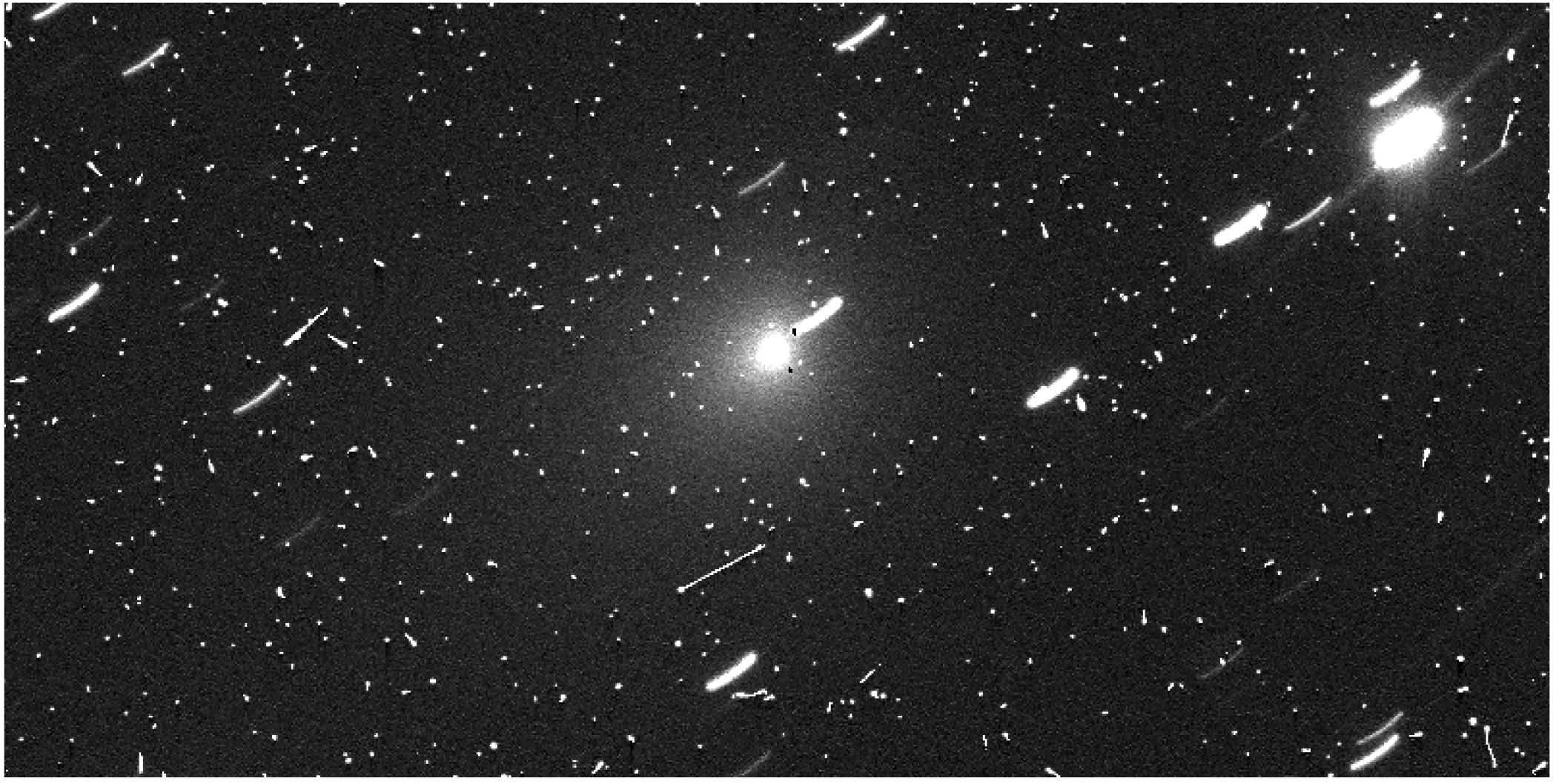
High-precision astrometry of moving targets with HST

Marc W. Buie
EU ESA Workshop
2025 Oct 7

Basic Requirements

- Accurate PSF across the field of view
- Good ephemeris
  - HST-centric distance of the ephemeris needs to be good, slight ephemeris angular offsets aren’t as important
- Accurate post-observation HST orbit reconstruction
- At least three stars per observation with good SNR

