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COMMISSION A1 ASTROMETRY

ASTROMETRY

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ANNUAL REPORT 2022

1. Activities of IAU Commission A1 during 2021-22

Commission A1 on Astrometry is pleased to share that the 2021–2022 year has been a year full of successes in the field of astrometry. 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 is scheduled for 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 2021-2022.

We look forward to new instruments such as the LSST, SKA, 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 this year's IAU General Assembly XXXI, in Busan, Korea where Focus Meeting 7, 'Astrometry for 21st Century Astronomy,' is scheduled for 10-11 August 2022. `http://www.busan2021fm7.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

A new Division A working group entitled “Multi-waveband ICRF” was set up in 2021 chaired by Patrick Charlot. The objective of this working group 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 includes the 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-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 next 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 does not show evidence for deformation larger than 0.03 mas between the two frames, in agreement with the ICRF3 noise level.

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 25% to 16.5 million. During the past year alone, twelve VLBA astrometry sessions at X/S band which were coordinated, scheduled and analyzed at the U.S. Naval Observatory. These observations have concentrated on improving the positions of the lesser observed X/S sources and on adding additional sources. As of March 2022, there were 5399 sources in the X/S catalog, an increase of 863 or 19% over the ICRF3 (Gordon et al, 2022). 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 two HartRAO-Hobart26 (S.Africa–Australia). These were coordinated and scheduled by P.I. Alet deWitt at the South African Radio Astronomy Observatory and analyzed at the USNO. The K-band reference frame currently has 1.76 million observations, a 270% increase over the ICRF3, and has added 211 sources for a total of 1035, a 25% increase. Source precision has also improved considerably at K-band to $\sim 45, 90$ μas in $\alpha \cos \delta$, δ, respectively—approximately as precise as S/X-band (Gordon et al, 2022).

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

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

X/Ka (32 GHz) work continues with a combined NASA, ESA, and JAXA network which has now produced 0.11 million observations. Median source precision has improved considerably at X/Ka-band to $47, 69$ 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 $131 \pm 19\mu$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 (deWitt et al, 2022a). In order to study these differences, much needed images at various wavelengths are being produced e.g. at S/X (Hunt et al, 2021 and at K-band (de Witt et al, 2022b).

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 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. New data is added on an ongoing basis. `http://bvid.astrophy.u-bordeaux.fr`.

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 111,396 brightness distributions of 17432 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) covering epochs from 1992 to 2017 and frequencies from 2.3 to 43 GHz. (`https://crf.usno.navy.mil/FRIDA`). USNO has spent the last two 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.

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: `https://crf.usno.navy.mil`.

2.3. *Dynamical Frame: Ephemerides DE440 and DE441*

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.

3. Space astrometry

3.1. *Gaia mission*

During 2021, activities related to the Gaia mission have been dominated by three parallel developments: the scientific exploitation of the data from previous releases; preparations for Gaia Data Release 3 in June 2022; and the ongoing processing of data aimed for Data Release 4 several years from now.

The scientific exploitation of the astrometric, photometric, and radial velocity data published in Gaia Data Release 2 (DR2) in April 2018 and the Early Data Release 3 (EDR3) in December 2020 have resulted in a very large number of publications covering an extremely wide range of topics from solar system and exoplanetary physics to cosmology. A rough indicator of the impact is that the Astrophysics Data System (ADS) lists over 1500 publications in 2021 that mention Gaia in the title or abstract. The overall description of Gaia EDR3 (Gaia Collaboration, Brown et al, 2021) was published in a special issue of Astronomy & Astrophysics (Volume 649) together with more specialized descriptions and science validation papers. These include the Gaia Catalogue of Nearby Stars, containing 0.3 million stars within 100 pc (Gaia Collaboration, Smart, et al., 2021), and the first optical determination of the galactocentric acceleration of the solar system (Gaia Collaboration, Klioner, et al., 2021). Among the many science highlights using EDR3 data are a number of papers investigating the complex patterns in the stellar kinematics (the phase spiral, bending modes, streams, etc.) that inform us on the dynamical history of the Milky Way. Systematic errors in the Gaia EDR3 parallaxes are known to exist at a level of about 0.05 mas and several papers attempt to obtain improved characterization of these and other systematics. The few examples mentioned here cannot do justice to the hundreds of investigations across most areas of astrophysics that fundamentally depend on Gaia data.

