Full-sky Astrometric Mapping Explorer

CTE Degradation in FAME CCD's: Anticipated Astrometric Effect and Mitigation

James D. Phillips

Smithsonian Astrophysical Observatory
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA

Workshop on Hubble Space Telescope CCD Detector CTE

Space Telescope Science Institute
31 Jan. - 1 Feb., 2000

Full-sky Astrometric Mapping Explorer

- Oct. 1999: Approved for MIDEX launch in 2004.
  - 2½ yr NASA mission, 2½ yr DoD extension.

- Oct. 2000: Phase B starts.

- Institutions collaborating:
  - USNO
    - Institution of the PI, Ken Johnston; data analysis.
  - SAO
    - Synthesis & verification of the scientific measurement system.
  - Lockheed
    - Instrument.
  - NRL
    - Spacecraft and Integration.

CCD Committee

Richard Vassar, LMCO, Chair
Earl Aamodt, LMCO
John Geary, SAO
Fred Harris, USNO
Scott Horner, LMCO
Mark Johnson, NRL
Ken Johnston, USNO
Paul Marshall, Consultant to NRL
Dave Monet, USNO
Jim Phillips, SAO
Ken Seidelmann, USNO

LMCO = Lockheed-Martin Corp.
NRL = Naval Research Lab.
SAO = Smithsonian Astrophysical Observatory
USNO = U.S. Naval Observatory

Outline

- Description of FAME from a CCD perspective.

- Radiation dose and damage.

- Mitigation.
  - I will present a number of options, and argue that injection of fat zero row(s) is required.

I seek comments on all aspects of FAME CCD’s, in particular,

- the damage estimate,
- the necessity of fat zero, and
- other options, including any that might advantageously replace the fat zero.

FAME Overview

- ❑ Astrometry of 40×10^6 stars.
  - Position, parallax, proper motion.
  - $\sigma_{\text{mission}} \leq$ 50 microarcsec (µas) – Bright ($m_V \leq 9$)
  - $\sigma_{\text{mission}} \leq$ 500 microarcsec (µas) – Faint ($9 < m_V \leq 15$)
  - Cf. Hipparcos (1989-93): 1 milliarcsec (mas), 10^5 stars, complete $m_V < 7.3$-9.

- ❑ Photometry.
  - Sloan g', r', i', z' filters.
  - 1 millimagnitude mission accuracy.

- ❑ Objectives include
  - Cepheid and RR Lyrae distance scales σ (distance) $\lesssim 2\%$.
  - Low mass companion survey:
    - ▲ Companion mass > 8×Jupiter; 24,000 solar-type stars; d<100 pc.
  - Map disk dark matter to ~1 kpc.
  - Variability of solar-type stars.

Continuously-Rotating Spacecraft, I

- ❑ Rotating telescope.
  - Focal length = 15 m.
  - 1.1° FOV.
  - 0.2 arcsec/pixel.
  - 1000 (2000) observations per star in 2.5 (5) yr mission.
  - Required single-observation position accuracy :
    - ▲ Bright 500 µas (averageable)
    - ▲ Faint 10 mas (averageable)

- ❑ Rotation period = 40 min.
  - Spin axis precesses about Sun direction every 20 days.
  - Full sky coverage, all directions, in 6 months (Earth orbit around Sun).

- ❑ Sky crosses focal plane at a uniform rate.

Continuously-Rotating Spacecraft, II

- ❑ Solar shield keeps instrument in Sun shadow at all times.
  - Thermal stability over few-minute period is critical.

- ❑ Two look directions separated by 81.5°.
  - Compound mirror superimposes look directions on one focal plane.
    - ▲ Angle not critical, stability is critical.

- ❑ Two apertures, one for each look direction. Each is
  - 0.6 × 0.25 m (= S × C, scan by cross-scan)

- ❑ Stellar background ~0.1 e/pixel.
  - This is too faint to fill traps and mitigate CTE degradation.

CCD Operation, I

- ❑ Time-Delayed Integration (TDI)
  - Charge clocked along columns to remain under the image.
    - E.g., 3 phase transfer, each phase having equal duration, to follow image closely.
  - Time on detector = 1.56 sec.
  - Line transfer time = 380 µsec.

