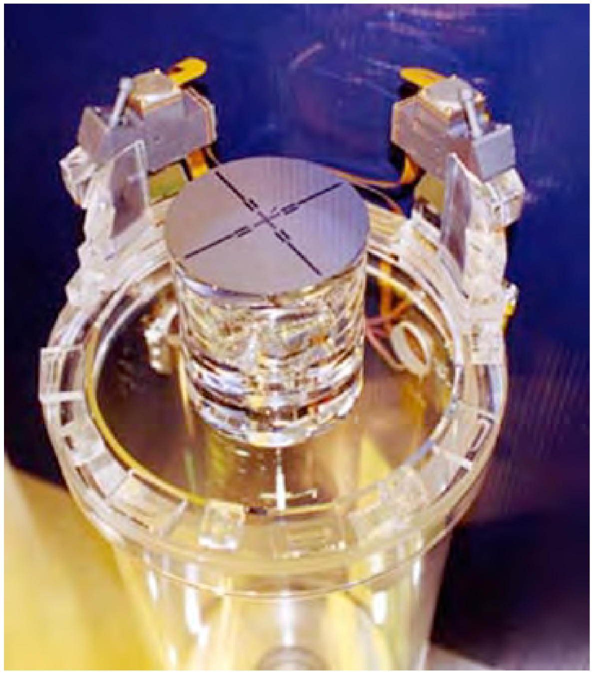
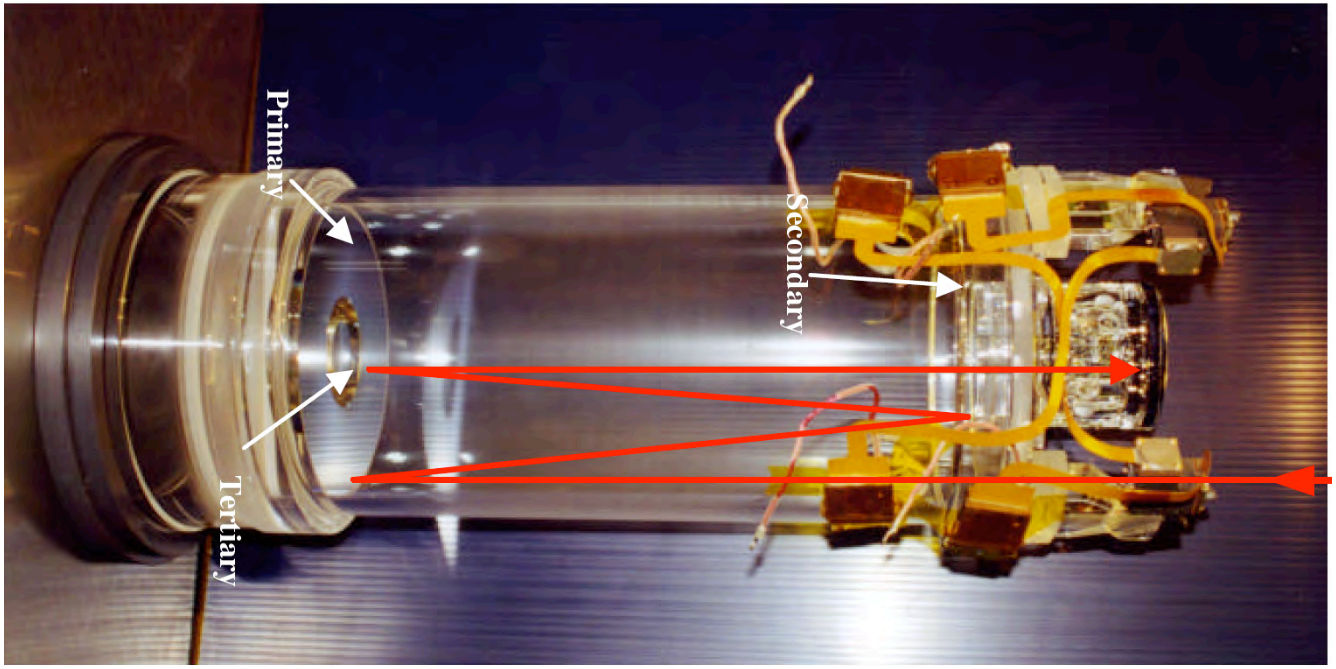
GP-B Telescope

John Mester

Stanford University



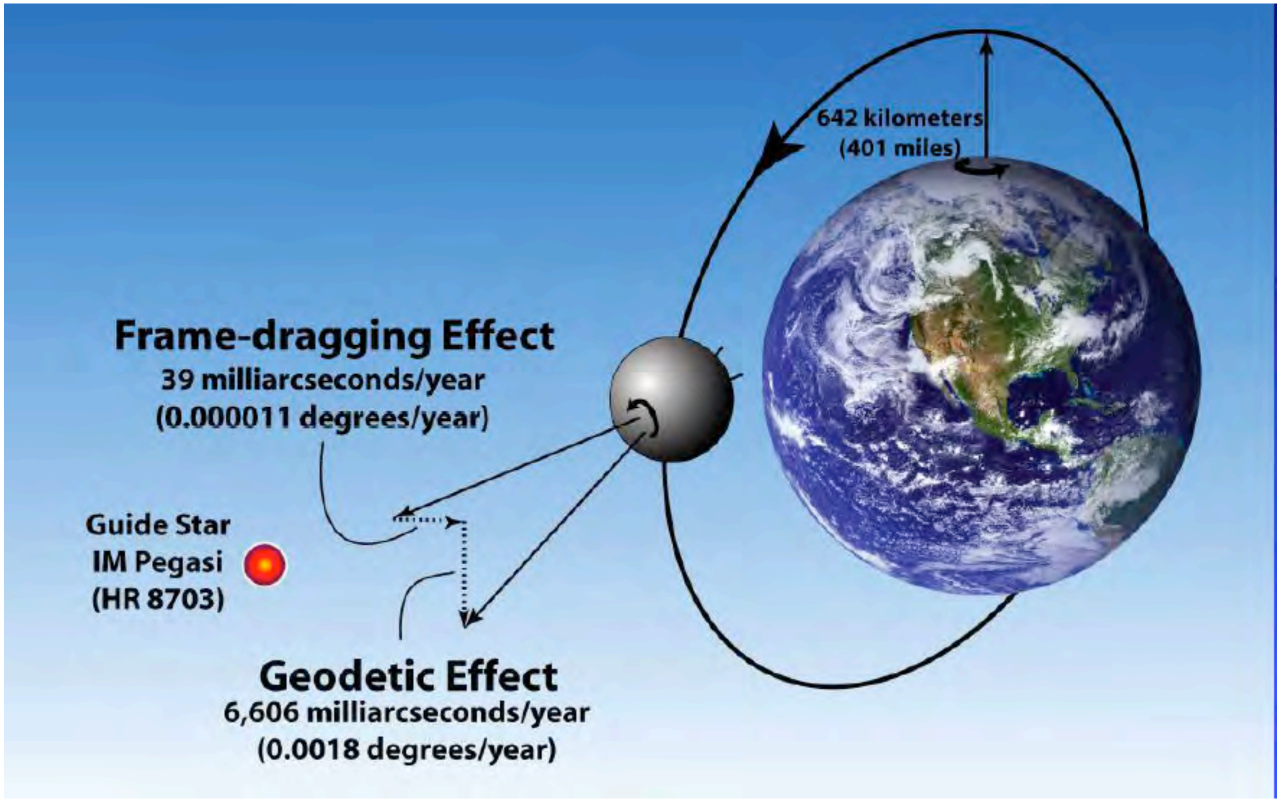


EXTERNAL REFERENCE

Gyro spin indicates direction in local inertial frame

Need to compare to external reference

⇒ Line of sight to guide star

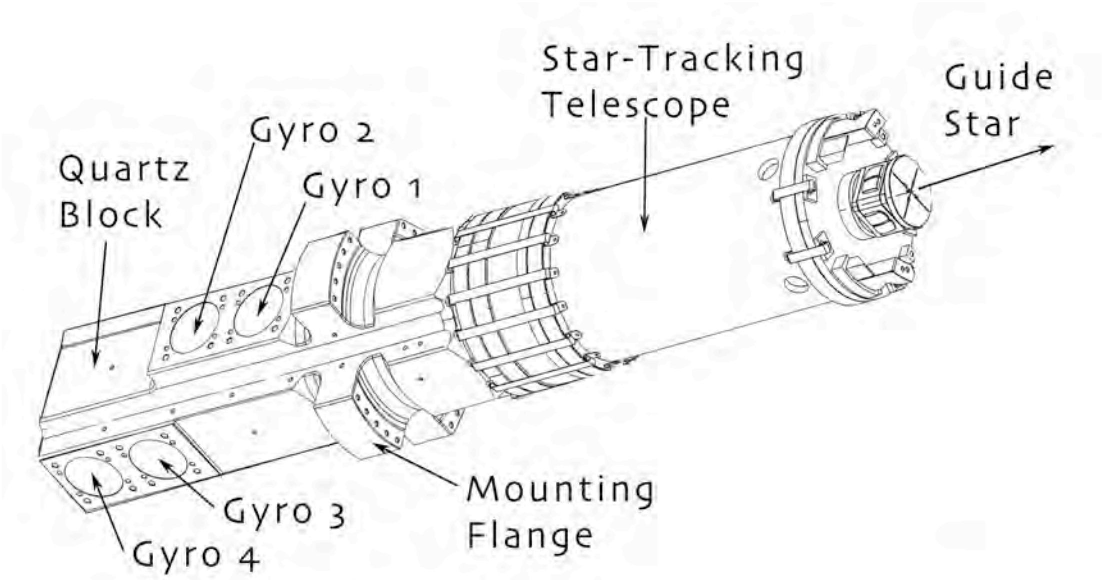


Star Tracking Telescope

Overview

- Schmidt-Cassegrain with tertiary mirror
- Fused Quartz with no adjustable components
- Bonded to the quartz block housing the Gyros
- Main structural elements cut from single boule of Heraus amersil => low differential contraction (absolute $<10^{-9}$/K)
- Hydroxide catalyzed bonding - Optobond™

Focal Length: 3.94 m
Clear Aperture: 0.144 m



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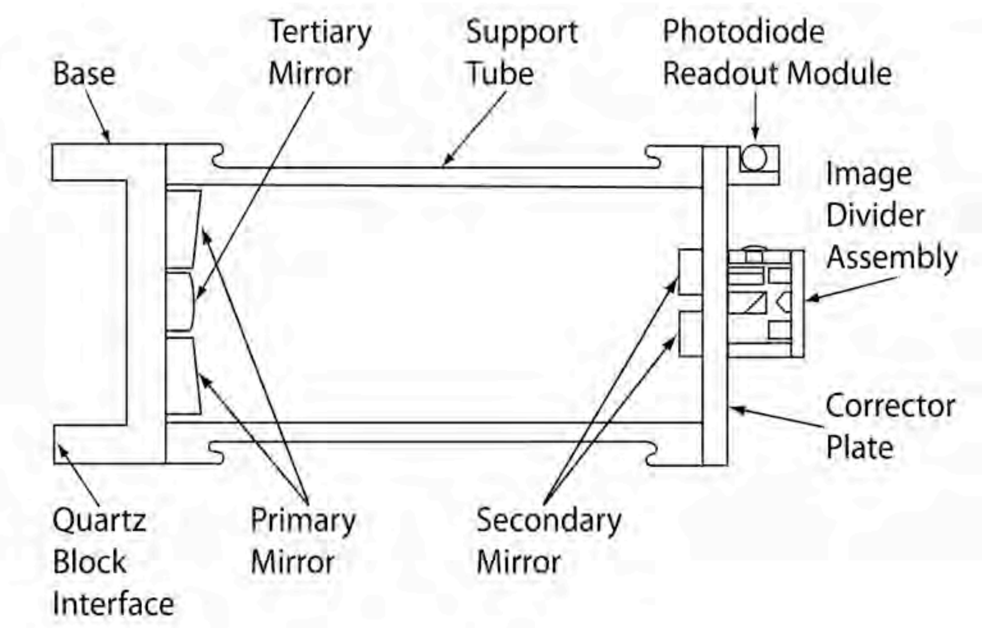
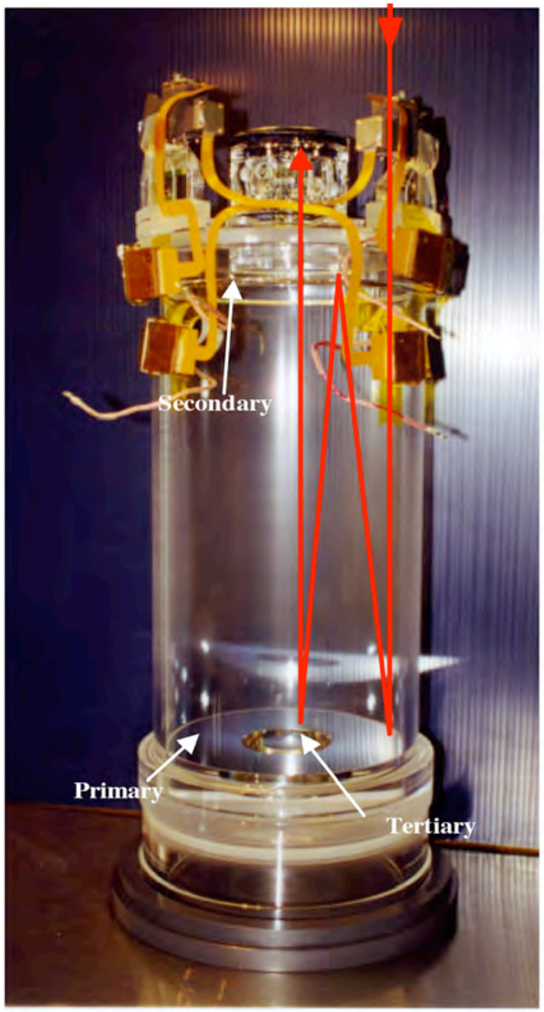
Telescope Optics Detail



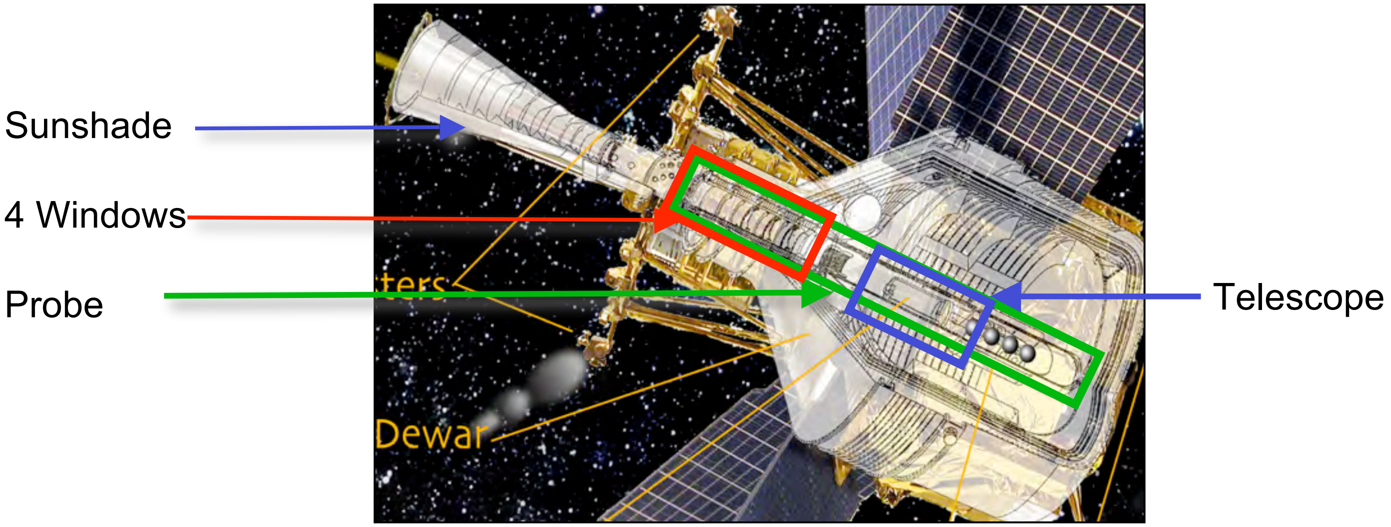
Key Design Features:

