Working with a Space-based Optical Interferometer
HST Fine Guidance Sensor 3
Small Field Astrometry

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ABSTRACT

Space-based interferometry already exists. We describe our experiences with on-orbit calibration and scientific observations with Fine Guidance Sensor 3 (FGS3), a white-light interferometer aboard Hubble Space Telescope. Our goal, 1 millisecond of arc precision small-field astrometry, has been achieved, but not without significant challenges. These included a mechanically noisy on-orbit environment, the self-calibration of FGS 3, and significant temporal changes in our instrument. Solutions included a denser set of drift check stars for each science observation, fine-tuning exposure times, overlapping field observations and analyses for calibration, and a continuing series of trend-monitoring observations.

HST FGS 3 will remain a competitive astrometric tool for faint targets in crowded fields and for faint small-separation binaries until the advent of large-aperture, ground-based and longer-baseline space-based interferometers.

Keywords: astrometry, space interferometry, HST, calibration, metrology

1. INTRODUCTION

We briefly outline a series of problems encountered while commissioning HST FGS3 for use in astrometry. A description of the hardware can be found in Bradley et al., 1991[1]. and in Nelan[2] et al, these proceedings. Routine astrometric per-observation precision of 0.001 arcsec (1 mas) and binary star resolution approaching 15 mas[3] attest to our success. This paper briefly reviews problems, solutions, and resulting data quality for POS (position) - mode astrometry.

2. THE CALIBRATION OF FGS3

Our initial **problem** included optical distortions in the HST Ritchey-Chretien telescope design with amplitudes exceeding 0.5 arcsec. There was no existing star field with cataloged 1 mas precision astrometry, our desired performance goal. Our **solution** was to use FGS3 to calibrate itself with multiple observations of a distant star field (M35). A distant field was required so that during the 2-day duration of data acquisition, star positions would not change. We obtained these data in early 1993 and reduced them with overlapping plate techniques to solve for distortion coefficients and star positions simultaneously. As a **result** of this activity distortions are reduced to better than 2 mas over much of the FGS3 field of regard. This model is called the Optical Field Angle Distortion (OFAD) calibration. Details can be found on-line at http://clyde.as.utexas.edu/95HST-ALW.html.

3. DEALING WITH THE ON-ORBIT ENVIRONMENT

3.1 Difficulties encountered during each observation set

A typical observation sequence (described in Benedict et al., 1994[4] and the FGS Instrument Handbook[5]) has a duration of about 40 minutes and consists of a serial collection of from 10 to 30 time-series of positions sampled at 40Hz. Each time series lasts from 30 to 300 seconds, depending on the target star brightness. We have identified sources of systematic and random position noise ranging from highest to lowest frequency as follows.

3.2.1 HST mechanical noise

Our first **problem** involves line-of-sight jitter (Fig. 1, top and middle panels), which, before the first servicing mission in late 1993, was caused primarily by the Solar Arrays. An initial, compute-intensive solution was to correct each 25 ms sample for jitter, using the dominant guide star as a witness to HST jitter. Since FGS1 is on the other side of the HST focal plane, -y in FGS1 is +y in FGS3. The correction is done by simply adding the Y signals. While local peak-to-peak noise was considerably reduced (Fig. 1, bottom panel), lower frequency noise was not corrected. FGS3 appears to rock back and forth in its (supposedly firmly latched) bay with a period of about a minute.

Our **solutions** to these problems were fairly simple. We characterized the power spectrum of the mechanical noise and determined that observing for 60 sec or longer adequately sampled the frequency domain. A median filter was determined to abstract the best position (i.e., the median is a robust estimator for this system). We encouraged the replacement of the original Solar Arrays, an easy task, since they were in danger of suffering catastrophic failure from the same mechanical flexure causing our problems. The **result** was very positive. Since replacement in early 1993 we enjoy a snap/crackle/pop[6] noise level reduced by nearly an order of magnitude, and the median filter, applied to raw time series, continues to deliver the required accuracy. Finally, the dispersion around the median provides an estimation of the observational error.

