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Improving HST Astrometry with Gaia

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Including contributions from Mike Fall, Brian McLean, Matt Lallo, Ed Nelan, Brad Whitmore, Rick White, Steve Lubow, Tamas Budavari, Jay Anderson, and others

HST yields very good relative astrometry

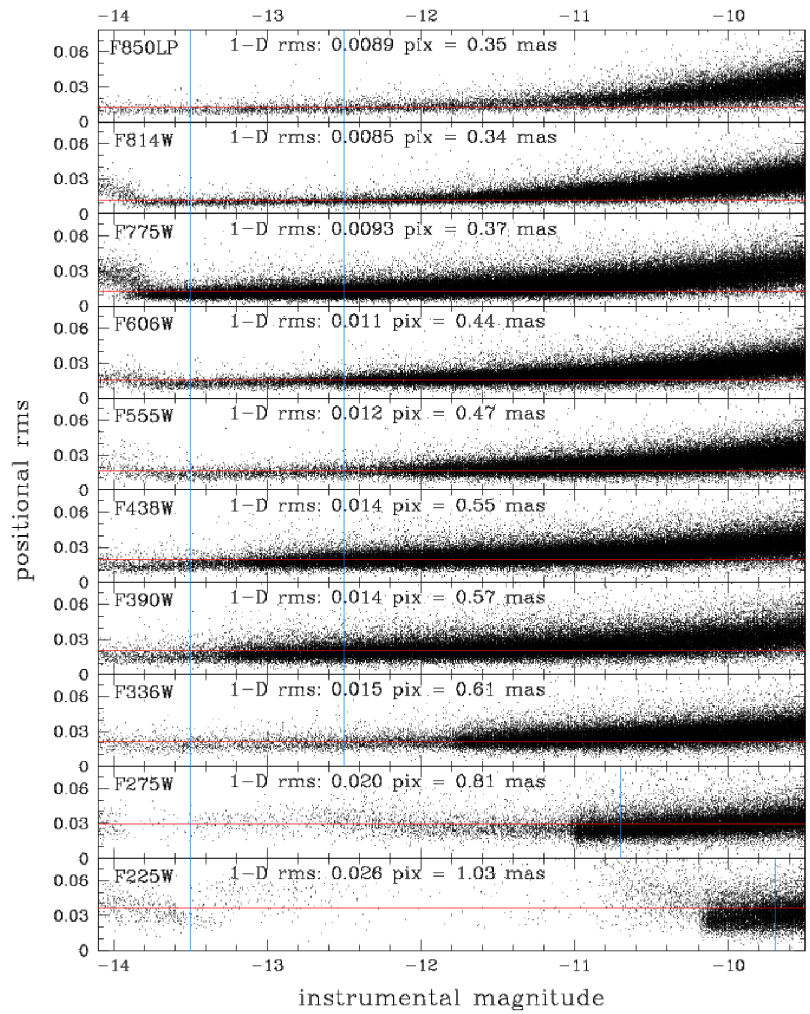
Pointed camera observations

(e.g. WFC3, F606W)

- PSF width 45 mas (rms)
- Pixel size 40 mas
- Requires careful PSF reconstruction (Anderson-Bellini)
- Geometric solution well established (might change at the 0.005 pixel level)
- Noise floor 0.01 pixel (0.4 mas) per observation (pixel properties, PSF changes)
- Up to 10^5 stars per image in crowded fields

FGS observations

- Measurement error 0.1-0.2 mas for very bright stars (V ~ 7)
- One star at a time



Bellini et al (2011)

