How We Do Astrometry with Hubble Space Telescope

The Distance to the Pleiades And Why You Should Care

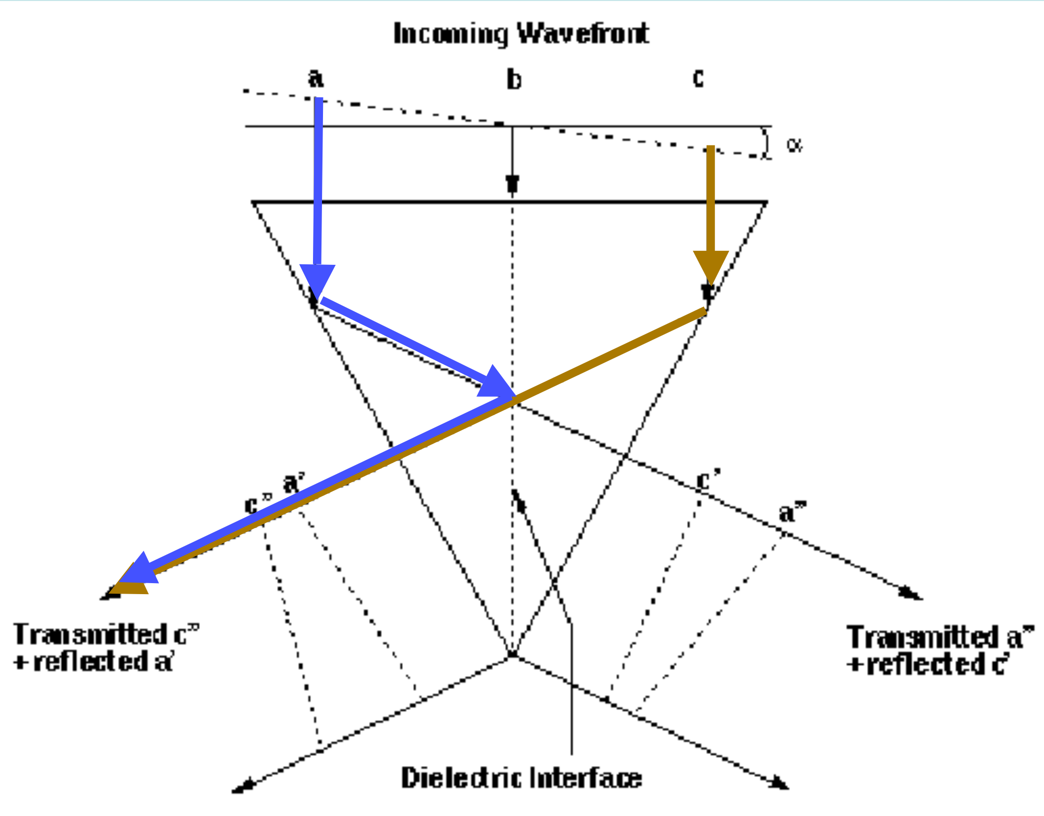
Fritz Benedict

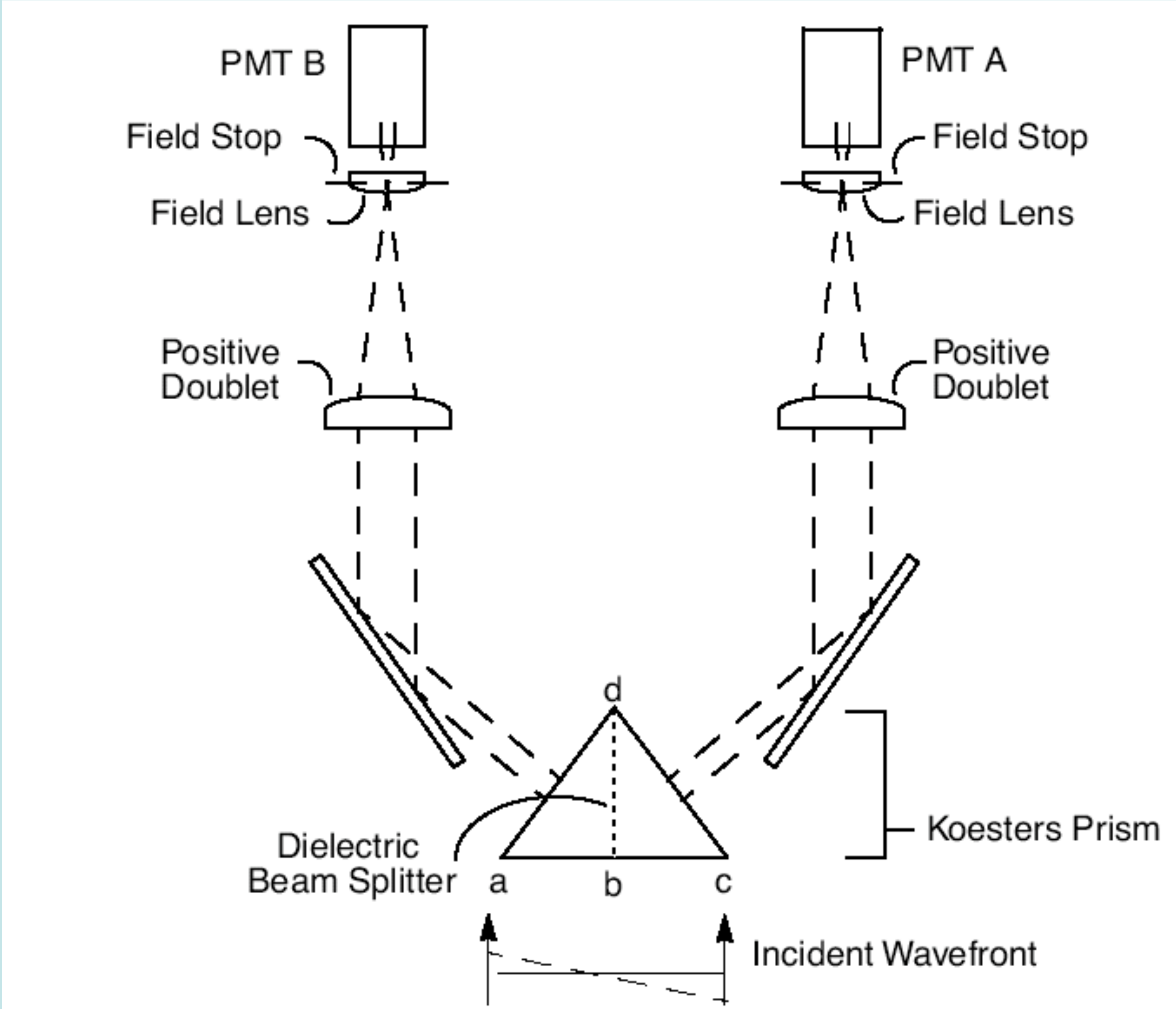
HST/FGS Astrometry - Outline

- The Fine Guidance Sensor, our astrometer:
  internals and calibration
- A Parallax for the Pleiades
  - The problem
  - The approach
  - The reference frame
  - Our result, or stellar interiors saved
- Why you can trust us on this one

It helps to have done this for awhile

The Koester's Prism - the Interferometric Heart of an FGS




PMT B
PMT A
Field Stop
Field Stop
Field Lens
Field Lens
Positive Doublet
Positive Doublet
d
Koesters Prism
Dielectric Beam Splitter
a
b
c
Incident Wavefront

The Fringe

Theory

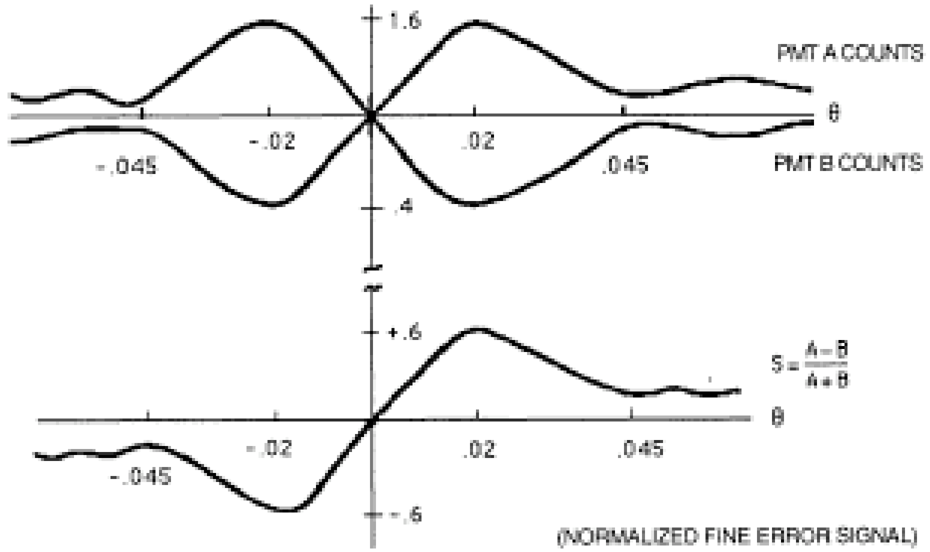
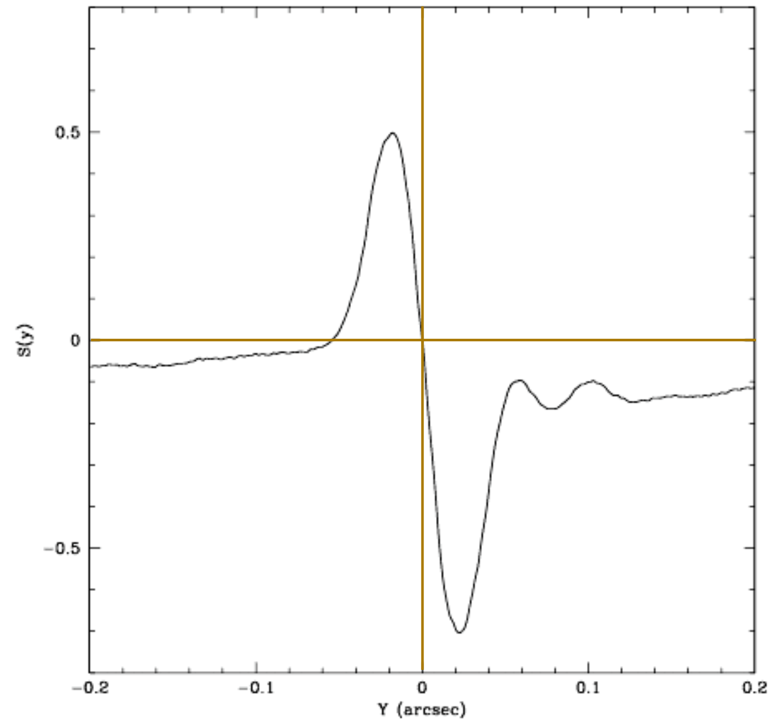


FIG. 6—Transfer function S-curve construction.