3.2.2 Drift during an observation sequence

Having successfully dealt with high frequency noise, our next **problem** involved lower frequency changes. We have evidence that over the course of one orbit guide stars autonomously drift. Fig. 2 shows observations of Barnard's Star and a reference star (where time series like those seen in Fig. 1 have been reduced to median values) over the span of 36 minutes. This was a particularly bad orbit where drift exceeded 30 mas. Note also that x and y drift rates are not similar and that the drift is not constant rate.

The **solution** is simple and effective, but imposes additional overhead, reducing the time available within an orbit to do science. An observation set must contain visits to one or more astrometric reference stars, multiple times during each observation sequence. Presuming no motion intrinsic to these stars over a span of 40 minutes, one determines drift and corrects the reference frame and target star for this drift. As a **result** we reduce the error budget contribution from drift to less than 1 mas.

3.1 Maintaining the astrometric calibration

The final **problem** discussed here involves changes over months and years. Some things that are supposed to change on-orbit, do change. The FGS3 graphite-epoxy optical bench was predicted to outgas for a period of time after the launch of HST. The outgassing was predicted to change the relative positions of optical components on the optical bench. The result of whatever changes were taking place was a change in scale. The amount of scale change was far too large to be due to true magnification changes in the HST optical assembly. Two parameters associated with the devices (star selectors) used to point the instantaneous field of view of the FGS cause a scale-like change, if they are allowed to vary with time. Shown in Fig. 3, these are ρ_A (the arm length of star selector A) and k_A (the offset angle of star selector A).

Our **solution** was to revisit the M35 calibration field periodically to monitor these scale-like changes and other slowly varying non-linearities. This is the never-ending LTSTAB (Long-Term STABility) series. LTSTABs will be required as long

as it is desirable to do 1 mas precision astrometry with FGS3. The **result** of this series is to model and remove the slowly varying component of the OFAD, so that uncorrected distortions remain below 2 mas for center of FGS 3. The character of these changes is shown in Fig. 4. They are generally monotonic with abrupt jumps in conjuction with HST servicing missions. See McArthur et al. 1997[8] for the details of this on-going monitoring process, also on-line at http://icarus.stsci.edu/~stefano/Papers_final_pdf.html .

4. SAMPLE SCIENCE RESULT

Last, we discuss the quality of astrometry produced by FGS3. Our example is from a project to detect low-mass companions to Proxima Centauri. The spatial distribution of reference stars used in the Proxima Centauri study over the field of regard of FGS3 for fifty-nine data sets is shown in Fig. 5. The goal is 1 mas astrometry over a field with a 200 arcsec diameter. The total study duration exceeds five years with nearly half the observation sets acquired in the first year.

4.1 Reduction and analysis pipeline

Once acquired, astrometric data from FGS3 passes through a pipeline processing to an analysis system. The steps include: centroid raw data, removing intra-observation jitter (using the median filter, see Fig. 1); remove velocity-induced aberrations; apply the OFAD calibration; and apply time dependent corrections to the OFAD. In subsequent steps we apply intra-orbit drift corrections (e.g. Fig. 2) and a lateral color correction (the FGS contains refractive optics). We finally model the systematic contributions to the astrometric reference frame from parallax (π) and proper motion (μ), explicitly

$$\zeta = ax + by + c - \mu_x - \pi_x \qquad (1)$$
$$\eta = dx + ey + f - \mu_y - \pi_y \qquad (2)$$

while constraining $\Sigma\mu = 0$, $\Sigma\pi = 0$ for the entire frame. We have found that the scale-like terms (a and e) are significantly different in x and y and should be retained for best results. Fig. 6 presents histograms of the residuals obtained from modeling these fifty-nine Proxima Centauri reference star data sets. These histograms support our assertion that FGS3 produces astrometry with 0.001 arcsec precision per-observation. The time scales successfully corrected for range from less than one second to over five years.