- Cassegrain-Schmidt with tertiary mirror
- Corrective primary mirror
- Roof prism image splitting
- Cryogenic detectors

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)	< 110

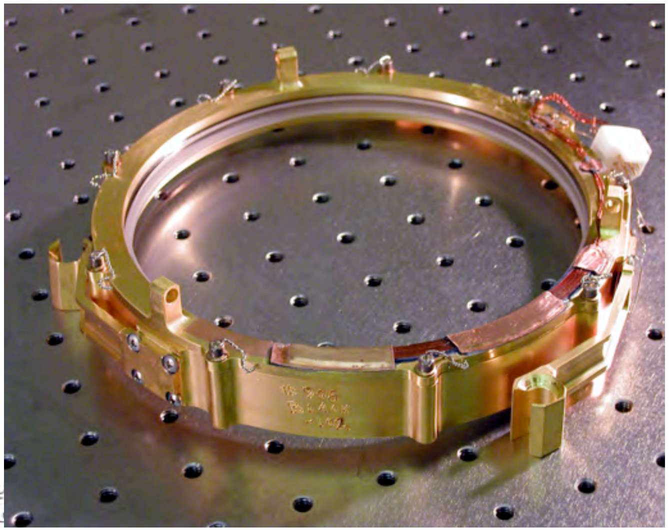


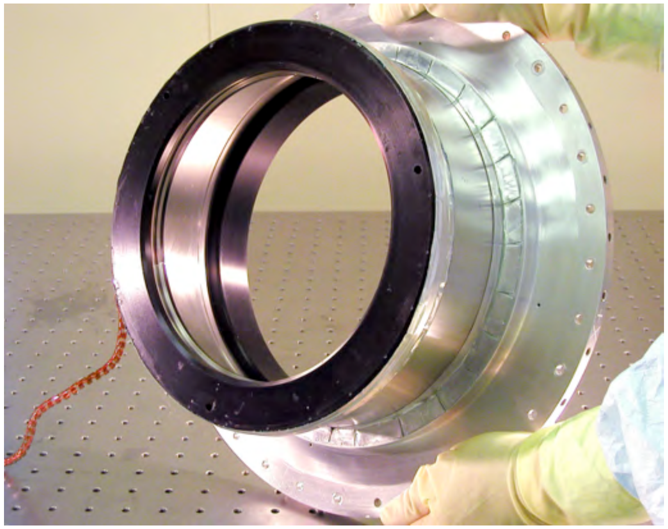
Position in Probe



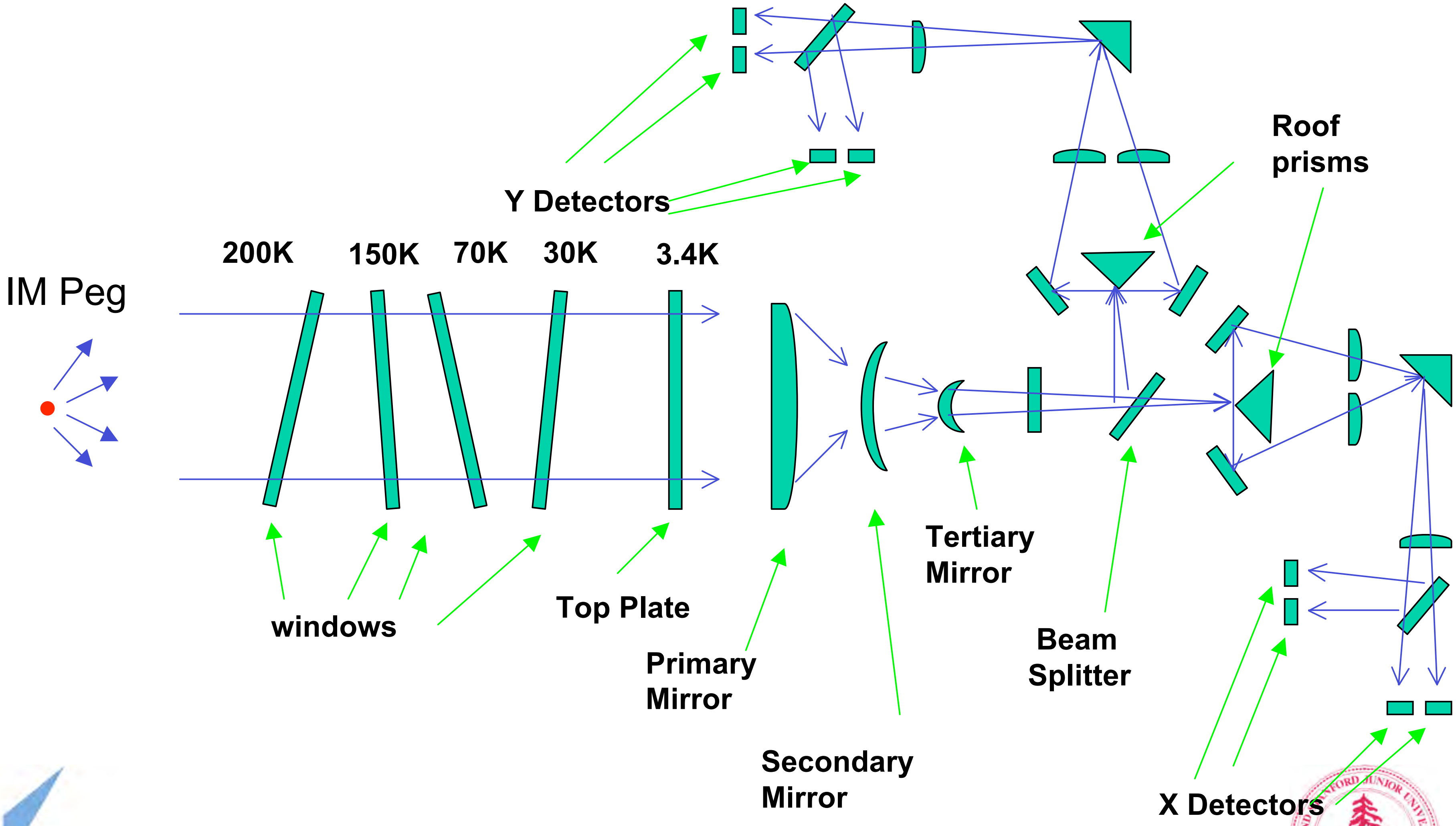
Window 1 - 4 Requirements: thermal link to probe heat stations

Window 4 Requirements: probe vacuum and faraday cage enclosure: must let light through but not rf =>SnO coating





Optical Schematic

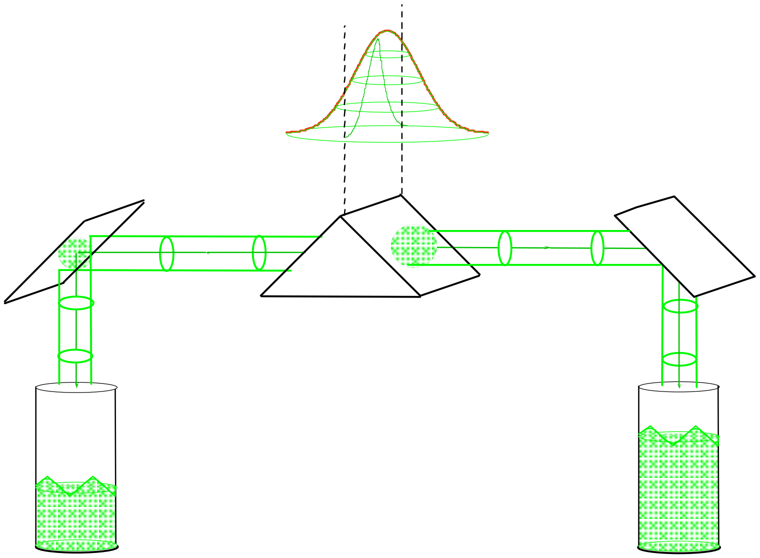


Pointing and Measurement Requirement

Pointing requirement   110 marcsec/√‾Hz
Measurement requirement sub marcsec

But for given dimensions telescope diffraction limit is ~ 1 arcsec!

So must divide image using a roof prism w/ submicron features



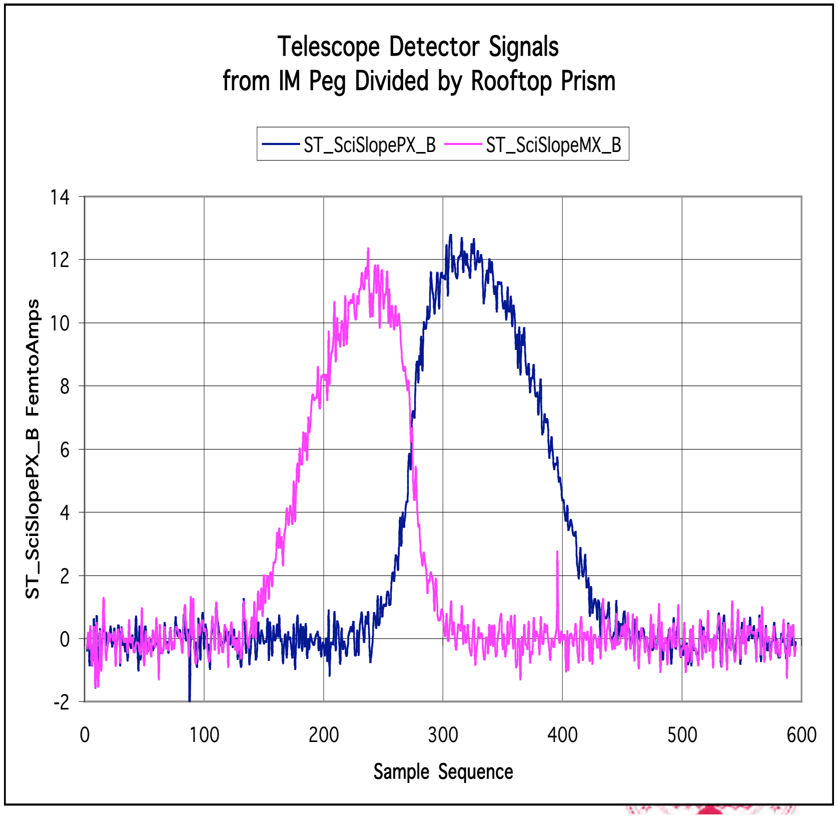


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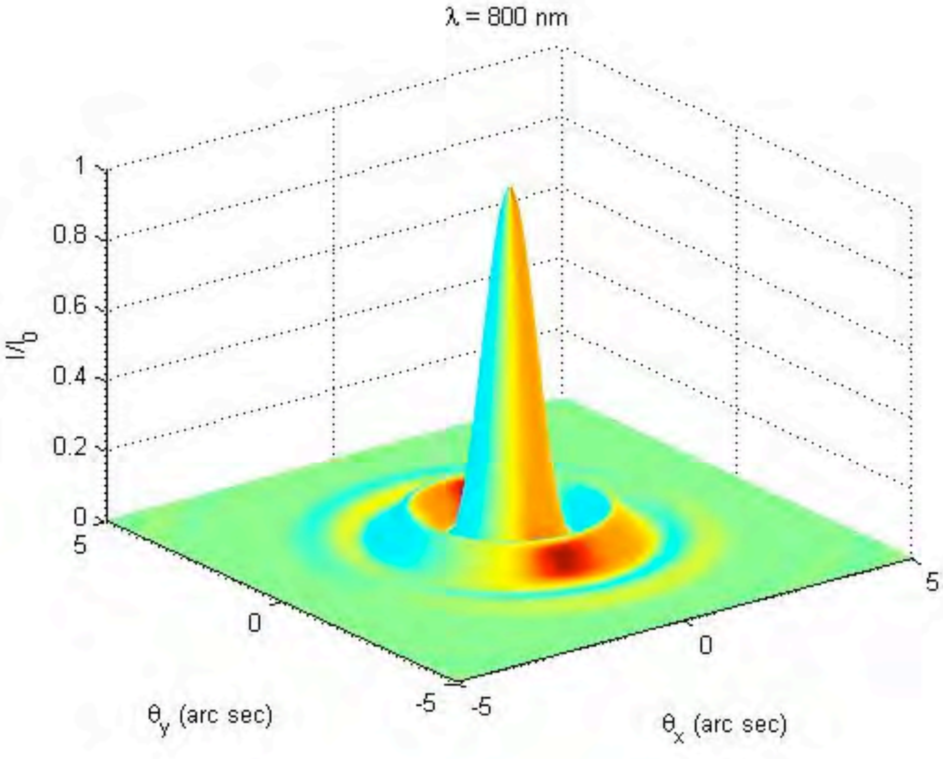
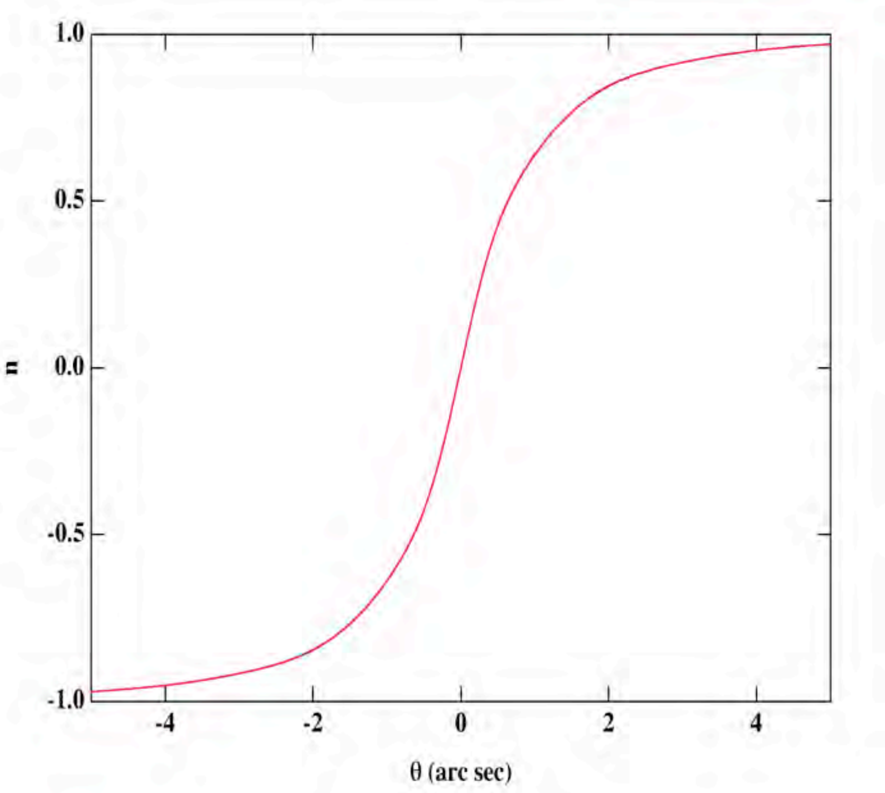
Image Function & Response Function