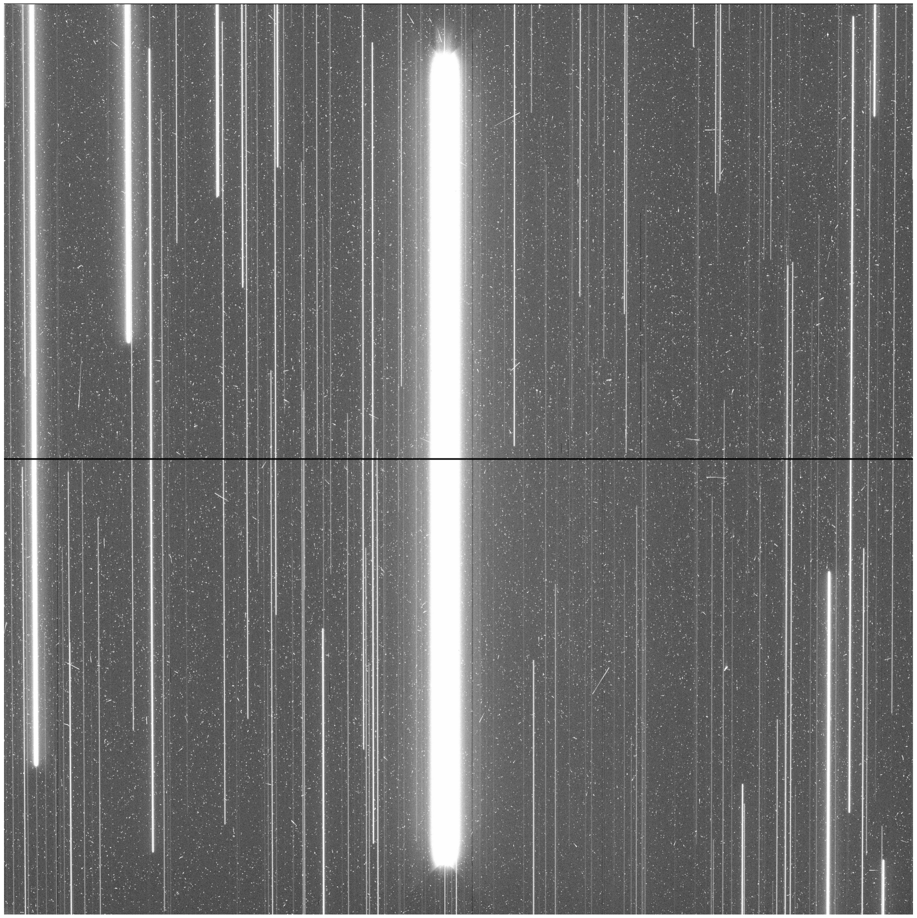
HST yields very good relative astrometry (2)

Spatial scanning

(WFC3, F606W)

- Averages over thousands of pixels
- One-dimensional measurement ~ 15 μas
- Suitable for V ~ 10-15
- Up to ~200 sources per observation
- Requires monitoring of geometric distortion variations, other effects
- Final parallax accuracy ~ 30-50 μas
  (dominated by geometry variations, dynamic range issues)