4.2 Planet detection results for Proxima Centauri

Details of the results of this study will be published in a future paper. Having demonstrated 1 mas precision per observation, our preliminary planetary mass detection limits for Proxima Centauri (presuming a stellar mass ~0.1 that of the Sun) are at or below 1 Jupiter mass for periods between 90 and 600 days. Our temporal sampling and measurement precision render very short period systems like 51 Peg and its 0.6 Jupiter mass companion undetectable.

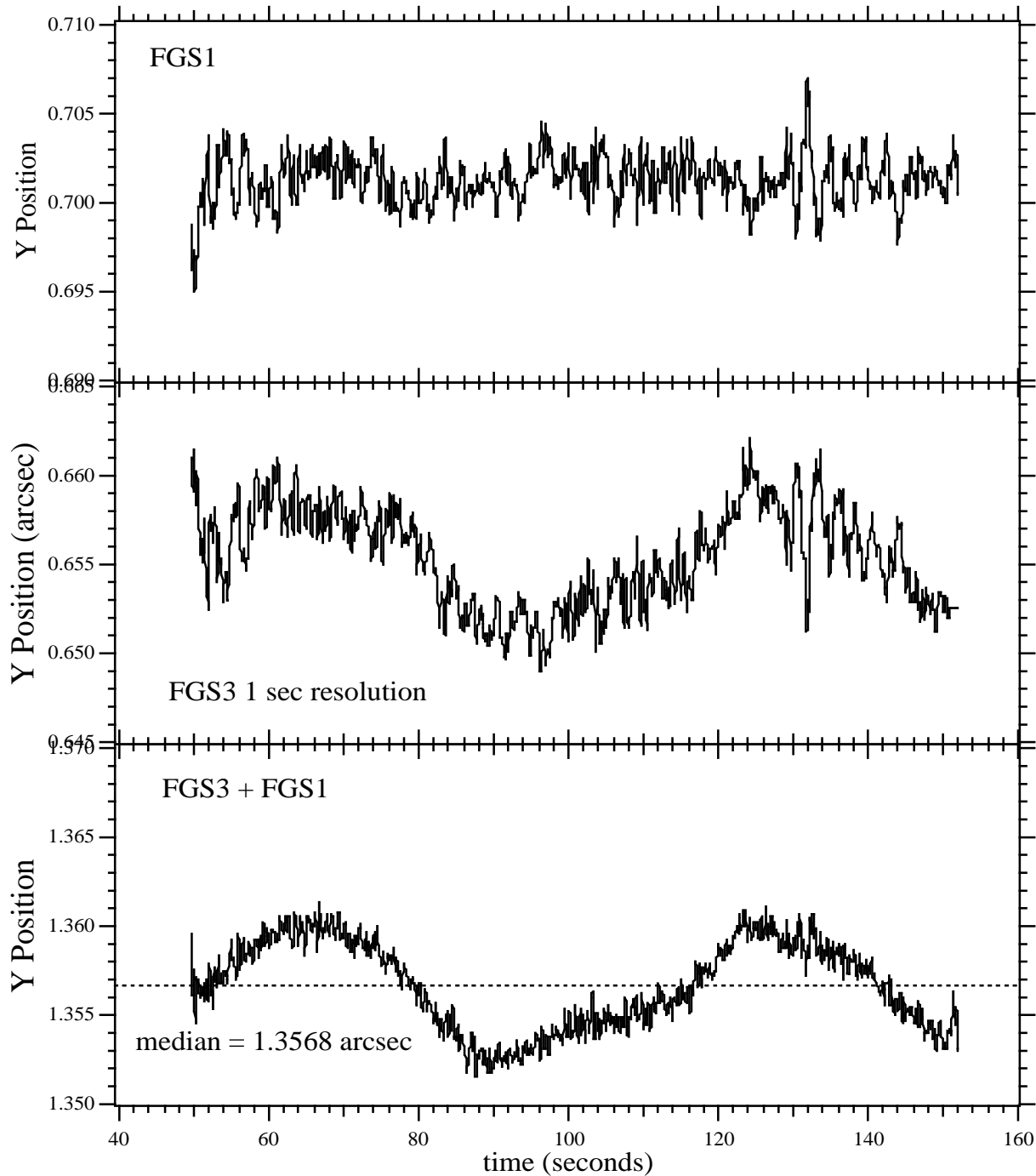## 5. ACKNOWLEDGMENTS

6. FIGURES

Fig. 1 - Dominant guide star (top), Proxima Centauri (middle), and Proxima Centauri corrected for HST line-of-sight jitter using the dominant guide star (bottom). Time series are smoothed to an equivalent 1 second resolution. FGS3 experiences motions not witnessed by FGS1. The median of the middle frame is within 0.1 mas of that of the jitter-corrected data in the bottom frame, obviating the