Example Image

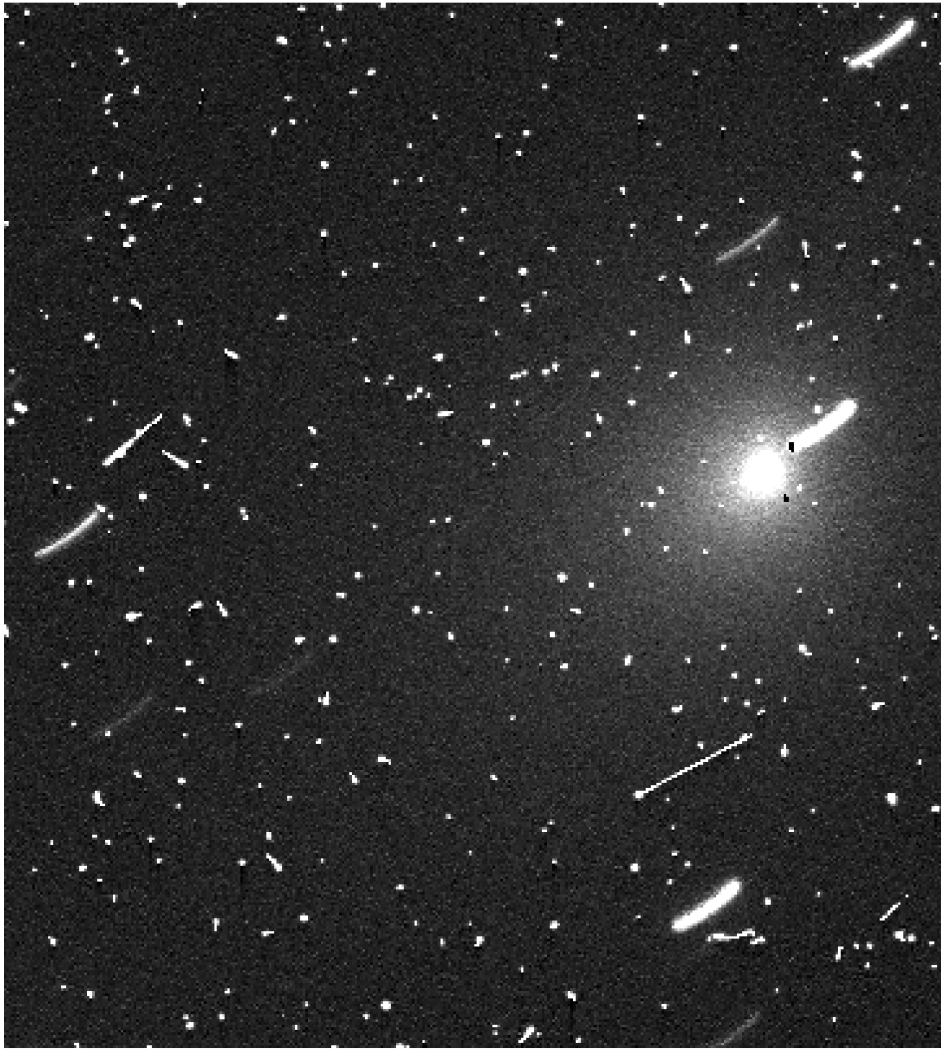


Example Image

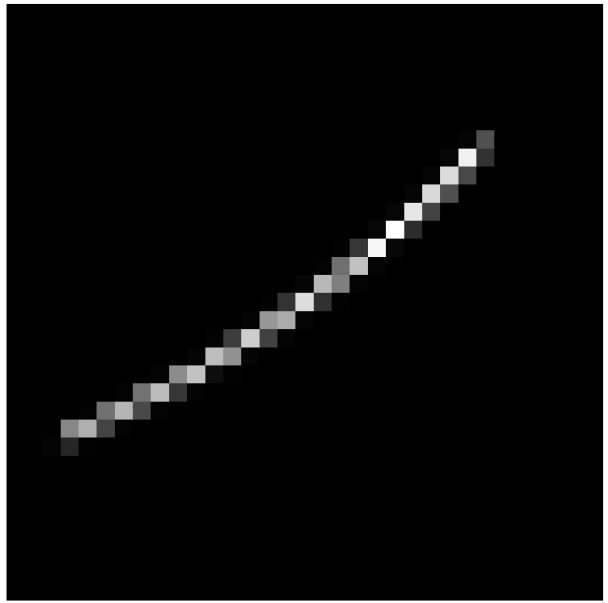
- 2I/Borisov tracked
  - geocentric ephemeris (Track 51 command with linear approximation)
  - on-board parallax correction
- Noise from energetic particles (points and tracks, erroneously described as cosmic-ray strikes)
- Background sources trailed

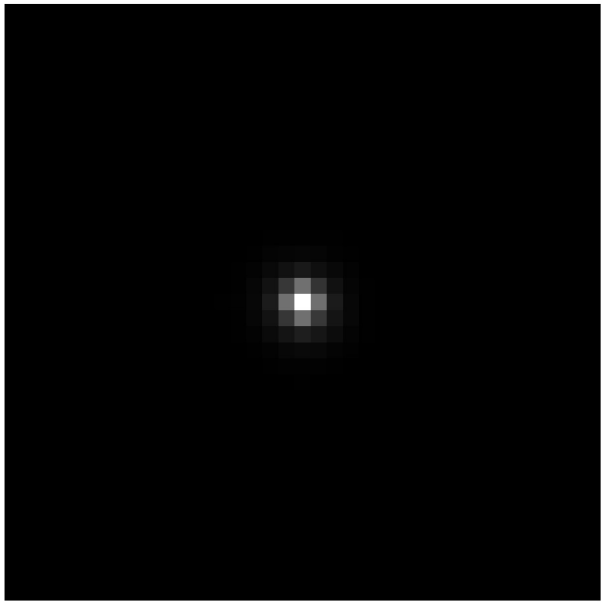
Mask image required for best results. I do this manually and simply flag those pixels to be excluded from the fit.