Gaia Data Release 3 (DR3)—to be published on 13 June 2022—is based on the same set of observations as EDR3, that is comprising 2.8 years of data collected until 28 May 2017. It combines the already published EDR3 data with new data products, among other things radial velocities for 33 million objects, mean low-resolution (BP/RP) spectra for 219 million sources, and non-single star solutions (astrometric, spectroscopic, eclipsing, orbit, and RV trend data) for 813 000 sources. Orbits and epoch astrometry are provided for more than 150,000 asteroids, and BP/RP reflectance spectra for 60,000 of them. All-sky total extinction maps are provided at different angular resolutions. As a foretaste of future epoch data products, the Gaia Andromeda Photometric Survey (GAPS) gives complete photometric time series for 1.2 million sources in a 5.5-degree radius field centered on the Andromeda galaxy (for the full content of DR3, see `https://www.cosmos.esa.int/web/gaia/dr3`). It should be noted that the astrometry for the vast majority of sources is unchanged from ED3 to DR3, while improved astrometry is expected in the non-single star solutions.

Data collection for Gaia Data Release 4 (DR4) ended in early 2020 and preparations towards DR4 are ongoing within the Gaia Data Analysis Consortium, but are still in an early phase. DR4 will be based on nearly 5.5 years of data, that is roughly twice of what was used for EDR3 and DR3. The expected improvements are about a factor 0.7 in the uncertainties in parallax and 0.35 in proper motion.

At the time of writing (end of March 2022) Gaia is still fully operational. Pending further approval by ESA of mission extensions, the data acquisition may continue for an additional two years. Currently Gaia DR5 is anticipated to contain all collected data. In the best scenario, this will bring a further improvement of the astrometry by a similar factor.

3.2. *Combining Gaia and HST observations for high-precision astrometry:*

Casetti-Dinescu et al. (2021) have astrometrically calibrated the WFPC2 camera using all archived exposures taken with filters F555W, F606W and F814W that could be linked to Gaia EDR3. Thus higher-order distortion terms were mapped out in an effort to improve the astrometric output of this camera which has archived observations dating back to mid 1990s. As an application of this new calibration, Casetti-Dinescu et al. (2022) have measured the absolute proper motion of the dwarf spheroidal galaxy Leo I using WFPC2 observations and Gaia EDR3. This new determination implies that Leo I's orbit pole is well aligned with that of the vast polar structure, defined by the majority of the brightest dwarf spheroidal satellites of the Milky Way.

3.3. *Anomalous Quasar Proper Motions*

Souchay et al (2022) carried out a complete analysis of the quasars of the LQAC-5 which were cross-identified with Gaia EDR3. This serves as an alternative and complementary study with respect to Gaia CRF2, involving a different population of quasars. A set of 41 quasars with a proper motion exceeding 10 mas/yr—which can be considered as very high for objects which are a priori fixed in the celestial sphere—were studied as candidates for considering their proper motion as real.

3.4. *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.

In 2019 ESA announced the next planning cycle for their long term Science Programme, called Voyage 2050. The program called for White Papers (Hobbs et al, 2021) outlining new ideas for future space mission themes. In June 2021 Voyage 2050 finally set sail, with ESA having chosen its future science mission themes. Our proposal on All-Sky Visible and Near Infrared Space Astrometry has been selected as one of two possible themes for a future Large category mission for ESA or as a Medium class mission with international partners. At this time, detector technology is being investigated as it is a key mission technology.

3.5. *JASMINE mission*

In Japan the development of the JASMINE mission continues with the goal of launch in the mid-2020s. Small-JASMINE is a space mission (Gouda, 2021) 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 the Galactic Center Archeology and Galacto-seismology by exploring the Galactic nuclear bulge and the Galactic plane, which lead to the elucidation of the formation histories 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, we plan 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.

3.6. *Square Kilometer Array*

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.

4. Ground-based optical astrometry

4.1. *USNO Bright Star Catalog:*

The USNO Bright Star Catalog (UBSC) is an operational product intended to complement the optical celestial reference frame realized by Gaia by improving the positions and proper motions of the optically brightest stars, where Gaia runs into incompleteness issues due to instrumental limitations and differences in calibration from fainter sources. The UBSC leverages data from the Hipparcos space mission, the USNO Bright-Star Astrometric Database [UBAD, Munn et al, 2022], and the USNO Robotic Astrometric Telescope [URAT], forming the Hipparcos-UBAD-URAT (HUU) solution. The UBSC contains a total of 1423 stars, 68 of which do not have a counterpart in Gaia, and is nearly complete to $V = 3$ mag. The corresponding publication will appear in Zacharias et al. (2022, submitted).

