We present absolute parallaxes and proper motions for seven members of the Hyades open cluster, pre-selected to lie in the core of the cluster. Our data come from archival astrometric data from fine guidance sensor (FGS) 3 and newer data for three Hyads from FGS 1r, both white-light interferometers on the Hubble Space Telescope (HST). We obtain member parallaxes from six individual FGS fields and use the field containing van Altena 622 and van Altena 627 (= HIP 21138) as an example. Proper motions, spectral classifications, and VJHK photometry of the stars comprising the astrometric reference frames provide spectrophotometric estimates of reference star absolute parallaxes. Introducing these into our model as observations with error, we determine absolute parallaxes for each Hyad. The parallax of vA 627 is significantly improved by including a perturbation orbit for this previously known spectroscopic binary, now an astrometric binary. Compared to our original (1997) determinations, a combination of new data, updated calibration, and improved analysis lowered the individual parallax errors by an average factor of 4.5. Comparing parallaxes of the four stars contained in the Hipparcos catalog, we obtain an average factor of 11 times improvement with the HST. With these new results, we also have better agreement with Hipparcos for the four stars in common. These new parallaxes provide an average distance for these seven members, \( D = 47.5 \text{ pc} \), for the core, \( \pm 1\sigma \) dispersion depth of 3.6 pc, and a minimum depth from individual components of 16.0 \( \pm 0.9 \text{ pc} \). Absolute magnitudes for each member are compared to established main sequences with excellent agreement. We obtain a weighted average distance modulus for the core of the Hyades of \( m - M = 3.376 \pm 0.01 \text{, a value close to the previous Hipparcos values,} m - M = 3.33 \pm 0.02 \).
parallaxes (Benedict & McArthur 2005). This approach has been applied successfully, resulting in parallax results in many papers (Benedict et al. 1999, 2000a, 2000b, 2002a, 2002b, 2003, 2006; Beuermann et al. 2003, 2004; Harrison et al. 2000; McArthur et al. 1999, 2001, 2010; Roelofs et al. 2007; Soderblom et al. 2005), including parallaxes used for a recent recalibration of the Leavitt Law, the Galactic Cepheid period–luminosity relation (Benedict et al. 2007a, 2007b). We report here on applying the improvements to these archival (and newer) FGS data. This effort has resulted in far more accurate and precise parallaxes for seven Hyads.

Our reduction and analysis of these data is basically the same as for our previous work on galactic Cepheids (Benedict et al. 2007a, 2007b). Our extensive investigation of the astrometric reference stars provides an independent estimation of the line-of-sight extinction as a function of distance for all reference stars, a significant contributor to the uncertainty in their distances. Using vA 622/627 as an example throughout, we present the results of spectrophotometry of the astrometric reference stars, information required to derive absolute parallaxes from relative measurements (Section 3), and derive an absolute parallax for each Hyad (Section 4). We discuss some astrophysical consequences of these new, more precise distances (primarily the estimation of an independent distance modulus, Section 5) and summarize our findings in Section 6.

Bradley et al. (1991) and Nelan (2007) provide an overview of the FGS instrument and Benedict et al. (1999, 2002c, 2007b) and Harrison et al. (2004) describe the fringe tracking (POS) mode astrometric capabilities of an FGS, along with the data acquisition and reduction strategies used in the present study. We time-tag all data with a modified Julian Date of mJD = JD − 2,400,000.5.

2. OBSERVATIONS AND DATA REDUCTION

From the HST archive we obtained 40 orbits of Guaranteed Time Observation FGS fringe tracking data secured by the HST Astrometry Science team using FGS 3. These data contain FGS observations of a total of seven science targets (confirmed members of the Hyades open cluster listed in Table 1) and 36 reference stars. These data were previously analyzed and resulted in parallaxes for these Hyads published in van Altena et al. (1997b). We have also secured additional, more recent observations with FGS 1r for three of the Hyads.

Using the vA 622, vA 627 field as an example, Figure 1 shows the distribution on the sky of the Hyads and their reference stars taken from the Digitized Sky Survey, via Aladin. For the vA 622/627 seven sets of astrometric data were acquired with FGS 3 and five sets with FGS 1r the aggregate spanning 16 years, for a total of 164 measurements of vA 622, 627, and reference stars. Each data set required approximately 33 minutes of spacecraft time. The data were reduced and calibrated as detailed in Benedict et al. (2002b, 2002c, 2007b) and McArthur et al. (2001)). At each epoch we measured reference stars and the target multiple times to correct for intra-orbit drift of the type seen in the cross-filter calibration data shown in Figure 1 of Benedict et al. (2002c).

Table 2 lists the epochs of observation for all six of our fields. Ideally (cf. Benedict et al. 2007a, 2007b), we obtain observations at each of the two maximum parallax factors4 at two distinct spacecraft roll values imposed by the requirement that HST roll to provide thermal control of a camera in the radial bay and to keep its solar panels fully illuminated throughout the year. This roll constraint generally imposes alternate orientations at each time of maximum positive or negative parallax factor over a typical two-year campaign. A few observations at intermediate or low parallax factors usually allow a clean separation of parallax and proper motion signatures. Unfortunately, we have intermediate observations for only three of our prime targets, vA 548, vA 622, and vA 627. For these three fields we were able to take advantage of science instrument command and data handling computer problems that took the only other then-operational science instrument (WFPC2) off-line in late 2008. This situation opened a floodgate of FGS proposals, temporarily rendering HST nearly an "all astrometry, all the time" mission. Consequently, we obtained additional epochs well separated in time from the original. This permitted a significantly better determination of relative proper motion for these targets (and for the perturbation orbit of vA 627, Section 4.1.2). For the other Hyad fields two-gyro guiding5 constraints did not permit re-observation.