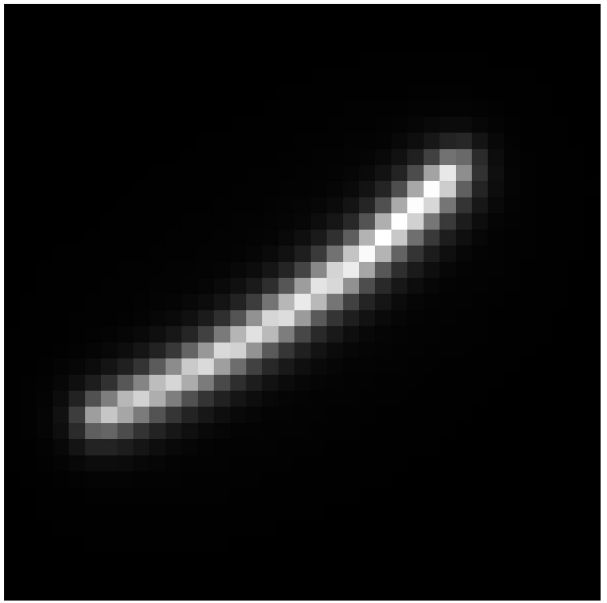
In principle, overlapping sources can be directly fit together. In practice, such cases are usually avoided to reduce the workload.



Example Image

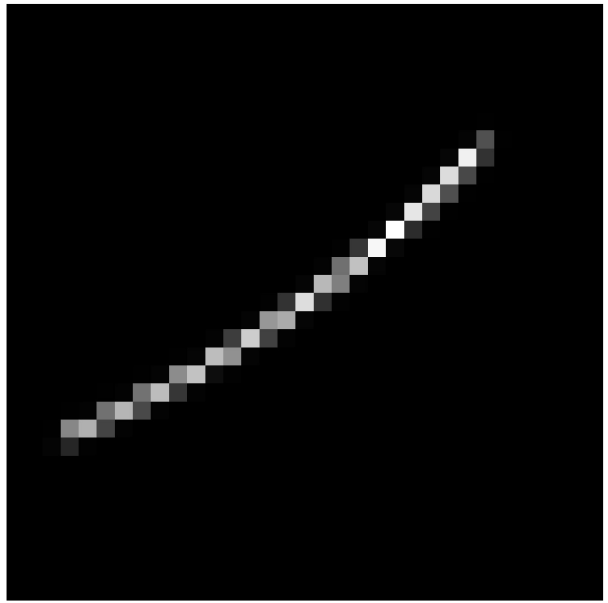


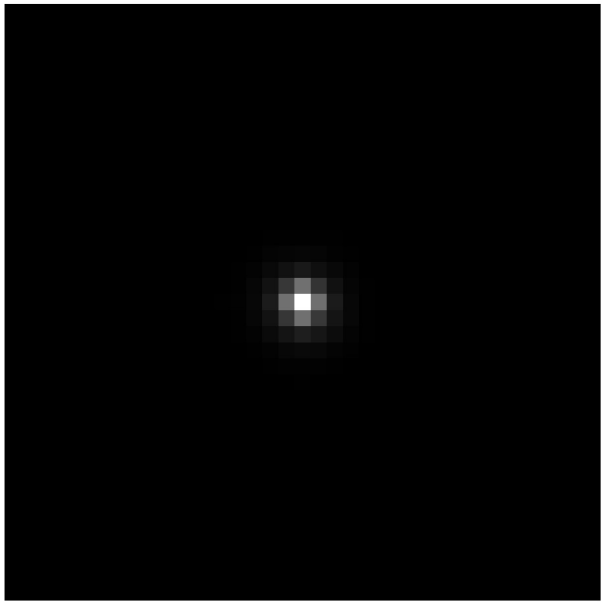


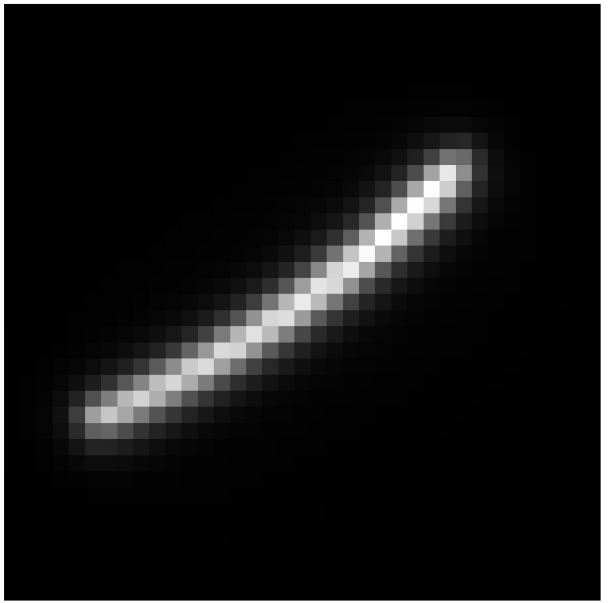


Panel B: discretized image of HST-centric object ephemeris with constant time sampling
→Positions converted to pixel location and summed (jitter kernel could be added if desired)
→Time sampling chosen to ensure non-zero pixels have at least a few points
→Apodize this image with a gaussian kernel convolution to push ~20% of the power in a single pixel out to the first “ring” of neighboring pixels.
→Normalize

