Improvements in HST Astrometry

January 2024:   For more information on Hubble Advanced Products (HAP), please see the following resources.

Resources	Source	Link	Last Updated
HAP: Single Visit Mosaics	MAST Newsletter	https://archive.stsci.edu/contents/newsletters/december-2020/hap-single-visit-mosaics-now-available	Dec 2020
HAP: Multi Visit Mosaics	MAST Newsletter	https://archive.stsci.edu/contents/newsletters/may-2022/multi-visit-mosaics-from-hubble-now-available	May 2022
Improved Absolute Astrometry for ACS and WFC3	HST Instrument Science Report	https://www.stsci.edu/files/live/sites/www/files/home/hst/instrumentation/acs/documentation/instrument-science-reports-isrs/_documents/isr2203.pdf	Aug 2022
Astrometric Information in HST FITS Files	DrizzlePac Handbook	https://hst-docs.stsci.edu/drizzpac/chapter-4-astrometric-information-in-the-header	Feb 2021
DrizzlePac Updates	DrizzlePac Webpage	https://www.stsci.edu/scientific-community/software/drizzlepac	Sept 2022
Drizzlepac Software	Readthedocs	https://drizzlepac.readthedocs.io/en/latest/	Jan 2024
MAST Drizzled Products	Readthedocs	https://drizzlepac.readthedocs.io/en/latest/explanation.html#hubble-archival-products	Jan 2024

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NEWS: September 9, 2022

In **August 2022**, a new ACS/WFC3 instrument science report (ACS ISR 2022-03; WFC3 ISR 2022-06) titled '**Improved Absolute Astrometry for ACS and WFC3 Data Products'** was published. This ISR describes updated WCS solutions in MAST data as well two new types of Hubble Advanced Products (HAP).

> *Abstract:*
> *As of late-2019, MAST data products for ACS and WFC3 include improved absolute astrometry in the image header World Coordinate System (WCS). The updated WCS solutions are computed during pipeline processing by aligning sources in the HST images to a select set of reference catalogs (e.g. Gaia eDR3). We compute statistics on the alignment fraction for each detector and estimate the uncertainties in the WCS solutions when aligning to different reference catalogs. We describe two new types of Hubble Advanced Products (HAP), referred to as Single Visit Mosaics (SVMs) and Multi Visit Mosaics (MVM), which began production in MAST in late-2020 and mid-2022, respectively. The SVM products include an additional relative alignment across filters in a visit, and the drizzled images are used to generate point source and segment catalogs during pipeline processing. These catalogs supersede those produced by the Hubble Legacy Archive and will be the basis of the next version of the Hubble Source Catalog. The MVM data products combine all ACS/WFC, WFC3/UVIS, or WFC3/IR images falling within a pre-defined 0.2° x 0.2° 'sky cell' for each detector+filter, which are drizzled to a common all-sky pixel grid. When combining observations over a large date range, MVMs may have photometric errors of several percent or systematic alignment errors when combining visits with different catalog solutions. We therefore recommend these to be used as 'discovery images' for comparing observations in different detectors and passbands and not for precise photometry.*

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PRIOR NEWS:

On **December 3, 2019**, the first set of improved astrometry data were released in MAST. The World Coordinate System (WCS) in the image header of all WFC3 and ACS datasets were updated and may include one or more corrections. The first makes use of a new version of the Hubble Guide Star Catalog (GSC version 2.4.0) which updates the coordinates of the guide stars with the positions from Gaia DR1. This reduces the typical uncertainties in the positions of the guide stars to **~200 mas** over the entire sky. Combining this with knowledge of the instrument distortions, an ***a priori*** correction was made. When possible, an additional correction was applied by aligning sources in each HST image directly to the Gaia catalog, referred to as an ***a posteriori*** correction. While some observing modes cannot be aligned to Gaia (e.g. grism and moving target observations) or the alignment may fail due to a lack of sources in either the HST image or the Gaia catalog, approximately 80% of ACS/WFC and 50% of WFC3/IR frames have been directly aligned. For these data products, the typical pointing uncertainty is reduced to **~10 mas**, although the uncertainties increase for observations further in time from the Gaia reference epoch (2015.0 for DR1, 2015.5 for DR2). The software used to produce these drizzled products is described on the Pipeline Astrometric Calibration page.

