ASTROMETRIC ACCURACY OF FAME

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1 Overview

The astrometric performance of the Fizeau Astrometric Mapping Explorer (FAME) is estimated in this note. The basic observation in FAME is of the time of transit of a star across the CCD array. The angular separation between two stars is obtained by multiplying the difference in transit time by the angular velocity. In the great-circle reduction, the abscissae of all stars along a great-circle scan are referred to a common origin. Abscissae of stars separated by large angles (other than the basic angle) are tied together by adding up the relative angular separations of the intervening stars. The accumulation of random errors is suppressed by application of the equations of constraint afforded by the basic angle. The greater the angular distance between stars that can be directly related, without recourse to intervening stars, the greater is the *rigidity* of the great-circle reduction.

Estimation of the astrometric performance of FAME is accomplished in three steps. First, the variance of the angular separation between stars observed within a short time interval is determined. Here, the concept of an *effective field of view* is introduced. Unlike HIPPARCOS, which had an instantaneous field of view of about one degree along the scan, the instantaneous FOV for FAME is essentially infinitesimal along the scan. The *effective* field of view (EFOV) is the extent along the scan over which relative abscissae of stars can be directly determined. The EFOV is limited by the accuracy with which the angular velocity is known. Operationally, the EFOV is defined as the extent along the scan which minimizes the variance of the angular separation between a star at the edge of the field, and the average abscissa of all the stars in the field. This variance is a function of the magnitude of the object star, and will be referred to as the single-observation error.

Thus, the single-observation error is the error associated with the abscissa of an object star referred to a local field center. The second step in evaluating FAME's astrometric accuracy is to compute the *non-rigidity, V.* This is the factor by which the errors are increased when the abscissae are referred to a common origin, such as one of the points where the great-circle scan intersects the ecliptic. The factor V is a function of the average number of stars contained in the EFOV. Finally, the errors in the position, proper motion, and parallax, as a function of stellar magnitude, are determined when all observations over the life of the mission are used.

2 Centroiding

A least-squares fit to the binned, theoretical point-spread function will yield the amplitude and one-dimensional abscissa in units of time. Centroiding errors due to Poisson statistics, quantum efficiency variation, and finite clock resolution are parameterized in this section. The centroid error, $\sigma_{\rm cent}$ is a random error affecting the abscissae of both the field center and the object star.

2.1 Clock Resolution

Taking the maximum clock resolution to be one over the clock frequency, ν, the astrometric error introduced by the finite clock resolution is

$$\sigma_{clock} = \frac{\Omega}{\sqrt{12}\,\nu}, \tag{1}$$

where $\Omega = 200"/s$ is the nominal angular velocity of the spacecraft. The proposed 10 MHz clock will introduce an error of about 5.77 μas. The effects of clock *stability* are discussed in the section on scale fluctuations.

2.2 Pixelation

Centroiding errors due to inter- and intra-pixel variations in QE are mitigated by the use of time-delay integration (TDI). Without the use of TDI, QE variations may lead to errors as small as 0.01 pixels, or 859 μas. Using TDI, this error is divided by the square root of the number of pixels in a row. Thus, the total pixelation error is

$$\sigma_{\rm pix} = 13.4\ \mu{\rm as}. \tag{2}$$

Centroiding along the axis perpendicular to the scan is necessary for purposes of attitude determination. In this direction, the pixels are binned 4:1, so that the effective pixel size is 687.5 mas. The expected pixelation error in this dimension is then

$$\sigma_{\rm pix} = 0.01(687.5\ {\rm mas})/2 = 3.44\ {\rm mas} \tag{3}$$

where the factor of 1/2 comes from the 4:1 on-chip binning.