Example Image

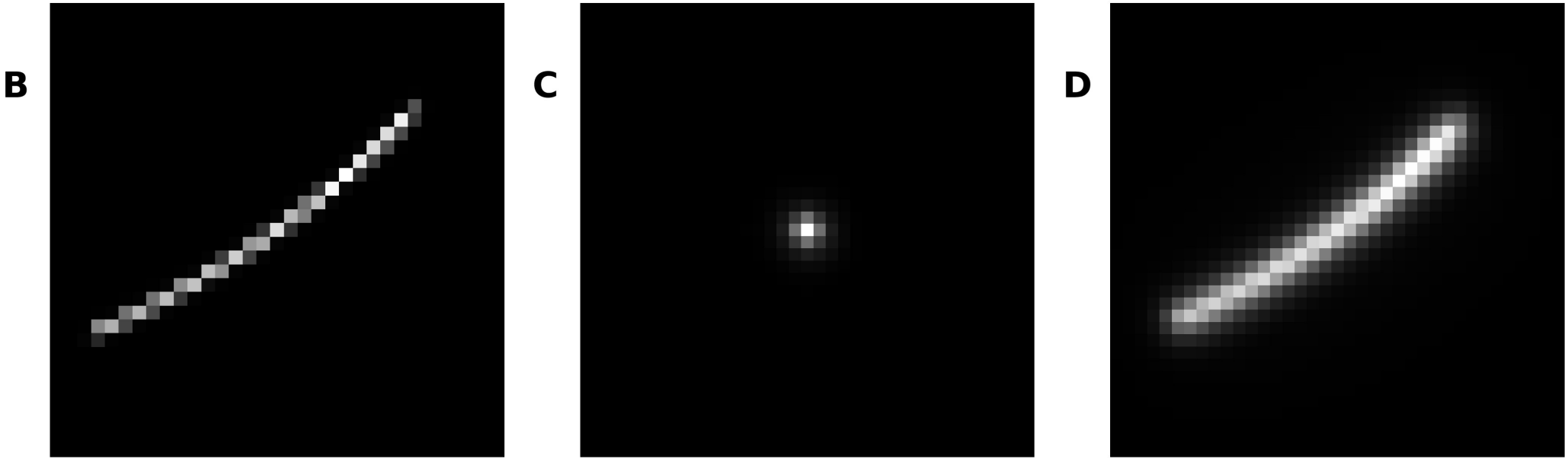






Panel B: discretized image of HST-centric object ephemeris with constant time sampling
Panel C: HST PSF (image scale doesn't show the usual complicated and distorted structure)
→ this PSF is recomputed at the location of each fitted source due to the spatially variable distortion, I use TinyTim to more easily capture this variation

Example Image



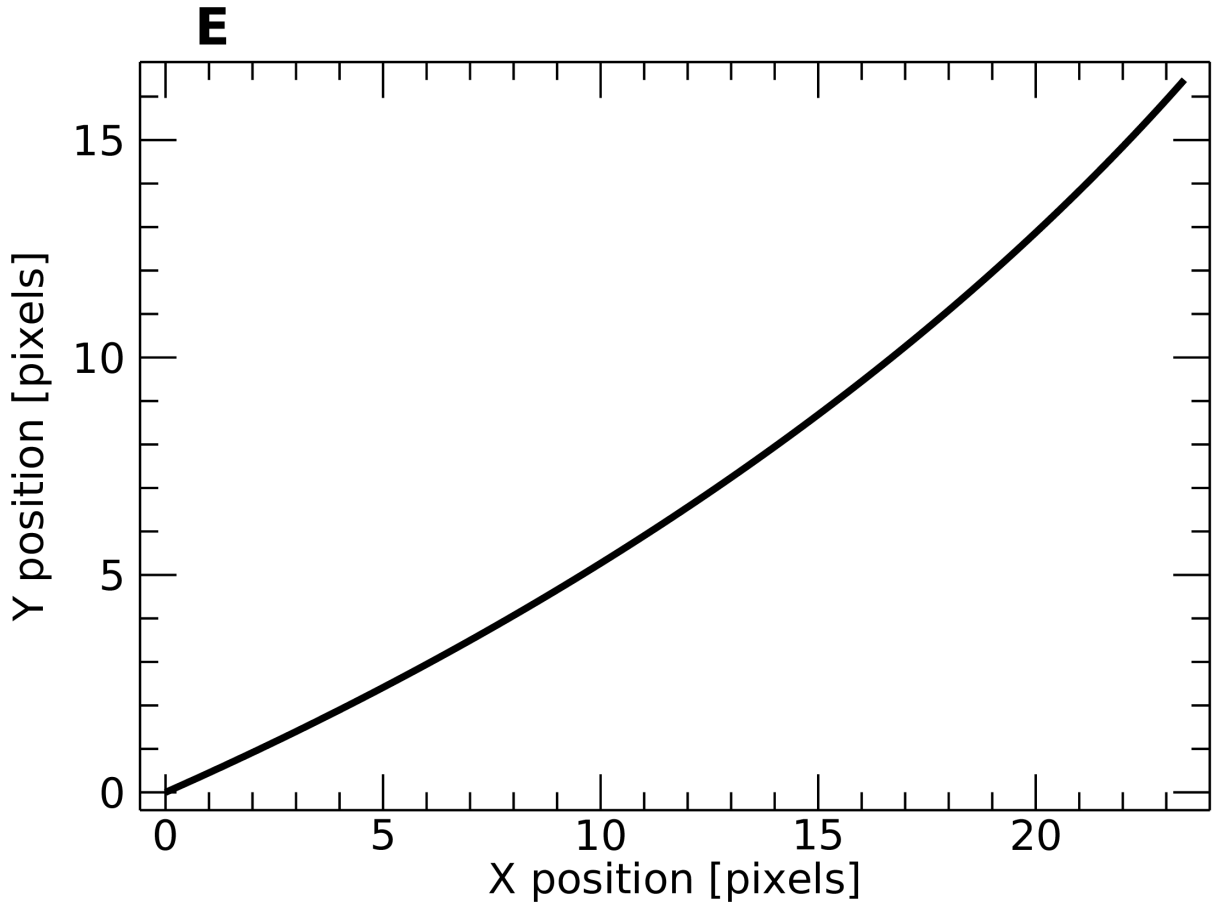
Panel B: discretized image of HST-centric object ephemeris with constant time sampling
Panel C: HST PSF (image scale doesn’t show the usual complicated and distorted structure)
Panel D: convolve B and C and normalize
→ this approach can also work for ground-based data and is symmetrical, it can be applied to either the target or the stars

Example Image

Plot of points that are discretized in Panel B

This plot is referenced to the exposure start but can be done relative to the mid-time if desired.