URAT-Bright in combination with the Hipparcos mission epoch astrometry provides precise proper motions of a thousand bright stars in the southern hemisphere on a time basis of about 25 years. Differences between these proper motions and Gaia EDR3 ones can reveal long-period Jupiter-like exoplanets in the nearest star systems. This technique can provide astrometric signals below 20 m/s (Makarov et al. 2021).

4.2. *USNO VLBI Spectroscopic Catalog*

USNO has developed a catalog of optical spectroscopic parameters (emission line fluxes, widths, etc.) for objects in ICRF3. This is the first such catalog to be developed, and will allow for astrometric quantities of interest to be compared with AGN spectral parameters. This catalog, the USNO VLBI Spectroscopic Catalog (UVSC), 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 will appear in Sexton et al. (2022, in review). Currently, the included spectroscopic data come entirely from SDSS/BOSS, but the catalog will be expanded to include archival spectroscopic data found elsewhere. The catalog will also be extended to include VLBI sources not currently in the ICRF, such as those in the recent USNO global solutions, and in VLBI source compilations such as OCARS (Malkin, 2018). Once published, the catalog will be hosted on VizieR (`https://vizier.u-strasbg.fr`) and the USNO CRF webpage (`https://crf.usno.navy.mil`).

4.3. *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. The primary instrument, a 4096 x 4096 camera system, which provides a 35' x 35' field of view (FOV), is currently undergoing repairs. 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 undergoing testing and development.

4.4. *UKIRT Hemisphere Survey*

USNO, in collaboration with the University of Hawaii (UH)/Institute for Astronomy (IfA), the Cambridge Astronomical Survey Unit (CASU), and the Royal Observatory, Edinburgh (ROE), has undertaken the UKIRT Hemisphere Survey (UHS), a ∼12,700 square degree, near infrared (K- and H-band) survey of the northern hemisphere over a declination range of $0 \leqslant \delta \leqslant 60$ deg in regions not covered by the UKIRT Infrared Deep Sky Survey (UKIDSS). The UHS was completed in J-band by Dye et al. (2018), data (imaging as well as catalog files) that are publicly available through the Wide-Field Science Archive (WSA) hosted by the ROE. The surveys have depths of J ∼19.6 mag (Vega), H ∼19.0 mag, and K ∼18.1 mag, nearly four magnitudes deeper than 2MASS in all three passbands. The UHS K-band survey is now effectively complete with an anticipated public release date in February 2023 also through the WSA. The UHS H-band survey is currently ∼54% complete, with an expected release date in 2024. The UHS and UKIDSS complement the VISTA Hemisphere Survey (VHS) in the southern hemisphere, which extends below declinations of 0° in J-, H-, and Ks-bands, to comparable depths.

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

USNO continues to maintain for IAU Commission G1 (formerly Commission 26) a suite of double star catalogs. These include, since 1964, the Washington Double Star Catalog

(WDS) which has grown by 30% (8%) in the number of measures (systems) since IAU-GA XXX (Vienna). We have also stood up a new Supplement to the WDS which consists of pairs that are typically wider and fainter and comes primarily from large astrometric surveys (such as Gaia). This catalog known as the WDSS is already 5.2(15.7) times larger in the number of measures (systems) than the WDS. We also continue to maintain both the Visual Orbit Catalog as well as the Linear Elements Catalog. The most current versions of these catalogs are accessible at our new website `https://crf.usno.navy.mil` under the IAU Double Star Center/WDS 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 the SOAR telescope as well as both the Gemini North and South telescopes. Sections 4.1 to 4.5 on USNO optical work are due to Cigan et al (2022).

4.6. *LSST*

The Vera C. Rubin Observatory 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). 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. Besides many classic astrometric applications of such a data base, we highlight here the possibility of measuring H0 directly from galaxy parallax. Specifically, galaxy parallax shifts due to Earth's motion with respect to the CMB frame may be detected by Rubin LSST (Croft, 2021).

4.7. *Speckle observations:*

At Southern Connecticut State University (SCSU) and Georgia State University the speckle observations program of K dwarf stars continues. While G and M dwarf stars have well-studied multiplicity rates, K dwarf stars do not. K dwarf stars are important for exoplanet research, as they are approximate analogues to our Sun in important ways. This program uses the Differential Speckle Survey Instrument (DSSI) and the NN-Explore Exoplanet Star and Speckle Imager (NESSI) on Gemini telescopes, Lowell DCT and WYIN in order to map out K-dwarf binary/multiplicity rate (Horch et al., 2021).

