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COMMISSION A1 ASTROMETRY

ASTROMETRY

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ANNUAL REPORT 2023

1. Activities of IAU Commission A1 during 2022-23

Commission A1 on Astrometry is pleased to share that the 2022–2023 year has been a year full of successes in the field of astrometry. Our commission hosted Focus Meeting 7 on 10–11 August 2022 as part of the IAU General Assembly in Busan, Korea. Many papers were presented including Lindegren's (2022) keynote overviewing the current state of astrometry. For details of the Focus Meeting see `https://www.busan2021fm7.org`

We report here progress in both global and differential astrometry at optical/IR and radio wavelengths.

The Gaia mission continues to revolutionize optical astrometry with the positions, motions, and physical properties of 1.8 billion objects over a vast range of scales from the solar system, to the galactic, to the extra-galactic. The third data release was made on 13 June 2022 (Gaia, 2022) and will doubtless stimulate progress in numerous areas including celestial mechanics, galactic kinematics, cepheids, dynamics of open and globular clusters, quasars.

A fundamental ongoing task in the scope of commission A1 is the construction of celestial frames, in particular, at radio wavelengths with the Very Long Baseline Interferometry (VLBI) technique and at optical wavelengths with Gaia.

A robust set of VLBI surveys is underway to increase the number of sources available for reference frame work. Differential VLBI astrometry such as the BeSSeL project to map the structure of the galaxy and ΔDOR spacecraft tracking are producing valuable scientific results. Work continues on the planetary ephemeris.

Ground based optical work ranging from surveys to speckle observations to Lunar Laser Ranging have added to our scientific knowledge during 2022-2023.

We look forward to new instruments such as the LSST, SKA, CART, JASMINE, and Voyage 2050 which in combination with Gaia will invigorate the activities of the commission for many years.

Finally, we call to your attention next year's IAU General Assembly XXXII, in Cape Town, South Africa for which we have proposed a Focus Meeting on 'Multi-wavelength Astrometry' for August 2024. `https://astronomy2024.org/`

For all these reasons we are thankful for the accomplishments of the past year and are looking forward to the work of commission A1 in the coming year.

2. Progress on Celestial Reference Frames

The "Multi-waveband ICRF" working group set up by Division A in 2021 continues under chair Patrick Charlot (Charlot et al., 2021). Its objective is to work toward the realization of a fully integrated multi-waveband celestial reference frame, incorporating positions in both radio and optical bands and ensuring their consistency over the various bands. Areas of work include agreeing on common values for the amplitude and direction of the Galactic acceleration vector, establishing common practices to align reference frames in different bands and to treat wavelength and time-dependent source positions, and defining a proper terminology for referring to the individual (per wavelength) components of the reference frame

2.1. *Gaia Optical Celestial Reference Frame 3 (gaia-CRF3)*

Gaia Celestial Reference Frame 3 (Gaia-CRF3)—Gaia's catalogue of 1.6 million astrometrically well-behaving quasars—has a detailed description of its content and the methods behind its construction (Gaia Collab., Klioner, et al. 2022). Gaia-CRF3 is the astrometric solution for a subset of sources included in the EDR3 release of December 2020. It consists of an astrometric catalogue of more than 1.6 million QSO-like sources selected from many existing catalogues and further filtered with Gaia data to ensure that the sample is as much as possible free of stellar contaminants. The G magnitude extends from 14 to 21, with a peak density at $G = 20.5$. There are 42,000 sources with $G < 18.1$. The formal uncertainty is primarily determined by the G magnitude, with a precision of 1 mas at $G = 20.6$, 0.4 mas at $G = 20$, and 0.1 mas at $G = 17.8$. There are 32,000 sources with formal positional uncertainty < 0.1 mas and 210,000 with uncertainty < 0.2 mas. The Gaia-CRF3 is an all sky catalogue with an avoidance area of about 6 deg on either side of the Galactic plane. The orientation is aligned to the radio ICRF3 by minimizing the position difference of the common sources.

