An Approach to FAME Data Processing

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Objectives of Talk

- Present a framework for data processing to
  - support algorithms
  - clarify relationships among algorithms
  - form the basis for the design of the software

- Not to address the selection of algorithms

Notes added after presentation:

1. Some people present at USNO objected to the term "centroid" on technical grounds. We need an acceptable name for the location (and for the process of finding the location) of the point within the PSF that represents the direction to the unresolved target.

2. On page 11 [A - II]: we now know that the PSF parameter estimates and star "centroid" estimates are improved by the use of the photometric data, which helps to determine the temperature parameter of the PSF model.

Outline of Talk

- Heritage and metaphor
- Data flow diagrams
- Functions of key processes in the DFD
- Some options

Heritage & Metaphor

- Analysis methods used over 30 year span for solar-system dynamics, tests of relativity, and planetary gravity.
  - LLR: σ = 1 cm; d = 4×10^{11} cm; ratio = 2.5×10^{-11}
  - Viking ranging: σ = 10 m; d = 1AU = 1.5×10^{11}; ratio = 7×10^{-11}
  - cf. FAME: 0.5 mas = 2.5×10^{-9}

- Report of Committee on "Data Modeling & Reduction — from Pixels to Product"
  Reasenberg, Greene, Horner, Van Buren, Jefferys, Monet, Phillips, Seidelmann, Urban, Vassar

- RDR draft text for FAME proposal (incorporated ideas from proposal text)

- Data Flow Diagram
  - Was an industry standard a few years ago (along with control flow, structure and state-transition diagrams)
  - Out of favor with s/w engineering community
  - May still be valid as means for scientists and engineers to discuss processes

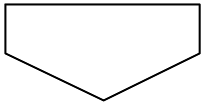
Define Symbols for DFD

A process. If shadowed, details are available on another page. Linked processes have a "link icon" above and to the left of the box.

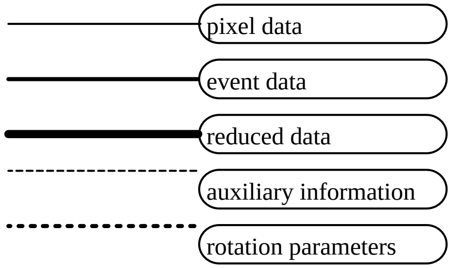
Information coming from or going to another level of the diagram.

A set of information (file, database, etc).

A set of externally supplied information, e.g., Hipparcos- or FAME-based estimates of star coordinates.

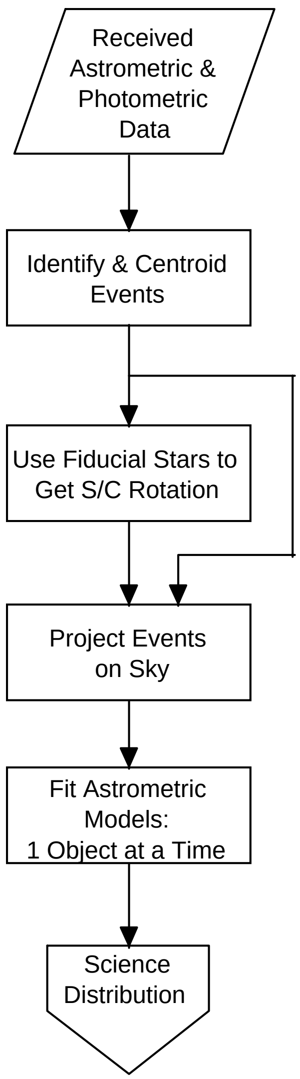


Product: output from the analysis.