5. LLR astrometry

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. Biskupek et al (2021) report estimates of relativistic parameters characterizing the temporal variation of the gravitational constant $\dot{G}/G_0 = (-5.0 \pm 9.6) \times 10^{-15}/yr$
the equivalence principle with $\Delta(m_g/m_i)EM = (-2.1 \pm 2.4) \times 10^{-14}$
and the PPN parameters: $\beta - 1 = (6.2 \pm 7.2) \times 10^{-5}$, $\gamma - 1 = (1.7 \pm 1.6) \times 10^{-4}$
The results show a significant improvement in the accuracy of the various parameters,

mainly due to better coverage of the lunar orbit, better distribution of measurements over the lunar retro-reflectors, and last but not least, higher accuracy of the data. Within the estimated accuracies, no violation of Einstein's theory is found and the results set improved limits for the different effects.

6. Bar and Spiral Structure Legacy (BeSSeL) Survey

The Bar and Spiral Structure Legacy (BeSSeL) Survey uses the Very Long Baseline Array to measure parallaxes and proper motions to extremely young (< 1 My) massive stars. Since radio waves are unaffected by the heavy optical extinction in the Galactic plane, and since BeSSeL has achieved parallax accuracies approaching ± 5 μas, BeSSeL is measuring distances to stars across the entire Galaxy. The goal of the Survey is to accurately map the spiral structure of the Milky Way and to better determine its fundamental parameters.

The recent summary by Reid et al (2019) analyzes about 200 parallaxes, combining BeSSeL Survey and Japanese VERA project results. The data strongly support a 4-armed over a 2-armed spiral. The distance to the Galactic center is 8.15 ± 0.15 kpc and the circular rotation speed at the Sun is 236 ± 7 km/s. Its "gold standard" rotation curve (using full 6-D phase-space measurement) rises from 223 km/s at 4 kpc radius, peaks at 237 km/s at 7 kpc, and slowly falls to 229 km/s at 12.5 kpc. They find that the Sun is only 5.5 ± 5.8 pc above the Galactic plane as defined by massive star-forming regions within 7 kpc of the center.

The BeSSeL Survey is being extended with a VLBI array in the southern hemisphere (Australia–New Zealand) and plans to complete the mapping of the Milky Way over the next three years.

7. Surveys of AGN and quasars

7.1. *VLBA Calibrator Surveys*

NASA's Goddard Space Flight Center (GSFC) astrometry program (Petrov, 2022) has extended the list of AGNs with milliarcsecond (mas) accurate positions and images determined by VLBI. In total, positions of 1793 sources never before observed with VLBI have been determined in five observing programs in 2021.

1) VLBA Calibrator Survey (VCS10) investigates the relationship between compactness, spectral index at kiloparsec (kpc) scale (angular size at arcsecond level), spectral index at pc scale (mas level), source size and its morphology at pc scales from VLBA images and kpc scales using VLA images from NVSS and VLASS. The key scientific questions are

a) Which parts of an AGN dominates in emission at different frequencies and different resolutions?

b) Can the spectral index be used as a discriminator of radio source properties? If yes, which properties and what are the eliminations?

c) How different the statistics of VLBI detected sources drawn from flat-spectrum biased parent samples are different from the statistics drawn from unbiased samples? How many compact sources do we miss? For instance, CGRaBS catalogue of flat spectrum sources was used by Fermi mission for associations of γ-rays sources with AGNs. How many AGN associations were missed due to the selection bias?

Input source list: 1) all sources from AT20G at declinations > -40 deg; 2) GB6 and

PMN in a zone with ecliptic latitude $|b| < 7.5$ deg brighter 70 mJy at 4.86 GHz. Status: astrometry analysis and imaging is in progress. Paper is in preparation.

2) VLBA Calibrator Survey (VCS11) – observation of all remaining known flat spectrum sources brighter 50 mJy.

The goal of the survey is to search for gravitational lens candidates based on multiple compact components that we can then follow up with VLBA observations to verify or disprove any candidate lenses, which we will use to test cold dark matter (CDM) versus alternative dark matter models.

