Full-sky Astrometric Mapping Explorer: An optical, astrometric survey mission

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ABSTRACT

The Full-sky Astrometric Mapping Explorer (FAME) is a MIDEX class Explorer mission designed to perform an all-sky, astrometric survey with unprecedented accuracy, determining the positions, parallaxes, proper motions, and photometry of 40 million stars. It will create a rigid, astrometric catalog of stars from an input catalog with $5 < m_V < 15$. For bright stars, $5 < m_V < 9$, FAME's goal is to determine positions and parallaxes accurate to < 50 μas, with proper motion errors < 50 μas /year. For fainter stars, $9 < m_V < 15$, FAME's goal is to determine positions and parallaxes accurate to < 500 μas, with proper motion errors < 500 μas /year. It will also collect photometric data on these 40 million stars in four Sloan DSS colors.

FAME uses a single optical telescope to observe two fields of view simultaneously. Both fields of view are imaged onto a single focal plane consisting of 24 CCDs operated in TDI mode. The TDI rate is synchronized with the 40 minute rotation period of the spacecraft. Solar radiation pressure on the Sun shield precesses the rotation axis of the spacecraft with a 20 day period so that FAME will cover the entire sky. FAME will observe continuously over its five year lifetime except during occasional station keeping maneuvers to maintain its position in geosynchronous orbit.

FAME is funded and is scheduled to launch in June 2004.

Keywords: astrometry, space instrumentation

1. INTRODUCTION

The Full-sky Astrometric Mapping Explorer (FAME) is a funded and approved NASA Explorer mission, MIDEX class, that will begin Phase B on 1 October 2000 and launch in June 2004. FAME will measure the positions, parallaxes, proper motions, and photometry of 4×10^7 stars. FAME evolved from Hipparcos mission design concepts using state of the art CCD technology to observe more and fainter stars. Like Hipparcos, FAME has a compound mirror consisting of two flats angled relative to each other[1, 2]. The compound mirror feeds two fields of view separated by the "basic angle" into a common telescope. As with Hipparcos, the two fields of view are used to control the growth of stochastic errors in determining the relative separations of stars.

FAME scans the sky by rotating with a period of 40 minutes perpendicular to the aperture plane. It observes as it smoothly rotates, reading out the 24 CCDs in the focal plane in time delayed integration (TDI) mode. FAME also smoothly precesses, with the solar radiation pressure on the Sun shield providing torque to precess the spacecraft. The FAME rotation axis will be initially aligned 45 degrees from the Sun; solar radiation pressure on the shield will result in precession of the rotation axis around the FAME-Sun line. Trim tabs at the edges of the Sun shield are adjusted to tune the precession rate to a nominal 20 days. Every 20 days the two FAME apertures will scan over the entire sky except for the regions within 45° of the Sun and the anti-Sun point.

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Dr. Kenneth J. Johnston of the U.S. Naval Observatory, who is the Principal Investigator of the FAME mission, leads the FAME team. The U.S. Naval Observatory is providing the oversight of the scientific objectives, budgetary oversight, mission operations and data analysis, and leading the education and public outreach effort. The Naval Research Laboratory is the home institution of the Project Manager, Mr. Mark S. Johnson, and is responsible for the project management, system engineering, and spacecraft bus development, integration, and test. The instrument design, fabrication, testing, and support are the responsibility of the Lockheed Martin Space Systems Advanced Technology Center. The Smithsonian Astrophysical Observatory is responsible for algorithm development and for the synthesis and verification of the scientific measurement system.

2. SCIENTIFIC OBJECTIVES

Astrometry involves the measurements of the most fundamental parameters of stars. Because it is the backbone upon which most of astronomy rests, a substantial improvement in astrometric precision can result in a revolution in many branches of astronomy and astrophysics. By improving the precision of astrometric measurements by a factor of 20 and increasing the sample of stars for which accurate distances are known by a factor of 400, FAME will enable advances across numerous branches of astrophysics and refine our model of the Universe.