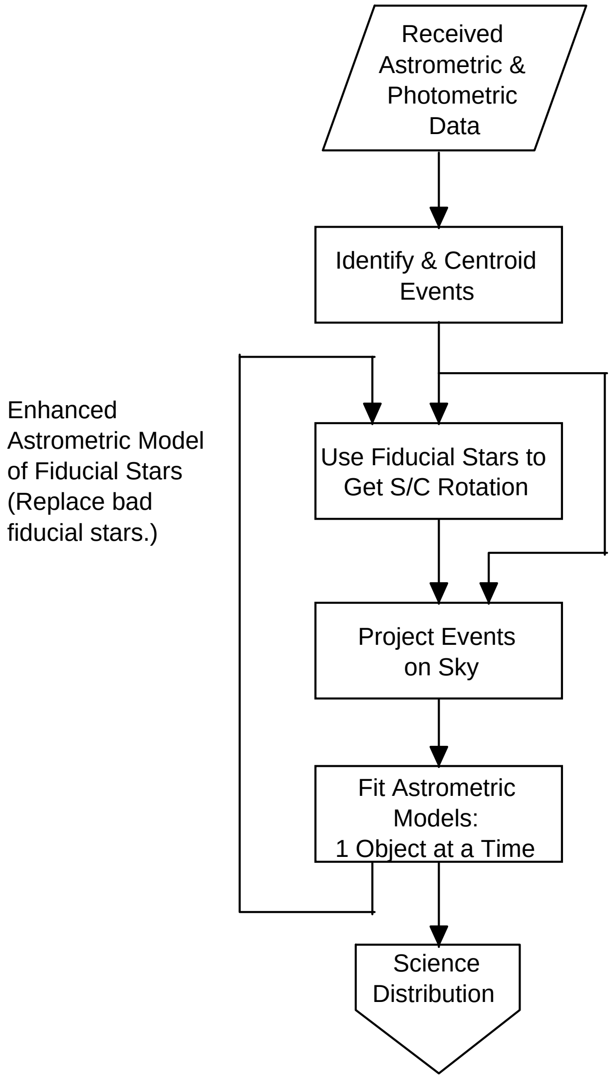
Simplified DFD

Simplified Data Flow for Astrometric Data



file = ...\usno-ast\f-data\DF99A1
last update = 7/15/99

Simplified DFD with Iteration

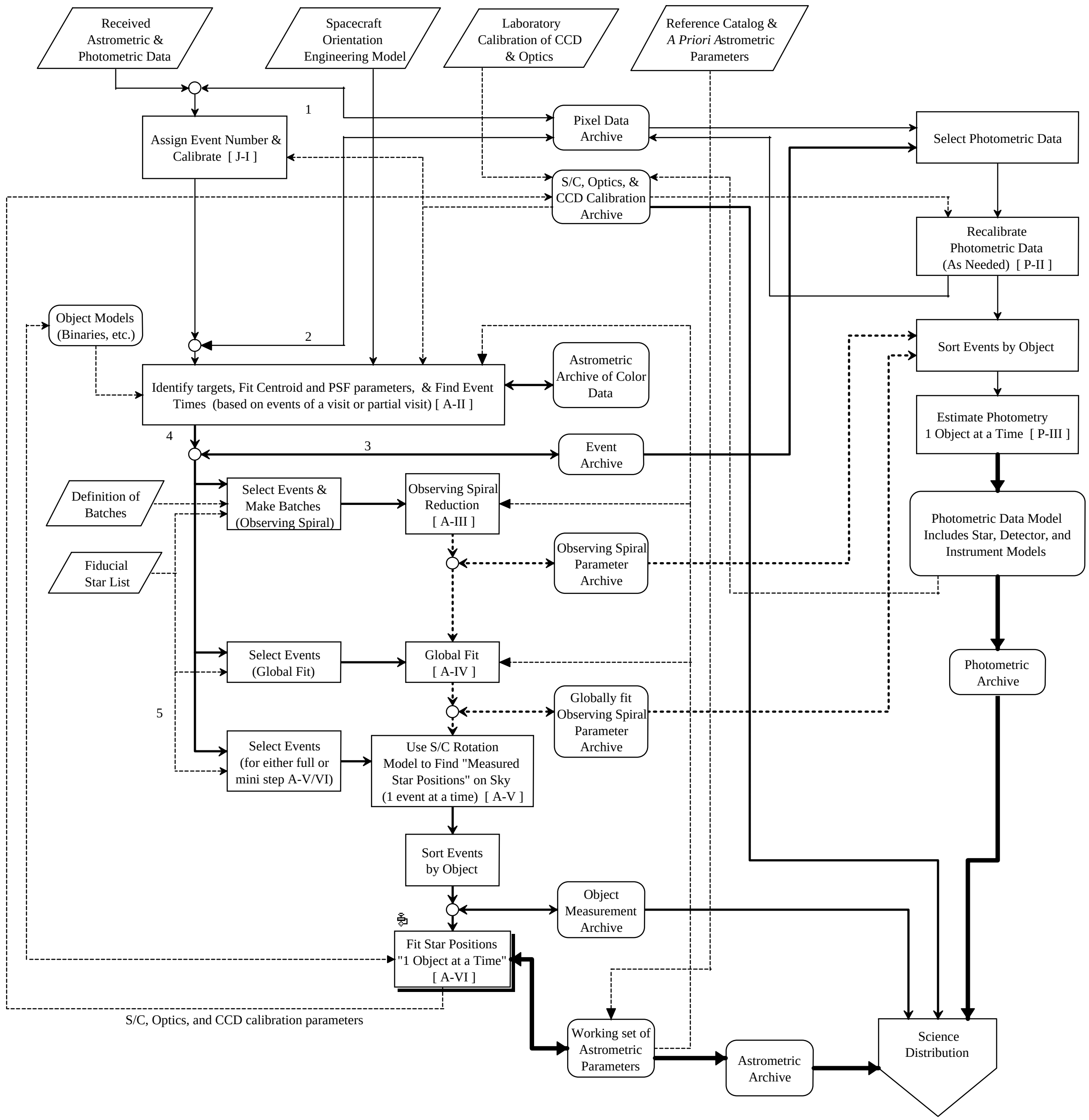


Net result of iteration:

