Imaging Astrometry with HST

Jay Anderson
Rice University
jay@eeyore.rice.edu

HST's Main Distinction

It is above the atmosphere

- Benefits
  - More concentrated PSF: fainter stars, more crowded fields
  - Very stable observing platform
  - Fewer color effects than ground-based astrometry
- Limitations
  - Older technology
  - Download rate
- Compromises
  - Small field of view
  - Undersampling in all detectors

Scientific Possibilities

1) Cluster-membership
- Deeper LFs, IMFs
- H-burning limit, WDs
- Tidal limit studies
- Equipartition

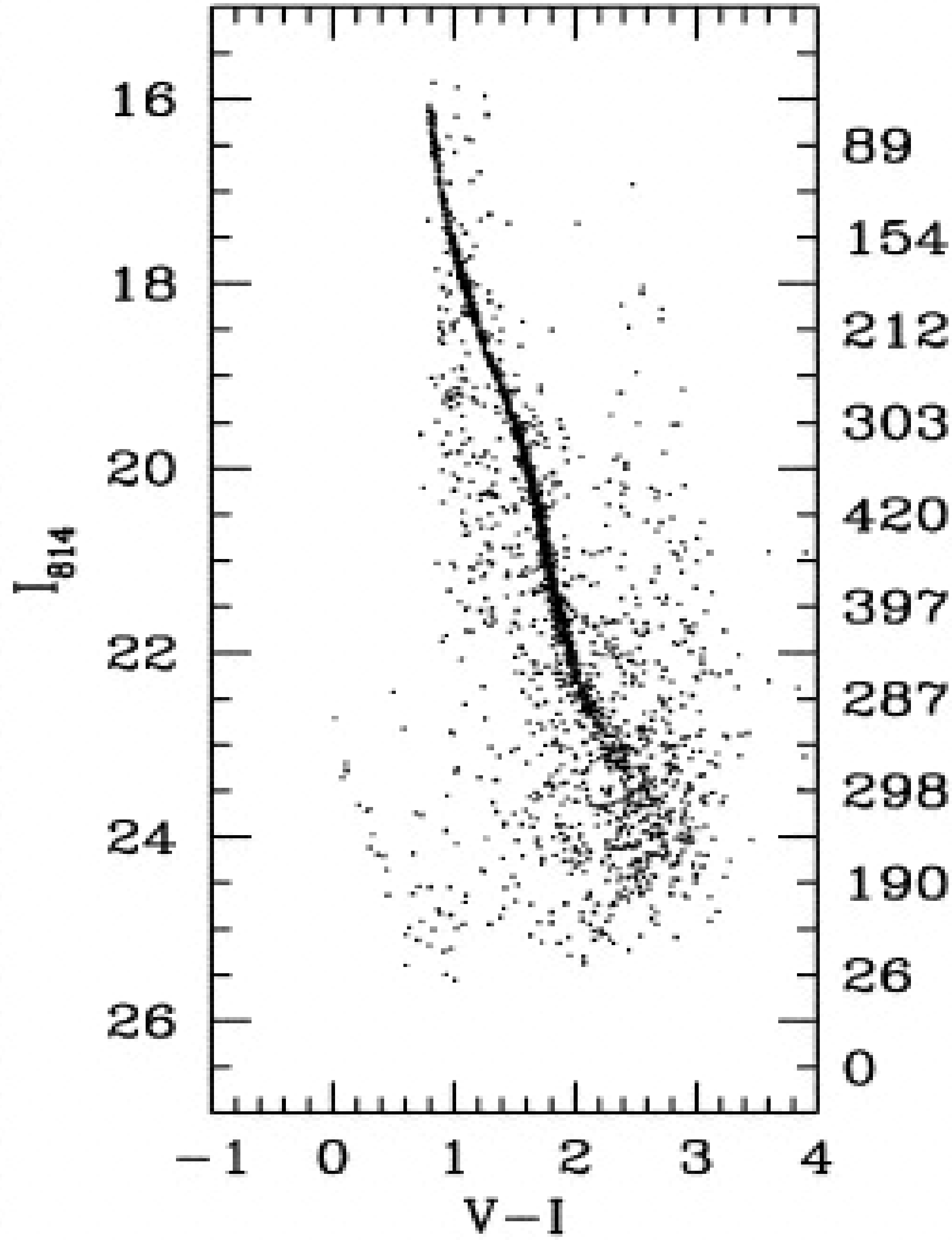
2) Internal Motions
- Dispersions, geometric distances
- Rotation
- Anisotropy
- Heavy Binaries, central BH
- Drukier 2003, McNamara 2004

3) Orbits
- For clusters or even galaxies (Piatek 2005)

