MAST Users Group Meeting

December 15-16, 2016

Improving HST Astrometry with Pan-STARRS and Gaia

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With the MAST team, the HSC/HLA team

and the Astrometry Working Group

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HST Absolute Astrometry

- HST is capable of extremely good *relative* astrometry (~0.4 mas with imaging, 0.2 mas with the FSG, 0.03 mas with spatial scanning)
- However, *absolute* astrometry has traditionally been much less accurate
  - Typical uncertainty 0.2" – 1" (4-20 times worse than angular resolution)
  - Spitzer, Galex, Chandra, Herschel have astrometric accuracy comparable to 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

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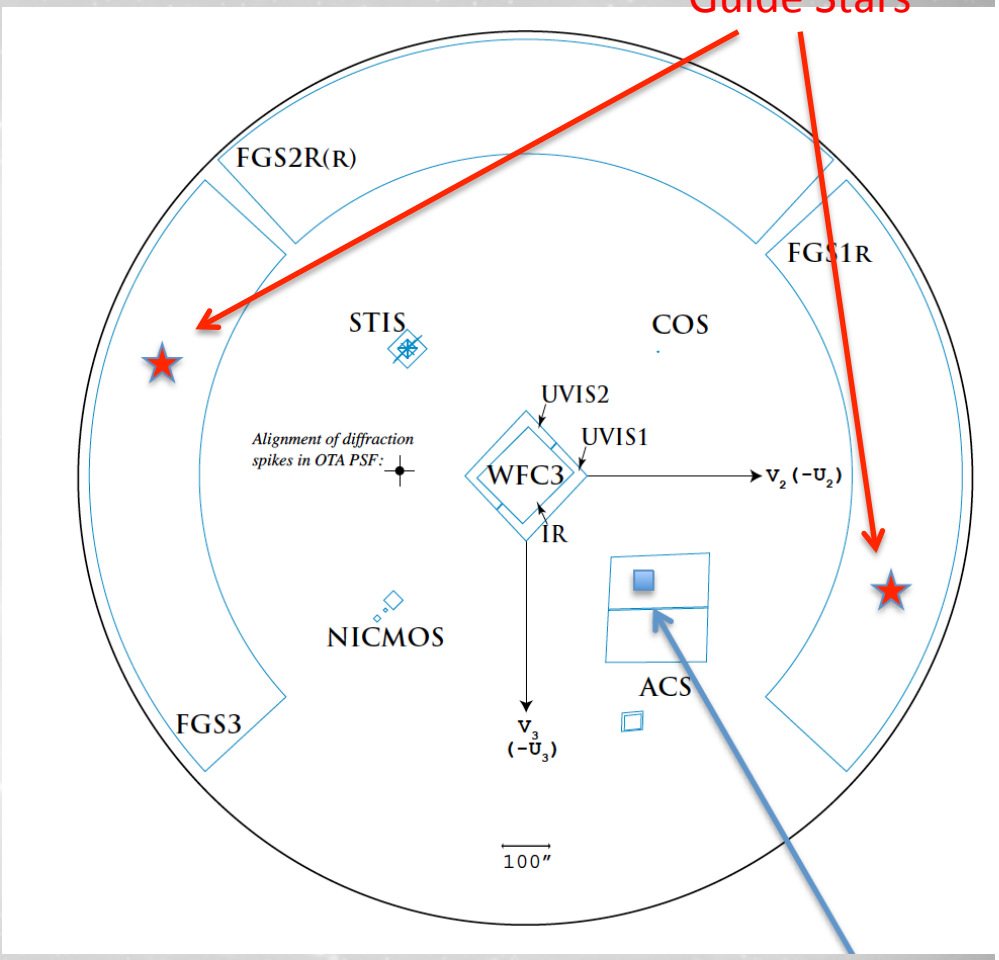
A priori astrometry