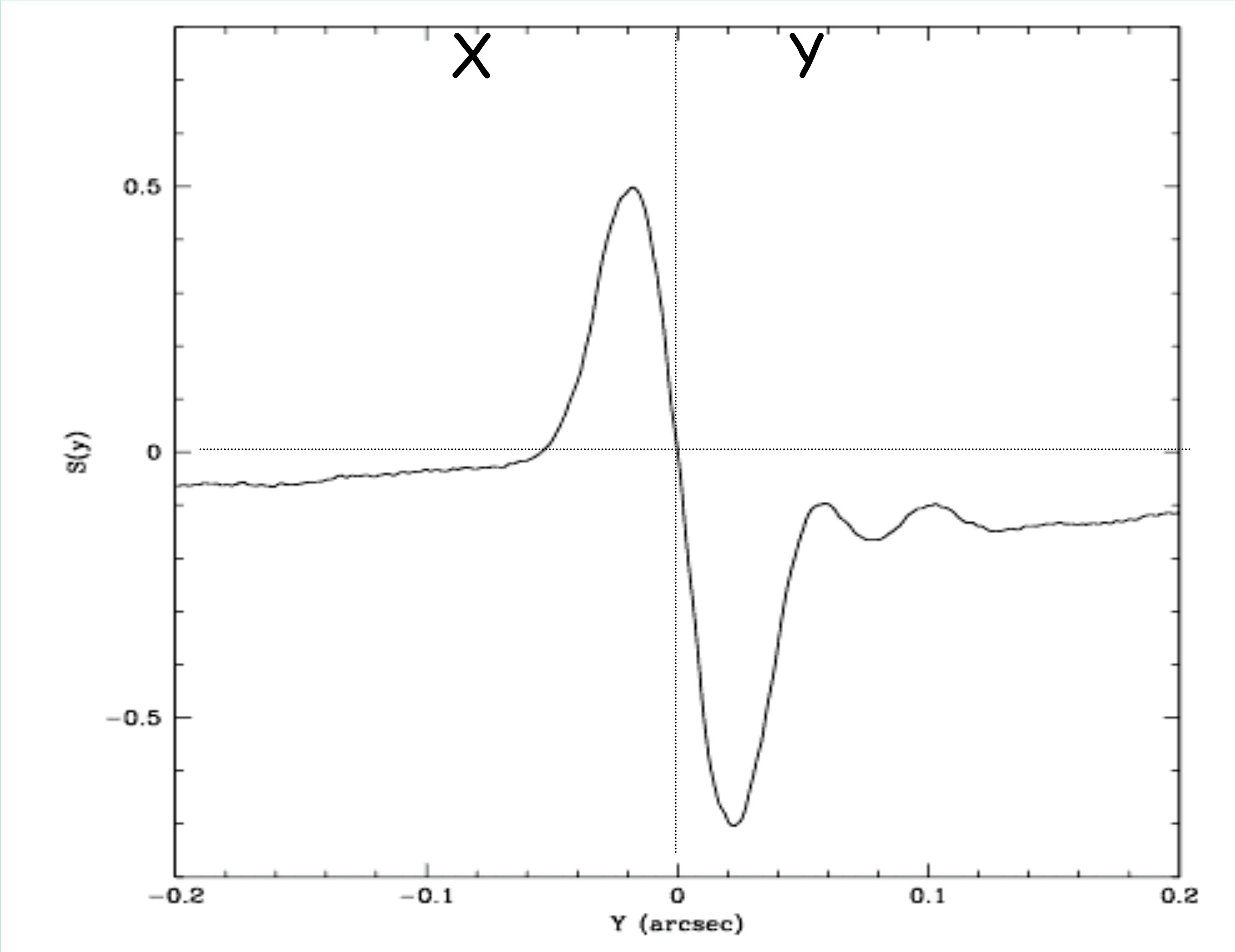
Practice

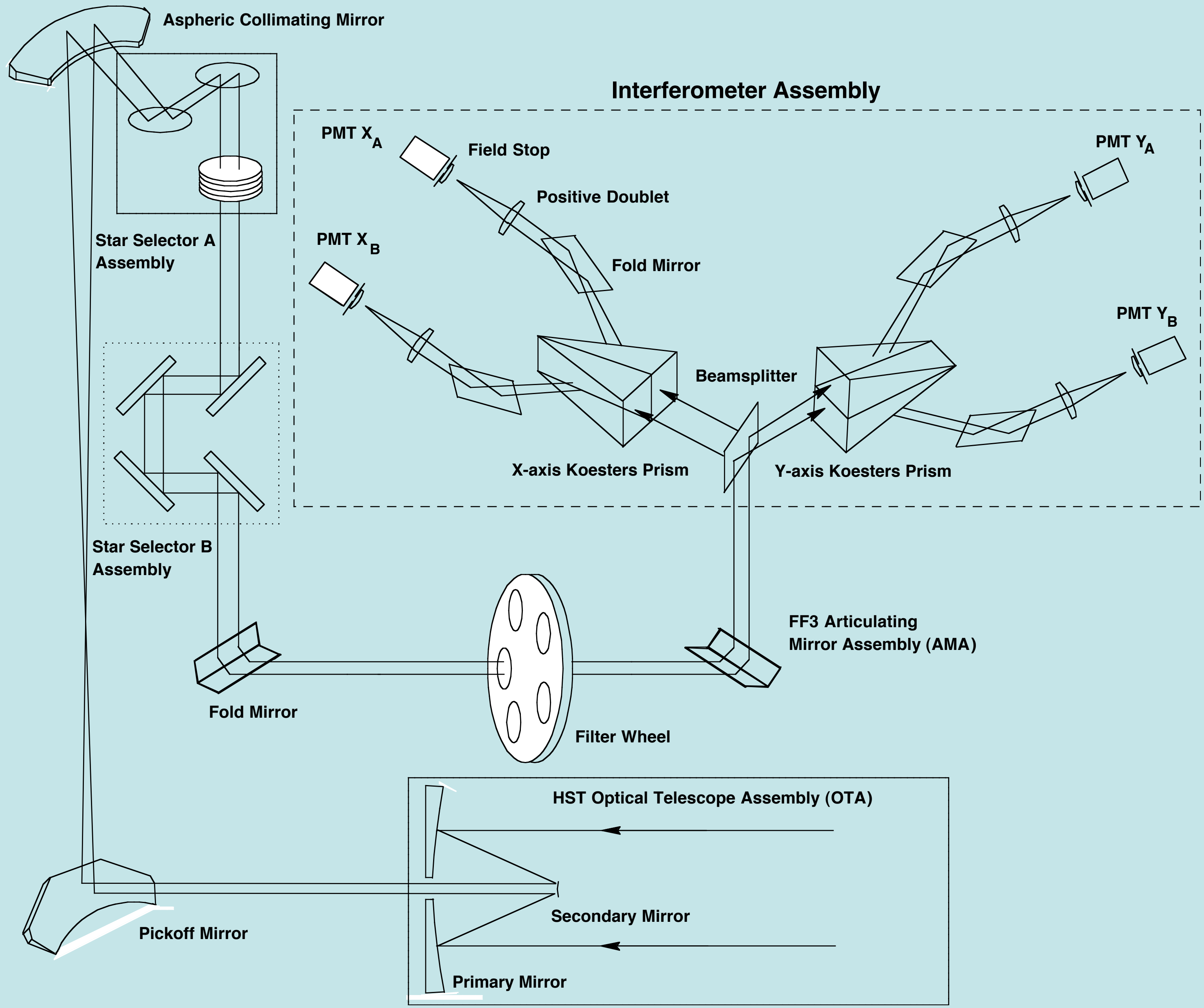


Technical details: Bradley, A., Abramowicz-Reed, L., Story, D., Benedict, G. F., and Jefferys, W., 1991, PASP, **103**, 317