4) Parallax measurments
- Pleiades, some NSs done
- Orion in cy14

5) Planet searches
- Possible, but orbit-consuming

NGC 6397
CMD


16
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2
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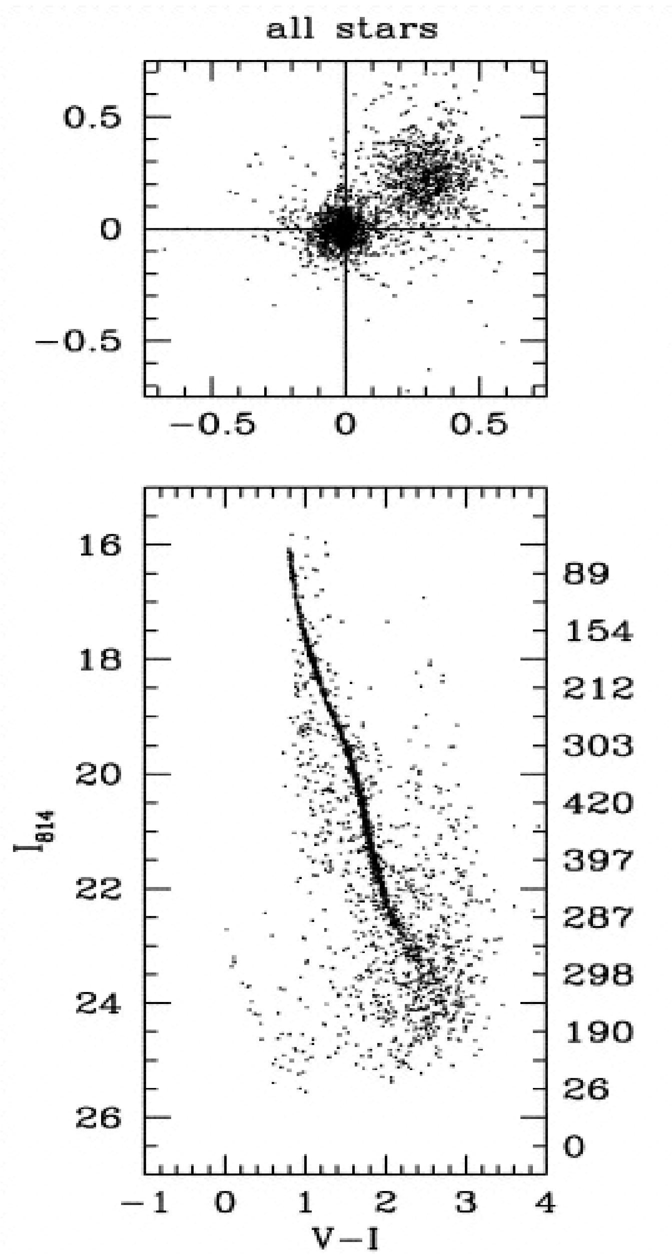
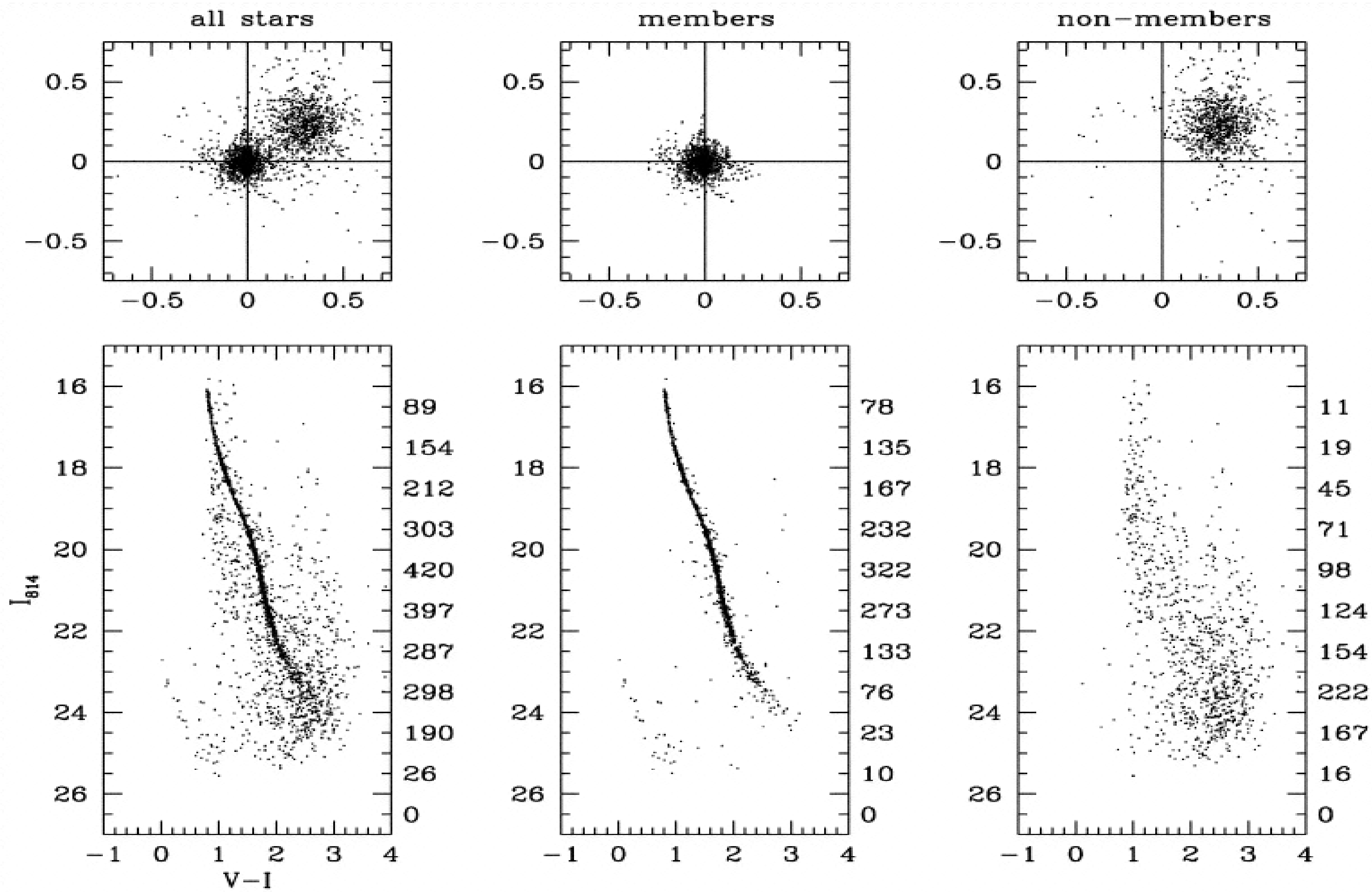
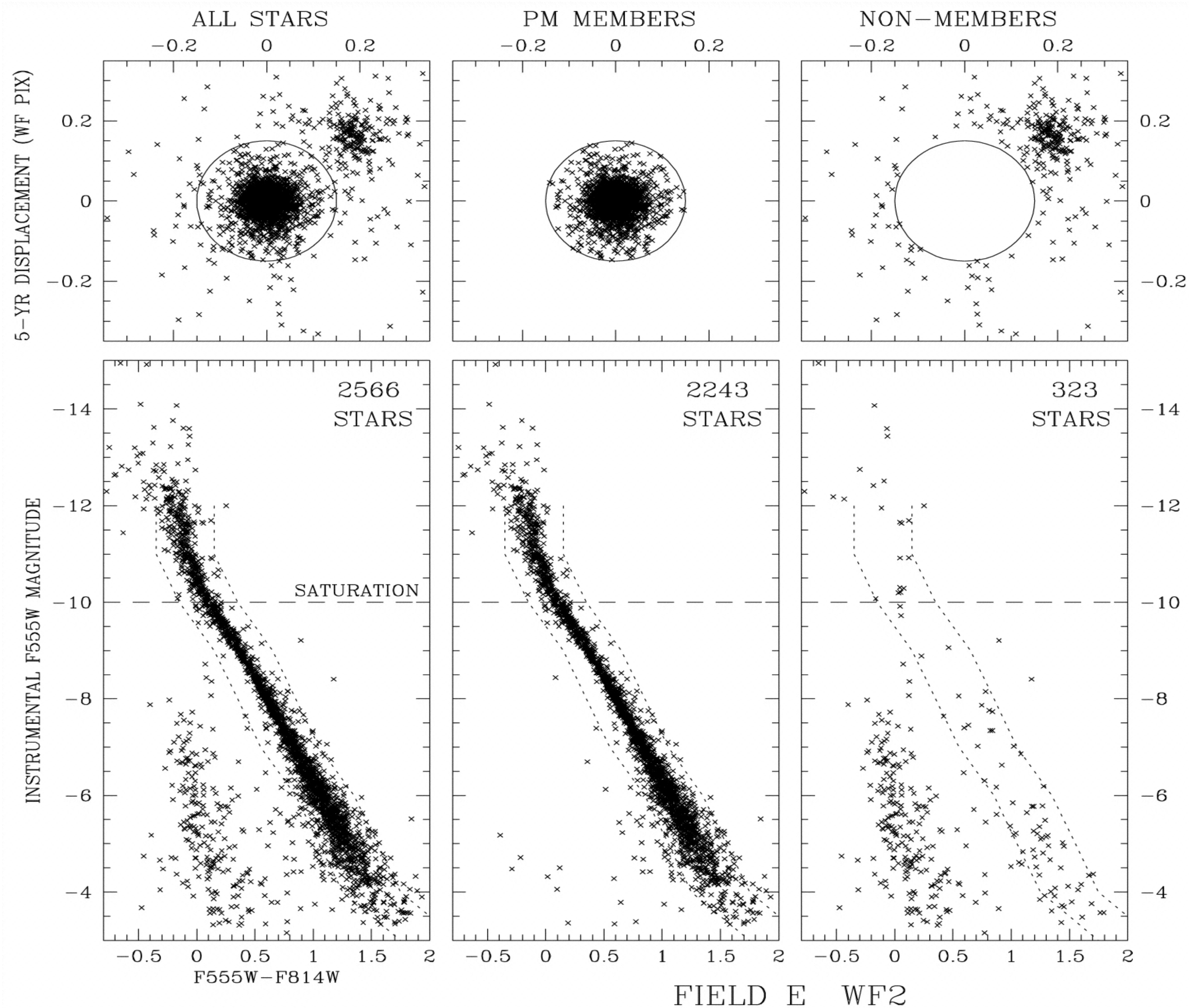
NGC 6397 with PMs



