HUBBLE SPACE TELESCOPE:
A GENERATOR OF SUB-MILLIARCSECOND PRECISION PARALLAXES

G. BENEDICT, W. JEFFERYS, B. MCARTHUR, E. NELAN, A. WHIPPLE, Q. WANG, D. STORY, P. HEMENWAY AND P. SHELUS
McDonald Observatory
University of Texas
Austin, TX 78712

W. VAN ALTENA
Astronomy Department
Yale University
New Haven, CT 06511

O. FRANZ
Lowell Observatory
Flagstaff, AZ 86001

R. DUNCOMBE
Aerospace Engineering
University of Texas
Austin, TX 78712

AND

L. FREDRICK
Astronomy Department
University of Virginia, Charlottesville, VA 22903

Abstract. Hubble Space Telescope Fine Guidance Sensor 3 can generate sub-milliarcsecond precision parallaxes in eighteen months. We discuss the internal precision and external accuracy of our observations of Proxima Centauri and Barnard's Star. For some classes of targets Hubble Space Telescope will remain the parallax tool of choice for years to come. It can offer 0.5 mas precision. It will remain useful by satisfying urgent needs for quick results, by offering a 13 magnitude dynamic range, and by providing an unparalleled binary dissection capability.

E. Høg and P. K. Seidelmann (eds.),
Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 89–94.

1. Introduction

We will discuss the precision and accuracy of parallaxes and proper motions acquired with Fine Guidance Sensor 3 (FGS 3) aboard the Hubble Space Telescope (HST). The FGS is a white light interferometer. A description of the FGS, its data products, and data processing can be found in Bradley *et al.* (1991). The FGS is operated in either TRANS or POS mode. TRANS produces a scan across a star, which results in a complete interferometer response (transfer) function. POS mode provides a string of position error signals, generated by the FGS as it attempts to track the zero-crossing of the transfer function. Parallax studies utilize POS mode.

Benedict *et al.* (1992) showed that FGS 3 had the best performance characteristics for astrometry of any of the three FGS aboard HST, then demonstrated (Benedict *et al.* 1994) that FGS 3 had the precision and stability required for long-term astrometric studies, such as parallax work. We obtain 1.5 milliarcsecond (mas) precision per axis per observation. No other ground- or space-based device can beat this noise figure for the very faint stars we study. Details of our Optical Field Angle Distortion (OFAD) calibration can be found in Jefferys *et al.* (1994). While stable enough for astrometry, FGS 3 does change over time. See Whipple *et al.* (1994) for a description of the character of these changes and of our OFAD monitoring strategy.

We now have data to determine parallaxes for Proxima Centauri and Barnard's Star. We chose these two targets for an astrometric search for planetary companions. The results of the Proxima Cen planet search will be reported elsewhere. The Barnard's Star planet search continues.

2. Proxima Centauri

• Background - Proxima Cen = GL 551 is the nearest star to us other than the Sun. It is a known flare star (V645 Cen), with quiescent $V = 11.22$. We have used HST FGS 3 in POS mode to monitor the position of Proxima Cen in an effort to detect perturbations due to very low mass companions. We have 48 data sets (orbits) from 23 March 1992 to 4 May 1994. The time coverage is not uniform, with gaps due to solar constraint and equipment difficulties. We secured many observations quickly because gas giants orbiting M stars may have short periods (Black and Scargle 1982). If one scales the temperature distribution in the solar preplanetary nebula around the far less luminous Proxima Cen, gas giants could form with orbital periods as short as 50 days.

A key element in planet searches is the determination of the proper motion of the star and the elimination of the effects of the earth's orbit. Anyone who has looked for planets around other stars has found that the earth orbits the Sun! Another key element, and one germane to parallax work, is the demonstrated random noise level of 1.5 mas per axis. This level is crucial to establishing upper limits for companion masses and for detecting actual perturbations.

• Results: Internal Precision - We analyse these data as described in Benedict *et al.* (1994), first showing what can be obtained with many more observations than any one proposer is likely to receive from the HST Time Allocation Committee. Given that constraint, we show the precision levels obtainable with far fewer (and, hence, more likely granted) observations.

Entire Data Series - A solution including all 48 observation sets yields a formal error (1-σ) for the parallax of 0.4 mas. For the proper motion (μ) we obtain 0.5 mas precision. See Table 1 for the parallax value. We reduce the relative parallax to absolute parallax (based on the faintness and galactic latitude of the reference frame, $V_{av} \simeq 14$) $\pi_{abs} = \pi_{rel} + 0.7$mas (van Altena, 1994).