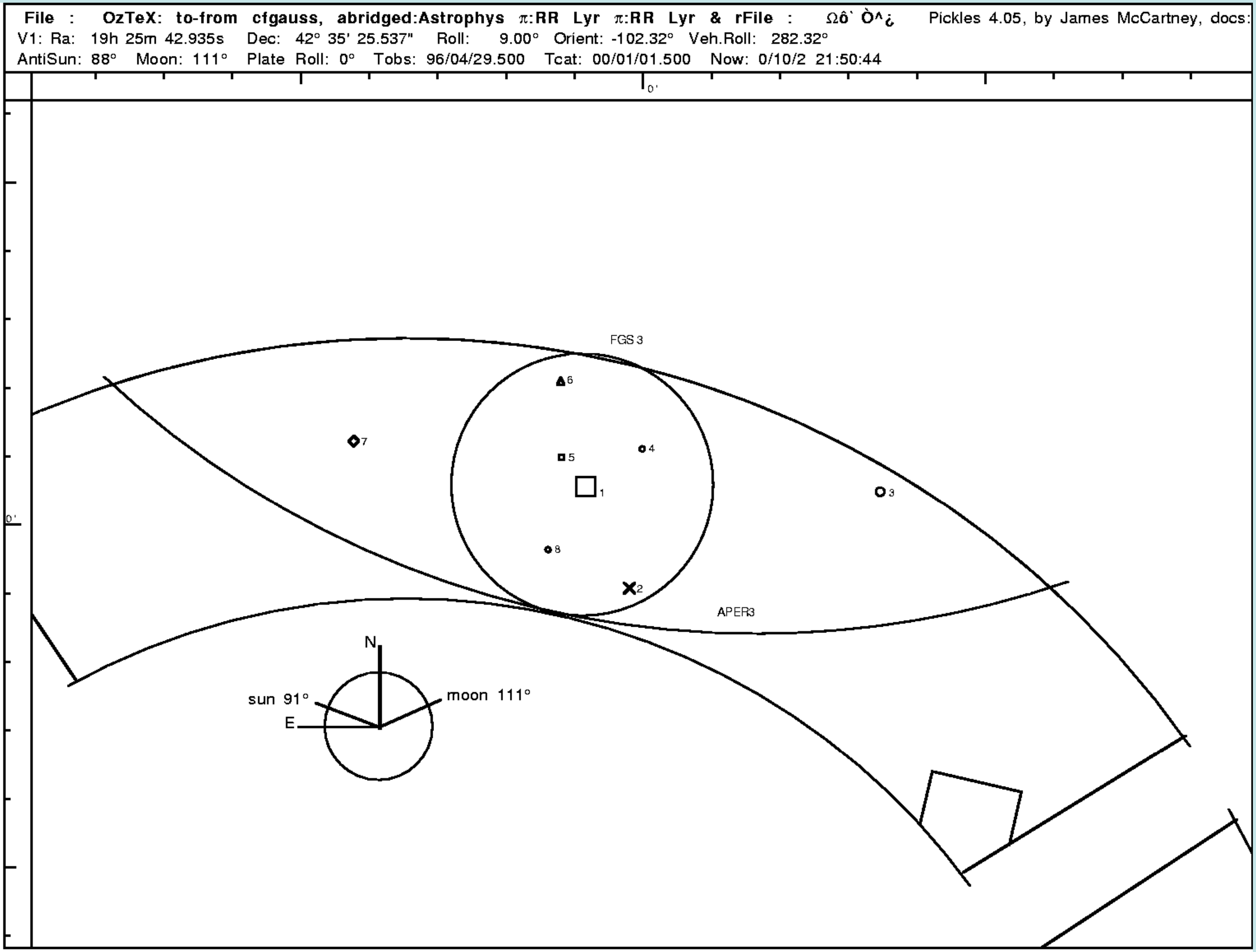
$S = (A-B)/(A+B)$

Fringe Tracking = where is the zero-crossing? Fringe Scanning = what is the morphology of the fringe?





Aspheric Collimating Mirror
Interferometer Assembly
PMT X_A
Field Stop
Positive Doublet
PMT Y_A
PMT X_B
Fold Mirror
Star Selector A Assembly
PMT Y_B
Beamsplitter
X-axis Koesters Prism
Y-axis Koesters Prism
Star Selector B Assembly
FF3 Articulating Mirror Assembly (AMA)
Fold Mirror
Filter Wheel
HST Optical Telescope Assembly (OTA)
Secondary Mirror
Pickoff Mirror
Primary Mirror


File : OzTeX: to-from cfgauss, abridged:Astrophys π:RR Lyr π:RR Lyr & rFile : Ωô` Ò^¿ Pickles 4.05, by James McCartney, docs:
V1: Ra: 19h 25m 42.935s Dec: 42° 35' 25.537" Roll: 9.00° Orient: -102.32° Veh.Roll: 282.32°
AntiSun: 88° Moon: 111° Plate Roll: 0° Tobs: 96/04/29.500 Tcat: 00/01/01.500 Now: 0/10/2 21:50:44
FGS 3
APER3
N
E
sun 91°
moon 111°

The Fringe and Astrometry

Calibration

Fringe Scanning - find a single star

Fringe Tracking - the OFAD

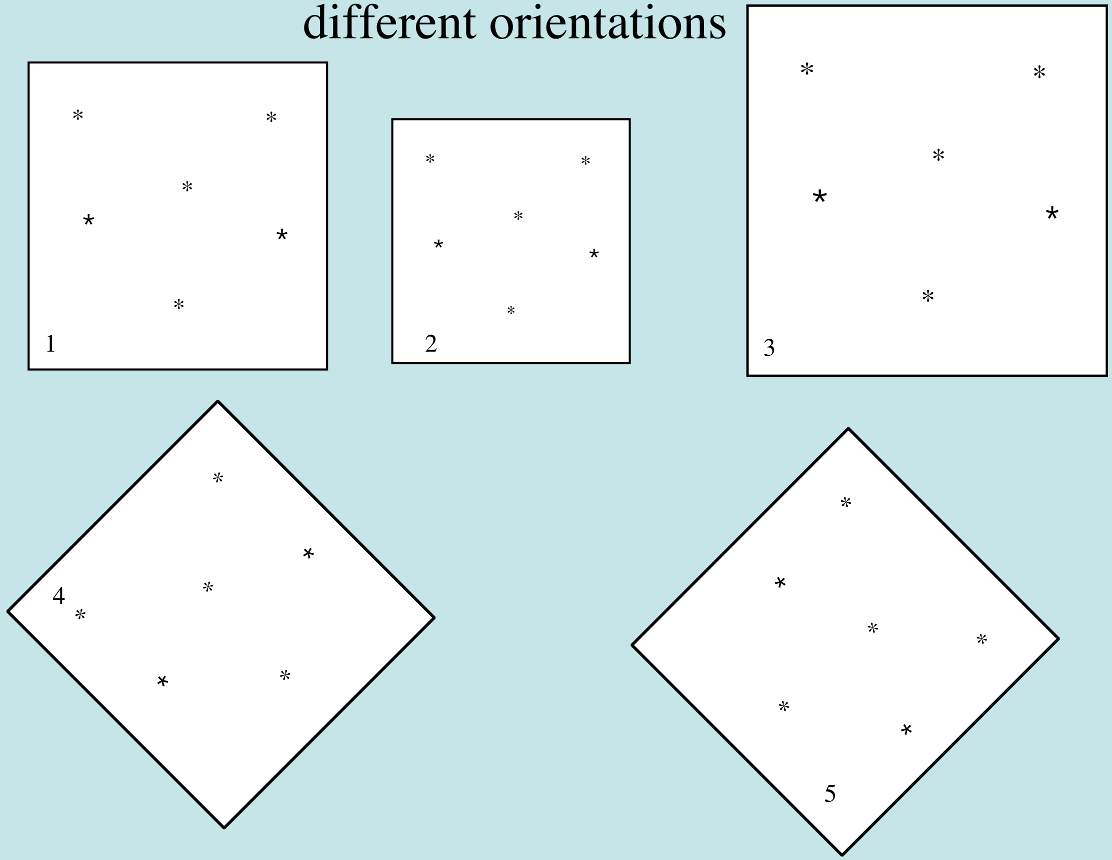
Jefferys. et al, 1993 in Proceedings Calibration Workshop at STScI November 15-17, 1993. ed by Blades and Osmer; Publisher, Space Telescope Science Institute, Baltimore, Maryland, 1993.

McArthur, B., Benedict, G. F., Jefferys, W. H. & Nelan, E.,1997, in 1997 HST Calibration Workshop with a New Generation of Instruments, ed by Casertanoet al, Baltimore, MD: Space Telescope Science Institute (1997)

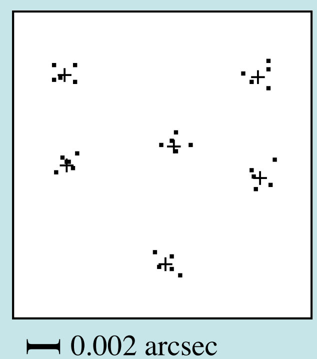
McArthur, B., Benedict, G.~F., Jefferys, W.~H., & Nelan, E. 2002, The 2002 HST Calibration Workshop:Proceedings of a Workshop held at the Space Telescope Science Institute, Baltimore, Maryland, October 17 and 18, 2002. Edited by Santiago Arribas, Anton Koekemoer, and Brad Whitmore.~Baltimore, MD: Space Telescope Science Institute, 2002., p.373

FGS Distortions more like a Lays regular potato chip than a Ruffles

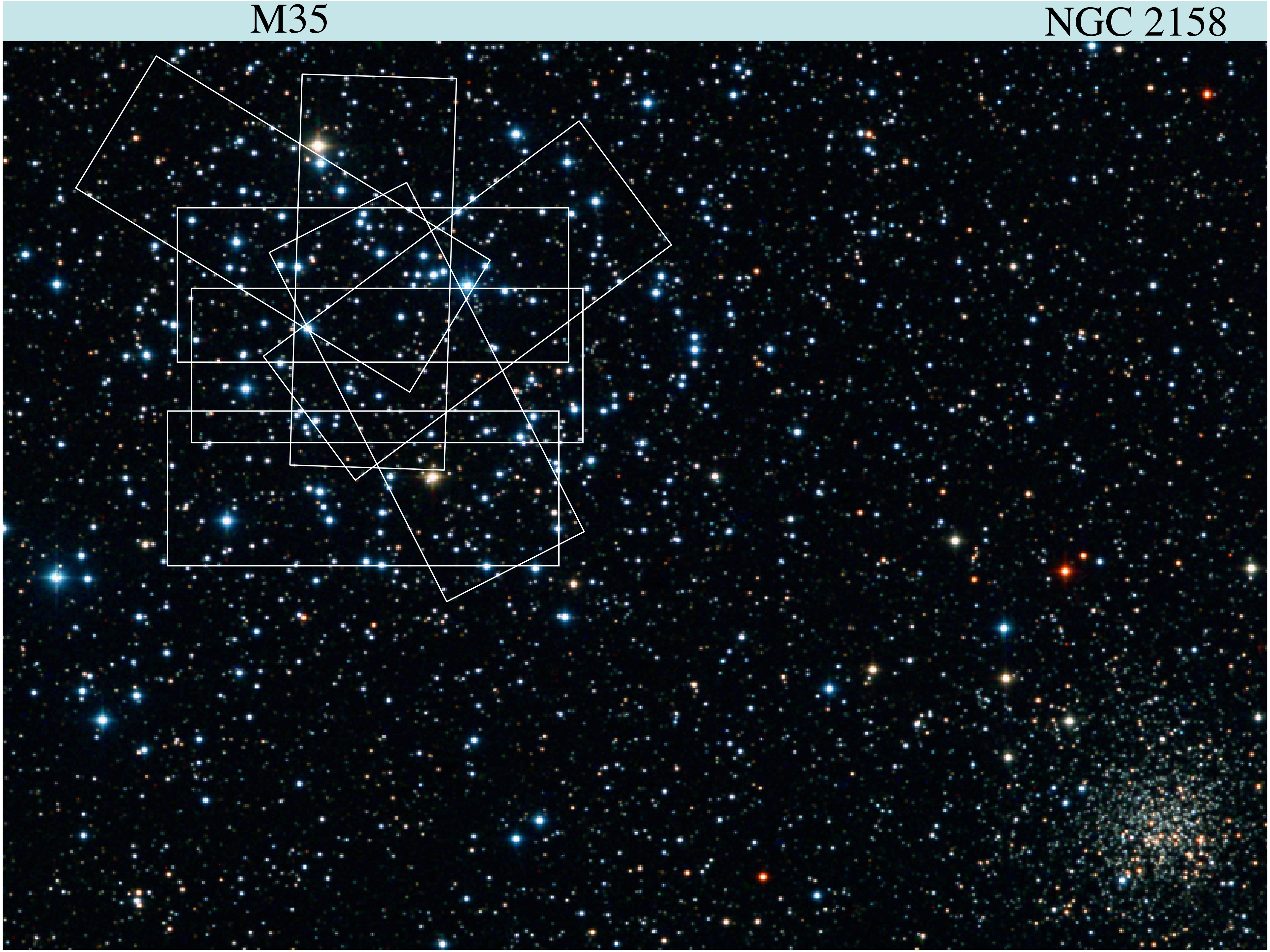
Astrometry, a simple example
5 "plates"
different scales
different orientations

