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COMMISSION A1 ASTROMETRY

.

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TRIENNIAL REPORT 2018–2021

1. Activities of IAU Commission A1 during 2018-2021

The activities of the commission A1 (Astrometry) during the triennial period (2018-2021) have been highly stimulated by the outstanding results of the Gaia mission which has revolutionized the field of astrometry by giving 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 Gaia mission gave birth to more than one thousand publications thus testifying to the value of astrometry to an incredible variety of astronomical domains such as celestial mechanics in the solar system, galactic kinematics, cepheids, dynamics of open and globular clusters, quasars etc.

A fundamental ongoing task in the scope of commission A1 is the construction of celestial frames, in particular, at radio wavelengths (VLBI) and optical wavelengths (Gaia CRF). Work towards a next generation ICRF will undoubtedly be a major focus of commission A1 in the next triennial period (2021-2024).

Finally, new instruments, such as the LSST, in combination with Gaia will invigorate the activities of the commission by enabling a tremendous set of investigations in astrometry such as the ephemerides of asteroids and the motions of quasars to cite two examples at completely opposite scales.

For all these reasons we strongly recommend maintaining commission A1 for the next triennial period (2021-2024).

2. Progress on the Celestial Reference Frame

2.1. *VLBI radio CRFs*

The last few years saw the completion and adoption of the next generation of the IAU's official International Celestial Reference Frame, the ICRF-3 (Charlot et al.,2020) which was adopted at the 2018 IAU General Assembly and became official on 2019 Jan 01. This work was achieved by a working group of the International Astronomical Union (IAU) mandated for this purpose. This new frame is based on nearly 40 years of VLBI observations carried out at the traditional 8.4 and 2.3 GHz radio frequencies devoted to astrometry and geodesy. The S/X frame was augmented by observational data collected at higher radio frequencies over the past 15 years, specifically, 24 GHz and dual frequency 32 and 8.4 GHz. Comparison of the ICRF3 with the recent optical Gaia Celestial Reference Frame 2 (see below) does not show evidence for deformation larger than 0.03 mas between the two frames, in agreement with the ICRF3 noise level.

In the time since the March 2018 cutoff for ICRF3, observations for celestial frames have continued. At S/X-band (8 GHz) the geodetic observations provide a steady stream of data on the subset of sources observed by IVS. In addition the USNO and Goddard Space Flight Center are running a survey program using the VLBA to improve the positions of about 5000 sources. On October 14, 2020, the directing board of the International VLBI Service for Geodesy and Astrometry (IVS) approved the establishment of an IVS Celestial Reference Frame Committee. The role of this newly established committee is that of an advisory group that makes recommendations to the IVS Directing Board on observing programs and strategies for the VLBI celestial reference frame at S/X-band. At the same time, it takes also an operational role for the implementation and monitoring of these programs. The details of the activities of the IVS Celestial Reference Frame Committee are available from the committee webpage at `https://ivscc.gsfc.nasa.gov/about/com/crfc/index.html`

At K-band (24 GHz) observations have continued in the far south with the HartRAO-Hobart baseline occasionally augmented with the Tidbinbilla 70-m. The VLBA's K-band program has also continued and was upgraded to dual-polarization 4 Gbps total data rate at the end of 2019. This both added the new dimension of full polarization observations and increased sensitivity. Information can be found in De Witt et al. (2019). Kurtz et al. (2020) showed that there is a significant potential for LMT (Large Millimeter Telescope) observations at centimeter wavelengths, although the LMT is initially designed to work in the 3mm and 1 mm bands.

X/Ka (32 GHz) work continues with both NASA's Deep Space network and ESA's Malargue, Argentina station. The big news is that the Japanese space agency (JAXA) has built a 54-m antenna at Misasa near Usuda which has joined the X/Ka effort. First fringes at X-band were achieved with the 54m in December 2019. First Ka-band fringes were finally obtained on 2020 September 22. We also note that Ka-band has become more mainstream with NASA's Parker Solar Probe, ESA's Bepi-Columbo, and JAXA's Hayabusa-2 missions all making astrometric navigation measurements with it.