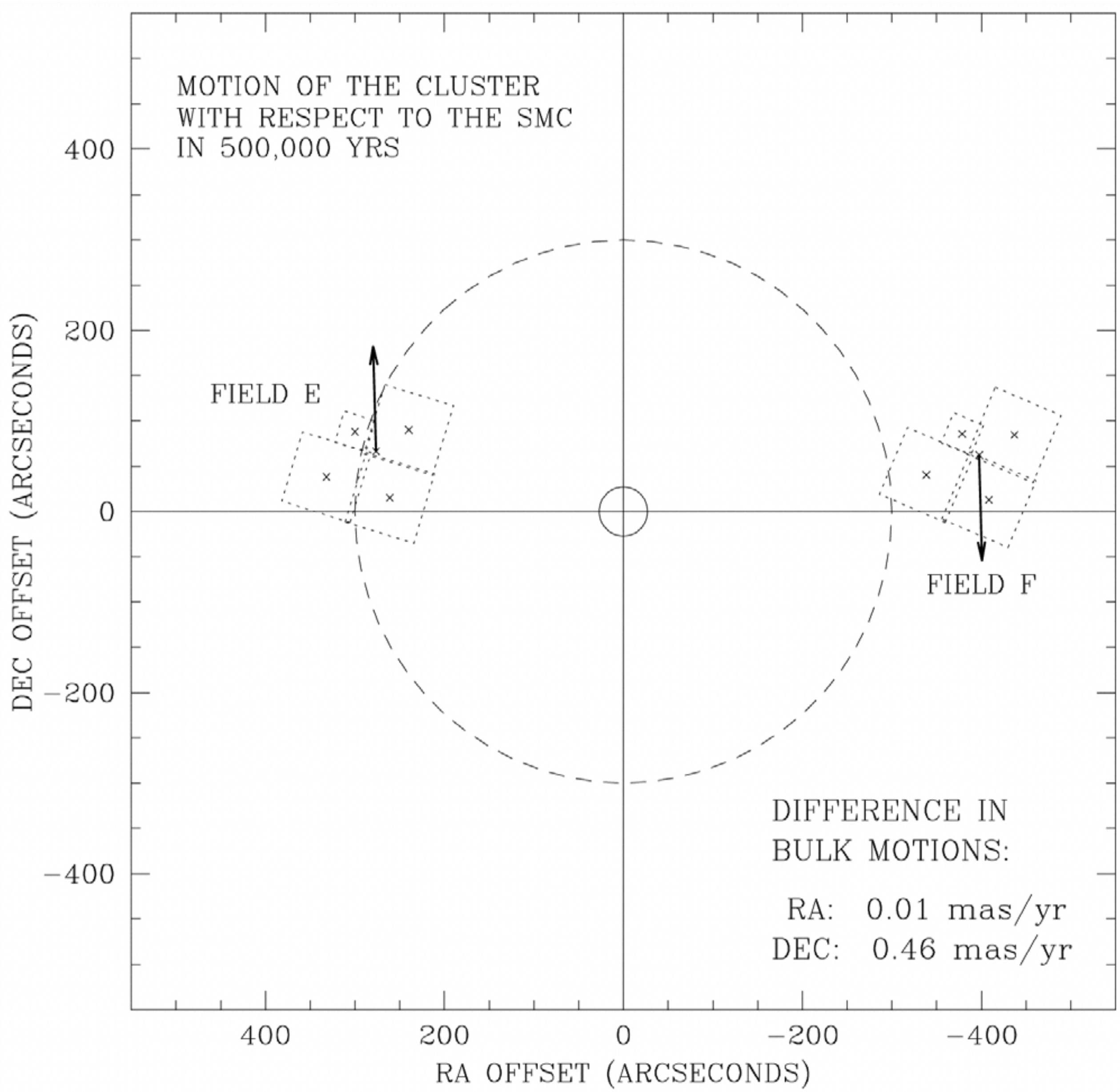
NGC 6397 (King et al 1998)



47 Tuc (Anderson & King 2001a)



47 Tuc Rotation



All HST Astrometry is Differential Astrometry

- Absolute pointing accuracy is 1″
- Even more “differential” than from ground
  - Small FOV (3’ x 3’ is the biggest detector)
  - Sensitivity
  - Small instabilities in distortion
- GAIA and large-field imager surveys may change this someday
- For now, all positions must be measured with respect to something else

General Differential Astrometry

Differential astrometry can be divided into two tasks:

1) measuring positions for individual stars in individual images
2) comparing positions measured in one image with those measured in another

Task 1: Measuring positions in images

- Ground-based approach
  - Gaussian or Moffat function
- Complications for undersampled detectors
  - Where is the star within the central pixel?
  - Not as impossible as you might think
    - "Stars have no hair"
    - 3 parameters: (x,y,f)
    - The ideal PSF for astrometry: Π
  - The challenge for undersampled images: translate pixel distribution into a position

Task Two: Comparing positions in different images

- Each image is taken in its own frame
  - We do not know much a priori about this frame
  - We depend on common stars to tell us how frames are related to each other
- To compare positions, we need to transform positions into a common frame
  - Remove distortions as well as possible
  - Linear transformations between frames
    - General 6-parameter linear transformations (not 3)
    - Common stars form the basis
    - Often require "local" transformations

TASK 1: Measuring Positions in individual images

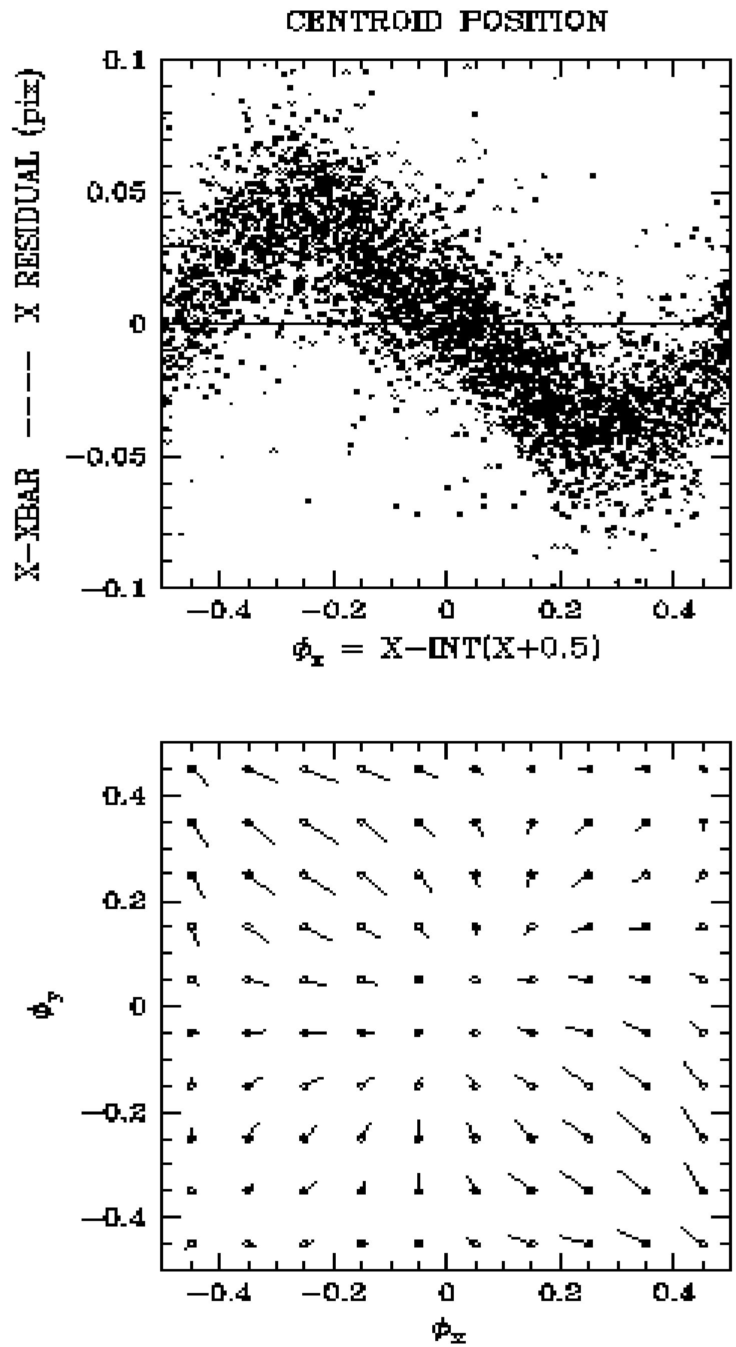
GOAL: distill the 5x5 array of pixels into (x,y,f)