A priori astrometric information depends on a chain of calculations

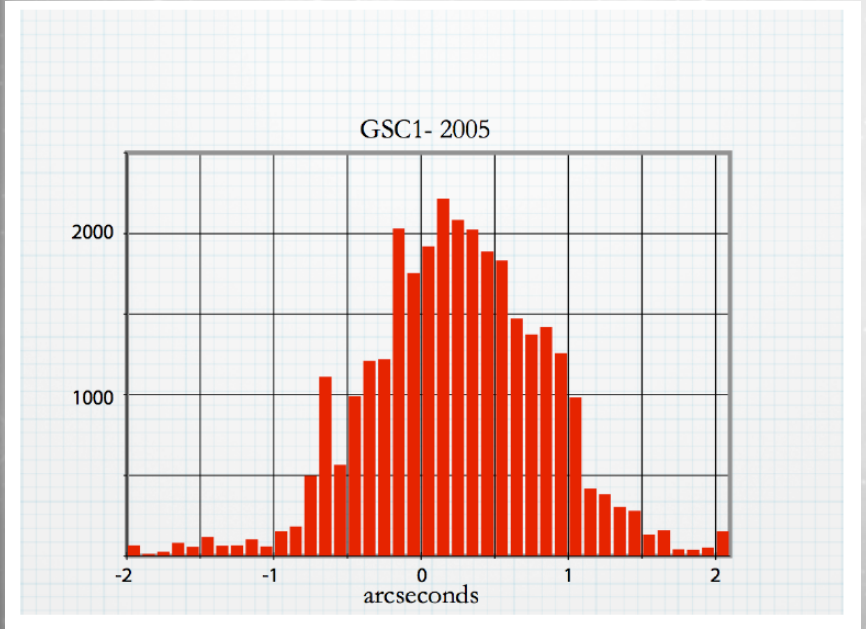
1. Absolute position of Guide Stars
2. Geometric solution for FGS => astrometry of FGS reference point
3. Calibration of FGS position in HST focal plane => astrometry of HST reference point
4. Calibration of observing instrument in HST focal plane => astrometry of instrument reference point
5. Calibration of geometric distortion inside instrument => astrometry of each pixel in detector

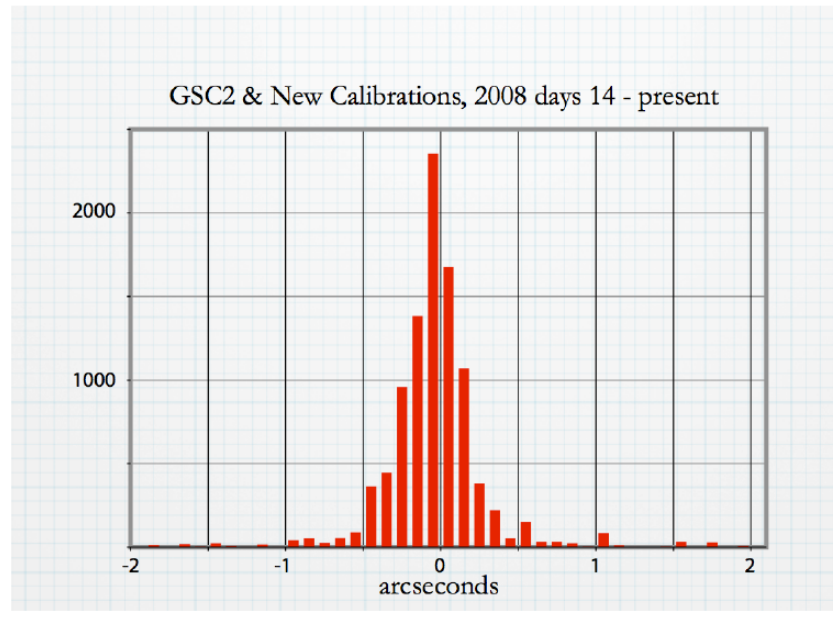
- The limiting quality is in 1. (absolute GS positions) and 3. minus 4. (only difference between FGS and instrument position matters for final astrometry)
- Transformations 2. and 5. are known accurately (to better than a few mas)