2.2. *VLBI radio Celestial Reference Frames*

The current generation of the IAU's official International Celestial Reference Frame, the ICRF-3 (Charlot et al.,2020) was adopted at the 2018 IAU General Assembly and became official on 2019 Jan 01. It contains components at three wavelengths: S/X (8.4 GHz), K (24 GHz), and X/Ka (32 GHz) enabling the potential for studying the astrophysical limitations of the ICRF. Comparison of the S/X-band radio ICRF3 with the optical Gaia Celestial Reference Frame 2 showed deformations at the 0.03 mas level between the two frames, in agreement with the ICRF3 noise level. A review paper by de Witt et al. (2022) reviews current status of the ICRF as well as future plans.

2.2.1. *S/X-band (8 GHz, 3.6 cm)*

Since the cutoff for ICRF3 in 2018, the number of S/X observations has increased by 29% to 17.5 million. During the past year alone, twelve Very Long Baseline Array (VLBA) astrometry sessions at X/S band were coordinated, scheduled and analyzed at the U.S. Naval Observatory (USNO). These observations have concentrated on improving the positions of the lesser observed X/S sources and on adding additional sources (Gordon et al. 2022). As of December 2022, there were 5608 sources in the X/S catalog, an increase of 1072 or 24% over the ICRF3. Also noteworthy is that this includes ∼400 additional ecliptic sources over ICRF3.

The International VLBI Service (IVS) has a Celestial Reference Frame Committee which makes recommendations to the IVS Directing Board on observing programs and strategies for the S/X-band ICRF `https://ivscc.gsfc.nasa.gov/about/com/crfc/index.html`.

2.2.2. *K-band (24 GHz, 1.2 cm)*

K band (24 GHz) ICRF work has continued with approximately monthly VLBA sessions and HartRAO-Hobart26 (S.Africa–Australia) single-baseline sessions. In order to improve the declination accuracy of the K-band CRF, the network geometry was recently improved by extending the network to include the Yebes 40-m antenna in Spain as well as the Korean VLBI Network (KVN) antennas and the Mopra antenna in Australia. These observations were coordinated and scheduled by P.I. Aletha de Witt at the South African Radio Astronomy Observatory (SARAO) and analyzed at the USNO. The K-band reference frame currently has 2 million observations–a 300% increase since ICRF3. There are now 214 more sources for a total of 1038. Source precision has improved considerably at K-band, and for sources overlapping with the S/X-band frame the median precision of the K-band CRF is $\sim 46, 80$ μas in $\alpha \cos\delta$, δ, respectively—comparable to the S/X-band frame. Recent K-band imaging is now available (de Witt et al., 2023), which provides sub-milliarsecond resolution VLBI images for more than 730 Active Galactic Nuclei (AGN) sources at up to 28 epochs with another ~50 epochs in the pipeline. A detailed analysis of the images has allowed us to determine several quantities that provide useful indicators of the quality of each image and the suitability of each source as a calibrator or reference source.

USNO has access to 50% of the observing time on the National Radio Astronomy Observatory's (NRAO) VLBA. The K-band VLBA sessions accounting for 99% of the data in the K-band frame are supported under the USNO time allocation.

2.2.3. *X/Ka-band (32 GHz, 0.9 cm)*

X/Ka (32 GHz) work continues to build a combined National Aeronautics and Space administration (NASA), European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) network which has now produced 0.12 million observations. Median source precision has improved at X/Ka-band to $44, 64$ μas in $\alpha \cos\delta$, δ, respectively—slightly better than the ICRF3-SX. Accuracy is currently limited by a quadrupole 2,0 "magnetic" distortion in the frame of $142 \pm 17 \mu$as. There are hints that accounting for the spatial and temporal correlations in the troposphere noise may reduce the quadrupole distortion. The large Z-dipole distortion seen in the ICRF3-XKa is now statistically insignificant as long as the full $\alpha - \delta$ parameter covariances are accounted for (Jacobs et al., 2022).

2.2.4. *Radio Imaging of ICRF Sources*

Now that radio astrometry is available at the sub-mas level at multiple wavelengths along with Gaia optical astrometry at similar levels of precision, inter-comparisons are revealing differences in positions that may be caused by source morphology (e.g. de Witt et al., 2022; Hunt el al., 2022)

There are several databases of radio images of sources that comprise the International Celestial Reference Frame (ICRF). These images were created and made available to study the effects of source structure on the positions of sources in the ICRF.