- ❑ Onboard catalog controls
  - Data windows
  - Fat zero injection
  - Start-Stop Technology (SST)
  - Binning

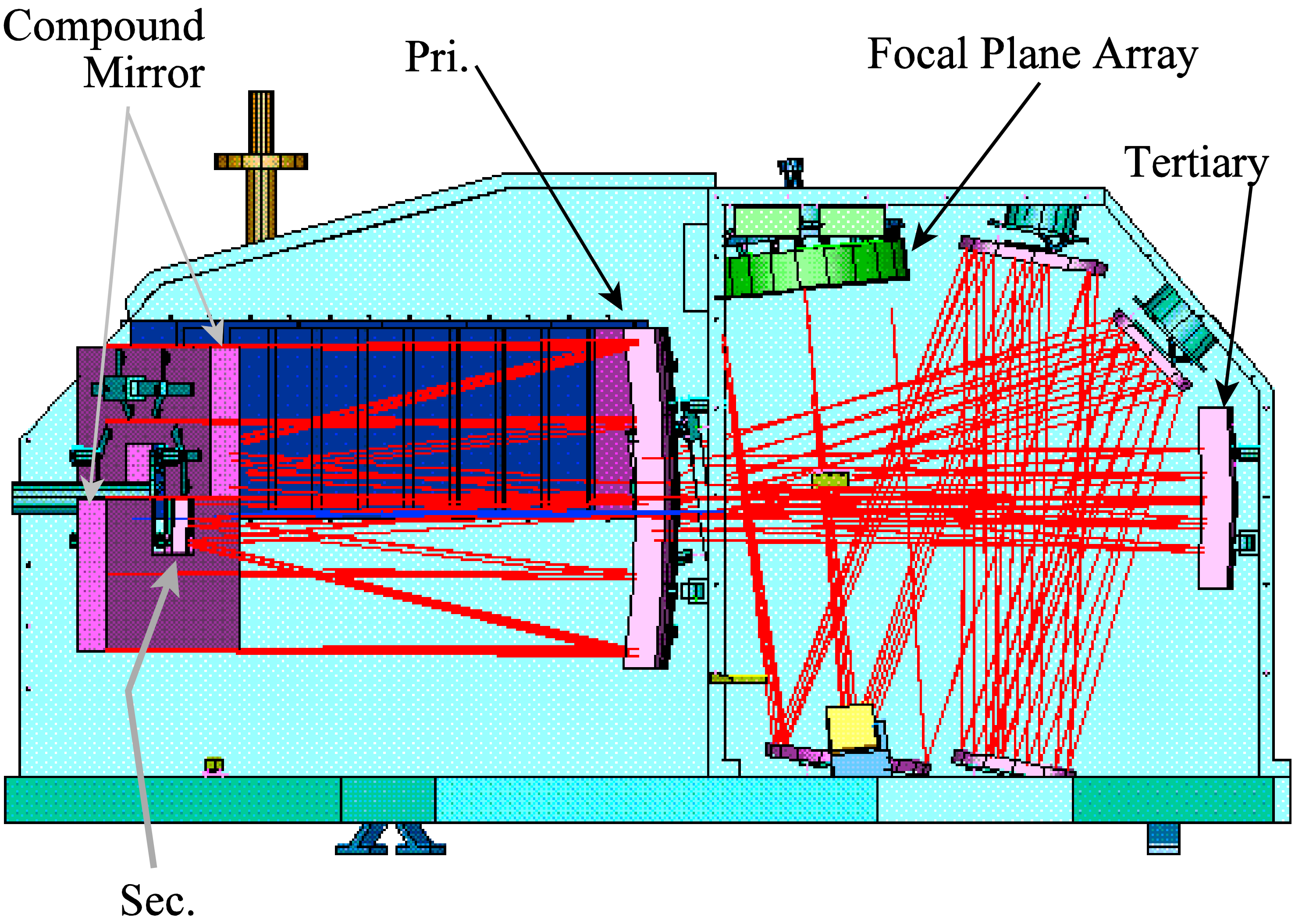
CCD Operation, II

- Start-Stop Technology (SST)
    - To avoid saturation on bright stars, interrupt clock to create multiple images.
    - An evolution of a GAIA concept (stop clock until star near enough to serial register).
        - FAME considering multiple stop-starts.
    - Alternative is ~7× and ~40× attenuating filters over some chips.
        - Significantly reduces information rate.

- Binning
    - On faint stars, co-add 20 pixels in serial register: send down 10 rows, each 1 co-added pixel wide.
        - Reduces read noise and telecom rate.
    - On bright stars, send down every pixel in 10 row × 20 column area.
        - Perhaps on some bright stars send only 10 rows × 2 co-added columns.
        - Bright stars are rare, so 10× telecom load is unimportant.