Talk by Adam Riess tomorrow

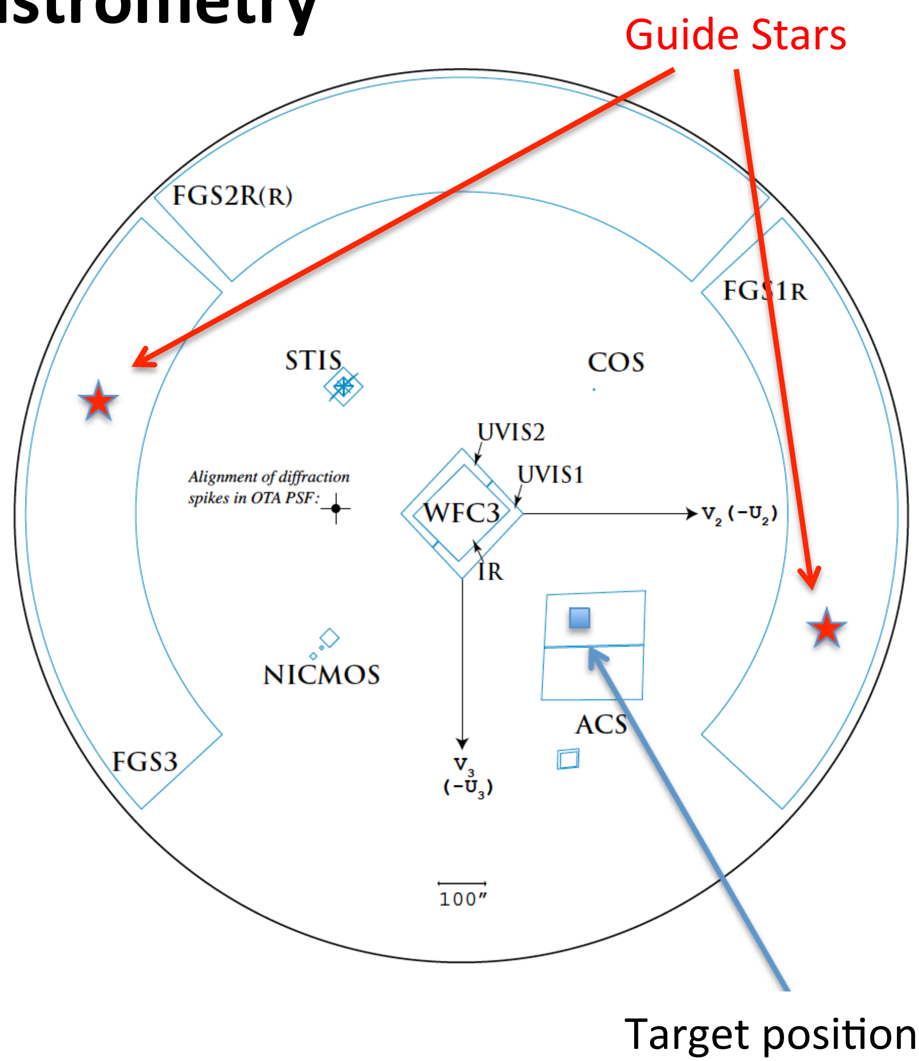


HST Absolute Astrometry

- Absolute astrometry with HST has been less accurate than for similar missions
  - Typical uncertainty 0.2” – 1” (4-20 times worse than angular resolution)
  - Spitzer, Galex, Chandra, Herschel have astrometric accuracy comparable or better than their angular resolution
- Two kinds of Astrometry:
  - “A priori” (blind pointing): determined from the Fine Guidance Sensors acquiring the desired Guide Stars
    - Available for all exposures (with caveats when target acquisition maneuvers are used)
    - Limited by several factors
  - “A posteriori”: determined from matching sources found in each image with external catalogs
    - Mostly available for cameras with ~1” FOV or larger (WFPC2, ACS, WFC3, NIC3, STIS)
    - Cross-matching may be difficult if wavelengths mismatched (e.g., UV images)
    - Occasionally few or no sources available
    - Accuracy limited by external catalog – typically 0.1”
- Until recently, only a priori astrometry available through normal HST archive (STScI, ESAC, CADC)
- Working Group led by Mike Fall to improve this situation