- Assume "semi-crowded" regime

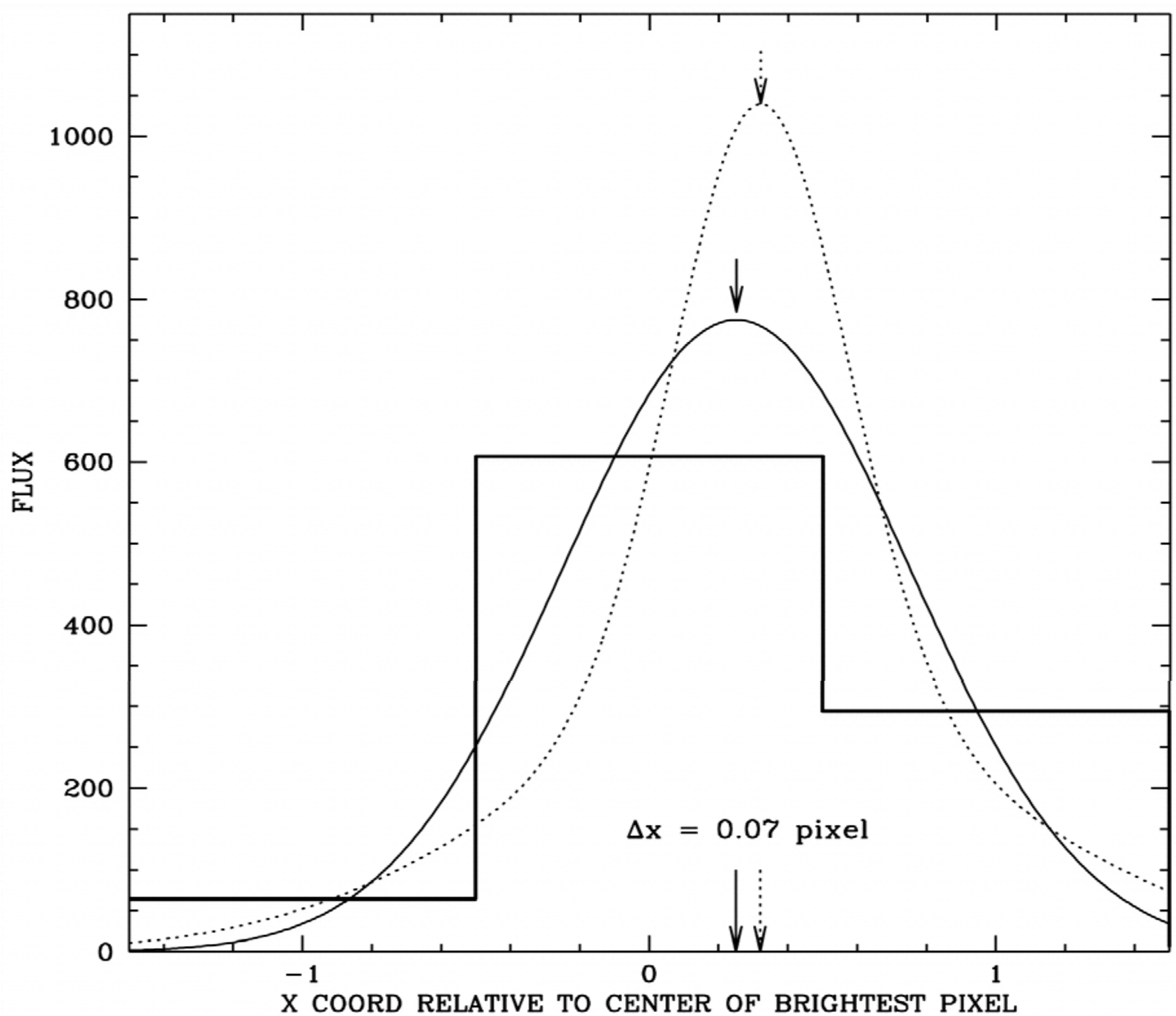
1) The PSF is crucial

- Centroid/Gaussian-fitting contains systematic error called "pixel-phase bias"
- 1-D illustration: one profile, two PSFs
- Fundamental degeneracy due to undersampling
- Need extra information

Pixel-phase bias: centroid positions



Two PSFs, one pixel profile

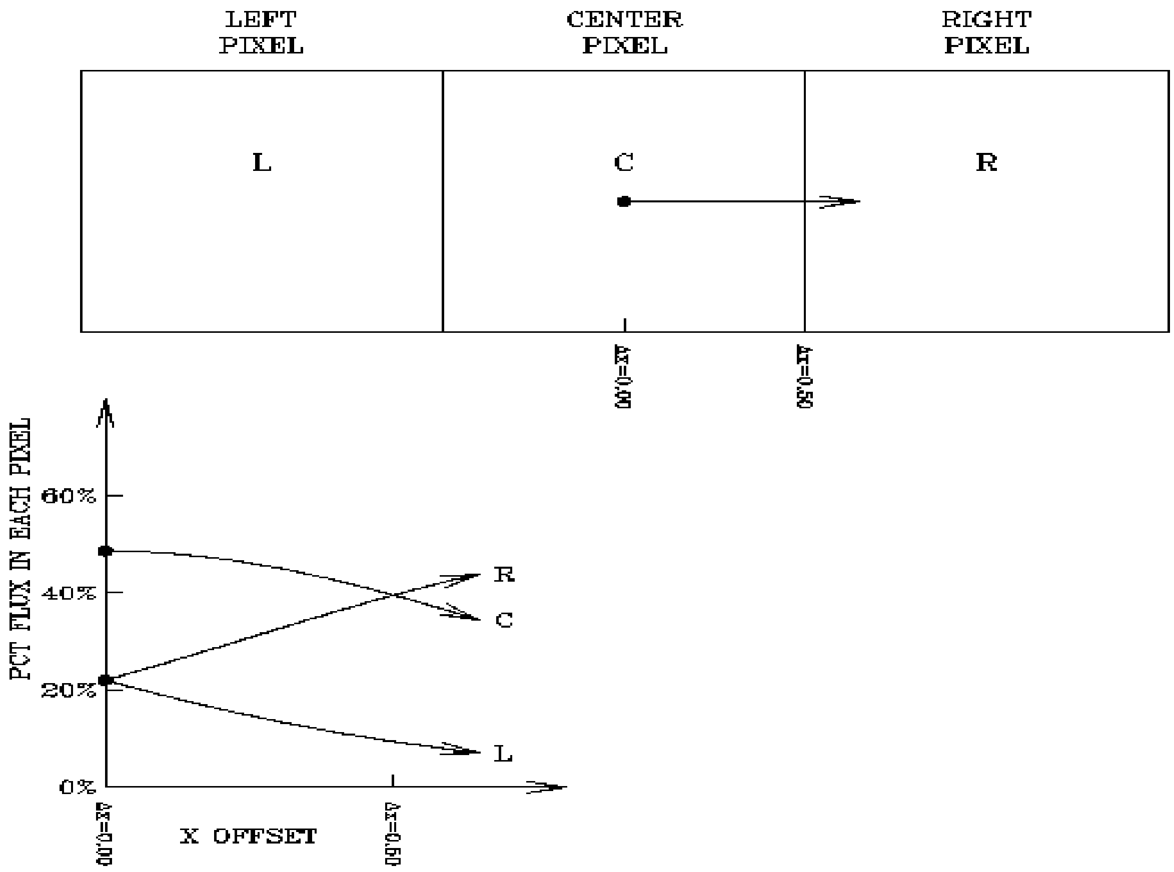


Task 1: continued (II)