A priori Astrometry (2)

- Until 2005, position were based on the original Guide Star Catalog (GSC), obtained from “quick V” plates
  - Nominal error 1”/coordinate (rms), with frequent outliers up to 3”
  - 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”-0.25”/coordinate
  - Led to increased effort to maintain focal plane calibration





Guide star separation errors before and after updates

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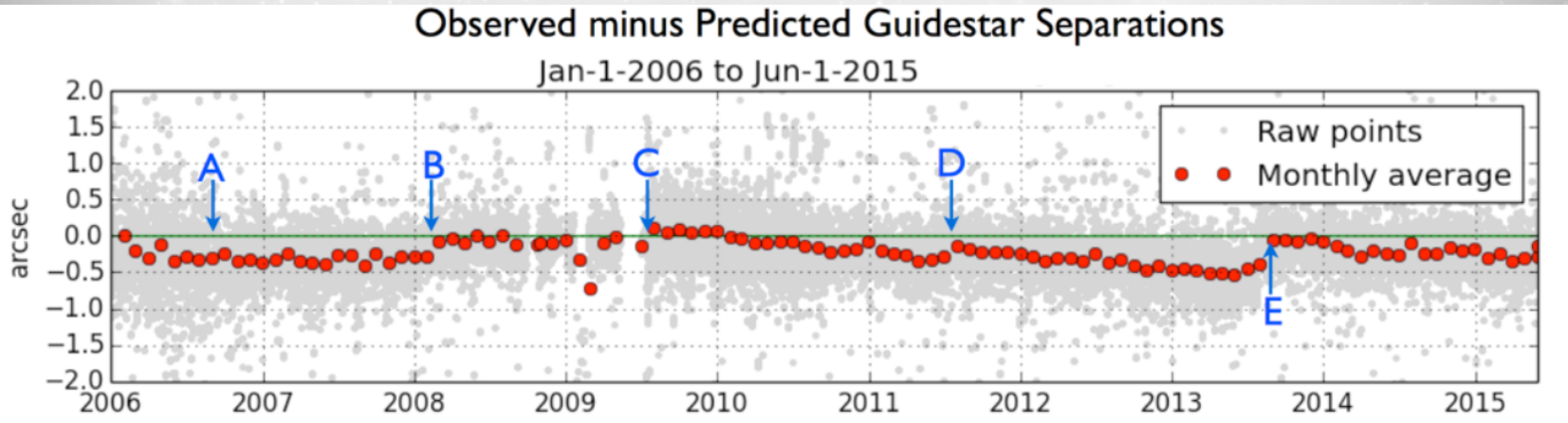
Focal plane calibration is difficult to maintain

- 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, dominant error is focal plane solution
  - Focal plane improvements highly 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

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Matching sources in HLA

HLA display screen (start from http://hla.stsci.edu)

One ACS field (part of 4-image observation)

Program 10581:

