Pointing performance of the Gravity Probe B inertial reference telescope

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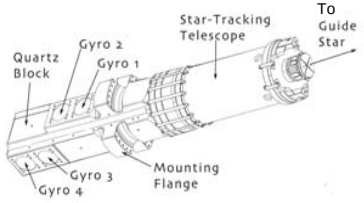
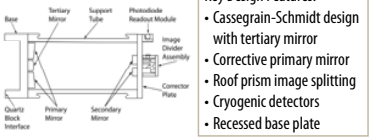
Introduction

GP-B uses a star-tracking optical telescope to lock onto a guide star to establish the inertial reference frame. The telescope is made of fused quartz with no movable components. All components are bonded together with an optical bonding technique developed by GP-B. The telescope itself is bonded to the quartz block which houses the gyroscopes. This ensures a very stable mechanical reference to all the gyroscope readout loops. The telescope provides pointing information to an accuracy of 0.1 milli-arc-sec in less than 4 days of averaging.



Design of the Telescope

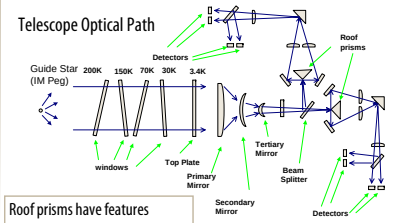


Key Design Features:
- Cassegrain-Schmidt design with tertiary mirror
- Corrective primary mirror
- Roof prism image splitting
- Cryogenic detectors
- Recessed base plate

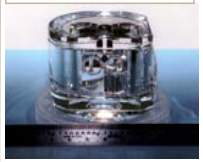
Key Design Parameters

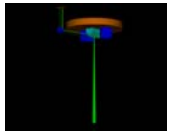
Parameter	Value
Central Obscuration (m)	0.070
Clear Aperture (m)	0.144
Focal Length (m)	3.81
Field of View at 10% Peak Intensity (arcs)	> 66
Range of Monotonic Response (arcs)	> 1
Perpendicularity of Readout Axes (degrees)	0.4 ± 0.2
Optical Transmission	> 13%
Scale Factor (arc sec)	3.2
Pointing Noise (marcs/$\sqrt{Hz}$ @10 Hz)	< 36.9

Image Dividing Scheme



Roof prisms have features smaller than 1 μm at roof edge and provides excellent scheme for image dividing.





Co-located detectors provide good common mode rejection.

Telescope Development

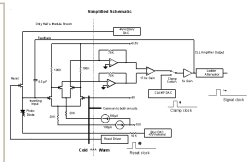
Telescope #1 was developed as a demonstration of concept. It demonstrated good thermal stability and linearity. Optical fiber coupled to PM tubes were used for readout for RT test.

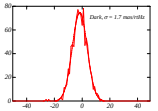
Telescope #1 was upgraded with LT readout and reference mirror for the cryogenic test. The first cryogenic test revealed a focal point shift of 5 cm; a big surprise!

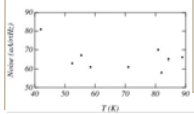
Telescope #2 was made from a single boule of Herasil 1-top fused quartz. It was the flight backup.
Telescope #3 was the flight telescope.

Cryogenic Readout

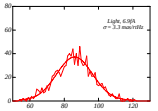
Features:
- Dual Si PIN diode co-located on the same chip
- JFET amplifiers with optimal noise performance near 70 K. JFET's made by NASA Goddard.
- Sapphire platforms heated to 72 K with thermal isolation to the surroundings at 3.5 K.





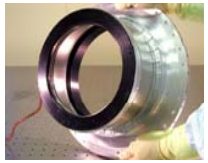


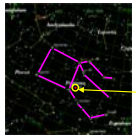
Electronic noise measured as a function of temperature.