This curve includes motion, parallax, and camera distortions.

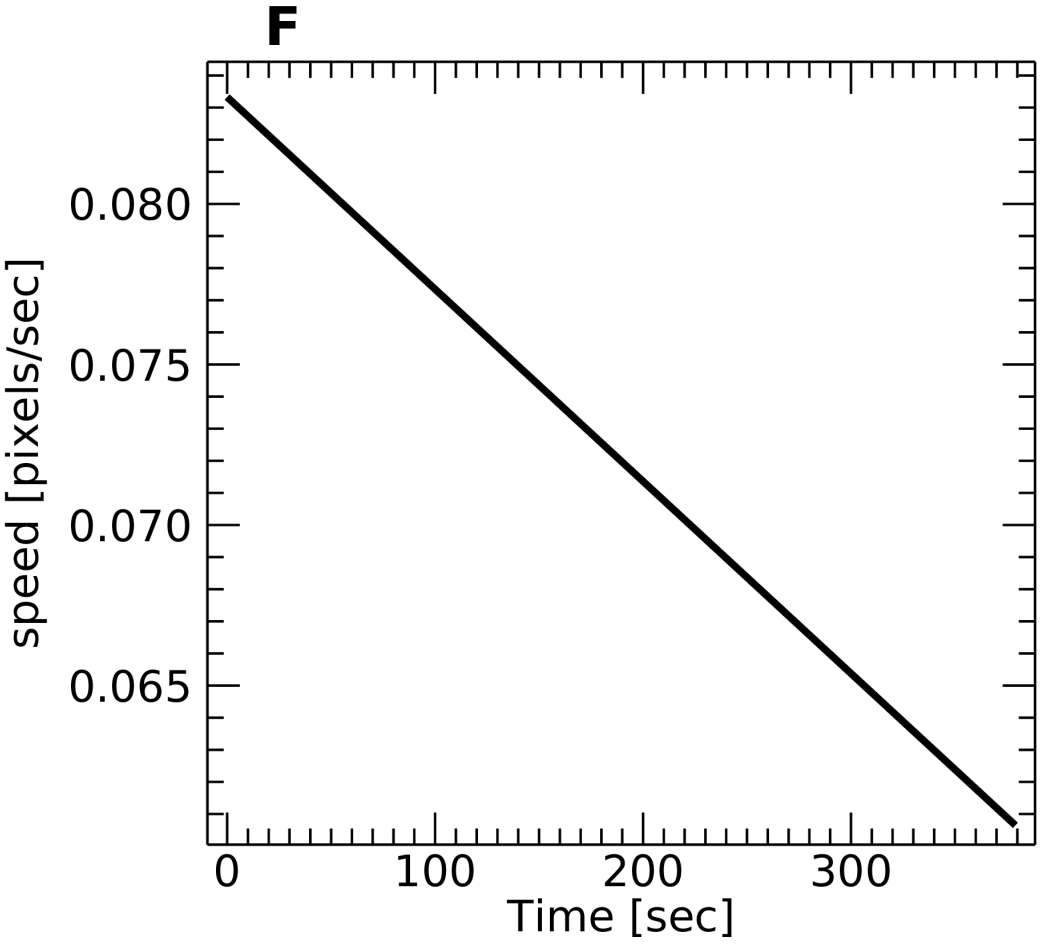


Example Image

Plot of the same points from the previous plot but shown as velocity versus time

This variation of speed is why you cannot use a linear trail approximation for HST, even if the trailed don’t appear to be curved.

This example was chosen to accentuate the curvature of the trail but many datasets only have the time-dependent velocity aspect along the trail direction.



Workflow

- Estimate size of fitting region
- Identify and save a rough measure of first star
  - Use initial WCS to overlay Gaia catalog star positions
  - interactively pick one star from the catalog
  - interactively pick that star from the image, offsets can be up to a few arcsec
  - This step creates the initial fitting condition and location of region to be fit.

Workflow

- Identify and save a rough measure of first star
- Compute offset between WCS and catalog
  - offset is applied to CRVAL → zero-point of WCS
  - update graphic, all stars should now line up between catalog and image

Workflow

- Identify and save a rough measure of first star
- Compute offset between WCS and catalog
- Identify 2-N additional stars
  - stars can be used from either WFC detector
  - goal is three stars per field but if there are sufficient stars, I use three stars per detector
  - total number of stars to use depends on details of your observation

Workflow

- Identify and save a rough measure of first star
- Compute offset between WCS and catalog
- Identify 2-N additional stars
- Review starting conditions (x,y,dw)
  - Entire star trail should fall in the fitted region with some background beyond ends of trail
  - ensure that the position centers the trail
  - manually revise region size up or down as needed