The plan is to combine all the above three bands of radio observations as well as Gaia optical observations into a multi-wavelength 4th generation ICRF. Patrick Charlot is the point of contact for organizing this future multi-wavelength ICRF (Charlot et al.,2020).

USNO has access to 50% of the observing time on the National Radio Astronomy Observatory's (NRAO) Very Long Baseline Array (VLBA). The USNO time allocation is used for the improvement and maintenance of the ICRF3. The USNO VLBA time allocation is also contributing 99% of data in the radio reference frame at 24 GHz (K-band). In addition to supporting the ICRF3 astrometry in the radio regime, the USNO is also using the VLBA for an imaging campaign designed to study source structure, spectral index, and flux densities at S,X, and K bands. These imaging data products will be made available through the USNO Fundamental reference Image Data archive (FRIDA).

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. 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. Based on this study, a global astrometry use case with a goal to observe 50000 Gaia counterparts was proposed.

2.2. *Gaia Optical CRF*

A full description of the statistics used to characterize the overall properties of the quasar sample has been done (Gaia coll., Mignard et al.,2018). It allows the construction of the Gaia-CRF2 which must be considered as the first realization of a non-rotating global optical reference frame meeting the ICRS prescriptions, in particular because it is based only on extragalactic sources. Gaia-CRF2 consists of the positions of a sample of 556869 sources in Gaia-DR2 obtained from a positional cross-match with the ICRF3 and All-WISE AGN catalogues. The sample constitutes a clean, dense, and homogeneous set of extragalactic sources with accurate positions in the range $15 < G < 20$. The median positional uncertainty of the selected sample is 0.12 mas for $G < 18$ and 0.5 mas at $G = 20$, whereas large scale systematics are found in the range 20 to 30 μas.

2.3. *Dynamical Frame: Ephemerides DE440 and DE441*

JPL has updated its dynamical frame with ephemerides DE440 and DE441 (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. This release adds seven years of new data and improves the dynamical models and data calibration. Jupiter's and Saturn's orbits have benefitted from new VLBI spacecraft tracking data relative to the ICRF. Pluto has benefitted from occultations of stars in the Gaia catalog.

3. Space astrometry

3.1. *Gaia mission*

July 16 2019 marked the end of Gaia's nominal five year mission. This date was chosen because it coincides with a major orbit maintenance manoeuvre, which is designed to keep Gaia out of the earth's shadow during the extended mission phase. The manoeuvre, having occurred on July 16th, was named the "Whitehead eclipse avoidance manoeuvre" in memory of Gary Whitehead from the Gaia Flight Control Team, who sadly passed away in 2019. It was executed without problem and was followed by one year of Gaia following a scanning law with a reversed precession direction (but the same spin direction) in order to aid breaking certain degeneracies in the astrometric solution. In addition slight optimizations of the scan law were done in connection with catching high signal-to-noise ratio observations of stars near Jupiter in 2020 for the experiment aimed at measuring the light bending due to the quadrupole moment of Jupiter's gravitational field. The spin axis precession went back to normal in the summer of 2020. The estimated end-of-life for Gaia (when the micro-propulsion fuel runs out) is early 2025. The process of extending the mission for the period 2023-2025 (thus covering end-of-life) is underway. The mission extension to 2022 has been approved. The Gaia DR2 was available starting from April 2018 (Gaia collaboration, Brown A.G.A et al.,2018). It delivers a five-parameter astrometric solution [equatorial coordinates, parallaxes, and proper motions] for more than 1.3 billion sources, with a limiting magnitude of $G = 21$ and a low limit at $G = 3$. Parallax uncertainties are highly dependent on the magnitude, ranging from 0.04 mas (milliarcsecond) for sources at $G < 15$, to 0.7 mas at $G = 20$.