A 1.5 year subset - We carried out an extension of a previous analysis (Benedict *et al.* 1994) with a 15 observation subset of the original 48 observations. This subset spanned 18 months and provides a formal error for the parallax of a ($V = 15$) reference star of 0.5 mas, and 1 mas for μ. We then reanalyzed Proxima Cen for this same subset and achieved similar results (Table 1). Note that in going from 15 to 48 observation sets we do not quite achieve a $\sqrt{n}$ reduction in the parallax error. This is probably due to not having 48 observation sets independent in time. There are many tight groupings of observations.

3. Barnard's Star

• Background - To date (8/94) we have 15 observation sets (from 2 February 1993 to 4 May 1994) of Barnard's Star, $V = 9.54$. The time interval between observations over this 14 months is not uniform. In particular, we have not sampled both extremes of the parallactic ellipse.

• Results: Internal Precision - Even though our study duration is strikingly less than a typical parallax series, and we have not sampled the entire parallactic ellipse, our precision is good. The (1-σ) precision for parallax is 0.9 mas and for μ is 1.3 mas. Our absolute par

allax ($\pi_{abs} = \pi_{rel} + 0.8$mas) is given in Table 1.

4. External Accuracy

Ideally, we should check against results with similar precision, but there are none. Rather, we compare against compilations of many less precise determinations, such as the Yale Parallax Catalog (van Altena *et al.* 1991, 1994). Our comparison is given in Table 1.

TABLE 1. Comparison with Yale Parallax Catalog

	Reduction	HST	YPC(1991)	YPC(1994)
1	Proxima Cen (48 obs)	0.7699±0.0004	0.7718±0.0041	0.7699±0.0004
2	Proxima Cen (15 obs)	0.7701±0.0005	0.7718±0.0041	0.7699±0.0004
3	Barnard's Star (15 obs)	0.5420±0.0009	0.5467±0.0008	0.5463±0.0013
4	Barnard's Star (USNO μ)	0.5442±0.0028	0.5467±0.0008	0.5463±0.0013

The last line in the table is a parallax value obtained by constraining μ of Barnard's Star to a previously determined value (Harrington & Dahn, 1980). Much of the difference between the HST and the YPC parallax values (line 3) is likely due to poor sampling of the parallactic ellipse by HST. We cannot yet separate parallax from proper motion. Finally, it should be noted that the ecliptic latitude is 27^o for Barnard's Star and -44^o for Proxima Cen. Thus, there is parallax information in two directions. A parallax for a target near the ecliptic might require more than 1.5 years.

5. The Future of HST Parallax Work

The only other program routinely providing milliarcsecond precision parallaxes at optical wavelengths is the ground-based CCD work of Monet *et al.* (1992). HST parallax precision is somewhat better than they typically achieve, and is attained in one half to one third the time. Once large array optical interferometers are in routine use (e.g. Simon *et al.* 1991), the list of potential parallax targets for HST may shrink, but not vanish. In this section we summarize the strengths of HST. We then point out a few examples of the kinds of objects for which HST is ideally suited. We end with a brief discussion of areas requiring further work.

5.1. WHY USE HST TO OBTAIN PARALLAXES?

• Precision - Our demonstrated precision for two stars in the Proxima Cen field is 0.5 mas. Given the precision we attained for Barnard's Star under less than ideal circumstances (§3), it is probable that we will reach 0.5 mas for most targets.

• Field of View - Often a parallax target is unmeasurable because reference stars are not located within the field of view of the measuring device, be it photographic plate or CCD. For the data discussed above sufficient reference stars existed within the 3.5 arcmin diameter center of the FGS field of view. If a larger field of view is necessary for a parallax series, one can trade study duration for field of view. Observations could be spaced by six months. The FGS field of view would then flip 180^o. The paraboloid-shaped region in common to the two orientations has a short axis = 3.5 and a long axis = 14 arcmin.

• Dynamic Range - FGS 3 can obtain POS mode position measures for stars in the range $4 \leq V \leq 17$. This large dynamic range is provided by a neutral density filter that reduces the magnitude of bright stars by 5 mag. The unfiltered range is $9 \leq V \leq 17$. There will be a small but unknown shift in position (due to filter wedge) when comparing the positions of the bright star to the faint reference frame. The shift is constant in direction (relative to FGS 3) and size, since the filter does not rotate within its holder. However, the shift can become a nuisance parameter in our model, because it represents another annual term, like parallax. The FGS field of view slowly rotates as the HST solar arrays are kept normal to the Sun throughout the year. To fully exploit this dynamic range, it is essential that the magnitude and direction of the filter wedge shift be determined by a cross-filter calibration.

