevitable radial temperature gradients in the windows. However, calculation and preliminary measurements indicate that this is a fairly small effect.

READOUT AND POINTING PERFORMANCE

The 0.1 mas maximum error budget for the average pointing error at the roll frequency was allocated equally to the readout electronics system and the optical system, with the latter including the spacecraft windows. In both cases, the dominant source of error appears to be the effect of solar radiation. A detailed thermal model of the spacecraft and instrument was developed, which verified for the optics system that the 0.05 mas requirement could be met if the external sunshade was equipped with a thermal blanket. The thermal model was also applied to the electronics design and a need for active temperature control was demonstrated.

The noise performance of the telescope sensor assembly to date is 26 mas rms measured from a single detector-preamp readout system. This corresponds to 8.2 mas/$\sqrt{\text{Hz}}$ over the bandwidth from approximately dc to 5 Hz for the worst case of using only one of the two redundant readout systems. This easily meets the telescope sensor noise requirement of < 10 mas/$\sqrt{\text{Hz}}$, derived assuming a 0.15 Hz pointing control bandwidth. As a result, the telescope sensor noise would contribute no more than 3.9 mas to the maximum random error of 20 mas rms allowed for the pointing system. For reference, the theoretical photon noise is 2.9 mas/$\sqrt{\text{Hz}}$ assuming the worst case of HR 1099 as the guide star, an optical transmission of 20% and Strehl ratio of 50%.

GUIDE STAR

The guide star selection work is being performed by the Smithsonian Astrophysical Observatory (Ratner *et al.* 1994). The most important requirements to be met by candidate stars are: proper-motion error $<$ 0.15 mas/year; brighter than about 5th magnitude; and low declination. The use of very long baseline interferometry to determine the proper motion by monitoring the angle between the guide-star and extragalactic quasars mandates that the stars be radio-visible. Currently, the three candidate guide stars are HR 5110, 1099, and 8703, with visual magnitudes of 5.0, 5.7 and 5.6 respectively. All are RS CVn binaries with close companions (within 1 to 4 mas) and with orbital periods of 2 to 25 days. Observations are being made to answer questions about presently unobserved companions, the diff- of the mission, the proper-motion error for HR8703 should be in the range of 0.08-0.2 mas/year, with 0.11 mas/year as its most likely value. Additional observations could improve the accuracy and precision of the proper-motion measurements beyond this level.

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