The data processing for Gaia EDR3 has been accomplished during the 2018-2020 period and the release was done on 2020, Dec. 3rd. This release is characterized by a significantly larger number of objects, i.e. 1.8 billion ones, and by and improved astrometry (positions, parallaxes, proper motions) and photometry (integrated $\mathrm{G}, \mathrm{G}_{\mathrm{BP}}, \mathrm{G}_{\mathrm{RP}}$), with respect to the DR2. For convenience the radial velocities from Gaia DR2 are included as well. Many new data products will become available with Gaia DR3 scheduled in the first half of 2022. As listed on `https://www.cosmos.esa.int/web/gaia/release`, we get :

- Gaia EDR3 contents (see above)
- Object classification and astrophysical parameters, together with BP/RP spectra and/or RVS spectra they are based on, for spectroscopically and (spectro-photometrically) well-behaved objects.
- Mean radial velocities for stars with available atmospheric-parameter estimates.
- Variable-star classifications together with the epoch photometry used for the stars.
- Solar-system results with preliminary orbital solutions and individual epoch observations.
- Non-single stars.
- Quasars and Extended Objects results
- An additional data set, called the Gaia Andromeda Photometric Survey (GAPS), consisting of the photometric time series for *all* sources located in a 5.5 degree radius field centred on the Andromeda galaxy.

During the three years period (2018-2021), the GBOT (Ground Based Optical Tracking) group is in charge of the daily optical tracking of the Gaia satellite as it was the case from the beginning of the mission (Altmann et al., 2014). The aim was to get an optimized position of the satellite with respect to the surrounding stars. The observations are made with the help of CCD frames taken at the focus of 1-2 meter class telescopes located at various places in the world. The requirements for the accuracy on the satellite position determination, with respect to the stars in the field of view is 20 mas, corresponding to 150 meters at the distance of Gaia. This accuracy is necessary to correct the relativistic aberrations as well as the parallax effects of solar system objects. More specifically, the "Data Storage and Processing Center of GAIA -GBOT" is a group located at Paris Observatory in charge of the GBOT database and image reductions programs specifically adapted for tracking moving objects. Thus, during the three years period, about 10000 frames containing the Gaia satellite have been reduced. A general technical study of the characterization of the astrometric precision limit within the GBOT project is developed exhaustively in Bouquillon et al., (2017).

3.2. *Jasmine mission*

In Japan the development of JASMINE missions (Gouda 2011) has been continued. ISAS (science division of JAXA) has selected a candidate JASMINE consisting in a NIR astrometry mission into the central part of our galaxy that will reveal its history from the origins, for a M-class slot. ISAS is determined to proceed to the budget request for JASMINE to be launched in 2028s when the space policy committee determines on the process chart of the space program at this time. Scientific aims of JASMINE are (1) to reveal the Milky Way's central core structure and formation history by measuring the distances and the motions of stars located as far as 26 thousand light-years away with high-precision astrometry observations in the near-infrared band, (2) to explore the formation history of the Milky Way related to the origin of human beings by revealing the evolution of the Galactic structures, which caused the radial migration of the Sun and other stars with their planetary systems, and (3) to find Earth-like habitable exoplanets, taking advantage of the time-series photometry capability required for the precision infrared astrometry. JASMINE has also been listed as one of the largest research programs in the Science Council of Japan.

JASMINE will determine positions and parallaxes with 25 microarcsec uncertainties for stars towards a region around the Galactic nuclear bulge and other small regions which include scientifically interesting target stars (e.g. Cyg X-1), brighter than Hw = 12.5 mag (Hw-band: 1.1 1.6 micron). Proper motions with 25 microarcsec yr-1 uncertainties for stars brighter than Hw=12.5mag, and 125 microarcsec yr-1 for stars brighter than Hw=15mag can be measured. We started the study of space qualified Japanese InGaAs IR detectors for ground-based astronomy. Along with this, the survey will be performed by a single beam telescope with 40 cm diameter for the primary mirror. JASMINE is discussing with a USA team led by USNO about their contribution to the development of data analysis and science cases. We are also discussing with ESA their ground station contribution for science data down-link. Development of data analysis software starts as an activity of consortium, and also international collaboration with ZAH-ARI. The JASMINE Consortium, responsible for data analysis (Yamada et al. 2017) and science activities, was organized, a kick-off meeting was held in September 2019, and is active in science cases and data analysis. As one of the consortium's working groups, a team for investigating detections of exo-planets is organized. We welcome the international partners to join the consortium in near future.