The Bordeaux VLBI image database (BVID) has served the community for many years and now contains 7862 images spread over 1514 sources at various wavelengths including S, X, K, and Q-bands and covering more than 20 years. New data is added on an ongoing basis at `http://bvid.astrophy.u-bordeaux.fr`. During the past year, the BVID has been used to extract the VLBI jet directions from all available images using a fully automatic method and compare this direction with optical-radio offset vectors derived from the Gaia EDR3-ICRF3 S/X position differences. The comparison showed that the optical-radio offset vector is aligned within 30° of the VLBI jet direction in roughly half of the sources (Collioud et al. 2023).

Another rich collection of radio images may be found at the astrogeo web site: `http://astrogeo.org/vlbi_images/`. The Astrogeo VLBI FITS image database contains 115,070 brightness distributions of 17758 compact radio sources—mainly Active Galactic Nuclei (AGN)—generated by analyzing Very Long Baseline Interferometry (VLBI) surveys. This database is updated as more data become available.

FRIDA: The USNO has a searchable, interactive radio image database called the Fundamental Reference Image Data Archive (FRIDA) with 15,000 images of over 3,700 sources covering epochs since 1992 and frequencies from 2.3 to 43 GHz. (`https://crf.usno.navy.mil/FRIDA`). USNO has spent the last three years working improving the user interface, increasing the total number images, as well as providing image quality metrics. New data will be added on an ongoing basis.

Imaging of ICRF3 sources at K band has also been pursued by using the 17 telescopes of the European VLBI Network (in Europe, Asia and South Africa), augmented with the four e-MERLIN out-stations in the UK and the 26 m antenna in Hobart (Australia), allowing for a resolution of 0.2 mas to be reached (Charlot et al. 2023)

Recently, the USNO sponsored VLBA imaging campaigns to study source structure, spectral index, and flux densities at S, X, K and Q (43 GHz) bands (Hunt et al., 2022). These imaging data products will be made available through the USNO's FRIDA website.

On the technical side, a new VLBI scheduling approach that bridges astronomical, astrometric and geodetic scheduling has been investigated (Schartner et al., 2023). The new approach significantly improves the imaging capability and astrometric performances of VLBI observations conducted in geodetic-mode, while also at the same time slightly improving geodetic precision.

2.3. *Variability and Optical-Radio Offsets*

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In line with the objectives of the Division A "Multi-waveband ICRF" Working Group, the issue of statistically significant optical-radio position offsets has been an ongoing research interest of the CRF community. While it has generally been shown that the position angles of significant optical-radio offsets is correlated with that of the putative radio jets where the latter is measurable (e.g., Kovalev et al., 2017), there has thus far not been a practical mitigation strategy for this issue, which affects ∼15% of the ICRF overall. Recently, Secrest (2022) showed that the prevalence, or rate, of significant optical-radio offsets shows a strong inverse correlation with optical variability, derived using the multi-epoch photometry information for sources in Gaia-CRF3. Whereas objects with little or no detectable optical variability exhibit a rate of offsets close to ∼20%, objects with fractional variabilities exceeding 0.4 exhibit a rate of offsets of only ∼2%, a full order of magnitude lower. This finding is attributed to the most optically variable objects being bona fide blazars, where the angle of the jet with respect to the line of sight is minimal and the optical contribution of the jet is maximized due to beaming, thereby minimizing apparent optical-radio position offsets. The blazar interpretation is supported by a strong correlation between high fractional variability and detection at γ-rays by Fermi LAT, as well as by high fractional variability objects exhibiting blazar-like optical photometric color, with low fractional variability objects exhibiting color consistent with radio-quiet quasars (Secrest, 2022). While only 9% of ICRF objects have fractional photometric variabilities exceeding 0.4, an apparently monotonic relationship between fractional variability and optical-radio offset prevalence found by Secrest (2022) presents the possibility of using variability information to weight the celestial reference frame: up-weighting strongly variable objects while down-weighting less variable objects. A key prediction made by Secrest (2022) is that the ~80% of low variability objects not currently exhibiting a statistically significant optical-radio position offset are more likely to develop one in the future, while the high variability objects are more likely to maintain good positional agreement, suggesting that weighting by photometric variability will produce an overall more stable CRF than weighting by positional consistency, the latter of which is time-dependent.