Example for ideal telescope

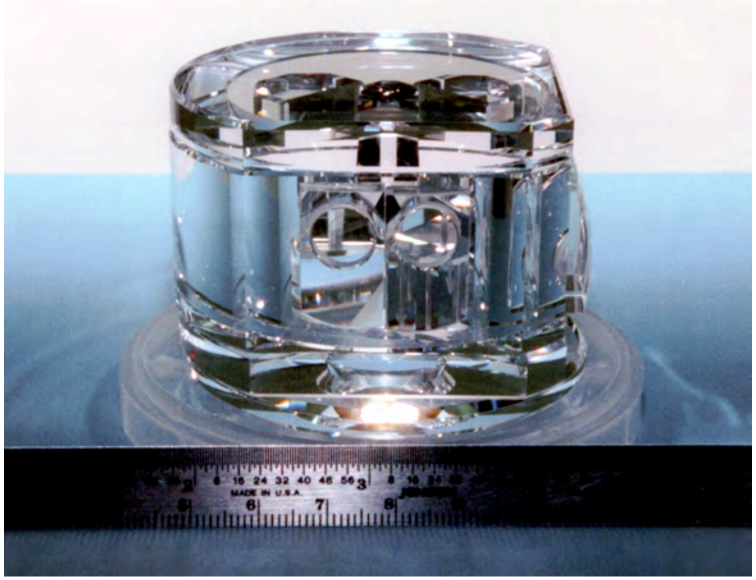


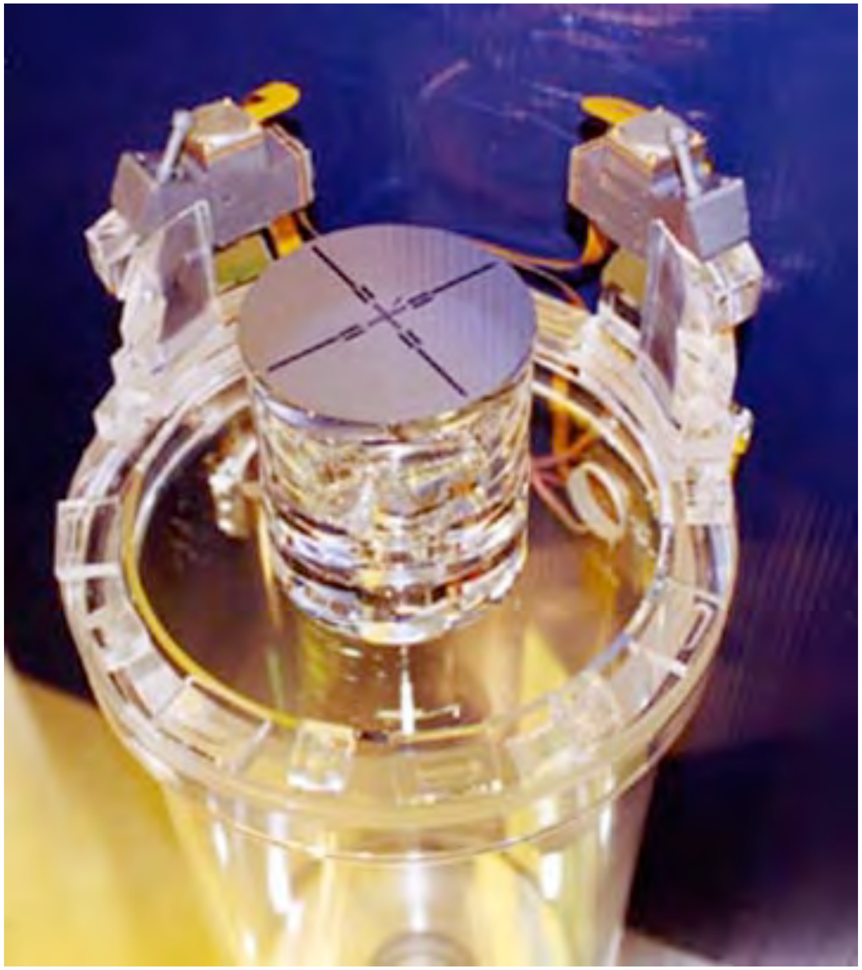


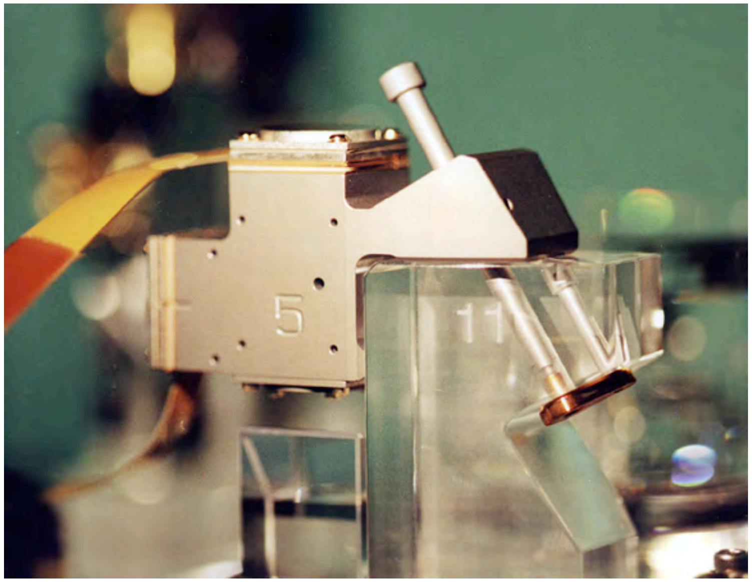
Normalized signal: $n = \dfrac{s_+ - ws_-}{s_+ + ws_-}$

Image Divider and Detector Assembly

- Image Divider Assembly Splits beam with roof prism
- 2 sets of + and – detectors on each axis
  - photodiodes - count photons
  - femptoamp level -10^{-15} A - dark noise current
  - - thermally isolated JFETs amplifiers

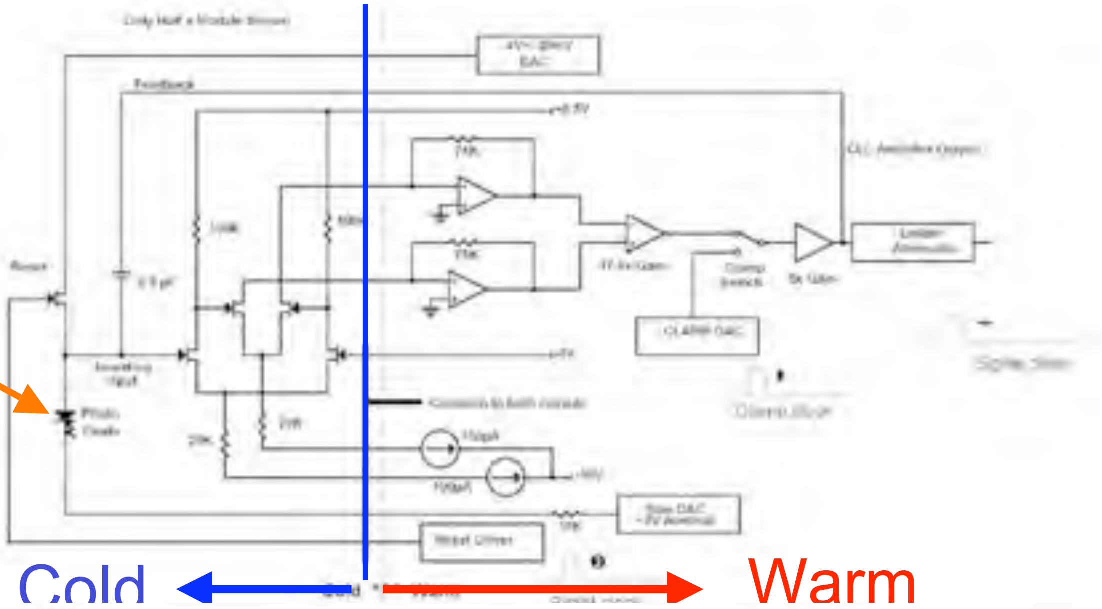


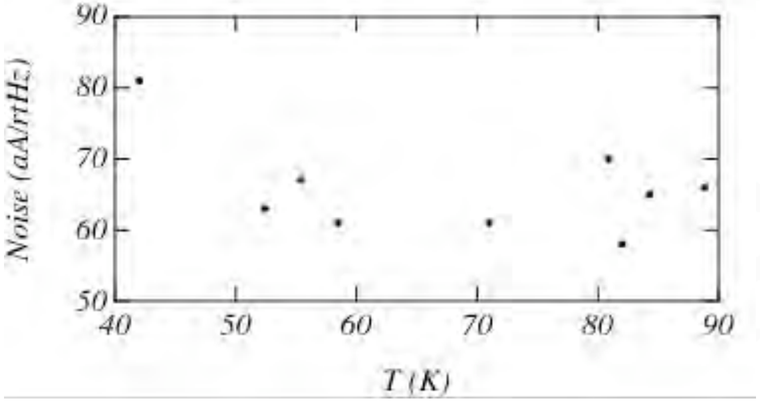


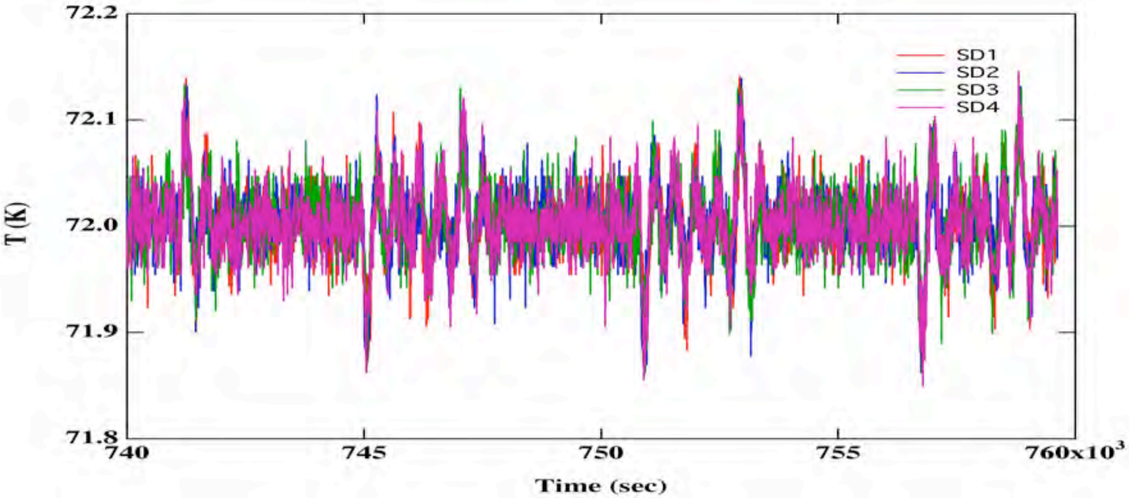


Cryogenic Detectors

Detector





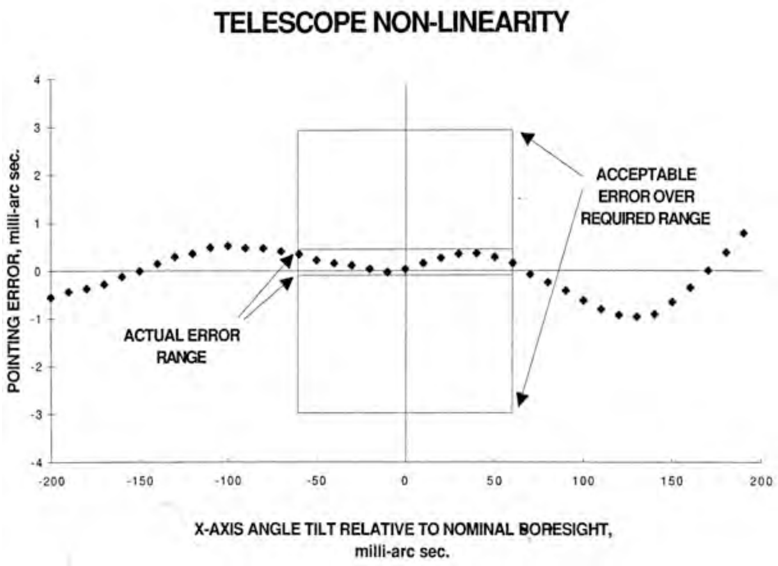


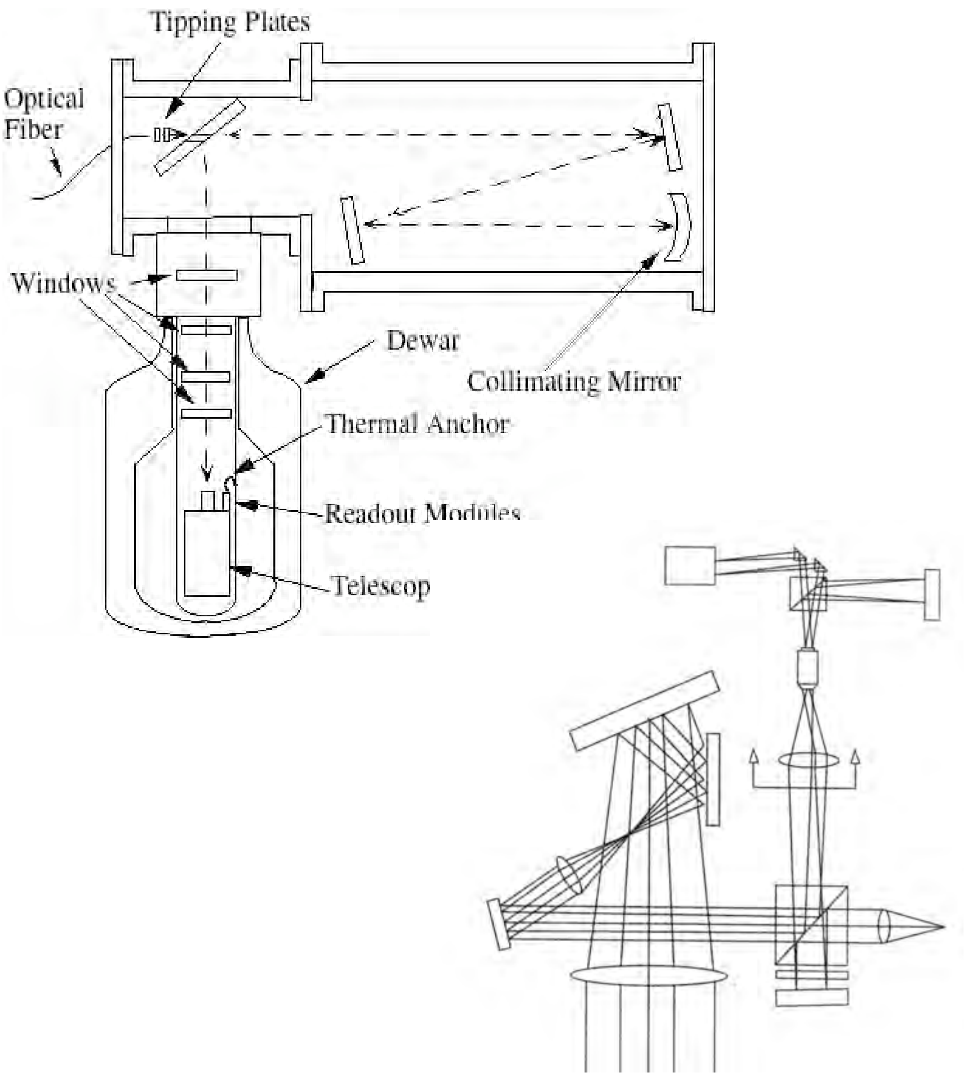
Operating temperature selected at minimum noise region