FAME will measure the positions of 4×10^7 stars based on an input catalog. For the bright stars ($5 \le m_V \le 9$), FAME will determine their positions to better than 50 microarcseconds (μas). For fainter stars ($9 \le m_V \le 15$), the lower signal-to-noise ratio resulting from fewer photons will degrade the astrometric precision to ≈500μas at the faint limit. The target accuracy as a function of stellar magnitude is shown in Table 1. A catalog with such high astrometric accuracy for a large number of stars will have broad applications in astrophysics, particularly in the areas of stellar evolution, brown dwarfs and exoplanets, galactic structure and rotation, and the extragalactic distance scale.

Table 1: FAME target accuracy as a function of star brightness

Magnitude	Accuracy
$5 \le m_V \le 9$	< 50 μas
$m_V = 10$	< 74 μas
$m_V = 11$	< 107 μas
$m_V = 12$	< 158 μas
$m_V = 13$	< 234 μas
$m_V = 14$	< 340 μas
$m_V = 15$	< 500 μas

1. Extragalactic distance scale

Standard candle stars, such as Cepheids and RR Lyraes, serve as the foundation of the extragalactic distance scale. The nearby Cepheids and RR Lyrae stars, which are used to calibrate distances to further stars, were too faint for Hipparcos to obtain accurate distances. The FAME magnitude range, however, is optimized for observing the nearby Cepheids and RR Lyrae stars. Figure 1 shows the distances and apparent magnitudes of the ≈198 known nearby Cepheids and ≈233 known RR Lyraes in relation to the FAME projected accuracies.

2. Stellar companions

The precision of FAME will allow the astrometric detection of companion masses to the FAME target stars. The minimum mass of the companions detectable is dependent on the mass of the target star, the distance to the star, period of the orbit, and the semi-major axis of the companion's orbit. FAME will detect hundreds of sub-stellar companions of solar type stars, as well as thousands of previously unknown stellar companions. FAME will be able to detect Jupiter mass planets in Jupiter like orbits around Sun-like stars (see Figure 2). FAME is particularly well suited for detecting masses in the speculated transition region between brown dwarfs and giant planets in the range of 10 to 30 M_{jup}. From the large sample in the FAME survey, researchers will be able to determine the frequency of solar-type stars orbited by brown dwarf companions in the mass range of 10 to 80 M_{jup} with orbital periods up to twice the duration of the FAME mission. It will also identify interesting stars with apparent astrometric variations due to planets or planetary systems that would be potential targets for SIM and TPF observations.

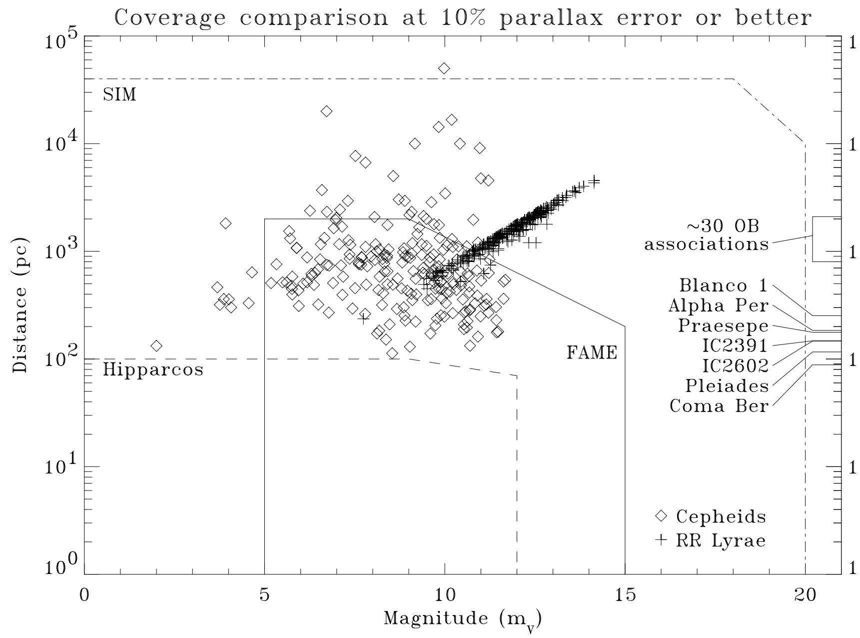

Figure 1: Comparison of the relative accuracies of Hipparcos, FAME, and SIM. The lines for the three missions indicate the distances for which the parallax error is 10%. Below the lines (for closer stars), the parallax error will be less than 10%. While SIM will provide much better accuracy, it is a pointed mission and cannot observe as large of a sample of stars as FAME. Diamonds (◇) indicate Cepheids and plusses (+) indicate RR Lyrae stars. Distances to open clusters are indicated on the right side of the figure.