Workflow

- Identify and save a rough measure of first star
- Compute offset between WCS and catalog
- Identify 2-N additional stars
- Review starting conditions (x,y,dw)
- Mark pixels to exclude from the fit
  - failure to do this will pollute the later uncertainty envelope calculation

Workflow

- Identify and save a rough measure of first star
- Compute offset between WCS and catalog
- Identify 2-N additional stars
- Review starting conditions (x,y,dw)
- Mark pixels to exclude from the fit
- Fit trailed PSF to all stars

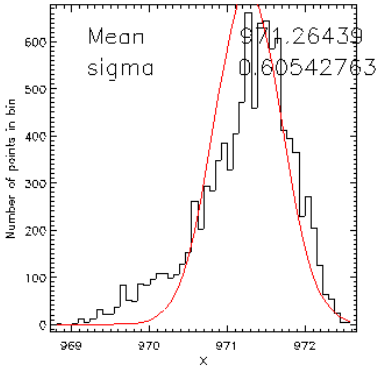
PSF fitting

- Nothing new here, χ^2 minimization, fitting x,y,flux
- For stars, use the trailed PSF
- Fot the target, use the HST PSF alone

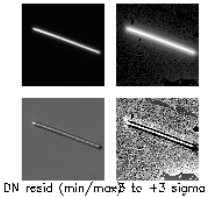
Uncertainties

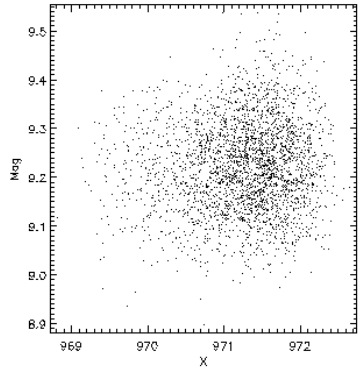
- Any problem that can be encapsulated by a χ^2 function can be addressed by MCMC
- For the star and target fits, start with the best fit and then build a probability cloud with MCMC
- Simple matter to take the star PDFs and generate a WCS PDF
- Combine the WCS PDF and target PDF to get a final measured PDF in celestial coordinates
- In necessary, PDF can be converted to an approximate gaussian error ellipse but this does reduce the fidelity of the results

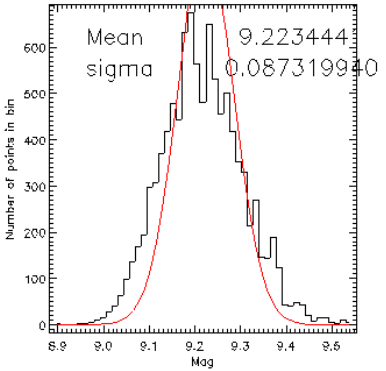
single star



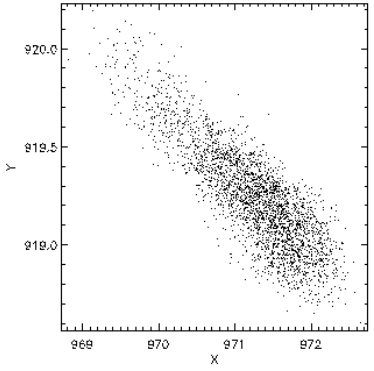
ie920414q
UVIS2
idx=145 hidx=60
NAV (969,915) [148.0]
Max (969,920) [4650.4]
sky=47.53+/−0.02
chisq=5.53
Fit (971.41,919.21)
Rmag=17.37
Flux=811649.1
imag=9.227
exptime=380s

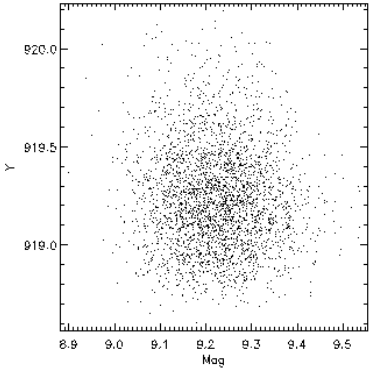


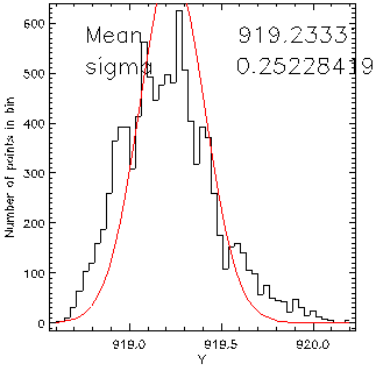




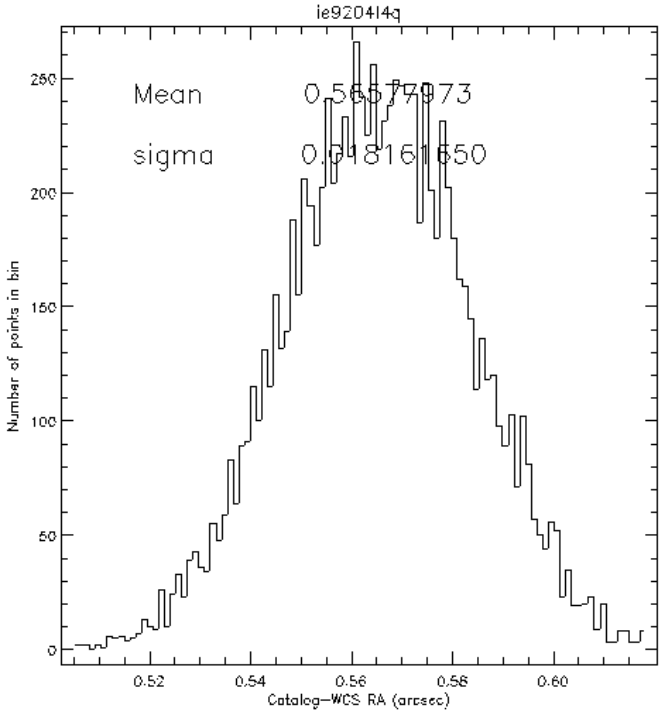
MCMC results
X mean 971.26
sigma 0.61
skew −0.78
kurt 0.46
Y mean 919.23
sigma 0.25
skew 0.52
kurt 0.28
mag mean 9.22
sigma 0.09
skew 0.24
kurt 0.10
flux=813996.2+/−65465.4
SNR=12.4
Nsamples 10000