On **December 17, 2020**, the MAST began production of **new ACS and WFC3 products** in the HST data calibration pipeline (see the following MAST Newsletter article. These Hubble Legacy Archive (HLA)-style mosaics comprise the data from a single HST visit which are aligned to a common astrometric reference frame. These new 'Hubble Advanced Products' (HAP) are referred to as 'Single Visit Mosaics' (SVMs) and are described in a MAST Newsletter article from December 2020. The data products are all drizzled onto the same north-up pixel grid and may include improved relative alignment across filters for datasets acquired within the same visit, enabling easy comparison of the images through multiple filters. When possible, sources in the images have been aligned directly to the Gaia catalog to improve the WCS. SVM data products with both relative alignment (by filter) and absolute alignment to Gaia will contain the string 'FIT_SVM_GAIA' in the 'WCSNAME' keyword in the science extension of the image header. The software used to compute these new data products is described in the DrizzlePac documentation for Single Visit Mosaic Processing.

On **November 23, 2021,** MAST began producing source catalogs as part of the SVM data products. Because SVM products include an additional relative a lignment across filters in a visit, the drizzled images may used to generate point source and segment catalogs during pipeline processing. These catalogs s upersede those produced by the Hubble Legacy Archive and will be the basis of the next version of the Hubble Source Catalog.

On **April 26, 2022**, the HST data calibration and archive pipelines began producing a new Hubble Advanced Product (HAP) to be distributed through MAST. These are cross-visit, cross-proposal mosaics called Multi-Visit Mosaics (MVM), which combine public observations of fields observed multiple times by ACS and WFC3 into a set of products drizzled onto a common, pre-defined pixel grid. These new products were described in a MAST Newsletter article from May 2022 and complement the existing HAP Single Visit Mosaics (SVM) released in December 2020.

Usage

Images downloaded from the archive after reprocessing with the new Enhanced Pipeline Products code will have headerlets added as extra extensions to the FITS file. **A new python notebook**, 'Using updated astrometry solutions', will familiarize users with the structure of the new FITS images and demonstrate how the primary WCS may be changed to any other preferred solution. These instructions will also show how to back out the new WCS updates entirely if desired (see the section below on 'Caveats').

Alternatively, any of the new WCS solutions may be downloaded from MAST/STScI as separate headerlet files and applied to existing data. For users who wish to manually reprocess existing data, the 'updatewcs' task in the STWCS package as used by the Enhanced Pipeline Products code will be able to automatically connect to the astrometry database to retrieve and apply the headerlets. Python functions for creating, updating, and applying headerlets to FITS images are described via the Headerlet User Interface.

Guide Star Catalogs

Historically, the accuracy of HST absolute astrometry has been limited primarily by uncertainties in the celestial coordinates of the guide stars as specified in the Guide Star Catalog. GSC 1.1 had nominal rms errors of ~0.5 arcsec per coordinate, with errors as large as ~13 arcsec reported near the plate edges. This accuracy improved substantially in October 2005 (during Cycle 15) with the introduction of GSC 2.3.2, where rms errors per coordinate were reduced to ~0.3 arcsec over the whole sky. An updated version of the catalog (GSC 2.4.0) was released in October 2017, improving the celestial coordinates with the positions from Gaia DR1 and reducing errors to < 30mas over the entire sky. After including uncertainties in the positions of the science instruments (SIs) in the alignment of the focal plane to the Fine Guidance Sensors (FGS), the total error in HST absolute astrometry is ~1 arcsec for observations made with GSC 1.1, ~0.3 arcsec for those with GSC 2.3.2, and ~0.2 arcsec for those with GSC 2.4.0. These errors are reduced to ~10 mas for observations with *a posteriori* alignment to Gaia. A summary of pointing errors over the HST lifetime and the expected accuracy of the updated WCS solutions is provided in Table 1.