2.4. *Dynamical Frame: Planetary Ephemerides*

The next-generation, general-purpose JPL planetary and lunar ephemerides called DE440/ DE441 were delivered in 2020 (Parks et al., 2021). DE440 covers the years 1550-2650 while DE441 is tuned to cover a time range of -13,200 to +17,191 years. Ongoing work continues to add new radio and optical data to improve dynamical models and data calibration. Recent work has focussed on refining knowledge of the satellites of the outer planets in preparation for visits by ESA's Jupiter Icy Moons Explorer (JUICE) and NASA's Europa Clipper missions (Emelyanov, et al., 2022) Also astrometric research is being done on Uranus including the use of archival photographic plates (Camargo et al. 2022), and milli-arsecond astrometry for the Galilean Moons using stellar occultations (Morgado et al., 2022).

3. Space-based optical astrometry

3.1. *Gaia mission*

In June 2022, Gaia published its Data Release 3 based on 33 months of data (Gaia Collab., Vallenari, et al., 2022). The main astrometric catalogue for that Data Release was published already in December 2020. The Data Release 3 has many new scientific products (Gaia DR3, 2022) and is accompanied with about 50 publications describing both the new aspects of data processing and some scientific applications. From the astrometric points of view, one can mention the first Gaia-based catalogue of non-single stars containing over 800,000 sources (Gaia Collab., Arenou, et al., 2022) as well as astrometry for 158,000 Solar System objects (Tanga, et al., 2022). Gaia Celestial Reference Frame 3—Gaia's catalogue of 1.6 million of astrometrically well-behaving quasars—has a detailed description of its content and the methods behind its construction (Gaia Collab., Klioner, et al., 2022). In Data Release 3, Gaia's own abilities to classify the celestial sources was demonstrated for the first time. In particular, many aspects and properties of quasar and galaxy candidates detected by Gaia itself were discussed (Gaia Collab., Bailer-Jones, et al., 2022).

Gaia is in good health and continues to collect astrometric observations at an average pace of over 28 millions per hour. Photometric and spectroscopic observations are collected in parallel. Gaia observations are expected to continue till the first quarter of 2025 when the cold gas will be exhausted and a precise attitude control of the satellite will no longer be possible.

Further scientific products will be published in Focused Product Release already this year. This will be followed by Gaia Data Release 4 based on 66 months of data—twice as many observations as for Data Release 3. Finally, Gaia Data Release 5 will be based on all Gaia data, presumably again doubling the data volume with respect to Data Release 4.

3.2. *Combining Gaia and HST for high-precision astrometry at the faint end of Gaia*

GaiaHub is a tool developed to combine Hubble Space Telescope (HST) observations with Gaia in order to derive proper motion of superior quality at the faint end (del Pino et al., 2022). Along the same line, HUBPUG is a similar tool developed by Warfield et al. (2023). Provided there is decent overlap in area and magnitude, these tools achieve better proper motions than Gaia alone at the faint end, G $>$ 18. A more targeted application of combining Gaia with HST is the study by Bennet et al. (2022) who determine the proper motions of the system of globular clusters in the Large Magellanic Cloud (LMC). Using a sample of 32 clusters they determine that the system was formed via a single formation mechanism in the disk of the LMC despite a large range in age and metallicity

3.3. *Astrometry with Deep Learning*

Deep learning, a class of machine learning based on convolutional neural networks has been applied to a series of astronomical topics, however in astrometry very little so far has been done. Recently, this technique has been successfully applied to under-sampled stellar profiles in HST/ Wide Field Planetary Camera2 (WFPC2) images (Castti-Dinescu et al., 2023) where classical state-of-the-art centering algorithms fail to account for the pixel-phase bias. This novel methodology yields improved (by 50%) stellar centers, and can be applied to other cameras that are affected by undersampling.

3.4. *JWST astrometry*

The first papers on James Webb Space Telescope (JWST) astrometry have appeared at the end of 2022 and beginning of 2023. Libralato et al. (2023) publish the point spread functions (PSFs) and distortion map of Near-Infrared Imager and Slitless Spectrograph (NIRISS) together with a proper-motion study at the center of the Large Magellanic Cloud. The early epoch is based on HST observations taken 16 years earlier. The median proper motion error at G=20 is 13 μas/yr. Nardiello et al. (2022) and Griggio et al. (2022) publish the PSFs and distortion map for the NIRCam, and a proper-motion study of globular cluster 47 Tuc (Nardiello et al., 2023) where brown dwarfs in the cluster are isolated via proper-motion membership.