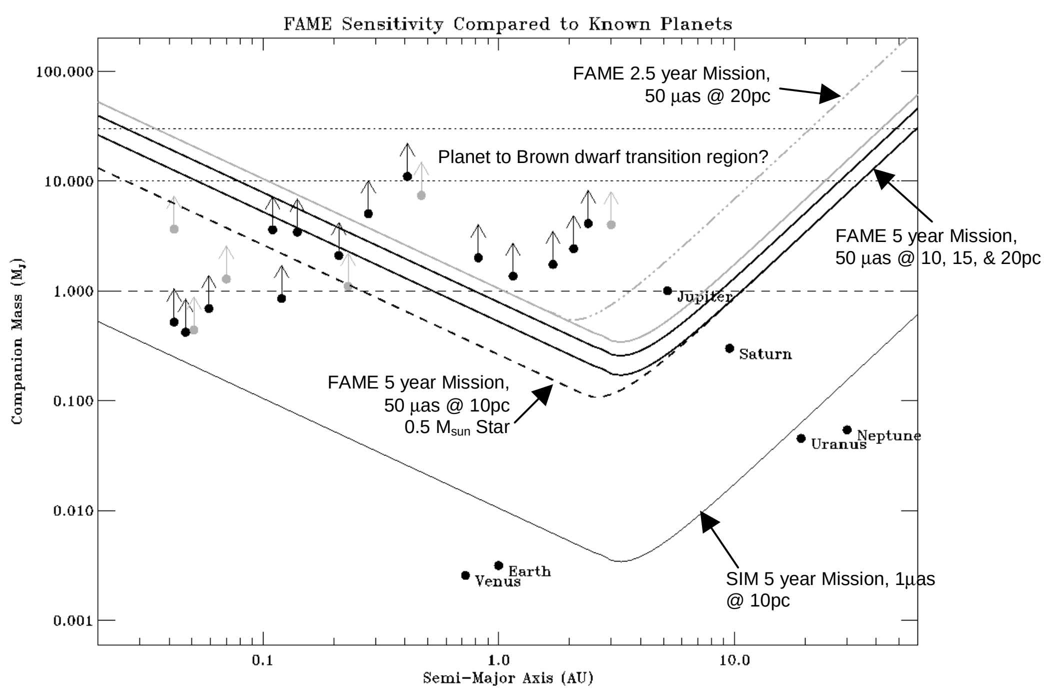

Figure 2: The precision of FAME is compared to the known exoplanets and the SIM predicted precision. The masses of the known planets are minimums because the inclinations of the systems are unknown. The FAME sensitivities are plotted for stars at 10, 15, and 20 parsecs for a host star mass of 1.0 M_{sun}. The dash-dot line is for the case of a 2.5 year FAME mission, and the dashed line is for a host star mass of 0.5 M_{sun}.

3. Long-term variability of Sun-like stars

Depending on the position of the star relative to the ecliptic, FAME will make photometric observations on a regular basis; for the case of Polaris, FAME will make photometric observations every 10 days. Table 2 lists the projected photometric precision of the FAME observations. Over the five-year lifetime of the mission, it will sample the long-term variability of ≈40,000 Sun-like stars in the FAME input catalog (see Table 3). This dramatically increases the number of stars by a factor of 100 available for accurate variability studies. Researchers will be able to use this database to search for magnetic activity cycles analogous to the 11-year solar activity cycle[3]. It will also enable us to put the Sun's activity level into context of other, similar stars. Is the current solar activity level a result of its intrinsic parameters, or is the Sun just going through a phase of lower activity? The long-term behavior of solar-type stars is important in that it has implications for climate changes or conditions inimical to life, as solar activity is related to the energy output of the Sun and thus also Earth's climate. The FAME data, given the large sample of Sun-like stars, will hopefully indicate whether Maunder minimum type behavior is common in Sun like stars.