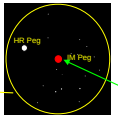


Photon noise limit achieved in lab

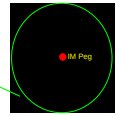
Windows and Guide Star







1/2 degree field

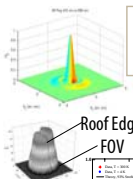


1 arc min field

Key Guide Star Features:
- RA: 22h53m2.27sec DEC:16d50m28.3sec
- Visual Magnitude ~ 6th magnitude
- Radio star for VLBI proper motion measurement *
- HR Peg only other bright star within 1/2 degree of field
- No star brighter than 16th mag within field of view
- Many names: IM Peg, HR8703, HD216489, HIP112997, …

* See poster by SAO for more details

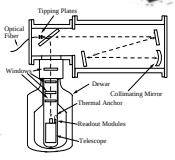
Ground Tests

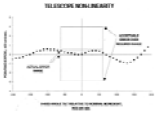


Normalized pointing signal used

$$I = \frac{S_+ - wS_-}{S_+ + wS_-}$$

Roof Edge FOV

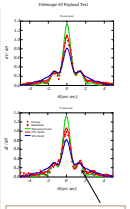




Artificial Star #1:
- RT tests of telescope #1
- Verification of linearity
- Stability of telescope out runs that of the star

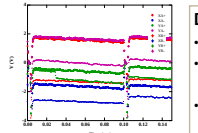
Artificial Star #2:
- Improved stability on mechanical structures
- Reference beam used to dynamically control stability of the beam
- Used for cryo-focal point location and for telescope performance verification
- Monochromatic light used

Artificial Star #3:
- Light weight for payload test
- Transmission optics
- Monochromatic light used
- Dynamic servo used to stabilize the light beam
- Focal point found shifted by 5.0 mm
- Successful graduate student project



Side lobes used as consistency check for angle calibration

Flight Data

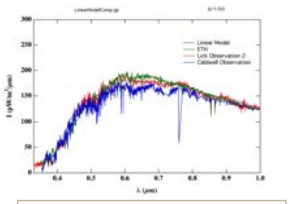


Telescope Readout Data

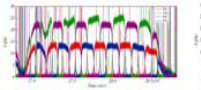
Axis	Estimated Current (fA)	Measured Current (fA)	Pointing Noise (mas)
XA	10.07	11.60	83.8
YA	24.07	21.60	51.6
XB	13.13	14.20	109.6
YB	14.65	14.20	73.7

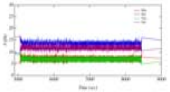
Data Stream:
- Snapshot data at 2.2 kHz
- Onboard processed at 10 Hz into level 1 data
- Cosmic ray hits removed during level 1 to level 2 data conversion

$$\theta = S\frac{S_+ - wS_-}{S_+ + wS_-} \equiv S \bullet n$$

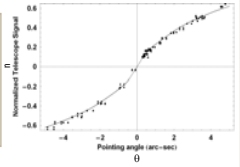


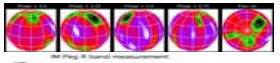
Non-linearity correction:
- Lowest order axially symmetric aberration is represented by 4th order Zernike polynomial modified for central obscuration
- Defocus: ~ 5.0 mm, Zenike coefficient: 415 nm
- Cubic term correction: $\theta = (b_1 + b_3 n^2)n$

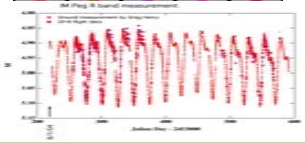


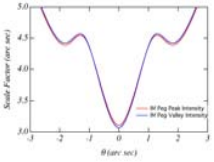


Scale factor variation due to star color change:
- Color synthesis based on spectra data
- Scale factor correction based on model
- Contribution is only significant when pointing has large roll rate error.
- Error before correction: < 1 milli arcsec/yr









Summary
- Telescope performed as expected
- Largest contributions to science data are from non-linearity and star color variation
- Impact on science data reduction < 1 milli arc sec

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This research supported by NASA on contract NAS8-39225