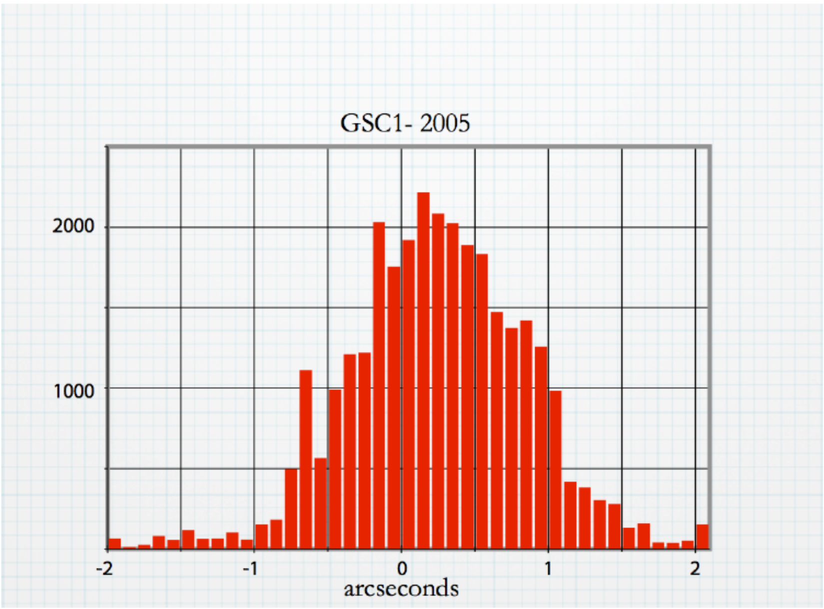
A priori astrometry

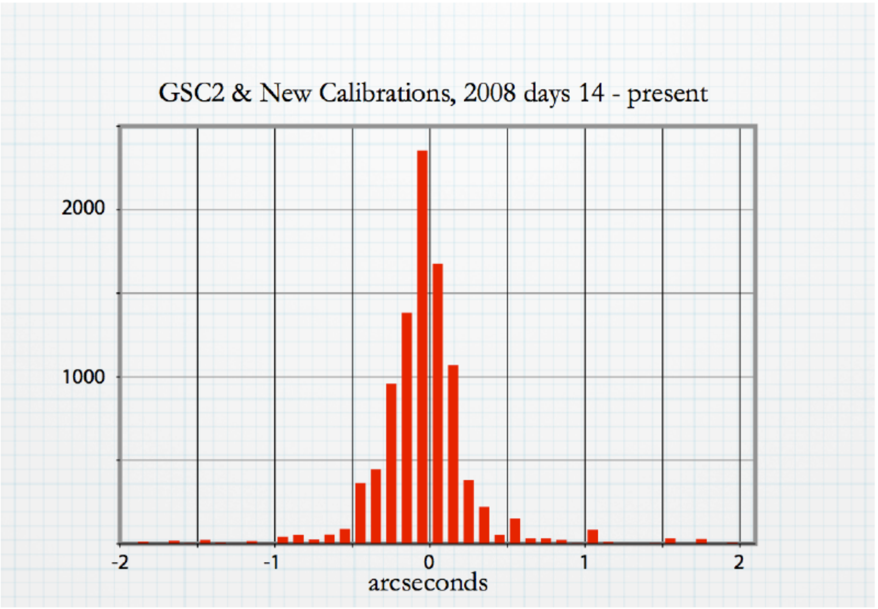
- Astrometric information depends on chain of calculations
  1. Absolute position of Guide Stars
  2. Geometric solution for FGS => astrometry of FGS reference point
  3. Calibration of FGS position in HST focal plane => astrometry of HST reference point
  4. Calibration of observing instrument in HST focal plane => astrometry of instrument reference point
  5. Calibration of geometric distortion inside instrument => astrometry of each pixel in detector
- The limiting quality is in 1. and 3.-4. (2., 5. are known to a few mas)



A priori Astrometry (2)

- Until 2005, position were based on GSC (nominal rms error 1”/coordinate, frequent outliers up to 3” – occasionally larger)
  – Modest effort put in focal plane calibration (GSC errors dominant)
- After conversion to GSC2 coordinates (2005) and improved FGS calibration (2007), typical errors 0.15”/coordinate
  – Increased effort in maintaining focal plane calibration