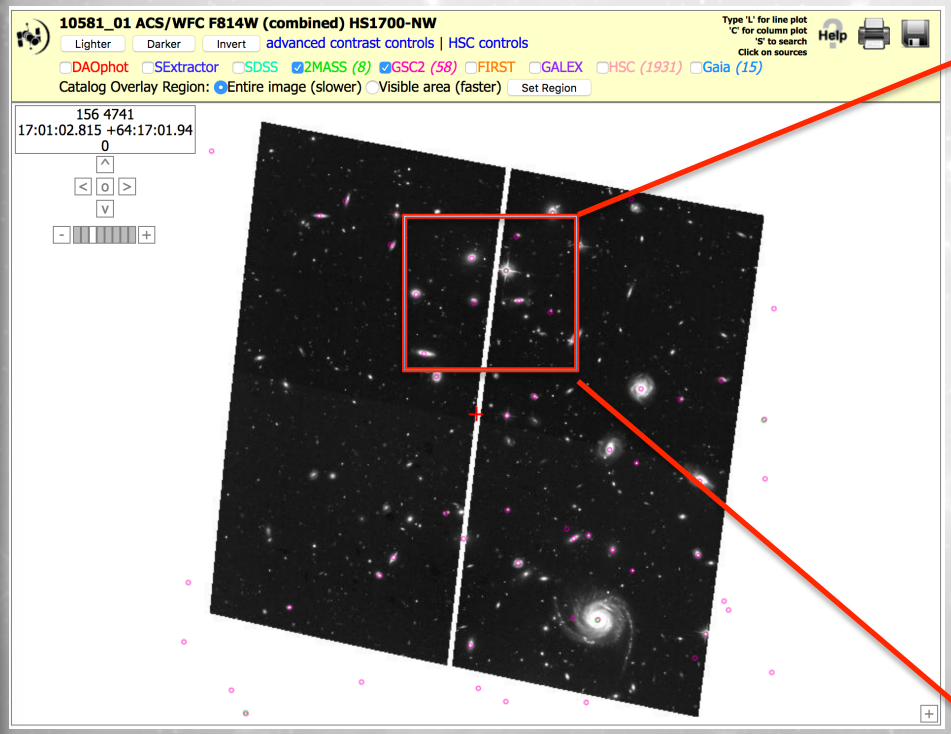
Galaxy overdensity at z > 1.5, PI Shapley

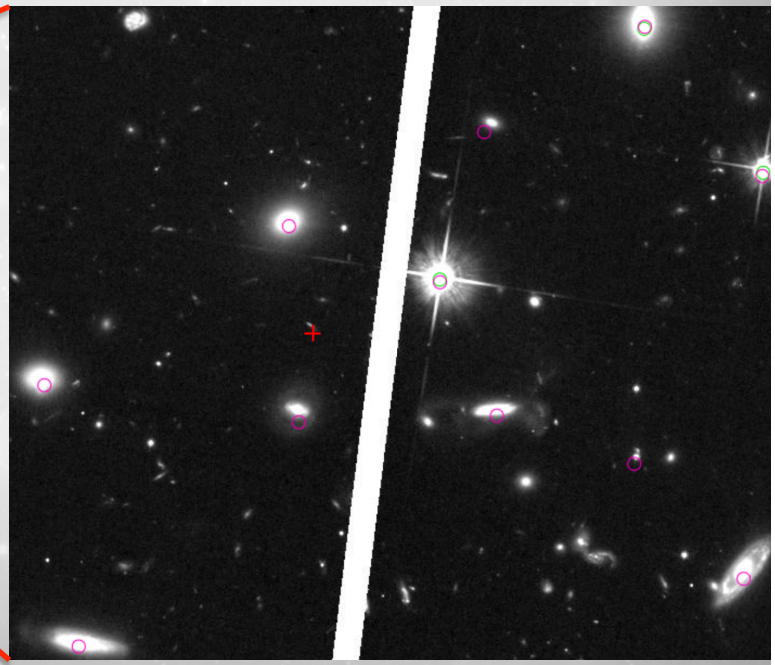
Zoom in to show source matches

Red circles: GSC2 (~30 matches)

Green circles: 2MASS (~8 matches)