Table 2: The photometric precision of FAME as a function of magnitude and filter compared to Hipparcos. The astrometric filter refers to the "white light" observations by the astrometric CCDs. The g', r', and i' filters are the Sloan Digital Sky Survey filter set.

Magnitude	Astrometric Filter	g', r', i' Filters	Hipparcos Hp
8	0.0010	0.0016	0.011
9	0.0016	0.0025	0.015
11	0.004	0.006	0.033
13	0.010	0.016	
15	0.025	0.040	

Table 3: A rough count of the number of stars in the FAME catalog of various spectral types and luminosity classes at m_V≈10 (a total of 500,000 stars)

Luminosity Class	O	B	A	F	G	K	M0
I, II, III				3700	30000	50000	20000
V	45	130000	50000	130000	40000	9000	1170
White Dwarf		25	10				

4. Stellar structure and evolution

The extensive FAME database of accurate distances will calibrate the absolute luminosities of a large variety of spectral types including both population I and II stars. Researchers will be able to determine distances and ages of galactic open and globular clusters using the determined absolute luminosities (see Figure 1). FAME will also resolve the discrepancy in distances to the Pleiades and other open clusters[4]. This will enable diverse studies of stellar and galactic evolution only possible with a large database containing the fundamental parameters of a large statistical sample of stars.

5. Galactic dynamics

The proper motions and distances obtained by FAME will give the distribution of matter, both luminous and dark, in the disk of our galaxy. For the first time we will have an accurate 3-dimensional map of a significant portion of our galaxy to understand its structure.

6. Pathfinder for future missions

In addition to its primary scientific objectives, FAME will also provide important scientific and technological data for future missions. FAME will define a reference grid that can be used by future NASA and ESA space interferometry missions such as the Space Interferometry Mission (SIM)[5], Terrestrial Planet Finder (TPF)[6], and Infra-Red Space Interferometer (IRSI) Darwin[7]. FAME will also serve as a technological stepping stone between the Hipparcos mission and the GAIA mission[8].

3. MISSION DESIGN

FAME is designed for operation in a geosynchronous orbit with an inclination of 28.7°. A geosynchronous orbit was chosen to minimize disturbances caused by gravity gradients, magnetic fields, and eclipses. It also simplifies operations and communications by permitting the use of a single antenna in continuous contact with the spacecraft. The FAME spacecraft rotates slowly with a period of 40 minutes with a rotation axis perpendicular to the look directions of the two fields of view. The CCDs in the telescope focal plane are clocked in time-delayed integration (TDI) mode (a.k.a. drift scan mode) so that the accumulated charge packets track the star image as they sweep across the CCD. The rotation rate was selected based on the focal length of the telescope and an achievable read rate of the CCDs based on currently available space qualified analog electronics and analog to digital converters.

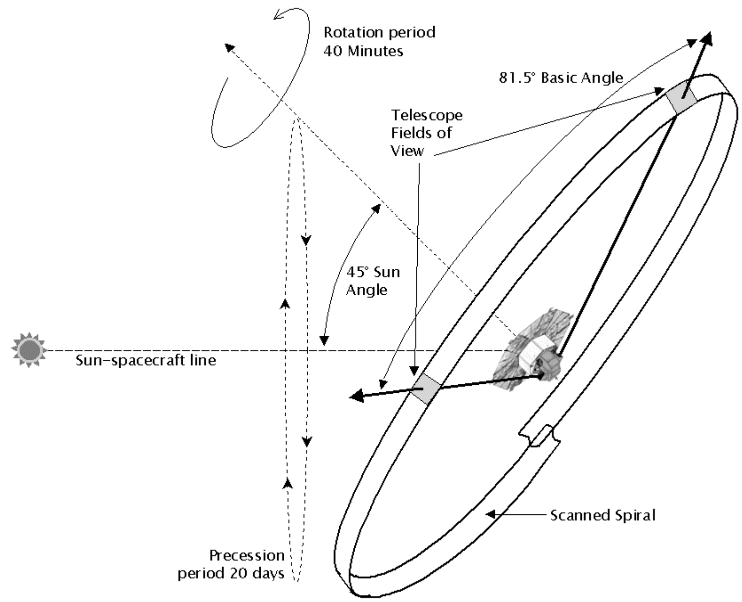

Figure 3: The axis of the FAME spacecraft is pointed 45° from the Sun and precesses around the Sun with a 20-day period. The FAME spacecraft rotates with a 40-minute period, sweeping out a spiral pattern on the sky. The two telescope fields of view are perpendicular to the rotation axis and are separated by an 81.5° basic angle.