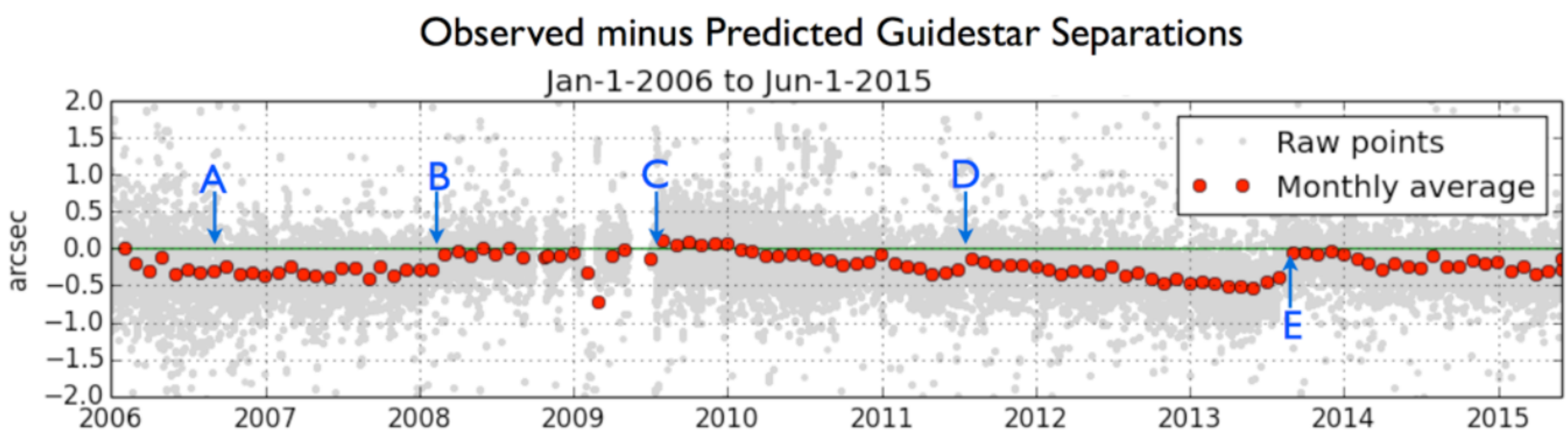




Guide star separation errors before and after updates

Focal plane calibration is difficult to maintain

- FGS positions evolve with time
  - Changes up to 0.2”/year
  - Calibration is complex, time-consuming
  - Typically executed every 2 years
    - More frequent executions have reduced benefits because of GS errors
  - Other instruments also move to a smaller extent
- With Gaia coordinates for GS, focal plane improvements desirable



A, B, C, D, E: FGS Alignment Calibrations
Mid-2009: Servicing Mission (COS, WFC3)