2.3 Photon and Read Noise

Lindegren has given an expression for the centroid error, in angular units, introduced by a Poisson process (Lindegren, 1978):

$$\sigma_p = \frac{\lambda}{2\pi A\sqrt{N}}, \tag{4}$$

where A is the rms aperture, and N is the number of counts above background due to photons. This equation may be generalized to include counts due to read noise, $\mathcal{R}$, which have no signal content:

$$\sigma_p = \frac{\lambda}{2\pi A}\frac{\sqrt{N+\mathcal{R}}}{N}, \tag{5}$$

where $\mathcal{R}$ is the product of the read noise squared, times the number of pixels in the image. The photon count, N is the product of the collecting area, the bandwidth, the encircled energy, the spectral photon flux, $\mathcal{F}_\lambda$, the integration time, the quantum efficiency of the detector, the Strehl ratio, and the transmittance of the optics. Values for these parameters are summarized in Table 1. The encircled energy fraction is estimated to be 0.6 for rectangular apertures. The value of $\mathcal{R}$ assumes a standard deviation of five read-noise electrons per pixel over four pixels, valid at 0.5 μ. The

TABLE 1
PARAMETER VALUES

Collecting Area	0.05	m^2
RMS aperture, A	37.86	cm
Bandwidth	400	nm
Encircled Energy	0.6	
Integration time	1.76	s
Quantum Efficiency	0.75	
Read Noise, $\mathcal{R}$	600	
Strehl ratio	0.77	
Transmittance	0.82	

spectral flux at 0.5μ may be obtained from the visual magnitude, VMAG, by

$$\mathcal{F}_{0.5\mu} = 2.7 \times 10^{(7.57-0.4\times\mathrm{VMAG})}\mathrm{m}^{-2}\mathrm{nm}^{-1}\mathrm{s}^{-1}. \tag{6}$$

The standard deviation, σ_{cent}, including effects of photon statistics, read noise, clock resolution, and pixelation is given in Table 2.

TABLE 2
CENTROID ERROR

VMAG	N (0.5 μ)	$\sigma_{\rm cent}$ (μas)	σ_η (mas)
6.0	3.99e+06	26.16	3.4
7.0	1.59e+06	37.36	3.4
8.0	6.33e+05	56.44	3.5
9.0	2.52e+05	87.69	3.5
10.0	1.00e+05	138.05	3.6
11.0	3.99e+04	219.04	3.7
12.0	1.59e+04	350.53	4.1
13.0	6.33e+03	570.31	5.1
14.0	2.52e+03	961.01	7.2
15.0	1.00e+03	1730.26	12.0
16.0	3.99e+02	3431.33	23.0

3 Field Rotation

The three sources of field rotation are: misalignment of the CCD's with respect to the optical axis; misalignment between the axes of symmetry and rotation; and errors in the determination of the attitude of the spacecraft. The first two effects lead to smearing of the images in the direction perpendicular to the scan since the images do not, in this case, travel parallel to the CCD rows. Errors in attitude determination lead to an apparent field rotation, in that the spacecraft is not scanning along the expected direction. Field rotation introduces a correction to the apparent abscissae of $\eta \cos r$, where η is the observed height of the star as it transits the CCD's, and r is the angle between the CCD array and the scan direction. The error in the determination of this correction is

$$\sigma^2_{\rm rot} = \eta^2 \sigma^2_{\cos r} + \cos^2 r \ \sigma^2_\eta. \tag{7}$$

Note that the first term represents a *systematic* error in star abscissa, since an error in $\cos r$ causes stars above and below the field center to be shifted in opposite directions by an amount proportional to the magnitude of their heights. This error will approximately average out in the determination of the field center, but must be retained in the expression for the abscissa error of the object star.

68% of the stars will transit within 0.167° of the center of the array. Thus, η will be set to 0.167° in the first term to obtain the one-sigma error. The expected centroiding error in the direction perpendicular to the scan, σ_η, is magnitude dependent, and is limited to about 3.4 mas by CCD pixelation. Values of σ_η are given in Table 2. It can be shown that $\cos r \sim \sin\psi \simeq \psi$, where ψ is the angle between the symmetry and rotation axes. This angle is expected to be a few arcminutes, so that $\cos r \sim 10^{-3}$. The precise value of $\cos r$ can be determined empiricly by comparing the the transit times of stars with their expected transit times when there is no field rotation. The latter is refined by iteration, starting from input-catalog positions. It may be assumed that the field rotation is a slowly-varying function of time. Thus, all stars crossing the detector in a ten-minute interval may be used to fit a smooth function to the observed field rotation. The resulting variance is :