Source list: 1,215 AGN from the CLASS catalogue brighter than 50 mJy at 8.4 GHz, which will augment existing archival VLBA observations of 5,122 CLASS objects brighter than 50 mJy at 8.4 GHz and hence make up a complete flux density limited sample of 6,337 CLASS AGN brighter than 50 mJy at 8.4 GHz. This sample, being statistically complete, will provide a firm statistical foundation for cosmological studies that aim to determine or limit the cosmological density of compact objects in the 10^6 to 10^9 solar mass range. The proposed program to look for gravitational lensing signatures in 6,337 AGN will provide a factor of 20 improvement over previous studies.

CRATES VLBA observations of 1,047 AGN above declination -40 deg will augment the existing archival VLBA observations of 6504 CRATES objects to complete the VLBA observations of all CRATES objects north of declination -40 deg. This will provide a second large sample of compact flat spectrum objects suitable for gravitational lensing searches for compact objects in the above mass range.

These two samples complement one another since the CLASS sample is statistically complete down to 50 mJy at 8.4 GHz, while the CRATES sample selects for compact flat spectrum objects.

The main goal of the problem is to find gravitational lenses at scales less than 200 mas what will impose important upper limits on the numbers of mass condensations with high enough central densities to produce strong lensing, which would place interesting limits on various dark matter candidates, such as black holes and some important exotic particle models. Status: astrometry analysis and imaging is finished. Paper is in preparation.

3) VLBA Calibrator Survey (VCS12): The goal of this survey is to reach completeness at the sky in the declination range $[-40, +90]$ deg and flux density 120 mJy at 8 GHz by observing with VLBI all bright sources that have not been observed with VLBI before. Specifically, the sources that satisfy these criteria are put in the target list:

a) 1847 sources from GB6 brighter than 100.0 mJy at $|b| > 4.0$ b) 1400 sources from PMN brighter than 100.0 mJy at $|b| > 4.0$ and brighter than 100.0 mJy at $|\beta| < 7.5$ c) 125 sources from VLASS brighter than 100.0 mJy at $|\beta| < 7.5$ d) 29 sources from VLASS brighter than 100.0 mJy at $|\delta| > 74.0$ e) 1626 sources from VLASS brighter than 120.0 mJy at $|\beta| > 7.5$ f) 129 Galactic plane sources from BeSSeL calibrator program to re-observe g) 170 Ecliptic plane sources from VEPS to re-observe where b is galactic latitude and β is the ecliptic latitude. Status: 2/3 of the sources in the list are observed and 886 has been detected. Positions of these source are determined. Imaging is pending completion of the program.

4) Improving position accuracy of VLBI Calibrators in the Galactic center region The goal of the program to observe at 22 and 43 GHz the list of 108 calibrators with 10 deg of the Galactic center detected with the KVN, derive their accurate positions and get their images in order to lay out a solid foundation for a number astronomy programs, such as stellar maser astrometry, astrometry of pulsars close to the Galactic Center, investigation of predicted excessive scatter in positions due to non-stationarity of the gravitational field. Status: 1/2 of the program has been observed. All target sources are

detected at K-band and 40% are detected at Q-band. Astrometry analysis is finished. Imaging is pending completion of the program.

5) Unveiling the nature of γ-ray sources in the 4FGL catalogue via LBA Observations. We run a program to observe all new unassociated γ-ray sources from the 4FGL Fermi catalogue at declinations < -30 deg. We pursue two major goals: 1) to provide a portion of the SED for radio to UV part of the spectrum for the AGN sample of γ-ray loud AGNs and 2) to provide a sub-sample of γ-ray sources that are non-AGNs for further observations that target determination of their nature. We will achieve it by following up the radio sources brighter 10 mJy detected with prior ATNF observation in the error ellipses of every unassociated 4FGL source. Proposed observations will eliminate the hemisphere bias in the number of associations of γ-ray sources. These observations significantly enhance the value of the Fermi mission by a) establishing the nature of those γ-ray sources that are associated, and therefore their radio-to-γ SED and redshift become known, and b) providing a clean list, free from AGN contamination, of those sources that are still unassociated. These scientific goals are a part of broader efforts to understand γ-ray sky. In particular, to answer the questions 1) what is the nature of "empty fields" discovered from prior radio observations; 2) are known γ-ray loud AGNs the tail of the distribution or there exists a population of radio-quiet γ-ray AGNs and characterize γ-ray sources through VLBI association that immediately allows γ-ray / Gaia association that provides optical color, IR-color, UV-color, redshift, etc. Status: two sessions have been observed. Astrometry analysis is finished. Imaging is pending.

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.

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2022 April 04

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