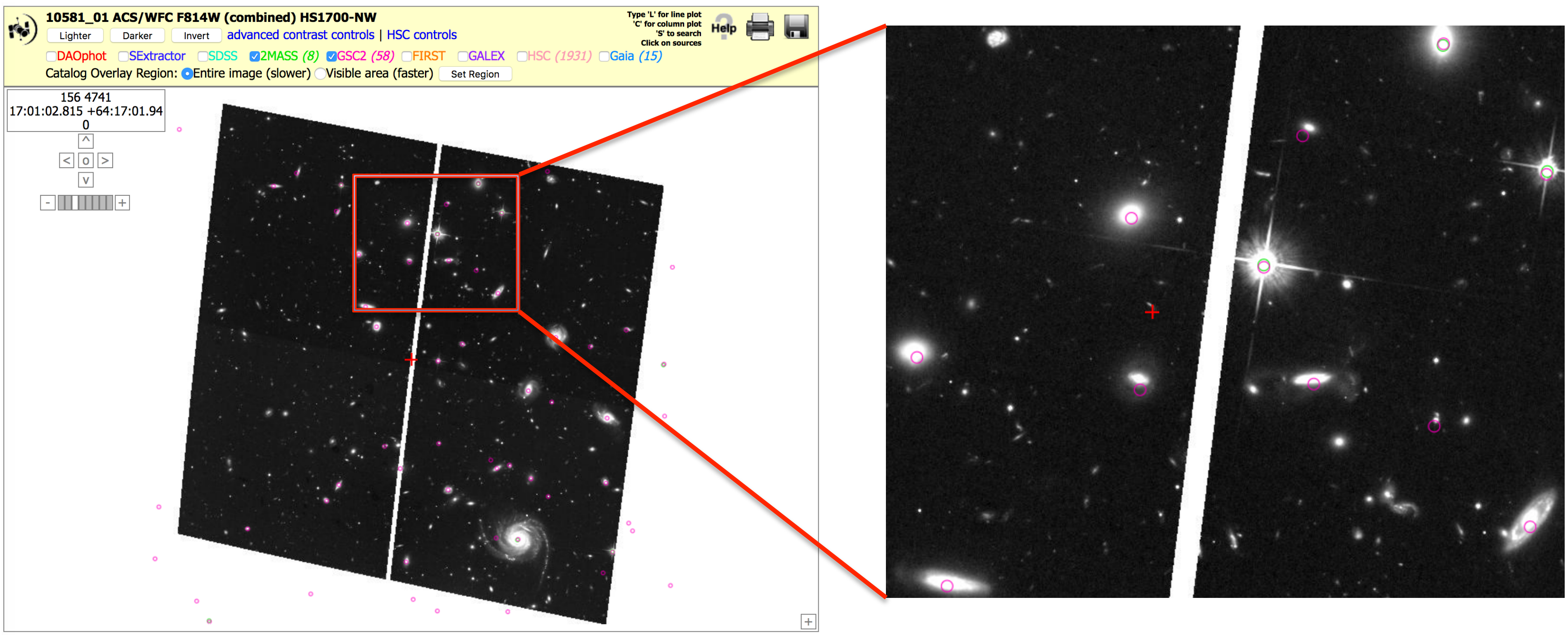
Determining a posteriori astrometry

- Matching conceptually simple
  - Identify sources in HST image
  - Cross-match to reference catalog (traditionally 2MASS, GSC2)
  - Adjust (3-parameter fit) to improve HST astrometry
  - Internal geometric distortion known to high accuracy (sub-mas)
- Typical WFC3, ACS images include several (2MASS) to tens (GSC2) of matches at high galactic latitude
  - Potential issues in some cases
    - Complex regions with diffuse, partially resolved emission, or close pairs
      - "Source" has different meaning for HST, ground
    - Observations in UV or narrow-band filters
      - Wavelength mismatch produces different sources
  - In principle, astrometry limited primarily by reference catalog accuracy
- However, source matching is not included in standard HST processing pipeline
  - Hubble Legacy Archive (HLA) post-processing has bulk updated astrometry (since ~2009)
  - Analysis showed good overall quality, occasional large (~1") errors

Matching sources in HLA

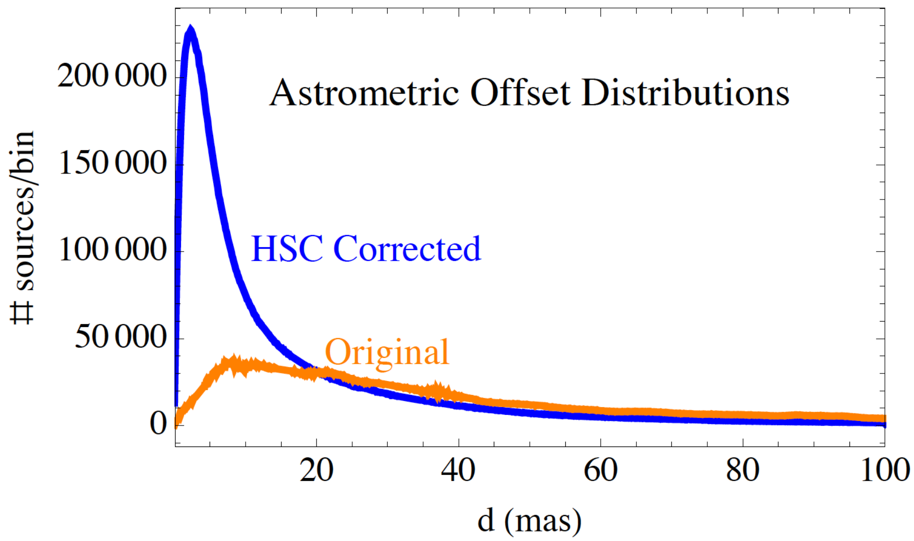
HLA display screen
One ACS field (part of 4-image observation)
Galaxy overdensity at z > 1.5, PI Shapley