- Clean set of fiducial stars. (Astrometrically bad stars replaced.)

- Consistent set of astrometric parameters for fiducial stars based on FAME accuracy.

- On average, fiducial stars consistent with catalog from which originally taken.



Received Astrometric & Photometric Data
Spacecraft Orientation Engineering Model
Laboratory Calibration of CCD & Optics
Reference Catalog & *A Priori* Astrometric Parameters
1
Assign Event Number & Calibrate [J-I]
Pixel Data Archive
Select Photometric Data
S/C, Optics, & CCD Calibration Archive
Recalibrate Photometric Data (As Needed) [P-II]
Object Models (Binaries, etc.)
2
Sort Events by Object
Identify targets, Fit Centroid and PSF parameters, & Find Event Times (based on events of a visit or partial visit) [A-II]
Astrometric Archive of Color Data
Estimate Photometry 1 Object at a Time [P-III]
4
3
Event Archive
Definition of Batches
Select Events & Make Batches (Observing Spiral)
Observing Spiral Reduction [A-III]
Photometric Data Model Includes Star, Detector, and Instrument Models
Fiducial Star List
Observing Spiral Parameter Archive
Select Events (Global Fit)
Global Fit [A-IV]
Photometric Archive
5
Globally fit Observing Spiral Parameter Archive
Select Events (for either full or mini step A-V/VI)
Use S/C Rotation Model to Find "Measured Star Positions" on Sky (1 event at a time) [A-V]
Sort Events by Object
Object Measurement Archive
Fit Star Positions "1 Object at a Time" [A-VI]
S/C, Optics, and CCD calibration parameters
Working set of Astrometric Parameters
Astrometric Archive
Science Distribution

Notes for numbered lines

1. Uncalibrated data flows from pixel data archive when recalibrating.

2. Calibrated data flows from pixel data archive when applying new object models.

3. Data flows from event archive when adding fiducial stars.

4. An event comprises the epoch of star passage, the chip number, the lateral centroid, the star identification, and the object model, if used.

5. The fiducial star list is needed by event selection for stage "mini-step A-V/VI", not for step A-V/VI

Assign Event Number and Calibrate Pixel Data

[J - I]

- Assign a unique event number (for both astrometric and photometric data).

- Check for quality and for signs of instrument irregularity immediately after downlink
  - Any anomalies will trigger an anomaly recovery activity.
  - Mark "junk events"

- Calibrate raw pixel data.
  - e.g., known column-specific variations in CCD detection efficiency

Fit Centroid and PSF Parameters

[A - II]

- Identify the target based on
  - knowledge of the spacecraft rotation (e.g., from on-board real-time analysis)
  - target catalog
- Fit centroid and PSF parameters using
  - calibrated pixel levels
  - auxiliary information including CCD column numbers and row-shift epochs
  - all events of a given star obtained during a single visit
- For targets determined to be unresolved binaries or more complex objects
  - use correspondingly augmented models
- Additional calibrations are applied to each event
  - calibration parameters will have only nominal values at the start of the mission, but will be usefully determined and applied during iteration
  - delay associated with the CCD
  - delay associated with the location within the CCD
  - function of time

PSF Model

- Algorithm development required

- SAO TM99-06 presents results of numerical studies with one class of algorithm.
  - PSF model parameters include stellar magnitude and temperature
  - Main sequence stars are fit with f.l. = 7.5 m
  - Biases from deliberate mismodeling investigated
  - PSF model parameters may also include metalicity and surface gravity
  - Gunn-Stryker objects to be studied

- Monet has studied a model with 15 spectral lines
  - The amplitude of each line is estimated

- Other approaches should be considered

- Key questions for each approach
  - Precision of centroid estimate
  - Bias as function of target type
  - Restrictions imposed by estimator – domain of applicability

- Are there auxiliary data available, especially for bright stars?