FAME
Full-sky Astrometric Mapping Explorer

Instrument cutaway view



FAME CCD Requirements

Parameter	Requirement
Architecture/Process	Triple-Poly, N-Buried Channel, Backside Illuminated. Perhaps notch.
Image Area Format	4096 pixels × 2048 pixels Full Frame. TDI along vertical (4096).
Number of chips	20 astrometric, 4 photometric
Gap between adjacent CCD's	Quasi-four-side buttable.
TDI independent of output transfer	Array transfer gate
Pixel Size	15 µm × 15 µm
Fill Factor	100%
Image Area Pixel Full Well	10^5 e^-
Vertical Transfer Rate	≥10 kHz (actual will be 2.6 kHz)
Signal Readout Rate	≥3 MHz
Conversion Gain	$\geq 2 \times 10^{-6}$ v/e.
Dark Current (-70°C)	<0.05 e^- /pixel/sec
Readout Noise (20× binned)	≤7 e^- rms @ 135 kHz, -70°C
Linearity 10% - 100% Full Well	≤5%
Operating Temperature	-70°C
Wavelength limitation	0.4 to 0.9 µm (window over FPA)

Detected Counts

- m_V = 9, blackbody, T=5777°K.
- Not accounted for here:
  - Precession spreads in cross-scan.
  - Charge diffusion spreads in both directions (FWHM ~ 18 µm).
- Pixel = 0.2 arcsec.
- λ_o/S = 0.2 arcsec (scan) λ_o=0.6µm
- λ_o/C = 0.5 arcsec (cross-scan).
- Observation: 10 pixels scan × 20* cross-scan. *co-added for m_V>9.

Electrons per pixel in 5×5 (5×6) pixel area surrounding image center.

Cross-scan

Scan

Star at Center of Pixel				
4403	17366	26715	17366	4403
4286	24228	44283	24228	4286
25239	136650	244050	136650	25239
4286	24228	44283	24228	4286
4403	17366	26715	17366	4403

Star Between Pixels				
2070	7391	11660	7391	2070
4206	24126	42654	24126	4206
15447	80323	142190	80323	15447
15447	80323	142190	80323	15447
4206	24126	42654	24126	4206
2070	7391	11660	7391	2070

Dose and Damage

- "Space Radiation 4" estimate of the proton fluence
    - 10 mm Al shielding – will probably use more.
    - 3 yrs at solar maximum, 5 yrs total
        - This analysis was done for '03 launch; nominal '04 launch avoids one year of solar maximum.
        - Will need to be re-run with updated orbit, epoch, and shielding.
    - Geosynchronous orbit
    - Yields 6×10^9 protons/cm^2 (probably pessimistic – shielding, epoch).

- This dose creates a trap density of roughly 10^{11} cm^{-3} (also pessimistic).

- A 1000 e$^-$ packet ($m_V = 15$) sees roughly 3000 traps at end of mission.
    - Background ~0.1 e$^-$/pixel.
    - Without mitigation, this star is not detected (but is required to be).

- A 100,000 e$^-$ packet ($m_V = 10$) sees roughly 30,000 traps at end of mission.
    - Average astrometric shift ~0.3 pixel = 60 mas (not Poisson distribution).
        - Cf 500 μas single-observation accuracy.
            - $\sigma(\text{shift}) > 60\,\text{mas}/\sqrt{30{,}000} = 0.35\,\text{mas}$ because trap distribution is not Poisson.
        - Mitigation required.

Mitigations (Unworkable?)

- Uniform fat zero, e.g., from uniform illumination.
  - To fill all the traps that interact with a large packet, fat zero must be as large as the large packet.
    - Even so, packet rides on top, sees additional traps.
    - Reduces effective full-well.
    - Shot noise from fat zero charge.

- Modeling, with no fat zero or notch.
  - Small packets *hardly get detected*.
  - Must remove a large effect for large packets.
    - A very accurate model is not necessarily possible.
      - Several trap lifetimes.
      - Effective trap density *vs.* packet size.
      - Traps increase sporadically with time.
      - Variation of numbers from column to column.

Candidate Strategies

- ❑ Notch.
  - Probably helps with small packets, but doesn't solve large-packet problem.
    - However, the large-packet problem *might* be manageable with modeling.
  - May be hard to prove that it's there.
  - Requires cost-benefit trade.

- ❑ Clocking.
  - Keep one phase high (integrating), and two phases low (barrier), except during brief switching intervals. 130 µsec/transfer; 380 µsec/row.
    - Charge re-emitted from short-lived traps ($\tau < 30$ µsec) mostly returns to packet it came from, over the integrating electrode.

- ❑ Change temperature.
  - Shift emission time constants (τ).
    - Lengthens or shortens τ for all traps at once.
  - Capture time constants not very sensitive to temperature.

- ❑ Additional shielding.
  - By itself, unlikely to solve large-packet or small-packet problem.