$$\sigma^2_{\cos r} = \left[\sum_{\rm VMAG} \frac{\rho\,\eta^2}{\psi^2\sigma^2_\eta + \sigma^2_o + \sigma^2_c} \right]^{-1} \tag{8}$$

where ρ is the number of stars of a given magnitude transiting the detector in a ten-minute interval. The subscripts o and c refer to *observed* and *computed*, respectively. Upon iteration, $\sigma_c \to \sigma_o$. Replacing η^2 by the mean-square value, $<\eta^2>= (0.144^\circ)^2$, setting $\psi = 10^{-3}$, and summing over all stars seen in a ten-minute interval, one obtains

$$\eta^2\,\sigma^2_{\cos r} = \frac{\eta^2}{<\eta^2>}\,(7.98\ \mu\text{as})^2 = (9.26\ \mu\text{as})^2. \tag{9}$$

This corresponds to an error in the angle r of about 2.6 mas. Thus, the contribution of field rotation to the single-observation error is

$$(9.26\ \mu\text{as})^2 + \psi^2\,\sigma^2_\eta + \psi^2 <\sigma^2_\eta> /m \tag{10}$$

where the last term represents the effect on the location of the average field center. The angular brackets represent an average over magnitude, weighted by the magnitude-dependent stellar density, and m is the number of stars in the EFOV.

4 Scale Errors

The *scale* for the FAME instrument in the along-the-scan direction is identical to the angular velocity of the spacecraft. Apparent scale changes are introduced by a variety of mechanisms including fluctuation of the satellite's attitude, angular velocity and temperature, and drift in the clock frequency. These scale changes are modeled using information from the rotation-rate sensors and star tracker. Errors in the scale determination lead directly to an error in the relative separation between the object star and the field center.

4.1 Clock Stability

During a 1.8 hour period, the relative clock frequency may change by as much as $\Delta\nu/\nu = 5 \times 10^{-11}$. Since $|\Delta\nu/\nu| = |\Delta t/t|$, this produces a scale change due to a change in the "length of the second" of

$$\sigma_{\Delta\nu} = \Omega \frac{\Delta\nu}{\nu} = 0.01\ \mu\text{as/s}. \tag{11}$$

Scale errors of this magnitude are negligible in comparison to those due to uncertainty in the angular velocity.

4.2 Projection Effects

An uncertainty in the field rotation of δr will introduce an apparent scale change of

$$\Omega(1 - \cos(\delta r)) = \tfrac{1}{2}\Omega(\delta r)^2. \tag{12}$$

It has already been estimated that r will be determined to about 2.6 mas, which would result in a negligible error in scale.

4.3 Angular Velocity

The angular velocity is obtained by dividing the angle, θ, separating a time-of-flight chip and a scientific CCD, by the time difference, Δt, between transits of a fringe across the two chips. The error in a single angular velocity measurement is given by the standard propagation-of-error formula as

$$\sigma_\Omega^2 = \left(\frac{1}{\Delta t}\right)^2 \sigma_\theta^2 + \left(\frac{\Omega}{\Delta t}\right)^2 \sigma_{\Delta t}^2 \tag{13}$$

where, for two chips separated by one chip width, nominal values of $\Delta t = 1.76$ s, $\theta = 0.098°$, and $\Omega = 200''/\text{s}$ are assumed. Errors in the knowledge of these nominal values are not critical since the average scale is calibrated by the closure conditions discussed below. Of more importance is knowledge of the changes in these values with time. σ_θ may be expressed in terms of the uncertainty in the temperature change, ΔT, and in the coefficient of thermal expansion, ϵ, as

$$\sigma_\theta^2 = (0.098°)^2 \left[\epsilon^2 \sigma_{\Delta T}^2 + (\Delta T)^2 \sigma_\epsilon^2\right]. \tag{14}$$

If ϵ is known to 1%, then the second term is probably negligible for $\Delta T < 0.01$ K. Thus, $\sigma_\theta \sim 2\,\mu$as when ΔT is known to ~ 3 mK. The contribution to the error in angular velocity due to centroiding is contained in the term $\sigma_{\Delta t}$, which may be obtained by multiplying the appropriate entry in Table 2 by $\sqrt{2}/\Omega$.