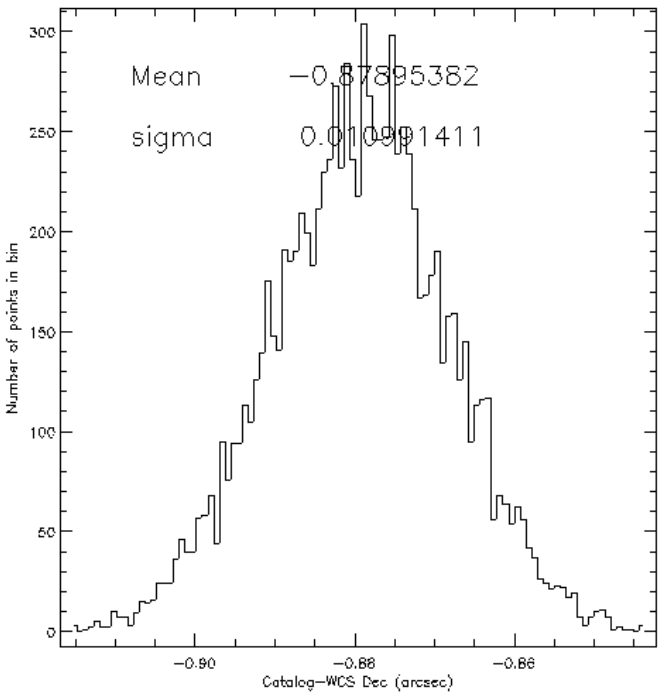


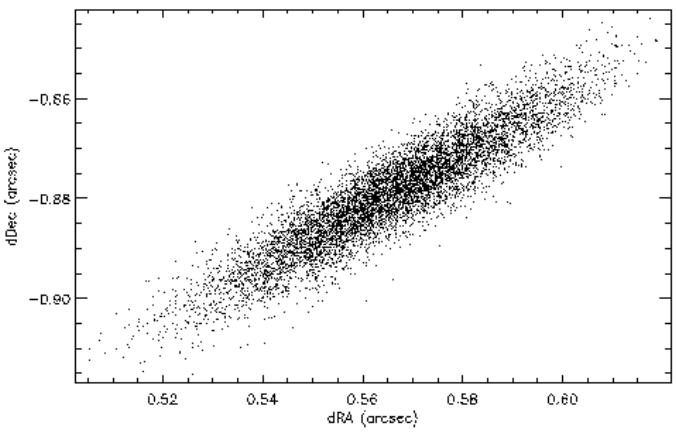




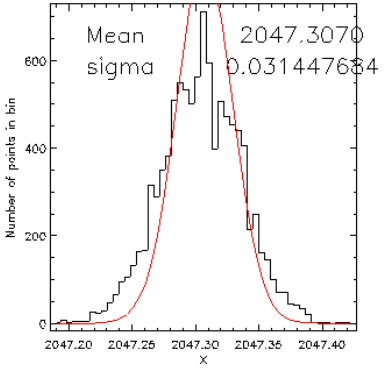
Single star relative to WCS





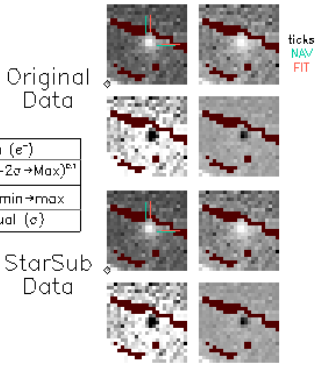


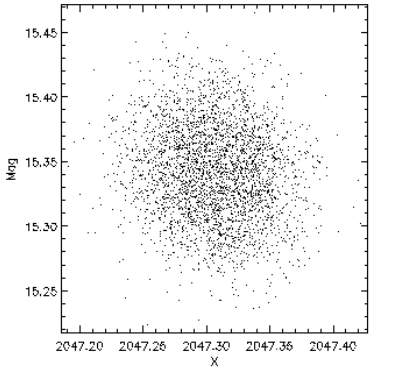
target

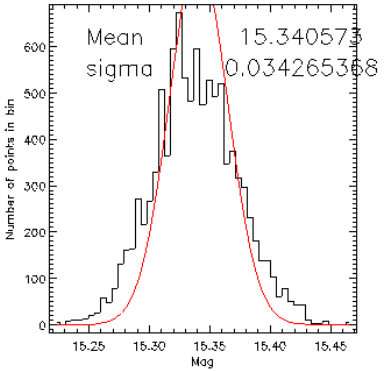


ie920414q
UVIS1
idx=30 hidx=59
NAV (2046,270) [171.5]
Max (2047,271) [183.3]
sky=49.23+/−11.24
chisq=13.00
Fit (2047.32,270.46)
Flux=2910.7
imag=15.340
exptime=380s
UT mid=2020/07/06 23:42:46