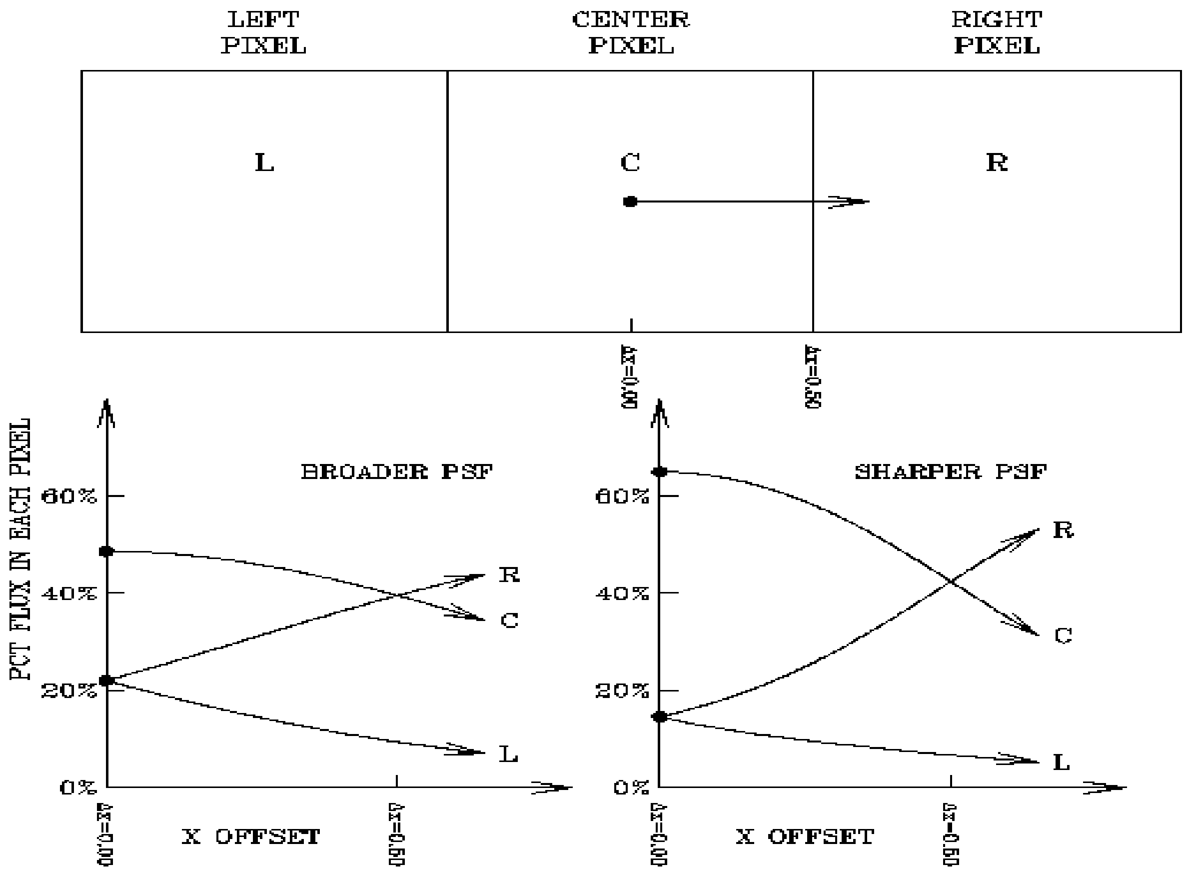
2) Ways to model the PSF

- DAOPHOT was designed for well-sampled photometry
- Photometry vs. Astrometry: sums vs differences
- Traditional PSFs
  - Analytical functions
  - Explicit integration over pixels
  - Not flexible models
- Back to the basics: a thought experiment

A thought experiment I

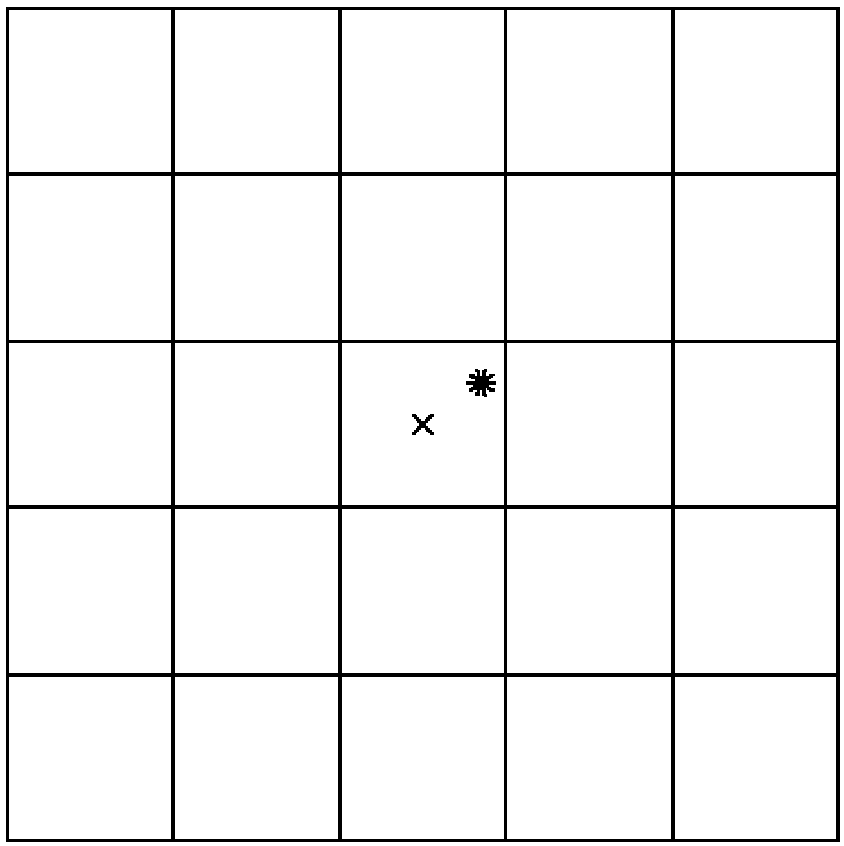


A thought experiment II



We would like:

a model to tell us what fraction of light should be in each pixel as a function of where the star is centered

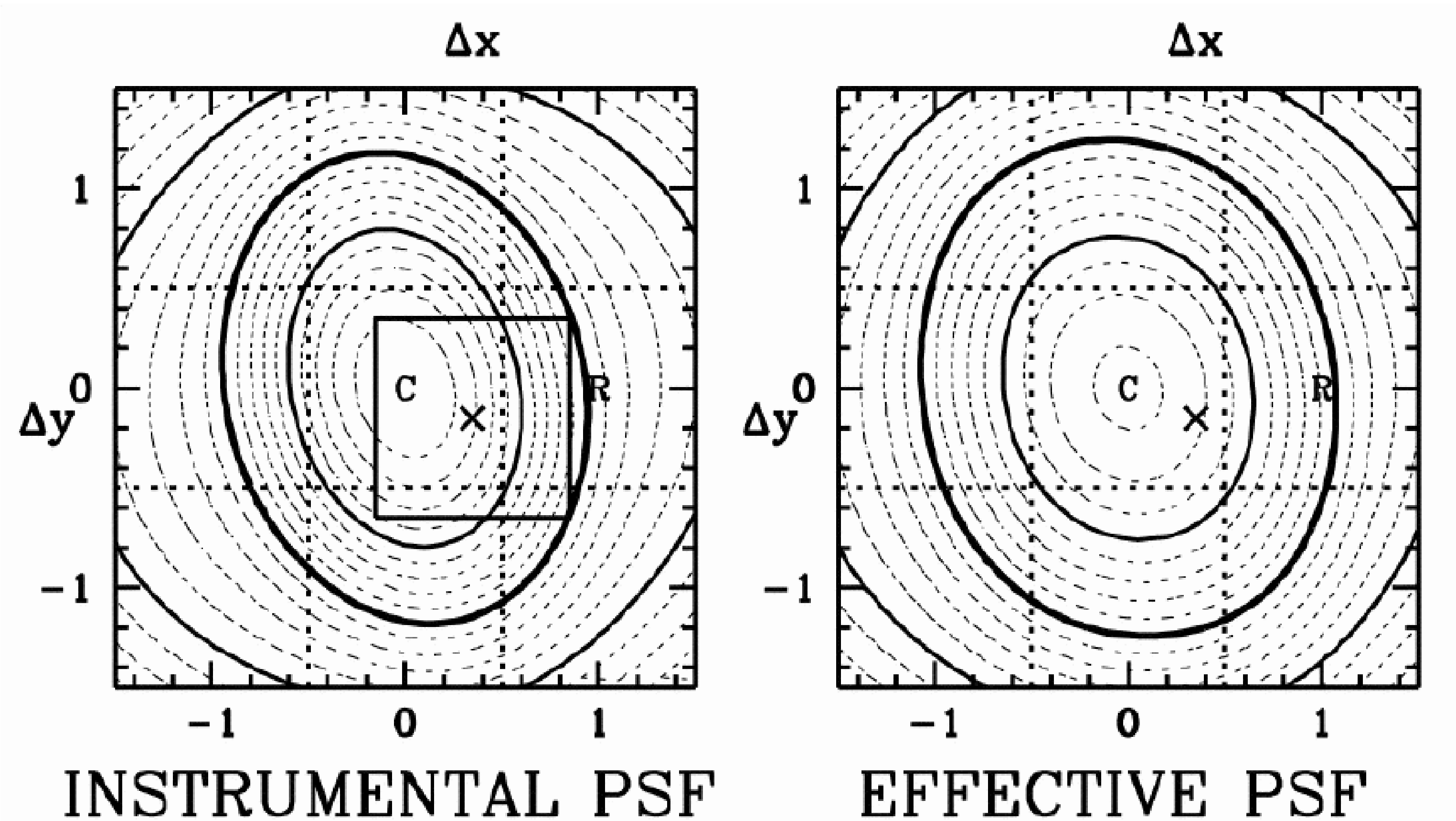


Task 1: continued (III)

3) The effective PSF

- Inspiration from Lauer (1999): "effective" image
- The instrumental PSF: we never see it, very indirect
- The "effective" PSF
  - Mathematically, ePSF = iPSF convolved with the PRF
  - It is a 2-d smooth function of (Δx,Δy)
  - Tells us the fraction of light that falls in a pixel at (Δx,Δy)

iPSF to ePSF



Δx
Δy
1
0
−1
−1
0
1
C
R
INSTRUMENTAL PSF
Δx
Δy
1
0
−1
−1
0
1
C
R
EFFECTIVE PSF

Task 1: continued (IV)

Economies of the ePSF

- Fitting stars:

  P_{ij} = SKY + FLUX*ePSF(i-x,j-y)