3. SPECTROPHOTOMETRIC ABSOLUTE PARALLAXES

OF THE ASTROMETRIC REFERENCE STARS

Because the parallax determined for the Hyads will be measured with respect to reference frame stars which have their own parallaxes, we must either apply a statistically derived correction from relative to absolute parallax (van Altena et al. 1995, hereafter YPC95) or estimate the absolute parallaxes of the reference frame stars listed in Table 3. In principle, the colors, spectral type, and luminosity class of a star can be used to estimate the absolute magnitude, $M_V$, and $V$-band absorption, $A_V$. The absolute parallax is then simply

$$
\pi_{\text{abs}} = 10^{-\left(V - M_V + 5 - A_V\right)/5}.
$$

(1)

The luminosity class is generally more difficult to estimate than the spectral type (temperature class). However, the derived absolute magnitudes are critically dependent on the luminosity class. As a consequence, we appeal to reduced proper motions in an attempt to confirm the luminosity classes (see below).

3.1. Broadband Photometry

Our bandpasses for reference star photometry include $BV$ (CCD photometry from a 1 m telescope at New Mexico State University) and $JHK$ (from the Two Micron All Sky Survey

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4 Parallax factors are projections along R.A. and decl. of the Earth’s orbit about the barycenter of the solar system, normalized to unity.

5 HST has a full compliment of six rate gyros, two per axis, that provide coarse pointing control. By the time these observations were in progress, three of the gyros had failed. HST can point with only two. To "bank" a gyro in anticipation of a future failure, NASA decided to go to two-gyro pointing as standard operating procedure.
Figure 1. Finding charts for subject Hyads and astrometric reference stars. Labels are immediately to the right of each star. Where scales are not indicated, the box size is 13′ × 13′, the north is at the top, and the east is to the left. (A color version of this figure is available in the online journal.)

(2MASS)6. Table 3 lists the visible and infrared photometry for all reference stars used in this study.

3.2. Spectroscopy, Luminosity Class-sensitive Photometry, and Reduced Proper Motion

The spectra from which we estimated spectral type and luminosity class come from the New Mexico State University (NMSU) Apache Point Observatory.7 The dispersion was 0.61 Å pixel−1 with wavelength coverage 4101–4905 Å, yielding R ~ 3700. Classifications used a combination of template matching and line ratios. The brightest targets had about 1500 counts above sky per pixel, or signal-to-noise ratio (S/N) ~ 40, while the faintest targets had about 400 counts pixel−1 (S/N ~ 20). The spectral types for the higher S/N stars are within ±1 subclass.

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6 The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology.

7 The Apache Point Observatory 3.5 m telescope is owned and operated by the Astrophysical Research Consortium.
Table 2
Log of Observations

| Set | mJD | $P_a$ | $P_b$ |
|-----|-----|------|------|
| 1   | 49252.9445 | 0.96275 | 0.12569 |
| 2   | 49407.2201 | -1.02765 | -0.16291 |
| 3   | 49601.8487 | 1.03632 | 0.15393 |
| 4   | 49768.0651 | -1.02281 | -0.16692 |
| 5   | 49943.0840 | 1.00037 | 0.17376 |
| 6   | 50128.2371 | -1.00929 | -0.17027 |
| 7   | 50331.9210 | 1.03261 | 0.15368 |

Table 3
Hyad Astrometric Reference Star Photometry, Spectral Classifications, and Estimated Spectrophotometric Parallaxes

| ID | V | $B - V$ | $V - K$ | $K - J$ | SpT | $M_V$ | $A_V$ | $\pi_{PAR}$ (mas) |
|----|---|--------|--------|--------|-----|-----|-----|-----------------|
| 50 | 15.07 | 1.25 | 2.97 | 0.66 | K1V | 6.2 | 1.1 | 2.87 ± 0.7 |
| 51 | 15.69 | 0.94 | 2.33 | 0.49 | G1V | 4.5 | 1.0 | 0.9 ± 0.2 |
| 52 | 14.67 | 1.33 | 3.29 | 0.77 | K2V | 6.2 | 1.4 | 3.8 ± 0.9 |
| 53 | 15.57 | 0.84 | 2.11 | 0.42 | F4V | 3.3 | 1.3 | 0.7 ± 0.2 |
| 54 | 16.11 | 1.23 | 2.86 | 0.65 | K2V | 6.2 | 1.1 | 1.7 ± 0.4 |
| 55 | 15.40 | 0.85 | 1.98 | 0.40 | F4V | 3.3 | 1.4 | 0.7 ± 0.2 |

We employ the technique of reduced proper motions to provide a confirmation of the reference star estimated luminosity class listed in Table 3. We obtain preliminary proper motions ($\mu$) from UCAC3 (Zacharias et al. 2010) and/or PPMXL (Roester et al. 2010), and $K, J$ photometry from 2MASS for a 1 deg$^2$ field centered on each Hyad. With final proper motions from our astrometric solution (Section 4.1) we plot Figure 2, which shows $H_K = K + 5 \log(\mu)$ versus $(J - K)$ color index for 10,000 stars. If all stars had the same transverse velocities, Figure 2 would be equivalent to an H-R diagram. The Hyads and reference stars are plotted as ID numbers from Table 3. Errors in $H_K$, calculated using our final proper motions, are now ~ 0.3 mag.

