214. Telescope calibration/pointing: 2

IN MY PREVIOUS ESSAY, I looked at the use of the space-based Hipparcos and Tycho Catalogues in revisiting the calibration of (ground-based) photographic plate and meridian circle surveys carried out over the preceding decades. Here, I will continue this theme, and look at how the Gaia reference system, and its positions and proper motions, are being used in the pointing and calibration of ground- and space-based telescopes.

BOTH the Hubble Space Telescope and James Webb Space Telescope rely on the Space Telescope Science Institute's Guide Star Catalog (GSC) for telescope pointing and instrument calibration. But HST's astrometry has long been limited by uncertainties in the catalogue's celestial coordinates, with additional uncertainties arising in the alignment of the science instruments to the Fine Guidance Sensors (FGS).

GSC 1.1 (Aug 1992) had rms errors of at least 0.5–1 arcsec in each coordinate. GSC 2.4.0 (Oct 2017) used positions/proper motions from Gaia DR1 to reduce these errors to below 30 milli-arcsec. Further updates have been made with each Gaia data release, with the most recent GSC 3 using Gaia DR3 as its base catalogue.

Today, both HST and JWST use the Gaia DR3 catalogue for identifying reference stars, for their image calibration pipeline, and for updating the astrometric 'World Coordinate System' in their headers. The astrometry of *archival* HST observations has also been reprocessed using the improved Gaia reference frame.

MORE WIDELY, GSC itself has been adopted for observation planning, preparing finding charts, and for the operation of ground-based telescopes. Amongst these, recalibration of the astrometry for Pan–STARRS1 has been carried out based on Gaia DR2 for the 1.7 billion objects in PS1/DR2 (Lubow et al., 2021) and later based on Gaia EDR3 (White et al., 2022).

The infrared Nancy Grace Roman Space Telescope (formerly WFIRST), due for launch in May 2027, makes use of the Gaia entries in GSC both for its guide stars, and for the pipeline image calibration. It is expected that GSC will have incorporated Gaia DR4 by that time.

FOR JWST, Gaia has also played a key role in the calibration of the optical distortion for all four instruments. These used a field of 180 000 bright stars in the Large Magellanic Cloud, lying within the telescope's 'continuous viewing zone', and with a star density sufficient for a very detailed distortion map. The field was first observed with HST–ACS/WFC in 2006, and again in 2017, both duly matched to the Gaia DR2 reference frame (Anderson et al., 2021). Other papers cover the astrometric calibrations for each instrument (Lützgendorf et al., 2022; Libralato et al., 2023; Patapis et al., 2024).

Gaia astrometry was also vital for knowing the positions of early science targets (e.g. high-z galaxy candidates previously found with HST) accurate enough that they could be observed using NIRSpec's Micro-Shutter Assembly: this consists of four separate 98×91 arcsec^2 quadrants each containing 365×171 individually addressable shutters whose open areas on the sky subtend 0.20×0.46 arcsec^2 (Ferruit et al., 2022). NIRSpec observations based on prior NIRCam exposures, which are placed on the Gaia reference frame, ensure that targets do fall within the 200 millli-arcsec wide MSA slitlets.

CONTINUING WITH the satellite theme, I described the principles of interplanetary spacecraft navigation in essay 52. As a prominent example, the New Horizons fly-by of Pluto and its moon Charon, in July 2015, was based on the JPL solar system ephemerides DE430, itself based on the celestial reference frame materialised by Hipparcos in the late 1990s. But the subsequent fly-by of the trans-Neptunian object Arrokoth on 1 Jan 2019 made use of the Gaia DR2 star positions to adjust the spacecraft's pointing.

When the closest flyby images came back, Arrokoth was framed perfectly. *'None of that would have happened if we hadn't had the Gaia catalogue'*, Marc Buie, discoverer of Arrokoth, is quoted as saying. *'It's a fundamental rewriting of how we do positional astronomy'.*

AT ESOC, ESA's satellite operations centre at Darmstadt, Germany, the Gaia catalogue is today used across all satellite operations and instrument pointing.

Autonomous Star Trackers are the primary sensors used for the 3-axis satellite attitude control of most satellites (e.g. Eisenman et al., 1997; Bürger et al., 2024). With their 20 deg full-cone field of view, magnitude limit of 5.5–6 mag (requiring some 3000 stars across the sky), and positional requirements of order 1 arcsec, the Hipparcos catalogue remains sufficient for many uses. The Gaia catalogue is now used in the 'very high-accuracy' star trackers which target an order of magnitude performance improvement. ESOC are using a design with full-cone field of 4 deg, requiring a much larger star catalogue with sub-arcsec positions and proper motions.