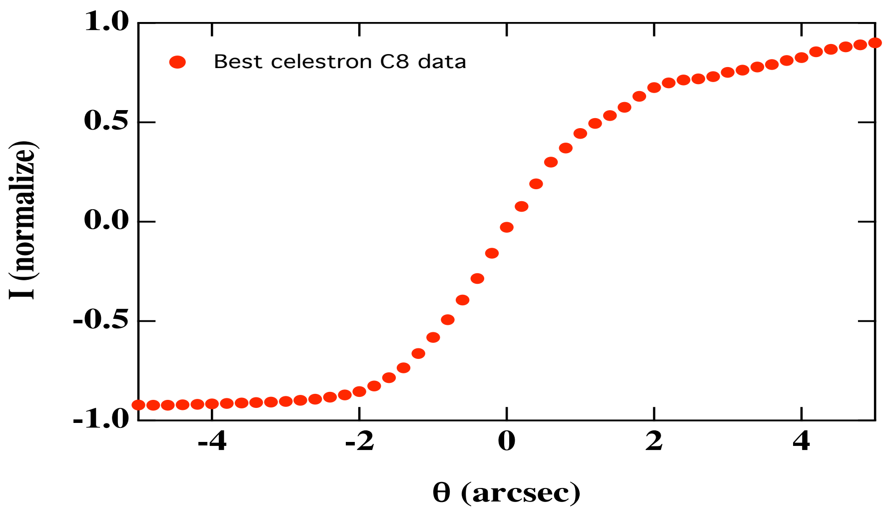
Kapton stand off allows circuit to self heat fro 2.5 K to ~72 K sweet spot

Telescope Ground Testing

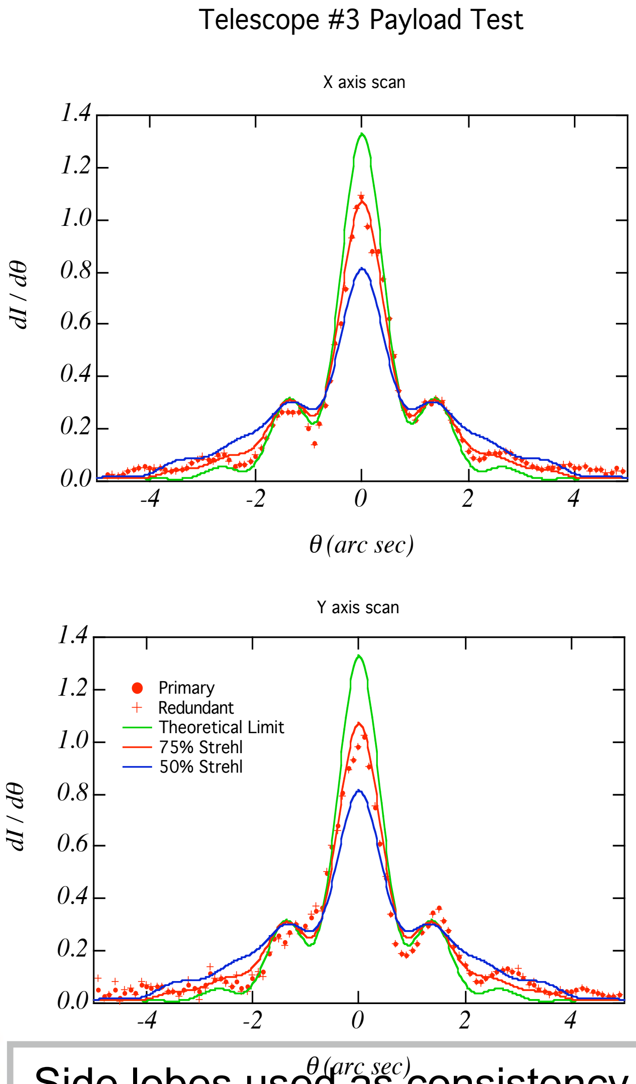
A series of 3 Artificial Star Light sources were fabricated to test telescope focus, detector noise and tracking liearity







Artificial Star 3



Side lobes used as consistency check for angle calibration

Guide Star Selection

Guide Star Requirements:

1. Low declination – position near equatorial plane to enable separation of geodetic and frame dragging
2. Not too near ecliptic to reduce interference from sun
3. No other bright optical star in direct vicinity
4. Sufficient optical brightness for given telescope detection capability
5. Sub-milliarcsec inertial reference

¡ Requirements 4 and 5 seem contradictory!

Telescope requires Optical brightness (≤ 6 magnitude) => galactic source

But only extra galactic sources are sufficiently distant to ensure proper motion
Is not too great

Guide Star Selection Solution

Find guide star that is both optically bright and radio bright

Use VLBI to calibrate guide star motion against distant radio source quasars

Constraints:

- Optically bright (< 6 magnitude)
- Radio detectable (>1 mJy correlated flux density)

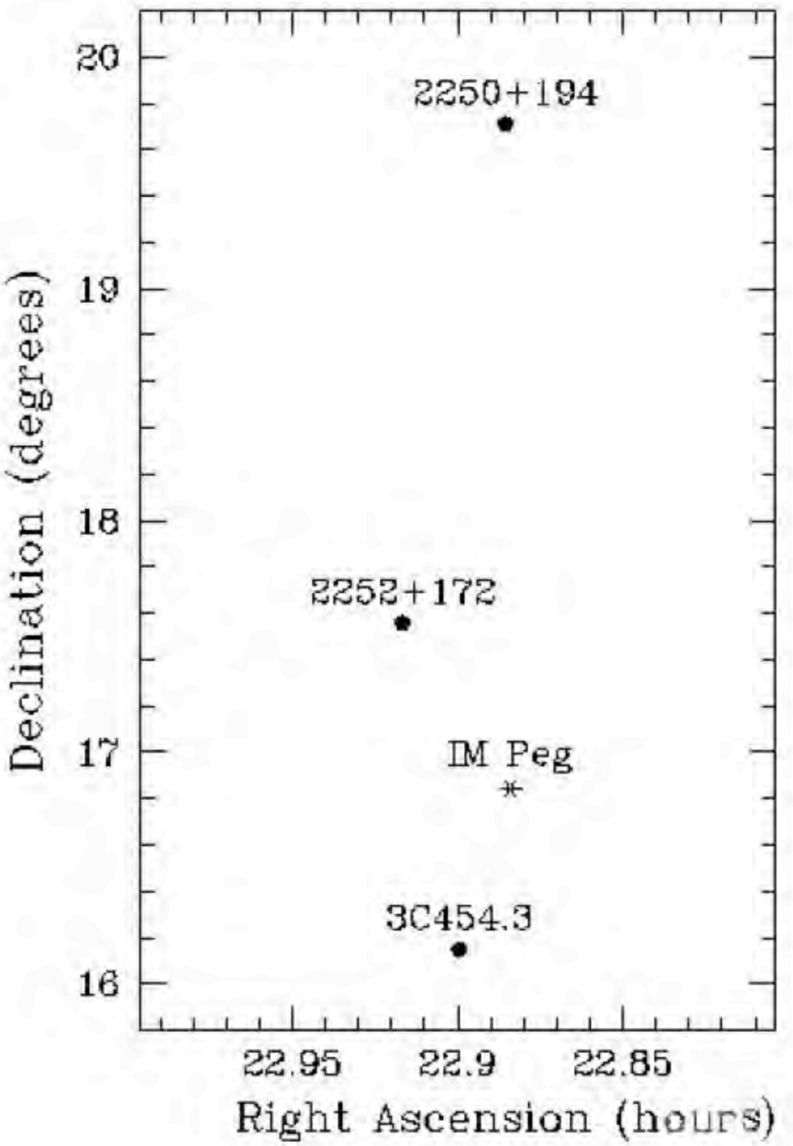
One “Survivor”:

- Binary star system : HR8703 (aka IM Pegasi or “IM Peg”)
- Orbit of binary : ~ 1 marcsec radius (circular)
  25 day period (very accurately known)
- Distance of binary from earth: ~ 100 parsecs

(~ 300 light years)

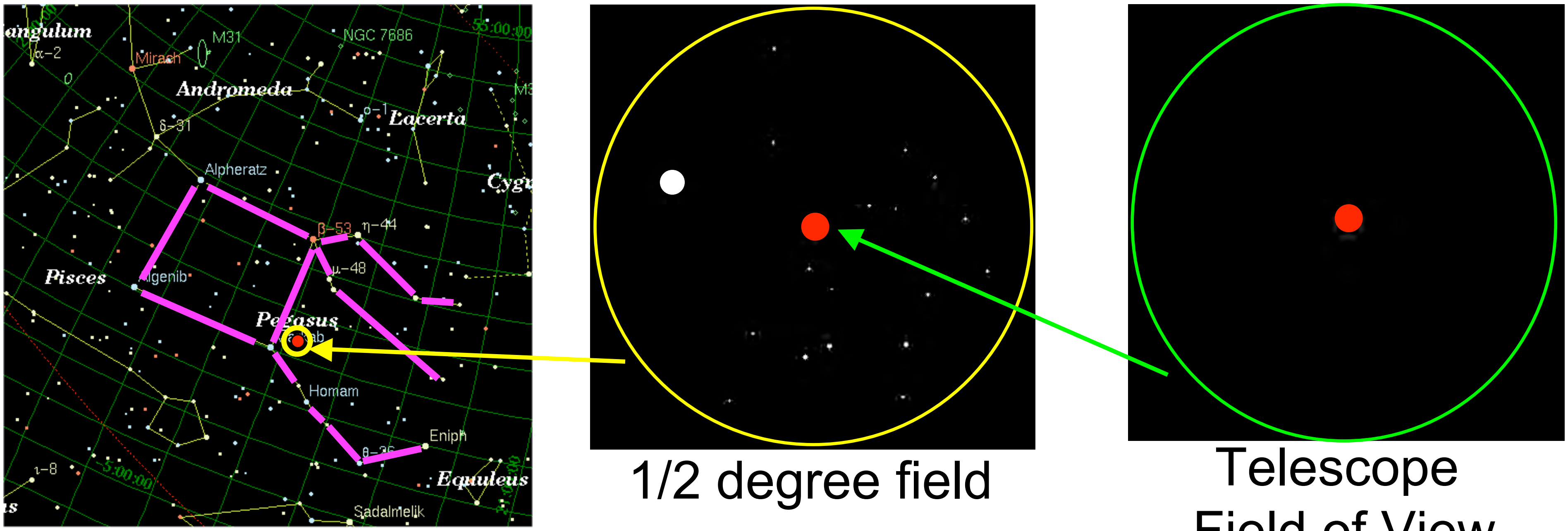
Work with Harvard SAO to measure proper motior

Extragalactic sources & IMPeg



Guide Star Features

IM Peg



1/2 degree field

Telescope Field of View

- RA: 22h53m2.27sec DEC: 16d50m28.3sec
- Visual Magnitude ~ 6th magnitude
- Radio star for VLBI proper motion measurement
- HR Peg only other bright star within ½ degree of field
- No star brighter than 16th mag within field of view

Differential VLBI

Need:

- Accuracy goal of experiment : ~ 0.4 marcsec/yr
(mean standard error of gyroscope drift-rate measurement)
- Accuracy goal for measurement of guide star proper motion
~ 0.15 marcsec/yr

Technique:

- Monitor motion of the guide star’s radio emission with respect to distant (“cosmological”) compact sources of radio radiation nearby on sky
- At present only VLBI can yield such accuracy of proper-motion measurement

Main Sources of Error:

- Motion of source of IM Peg’s radio radiation with respect to primary of IM Peg System
- Possible (distant) third body in IM Peg System
- Motions of centers of brightness of reference sources with respect to their centers of mass
- Model of ionosphere
- Signal-to-noise ratios (only when IM Peg radio signals very weak)

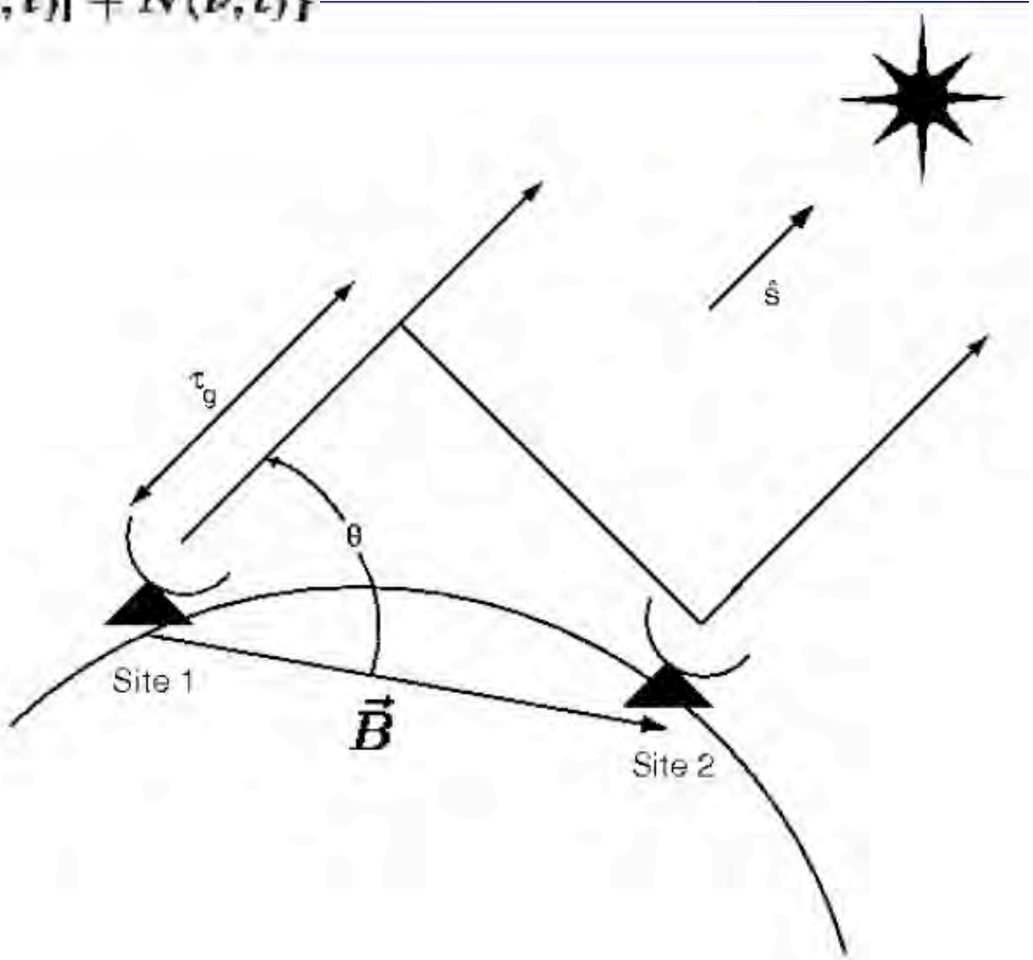
VLBI Measurement Principle

Principal VLBI observable: “fringe phase”:

$$\phi(\nu,t) = 2\pi\left\{\nu\left[\tau_{geom}(t)+\tau_{inst}(t)+\tau_{atm}(t)+\tau_{ion}(\nu,t)\right.\right.$$
$$\left.\left.+\tau_{struc}(\nu,t)+\tau_{noise}(\nu,t)\right]+N(\nu,t)\right\}$$

$$\tau_{geom} \approx \frac{1}{c}\left(\vec{B}\cdot\hat{s}\right)$$

Very Large Array, Socorro, New Mexico



Summary of Harvard SAO VLBI Observations

- 35 Sessions of VLBI observations between January 1997 and July 2005
- Duration of each session: between 12 and 18 hours
- 12 to 16 VLBI antennas per observing session