3.3. Interstellar Extinction

To determine interstellar extinction we first plot these stars on several color–color diagrams. A comparison of the relationships
between spectral type and intrinsic color against those we measured provides an estimate of reddening. Figure 3 contains a $J - K$ versus $V - K$ color–color diagram and reddening vector for $A_V = 1.0$. Also plotted are mappings between spectral type and luminosity class V and III from Bessell & Brett (1988) and (Cox 2000, hereafter AQ2000). Figure 3, and similar plots for the other measured colors, along with the estimated spectral types, provides an indication of the reddening for each reference star. Assuming an $R = 3.1$ galactic reddening law (Savage & Mathis 1979), we derive $A_V$ values by comparing the measured colors (Table 3) with intrinsic $B - V$, $J - K$, and $V - K$ colors from Bessell & Brett (1988) and AQ2000. Specifically, we estimate $A_V$ from three different ratios, each derived from the Savage & Mathis (1979) reddening law: $A_V/E(J - K) = 5.8$; $A_V/E(V - K) = 1.1$; and $A_V/E(B - V) = 3.1$. The resulting average reference star $A_V$ are collected in Table 3.

3.4. Adopted Reference Frame Absolute Parallaxes

We derive absolute parallaxes for the reference stars with $M_V$ values from AQ2000 and the $(A_V)$ derived from the photometry. Our parallax values are listed in Table 3. We produce errors on the absolute parallaxes by combining contributions from uncertainties in $M_V$ and $A_V$, which we have combined and set to 0.5 mag for each reference star. Individually, no reference star parallax is better determined than $\frac{\sigma}{\pi} = 23\%$. The average absolute parallax for the vA 622, 627 reference frame is $\langle \pi_{abs} \rangle = 1.2$ mas. As a sanity check, we compare this to the correction to absolute parallax discussed and presented in YPC95 (Section 3.2, Figure 2). Entering YPC95, Figure 2, with the vA 622 galactic latitude, $l = -19^\circ$, and average magnitude for the reference frame, $(V_{ref}) = 6.0$, we obtain a galactic model-dependent correction to absolute of 1.3 mas, in agreement.

4. ABSOLUTE PARALLAXES OF THE HYADS

Sections 4.1.1–4.1.4 detail our astrometric modeling of the vA 622, 627 field. Any differences in modeling for other Hyads are noted in Section 4.1.5.

4.1. The vA 622, 627 Astrometric Model

With the positions measured by FGS 3 and FGS 1r we determine the scale, rotation, and offset “plate constants” relative to an arbitrarily adopted constraint epoch (the so-called master plate) for each observation set (the data acquired at each epoch). The mJD of each observation set is listed in Table 2. The vA 622, 627 reference frame contains six stars. We employ a four-parameter model for those observations. For the vA 622, 627 field all the reference stars have colors similar to the science target. Nonetheless, we also apply the corrections for lateral color discussed in Benedict et al. (1999).

As for all our previous astrometric analyses, we employ GaussFit (Jefferys et al. 1988) to minimize $\chi^2$. The solved equations of condition for vA 622, 627 are

$$x' = x + l_c (B - V),$$

$$y' = y + l_c (B - V),$$

$$\xi = A x' + B y' + C - \mu_x \Delta t - P_x \pi_x,$$

$$\eta = - B x' + A y' + F - \mu_y \Delta t - P_y \pi_y,$$
Table 4  
Orbital Elements of Perturbation Due to vA 627 B

| Parameter | Value |
|-----------|-------|
| $\sigma_i$ | 14.58 ± 0.24 mas |
| $p$ | 843.94 ± 0.34 days |
| $T_0$ | 2.31 ± 0.001 yr |
| $e$ | 0.20 ± 0.01 |
| $i$ | 134.1 ± 0.9° |
| $\Omega$ | 251° ± 4° |
| $\omega$ | 334° ± 2° |
| $K_1$ | 6.34 ± 0.3 km s$^{-1}$ |
| $M_A$ | 0.83 ± 0.05 $M_\odot$ |
| $M_B$ | 0.42 ± 0.05 $M_\odot$ |

where $x$ and $y$ are the measured coordinates from *HST*; $lc_x$ and $lc_y$ are the lateral color corrections from Benedict et al. 1999; and $B - V$ are those colors for each star. $A$ and $B$ are scale and rotation plate constants; $C$ and $F$ are offsets; $\mu_x$ and $\mu_y$ are proper motions; $\Delta t$ is the epoch difference from the mean epoch; $P_x$ and $P_y$ are parallax factors; and $\pi_x$ and $\pi_y$ are the parallaxes in $x$ and $y$, respectively, which are constrained to be equal. We obtain the parallax factors (projections along R.A. and decl. of the Earth’s orbit about the barycenter of the solar system normalized to unity) from a JPL Earth orbit predictor (Standish 1990), upgraded to version DE405. Additionally, given the previous identification of vA 627 as a spectroscopic binary (Griffin et al. 1985) and the higher than typical residuals modeling with only the above equations, we add Keplerian perturbation orbit terms to the model (cf. McArthur et al. 2010; Benedict et al. 2010).