Astrometry updated from matches





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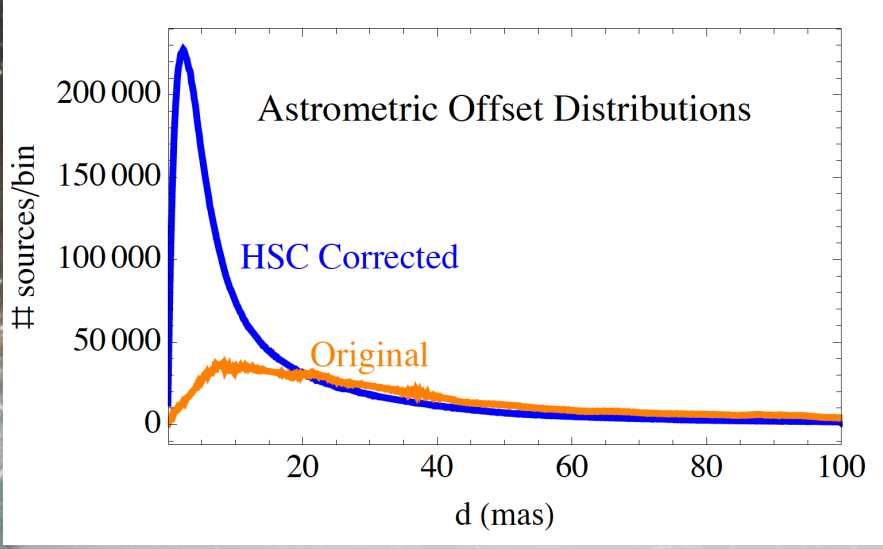
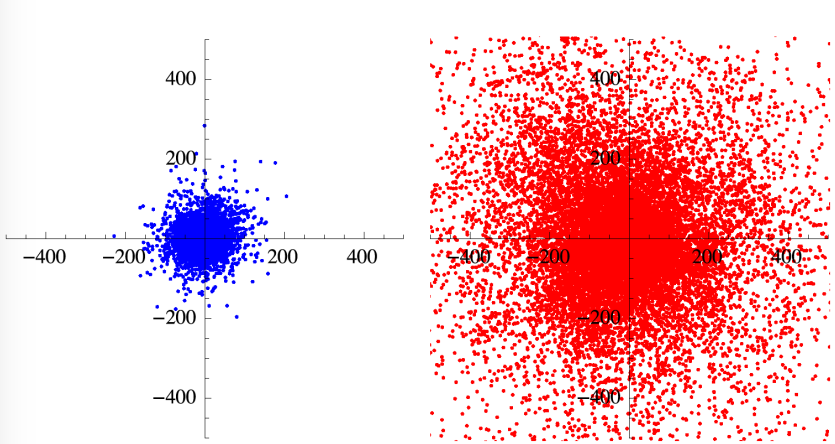
The Hubble Source Catalog

- 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 across multiple images
- Background catalog (PanSTARRS if available) to set absolute astrometry
- Updated astrometry still not available in standard HST processing
  - HLA images will soon be updated with HSC positions
- Reference: Whitmore et al, AJ 2016, 151, 134



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



Improvement in absolute astrometry after HSC adjustments (mas)