Selectively-Injected Fat Zero

- ❑ Just before a star comes onto the chip, inject charge.
  - Whole row
    - *Via* dump drain.
  - Half row.
  - Partial row, just that part in front of the star.
    - *Via* an input serial register.
    - Minimizes interference with other stars, but may require substantial customization of CCD design.

- ❑ Charge travels ahead of the star, filling traps.
  - Larger packets see more traps, so need large fat zero.
    - To assure that fat zero is large enough at the end of the columns, may need to inject > 1 row – optimization to be performed.
  - Smaller packets may be affected by shot noise from re-emitted fat zero charge.
    - *If so,* inject smaller fat zero for fainter stars.
    - Effect of re-emitted fat zero charge:
      - From long life traps (defined below): probably OK.
      - From medium life traps: depends on lifetime & density.

- ❑ For long-lived traps, the problem is solved.

- ❑ Remaining error (from medium life traps) must be removed by modeling.

Trap Lifetimes

- Long life traps
  - $\tau \gtrsim 20$ msec: traps still full when image arrives (3-10 msec after fat zero).

- Medium life traps
  - $\tau \lesssim 20$ msec: some fat zero charge is re-emitted before image arrives, and
  - $\tau > 30$ μsec: some trapped signal stays trapped during a 130 μsec transfer.

- Short life traps
  - $\tau < 30$ μsec: trapped signal re-emitted into signal packet (if equal time in each clock phase, one phase integrating at a time).

- The most abundant traps have long or short life, not medium.
  - Si-E centers, $\tau \gtrsim 100$ msec.
  - Shallow divacancy level, $\tau \sim 1$ μsec.

- Mitigate by making capture time >> transfer time?
  - Capture time at -70°C ~1 μsec.
    - Only a weak function of temperature.
    - A function of density, but need very low density (very small signal packet) to make

Effect of Medium Life Traps

- ❑ Estimate number of medium life traps, and its standard deviation.
  - *Suppose* that 10% of traps have medium life (this may be very pessimistic).
    - ▲ 300, for 1000 e^- packet.
    - ▲ 3000, for 100,000 e^- packet.
  - If distribution were Poisson, standard deviation of <u>the number of traps in a column</u> about the mean number in a group of similar columns would be 17 (55).
  - Roughly half the traps are created by a few nuclear and (p,n) reactions.
    - ▲ Suppose that the standard deviation is actually 50 (150).
  - Could adjust CCD temperature to change distribution of trap lifetimes.

Both the estimates of the fraction of medium life traps and of their standard deviation are very preliminary.

Modeling Medium Life Traps

For faint stars, the worst case.

- ❑ Bias variation, column to column, on 1000 e^- packet, resulting from σ(# of single-electron traps) = 50

$$\sigma(\text{angle}) \sim \frac{50}{1000}\,\text{pixel} = 10\,\text{mas}$$

- ❑ Mission accuracy for $m_V = 15$ is 500 µas. Requires total single-observation error < 10 mas (lower if there are correlations).

- ❑ Bias is different for each column.

- ❑ Bias is the same for all observations in one column at a particular epoch.
  - ● 10^6 observations per column, ~10^4 before significant additional radiation.
  - ● Each observation has a precision of ≤ 10 mas.
  - ● Average of 10^4 can have a precision of ≤ 100 µas, amply adequate.

- ❑ Can estimate time-dependent, magnitude-dependent bias, on a column-by-column basis.

Fat Zero Bars as Probes of CTI

Post script, written Wed. 2/2/00.

- The fat zero bars can serve as frequent, controlled probes of CTI.
    - If amplitude of fat zero is matched to star brightness, fat zeroes of many amplitudes are automatically generated.
        - Sending to the ground only a tiny proportion of fat zero bars will constitute a thorough sampling of the column-by-column CTI variations.
            - Probes as a function of magnitude and time.
        - Need to investigate how well the amplitude of the fat zero can be known.
    - Determine
        - The number of medium-life traps (most important – see above)
            - Charge in a tail several pixels long following the fat zero bar.
        - The number of long-life traps (of interest)
            - Charge missing from the fat zero.
        - The number of short-life traps (perhaps of interest)
            - Could, if necessary, do a calibration fat zero, with clocking designed *not* to keep the re-emitted charge in the packet.
    - Possibility of determining the CTI, to the level required by FAME, independent of the astrometric solution.
        - If so, it is a considerable simplification.
    - This idea suggested at approximately the same time by P. Marshall, J. Geary, and R. Reasenberg. S. Casertano raised the possibility of injecting a noiseless fat zero bar.