The angular velocity may be assumed to be a slowly varying function of time in between thruster firings. Thus, higher accuracy may be obtained by fitting all angular velocity measurements obtained between thruster firings to a smooth function. The random errors will then be diminished by the square-root of the sum of the weights. In the worst case, one field of view is pointing at the galactic pole while the other field has an average density of stars. The numbers of stars seen by the time-of-flight (TOF) chip per minute are given in Table 3 for a 1 σ star density. Using these data

TABLE 3

VMAG	stars/sq. deg			stars/minute
	avg.	worst	1 σ	on TOF chips
6-7	0.132	0.101	0.12	0.098
7-8	0.358	0.270	0.33	0.269
8-9	0.986	0.728	0.89	0.725
9-10	2.620	1.862	2.34	1.907
10-11	7.052	4.881	6.26	5.101
11-12	17.62	11.88	15.52	12.65
12-13	45.29	29.56	39.55	32.23
13-14	107.8	67.27	93.00	75.78

and the expected centroiding error from section 2, one obtains a standard deviation of the mean angular velocity over a ten-minute interval of

$$\sigma_\Omega = 8.30\,\mu\text{as/s}. \tag{15}$$

One may assume that the error in angular velocity is constant during the time it takes to scan through the effective field of view (EFOV). Then all the stars in the EFOV will be displaced in the same direction relative to the object star located at the edge of the field. If there are m uniformly-spaced stars in the EFOV, each transiting a time δt from the next, then the angular velocity error contributes

$$\frac{m\,\delta t\,\sigma_\Omega}{2} = \frac{\text{EFOV}\,\sigma_\Omega}{2\Omega} \tag{16}$$

to the single-observation error.

5 Orbit Determination

The errors arising from imperfect orbit determination are discussed in this section. Uncertainty in the spacecraft velocity represents a major source of astrometric error for FAME. Of somewhat lesser importance is the knowledge of the satellite position, which is relevant for astrometry of solar-system objects.

5.1 Velocity Determination

Uncertainty in the satellite velocity leads directly to errors in the source positions due to uncompensated aberration. The error is largest for fields located in a direction perpendicular to the velocity vector. In this case, letting $\mathbf{r}$ be the true position vector of the source relative to the observer, and $\mathbf{r}'$ the apparent position vector,

$$\cos\theta_{\rm abr} = \mathbf{r}/\mathbf{r}' = \frac{1}{\sqrt{1+\beta^2}} \tag{17}$$

where $\beta = v/c$. Expanding both sides, one finds that $\theta_{\rm abr} \simeq \beta$ in radian measure. Within a given field of view, the apparent displacement due to velocity errors will be the same for all stars. Thus, there is no error in relative position for stars in the same field of view. There will be an apparent displacement between the stars in different fields of view, however. For an uncertainty in the satellite velocity, σ_v, measured in centimeters/second, the relative shift of one field relative to the average field center is

$$\sigma_{\rm abr} = 3.44\,\sigma_v \ \mu{\rm as} \tag{18}$$

for two fields having approximately the same density of stars.

5.2 Position Determination

The position of the satellite in its orbit must be known for accurate astrometry of solar-system objects. Position errors perpendicular to the line of sight have the largest effect. In this case, the astrometric error in an observation of a solar-system object at a distance D, arising from a satellite position uncertainty δr, is $\sigma_r = \delta r/D$ in radian measure. Thus, for an object at the distance of Mars at opposition ($D = 7.8 \times 10^7$ km), an uncertainty in satellite position of 100 meters will introduce a maximum astrometric error of 264 μas. For an object in the outer solar system, say at 10^9 km, the same position uncertainty leads to an astrometric error of 21 μas. Solar-system objects are not part of the principle scientific objectives of FAME, so this source of error is ignored in the following.