Table 1: Key Guide Star Catalog releases and associated errors

Catalog	Release Date	Mean Epoch of catalog positions	Typical errors	Worst errors	Total Error (including SI to FGS alignment)	Comment
GSC 2.4.0 + Gaia Fit	**Dec 2019**	**2015.5**	**0.01"**		**0.01"**	WCSNAME= 'IDC*_FIT_*_GAIADR*'
GSC 2.4.0	Oct 2017	2015.0	0.03”		~0.2”	GSC2.3.4 aligned to Gaia DR1 Complete GSC Summary WCSNAME= 'IDC*-GSC240', 'IDC*-HSC30'
GSC 2.3.3	Oct 2009					**WFC3 installed May 2009**
GSC 2.3.2	Oct 2005	1992.5	0.3”	0.75”	~0.3”	Public Release GSC 1.1 and GSC 2.3.2 Comparison
GSC 2.2.0	Jun 2001					Public Release **ACS installed Mar 2002**
GSC 2.0	Jan 2000					Science target fields only; GSC2 summary
GSC 1.1	Aug 1992	1981.8	0.5”	~1”	~1”	First version published for the user community Used by HST operations prior to Cycle 15 **WFPC2 installed Dec 1993**
GSC 1.0	Jun 1989			1-2”		GSC1 summary

HST Astrometry Project

The coordinates populated in the FITS headers of HST observations retrieved from DADS (the HST Data Archiving and Distribution Service) were derived based on the guide star coordinates in use at the time of the observation. As the accuracy in these catalogs were refined over time, the pointing accuracy of HST has also improved. Table 1 lists the catalog in use at the time of installation of the three main imaging cameras (WFPC2, ACS, and WFC3) and the typical errors at each epoch.

The goal of the HST Astrometry Project is to correct these inconsistencies in the archival data products as much as possible. As observations are processed or reprocessed in the HST pipeline, their World Coordinate System (WCS) will be updated to use the most accurate solution available. There are two types of corrections that can be performed:

- *a priori* : correct the coordinates of the guide stars in use at the time of observation to the coordinates of those stars as determined by Gaia, applying a global offset to the WCS
- *a posteriori* : identify sources in the HST image and cross-match with positions from an external reference catalog (such as Gaia) to improve the WCS (fitting x/y to RA/Dec)

Note that *a priori* corrections are only relevant for observations which executed prior October 2017 (eg. prior to the release of GSC 2.4.0), and these will still include small errors in the alignment of the science instruments to the HST focal plane. The *a posteriori* corrections are limited to imaging instruments for which there are an adequate number sources to define a reference catalog for matching. These solutions remove uncertainties in the focal plane and are expected to have the smallest absolute astrometric error.

Implementation

The key to implementing improvements to the astrometry is the use of *headerlets,* self-contained FITS extensions containing a WCS transformation which can be attached to a FITS file and applied to the primary WCS. An observation can have multiple headerlets, each of which may have astrometry derived by differing methods. As HST data is processed/reprocessed, all available headerlets will be present as FITS extensions in the archived image with the *best* solution applied to the primary WCS. More details on how the WCS information is stored in headerlets may be found on the page Astrometry in Drizzled Products.

WCS Naming Conventions

Successfully aligning an observation to Gaia using the *a posteriori* processing will result in an update of the 'active' WCS of the image with the new solution and the new headerlet extension. This headerlet not only includes the WCS keywords which define the transformation from pixels to Gaia-aligned positions on the sky, but it also contains information about how this solution was derived along with the errors to be expected based on the fit.