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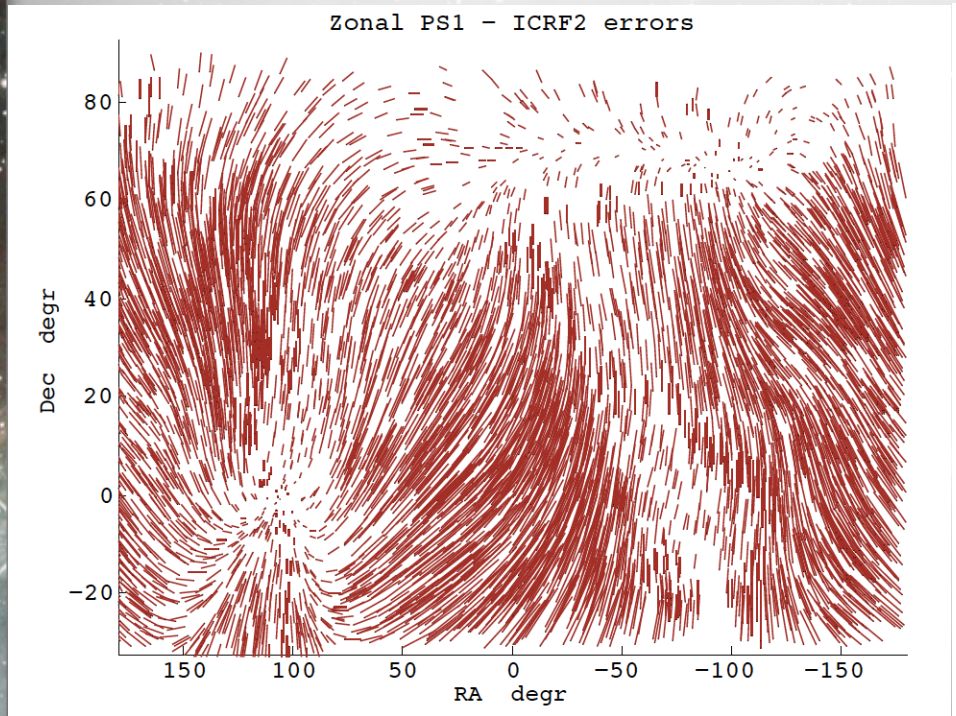
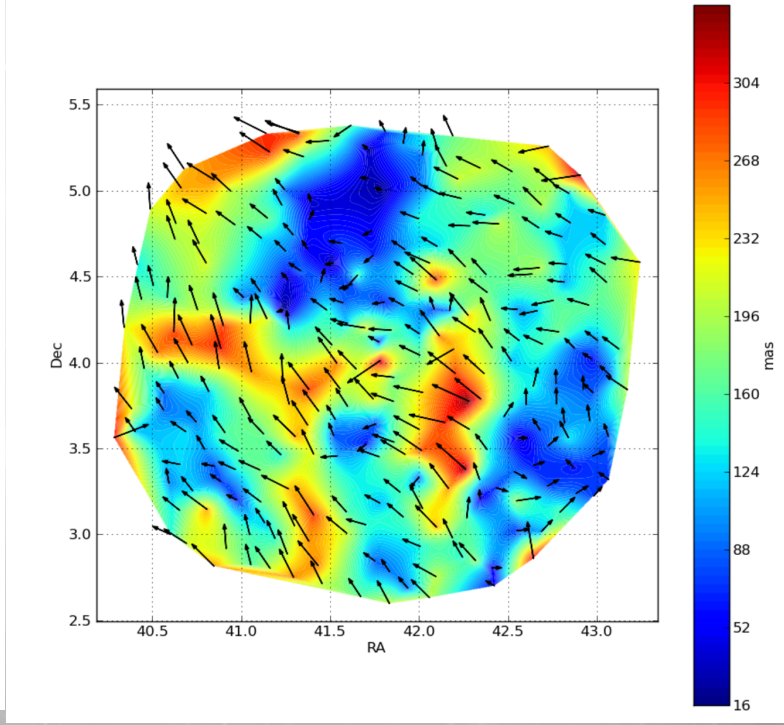
Absolute “a posteriori” astrometry in HSC now limited by reference catalog

- 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
- Tentative position update announced by PanSTARRS consortium; details unclear
  - More detailed analysis (back to individual detections and detector geometric distortion) planned within next 6 months by USNO
  - Likely will result in < 10 mas systematic zonal uncertainties on all scales





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

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Improving absolute astrometry for HST users (1)

Steps to obtain better astrometry for HST data and incorporate it in the Archive:

1. Improve guide star positions and eventually focal plane solution
2. Link external catalogs (especially PanSTARRS) to Gaia
3. Match sources to external catalogs
4. Prepare database for improved astrometry
5. Transfer astrometry information to archived data

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Improving absolute astrometry for HST users (2)

- Step 1: Improve Guide Star positions
  - Cross-match guide stars to Gaia catalog (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)
    - Planned release date is December 19, 2016
  - Current version includes preliminary Gaia-based astrometry
  - Improved solution at the detector level (in coordination with USNO) will probably be carried out in early 2017
    - Reduce systematic errors below 10 mas
    - Solution may be affected by PanSTARRS-Gaia epoch difference until DR2
- Step 3: Match sources to PanSTARRS or other external catalogs
  - Same process as used for Hubble Source Catalog
  - Expected to achieve absolute astrometry up to ~ 10 mas for most HST imaging data (depending on number and brightness of matches)

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Improving absolute astrometry – for HST users (3)