Standard array of antennas consisted of:

  – NRAO's ten 25 m VLBA antennas (all or most included in every session)

  – NRAO's "phased" VLA (included in 31 sessions)

    - Most sensitive VLBI antenna we used (largest collecting area)
    - Use of VLA enabled intra-session monitoring of guidestar radio brightness

  – MPIfR's 100 m antenna in Effelsberg, Germany (29 sessions)

  – NASA's 70 m DSN antennas in Goldstone, California (33 sessions),

  – Robledo, Spain (34 sessions),

  – Tidbinbilla, Australia (28 sessions)

- All astrometric observations made at radio wavelength of 3.6 cm

+ four additional sessions made in 1991-1994 by J.-F. Lestrade et al. in support of Hipparcos-usefull constraining proper acceleration

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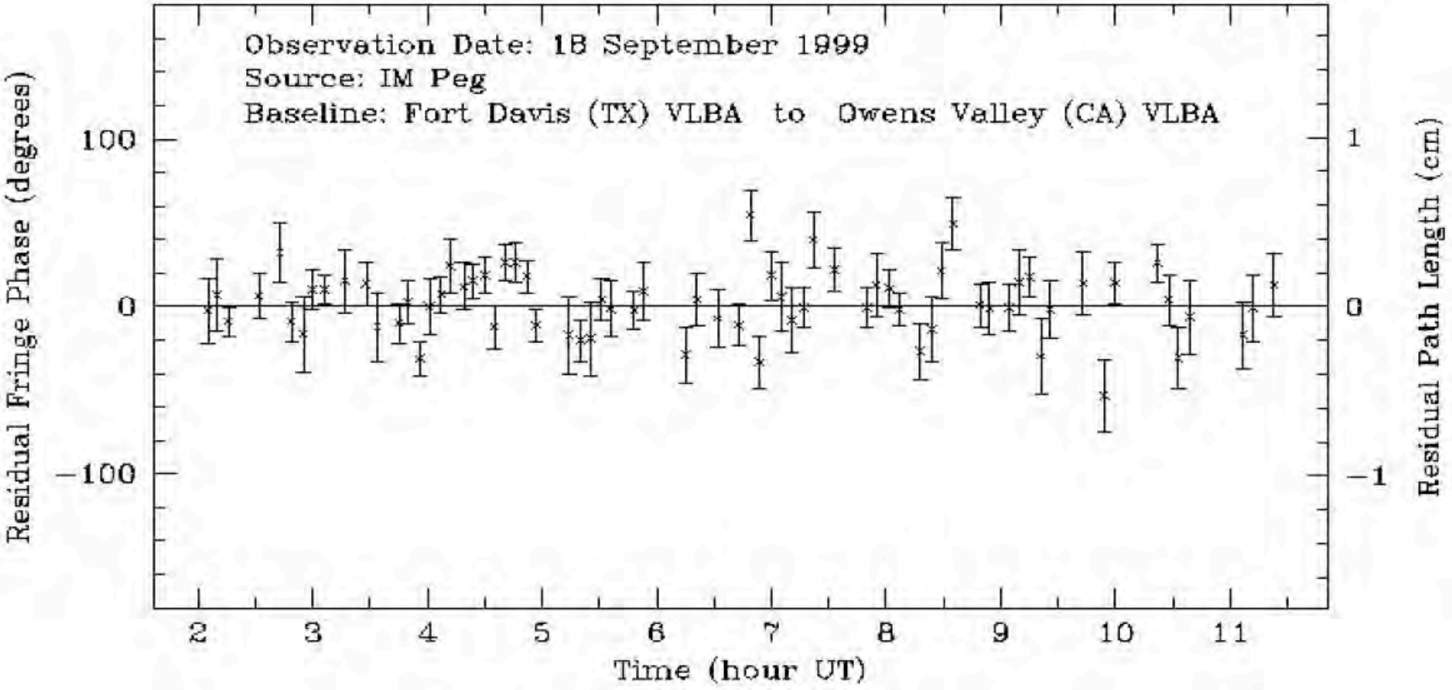
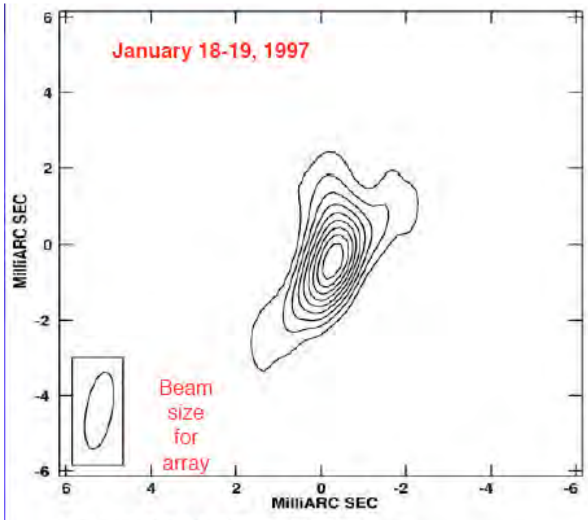
Typical VLBI Data Set



VLBI Error Sources

Intrinsic motions and non-pointlike brightness distributions of IM Peg radio emissions relative to center of optical disk

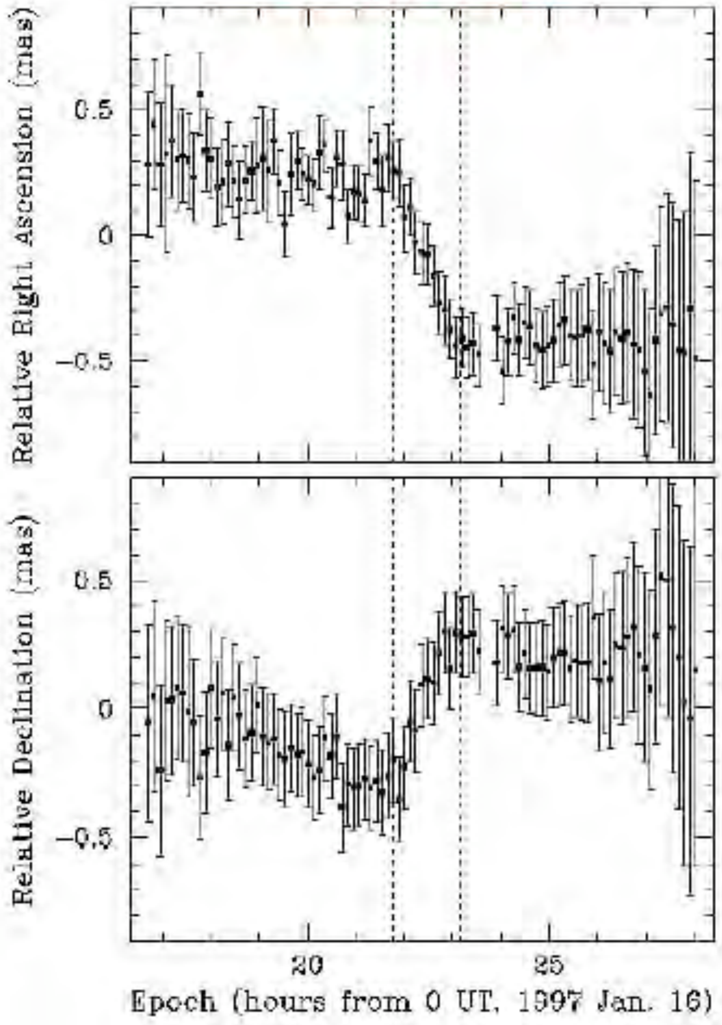


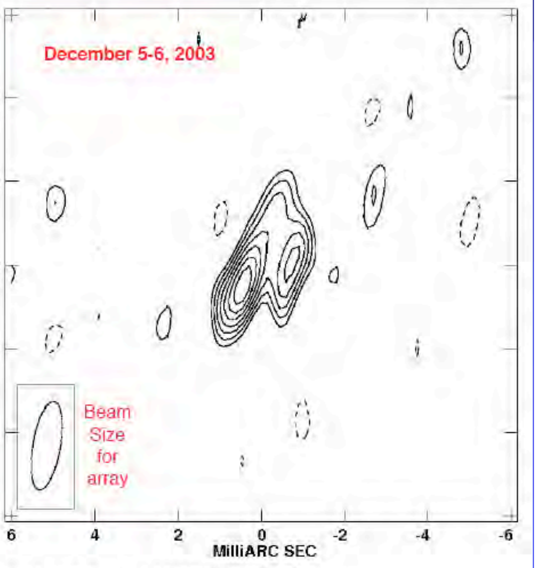
January 18-19, 1997

Beam size for array

Cont peak flux = 4.7516E-03 JY/BEAM
Levs = 4.752E-05 * (-10, 10, 20, 30, 40, 50, 60, 70, 80, 90)

January 16-17, 1997





December 5-6, 2003

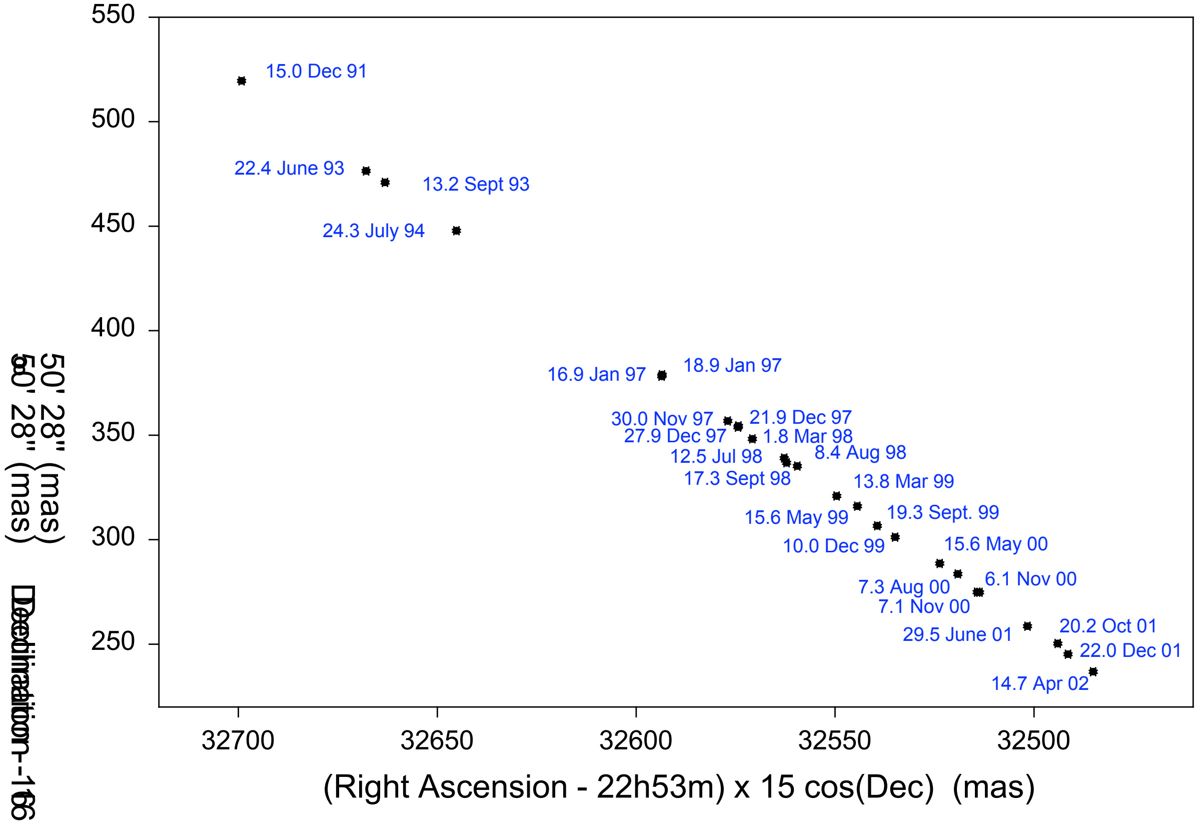
Beam Size for array

Cont peak flux = 4.2199E-04 JY/BEAM
Levs = 4.220E-06 * (-30, 30, 40, 50, 60, 70, 80, 90)

Intrinsic motions (on hour, day, month, and year time scales) constitute source of error

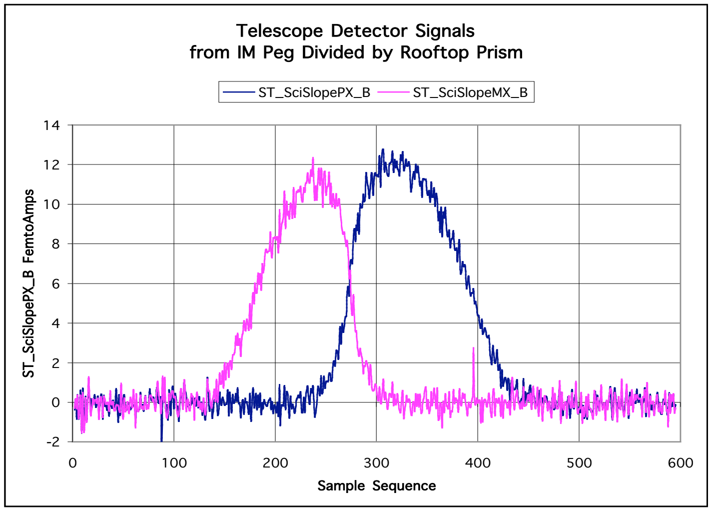
GP-B Guide Star HR 8703 (IM PEG)

Preliminary HR 8703 Positions for Peak of Radio Brightness
Solar System Barycentric, J2000 Coordinate System