necessity of 40Hz dejittering. These data contained (at time ~ 130 seconds) an observation of a major stellar flare on or near the surface of Proxima Centauri[7].
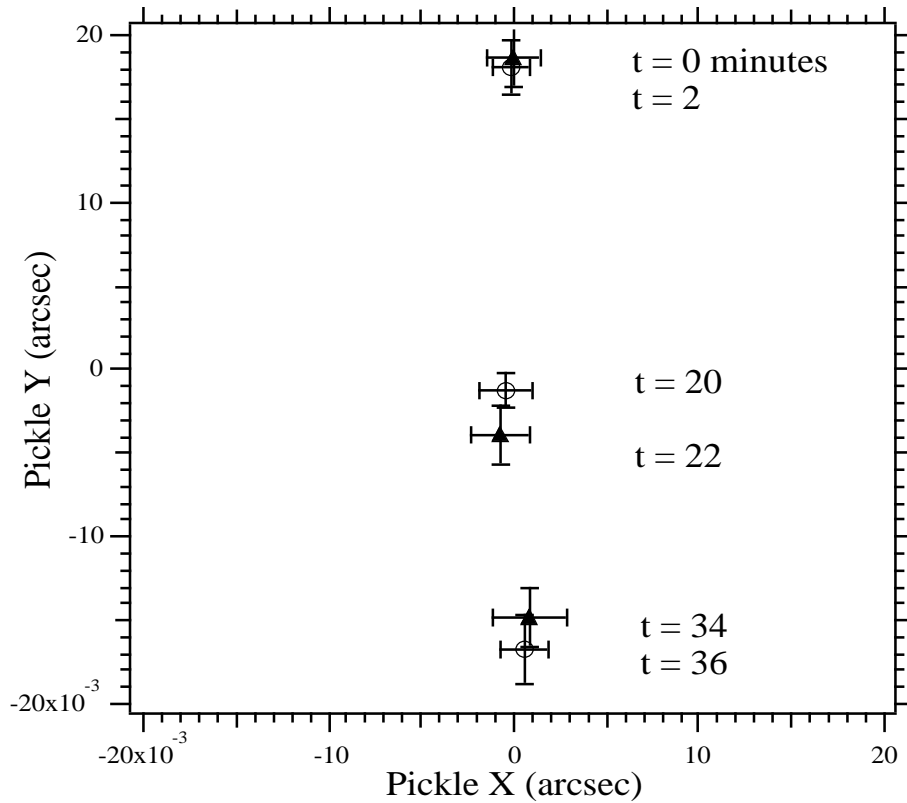
Fig. 2 - Positions of Barnard's Star (open symbol) and a local reference star (filled symbol) with associated error bars. Time tags are in minutes elapsed from the first observation. Drift amplitude was over 30 mas in y, less than 5 mas in x.
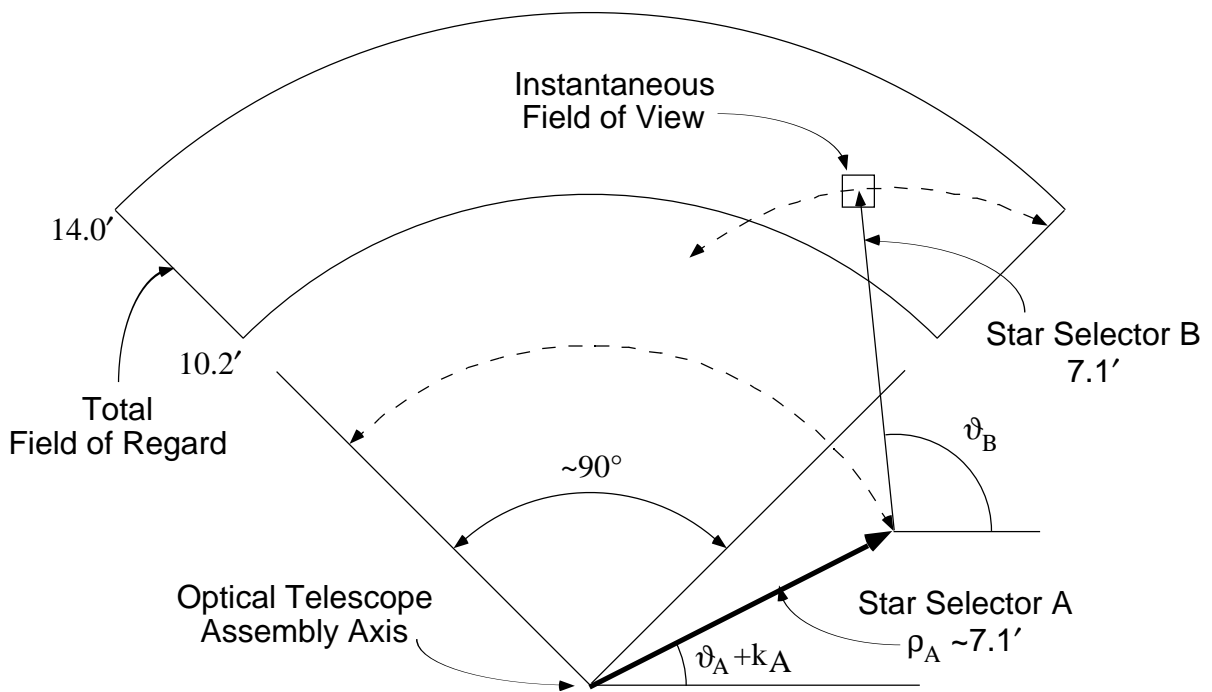