3.5. *Voyage 2050 Near-Infrared mission*

Our Galaxy contains many different types of stars and planets, interstellar gas and dust, and dark matter. These components are widely distributed in age, reflecting their formation history, and in space, reflecting their birth place and subsequent motion. Objects in the Galaxy move in a variety of orbits that are determined by the gravitational force, and have complex distributions of different stellar types, reflecting star formation and gas-accretion history. Understanding all these aspects in one coherent picture is being partially achieved by Gaia, which surveys around 1% of the Galaxy and is still ongoing today. However much more could be done by using Near InfraRed light to peer through the dust and gas to reveal the hidden regions of the Galaxy.

A new all-sky Near InfraRed astrometric mission will expand and improve on the science of Gaia using basic astrometry. Near InfraRed astrometry is crucial for penetrating obscured regions and for observing intrinsically red objects. The new mission is aimed at surveying around 10–12 billion stars of the Galaxy, revealing important new regions obscured by interstellar gas and dust while also improving on the accuracy of the previous results from Gaia. In the stellar fields, the proposed mission could be combined with the Gaia catalogue (1.8 billion stars), with a 25–35 years baseline, in order to determine proper motions much more accurately than Gaia itself by an order of magnitude. At the same time, big improvement is scheduled in the determination of parallaxes, when astrometric measurements of both space missions will be combined. The mission will explore the Galaxy, particularly the hidden regions, to reveal nature's true complexity and beauty in action in a number of scientific areas (Hobbs et al., 2022).

3.6. *JASMINE mission*

In Japan the development of the Japan Astrometry Satellite Mission for Infrared Exploration (JASMINE) mission continues with the goal of launch in 2028. Small-JASMINE is a space mission (Gouda, 2022) to provide astrometric data with high precision (20 μas level) in a near infrared band for stars in the Galactic central regions. The primary scientific objective is to carry out Galactic Center Archeology and Galacto-seismology by exploring the Galactic nuclear bulge and the Galactic plane, in order to elucidate the formation history of the Galaxy and the supermassive black hole at the center, and the Galactic Habitable Orbits which are necessary for life to be created and maintained. Furthermore, the mission plans to observe other specific astronomical objects such as the transit observations to search for Earth-type planets in the habitable zone around M-type stars. Small-JASMINE was selected in May 2019 as the unique candidate for the competitive 3rd Medium-class science satellite mission by ISAS/JAXA.

4. Ground-based optical astrometry

4.1. *CHARA*

The Center for High Angular Resolution Astronomy (CHARA) is located on Mt. Wilson, above Pasadena, CA. The optical/near Infrared (NIR) interferometer composed of six 1-m telescopes routinely offers up to 330-m baselines, resolving 0.2 mas objects at visible wavelengths and 0.5 mas in the NIR. Currently the CHARA array is developing a 7th 1-m telescope that can be placed at multiple locations at the Mt. Wilson site (Scott et al., 2023), potentially extending the baseline and better covering the uv space. Recent science highlights include the detection of the innermost dusty ring around a supermassive black hole (Kishimoto et al., 2022), revealing the inner astronomical units (AUs) of circumstellar disks, imaging surfaces of red giant and supergiant stars and continuing work on binary stars—see Eisenhauer et al (2023) for a review.

4.2. *VLTI*

The Very Large Telescope Interferometer's (VLTI) GRAVITY project includes four 8-m telescopes, adaptive optics (AO), fringe-tracking and dual-beam interferometry thus observing objects that are fainter than 19th magnitude (current sensitivity limit is K $\sim$19.5). Well-known for probing the super massive black hole (SMBH) at the Milky Way's center, the GRAVITY collaboration provided precision tests of the general theory of relativity, and it is so far the strongest experimental evidence that the compact mass in the Galactic center is black hole. New results by Hinkley et al. (2023) using GRAVITY on the exoplanet HD206893c have confirmed the capacity of this instrument to reliably obtain 50–100 microarcsecond narrow-angle astrometry of massive exoplanets.

