Date: December 10, 2001 (v 3)

To: FAME Project Team, FTM-2001-17

From: Ralph Gaume

Subject: FAME Optics Design Metric

Introduction

FAME will provide the positions, proper motions, parallaxes, and photometry of 40 million stars, including nearly all stars as faint as 15th visual magnitude, with mission accuracies of 50 microarcseconds (μas) at 9th visual magnitude and 500 μas at 15th visual magnitude. Mission astrometric accuracies are derived from ~1500 observations of individual stars, each obtained with a required accuracy of 1/350 pixel (840 microarcseconds).

Measuring the position of a FAME stellar image (centroiding) involves fitting a model to a pixelated intensity distribution produced by a stellar observation under specific, temporally variable observational circumstances. Thus far no simple, direct method has been identified to translate the FAME single measurement centroiding requirement of 1/350 pixel into a Fabrication Metric (FM) such as encircled energy, Strehl ratio, or Wave Front Error (WFE). An immediate goal of the FAME optics working group is to identify a FM to ensure that the single measurement centroiding performance can be achieved by an as-built, as-flown FAME Telescope System (FTS). It is anticipated that the current effort may trigger changes in certain documents such as the FAME Instrument Requirements Document.

Current Status

The measurement error associated with an individual stellar observation (1/350 pixel) is expected to posses both systematic and random components. A realistic (pre-launch) treatment of observatory single measurement and final mission centroiding performance necessarily involves a detailed study of the reduction of single measurement errors into final mission accuracies. Due to the iterative nature of the FAME data reduction process, FAME observatory centroiding performance cannot be determined from an isolated study of centroiding algorithms, but necessarily involves a complete software package capable of simulating on-orbit spacecraft data collection, in concert with a robust data analysis pipeline capable of processing individual stellar observations into global astrometric solutions. Development of the data simulator and data analysis pipeline are currently underway. A functional prototype simulator and analysis pipeline will be available before FAME observatory Critical Design Review; unfortunately, the data analysis prototype development schedule does not adequately support instrument design efforts.

The centroiding performance of individual FAME observations and the functional reduction of random and systematic measurement errors to final mission accuracies are closely related to the quality and stability of the FAME Telescope System (FTS) Point Spread Function (PSF). To date, the evaluation and refinement of the FTS has centered on the analysis of estimated on-orbit PSFs. To help develop a Fabrication Metric (FM) for the FTS, in lieu of a functional data simulator and analysis pipeline, the USNO project team has written standalone simulation and analysis software to estimate FTS astrometric centroiding performance. This will be referred to as the Astrometric Metric (AM). Given a candidate FTS PSF, the USNO AM, incorporating in-scan and cross-scan smearing of 0.5 and 4.0 pixels respectively, fits a one dimensional Gaussian function with 4 free parameters (amplitude, width, position, background) to a one dimensional marginal distribution of a simulated stellar image. The software then reports the difference between the measured and known image position as a function of sub-pixel phase, in 0.001 pixel steps. The Gaussian fitting algorithm employed by the AM is a simple robust estimator of astrometric position, with extensive astrometric heritage. The USNO project team is currently carrying out numerical experiments to investigate optimal centroiding algorithms for use in the operational data analysis pipeline. The Gaussian algorithm coded into the current USNO AM may very well be used exclusively, in combination with supplemental algorithms, or replaced entirely in the production FAME data analysis pipeline.

Initial evaluation of FTS PSFs using the USNO AM has demonstrated a clear correlation between PSF asymmetry and sub-pixel phase bias in single observation centroid measurements. Previous efforts to mitigate or control PSF asymmetry have been concerned with reduction of the overall rms WFE. Unfortunately, rms WFE has not proven to be a useful FM. Calculation of a number of FTS PSFs, including “as built” levels of manufacturing errors and alignment tolerances, have shown that controlling the rms WFE to λ/13.5 still produces PSFs with significant degrees of asymmetry (Figure 1) resulting in large residual systematic errors as a function of sub-pixel phase (Figure 2).