4.1.1. Prior Knowledge and Modeling Constraints

In a quasi-Bayesian approach, the reference star spectrophotometric absolute parallaxes (Table 3) and proper motion estimates for the reference stars from PPMXL (Roeser et al. 2010) along with the lateral color calibration and $B - V$ color indices were input as observations with associated errors, not as hard-wired quantities known to infinite precision. Input proper motion values have typical errors of 4–6 mas yr$^{-1}$ for each coordinate. To assess these input parallaxes and proper motions, the reference frame is modeled without the target to evaluate the goodness of fit of the a priori assumptions. After the target is included in the modeling, each reference star is systematically removed one at a time to assess impact on the target parallax and proper motions. Using these techniques we can assess the inputs for the reference frame, identify double stars in the reference frame, and occasionally solve for an orbit for the reference stars that have companions. Typically, at least 50–100 models are run in our process to determine the parallax. We essentially model a three-dimensional volume of the space that contains our science target and reference stars, all at differing distances.

4.1.2. vA 627 Perturbation Orbit

The Keplerian elements for the best-fit perturbation orbit for vA 627 are presented in Table 4. Astrometry from FGS 3 and FGS 1r and radial velocities from Griffin et al. (1985) were modeled simultaneously, using the methods described in McArthur et al. (2010). The orbit and residuals are presented in Figure 4. Assuming a mass for the K2 V primary, $M_A = 0.74 M_\odot$, yields a secondary mass $M_B = 0.42 M_\odot$, consistent with an infrared detection of the secondary spectrum by Bender & Simon (2008). The secondary is evidently an M2 V star.

The estimated magnitude difference between vA 627 A (K2 V) and vA 627 B (M2 V) is $\Delta m = 3.6$ mag. The total effect of component B on the apparent magnitude of the vA 627 system would be $\sim -0.04$ mag. Hence, the effect of the companion on the size of the actual perturbation orbit (the photocentric orbit; cf. van de Kamp 1967, Section 11.3) is negligible.

4.1.3. Assessing Reference Frame Residuals

The Optical Field Angle Distortion calibration (McArthur et al. 2002) reduces as-built *HST* telescope and FGS distortions with amplitude $\sim 1''$ to below 2 mas over much of the FGS field of regard. From histograms of the target and reference star astrometric residuals (Figure 5), we conclude that we have obtained satisfactory correction in the region available at all *HST* rolls. The resulting reference frame “catalog” in $\xi$ and $\eta$ standard coordinates (Table 5) was determined, and it has a weighted ($\sigma_\xi$) = 0.6 and ($\sigma_\eta$) = 0.7 mas. Relative proper motions along R.A. (x) and decl. (y) are also listed in Table 5. The proper motion vector is listed in Table 6, as are astrometric results for the other Hyads, including catalog statistics.

To determine if there might be unmodeled—but possibly correctable—systematic effects at the 1 mas level, we plotted the vA 622, 627 reference frame $x$ and $y$ residuals against a number of spacecraft, instrumental, and astronomical parameters. These included $x$, $y$ position within the pickle-shaped FGS field of regard, radial distance from the center of the FGS field of regard, reference star V magnitude and $B - V$ color, and epoch of observation. We saw no obvious trends, other than an expected increase in positional uncertainty with reference star magnitude.

4.1.4. The Absolute Parallaxes of vA 622 and vA 627

Because of the low ecliptic latitude, most of the parallax signature is along R.A. We obtain for vA 622 a final absolute parallax $\pi_{ab} = 24.11 \pm 0.30$ mas. This disagrees by almost...
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Table 5

| ID        | $\xi^a$        | $\eta^b$        | $\mu_x^c$ | $\mu_y^c$ | $\pi^c_{abs}$ |
|-----------|----------------|-----------------|------------|------------|---------------|
| vA 622    | $-22.3540 \pm 0.0003$ | $69.9153 \pm 0.0004$ | $102.21 \pm 0.04$ | $-32.60 \pm 0.03$ | $24.11 \pm 0.30$ |
| vA 627    | $86.5143 \pm 0.0003$  | $21.4862 \pm 0.0003$  | $105.87 \pm 0.04$  | $-30.86 \pm 0.04$  | $21.74 \pm 0.25$  |
| 113       | $-231.3496 \pm 0.0005$ | $-40.4306 \pm 0.0005$ | $0.53 \pm 0.06$ | $-2.94 \pm 0.09$ | $1.30 \pm 0.14$ |
| 112       | $-283.1685 \pm 0.0006$ | $-20.8358 \pm 0.0008$ | $0.52 \pm 1.48$ | $0.38 \pm 1.21$ | $0.57 \pm 0.07$ |
| 116       | $-300.6054 \pm 0.0011$ | $-2.0963 \pm 0.0011$ | $6.23 \pm 0.06$ | $-5.77 \pm 0.07$ | $1.11 \pm 0.12$ |
| 109       | $-198.8201 \pm 0.0006$ | $18.9788 \pm 0.0012$ | $6.59 \pm 0.05$ | $-8.81 \pm 0.05$ | $1.29 \pm 0.14$ |
| 111       | $234.1750 \pm 0.0024$ | $-43.6231 \pm 0.0021$ | $2.66 \pm 1.12$ | $-2.54 \pm 1.14$ | $0.56 \pm 0.06$ |
| 115       | $276.3116 \pm 0.0015$ | $35.7347 \pm 0.0019$ | $3.08 \pm 0.62$ | $-3.0 \pm 0.72$ | $0.98 \pm 0.11$ |
| 117       | $340.4222 \pm 0.0015$ | $2.2211 \pm 0.0009$ | $15.67 \pm 0.67$ | $-16.64 \pm 0.55$ | $1.96 \pm 0.24$ |

Notes.