The GRAVITY instrument is presently being upgraded, with the goal to improve its sensitivity to $K > 22$ as well as improve sky coverage (GRAVITY+ Collab. 2023). The part of this upgrade that is intended to enable off-axis fringe stabilization up to a relatively large separation of $30'$ (the GRAVITY Wide capability) is already available to the community (GRAVITY+ Collab. 2022). For a thorough review of the progress of optical interferometry over the last 15 years see Eisenhauer, Monnier & Pfuhl (2023).

We also note that the VLTI has been used with a broad range of high angular resolution instruments of the VLT/VLTI (VISIR, NACO, SPHERE, AMBER, PIONIER, GRAVITY, and MATISSE) over a period of 13 years (2006–2019), for example, to monitor the orbital parameters of Achernar B—the closest and brightest classical Be star—and its companion Archernar B proving that no significant interaction occurred between the components and demonstrating that Be stars can form without mass transfer (Kervella et al., 2022).

4.3. *Speckle interferometry*

Speckle interferometry observations continue in various programs that aim to characterize multiplicity rates and masses of various types of low-mass stars: K dwarfs (Lesley et al., 2023), M dwarfs (Clark et al., 2023; Tokovinin et al., 2023). Speckle imaging has been ongoing for a few years at the SOAR 4.1m and the Gemini South 8.1m telescopes to obtain orbital elements, orbital parallaxes and individual masses for resolved double-line spectroscopic binaries (Anguita-Aguero et al., 2022) and visual binaries (Gomez et al., 2022).

4.4. *USNO VLBI Spectroscopic Catalog*

U.S. Naval Observatory maintains a catalog of optical spectroscopic parameters (emission line fluxes, widths, etc.) for VLBI sources, including those that comprise ICRF3. This is the first such catalog to exist, and allows astrometric quantities of interest to be compared with spectral parameters. This catalog, the USNO VLBI Spectroscopic Catalog (UVSC; Sexton et al., 2022), uses an updated version of the Bayesian spectral fitting code developed specifically for AGNs and quasars that fits all spectral components such as AGN/stellar continua and emission lines simultaneously, using a Markov Chain Monte Carlo sampler to obtain robust parameter posterior distributions. In addition to fit spectral parameters, the UVSC also contains derived parameters where possible, such as estimates of the black hole masses, AGN bolometric luminosities, and Eddington ratios. The catalog is hosted on the USNO CRF Department website: `https://crf.usno.navy.mil/icrs`, and contains data for ICRF3 objects. Currently, the included spectroscopic data come entirely from Sloan Digital Sky Survey (SDSS)/Baryon Oscillation Spectroscopic Survey (BOSS), but the catalog is being expanded to include archival spectroscopic data found elsewhere, as well as new data that USNO is obtaining. The next version of the catalog, scheduled for release in 2023, will include spectral parameters for all known VLBI sources where available, not just those in ICRF3. In the long term, the UVSC may be folded into a larger catalog of photometry and spectral energy distribution estimates, as well as being available interactively via USNO's Fundamental Reference Image Data Archive (FRIDA).

4.5. *USNO Deep South Telescope*

The USNO Deep South Telescope (DST; Zacharias 2020) is a 1-meter, optical-NIR telescope deployed at Cerro Tololo Interamerican Observatory (CTIO) for the purpose of providing a high cadence monitoring capability in support of the ICRF and related projects. Repairs are being finalized for the primary instrument, a 4096 × 4096 camera system, which provides a $35'$ x $35'$ field of view (FOV). In its place is a backup sCMOS with a smaller $13'$ x $13'$ field of view that is currently operational. A new, near-IR camera system is being readied for deployment.

4.6. *UKIRT Hemisphere Survey*

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The United Kingdom Infrared Telescope (UKIRT) Hemisphere Survey (UHS), a collaboration between USNO, the University of Hawaii (UH) / Institute for Astronomy (IfA), the Cambridge Astronomical Survey Unit (CASU), and the Royal Observatory, Edinburgh (ROE), continues on the UKIRT telescope. Covering ∼12,700 square degrees, the K-band survey will be released summer of 2023, and the H-band survey, now approximately 80% done, will be released in 2024. Additionally, a Y-band survey and a second epoch J-band survey has commenced covering the footprints of both the UHS and the UKIRT Infrared Deep Sky Survey (UKIDSS).