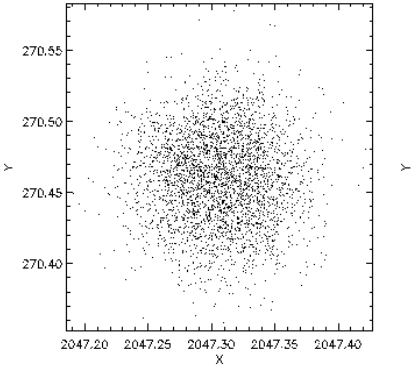
Data (e^-)	
±3σ	(−2σ→Max)^{e1}
±3	min→max
Residual (σ)	

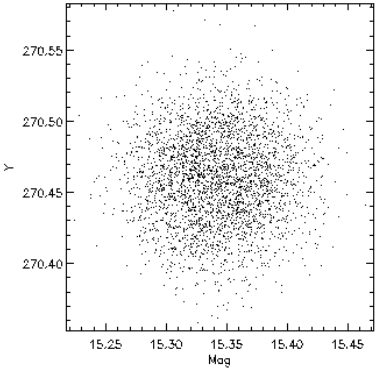


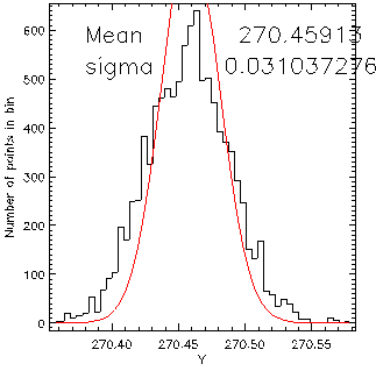




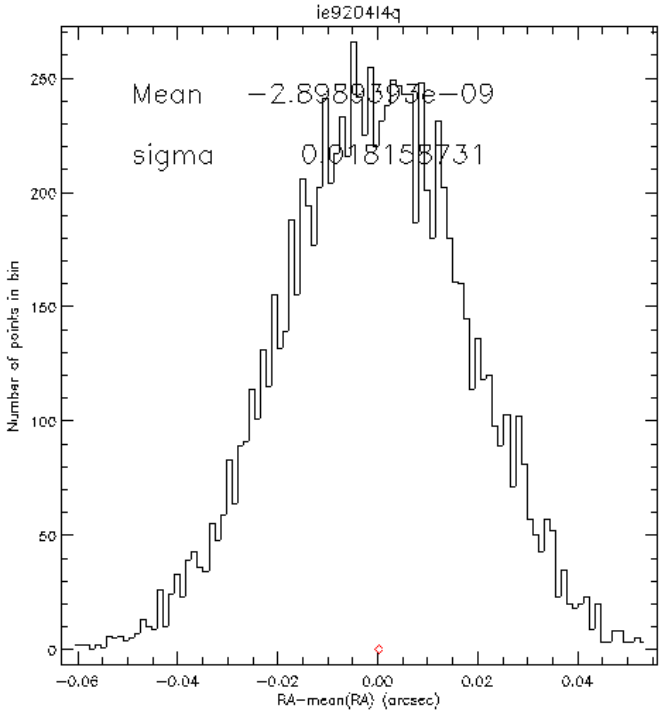
MCMC results
X mean 2047.307
sigma 0.031
skew −0.05
kurt 0.01
Y mean 270.459
sigma 0.031
skew 0.03
kurt 0.04
mag mean 15.341
sigma 0.034
skew 0.09
kurt −0.02
flux=2909.2+/−91.8
SNR=31.7
Nsamples 10000

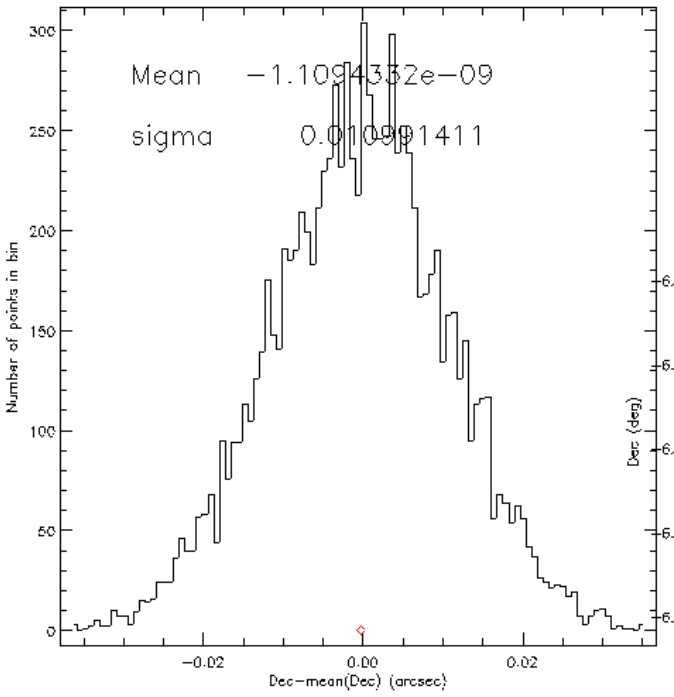






one-dimensional error distributions of target





Target relative to ephemeris