3.3. *Voyage 2050 Near-Infrared mission*

During these last years, an ambitious proposal led by David Hobbs (Lund observatory) was elaborated. It concerns a space mission in the Near Infrared (NIR) domain. The leading argument for such a mission is that the combination of All-sky visible and NIR astrometry with a wavelength cut-off in the K-band will provide an additional foundation for all branches of astronomy from the solar and stellar systems to compact galaxies, quasars, binaries, neutron stars and Dark Matter (DM) substructures. Concerning the construction of reference frames starting from AGNs, the output of such a mission would be precious: it should allow the slowly degrading accuracy of the Gaia visible reference frame, which will be the future fundamental Celestial Reference Frame to be reinitialized back to a maximal precision. The degradation comes from the uncertainty in the spin of the frame, and the presence of small proper motion patterns which are not accounted for. In the stellar fields, the proposed mission could be combined with the older Gaia catalogue (1.8 billion stars), with a 25-35 years baseline, in order to determine proper motions much more accurately than Gaia itself, with a factor of 14-20 for both components. At the same time, big improvement is scheduled in the determination of parallaxes, when astrometric measurements of both space missions will be combined.

4. Ground-based optical astrometry

USNO, working with the University of Hawaii's Institute for Astronomy (IfA), the Cambridge Astronomical Survey Unit of the Institute of Astronomy, Cambridge University, and the Wide Field Astronomy Unit at the University of Edinburgh, is continuing the 'USNO-UKIRT Hemispherical Survey' (U2HS), a near complete northern hemisphere survey from DEC = 0 - 60°, down to magnitudes H = 19.0 and K = 18.4. Observations are currently 86% and 12% complete for the K-band and H-band surveys, respectively. K-band positional errors are typically 8 mas and, when compared with the UKIRT J-band UHS data (Dye et al. 2018) of characteristically 2 mas/y, depending on the epochs of the observations. The Deep South Telescope (DST), a 1-meter aperture PlaneWave robotic telescope was installed at CTIO in March 2019 and began routine operation in Aug 2019. A 4k CCD camera and multiple filters are used for high cadence observations of about 200 compact, extragalactic sources (volume limited AGNs and ICRF sources) with emphasis on targets with discrepant optical and radio positions, as part of the Fundamental Reference Frame astrometric Monitoring Experiment (FRAMEx) collaboration between USNO and Paris Observatory. Since 2015, Paris observatory is in charge of a project of 1-meter aperture robotic telescope to be installed in the French Alps (Saint-Véran, near the Italian border). The project is currently well advanced, half of the budget was obtained in 2019, the second part being obtained between March and June 2020. The scientific program of this telescope concerns mainly the observation of quasars for the link of reference systems. It will observe the ICRF optical counterpart of extragalactic radio-sources, the goal being to select by statistical methods (Allan variance) the more suitable targets for the link ICRF-Gaia CRF. In addition it will observe asteroids, exoplanets and optical counterpart of Gamma ray Burst in the framework of Gaia, CHEOPS and SVOM missions. The U.S. Naval Observatory Flagstaff Station (NOFS) is discontinuing its current infrared parallax program, due to technical upgrades and other demands on the 1.55 m Strand astrometric telescope at NOFS. The object of this program was to obtain the highest quality parallaxes and proper motions of about 175 astrophysically import brown dwarfs between spectral types early-L through late-T. Final reductions are currently underway with expected median parallax and proper motion errors of 2 mas and 1 mas/y, respectively, although well-observed objects will have considerably smaller errors.