Harvard SAO Astrometry Team will keep its result secret from Gyroscope Team until analysis judged complete by both teams

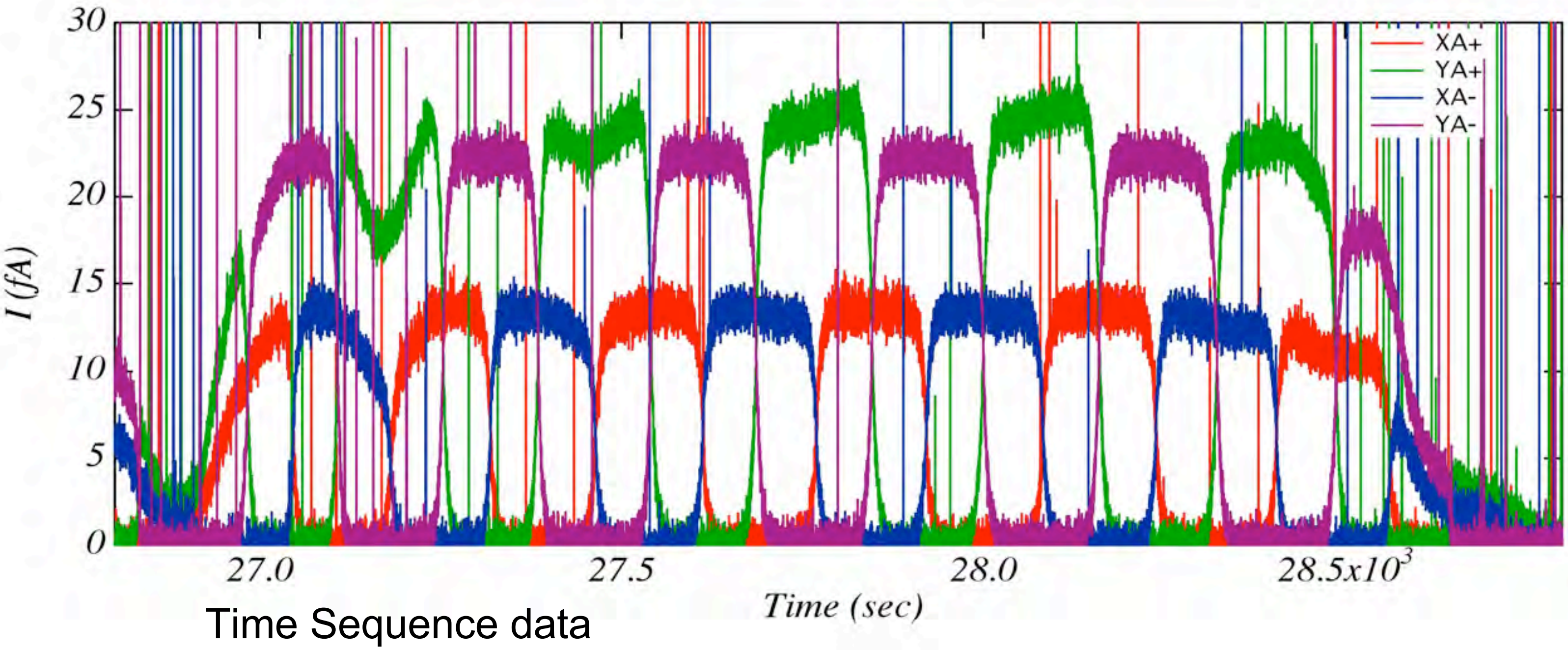
Telescope Flight Data



Angular scan data

Data Stream:

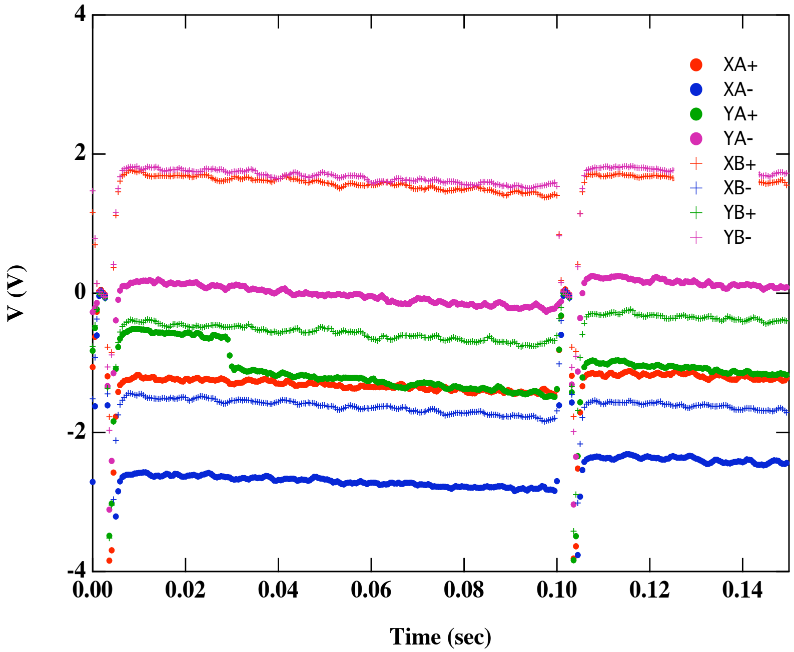
- Snapshot data at 2.2 kHz
- Onboard processed at 10 Hz into level 1 data
- Cosmic ray hits removed during level 1 to level 2 data conversion

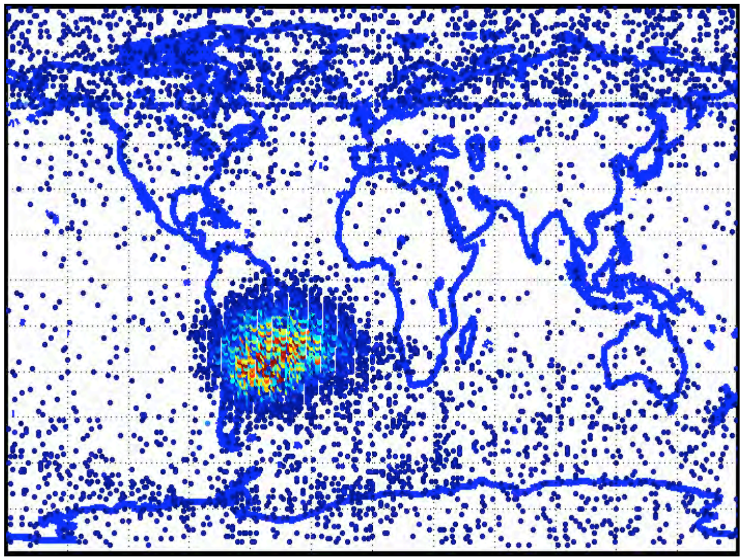


Time Sequence data

Cosmic Ray and SAA Events

Telescope detectors are sensitive to proton hits

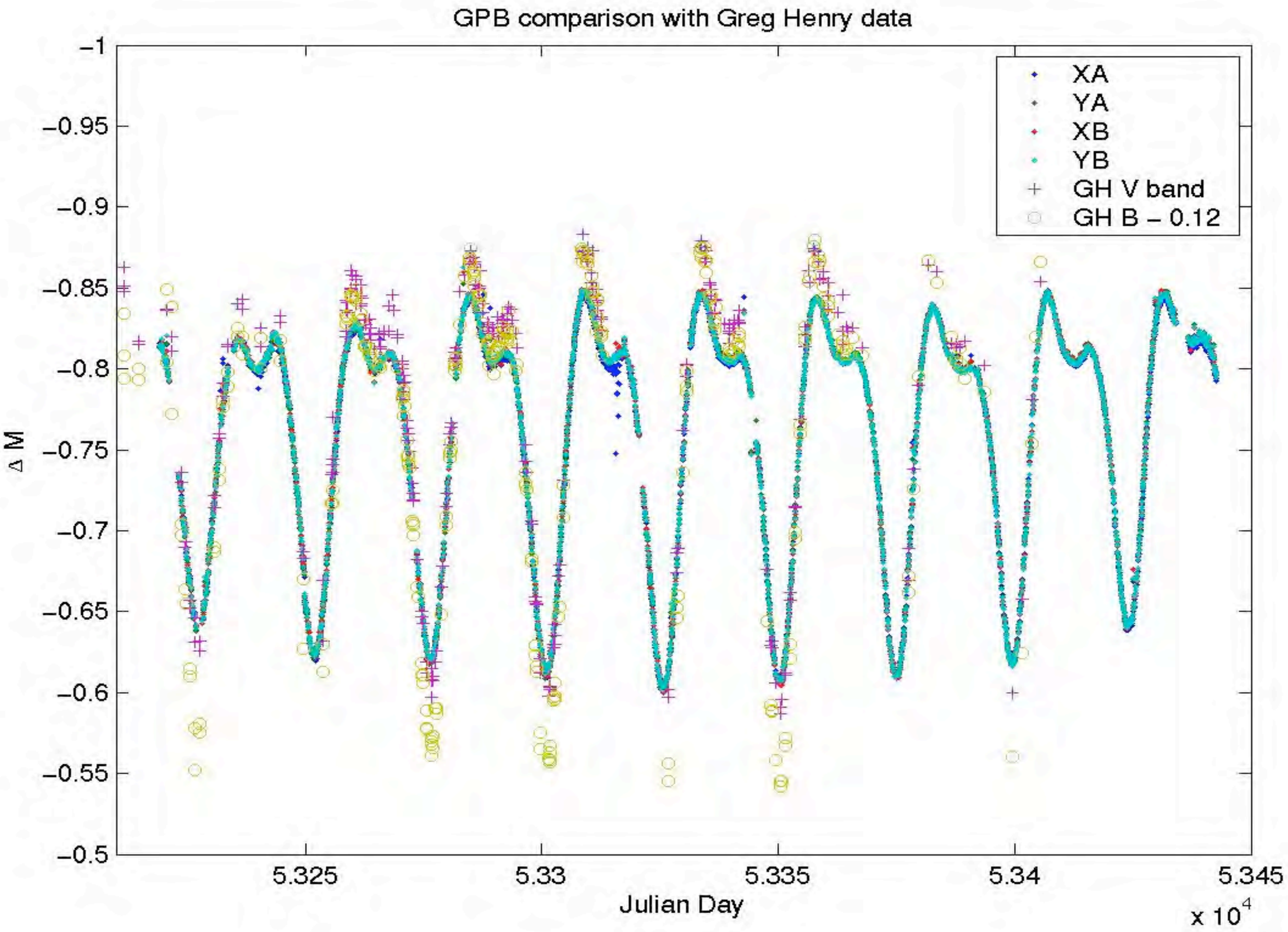




With proper filtering - developed during flight - pointing could be maintained
Throughtout the South Atlantic Anomaly