• Binary Stars - HST can obtain precise parallaxes for close binaries. In POS mode, the FGS will lock on a null position which is generated by two closely overlapping s-curves. A nearly simultaneous TRANS mode observation gives the relative positions of the two components. One can determine the null position with an accuracy and precision of 1 mas relative to the two components, once the s-curves from the two stars are deconvolved (Franz *et al.* 1994a). POS and TRANS mode measurements provide the null position and component positions relative to reference stars.

• Timeliness of Result - One no longer need wait 3-6 years for the parallax of astrophysically interesting objects. The distance to a sufficiently interesting and important object can be obtained on the same time scale as other astrophysical information. *Without distances, no one does astrophysics.* If an object or class of objects is interesting now, a theory can be tested now. A caveat; accuracy will require complete sampling of the parallactic ellipse.

5.2. TARGET EXAMPLES

• Targets requiring the dynamic range and precision of HST include the classical cepheid variable, SU Cas and the defining member of the class, RR Lyrae.

• As an example of the need for speed, consider asteroseismology, a particularly active research area. It may be possible to measure distances to very bright (young) white dwarf stars by photometric study of their vibrational modes (Kawaler and Bradley 1994). The technique requires calibration. These stars are all quite distant, with very poorly determined distances. As soon as HST can provide a more precise distance for (e.g.) PG 1159-035, astronomers may have a new distance scale tool.

• We have discovered many previously unknown faint binaries in the Hyades (Franz *et al.* 1994b). Precise mass determinations require precise distances. Given the nearness and depth of this cluster, we must obtain parallaxes for each binary, rather than rely on an average cluster distance.

5.3. FUTURE IMPROVEMENTS

After working with FGS 3 for several years, we feel that improvements are still possible. Why do we need 6 coefficients in our overlapping plate model? Avenues of investigation include the spatial resolution of our OFAD calibration and color effects (FGS has refractive elements). In December 1993, NASA serviced HST. This introduced some rather large and, as yet, unexplained changes in our OFAD. To fully exploit the dynamic range of FGS astrometry, we will push for a cross filter calibration. The precision, field of view, dynamic range, and speed of HST/FGS POS mode astrometry demand that we press for the best possible treatment of the data.

References

Benedict, G. F. *et al.* (1992) *PASP*, 104, 958

Benedict, G. F. *et al.* (1994) *PASP*, 106, 327

Black, D. and Scargle, J. (1982) *ApJ*, 263, 854

Bradley, A. *et al.* (1991) *PASP*, 103, 317

Franz, O. G. *et al.* (1994a) "Binary Star Astrometry and Photometry from Transfer-Function Scans" in *Calibrating Hubble Space Telescope*, ed. by J. C. Blades and S. J. Osmer, STScI

Franz, O. G. *et al.* (1994b) *BAAS*, 26, 929

Harrington, R.S. and Dahn, C.C. (1980) *AJ*, 85, 454

Jefferys, W. H. *et al.* (1994) "Optical Field Angle Distortion of FGS 3", in *Calibrating Hubble Space Telescope*, ed. by J. C. Blades and S. J. Osmer, STScI

Kawaler S. and Bradley, P. (1994) *ApJ*, in press

Monet, D. G. *et al.* (1992) *AJ*, 103, 638

Simon, R. S. *et al.* (1991) "Imaging Optical Interferometry" in *IAU Coll. 131* ASP Conf. Ser. Vol 19, 358.

van Altena, W. F., Lee J. T., and Hoffleit E. D. (1991) *The General Catalogue of Trigonometric Parallaxes, Preliminary Version*, in Astronomical Data Center CD-ROM Selected Astronomical Catalogs, Volume 1, L. E. Brotzman, S. E. Gessner, J. M. Mead and M. E. Van Steenberg, eds., Goddard Space Flight Center, Greenbelt.

van Altena, W. F., Lee J. T., and Hoffleit E. D. (1994) *The General Catalogue of Trigonometric Parallaxes*, Yale University Observatory, New Haven.

van Altena, W. F. (1994), private communication

Whipple, A. L. *et al.* (1994) "Maintaining the FGS 3 OFAD Calibrations with the Long-Term Stability Test", in *Calibrating Hubble Space Telescope*, ed. by J. C. Blades and S. J. Osmer, STScI