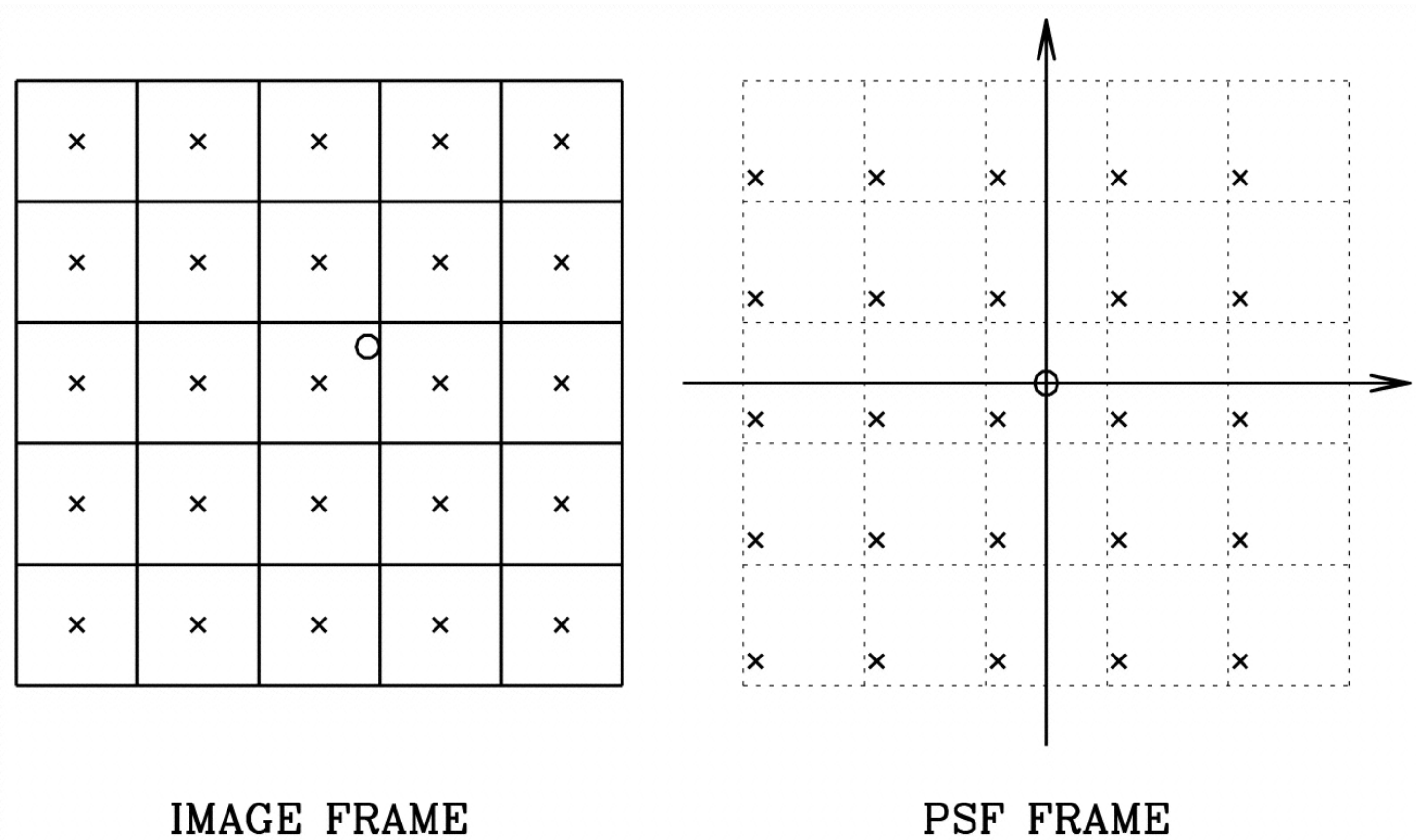
  - Fit directly, no integration
  - Linear relationship

- Solving for ePSF:
  - Each pixel in each star image gives one point-estimate:

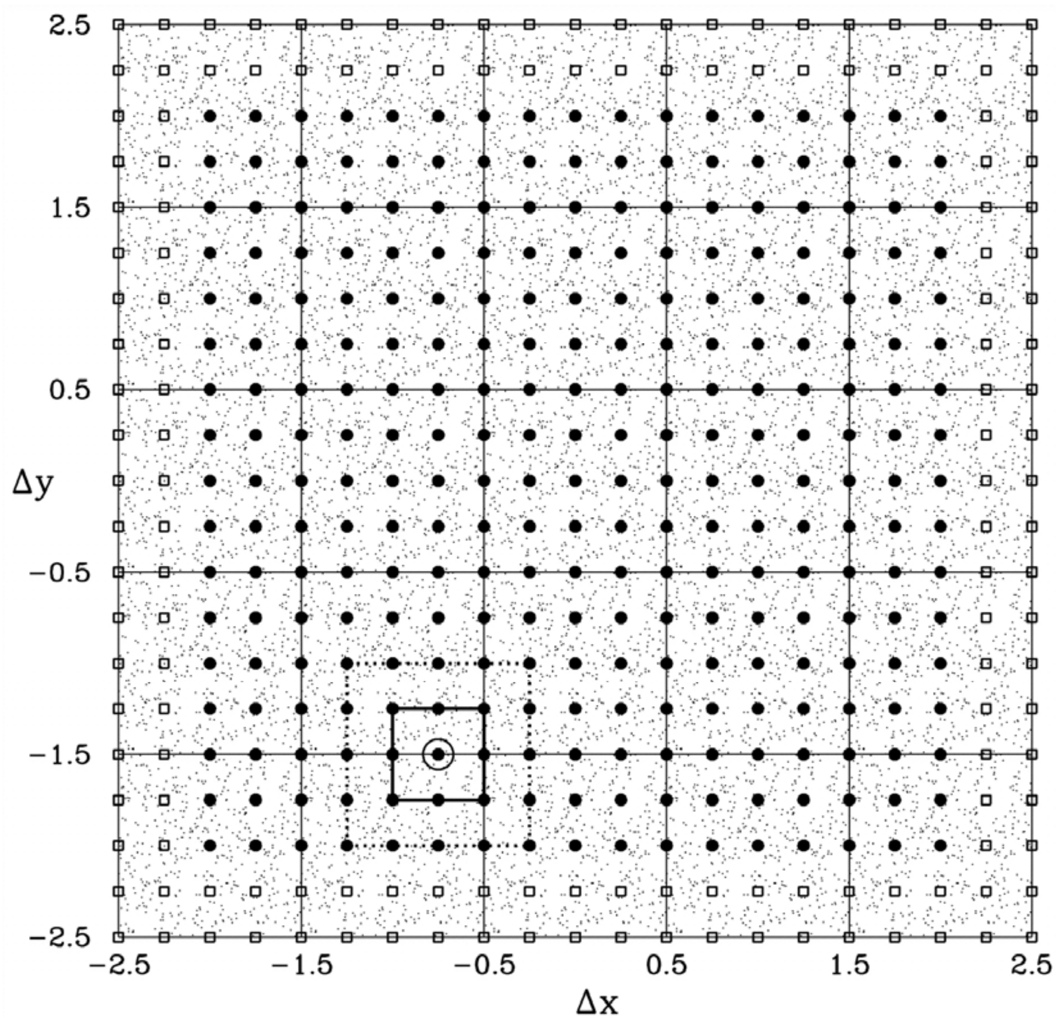
    $$\text{ePSF}(\Delta x,\Delta y) = (P_{ij} - \text{SKY})/\text{FLUX}$$

  - We see the ePSF directly in star images
  - Enormous number of point-samplings
  - How to build a simple model?