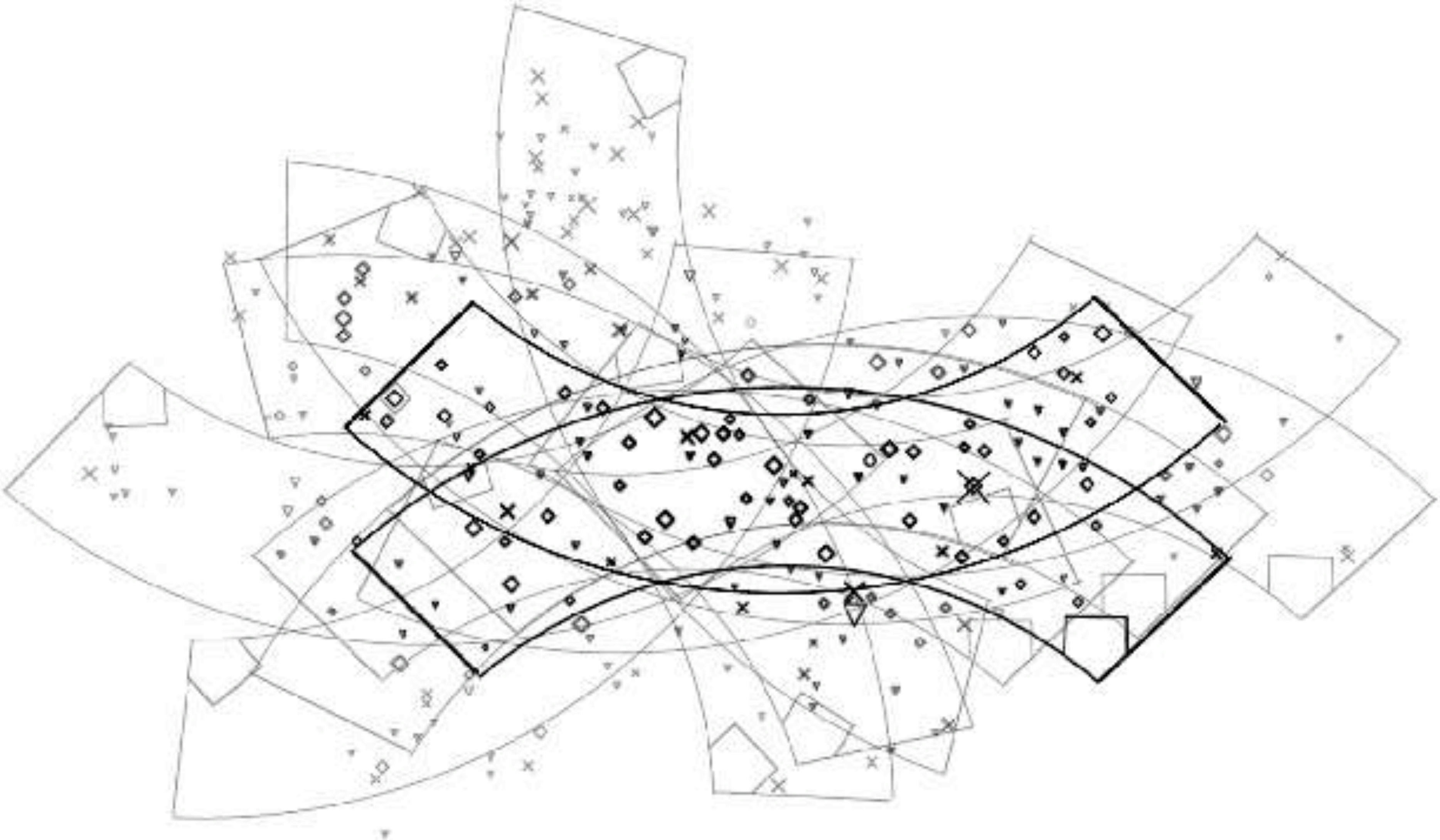


Result of Overlap
Solution to
Plate #1



Precision = standard deviation of the distribution of residuals (▪) from the model-derived positions (+)


M35
NGC 2158



Analysis

We employed GaussFit (Jefferys, Fitzpatrick, & McArthur 1987, Celestial Mechanics, 41, 39) to simultaneously estimate the relative star positions, the pointing and roll of the telescope during each orbit, the magnification of the telescope, the OFAD polynomial coefficients, and four parameters that describe the star selector optics inside the FGS (McArthur et al. Proc 1997. HST Calibration Workshop)

The Distortion Model

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

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

Why Not Calibrate Before Launch?

Gravity release, out-gassing of graphite-epoxy structures within the FGS, and periodic adjustments of the HST secondary mirror require that the final determination of the OFAD coefficients a_{ij} and b_{ij} be made by an on-orbit calibration.

Once calibrated, maintenance requires periodic re-observation of the field (LTSTABs)

How well did we do?

Calibration Residuals

Compare FGS 3 residuals with FGS 1r residuals. FGS 1r appears to calibrate better than FGS 3.

A Parallax for The Pleiades

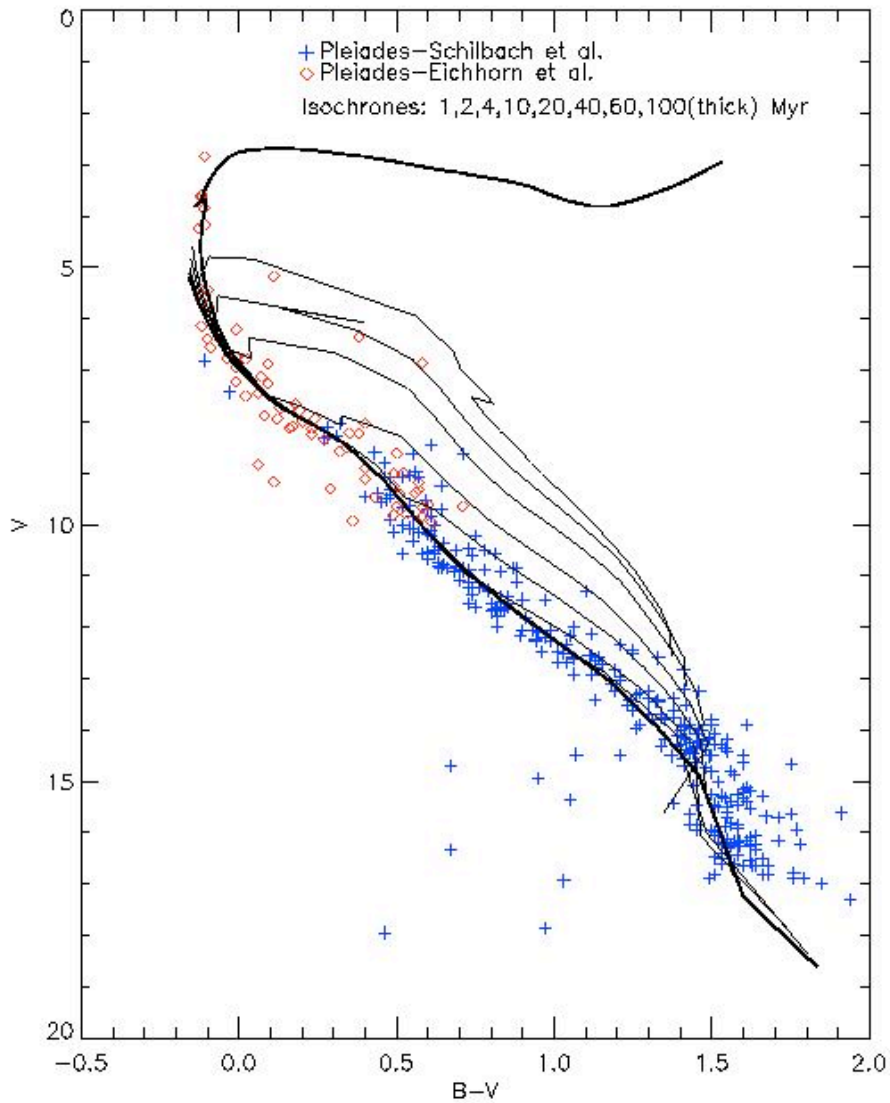
- Originally a fringe tracking and scanning project to obtain resolved orbits with which to derive dynamical parallaxes for three spectroscopic binary stars in The Pleiades
- Alas, FGS 1r could not resolve them
- What to do?

A Parallax for The Pleiades

- One field contains three stars whose membership in The Pleiades is supported by HIPPARCOS parallaxes and ground-based proper motions

- Project redefined as fringe tracking, relative astrometry only to obtain parallaxes

- Why do The Pleiades again?!?!?