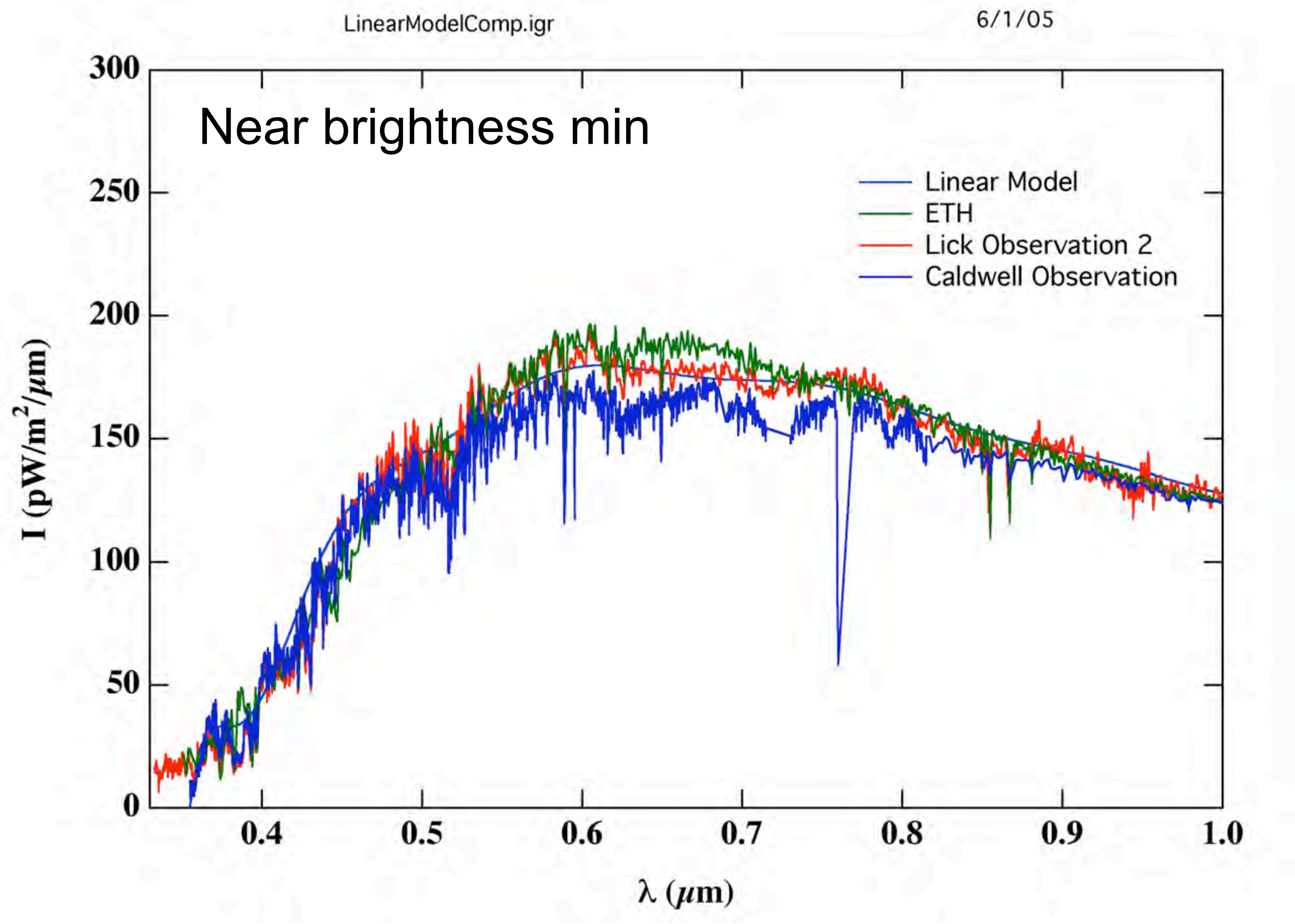
Telescope Flight Operations

Guide Star Features – Comparison in V and B bands



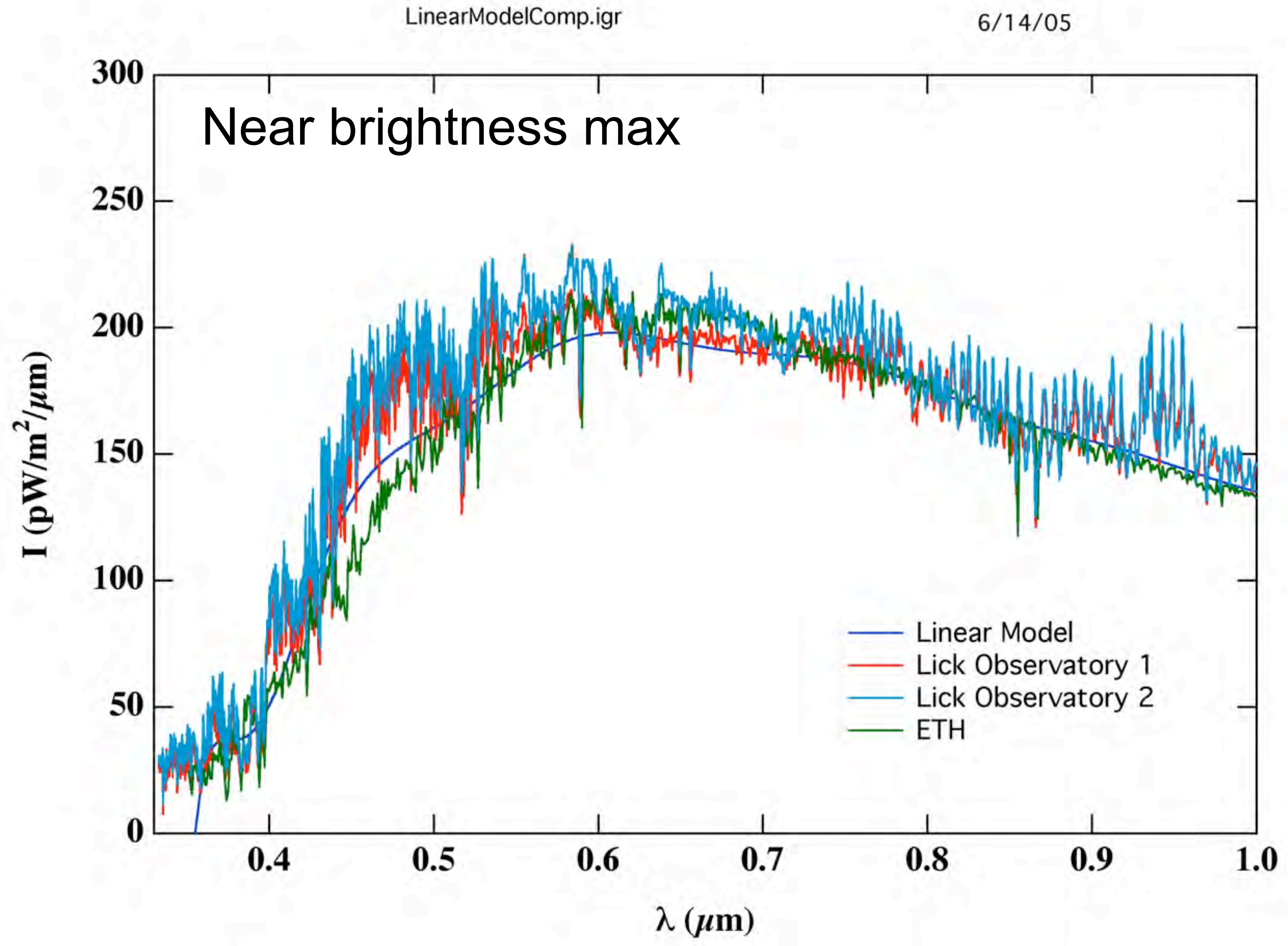
Telescope Flight Operations

Guide Star Features – Color Variation



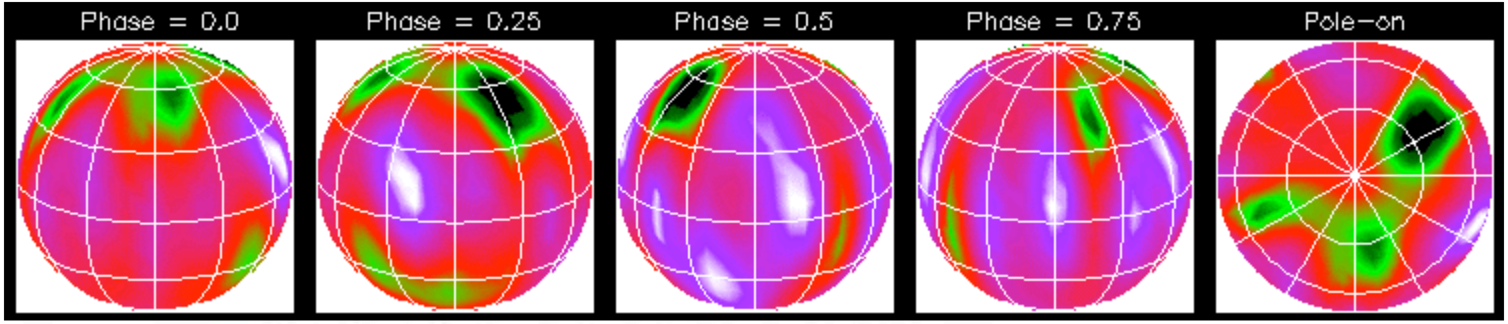
Telescope Flight Operations

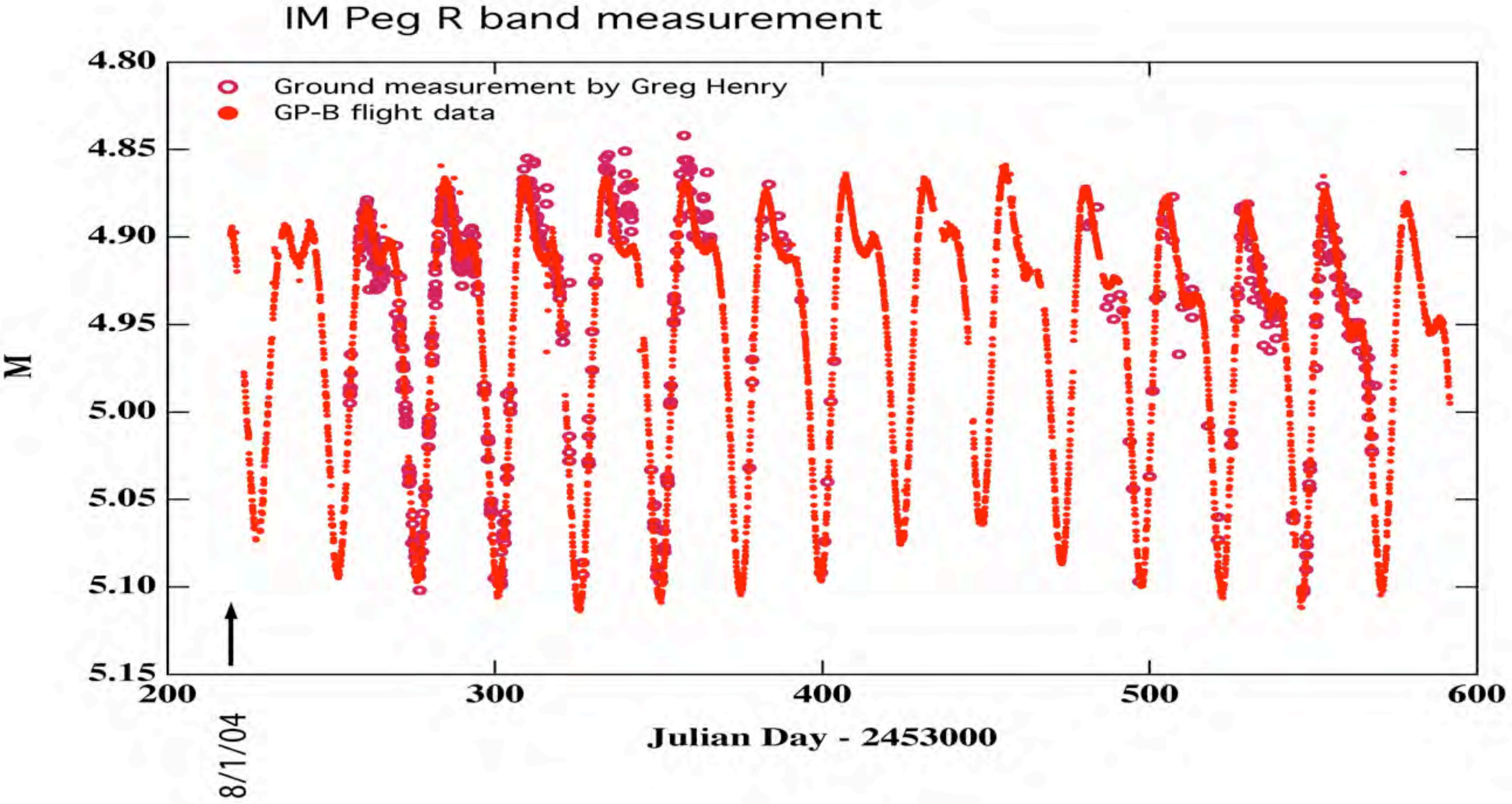
Guide Star Features – Color Variation



Telescope Flight Operations

Guide Star Features - Magnitude Variation





Telescope Data Reduction

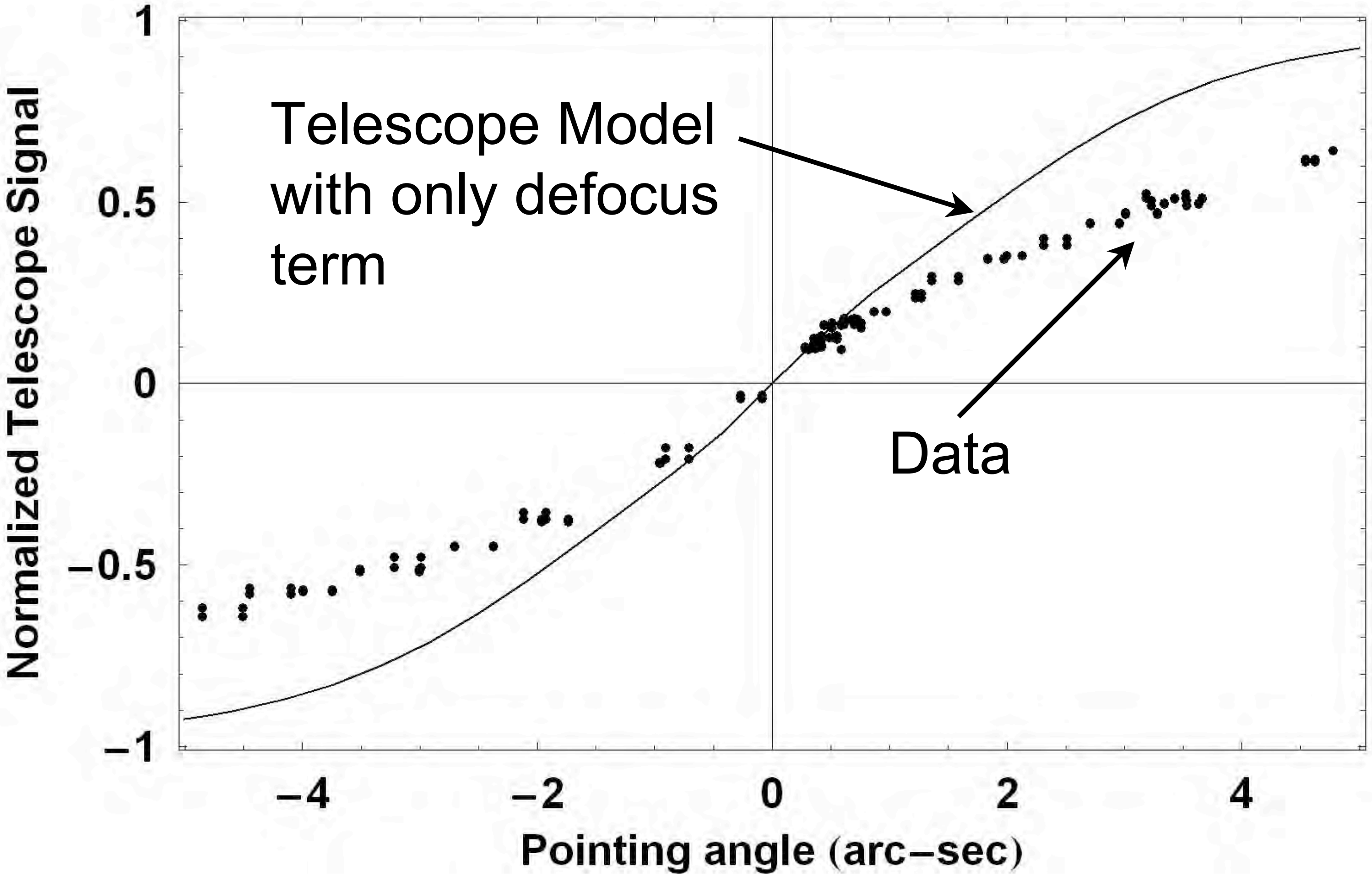
Telescope and Gyroscope Scale Factor Matching

- Scale Factor $\theta = S \cdot n$
- Dither on X and Y axis with different frequency.
  - X-axis: 29 sec
  - Y-axis: 34 sec
- Matching at the dither frequencies.
  - Better noise rejection
  - Less model dependent
- Matching at all frequencies except the roll frequency.
  - More useful at large angles for non-linearity analysis
- Cubic model $\theta = \left(b_1 + b_3 n^2\right) n$

Telescope Data Reduction

On orbit data scale factor matching compared with telescope optical model with net defocus term and color integration.