The various WCS solutions are identified by the WCSNAME keyword found in each FITS headerlet and use the following naming convention:

wcsName = OriginalSolution - CorrectionType

where **OriginalSolution** may be either

- OPUS : initial ground system wcs, no distortion correction
- IDC_xxxxxxxxx : initial distortion corrected wcs (where xxxxxxxxx = geometric distortion model used, eg. the rootname of the IDCTAB reference file)

and **CorrectionType** may have several forms

- GSC240 : '*a priori'* WCS where guide star coordinates are corrected from the original reference frame (e.g. GSC1.1 or GSC2.3) to the Gaia DR1-based GSC2.4.0
- HSC30 : '*a priori'* WCS corrected from the original reference frame to the Hubble Source Catalog (HSC v3.0) frame, which is based on Gaia DR1
- FIT-IMG-RefCat : '*a posteriori'* WCS matched to a reference catalog, where 'IMG' implies **each FLT is separately aligned** to the reference catalog
- FIT-REL-RefCat : '*a posteriori'* WCS matched to a reference catalog, where 'REL' implies that **FLTs within the same filter within the same visit are aligned** before a global catalog alignment
- FIT-SVM-RefCat : '*a posteriori'* WCS matched to a reference catalog, where 'SVM' implies that **FLTs in multiple filters within the same visit are aligned** before a global catalog alignment

More details on interpreting the WCS names may be found on the Astrometry in Drizzled Products page. A list of possible 'active' WCSNAME values populated in the image headers is provided in Table 2.

Table 2: Sample active WCSNAME keyword values and the corresponding WCSTYPE description

WCSNAME	WCSTYPE	Comment
OPUS	'distorted not aligned'	**No distortion correction** has been applied; analysis of these FLT/FLC files may only be performed if corrected by the instrument-specific pixel area map
IDC_0461802ej	'undistorted not aligned'	Distortion-corrected using the IDCTAB reference file '0461802ej_idc.fits', but not aligned to an external catalog
IDC_0461802ej-GSC240	'undistorted ***a priori*** solution based on GSC240'	Alignment based on Guide Star Catalog v2.4.0 (GSC240). Absolute errors ~0.1"
IDC_0461802ej-HSC30	'undistorted ***a priori*** solution based on HSC30'	Alignment based on Hubble Source Catalog v3.0. HSC30 errors are typically smaller than GSC240. If both corrections are available, HSC takes precedence.

IDC_0461802ej-FIT_REL_catalog	'undistorted ***a posteriori*** solution relatively aligned to catalog'	Exposures aligned to one another, and then aligned as a set to the reference catalog
IDC_0461802ej-FIT_REL_NONE	'undistorted ***a posteriori*** solution relatively aligned to NONE'	Exposures relatively aligned to one another, but the quality of the fit to an absolute reference catalog is unverified and should be checked by the user
IDC_0461802ej-FIT_IMG_catalog	'undistorted ***a posteriori*** solution aligned image-by-image to catalog'	Exposures individually aligned to the reference catalog (not as a set)
IDC_0461802ej-FIT_IMG_NONE	'undistorted ***a posteriori*** solution aligned image-by-image to NONE'	Exposures individually aligned to a reference catalog, but the quality of the fit is unverified and should be checked by the user
IDC_0461802ej-FIT_SVM_catalog	'undistorted ***a posteriori*** solution relatively aligned filter-by-filter to catalog*'	****NEW**** Exposures aligned to a reference catalog and include improved relative alignment across filters in a visit

Caveats

While the majority of calibrated HST data products are now aligned to a common absolute reference frame, further improvements may be possible via manual realignment using the drizzlepac tools. This is particularly true for exposures acquired in the same visit where the WCSNAMEs does not contain the string 'FIT_SVM_GAIA'. For standard drizzled data products:

- Short and long exposures obtained in the same visit may no longer be aligned due to potentially different number of Gaia matches.
- Exposures in different filters (eg. narrowband vs broadband) which were obtained in the same visit may no longer be aligned to one another, for example, if each filter had a different number of matches to Gaia.

Furthermore, grism images will now be offset from their direct image counterparts, where only the later of which may be aligned to an external reference catalog. In order to preserve relative alignment between grism and direct images, users may wish to back out the updated WCS solutions entirely, as described in Section 5 of the python notebook, 'Using updated astrometry solutions'.