4.7. *USNO Washington Double Star (WDS) Activities*

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USNO continues to maintain for IAU Commission G1 a suite of double stars catalogs. These include the Washington Double Star Catalog (WDS), the Washington Double Star Supplement (WDSS), the Visual Orbit Catalog, and the Linear Elements Catalog, all available at `https://crf.usno.navy.mil` under the IAU Double Star Center pages. Observing in support of all of these catalogs continues to be conducted with the USNO 26” telescope in Washington DC, the Navy Precision Optical Interferometer (NPOI) in Flagstaff AZ, and through collaborative relationships with the SOAR telescope as well as both the Gemini North and South Telescopes.

4.8. *LSST*

The Vera C. Rubin Observatory (`https://www.lsst.org`) is an almost completed ground based observatory which will survey the entire southern sky every few nights for ten years thus carrying out the Legacy Survey of Space and Time (LSST). Planned to start in 2024, the Rubin LSST is a unique facility that combines high spatial resolution, high cadence, and high sensitivity thus contributing to nearly all fields of astronomy with an unprecedentedly rich data set (see e.g. Li et al., 2022). Ivezic et al. (2019) discuss the design of the instrument. While the survey’s main focus is photometry, the astrometry provided will encompass an enormous dataset with billions of objects measured, including many background galaxies. For example, Rozek (2023) discusses the use of the Vera Rubin for solar system bodies.

5. LLR astrometry

The Artemis program is driving renewed interest in lunar studies. Since 1969, Lunar Laser Ranging (LLR) data have been collected by various observatories and analysed by different analysis groups. In recent years, observations with bigger telescopes (APOLLO) and at infra-red wavelength (OCA) have been carried out, resulting in a better distribution of precise LLR data over the lunar orbit and the observed retro-reflectors on the Moon.

Work on LLR is active in several areas: Baquet et al. (2022) discuss the need for lunar tidal models. Hilton et al. (2023) discuss using VLBI to improve the Lunar ephemeris. Singh et al. (2022) discuss extracting earth rotation parameters from LLR. Singh et al. (2022b) discuss improvements in lunar reference frames. Biswas et al. (2022) discuss efforts to improve the lunar ephemeris to the sub-micro-arcsecond level. Williams et al. (2022) discuss next generation LLR lunar network looking forward to an era with Artemis missions and commercial lander payload services.

6. Ground-based Radio Astrometry

6.1. *Mapping the Spiral Structure of the Milky Way*

Two major initiatives have been making major advances in mapping the large-scale spiral structure of the Milky Way: the Bar and Spiral Structure Legacy (Bessel) Survey and the VLBI Exploration of Radio Astrometry (VERA) project. Both use Very Long Baseline Interferometry (VLBI) at radio wavelengths to measure trigonometric parallaxes to masers associated with massive, young stars. These stars are less than 0.1 Myr old and, therefore, are excellent tracers of spiral structure. With parallax accuracies approaching ±5 micro-arcseconds (μas) and unhindered by interstellar extinction, the entire Milky Way is available for observation. To date, approximately 250 parallaxes have been measured —see Reid et al. (2019) and Vera Collaboration, et al. (2020) for collected results.

Astrometric techniques for parallax and proper motion measurements of target sources relative to nearby (on the sky) background quasars advanced considerably in the last year. One major advance was the demonstration of the "inverse" MultiView (iMV) technique, which effectively removes ionospheric delays that had limited VLBI astrometry at frequencies below about 10 GHz. The iMV approach is an extension of the MultiView calibration method developed by Rioja & Dodson (2017); it involves observing a strong target (T) and multiple surrounding quasars (Qn) in a sequence T, Q1, T, Q2, T, Q3, ... One then uses the target as the phase reference, in order to extend interferometer coherence times, followed by fitting the Qn phases to a tilted plane model on the sky. The model phase at the T position is used to calibrate and remove "ionospheric wedges" from the VLBI data. Hyland (2022) demonstrated the power of iMV calibration for observations at 8.3 GHz by achieving single-epoch accuracies of ±20 μas using a sparse 4-antenna array. Reid (2022a) published a "tutorial" paper summarizing techniques currently used for high-accuracy VLBI astrometry.