The astrometric precision of FAME is enhanced by uninterrupted, smooth rotation so the telescope maps out a smooth trajectory across the sky[9]. To maintain a smooth trajectory of the telescope fields of view across the sky, yet scan the entire sky, solar radiation pressure is used to precess the rotation axis of the spacecraft. The rotation axis of the FAME spacecraft will be aligned 45º from the Sun-spacecraft line (see Figure 3). The spacecraft Sun-shield will not be a flat surface but will be slightly swept back (≈3°) to provide a primary control surface. The solar radiation pressure on the Sun-shield will provide the necessary torque of $\sim 3 \times 10^{-6}$ N-m. Trim tabs (Figure 4) attached to the edges of the Sun-shield will be actuated to fine tune the solar precession rate to a nominal 20 day period. During a 20 day precession period, the two FAME apertures will scan the entire sky except for the areas within 45° of the Sun and the anti-Sun point. These remaining areas of the sky are scanned as the Earth moves in its orbit about the Sun.

FAME will not conduct pointed observations. It will initially be aligned with its spin axis 45º from the Sun-spacecraft line, then it will be spun-up and precess on its own. Interruptions to observations during its five years of operation will be limited to station keeping maneuvers. Orbital and communications options are being investigated to determine the feasibility of eliminating the requirements of station keeping, thus allowing five years of continuous observations with FAME. Observation planning is thus minimal, requiring only the periodic updating of the FAME input catalog with positions for high proper motion targets or new targets.

4. SPACECRAFT BUS DESIGN

The FAME spacecraft bus design is being developed by the Naval Research Laboratory's Naval Center for Space Technology. Many of the components and procedures used on the spacecraft bus have heritage from the highly successful, fast-paced, low-cost Clementine satellite. The NRL Naval Center for Space Technology has built and launched over 87 satellites since 1960, thus NRL has extensive experience with spacecraft development. Figure 4 is a line drawing of the FAME spacecraft in its deployed configuration.

The FAME spacecraft bus was designed with a central thrust tube and structure to accommodate an apogee kick motor and a hydrazine propulsion system. Figures 5 and 6 show the FAME spacecraft in its stowed configuration and an exploded view. The apogee kick motor will be ejected in the disposal orbit prior to the beginning of science operations because of the