- Step 4: Generate database of improved astrometry
  - Include improved a priori and a posteriori astrometry
  - Database populated under scientist supervision
  - Multiple astrometric solution possible; may ultimately include external input (e.g., registration based on procesing by GO teams)
  - Will also allow inclusion of community-provided astrometry for special fields
    - Details of information definition and propagation to be discussed
- Step 5: Modify pipeline to read astrometry from database
  - Multiple solutions included; database will identify preferred solution, but users can modify that choice
  - Original solution also retained as alternate
  - Mediating through database insulates pipeline from potentially complex astrometric matching, allows for later registration
  - Will enable propagation of improved astrometry to all data, including those without source matching
  - Expected to be completed at the same time as Step 2

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GAIA Astrometry for Mission Operations Task status

- GAIA catalog availability
  - DR1 released to data centers Sept 16 (day after public release)
  - Downloaded gbin files (36 hours)
- Read gbin files and load SQLserver
  - Loaded SQL server database (30 hours).
  - Created auxiliary tables needed for MAST services, created table indexes for 'main' columns (48 hours) [add more later].
  - Created separate copy for MAST Ops server
- Provide web service to read GAIA catalog (standard catalog access methods)
  - Setup up catalog webservices & casJobs (using Ops copy)
- Cross-Match GAIA with GSC2
  - Initial matching done (also match to SDSSdr13, VISTAdr3, WISE)
  - Performing statistical analysis
  - Only 50% GAIA objects have GSC2 match
    - primarily due to deeper mags in galactic plane
- Transfer available astrometry (coordinates, proper motions, errors) to GSC2
  - Extended GSC catalog schema to accommodate GAIA data (GSC2.4.0)
  - Extended schema to accommodate SDSS dr13 and ESO VISTA surveys (new JWST requirement they are funding)
- Generate new version of GSC2 for Operations
  - Spring 2017

Astrometry Database for Reprocessing – Task status

- Create database with all available astrometric information for every HST (JWST) observation
  - Guide stars, pointing coordinates, astrometric solutions, wcs keywords
- RIA assigned
  - Estimated start Jan/Feb 2017
  - 50% effort for 6 months
- Get headerlet tools and recipes from SSB
  - Create headerlets for all existing HST datasets from on-line cache
  - Create headerlets based on HLA/HSC
  - Compute astrometric updates to headerlets based on GAIA astrometry
    - Dominant GS pointing update (zero point shift)
    - Pair GS pointing update (zero point, rotation, scale)
    - HLA/HSC after PS1/GAIA updates
- Provide web service to provide updated wcs keywords for any specified observation to bring it onto GAIA reference frame
- Update astrometry for all observations in HST/JWST cache
- Integrate astrometric update into processing pipeline
  - Fall 2017

Can we do even better?

Some additional avenues for future 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 Gaia DR2 (proper motions) for application to past data
    - Lack of proper motions is the limiting factor for use of PanSTARRS as reference
- 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

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Additional tools for MAST users: Gaia Interfaces

Incorporate into the existing MAST interfaces

- Casjobs
- Portal cross-match, catalog advanced search and export
- Catalog overlay in interactive display
- Catalog web services (cone search with output format options)