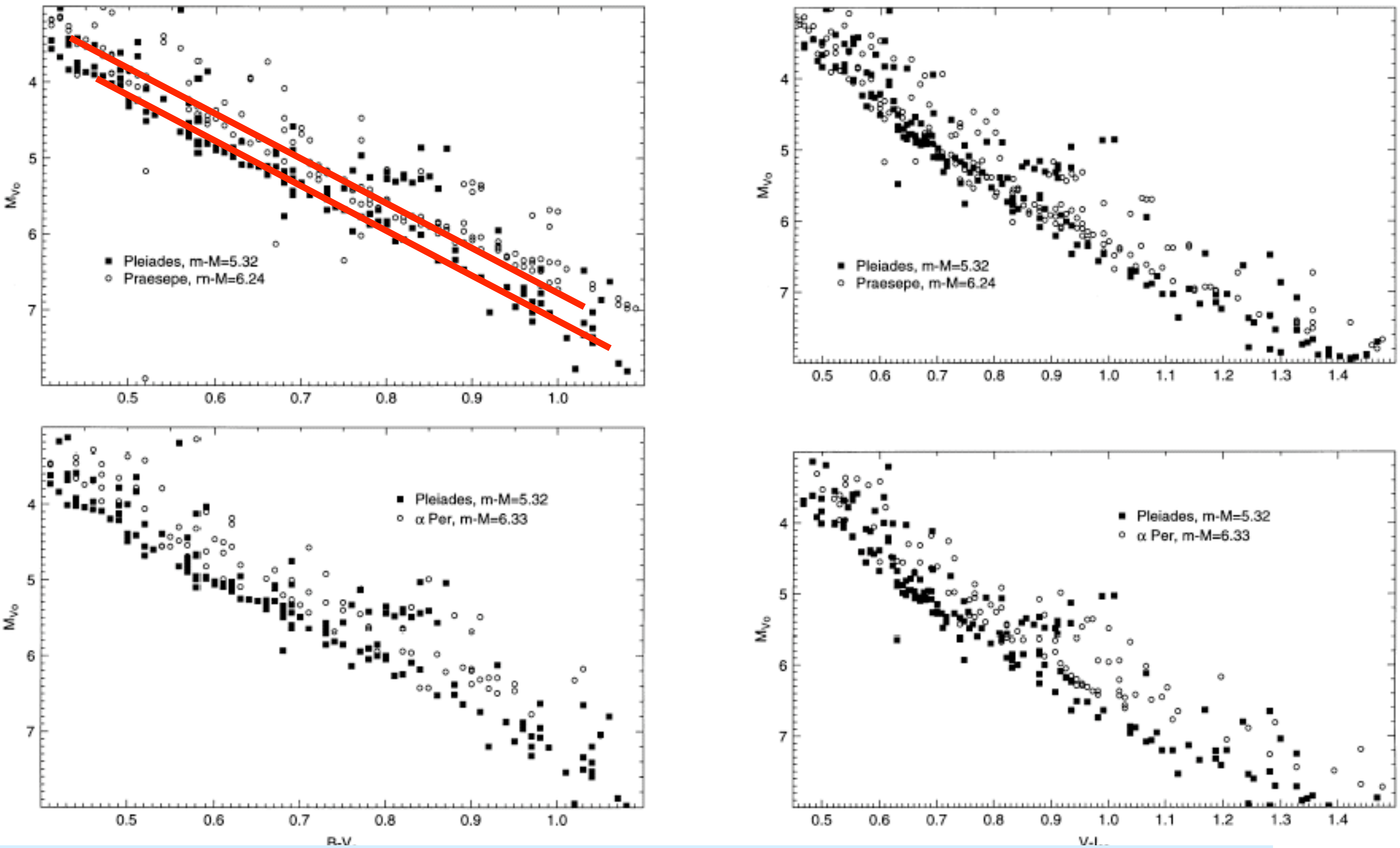


Who cares about the distance to The Pleiades?

The luminosity derived from stellar interiors models can only be compared to real stars with known distance.

Gl

PINSONNEAULT et al 1998, ApJ 504, 170



According to HIPPARCOS, the Pleiades and Praesepe MS are offset!

Recent reports of a re-analysis of the HIPPARCOS dataset

<u>A new reduction of the raw Hipparcos data</u>, van Leeuwen, F., & Fantino, E. 2005, ArXiv Astrophysics e-prints, arXiv:astro-ph/0505432

<u>Rights and wrongs of the Hipparcos data: A critical assessment of the Hipparcos catalogue</u>, van Leeuwen, F. 2005, ArXiv Astrophysics e-prints, arXiv:astro-ph/0505431

8. Conclusions

Above all, it should be recognised that the two data reduction consortia, in close collaboration with the ESA teams at ESOC and ESTEC, produced a Hipparcos catalogue with astrometric accuracies well exceeding the original aims and expectations of the mission, and did so under the very difficult conditions set by the orbit anomaly. Criticisms that have been expressed, concern the reliability of the catalogue for one or two small areas of the sky, where conditions for reconstructing the best possible astrometry may not have been sufficiently well understood during the data reductions. These aspects, and a range of other

The Pleiades Field

HST Observations

- Six observational epochs 2000 - 2003, each near maximum parallax factor
- 9 Reference stars
- 2-3 observations of each Pleiad at each epoch
- All observations taken with FGS 1r

The Astrometry Model

Modeled using GaussFit
(Jefferys, McArthur, & Fitzpatrick 1988, Cel Mech, 41, 39)

Model requires as input (with variances)

Lateral Color Calibration - FGS contains refractive optics. Position of a blue star is displaced relative to the position it would have, if it were red. Range for targets and reference stars is $-0.1 < B-V < 2$

B-V Color Indices - required for lateral color correction.

Reference Frame Absolute Parallaxes - from spectral types and photometry data. Required to obtain absolute parallax for the science target.

Proper motions - from UCAC2 (Zacharias *et al.* 2004, AJ 127, 3043) and Schilbach *et al.* (1995 A&A, 299, 696) catalogs

Solution process is allowed to adjust these input parameters (by amounts depending on the variances) to find the 'best' solution.