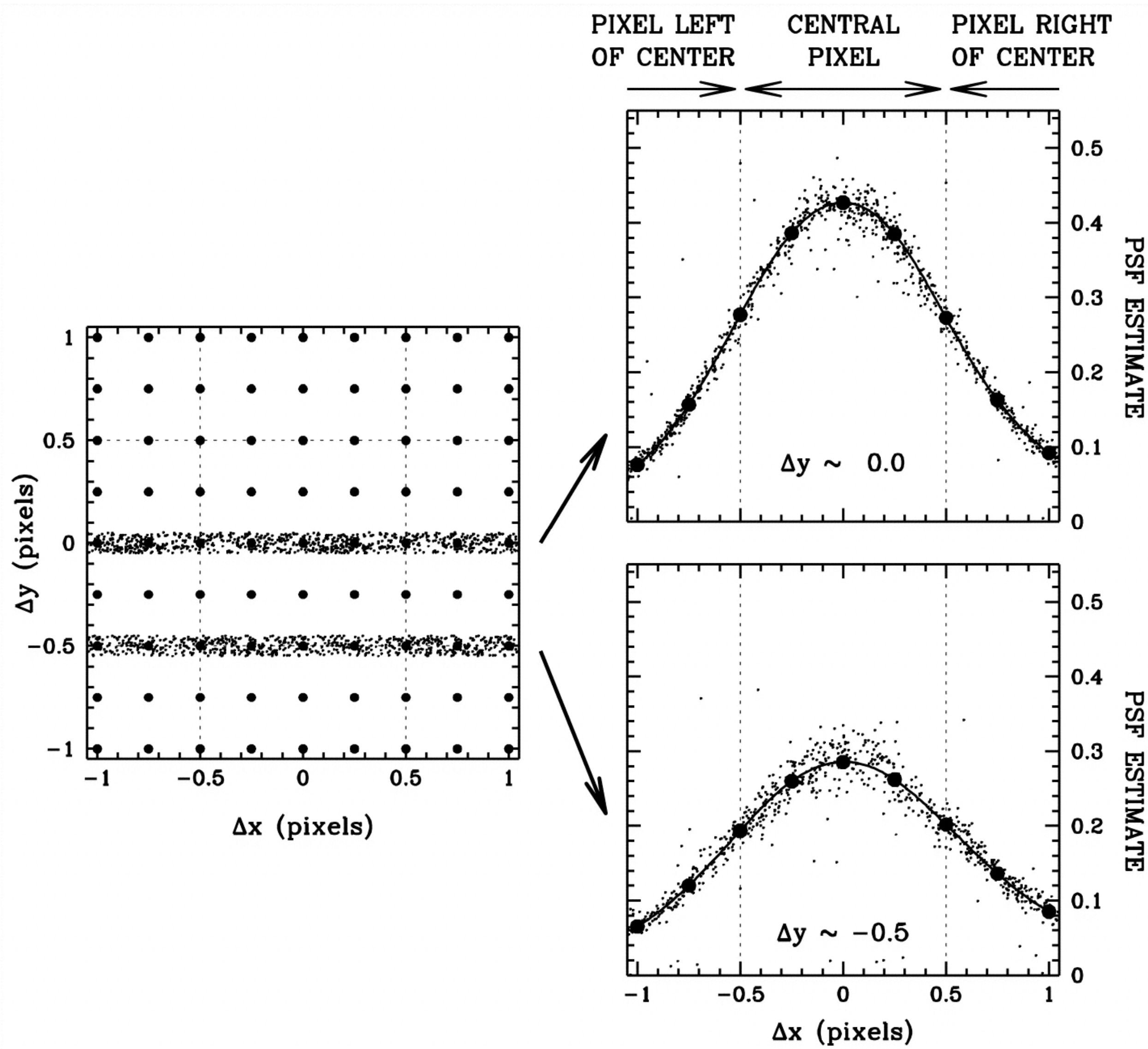
Each star samples the ePSF at an array of points



Many ePSF point-samplings from many stars



The ePSF is seen directly in the stellar images

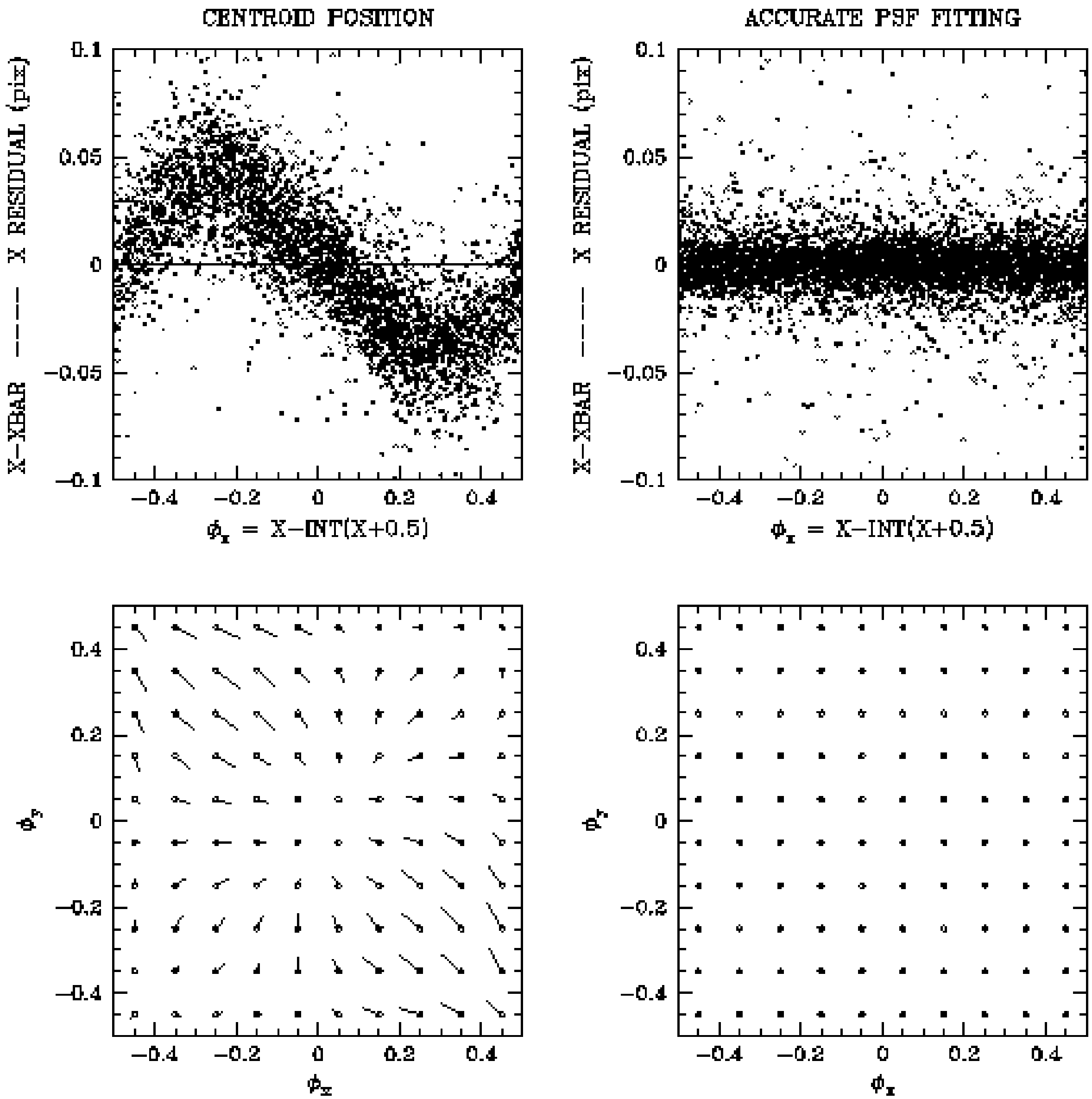


Task 1: continued (V)

4) Modeling the ePSF

- How to go from a myriad of point sampling to a simple predictive model?
- Analytical functions?
- We adopt a simple empirical grid, supersampled x4
  - Distill information from many samplings into grid points
  - Constraints
    1) overall normalization
    2) sub-pixel normalization
    3) centering
    4) smoothness
  - When properly modeled, the results are very good
- We still need to remove degeneracy

Pixel-phase bias



Task 1: continued (VI)