6 Metrology System

The metrology system measures changes in the angle between each mirror in the collimating mirror assembly (CMA), and the optical axis to an accuracy of $\sigma_{\rm met} = 34$ μas. Two such measurements are needed to determine the change in basic angle, γ, so that the uncertainty in γ is $\sigma_\gamma = \sqrt{2}\,\sigma_{\rm met}$. By an argument similar to the one employed in the analysis of aberration errors, only one half of this error contributes to the uncertainty in the position of a star relative to the average field center. Thus, the contribution to the single-observation error due to uncertainties in the basic angle is

$$\sigma_\gamma/2 = \sigma_{\rm met}/\sqrt{2} = 24.04\ \mu{\rm as}. \tag{19}$$

7 Great-Circle Reduction

This stage of the data reduction involves applying closure conditions to the abscissa values, obtained from the fringe-fitting stage, so that errors arising from uncompensated scale changes do not accumulate when the abscissa of a star is referred to an origin many degrees away. The effectiveness of the great-circle reduction in removing scale fluctuations is parameterized by the *non-rigidity* factor, V, defined by

$$\sigma_a^2 = \tfrac{1}{2} V\,\sigma_x^2, \tag{20}$$

where σ_a is the abscissa error referred to a common origin, and σ_x^2 is the variance of the relative distance between the object star and an average field center. The factor of $\frac{1}{2}$ arises from the fact that each star is observed twice, once in each field of view, per great-circle scan.

In order to apply the non-rigidity formalism to the FAME observations, one must define an effective instantaneous field of view (EFOV), which is needed in the calculation of both V and σ_x.

7.1 Effective Field of View

For an EFOV containing m uniformly-spaced stars, each transiting a time $\delta t = 0.117\ s$ from the next, the error in the relative separation between the average field center and an object star at the edge of the field is

$$\sigma_x^2 = \frac{<\sigma_{\rm cent}^2> + <\sigma_\eta^2> \cos^2 r}{m} + \left[\frac{m\,\delta t\,\sigma_\Omega}{2}\right]^2 + \frac{\sigma_\gamma^2}{4} + \sigma_{\rm abr}^2 + \sigma_{\rm cent}^2 + \eta^2 \sigma_{\cos r}^2 + \cos^2 r\,\sigma_\eta^2, \tag{21}$$

where the angular brackets indicate an average over magnitude, weighted by the magnitude-dependent stellar density. Values of magnitude-independent errors are collected in Table 4. To find the EFOV, the derivative of σ_x^2 with respect to m is set equal to zero. Solving for m, one obtains

$$m = \left[\frac{2(<\sigma_{\rm cent}^2> + <\sigma_\eta^2> \cos^2 r)}{(\delta t\,\sigma_\Omega)^2}\right]^{\frac{1}{3}}. \tag{22}$$

The EFOV is obtained from m by multiplying by $\delta t\,\Omega$. The result is $m = 92$, which corresponds to an EFOV=0.60°. A refinement of this procedure is to take into account the m dependence of the non-rigidity factor, V, which is computed in the next section. This will result in an EFOV which is optimized for the magnitude of the object star.

TABLE 4

Source of Error	Expression	Value
avg. field center	$\sqrt{(<\sigma^2_{\rm cent}> + \psi^2 <\sigma^2_\eta>)/m}$	64.30 μas
rotation rate	$\frac{1}{2}\,{\rm EFOV}\,\sigma_\Omega/\Omega$	44.83 μas
basic angle	$\sigma_\gamma/2 = \sigma_{\rm met}/\sqrt{2}$	24.04 μas
pixelation	—	13.43 μas
field rotation	$\sqrt{\eta^2\sigma^2_{\cos r} + \cos^2 r\,\sigma^2_\eta}$	9.26 μas
aberration	$\sigma_{\rm abr} = 3.45\,\sigma_v$	6.88 μas
clock resolution	$\Omega/(\sqrt{12}\,\nu)$	5.77 μas

7.2 Non-Rigidity Factor

The equations for computing V are derived from a harmonic decomposition of scale changes around a great-circle scan. This has been done in the appendix of Høyer, *et al.* (1981):

$$V = \frac{4m}{n}\sum_{\ell=1}^{n/2}\frac{1}{K_\ell} \tag{23}$$

with

$$\begin{aligned} K_\ell &= 2(m-1) - 4\sum_{k_{\rm odd}=1}^{m-1}\frac{m-k}{m}\cos\left(\frac{\pi k\ell}{n}\right)\cos(\gamma\ell) \\ &- 4\sum_{k_{\rm even}=2}^{m-1}\frac{m-k}{m}\cos\left(\frac{\pi k\ell}{n}\right), \end{aligned} \tag{24}$$

where m is the number of stars per EFOV, $n = 27,600$ is the number of stars in a great-circle scan, and γ is the basic angle. The non-rigidity is about 7 for $m = 2$, and approaches unity for large m.