Fig. 3 - FGS3 field of regard and instantaneous field of view, showing the simple model representing the effect of star selector lever arm lengths and offset angles on the selection process. Changing ρ_A (the arm length of

star selector A) and k_A (a small correction to θ_A) introduces scale-like changes into the astrometry.
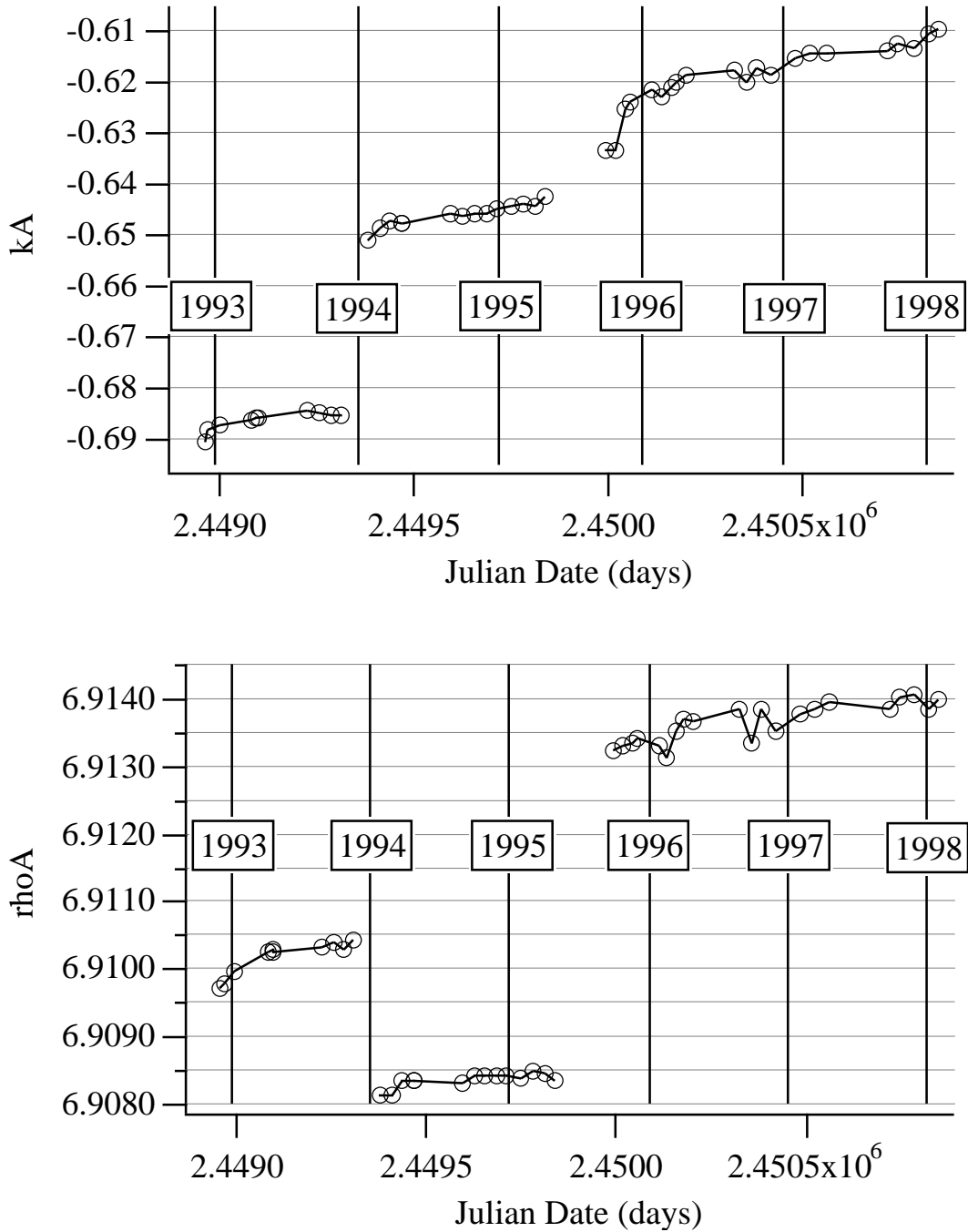