While VLBI astrometric accuracy allows parallax measurements across the entire Milky Way, as demonstrated by Sanna (2017) with a measured parallax distance of 20 kpc with ±12% accuracy, it would take unrealistic amounts of observing time to obtain large numbers of very high-accuracy parallaxes for such sources. However, Reid (2022b) demonstrated that very accurate distances to sources beyond the Galactic center could be obtained with the novel technique of 3-dimensional kinematic distances, by measuring proper motions and line-of-sight velocities and comparing them to the now well-measured rotation curve of the Milky Way.

6.2. *VLBI Calibrator Surveys*

Astrometry activities at NASA Goddard Space Flight Center (GSFC) were focused on further extension of the list of AGNs which positions are determined with VLBI with milli-arcsecond accuracies and imaging of the target sources. In total, positions of 1622 sources not previously observed with VLBI have been determined in 2022. NASA GSFC has prepared observations and performed data analysis of three observing programs in 2022: VLBA Calibrator Survey (VCS) 11, VLBA Calibrator Survey 12, and VLASS-Selected Unassociated Gamma-Ray Sources in the 12-Year Fermi-LAT Catalog. Astrometric analysis of VCS-11 and VCS-12 has been completed.

6.3. *Ionospheric Calibration for Single-Band radio Astrometry*

NASA scientists developed the optimal procedures of data analysis of single-band VLBI astrometric observations for two important cases: when observations are made simultaneously in two bands, but delays in only one band are available for a subset of observations; and when observations are made in one-band by design. The residual contribution of the ionosphere on path delay after applying the a priori path delay derived from Global Navigation Satellite System (GNSS) ionosphere maps has been investigated in detail. The stochastic model, accurate to a 15% level, that describes ionospheric errors has been developed, and its impact on source position estimates has been evaluated. Key findings: using GNSS ionospheric maps as is introduces serious biases in estimates of declination. These biases most likely originate from inadequacy of the ionospheric mapping used for deriving GNSS ionospheric maps. Scaling the ionospheric biases and applying an empirical de-bias correction substantially mitigate systematic errors. The scaling bias was independently confirmed by analysis of satellite altimetry data. It was shown that residual ionospheric errors after applying the a priori ionospheric path delay derived from GNSS maps cause errors at a level of 0.1 mas in both right ascension and declination of Northern Hemisphere sources from processing VLBA K-band data. Declination error grows with declination for sources in the Southern Hemisphere and reaches 0.3 mas at declination -40 deg. A conclusion is made that 0.1–0.3 mas is the error floor for K-band VLBA astrometry, unless a significant progress in improvement of ionosphere modeling will be achieved in the future.

6.4. *China-Argentina Radio Telescope*

Progress is being made to fill the need for radio telescopes for astrometry in the southern hemisphere. The China-Argentina Radio Telescope (CART), a 40m dish antenna being built at the Cesco Observatory in the San Juan Province, Argentina is slowly going back to its tracks, after the pandemic. Its concrete base is finished and the radio telescope is planned to arrive in Argentina as soon as May 2023. To celebrate and prepare for this, the Chinese Academy of Science National Astronomical Observatories and the Universidad Nacional de San Juan are preparing their second CART workshop, from September 25th to 28th 2023 in San Juan City. By then, the radio telescope should be partially assembled. Further information can be found at `http://cart.unsj.edu.ar/` where updates are expected to be published soon.

6.5. *Square Kilometer Array*

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Looking into the more distant future, an investigation of the potential of the Square Kilometer Array (SKA) for massively densifying the celestial reference frame was conducted (Charlot, 2012). Due to its unsurpassed sensitivity, this instrument when used as an element of a VLBI array will make it possible to increase the number of sources in the ICRF by at least an order of magnitude. Its large field of view will also offer the possibility to make commensal observing, which is very attractive since observations for the celestial frame could then be acquired in the background of other programs, thus not requiring dedicated observing time on the SKA. Global astrometry maybe possible for up to 50,000 Gaia counterparts.

Acknowledgments:

This report attempts to give an overview of developments in astrometry over the last year. As the commission president and editor of this report, I take responsibility for any errors or omissions. Please feel free to update me on significant developments in our field for inclusion in the next report.

Thank you to the commission members who contributed to this report and to their sponsoring agencies. The bibliography below gives specific credit to the researchers who produced the results.

Thank you to all the members of the commission for making astrometry an exciting and vital field of study.

Christopher S. Jacobs
Jet Propulsion Laboratory, Calfornia Institute of Technology
President of the Commission
2023 April 15

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