Matched sources (red: GSC2; green: 2MASS)
Astrometry updated from matches

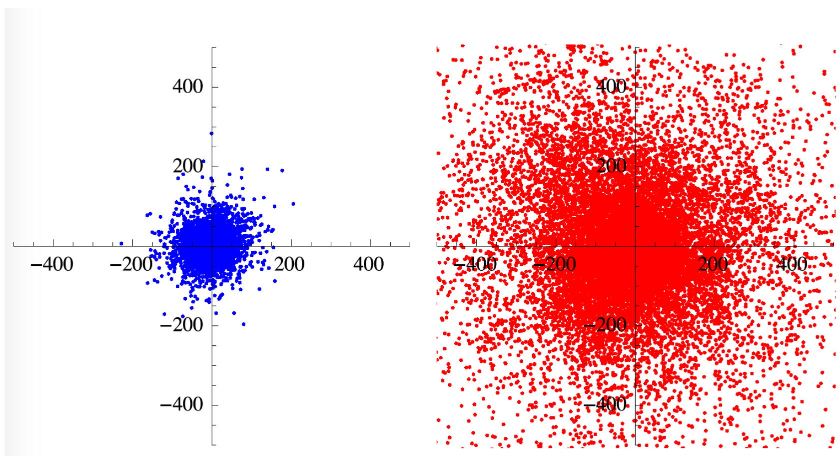


The Hubble Source Catalog

- Started in 2012 to obtain homogeneous source information across most HST data (Whitmore, Lubow Budavari, White, et al)
- Sources matched across HST images
  - Substantial improvement in relative astrometry
- Background catalog (PanSTARRS if available) to set absolute astrometry
- Updated astrometry still not available in HST processing



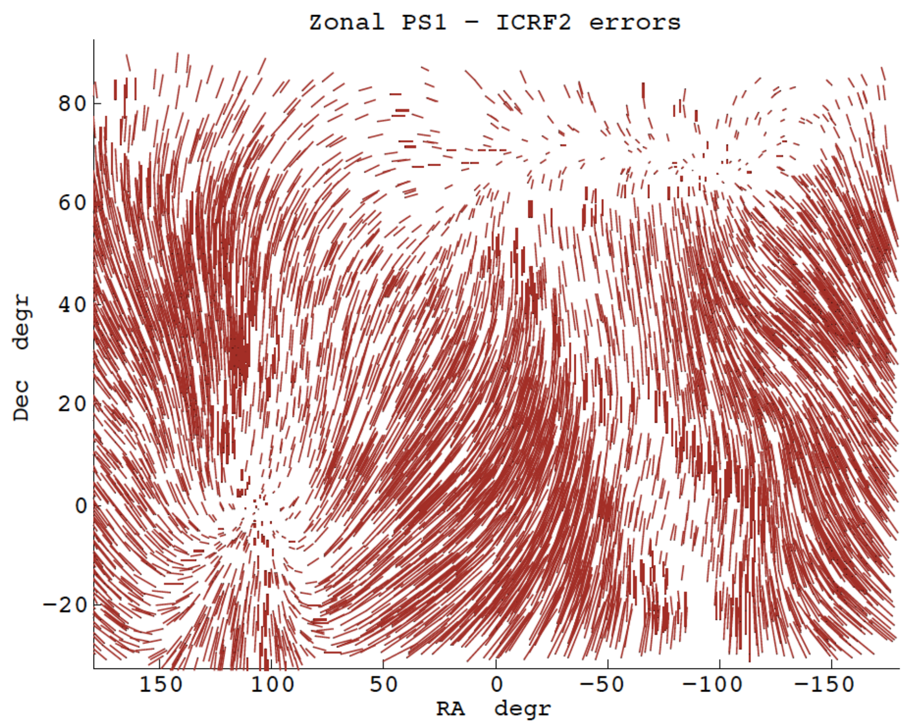
Improvement in relative astrometry with the Budavari-Lubow source matching algorithm