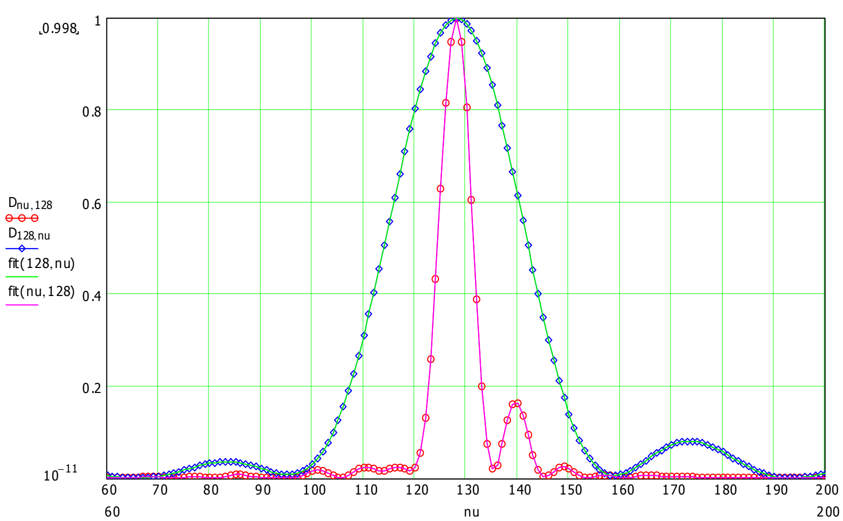


Figure 1. In-scan (red) and cross-scan (blue) on-axis PSFs for the current FTS (Cass design) For one “roll of the dice” wrt as-built manufacturing errors and alignment tolerances.

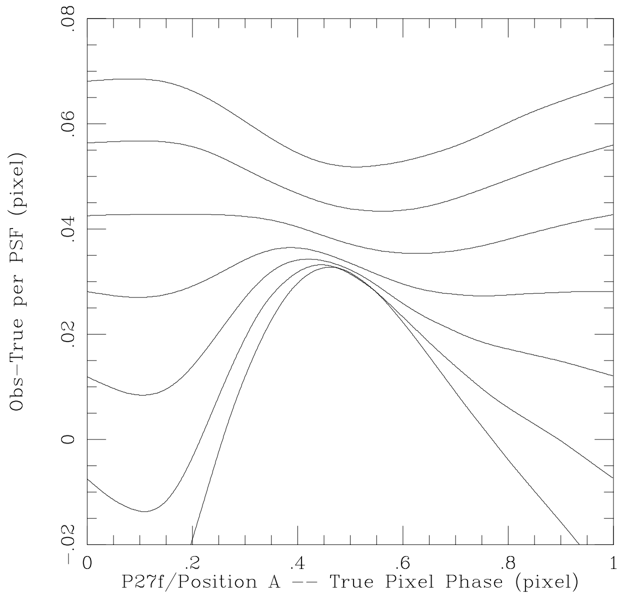


Figure 2. Sub-pixel phase bias as determined by the USNO Astrometric Metric (AM) software for the as-built PSF shown in Figure 1. The individual curves represent different wavelengths which are displaced vertically for display purposes.

Goodrich personnel have recently suggested that controlling rms WFE is not the most appropriate Fabrication Metric (FM) for minimizing single measurement centroiding bias (Goodrich memo FAME-01-019). Instead, Goodrich has suggested a FM which quantifies the ratio of PSF wings (PSF wing asymmetry). FTS fabrication tuned to this FM may produce more satisfactory centroiding performance by minimizing PSF asymmetry. Goodrich believes that FTS fabrication can selectively minimize the odd component of the WFE, which is largely responsible for PSF asymmetry (the even component of WFE primarily affects Strehl ratio). Figure 3 depicts the as-built PSF shown in Figure 1 both before (Fig. 3a) and after (Fig. 3b) “perfect” asymmetry correction (the odd component of the WFE is set to 0).