A Parallax for The Pleiades

The Model

$$x' = x + lcx(B - V)$$

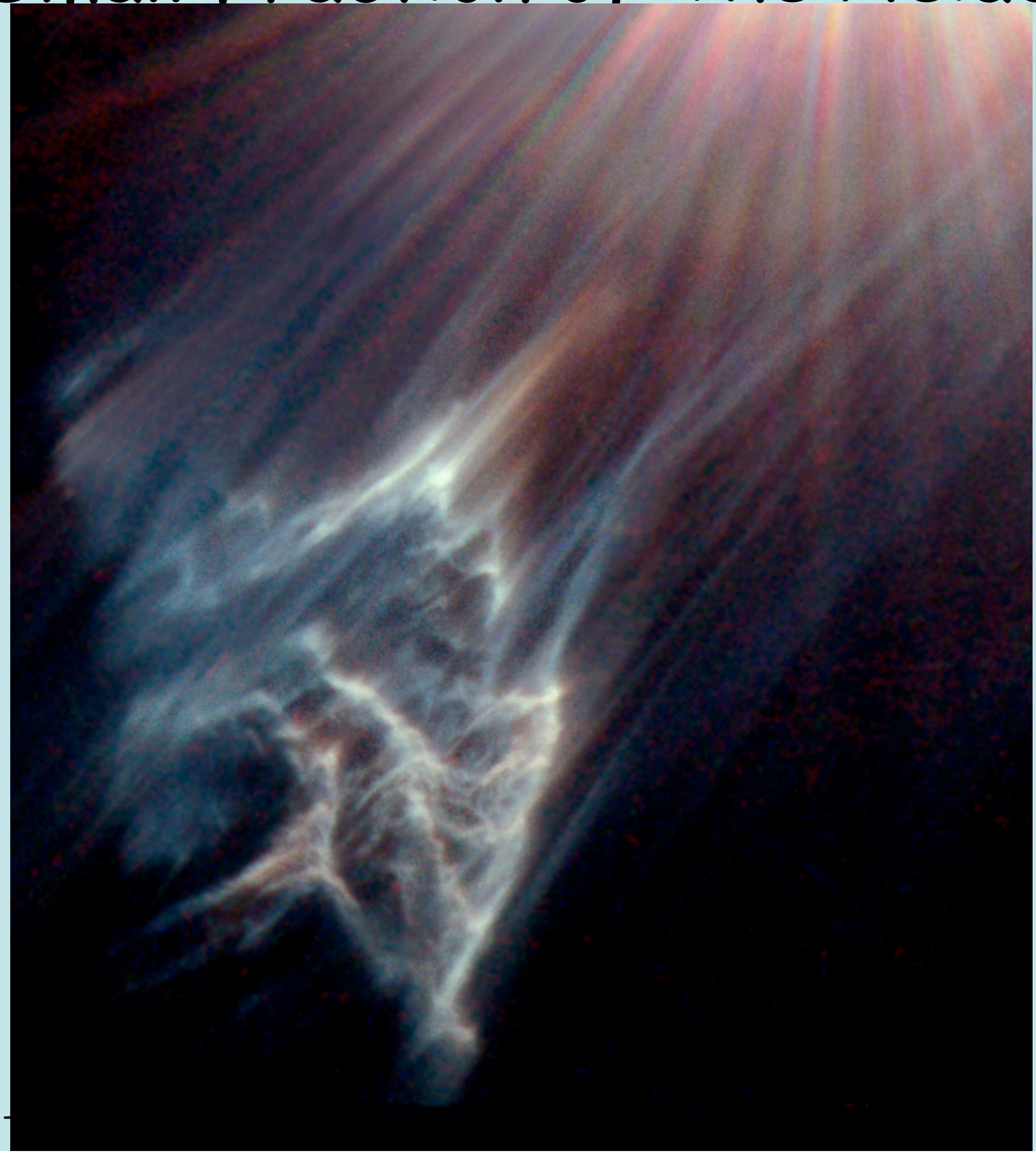
$$y' = y + lcy(B - V)$$

$$\xi = Ax' + By' + C - \mu_x \Delta t - P_\alpha \pi_x$$

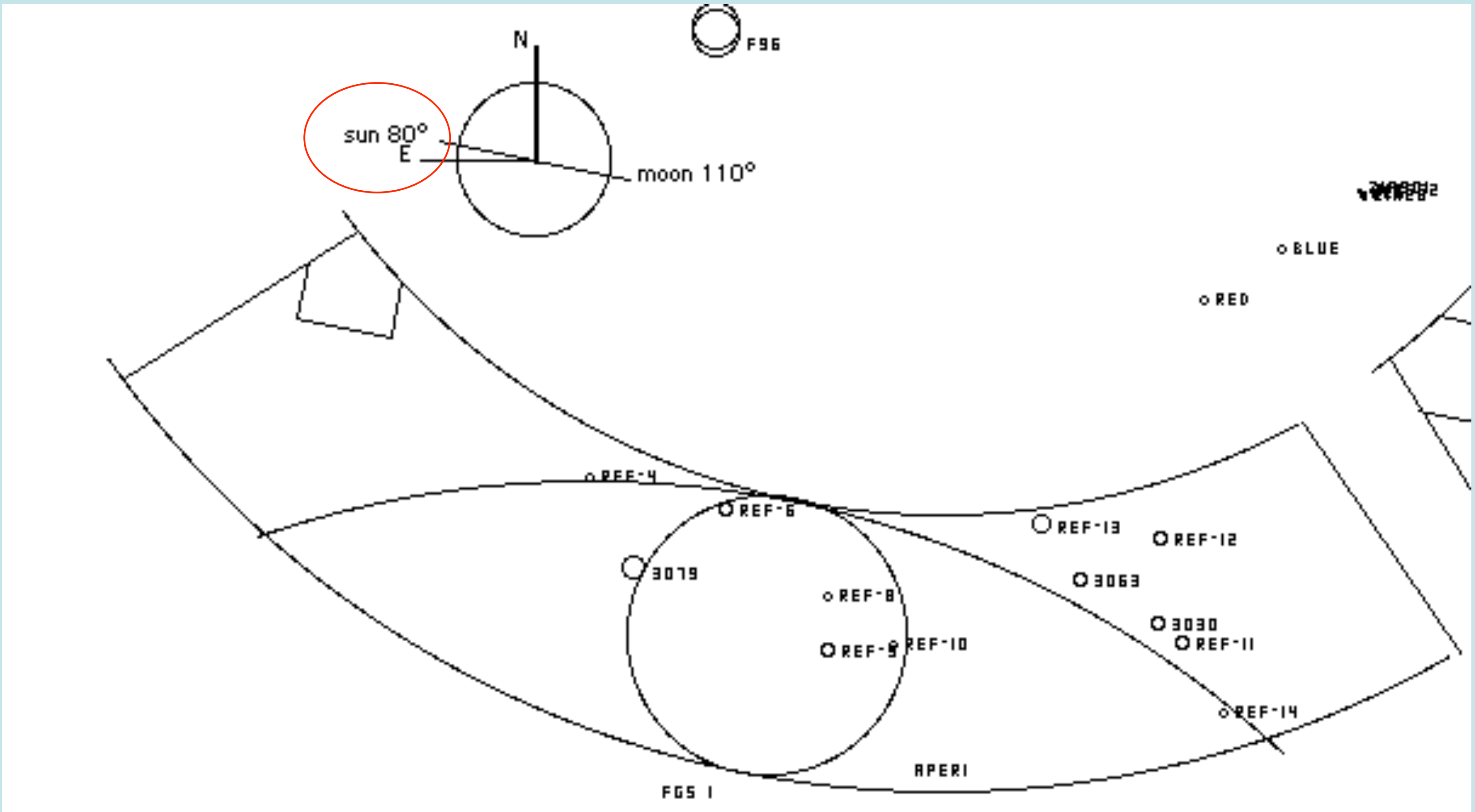
$$\eta = Dx' + Ey' + F - \mu_y \Delta t - P_\delta \pi_y$$

The Pleiades

A Small Fraction of The Pleiades



Our Field in The Pleiades



The Pleiades Reference Frame Absolute Parallaxes

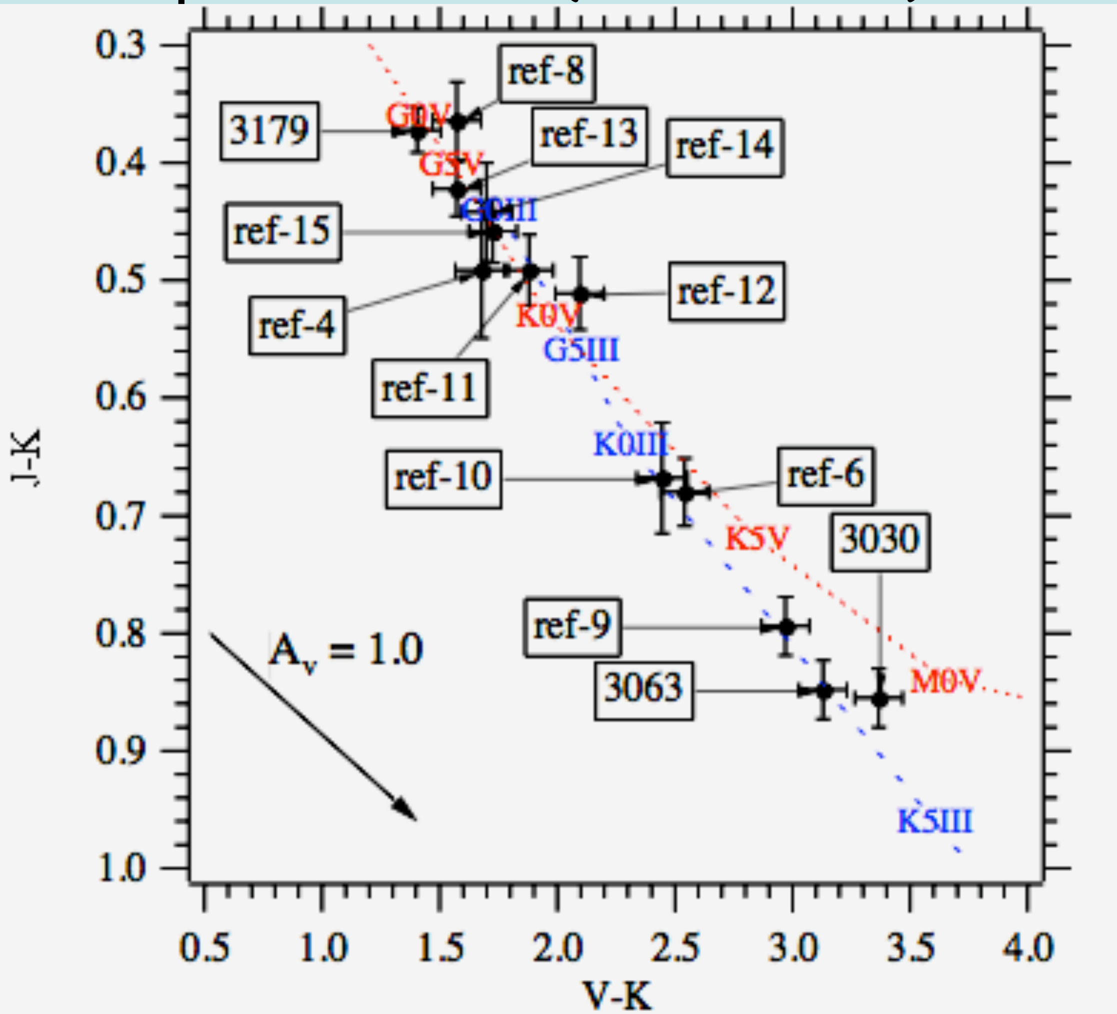
- Spectral types and luminosity classes from classification-dispersion spectra
- M_v and unreddened colors vs spectral type from AQ2000
- A_v from comparison of Sp.T. and colors
- Absolute Parallaxes

$$\pi_{abs} = 1/10^{(m-M+5-Av)/2.5}$$

Pleiades Reference Frame

Color-color diagrams

- Mapping to Sp. T. from Bessell & Brett 1988 (PASP, 100, 1134)
- 2MASS to SAAO from Carpenter 2001 (AJ, 121, 2851)
- J-K vs V-K



Another Estimate of Reference Star Luminosity Class

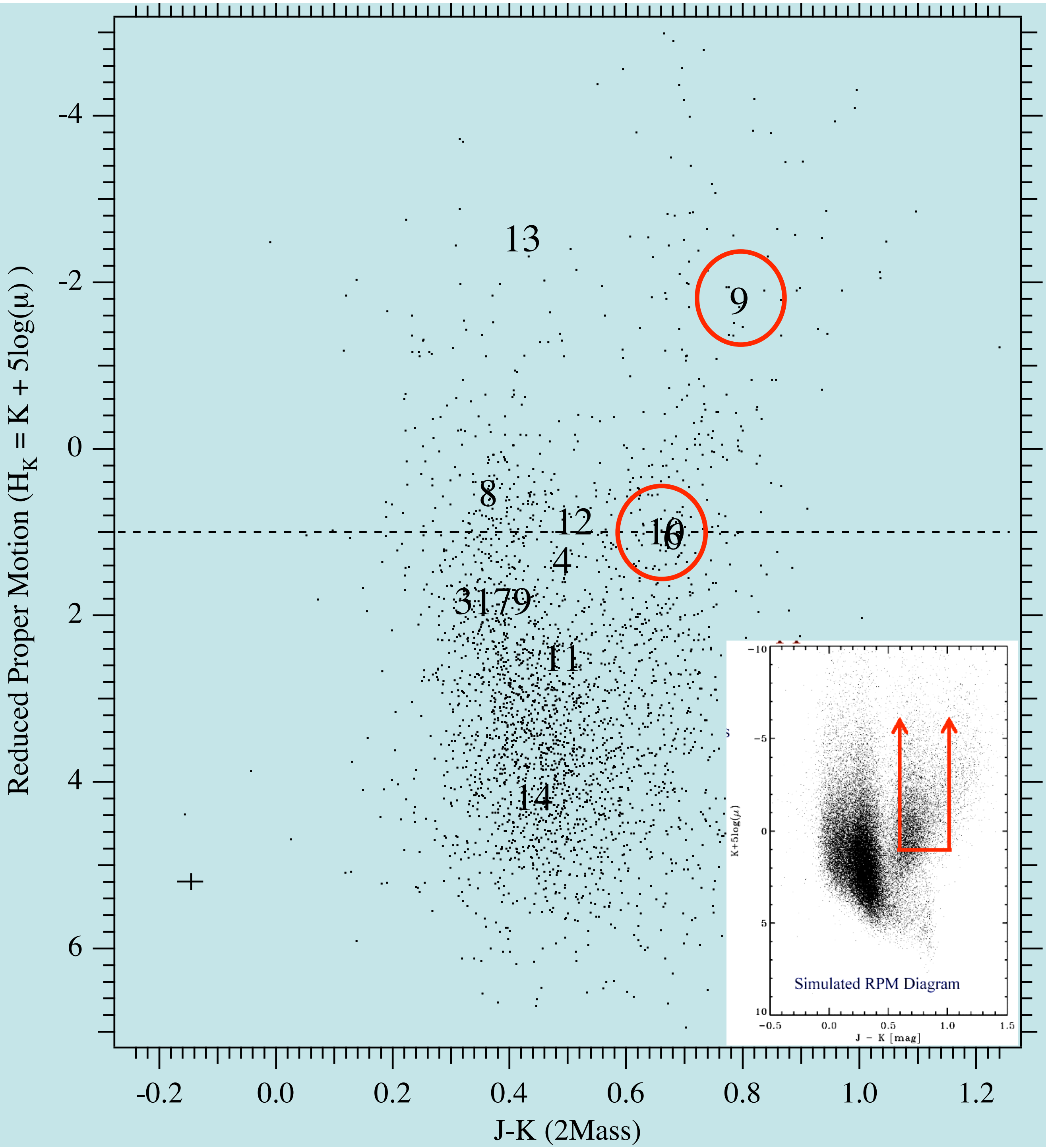
- Reduced Proper Motions (RPM)
  - RPM diagrams simulate color-magnitude diagrams
  - In general more distant stars have lower proper motions (μ) - μ used as a proxy for parallax