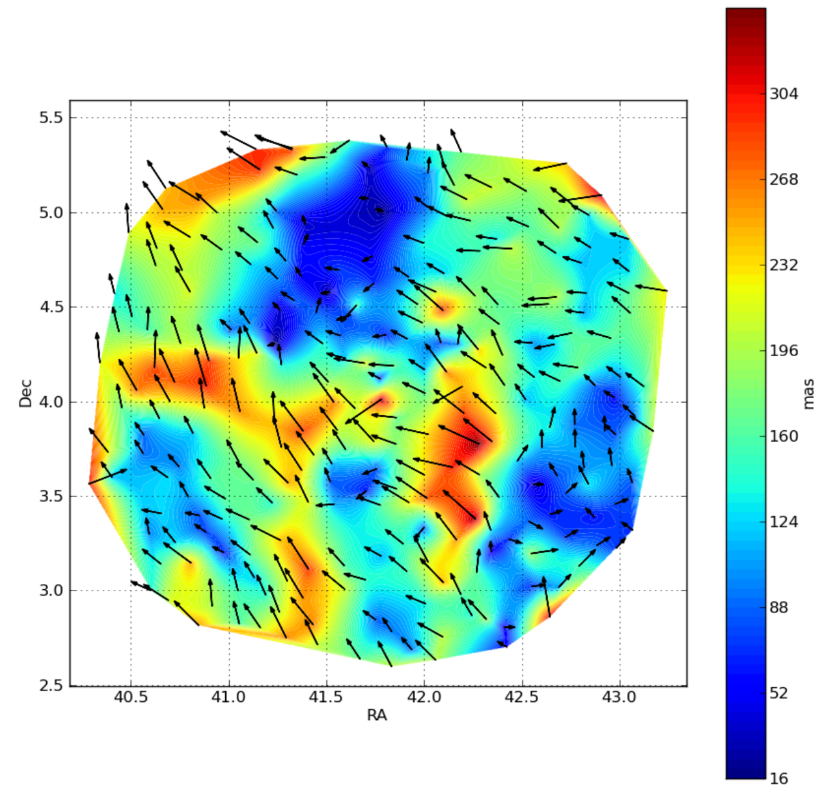


Improvement in absolute astrometry after HSC adjustments (mas)

Absolute "a posteriori" astrometry now limited by reference catalog

- PanSTARRS default solution referenced to 2MASS
  - Large scale pattern error (median ~56 mas)
  - Small (single-FOV) errors ~ 150 mas
  - Both can be corrected with global solution based on Gaia DR1





(Courtesy: V. Makarov, C. Berghea, USNO)

Improving HST absolute astrometry – the near future

- Step 1: Improve Guide Star positions
  - Cross-match completed (Brian McLean)
  - Currently performing statistical analysis
  - Updated positions will be transferred to operational guide star catalog starting spring 2017
  - Will result in ~ 100 mas "a priori" positions for all new HST data
- Step 2: Obtain improved PanSTARRS astrometry
  - Requires final PanSTARRS database (currently being tested at STScI)
    - Release expected December 2016
  - Analysis and improved astrometry will likely take ~ 1 year
    - Work in coordination with USNO
  - Will result in ~10 mas absolute astrometry for most HST imaging data
    - Solution may be affected by PanSTARRS-Gaia epoch difference until DR2

Improving HST absolute astrometry – the near future (2)

- Step 3: Propagate improved astrometry to data retrieved from archives
  - Requires development of database of improved astrometry and modifications to pipeline
  - Expected to be completed at the same time as Step 2
  - Will result in improvements of both "a priori" and "a posteriori" astrometry
  - Multiple solutions will be available from the Archive
  - Will also allow inclusion of community-provided astrometry for special fields
    - Details of information definition and propagation to be discussed

Can we do better?

Some additional avenues for improvement include:

- Leverage very accurate guide star and source positions to improve HST focal plane solution
  - Greatly enhance historical knowledge
  - Replace expensive FGS calibration for future data
  - Would result in improvement of a priori positions for *all* HST data
  - Possible, but not yet evaluated quantitatively
- Use Gaia stars directly when possible
  - Lower source density, but would avoid less precise PanSTARRS measurements
  - Potential for mas-level astrometry when enough matches are available
  - Requires DR2 (proper motions) for application to past data
- Improve single-source measurements
  - Currently done with simple centroiding (up to 5-10 mas pixel-phase errors)
  - Anderson-Bellini method can achieve 0.5 mas (1.5 mas in IR) for high S/N sources
  - Proposal to reprocess sources for all WFC3 data currently under consideration

In summary…

- Absolute astrometry of HST data will improve enormously by the end of 2017
  - A priori astrometry will go from 300-500 mas to 50-100 mas thanks to Gaia positions for guide stars
  - A posteriori astrometry will go from 60 to 10 mas thanks to Gaia calibration of PanSTARRS astrometry
- Further improvements may yield an additional order of magnitude in both