$^a$ $\xi$ (R.A.) and $\eta$ (decl.) are relative positions in arcseconds.

$^b$ $\mu_x$ and $\mu_y$ are relative motions in mas yr$^{-1}$, where $x$ and $y$ are aligned with R.A. and Decl.

$^c$ Absolute parallax in mas.

$^d$ R.A. = $4^h31^m31^s +17^\circ44'59.1''$, J2000, epoch = mJD 50331.9705.

Table 6

Reference Frame Statistics and Hyad Parallax and Proper Motion

| Parameter                  | vA        | HST        | $HST$ (mas yr$^{-1}$) |
|----------------------------|-----------|------------|-----------------------|
| Hyad                       | 310       | 383        | 472                   |
| $HST$ study duration (yr)   | 2.95      | 2.54       | 2.97                  |
| Observation sets (no.)      | 7         | 6          | 7                     |
| Ref stars (no.)             | 6         | 8          | 3                     |
| Ref stars (V)               | 15.42     | 15.55      | 14.59                 |
| Ref stars ($B-V$)           | 1.07      | 1.22       | 1.49                  |
| $\langle \sigma_x \rangle$  | 0.3       | 0.4        | 0.9                   |
| $\langle \sigma_y \rangle$  | 0.4       | 0.4        | 0.9                   |
| $HST$ $\pi_{abs}$ (mas)     | 20.13     | 21.53      | 21.70 ± 0.15          |
| $HST$ relative $\mu$ (mas yr$^{-1}$) | 106.11 ± 0.1 | 103.3 ± 0.1 | 104.66 ± 0.05 |
| In position angle ($\circ$) | 106.4     | 102.4      | 102.4                 |
| HIP97 $\pi_{abs}$ (mas)     | 19.39     | 21.29      | 21.91                 |
| HIP97 $\mu$ (mas yr$^{-1}$) | 117.51    | 108.70     | 1.96                  |
| In position angle ($\circ$) | 107.7     | 107.7      | 99.5                  |

from the van Altena et al. (1997b) determination, $\pi_{abs} = 16.5 \pm 0.9$ mas. Our new vA 627 result agrees with previous parallax measurements from Hipparcos, $\pi_{abs} = 23.4 \pm 1.7$ mas (Perryman et al. 1998) and $\pi_{abs} = 22.75 \pm 1.22$ mas (van Leeuwen 2007). We note that this object is another for which the Hipparcos re-reduction has improved agreement with HST. This is not always the case. See Barnes (2009) for a few counter-examples involving galactic Cepheids. Parallaxes and relative proper motion results for all fields from HST and four fields from Hipparcos are collected in Table 6. Even though both HST proper motion determinations are relative, the proper motion vectors for vA 622, 627 agree with the absolute motions determined by Hipparcos.

4.1.5. Modeling Notes on the Other Hyads

For all targets the reference star average data, HST (and if available) Hipparcos parallaxes, and proper motions are collected in Tables 6 and 7. In all cases $\pi_x$ and $\pi_y$ are constrained to be equal. Three plate models are usually considered with HST astrometry. All models have offset terms $C$ and $F$. The differences are in the scale terms. The first model has an equal scale in $x$ and $y$, which is the model used for the vA 622 and vA 627 field using Equations (4) and (5). The second model has separate scale in $x$ and $y$, adding two parameters ($D$ and $E$) to

Figure 5. Histograms of $x$ and $y$ residuals obtained from modeling vA 622, vA 627, and the astrometric reference stars with Equations (4) and (5), including Keplerian orbit terms for vA 627. Distributions are fit with Gaussians whose $\sigma$’s are noted in the plots.

3$\sigma$ with the van Altena et al. (1997b) determination, $\pi_{abs} = 21.6 \pm 1.1$ mas. We have achieved a significant reduction in formal error. For vA 627 we obtain a final absolute parallax $\pi_{abs} = 21.74 \pm 0.25$ mas, a value that differs substantially
the first model:

\[ \xi = A x' + B y' + C - \mu_x \Delta t - P_a \pi_x , \]  

(6)

\[ \eta = D x' + E y' + F - \mu_y \Delta t - P_b \pi_y . \]  

(7)

The third model has equal scale in \( x \) and \( y \) as the first model does, but also includes the addition of two radial terms in each axis (\( G \) and \( H \)):

\[ \xi = A x' + B y' + G (x^2 + y^2) + C - \mu_x \Delta t - P_a \pi_x , \]  

(8)

\[ \eta = -B x' + A y' + H (x^2 + y^2) + F - \mu_y \Delta t - P_b \pi_y . \]  

(9)

The number of reference stars and the distribution of those stars dictate the model that is used. All fields are tested with all three models and the \( \chi^2 \) and degrees of freedom are compared for goodness of fit.