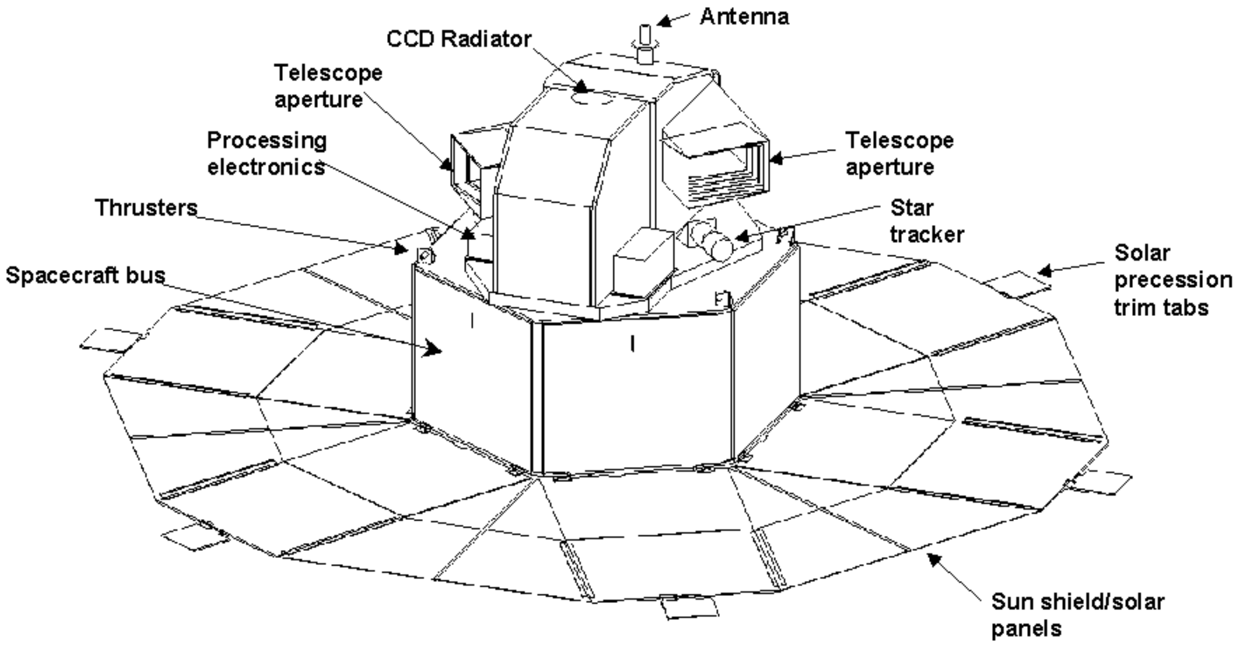

Figure 4: The FAME spacecraft shown in its deployed configuration. The Sun shield serves as a thermal shield, structure for the solar arrays, blocks sunlight from entering the telescope apertures, and as a "solar sail" to precess the rotation axis of the spacecraft. Trim tabs at the edge of the shield can be actuated to adjust the precession rate.

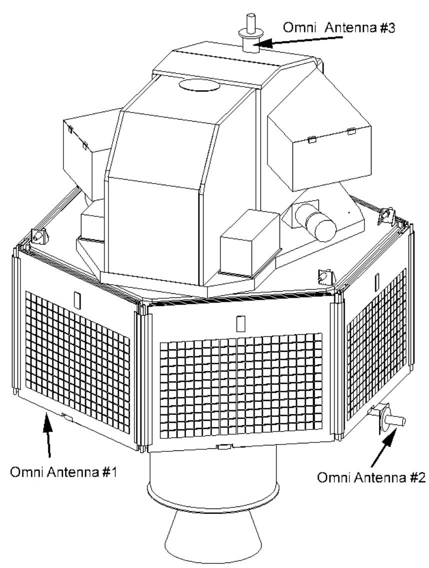

Figure 5: The FAME spacecraft in its stowed configuration. The solar panels are on the outside of the solar shield when stowed to supply power before deployment. Antennas 1 and 2 are used prior to the shield deployment.

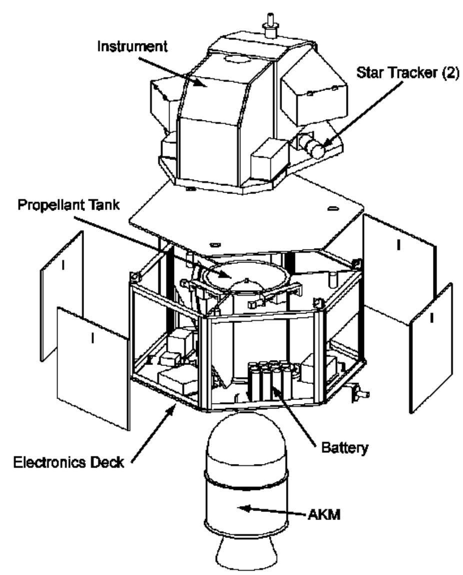

Figure 6: An exploded view of the FAME spacecraft. The spacecraft bus is designed with a central thrust tube and structure to accommodate an apogee kick motor (AKM) and a hydrazine propellant tank. The instrument subsystem is mounted using three point flexures.

uncertainty of the distribution of unburned propellant remaining in the motor, adding uncertainty to the spacecraft balance. Ejecting the motor allows the spacecraft to be accurately balanced on the ground and trimmed with balance masses on orbit to achieve the spin axis alignment required to effect the scientific goals.