Example of HSC and Gaia overlays on an HLA image

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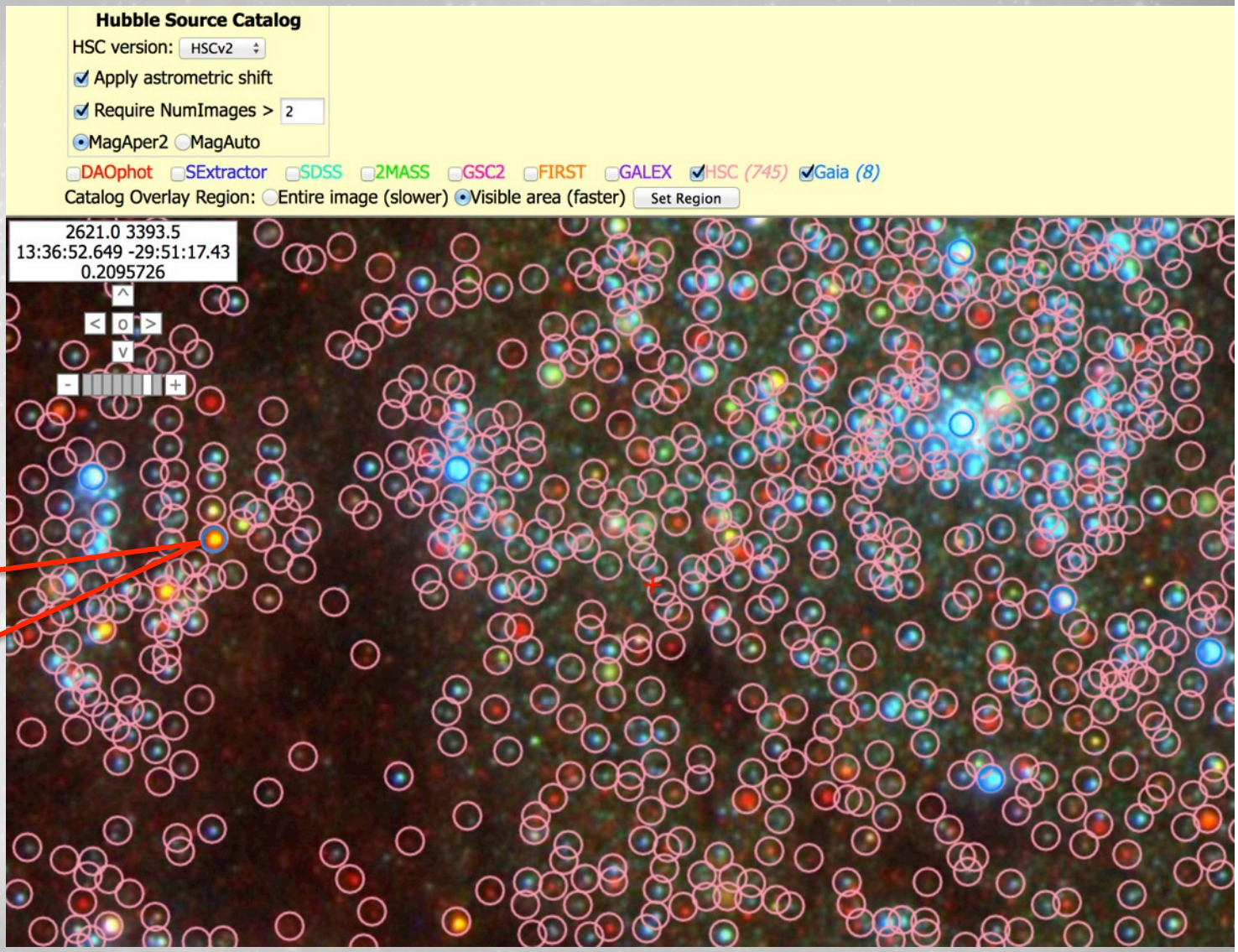

12513_05 WFC3/UVIS (color) M83-F5
f814w / f438w / f336w

HSC

Results 1-1

Click column heading to sort list - Click rows to select
Show catalog columns: Main All Column descriptions: Show Hide
Text boxes under columns select matching rows Apply Filter Clear Filter

MatchID	MatchRA	MatchDec
3940397	13:36:53.231	-29:51:22.46

Gaia

Results 1-1

Click column heading to sort list - Click rows to select
Show catalog columns: Main All Column descriptions: Show Hide
Text boxes under columns select matching rows Apply Filter Clear Filter

source_id	ra	dec
6175803470000915584	13:36:53.23	-29:51:22.49

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
  - Timeline for full implementation ~ 1 year
- Further improvements may yield an additional order of magnitude in both
  - Will require Gaia DR2 (with proper motions, late 2017/early 2018) for highest precision
- Gaia data are being integrated into MAST