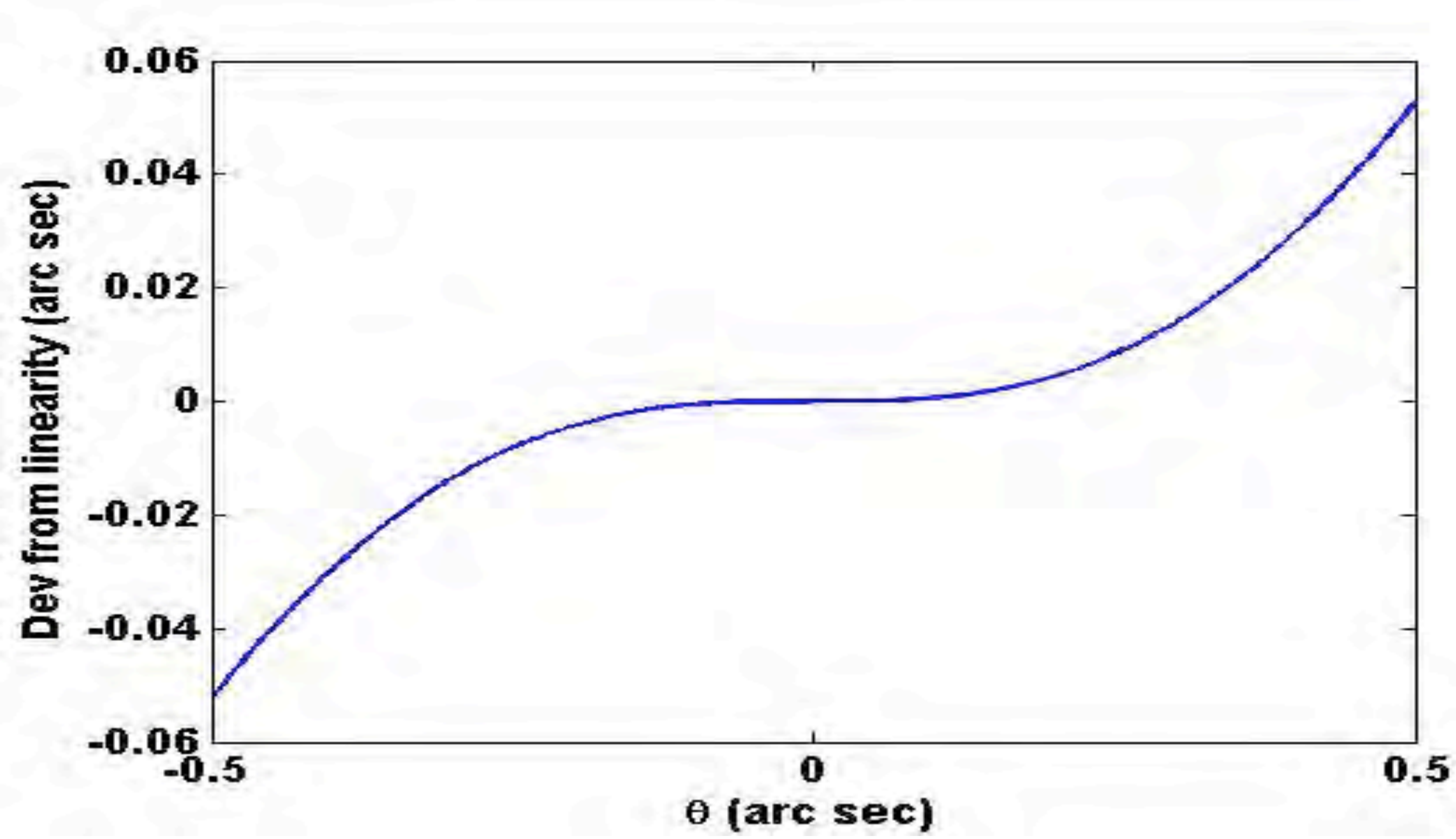
→ Model not sufficient to explain the data



Telescope Data Reduction

Larger than expected pointing error requires non-linear correction

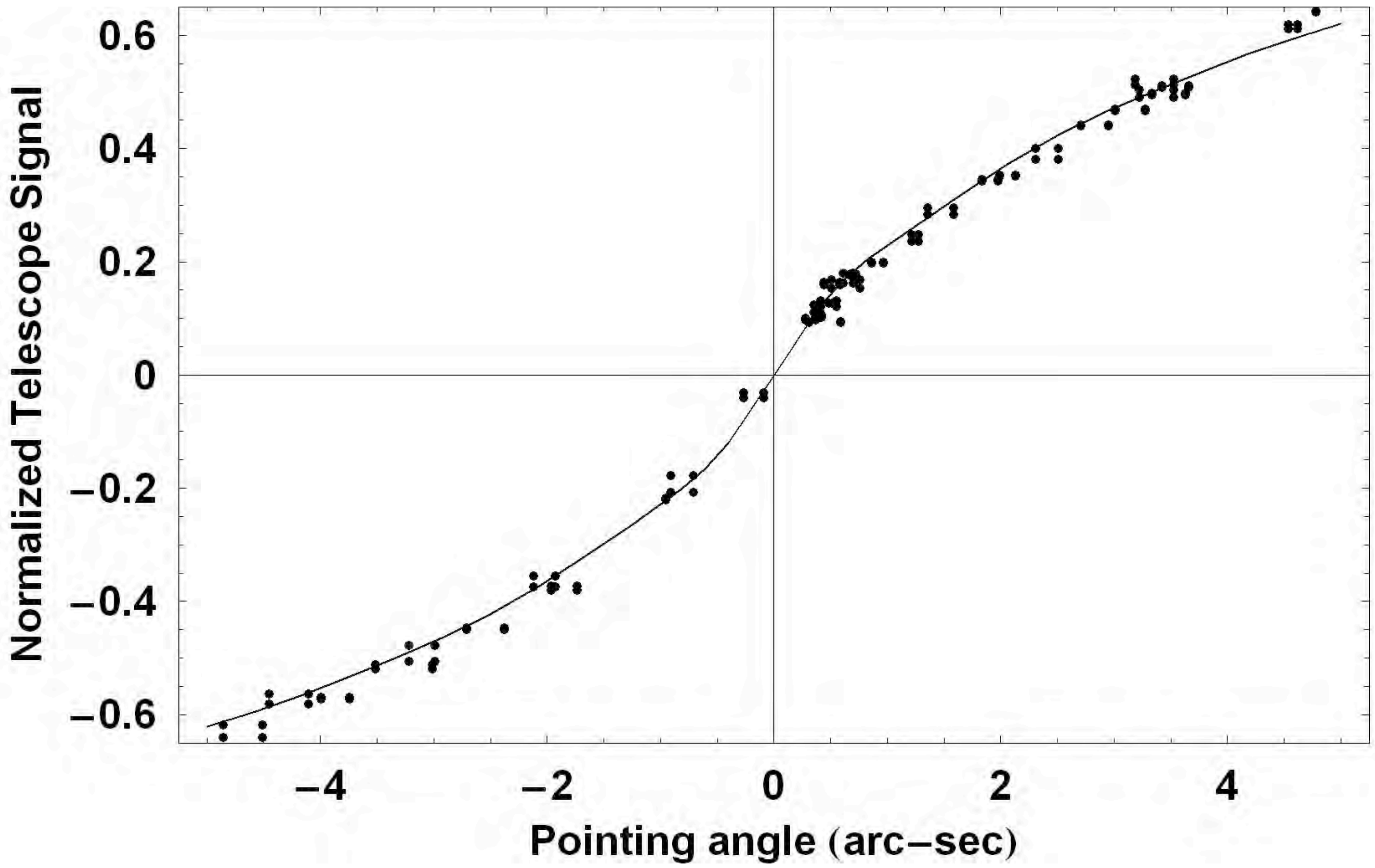
- Expected error with linear model: up to 1.4%
- Estimated error with cubic model: up to 0.13%



Telescope Data Reduction

Lowest order axially symmetric aberration is represented by 4th order Zernike polynomial modified for central obscuration

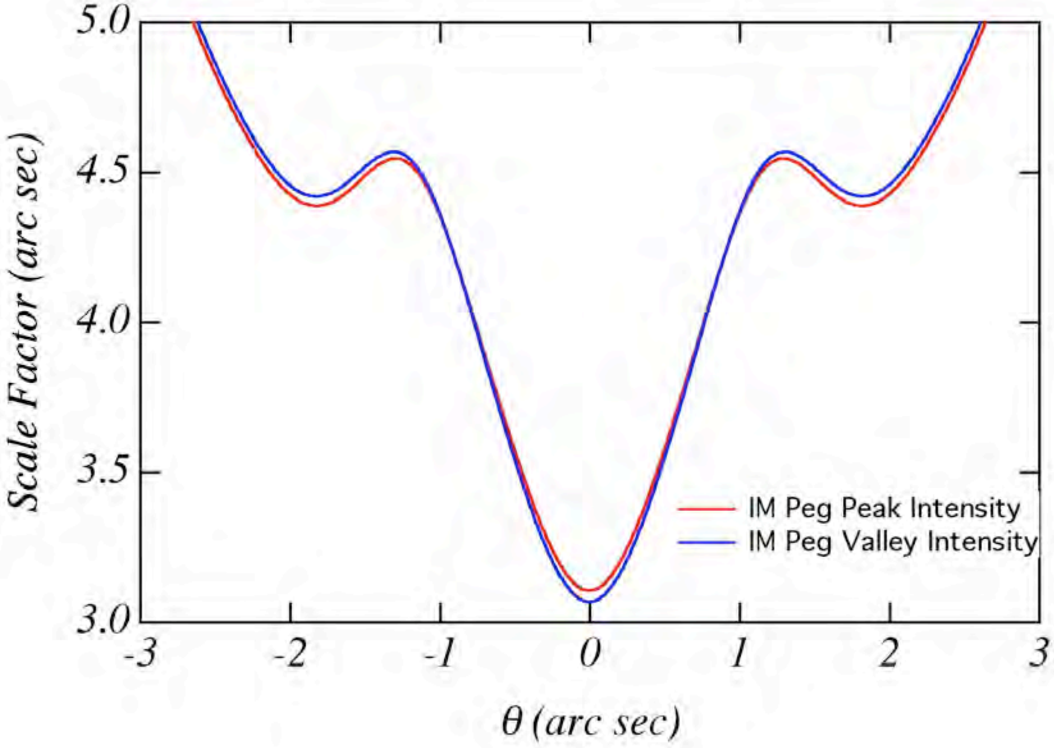
Defocus: - 5.0 mm, Zenike coefficient: 415 nm



Telescope Data Reduction

Star color variation causes scale factor variation:

- Expected variation due to color change: 1%
- Three independent measurements to provide consistency check on color model.



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Telescope Data Reduction

- Star color variation causes weighting factor variation:
  - Effect on the pointing bias of 50 mas at the star period. Estimated impact on science signal at micro-arcsec level.
- Star magnitude variation causes apparent pointing change:
  - Estimated impact on science signal less than 50 micro-arcsec.
- Instrument Effects (thermal, electronic, aging):
  - Also Small

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Summary

- Star-tracker telescope performance in flight was as expected.
- The defocus of the telescope is the same in flight as on the ground within the measurement error.
- The major effects on the science data reduction are non-linearity and guide star color variation. Both effects can be reduced with no significant effect on experiment by simple modeling.

Acquiring the Star 5000 times per year

Telescope performance met all experiment requirements

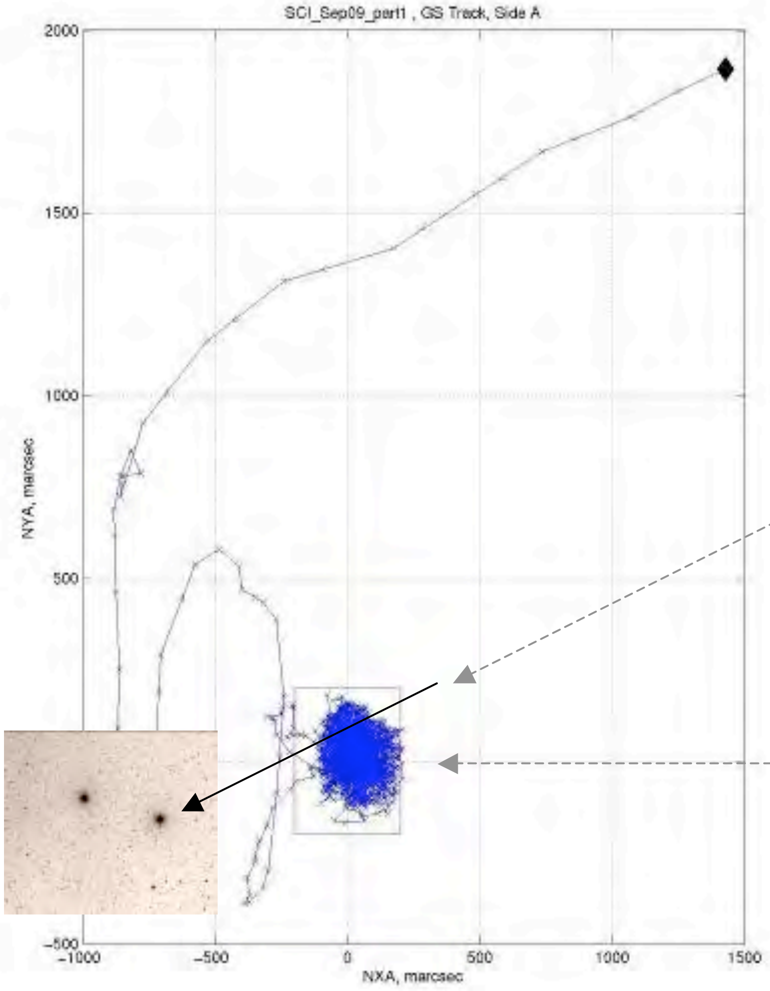
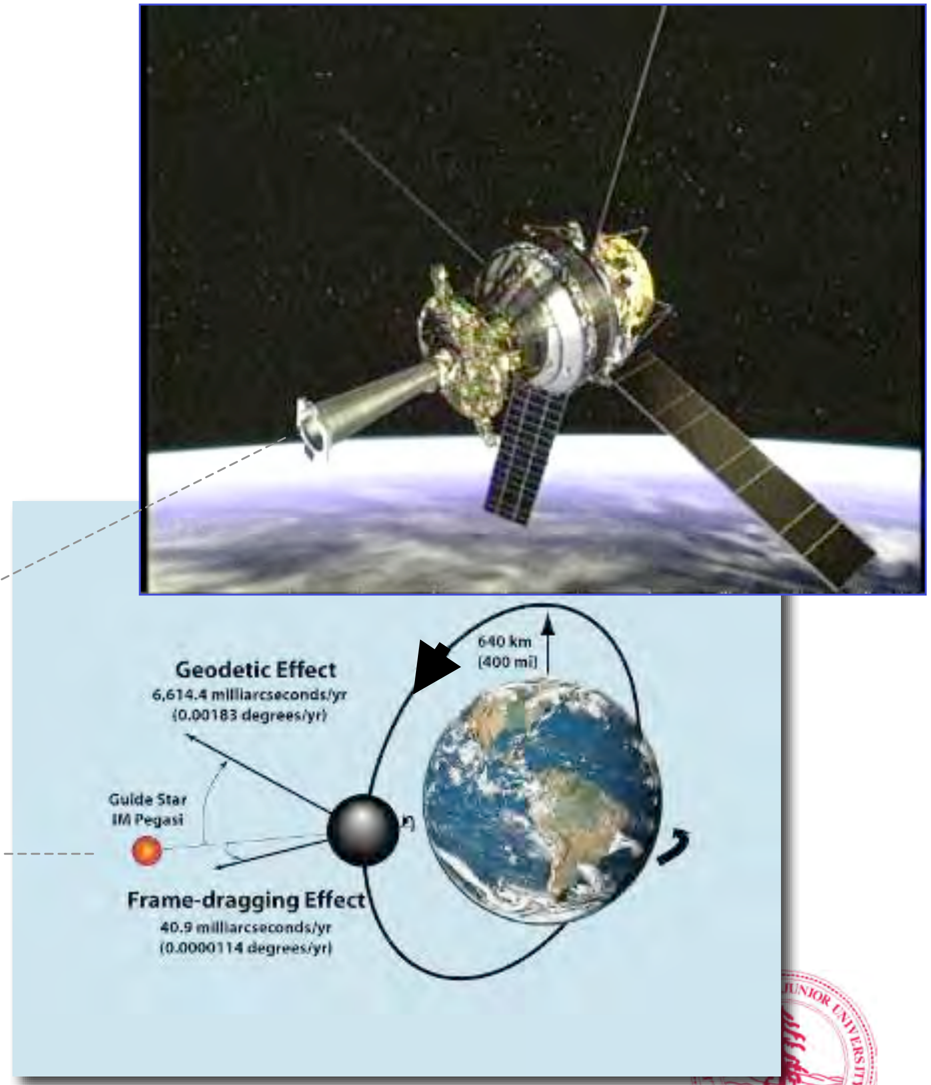


Fig. 705 SCI_Sep09_part1-L2 . GS Track (during GS Valid), Side A Start time: 146031616 sec Total 54.0 min



Systematic Error Checks