The Sun shield screens the spacecraft bus and instrument from the thermal effects of direct illumination by the Sun, provides a structure on which the solar arrays are mounted, blocks sunlight from entering the telescope apertures, and acts as a "solar sail" to provide the torque required to precess the spacecraft. The shield will deploy on-orbit and will be slightly swept back (≈3°). The solar panels will be mounted on the six rectangular panels of the shield and it will be hinged such that the panels are on the outside when the shield is in its stowed position such that they can supply power to the spacecraft during early mission phases. Design trades are underway to determine how best to fill in the shield between the solar arrays.

5. INSTRUMENT DESIGN

Like Hipparcos, the FAME instrument uses a compound mirror to observe two fields of view simultaneously. The FAME compound mirror consists of two flats that feed a common telescope with fields of view separated by 81.5°. The separation of the fields of view is referred to as the "basic angle." This allows you to compare the position of a given star not only with its neighbors within the field of view, but also with its neighbors in the other field of view. This limits the growth of errors in relative star positions over large angles in the sky. The basic angle can be somewhat arbitrarily selected as long as integer factors of 360° are avoided. A large basic angle was selected for FAME to allow the telescope primary mirror to be positioned close to the compound mirror for a compact instrument design.

The two fields of view are fed into a common telescope with 15m focal length and a 58cm × 60cm rectangular primary; each field of view has a 25cm × 60cm aperture. The FAME telescope is a three mirror astigmat with five folding flats to fit the back focal length into the available volume.

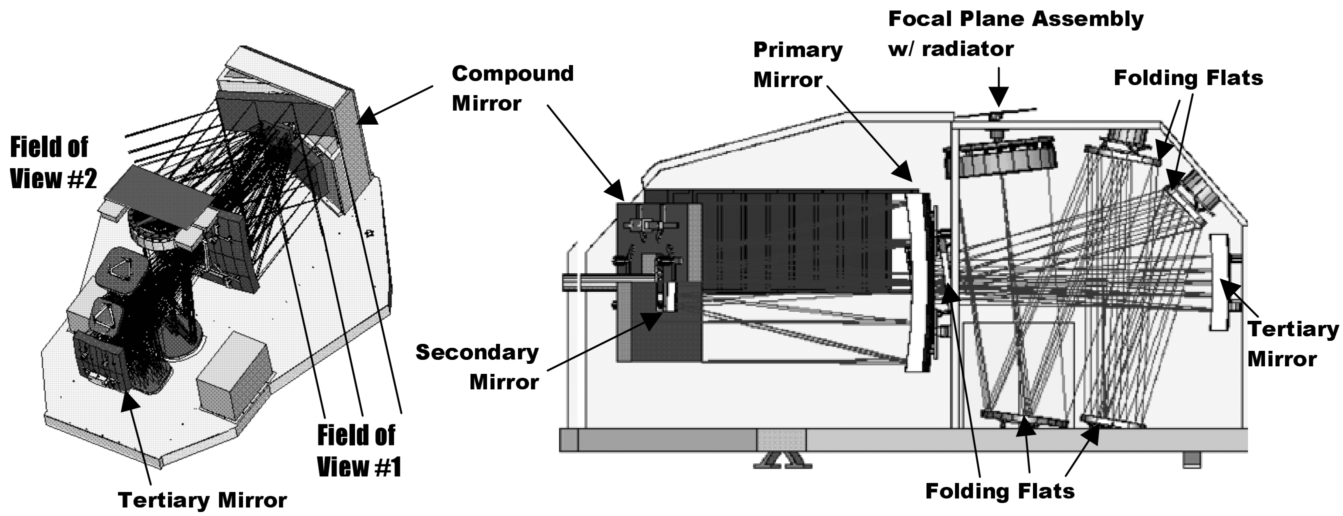

Figure 7: Angled and side views of the FAME instrument. The FAME instrument consists of a single telescope fed by a compound mirror. The telescope consists of a three mirror astigmat folded into the available volume using 5 fold flats. The focal plane assembly is mounted near the top of the instrument with a radiator panel mounted on the outside surface for passive cooling of the focal plane.