- Reduced Proper Motions (RPM)
  - Define

    $$H_K = K + 5\log(\mu) = M_K + 5\log(V_t/4.74)$$

  - If all stars had the same transverse velocity (V_t), RPM diagram would be identical to CMD (with vertical offset)

5542 stars within 1° of Pleiades center



Why 9 is III, and 6 and 10 are IV

Input Reference Frame Parallaxes

Table 4. Astrometric Reference Star Spectral Classifications and Spectrophotometric Parallaxes

ID	Sp. T.	V	M_V	A_V	m-M	π_{abs}(mas)
ref-4	G5V	15.68	5.1	0.14	10.6±0.7	0. 8±0.3
ref-6	K1IV	14.5	3.4	0.23	11.2±2	0.06±0.6
ref-8	G3V	14.48	4.8	0.14	9.7±0.7	1.2±0.4
ref-9	K2III	13.61	0.5	0.23	13.1±0.7	0. 3±0.1
ref-10	K1IV	15.85	3.4	0.23	12.5±2	0. 4±0.3
ref-11	G8V	14.63	5.6	0.14	9.1±0.7	1.7±0.5
ref-12	K0V	14.24	5.9	0.14	8.3±0.7	2.3±0.7
ref-13	G3V	12.14	4.8	0.14	7.3±0.7	3.66±1.2
ref-14	G5V	15.48	5.1	0.14	10.4±0.7	0. 9±0.3

$\langle\pi_{abs}\rangle = 1.3$ mas

Compare with Yale Parallax Catalog (1995)
Galaxy model which predicts $\langle\pi_{abs}\rangle = 1.0$ mas
for $\langle V\rangle = 14.5$ and $b = -23°$

One Last Model ‘Soft’ Constraint

An estimated depth of the Pleiades cluster

Depth Constraint

solve for a line of sight dispersion in the parallaxes of the three Pleiades members with the 'observation' derived from the 1-σ angular extent of the Pleiades (1°, from Adams et al. 2001) and an assumption of spherical symmetry.

From this we infer

1-σ dispersion in distance in this group is 1°/radian =1.7%.

1-σ dispersion in the parallax difference between Pleiades members is

$\Delta\pi$ = 1.7% x $\sqrt{2}$ x 7.7 mas = 0.20 mas (--> 6pc)

where we have here temporarily adopted a parallax of the Pleiades, $\langle\pi\rangle$ = 7.7 mas.

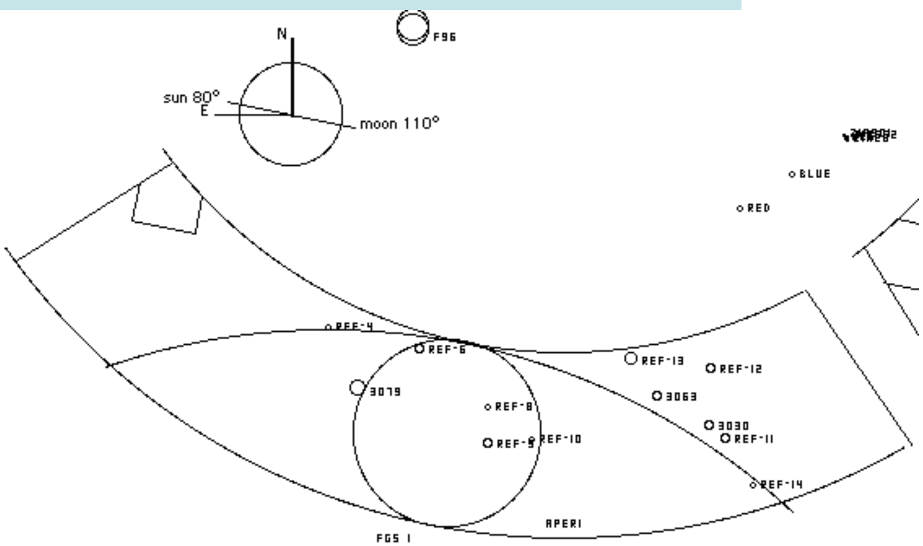
The parallax dispersion among targets 3030, 3179, and 3063 becomes an observation with associated error fed to our model, an observation used to estimate the parallax dispersion among the three stars, while solving for their parallaxes.

Loosening the cluster 1-σ dispersion to 2° ($\Delta\pi$ = 0.38 mas) and/or using the HIPPARCOS Pleiades parallax had no effect on the final average parallax.

No parallax measurements were used as direct priors.

•High quality astrometry?

•Not too shabby.



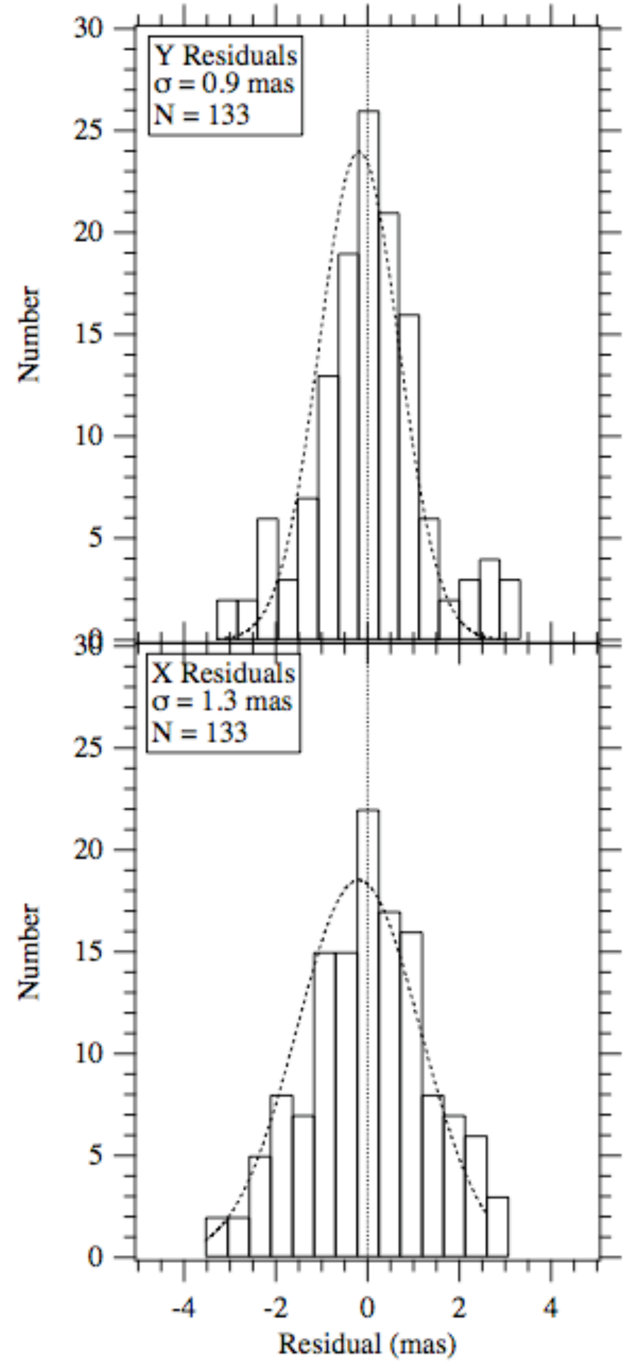


Table 7. Pleiades and Reference Star Parallaxes and Transverse Velocities

ID	μ[a] mas yr^{-1}	π_{abs}[b] mas	V_t[c] km s^{-1}
3179	50.36±0.40	7.45±0.16	32
3063	45.30±0.53	7.43±0.16	29
3030	43.20±0.48	7.41±0.18	28

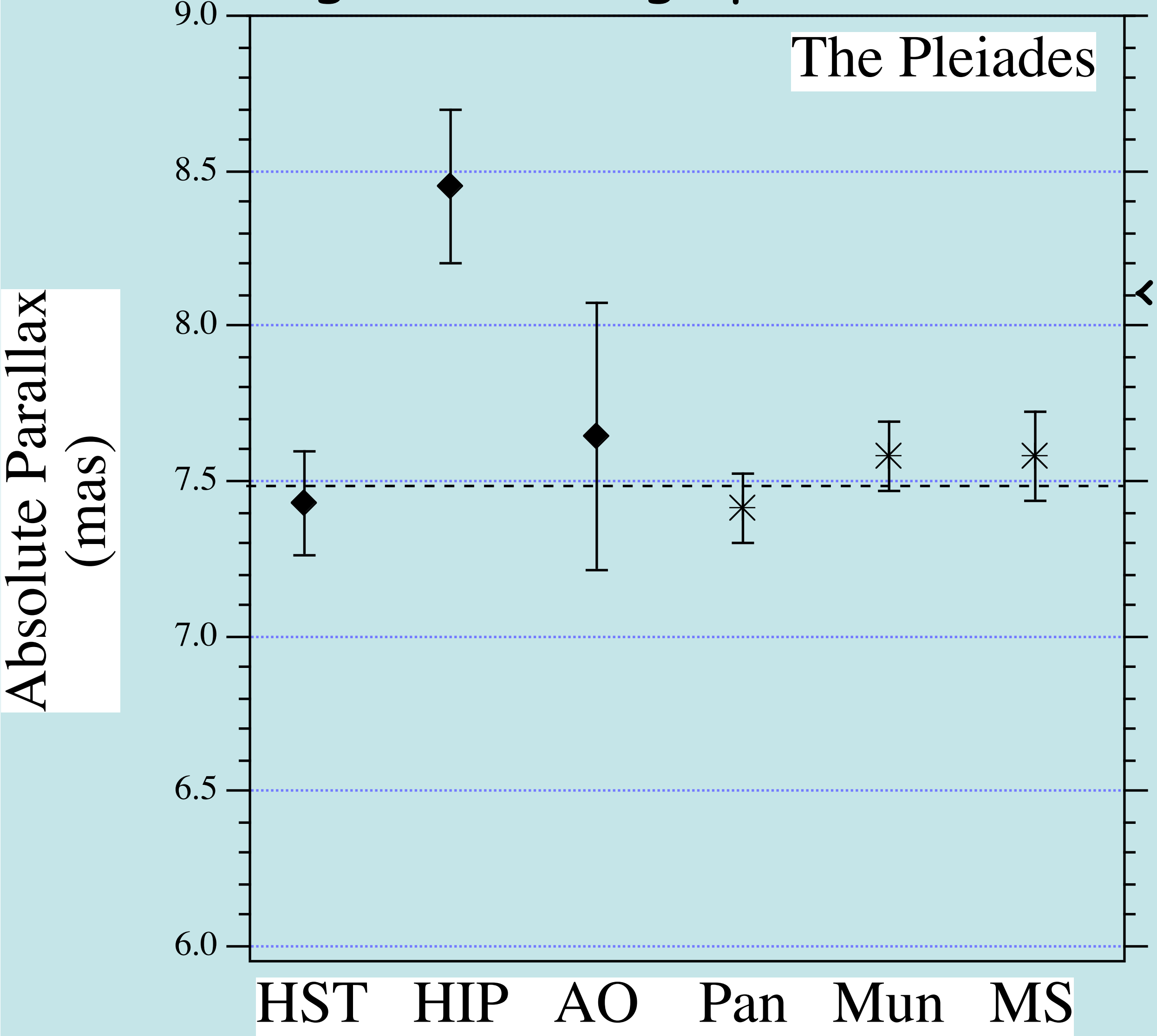
π_{abs} = 7.43 ± 0.17 mas

D = 134.6 ± 3.1 pc

Can't reduce error by stating the standard deviation of the mean because of the cluster depth constraint