Fig. 4 Variations in ρ_A (bottom) and k_A (top) as a function of time in days. Formal (1-σ) errors are smaller than the plotted symbols. Calendar years are noted. Discontinuities are associated with HST servicing missions.
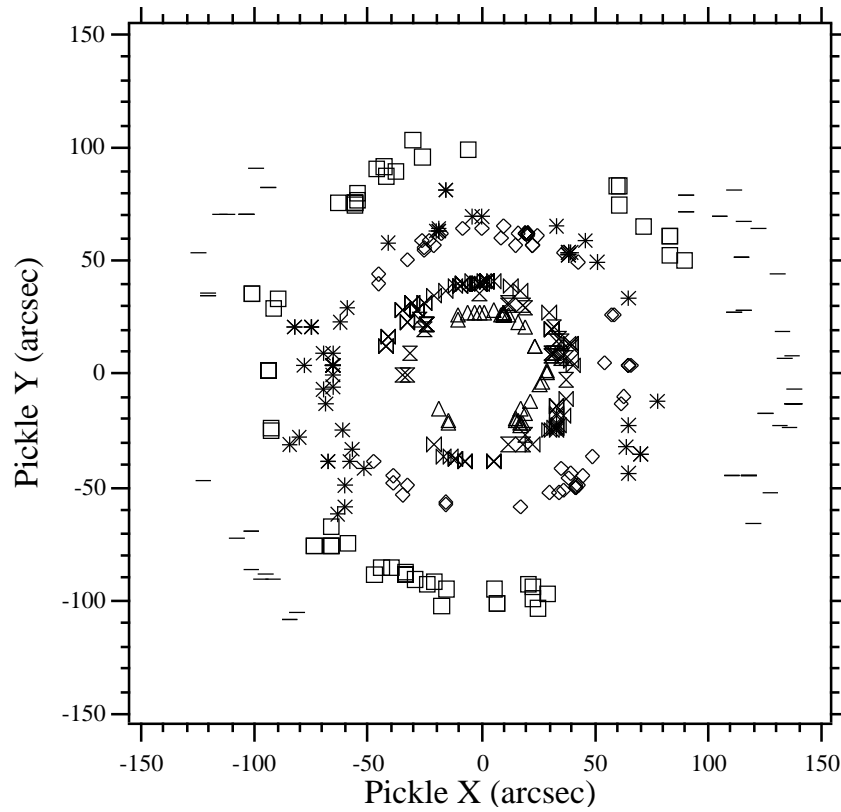
Fig. 5 - Locations within FGS3 for 419 observations of eight different (shown by eight unique symbols) reference stars, secured during 59 visits to the field over 5.5 years.
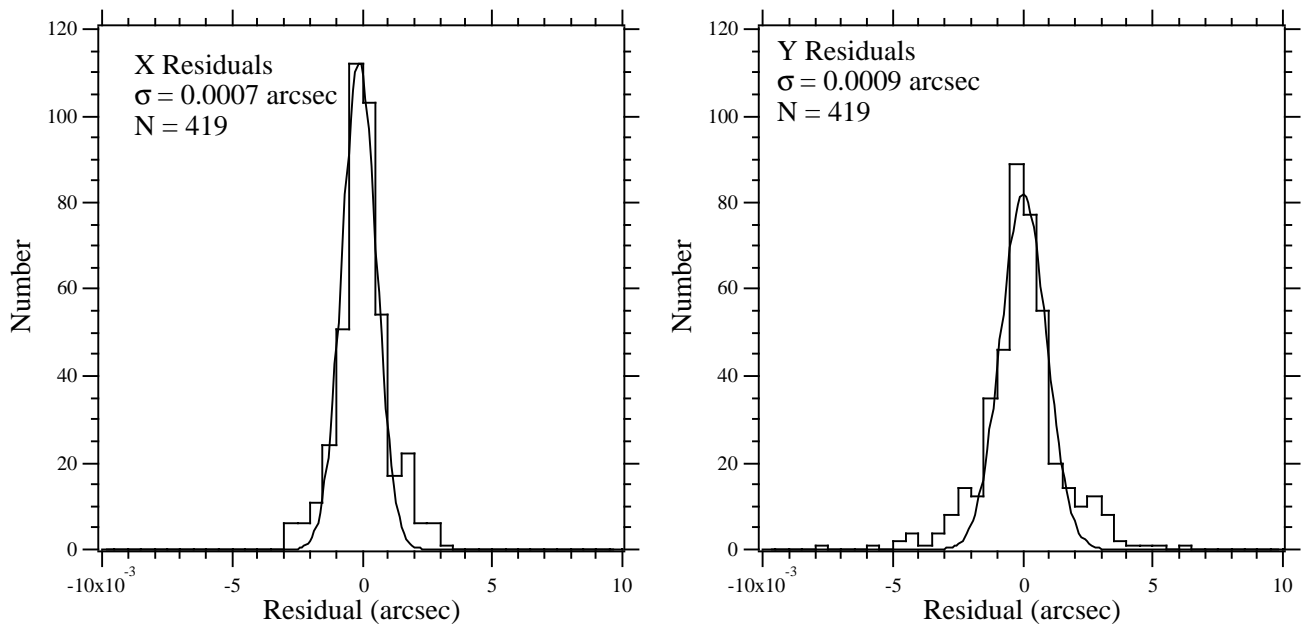

Fig. 6 - Histograms of the x and y residuals to the model (Equation 1 and 2). These 419 measurements were secured from 59 separate visits to this field during the 5.5 year duration of the study. These histograms argue that our per-observation precision is at or below 1 mas.

7. REFERENCES

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