The telescope provides a flat image plane consisting of an array of large format CCDs, as shown in Figure 8. A total of 24 4k×2k CCDs with 15μm square pixels are read out in TDI mode to transfer the charge across the devices at the same rate the images are moving due to the spacecraft rotation. A BK-7 window covers the focal plane to control contamination of the CCDs, on-orbit CCD temperature, and the spectrum transmitted to the CCDs. Fourteen of the CCDs in the focal plane are used for astrometry of fainter stars ($9 \le m_V \le 15$) and "white light" photometry. The window is coated with both an IR rejection filter and an anti-reflective coating that also serves as bandpass filter, limiting the passband to 400 to 900 nm. Six of the CCDs have neutral density filters placed in front of them for astrometry of brighter stars ($5 \le m_V \le 9$) and "white light" photometry. The remaining four CCDs are used for wide band photometry using the Sloan Digital Sky Survey g′, r′, i′, z′ filters[10]. Each of the four photometric CCDs is covered by two Sloan filters; half of the CCD is covered by one filter and the other half by a different filter. This spreads the data collection in a single color across two CCDs to ensure that if one of the CCDs or signal chains fails, we do not loose all of the information in a single color band.

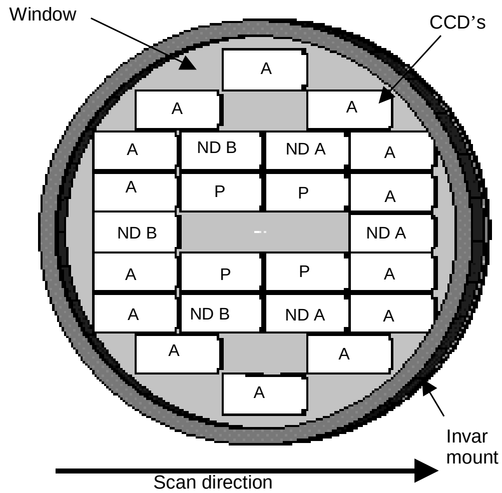

Figure 8: The FAME focal plane assembly. The 24 CCDs are arranged in the 1.1° diameter field of view (30.48 cm). Devices marked with a 'P' are the 4 photometric CCDs with Sloan DSS filters and those marked with an 'A' are the 14 astrometric CCDs. The 6 devices marked with 'ND' have neutral density filters for astrometry of brighter stars.

Given the 40 minute rotation period and the 15m focal length, the CCDs are clocked out full frame every 1.56 s, or 0.382 ms per row. To reduce the data rate to a more manageable level, on-board processing windows the pixels around stars in the FAME input catalog and only sends the data from those pixels to the ground. This data is also binned in the cross-scan direction to further reduce the downlink rate required.

6. DATA ANALYSIS

The data analysis for FAME will proceed in five major stages. First, the star images in the binned windows telemetered from the instrument will be centered to 1/350 of a pixel in the scan direction[11]. As FAME rotates and precesses, the fields of view will map out a spiral band, or observing spiral, on the sky. The second stage of the data reduction is to determine the relative positions of the centered images along the observing spiral. The observing spirals are then combined to form a single, global system in the sphere reconstruction phase, the third stage of the data reduction. The fourth stage is the determination of the individual star's astrometric parameters using least squares or Bayesian fit. The fifth stage is the photometric data reduction, which is actually performed in parallel with stages two through four. The improved photometric data on the star, which improves the model of the stellar point spread function and thus the centering fit, is fed back into the next iteration of the analysis along with the improved initial estimates of the astrometric parameters. The process will be iterated until it converges. The result will be an astrometric catalog more precise and rigid than any existing reference frame. Since this final solution may have a global rotation, the entire solution will be aligned with another established frame such as the ICRF.

7. SUMMARY

NASA selected FAME in October 1999 for the second of two MIDEX launches, one in 2003 and the second in 2004, with Phase B funding beginning in October 2000. During Phase B, the baseline design presented here will be reviewed and enhanced. In the interim, we are undertaking tasks to reduce program risk. Our foremost effort is to begin procurement of the focal plane CCDs since these are critical components that require a long lead time for delivery. This procurement process is now well underway.

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FAME is a joint development effort of the U.S. Naval Observatory, Lockheed Martin Space Systems Advanced Technology Center, Naval Research Laboratory, and Smithsonian Astrophysical Observatory.

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