5) PSF variability

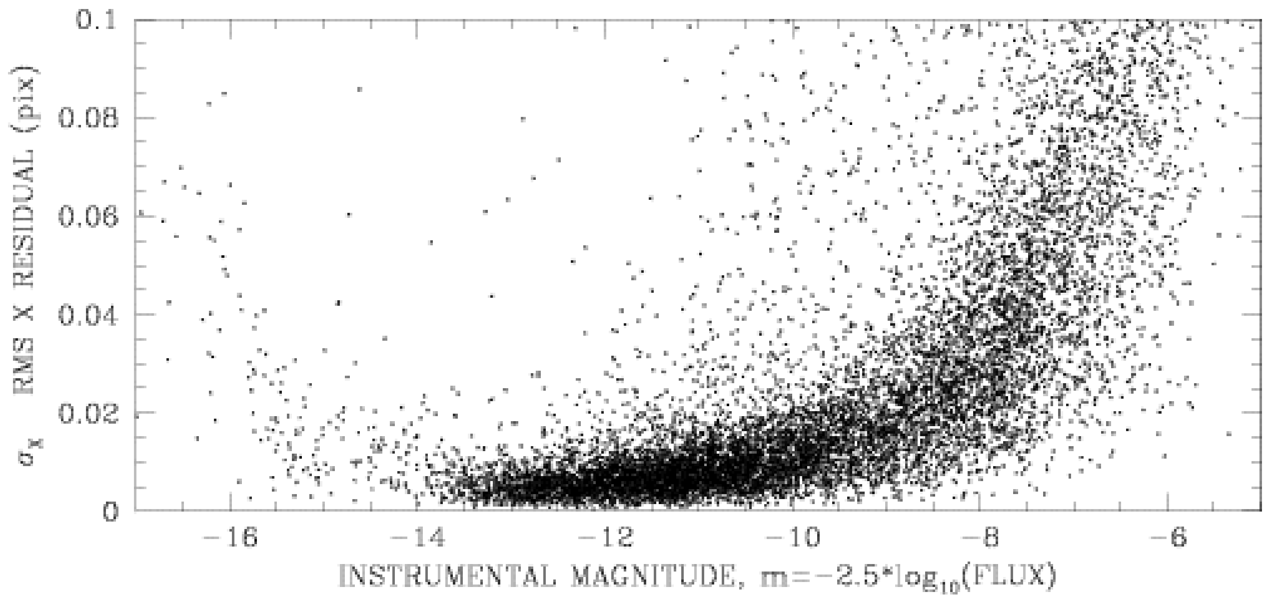
- Spatial variability
  - WFPC2: 3x3 array of PSFs for each chip
  - WFC: 9x5 array for each chip (9x10 overall)
- Color variability
  - Must construct one PSF for each filter
  - No observed star-color effects
- Temporal variability
  - Surprisingly stable over time
  - WFC shows perturbations of ~1%

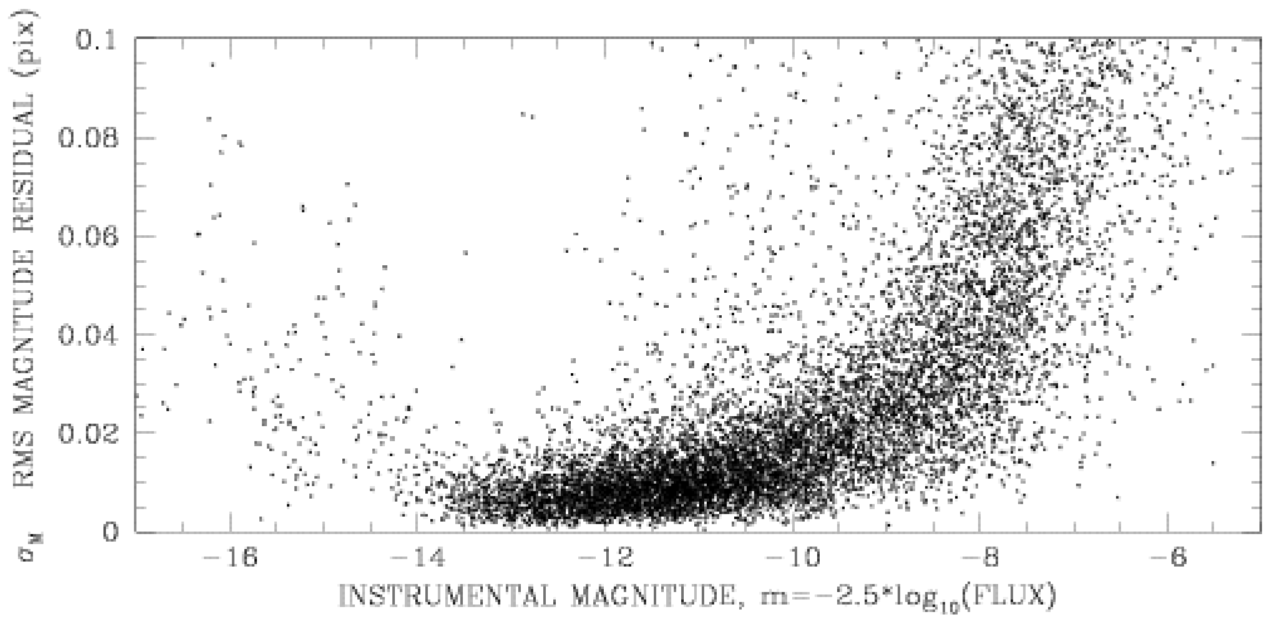
Task 1: continued (VII)

6) Fitting stars

- Chi squared minimization for (x,y,f)
- Gradient search or grid search
- Accuracy for bright stars in an image
  - WF chips: 0.02 pixel --- 2.0 mas
  - PC chip : 0.02 pixel --- 1.0 mas
  - WFC : 0.01 pixel --- 0.5 mas
  - HRC : 0.01 pixel --- 0.25 mas
- The final proper-motion accuracy still depends on transformations

Astrometric and photometric errors





PSF summary

- Hard concepts, new ideas
- Anderson & King (2000) gives details
- The ePSF may not be the only way, but seems to be the simplest
- Much is already programmed, no need to start from scratch

Task 2: Comparing positions

- Header information is only good to about 1″
- We must define our own reference frame
- First, we need to address distortion
  - HST different from ground
    - Orientation
    - Stability
    - FOV
    - Precision

Sources of distortion in HST (I)

1) Periodic distortions

- WFPC2: 34-row skip, 0.03-pixel amplitude
- WFC: 68-column pattern, 0.005-pixel amplitude

2) General optical distortions

- WFPC2:
  - on-axis, but each chip refocused
  - 3 pixels over 400 pixels; see Anderson (2001)
- WFC/HRC:
  - off-axis, rhombus shape FOV
  - huge linear and other terms (10%)
  - originally modeled by Meurer et al (2002)

Sources of distortion in HST (II)

3) Filter-dependent distortions

- WFPC2: small, regular effect (Platais et al 2003)
- HRC/WFC: each filter perturbs the solution
  - Amplitude 0.15 pixel
  - Spatial scale: 100 pixels
  - I model with a table of residuals
  - Available in my ISRs on STScI's website

4) Breathing-induced distortions

- Focus-variations around orbit, cannot model predictively
- Low spatial frequency
- Linear ~0.1 %, smaller in higher-order terms
- Varies from exposure to exposure

5) Secular distortions

- WFPC2: chips move at 1 pixel / 10 years
- WFC: chips move in together, change linear terms

The Transformations (I)

- The basis for the transformations: common stars
  - (x1,y1,x2,y2) associations for N stars
  - 6-parameter linear transformation:

$$x2t = A*(x1-x1o) + B*(y1-y1o) + x2o$$

$$y2t = C*(x1-x1o) + D*(y1-y1o) + y2o$$

    - A, B, C, D are linear terms
    - x1o, y1o, x2o, y2o are centroids

The Transformations (II)

Transformations are only as good as the stars that define them

- Assumption: stars in same place in space
  - Stars have measurement error
  - Stars move!
- Imperfect associations; what to do?
  - Use only well-measured stars
  - Iterate to include only consistent associations
- What is the astrometric goal?
  - Cluster-field separation: use only CMD-member stars
  - Parallax: use background objects only
  - Internal motions: use all stars
- Remember: everything is measured with respect to something else

The Transformations (III)

To minimize the effects of uncorrected distortion:

Use local transformations

- Define a local reference net for each star
- Use nearest 25, 50, or 100 stars
- Statistical corrections necessary
- Do not use a star in its own transformation!

An additional complication

- Usually not just one observation at each epoch
- Need to use transformations within an epoch

Planning Observations

1) Dithering
   - To detect any systematic errors
   - For PSF reconstruction
   - Not necessary for distortion solution

2) Repeat observations with similar pointings
   - Minimize distortion errors
   - Maximize field coverage

Conclusions

Science to come

- Many projects in the works
- Very accessible archive
  - Rich with multiple epochs already
  - Even richer with 2nd-epoch flexibility
  - Parallax requires proper motion

Remaining challenges

- Measuring galaxies: GSF?

Applications beyond HST

- Ground-based reductions could also benefit from the ePSF approach and local transformations

References

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Piatek, Pryor, Bristow, Olszewski, Harris, Mateo, Minniti, & Tinney 2005 AJ 130:95-115