vA 310—This field provided six reference stars and we obtained seven usable epochs. We use a six-parameter model, where two terms (\( D \) and \( E \)) provide independent scale in \( y \) shown in Equations (6) and (7). The \( HST \) parallax, \( \pi_{ab} = 20.13 \pm 0.17 \) mas, agrees within the \( Hipparcos \) errors for both the 1997 and 2007 \( Hipparcos \) results. Our new parallax is considerably larger than the previous \( HST \) value, \( \pi_{ab} = 15.4 \pm 0.9 \) mas, with a significantly improved formal error.

vA 383—This field provided eight useful reference stars, but we were only able to secure six usable epochs. The astrometric model for this field required the addition of radial terms (\( G \) and \( H \)), using the six-parameter model shown in Equations (8) and (9). The introduction of the radial terms reduced the number of degrees of freedom by 13%, but reduced the \( \chi^2 \) by 62% from the four-parameter model shown in Equations (4) and (5). Our vA 383 parallax is \( \pi_{ab} = 21.53 \pm 0.20 \) mas. The original 1997 \( HST \) value was \( \pi_{ab} = 16.0 \pm 0.9 \) mas.

vA 472—This field provided four useful reference stars and seven usable epochs. One of the reference stars, ref-86, is the only giant in our fields, obvious in the reduced proper motion diagram (Figure 2). In addition to the visual inspection of the classification spectrum and the evidence from the reduced proper motion diagram, a model input that assumes a dwarf classification for ref-86 increases \( \chi^2 \) by 9%. The astrometric model for this field is a hybrid using four parameters (Equations (4) and (5)) for one observation set containing an unusable reference star observation, and six parameters (Equations (6) and (7)) for the other observation sets. The resulting reference frame “catalog” in \( \xi \) and \( \eta \) standard coordinates (Table 5) was determined with a weighted \( \langle \sigma_\xi \rangle = 0.9 \) and \( \langle \sigma_\eta \rangle = 0.9 \) mas. Our vA 472 parallax is \( \pi_{ab} = 21.70 \pm 0.15 \) mas. This agrees with both the 1997 and 2007 \( Hipparcos \) results. Our new parallax with a formal error \( \sim 10 \) times smaller disagrees (4\( \sigma \)) with the van Altena et al. (1997b) result.

vA 548—Seven reference stars, 12 epochs, and six-parameter radial term modeling (Equations (8) and (9)) yielded a parallax, \( \pi_{ab} = 20.69 \pm 0.17 \) mas, one that differs substantially from the 1997 \( HST \) value, \( \pi_{ab} = 16.8 \pm 0.3 \) mas.

vA 645—Five reference stars, six epochs, and six parameter radial modeling (Equations (8), (9)) yield \( \pi_{ab} = 17.46 \pm 0.21 \) mas. The vA 645 parallax agrees with an average of the 1997 and 2007 \( Hipparcos \) values. Again, the new \( HST \) result is larger (1.5\( \sigma \)) than the 1997 \( HST \) parallax.

The parallaxes from the previous analysis of \( HST \) FGS data (van Altena et al. 1997b), our new analysis including newer data (Section 4.1), the original \( Hipparcos \) results (Perryman et al. 1997), and the recent re-reduction of the \( Hipparcos \) data (van Leeuwen 2007, 2009) are collected in Table 8.

4.2. New Analysis Improvements

In Table 8 we see that our new analysis yields results that have lower error, are significantly different than our earlier results, and in general are more in agreement with both \( Hipparcos \) results. Several factors have contributed to this improvement. We now have a longer baseline on three of our seven Hyads, and we were able to fit a perturbation orbit to vA 627. Our OFAD is greatly improved, with a baseline of 18 years instead of the 3 years of OFAD data we had when the initial Hyades study was conducted. Since the early OFAD, which depended upon ground-based proper motions of M35, we have been able to solve for \( HST \)-based motions, and we have added additional distortion fitting to the original OFAD model. We now have superior information about the reference frame, with improved proper motion and spectrophotometric parallaxes, which we treat as observations with error in the modeling, yielding absolute rather than relative parallaxes. All these factors combined yield more accurate and precise

| Parameter | vA 548 | vA 645 | vA 310 | vA 383 | vA 472 |
|-----------|--------|--------|--------|--------|--------|
| Hyad      | 7      | 3      | 2      | 1      | 1      |
| HST study duration (yr) | 15.34  | 16.50  | 16.05  | 6.02   | 20.07  |
| Observation sets (no.) | 12     | 12     | 12     | 6      | 6      |
| Ref stars (no.) | 7      | 6      | 6      | 5      | 5      |
| Ref stars \((V)\) | 14.74  | 15.09  | 15.09  | 15.95  | 15.95  |
| Ref stars \((B - V)\) | 1.09   | 0.91   | 0.91   | 1.30   | 1.30   |
| \((\sigma_\xi)\) (mas) | 0.4    | 0.6    | 0.6    | 0.5    | 0.5    |
| \((\sigma_\eta)\) (mas) | 0.3    | 0.7    | 0.7    | 0.6    | 0.6    |
| \(HST\) \(\pi_{ab}\) (mas) | 20.69 ± 0.17 | 24.11 ± 0.30 | 21.74 ± 0.25 | 17.46 ± 0.21 |
| \(HST\) relative \(\mu\) (mas yr\(^{-1}\)) | 105.74 ± 0.03 | 107.28 ± 0.05 | 110.28 ± 0.05 | 101.81 ± 0.76 |
| In position angle (\(\circ\)) | 101.18 ± 0.02 | 107.7 ± 0.1 | 106.3 ± 0.1 | 105.19 ± 0.35 |
| HIP97 \(\mu\) (mas yr\(^{-1}\)) | 110.25 ± 2.0 | 103.44 ± 5.6 | 106.3 | 103.1 |
| In position angle (\(\circ\)) | 22.75 ± 1.22 | 19.13 ± 5.45 | 105.9 | 104.2 |
results. The older modeling technique used the ground-based catalog technique of summing the reference star information to 0, which is more appropriate for a larger reference frame, and making adjustments from a relative to absolute parallax. The combination of the initial OFAD calibration with the older modeling technique resulted in parallaxes that were consistently lower than the new values. The new results are calibrated and modeled consistently with the other HST parallax objects discussed in Section 4.3.