Observing Spiral Reduction, I

[A - III]

- Yields spacecraft rotation model for "batch interval:" a few hours to a few days
  - Address the "fiducial-star" events collected during a batch interval

- Objective: a "rigid spiral"
  - orientation (e.g., Euler angles with respect to the ICRS) is correct but not well determined
  - rigid ⇒ uncertainty in angular separation between look directions at different times is small compared to measurement uncertainty

- Weighted-least-squares (WLS) fit of the parameters of the spacecraft rotation and instrument observing models
  - numerical integration of the (six first-order) ODE of rotational motion
  - variational equations for the rotation parameters, including initial conditions
  - *a priori* estimates of the coordinates of the fiducial stars
    - initially FAME input catalog, but 10 mas < σ_a < 100 mas (or so)
    - later bootstrap to be FAME results

      (Raises a technical question about double counting data.)

Observing Spiral Reduction, II -- Parameter Set

- Torque models
  - solar fluctuation (if not measured)
  - terrestrial weather
  - spacecraft mass distribution
  - solar shield geometric and optical properties

- Instrument variation with time
  - creep

- Instrument variation with thermal change
  - telemetry data
  - engineering models

Observing Spiral Reduction, III

Numerological example

Batch interval = 24 rotations at 40 minutes = 16 hours
Precession rate = 0.5 deg per rotation
FOV = 1.1 deg
Density of fiducial stars = 3 / sq deg
Number of fiducial stars observed during batch interval = 7000
Number of fiducial star observations = 165,000

At CfA, using "CfA0" (which is a fast machine), 1291 parameters inverted in 315 sec = 6.25 min.
14,000 star parameters plus 500 spiral parameters would take 5.2 days.

Global Fit, I

[A - IV]

- Objective: Interconnect the observing-spiral rotation models to yield single spacecraft rotation model
  - 3 parameters (e.g., Euler angles) remain undetermined by FAME data

- WLS fit to observations of subset of fiducial stars
  - astrometric parameters of fiducial stars (i.e., five each)
  - free parameters of rigid spirals (e.g., 3 Euler angles each)

- May need no more than 1000 fiducial stars
  - no harm in changing global-fit fiducial stars
  - repeating the fit with a different set of fiducial stars is one of the checks on the performance of the analysis system

- Global fit could first be performed well (position only ?) with ~3 months' data

Global Fit, II

Numerology example

Batch interval = 24 rotations at 40 minutes = 16 hours
Number of fiducial stars for global fit = 1000
Mission life = 2.5 years
Number of spirals = 1370
Number of spiral parameters = 4110
Number of fiducial-star parameters = 5000

The inversion time for the "reduced" normal equations (4110 spiral parameters only), using a high-power workstation purchased at the start of Phase E, would likely be of order two hours. For the complete set (9110 parameters), the required time would be an order larger. (The equations for Partial PreReduction, which would yield the reduced normal equations, are contained in a tech memo posted to the FAME web site: FTM99-07 = MIT-TM75-03)

Transform Centroids from Spacecraft Coordinates to Celestial Coordinates

[A - V]

The models and parameters determined during Steps A-III and A-IV describe the instrument pointing as a function of time. These are used to transform the events from an instrument coordinate frame to a frame tied to the celestial sphere.

- May be limited to the fiducial stars (in support of iteration)

Fit a Kinematic Model to Data -- Star by Star

[A - VI]

- Look at each star with long span (full mission) of data.

- Fit standard 5 astrometric parameters
  - Examine residuals for signs of peculiar motion or a companion

- Examine PSF for indications of multiplicity, etc
  - periodic variation in (color) magnitude
  - periodic variation in size along an axis
  - size that depends on axis orientation

- If warranted, perform detailed search for periodic effects.
  - threshold initial set high, and lowered as the data are generally better modeled

(SAO-PAG has algorithms that can be further honed for the FAME problem and made to run autonomously. [R.D. Reasenberg, R.W. Babcock, J.F. Chandler, and J.D. Phillips, "POINTS Mission Studies: Lessons for SIM," in *Planets Beyond the Solar System and the Next Generation of Space Missions*, D.R. Soderblom, ed., ASP Conference Series Vol. 119, Astronomical Society of the Pacific, San Francisco, pp 191-205, 1997.])

Some Options

- Orient global fit to ICRS

- If observation spirals are not rigid enough
  - make batch interval smaller
  - preserve additional parameters to be estimated during the global fit (e.g., low-order spacecraft rotation terms) (may require larger number of fiducial stars in global solution)
  - wider FOV and slower precession

- For stars that show no temporal variation, lock PSF to be constant
  - does this permit a better PSF? ... better centroid?
  - this approach raises technical questions about "system identification" *vs* parameter estimation