The Optical Field Angle Distortion Calibration of HST Fine Guidance Sensors 1R

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The usual suspects
last meeting of the STAT, 10/96
The OFAD

- **Geometric distortion** in the FGS is referred to as the Optical Field Angle Distortion (OFAD).

- Distortion alters the measured positions of stars in the FGS FOV by more than 1.0" (scale-like) and 0.5" (non-linear components).
  - For comparison, typical science objective is to obtain parallaxes accurate to 0.3 mas or better.

- **How to calibrate?** Use a star field in M35.
Calibration Field --- Open Cluster M35

• M35 contains many stars with $8 < V < 14$, ideal for the FGS calibration.

• M35 is near the ecliptic ($\text{Dec} = +24^\circ 25'$). It can be observed nearly year round (in 3-gyro mode), which makes it suitable to monitor FGS1r performance over time.

• FGS1r calibration data acquired in December 2000, while M35 was at “anti-sun” (proposals FGS/CAL 8469, AR 9190)

• Analysis of FGS1r was assisted by having a 1 mas catalog of this region from earlier calibrations of FGS3.
FGS1r OFAD Calibration
FGS3 OFAD Calibration
Analysis

We employed GaussFit\textsuperscript{1} to \textit{simultaneously} estimate the

- relative star positions (generate a catalog)
- \textbf{pointing} \& \textbf{roll} of the HST during each orbit
- \textbf{magnification} of the telescope
- \textbf{OFAD polynomial coefficients}
- $\rho A$, $kA$, two parameters that describe the star selector optics\textsuperscript{2}

The Distortion Model

\[ x' = a_{00} + a_{10}x + a_{01}y + a_{20}x^2 + a_{02}y^2 + a_{11}xy \]
\[ + a_{30}x(x^2+y^2) + a_{21}x(x^2-y^2) + a_{12}y(y^2-x^2) \]
\[ + a_{03}y(y^2+x^2) + a_{50}x(x^2+y^2)^2 + a_{41}y(y^2+x^2)^2 \]
\[ + a_{32}x(x^4-y^4) + a_{23}y(y^4-x^4) + a_{14}x(x^2-y^2)^2 \]
\[ + a_{05}y(y^2-x^2)^2 \]

\[ y' = b_{00} + b_{10}x + b_{01}y + b_{20}x^2 + b_{02}y^2 + b_{11}xy \]
\[ + b_{30}x(x^2+y^2) + b_{21}x(x^2-y^2) + b_{12}y((y^2-x^2) \]
\[ + b_{03}y(y^2+x^2) + b_{50}x(x^2+y^2)^2 + b_{41}y(y^2+x^2)^2 \]
\[ + b_{32}x((x^4-y^4) + b_{23}y(y^4-x^4) + b_{14}x(x^2-y^2)^2 \]
\[ + b_{05}y(y^2-x^2)^2 \]
Motions M35 Proper

In 2004 we determined the internal proper motions of selected stars in M35 based upon 12 years of HST FGS data.

- Previously we had used ground-based determinations from the McNamara catalog.
- Only stars that have been observed at more than 4 epochs over the course of the 12 years were included in the analysis.
- Proper motion amplitudes ranged from 0 to ~20 mas/yr.

A new OFAD in both FGS3 & FGS1r and a new M35 catalog were recalculated using the more accurate proper motions.
### Epochs of FGS OFAD calibrations in M35

<table>
<thead>
<tr>
<th>FGS</th>
<th>date</th>
<th># HST orbits</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>12/90</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>01/93</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>09/95</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>12/00</td>
<td>12</td>
</tr>
</tbody>
</table>

In addition, there have been ~6 observations / year of a field in M35 to monitor OFAD calibration.
M35 Proper Motions
milli-arcseconds per year
New FGS3 OFAD

fgs3 X
σ = 1.5 mas
N = 490

fgs3 Y
σ = 1.8 mas
N = 490

X residuals in arcseconds

Y residuals in arcseconds
New FGS1 OFAD

**fgs1 X**

- \( \sigma = 1.3 \) mas
- \( N = 420 \)

**fgs1 Y**

- \( \sigma = 1.3 \) mas
- \( N = 420 \)
OFAD Calibration Improvement with M35 Proper Motions

With the determination of the proper motion of the M35 field we have significant improvement in the quality of the OFAD calibration in both FGS1r & FGS3.

<table>
<thead>
<tr>
<th>Previous OFAD</th>
<th>New OFAD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FGS 3</strong></td>
<td><strong>FGS 3</strong></td>
</tr>
<tr>
<td>$\sigma_X = 2.3$ mas</td>
<td>$\sigma_X = 1.5$ mas</td>
</tr>
<tr>
<td>$\sigma_Y = 2.2$ mas</td>
<td>$\sigma_Y = 1.8$ mas</td>
</tr>
<tr>
<td><strong>FGS1r</strong></td>
<td><strong>FGS1r</strong></td>
</tr>
<tr>
<td>$\sigma_X = 1.6$ mas</td>
<td>$\sigma_X = 1.3$ mas</td>
</tr>
<tr>
<td>$\sigma_Y = 1.7$ mas</td>
<td>$\sigma_Y = 1.3$ mas</td>
</tr>
</tbody>
</table>
HST/FGS and Hipparcos