4.3. Assessing HST External Error Using Hipparcos

For the four Hyads in common with Hipparcos, we obtain an internal parallax precision a factor of 11 better than Hipparcos. We assess our external accuracy by comparing these and past HST parallaxes with others from Hipparcos, specifically the re-reduction of van Leeuwen (2007). A total of 28 stars are listed in Table 9 and include exoplanet host stars (e Eri, v And, HD 138311, GJ 876, 55 Cnc, HD 38529), binary stars (Wolf 1062 AB, Feige 24, HD 33636, Y Sgr), M dwarfs (Proxima Cen, Barnard’s Star, Wolf 1062 AB), Cepheids (l Car, ζ Gem, β Dor, W Sgr, X Sgr, Y Sgr, FF Aql, T Vul, δ Cep, RT Aur), and the four Hyads of this paper (v A 310, v A 472, v A 627, v A 645). We plot Hipparcos parallaxes against HST values in Figure 6. For three of our earliest analyses, rather than utilize spectrophotometrically derived reference star parallaxes, we applied a model-based correction to absolute parallax discussed in van Altena et al. (1995). These are plotted in lighter gray.

| vA      | HST (97)  | HST (11)  | HIP97* | HIP07* |
|---------|-----------|-----------|--------|--------|
| 310     | 15.40 ± 0.9 | 20.13 ± 0.17 | 19.35 ± 1.79 | 19.31 ± 1.93 |
| 383     | 16.00 ± 0.9 | 21.53 ± 0.20 |        |        |
| 472     | 16.60 ± 1.6 | 21.70 ± 0.15 | 21.29 ± 1.91 | 21.86 ± 1.71 |
| 548     | 16.80 ± 0.3 | 20.69 ± 0.17 |        |        |
| 622     | 21.60 ± 1.1 | 24.11 ± 0.30 |        |        |
| 627     | 16.50 ± 0.9 | 21.74 ± 0.25 | 23.41 ± 1.65 | 22.75 ± 1.22 |
| 645     | 15.70 ± 1.2 | 17.46 ± 0.21 | 15.11 ± 4.75 | 19.13 ± 5.45 |
| Weighted average | 16.80 ± 0.24 | 20.81 ± 0.19 | 21.19 ± 1.00 | 21.72 ± 0.87 |
| Average  | 16.94 ± 0.99 | 21.05 ± 0.21 | 19.79 ± 2.04 | 20.76 ± 1.05 |
| Median   | 16.50 ± 0.99 | 21.52 ± 0.20 | 20.32 ± 2.04 | 20.59 ± 1.05 |
| Average∿   | 16.05 ± 1.15 | 20.26 ± 0.19 | 19.79 ± 2.04 | 20.76 ± 105 |

HIP mean parallax

21.53 ± 2.76 ± 0.23

Notes.

4 Parallaxes from the original analysis (van Altena et al. 1997b).
5 Parallaxes from the present study (Section 4.1).
6 Parallaxes from the original Hipparcos reduction (Perryman et al. 1997).
7 Parallaxes from the Hipparcos re-reduction (van Leeuwen 2007).
8 Parallax average considering only those stars in common with Hipparcos.
9 The mean parallax of selected Hipparcos stars (van Leeuwen 2009).

Table 8

Hyad Absolute Parallaxes (mas)

| vA      | HST (97)  | HST (11)  | HIP97* | HIP07* |
|---------|-----------|-----------|--------|--------|
| 310     | 15.40 ± 0.9 | 20.13 ± 0.17 | 19.35 ± 1.79 | 19.31 ± 1.93 |
| 383     | 16.00 ± 0.9 | 21.53 ± 0.20 |        |        |
| 472     | 16.60 ± 1.6 | 21.70 ± 0.15 | 21.29 ± 1.91 | 21.86 ± 1.71 |
| 548     | 16.80 ± 0.3 | 20.69 ± 0.17 |        |        |
| 622     | 21.60 ± 1.1 | 24.11 ± 0.30 |        |        |
| 627     | 16.50 ± 0.9 | 21.74 ± 0.25 | 23.41 ± 1.65 | 22.75 ± 1.22 |
| 645     | 15.70 ± 1.2 | 17.46 ± 0.21 | 15.11 ± 4.75 | 19.13 ± 5.45 |
| Weighted average | 16.80 ± 0.24 | 20.81 ± 0.19 | 21.19 ± 1.00 | 21.72 ± 0.87 |
| Average  | 16.94 ± 0.99 | 21.05 ± 0.21 | 19.79 ± 2.04 | 20.76 ± 1.05 |
| Median   | 16.50 ± 0.99 | 21.52 ± 0.20 | 20.32 ± 2.04 | 20.59 ± 1.05 |
| Average∿   | 16.05 ± 1.15 | 20.26 ± 0.19 | 19.79 ± 2.04 | 20.76 ± 105 |

5. HYADES DEPTH AND DISTANCE MODULUS

The high-precision absolute parallaxes in Table 8 (column HST11) provide us an independent estimate of the depth of the Hyades core. Assuming a Gaussian distribution of Hyades yields a ±1σ core dispersion of 3.6 pc. Back to front, differencing the distances of v A 622 and v A 645 we find a minimum diameter 16.0 ± 0.9 pc. The average distance of this particular sample is D = 47.5 pc.