Space science observatories today also often require 'fine guidance sensors' to ensure stable long-duration pointing, and these are all making use of the Gaia catalogue. Amongst these, Euclid, launched in 2023 and operated at L2, uses stars down to 18 mag (Euclid Collaboration et al., 2024). Missions under development, and making use of Gaia for their fine guidance sensor control, include Plato (Grießbach et al., 2021), and Ariel (Mösenlechner et al., 2024).

LET ME TURN to a just a few examples in ground-based telescope operations. For the 11-m SALT, the South Africa Large Telescope, Gaia is used to select guide stars, and for pre-positioning the guiders during pointing, significantly increasing acquisition efficiency. Gaia's radial velocity information is also used to monitor the stability of their high-resolution spectrograph.

Elsewhere at the South African Astronomical Observatory, SAAO, their fully automated Lesedi 1-m telescope relies on the Gaia catalogue to generate suitable guide stars, operating as a background automated service and ensuring real-time targeting accuracy. For Meerlicht, the 'optical eye' of the radio MeerKAT telescope, Gaia provides absolute photometric calibration of every point source within the survey images. This has enabled rapid tagging and alerting of transient sources, integrating Gaia's precision into their alerting infrastructure.

Stephen Potter, SAAO's Head of Astronomy, summarised Gaia's contributions this way: *'Many of our new observatory operational and scientific developments have directly benefited from Gaia data releases in ways that were simply not possible before. Its high-precision astrometric and spectroscopic data has been transformative for both our operations and our science.'*

FOR SDSS, the Sloan Digital Sky Survey, Gaia *'has been transformative'*. It now provide a reliable and dense set of guide stars for wide-field spectroscopy across the entire sky, especially for the southern hemisphere. Mike Blanton commented that *'Before Gaia, many many hours were spent cobbling together various sources of guide stars, ensuring they were on the same system, estimating magnitudes, etc. This instantly became a completely solved problem when Gaia data was available'*. For SDSS–V, which provides multi-epoch optical and infrared spectroscopy, Gaia plays a key role. Targets come from many sources, including SDSS imaging, Pan–STARRS1, 2MASS, WISE, DECam, SkyMapper, and Gaia. The Gaia catalogue forms the base layer for the process of object cross-matching, as well as the most reliable source of coordinates (and, importantly, their proper motions) for the fibre placement.

Beyond the operational aspects, Gaia data is used in star selection for the 3 million star SDSS–V Milky Way Mapper program, using cuts on Gaia parallax, colour, and absolute magnitude (Almeida et al., 2023).

AT THE 4.2-m William Herschel Telescope on La Palma, Gaia is one of the main reasons for building the new fibre-fed multi-object spectrograph, WEAVE, which will take spectra of up 1000 objects simultaneously. The instrument was built to provide spectroscopic follow-up for several large survey facilities, and in particular Gaia. Use is also made of the Gaia magnitudes of the guide stars to monitor the transparency of the sky while observing. This allows observations to be extended (or rescheduled) as required, again promoting more efficient use of the night.

More widely, use of Gaia's accurate coordinates, for both targets and guide stars, has made acquisition onto slits and fibres significantly more accurate than before, thereby improving instrument throughput, and the efficiency with which observing time can be used.

Similarly, LAMOST uses Gaia astrometry both as the Gaia identifier (GID, where 99% of targets have Gaia observations), and as the source catalogue for the proposed scientific targets, which is used to establish the accurate pointing of the telescope's 4000 optical fibres.

WITH FIRST LIGHT in July 2025, the Vera C. Rubin Observatory presents various challenges for its astrometric calibration. With a 7 mag fainter limit than Gaia, it will embrace at least an order of magnitude more stars. And it uses the 3-colour Gaia photometry to transfer Gaia's rigid photometric system above the atmosphere to all objects observed (Ivezić et al., 2019).

Ivezić et al. (2019) continues: *'Astrometric calibration will be based [on Gaia], which will provide numerous high-accuracy astrometric standards in every [LSST] field'*. Wilson (2023) details the practical challenges involved in object matching, given that 90% of the sources are significantly fainter than the Gaia survey limit.

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