Outstanding Issues

The following issues are to be resolved by the FAME optics working group:

- How much PSF asymmetry can be tolerated by the data analysis pipeline reduction algorithms? The pipeline algorithm development schedule calls for the identification of centroiding algorithms by April 2002. Steps are being taken to accelerate the schedule.
- How much of the optics surface rms WFE is odd? Each term of the optics WFE budget is currently being evaluated by Goodrich for sensitivity to even vs. odd WFE.
- What are other sources of odd WFE in the FAME instrument? In addition to the optical surfaces, other sources of odd WFE must be evaluated. Are sources of odd WFE introduced during manufacture, assembly, alignment, or integration of the

structure? Does the on-orbit environment (thermal, outgas, etc) introduce odd WFE?

- To what extent can the odd component of the WFE be controlled during manufacture? PSF asymmetry mitigation may involve additional steps in the assembly, alignment, and integration stages.
- To what extent can the odd component of the WFE be controlled during operation of the FAME observatory. On-orbit PSF asymmetry control may involve instrument design modifications. The FAME telescope focus adjust mechanism (FAM), may need to be evaluated for the capability to control the odd component of the WFE.

Figure 3a. As built in-scan, cross scan PSF

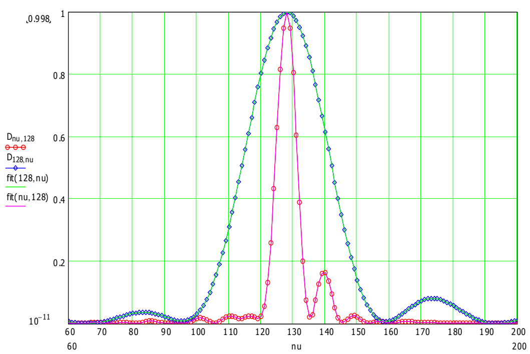
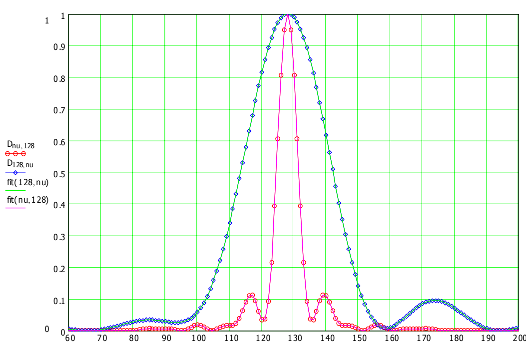


Figure 3b. As built in-scan, cross scan PSF. Fabrication asymmetry correction applied in-scan.



Near-term activities

Near term activities of the FAME optics working group must focus on the development of a Fabrication Metric (FM) for controlling PSF asymmetry. This metric should be reflected in project documents, e.g. the Instrument Requirements Document. To resolve outstanding issues, support development of a FM, offer potential support for the December NASA-HQ review and the upcoming Goodrich CDR, the following near-term activities are indicated:

- An Astrometric Metric (AM) is currently available at USNO-Flagstaff. PSFs processed through the AM which exhibit peak-to-peak variations less than or equal to 10 (TBR) millipixels @ 550nm (TBR) are deemed capable of meeting single measurement centroiding requirements. By 21 December, USNO-Flagstaff will repackage the AM for possible off-site operation by FAME project team members. USNO-Flagstaff will investigate the addition of lateral color to the AM by January 2002. The current AM will be replaced by an increasingly capable data analysis pipeline, by April 2002 (schedule to be accelerated).

- A Fabrication Metric (FM) will be developed and adopted by Goodrich and LMATC with the cooperation and concurrence of the FAME optics working group.

- Goodrich and LMATC will evaluate the optics WFE budget sensitivity to even vs. odd WFE.

- Goodrich and LMATC will identify a team and preliminary schedule for study of the degradation of as-built optics performance under on-orbit conditions and options for mitigation/control. Upon completion of this study a TBD number of as-built PSFs with asymmetry mitigation will be provided to the Project Team for analysis with the AM.