The product of V and σ_x as a function of m goes through a minimum, the location of which depends on the magnitude of the object star. The results are summarized in Table 5. One can understand why the EFOV should be larger for fainter object stars, since in this case, the errors due to uncertainty in the angular velocity remain small in comparison with the centroiding error of the object star until the time difference becomes relatively large.

TABLE 5

VMAG	V	EFOV	σ_a (μas)	σ_Π (μas)
6.0	1.11	0.63°	64.7	20.9
7.0	1.11	0.65°	65.9	21.3
8.0	1.11	0.66°	70.5	22.9
9.0	1.11	0.67°	80.9	26.1
10.0	1.11	0.68°	102.5	33.1
11.0	1.10	0.70°	143.3	46.3
12.0	1.10	0.71°	214.8	69.5
13.0	1.10	0.72°	336.9	108.9
14.0	1.10	0.74°	549.8	177.8
15.0	1.10	0.75°	948.8	306.9
16.0	1.10	0.76°	1784.5	577.1

7.3 Thruster Firings

When the gas thrusters are fired to bring about an attitude correction, both the attitude and the angular velocity undergo rapid change in a period of about 20 ms. Since the average time interval between star transits is greater than 100 ms, sufficient data is not available to monitor the changes in attitude and angular velocity during the course of a thruster firing. It is anticipated that corrections to the rotation rate will be made only when the spacecraft is "precessed" to begin a new great-circle scan. Thus, thrusters will only be fired only in order to make corrections to the pitch and yaw during the course of a great circle scan. It is estimated that these impulses will change the angular velocity by about 1 mas/s due to misalignment of the thruster clusters with respect to the axis of symmetry of the spacecraft. The average angular acceleration is therefore $(1\,\mathrm{mas\,s^{-1}})/(20\,\mathrm{ms}) = 50\,\mathrm{mas/s^2}$, applied over 20 ms. This leads to an angular displacement of about 10 μas. The precise value depends upon the exact misalignment of the thrusters, and on the actual time dependence of the acceleration. Nevertheless, 10 μas may be taken to be the typical abscissa error arising from thruster firings. This will increase slightly the single-observation error of the fewer than 2% of the stars which happen to fall close to a thruster firing.

Occasionally, a larger angular velocity impulse may occur, for example in the event of a (rare) angular velocity correction during the course of a great-circle scan, In this case, it is possible to tie together segments of a great-circle scan that are on opposite sides of the perturbation using information from an adjacent scan. This will work provided that a perturbation does not occur at the same point on both scans. This will result in higher single-observation errors for a small number of stars, but would have a negligible effect on the average abscissa error for the whole scan.

7.4 Condition Number

The astrometric accuracy will also depend upon the condition number of the normal-equations matrix (Makarov, Høg, and Lindegren, 1994). A large condition number means that periodic errors having a period near the basic angle are amplified. This affect would be minimized if two basic angles were used. The impact of this error source on FAME is yet to be determined.

8 Sphere Reconstruction

It takes about 235 great-circle scans to cover the entire celestial sphere. Since each scan is completed in 1.8 hours, each star can be scanned an average of 52 times in a 2.5 year mission. It is estimated that 68% of the stars will be scanned 38 or more times. Høyer *et al.* (1981) derived the relationship between the single-observation error, and the error in parallax, σ_Π, resulting from N great-circle scans of each star :

$$\sigma_\Pi^2 = \frac{\sigma_a^2}{N\,\frac{1}{2}\,\sin^2\xi} \tag{25}$$

where $\xi = 45°$ is the angle between the axis of rotation, and the sun vector. The results are tabulated in the last column of Table 5.

9 References

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