<table>
<thead>
<tr>
<th>Object</th>
<th>$\pi_{HST}$ (mas)</th>
<th>$\pi_{Hip}$ (mas)</th>
<th>$HST$ Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proxima Cen...</td>
<td>769.7 ± 0.3</td>
<td>772.33 ± 2.42</td>
<td>1</td>
</tr>
<tr>
<td>Barnard's Star</td>
<td>545.5 ± 0.3</td>
<td>549.3 ± 1.58</td>
<td>1</td>
</tr>
<tr>
<td>Gliese 876...</td>
<td>214.6 ± 0.2</td>
<td>212.7 ± 2.1</td>
<td>2</td>
</tr>
<tr>
<td>Feige 24...</td>
<td>14.6 ± 0.4</td>
<td>13.44 ± 3.62</td>
<td>3</td>
</tr>
<tr>
<td>Wolf 1062...</td>
<td>98.0 ± 0.4</td>
<td>98.56 ± 2.66</td>
<td>4</td>
</tr>
<tr>
<td>Pleiades...</td>
<td>7.43 ± 0.17</td>
<td>8.45 ± 0.25</td>
<td>5</td>
</tr>
<tr>
<td>RR Lyrae...</td>
<td>3.60 ± 0.20</td>
<td>4.38 ± 0.59</td>
<td>6</td>
</tr>
<tr>
<td>$\delta$ Cephei</td>
<td>3.66 ± 0.15</td>
<td>3.32 ± 0.58</td>
<td>7</td>
</tr>
<tr>
<td>HD 213307...</td>
<td>3.65 ± 0.15</td>
<td>3.43 ± 0.64</td>
<td>7</td>
</tr>
</tbody>
</table>
Absolute Parallaxes
HST = 0.991 ± 0.006 HIP
PRECISE MASSES FOR WOLF 1062 AB FROM HUBBLE SPACE TELESCOPE INTERFEROMETRIC ASTROMETRY AND McDONALD OBSERVATORY RADIAL VELOCITIES


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ABSTRACT

We present an analysis of astrometric data from Fine Guidance Sensor 3 (FGS 3), a white-light interferometer on HST, and of radial velocity data from two ground-based campaigns. We model the astrometric and radial velocity measurements simultaneously to obtain parallax, proper motion, and component masses for Wolf 1062 (Gl 748; M3.5 V). To derive the mass fraction, we relate FGS 3 fringe scanning observations of the science target to a reference frame provided by fringe tracking observations of a surrounding star field. We obtain an absolute parallax (abs = 98.0 ± 0.4 mas) yielding $M_A = 0.379 ± 0.005 M$ and $M_B = 0.192 ± 0.003 M$, high-quality component masses with errors of only 1.5%.
Wolf 1062 - Orbits and RV

$M_{\text{Tot}} = 0.568 \pm 0.008 M_{\odot}$

$M_A = 0.381 \pm 0.006 M_{\odot}$

$M_B = 0.187 \pm 0.003 M_{\odot}$

$\pi_{\text{abs}} = 98.1 \pm 0.4 \text{ mas}$
A Mass for the Extrasolar Planet Gliese 876b Determined from 
_Hubble Space Telescope_ Fine Guidance Sensor 3 Astrometry and 
High-Precision Radial Velocities

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**ABSTRACT**

We report the first astrometrically determined mass of an extrasolar planet, a companion previously 
detected by Doppler spectroscopy. Radial velocities first provided an ephemeris with which to schedule a 
significant fraction of the _Hubble Space Telescope (HST)_ observations near companion peri- and apastron. 
The astrometry residuals at these orbital phases exhibit a systematic deviation consistent with a 
perturbation due to a planetary mass companion. Combining _HST_ astrometry with radial velocities, we 
solve for the proper motion, parallax, perturbation size, inclination, and position angle of the line of nodes, 
while constraining period, velocity amplitude, longitude of periastron, and eccentricity to values 
determined from radial velocities. We find a perturbation semimajor axis and inclination, \( a = 0.25 \pm 0.06 \) 
mas, \( i = 84 \pm 6 \), and Gl 876 absolute parallax, \( \text{abs} = 214.6 \pm 0.2 \) mas. Assuming that the mass of the 
primary star is \( M^* = 0.32 \, M \), we find the mass of the planet, Gl 876b, \( M_b = 1.89 \pm 0.34 \, M_{\text{Jup}} \).
# Orbital Elements of Perturbation Due to Gl 876b

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$0.25 \pm 0.06$ mas...</td>
</tr>
<tr>
<td>$a$</td>
<td>$0.0012 \pm 0.0003$ AU ($\pm 28,000$ miles!)</td>
</tr>
<tr>
<td>$i$</td>
<td>$84^\circ \pm 6^\circ$</td>
</tr>
<tr>
<td>$P$</td>
<td>$61.02 \pm 0.03$ days</td>
</tr>
<tr>
<td>$T0$ (JD)</td>
<td>$2,450,107.87 \pm 1.9$</td>
</tr>
<tr>
<td>$E$</td>
<td>$0.10 \pm 0.02$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$25^\circ \pm 4^\circ$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$338.96 \pm 036$</td>
</tr>
<tr>
<td>$K1$</td>
<td>$0.210 \pm 0.005$ km s$^{-1}$</td>
</tr>
</tbody>
</table>
What’s coming for Position Mode?

• Inclination & mass of the ε Eridani and υ Andromeda planetary systems (nearly all data collected)
• Inclinations and masses of 6 more extrasolar planets
• Parallaxes:
  • 13 Galactic Cepheids
  • 3 PN
  • 1 CV
  • 1 brown dwarf
  • 3 Pop II Sub-Giants (to determine the age of the Halo)
  • (and masses) of 7 white dwarfs.