The Distance Modulus of The Pleiades

Weighted average parallax from HST, Pan, Mun, AO



$\langle \pi_{abs} \rangle = 7.49 \pm 0.07$ mas

$D = 133.5 \pm 1.2$ pc

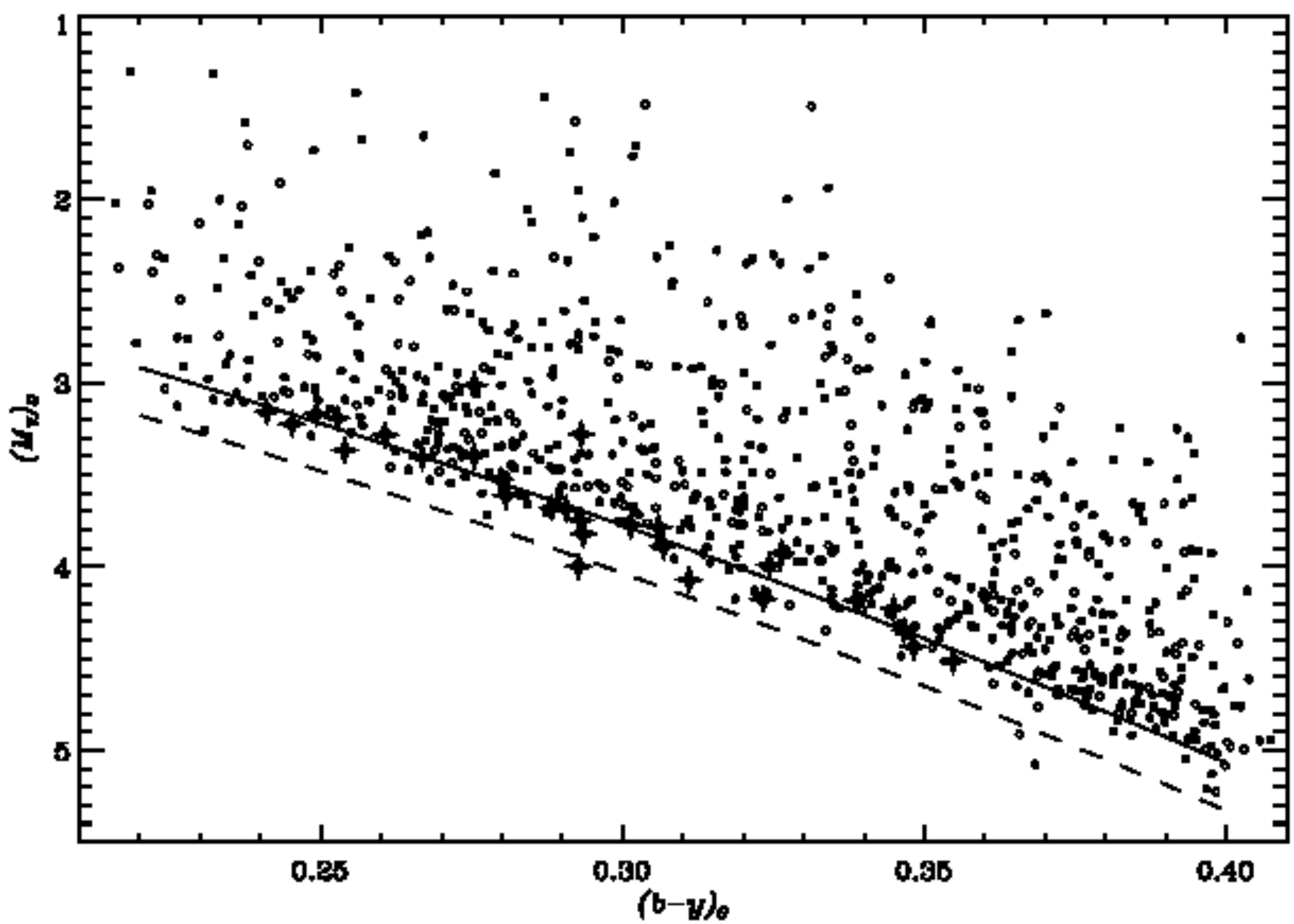
Munari et al. 2004
A&A, 418L, 31
SB2, eclipsing

Pan et al. 2004
Nature, 427, 326

Distance Modulus (π_{abs}) now $(m-M)_0$ = 5.65 ± 0.03. Stellar interiors models are once again consistent with observation, and ZAMS from field stars agrees with the Pleiades

D. Stello and P. E. Nissen: The problem of the Pleiades distance

is resolved



GF

Are our parallaxes any good?

Comparing Parallaxes

	HST		HIPPARCOS	
Prox Cen	769.7 ±	0.3 mas	772.3 ±	2.4 mas
Barnard's Star	545.5	0.3	549.3	1.6
Feige 24	14.6	0.4	13.4	3.6
Gl 748 AB	98.0	0.4	98.6	2.7
RR Lyr	3.60	0.20	4.38	0.6
δ Cep	3.66	0.15	3.32	0.56
HD 213307	3.65	0.15	3.43	0.64
Gl 876	214.6	0.2	212.7	2.1
Pleiades	7.43	0.17	8.45	0.25

Precision looks good

$\langle\sigma_\pi\rangle$ = 0.26 mas

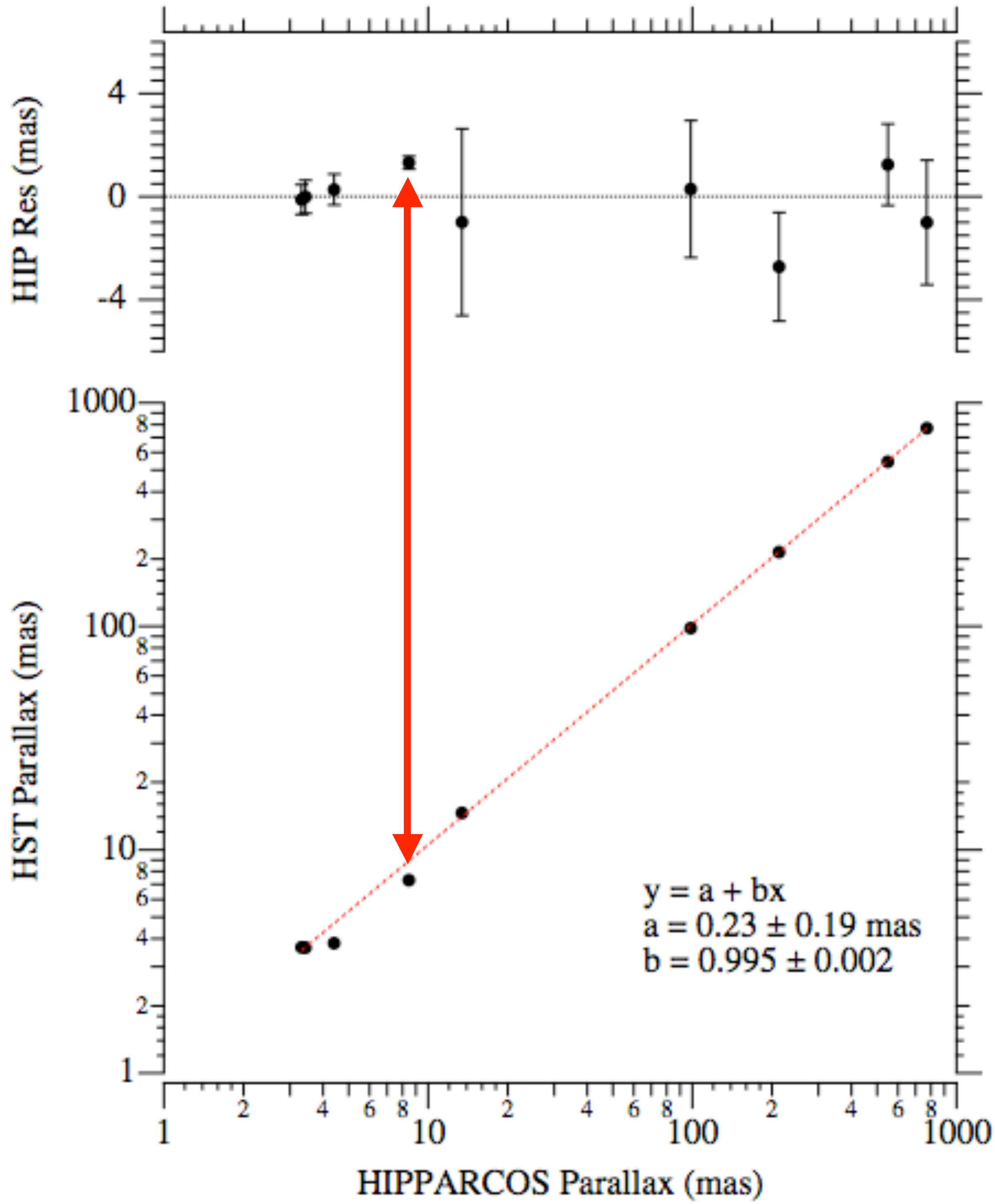
Accuracy looks good, too.

Impartial regression line excludes Pleiades, yielding

$\chi^2_{red} = 0.265$

With Pleiades

$\chi^2_{red} = 0.551$



Again, SIM could and should do FAR better.