By computing absolute magnitudes for these seven Hyads, we can produce a sparsely populated color–absolute magnitude diagram and estimate a distance modulus, m–M, for the entire cluster. With parallaxes in hand (Table 8), we use v A 627 as an example to illustrate the steps required to obtain absolute magnitudes for these Hyads.

5.1. Absolute Magnitudes and the Lutz–Kelker–Hanson Bias

When using a trigonometric parallax to estimate the absolute magnitude of a star, a correction should be made for the Lutz–Kelker bias (Lutz & Kelker 1973) as modified by Hanson (1979). See Benedict et al. (2007b), Section 5, for a more detailed rationale for the application of this correction to single stars. Because of the galactic latitude and distance of the Hyades, and the scale height of the stellar population of which it is a member, we calculate Lutz–Kelker–Hanson (LKH) bias assuming a disk distribution. The LKH bias is proportional to (σ_p/π)^2. Presuming that any member of the Hyades belongs to the same class of object as δ Cep (young main-sequence stars), we scale the LKH correction determined for δ Cep in Benedict.
5.2. The Absolute Magnitude of vA 622

According to Taylor (2006), Hyades extinction is characterized by $E(B - V) \leq 0.001$ mag, obviating the necessity for extinction-induced corrections to absolute magnitude or color. Adopting for vA 622 $V = 11.90 \pm 0.01$ (SIMBAD) and the absolute parallax, $\pi_{abs} = 24.11 \pm 0.30$ mas from Table 8, we determine a distance modulus, $m - M = 3.09 \pm 0.04$. To obtain a final absolute magnitude, we would normally correct for interstellar extinction. However, with $E(B - V) \leq 0.001$ mag, $V_0 = V = 11.90$. The distance modulus and $V_0$ provide for vA 622 an absolute magnitude $M_V = 8.82 \pm 0.03$. This and the absolute magnitudes for the six other Hyads are collected in Table 10. All absolute magnitude errors contain only the contribution from the parallax uncertainty.

Figure 7 presents an H-R diagram constructed from our Hyad absolute magnitudes (Table 10). The figure also contains a Hyades main sequence constructed with $V, B - V$ photometry from Joner et al. (2006) transformed to $M_V$ using the van Leeuwen (2009) distance modulus and an M67 main sequence from Sandquist (2004). There are too few stars with $HST$...
5.3. A Hyades Distance Modulus

Including all seven stars, we obtain a weighted average Hyades distance modulus, \( m - M = 3.376 \pm 0.012 \). We note that from \textit{Hipparcos} parallaxes both Perryman et al. (1998) and van Leeuwen (2009) obtain an average distance modulus of \( m - M = 3.33 \pm 0.02 \) from their entire sample of Hyads. With our entire (small) sample, we get a distance modulus that is very close to \textit{Hipparcos} 1997 or 2007. Our distance modulus determinations are listed in Table 11, along with other recent distance moduli. We note the agreement between our value and the results from the studies of binaries yielding orbital parallaxes (Torres et al. 1997a, 1997b, 1997c).

Those interested in an even more detailed description of the distance and structure of the Hyades will anticipate the results from \textit{Gaia} (Lindegren et al. 2008). Parallax and proper motion precision factors of 10–100 times better than \textit{HST} are expected by \( \sim 2018 \).

6. SUMMARY

We have reanalyzed older FGS 3 data of six fields and supplemental newer FGS 1r astrometric data of two fields in the Hyades, containing seven confirmed Hyads. We employ techniques (Harrison et al. 1999; Benedict et al. 2007b) devised since the original analysis (van Altena et al. 1997b). These new absolute parallaxes now provide

1. an average distance for these seven members, \( D = 47.5 \) pc, with individual parallax errors lower by an average factor of 4.5 compared to the original study (van Altena et al. 1997b) and a factor of 11 times better than \textit{Hipparcos} for the four stars in common;
2. a \( \pm 1\sigma \) dispersion depth of 3.6 pc and a minimum diameter 16.0 \( \pm 0.9 \) pc;
3. absolute magnitudes for each member, yielding a sparsely populated main sequence;
4. a weighted average distance modulus of \( m - M = 3.376 \pm 0.01 \), a value that agrees within the errors to results from the orbital parallaxes of Hyades binaries (Torres et al. 1997a, 1997b, 1997c) and is very close to both \textit{Hipparcos} results (Perryman et al. 1998; van Leeuwen 2009); and
5. an independent parallax and distance modulus for the Hyades confirming the assertion of Narayan & Gould (1999b) that \textit{Hipparcos} “got it right.”

Support for this work was provided by NASA through grants NAG5-1603 and AR-11746 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. These results are based partially on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium. This publication makes use of data products from the Two Micron All Sky Survey, which is
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