The USNO Bright Star Astrometric Database (UBAD) internally released its final catalog, comprised of most northern hemisphere stars with $V < 3.5$, or $I < 3.5$ and $V < 6$, including 36 stars not included in Gaia EDR3. The catalog achieves positional accuracies of around 2 – 3 mas, calibrated against Gaia EDR3, and validates the accuracy of the positions of the brightest stars in Gaia EDR3.

At a time when a handful of major astronomical large facilities with astrometric capability was on process of installation in South America, like ELT, Alma and the GMT, the astrometry in the region was booming during the years 2018-19, despite the fierce political dispute in many countries that caused some irregularity in the flux of funds. Among breakthrough results that combine astrometry and other techniques, one can highlight (Abuter et al., 2018) on the "Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole", (Boizelle et al., 2019) on the "Precision Measurement of the Mass of the Black Hole in NGC 3258 from High-Resolution ALMA Observations of its Circumnuclear Disk" and (Fernandes et al., 2019) on "Runaways and shells around the CMa OB1 association". Naturally such ebullition came to halt in 2020 due to the Covid19 with observatories shutdown, interdiction of travels, and contingency of resources.

5. LLR astrometry

The LLR community will continue to improve analysis model by implementing more and more small effects affecting the Earth-Moon dynamics like geocenter variations, non-tidal loadings, similar for the body of the Moon. As one result we will obtain better ephemeris of the Moon and of the Earth; therefore this leads to a better realization of the celestial reference system by the intermediary of the lunar orbit. As further result, we can determine many parameters of the Earth-Moon system with higher accuracy, including many quantities to verify Einstein's theory of Relativity, such as the equivalence principle, the constancy of the gravitational constant and metric parameters. Finally, we will also prepare our analysis package to include new differential measurements to the reflectors on the Moon as they are planned / prepared by agencies in USA.

6. Astrometry of the past sky : the NAROO project at Paris observatory

The NAROO project (New Astrometric Reduction of Old Observations) has been developed at Paris observatory to digitize, analyze and reduce old observations (Robert et al.,2019). A brand-new sub micrometric digitizing machine is now available at Paris observatory for this purpose. Thus, the NAROO team intend to test the proper motion of stars modeled in the GAIA reference star catalogue for modeling the galactic dynamics, to make pre-discoveries of many comets and asteroids (NEO, TNO) on old photographic plates at a time they were not known but available on observations among stars, and also to observe the planets and natural satellites with the best accuracy on a large time span, allowing to quantify cumulative effects, signature of dissipation of energy as tides.

7. Catalogues of AGN and quasars

A new version of the OCARS (Optical Characteristics of Astrometric Radio Sources) catalog is completed (Malkin,2018). This compiled catalog includes radio sources observed in different VLBI programs and experiments that result in accurate source position determination, their redshift and photometry in the visible and near-infrared bands. A cross-identification with other catalogs in radio, optical, infrared, ultraviolet, X-ray, and gamma-ray bands is also provided.

The LQAC (Large Quasar Astrometric Catalogue) is a general compilation of all the recorded quasars, coming from large surveys (SDSS,2QF) as well as from small ones. Its first aim is to give a priori more precise and accurate values of the equatorial coordinates of each object, in priority those coming from the Gaia DR2. Moreover it contains various information (when available) as redshifts, multi-band magnitudes, radio-fluxes. Specific determinations resulting in complementary data concern the morphology index and the absolute magnitudes. A new up-date of the catalogue, the LQAC-5 was published recently (Souchay et al.,2019). It contains 592809 quasars. This represents roughly a 34% increase with respect to the number of 443725 objects recorded in the previous version, the LQAC-4 (Gattano et al.,2018). Among them, 398697 objects were found in common with the Gaia DR2, within a 1" search radius. This corresponds to 67.26% of the whole population of the compilation, which is considerably more than the 248788 objects found in common with the Gaia DR1 catalogue in the LQAC-4 with the same search radius.

The Wide Field Infrared Explorer (WISE) data are being reprocessed by USNO using a new reference star catalog based on 2MASS and Gaia data. In several iterations WISE frame-by-frame atlas images are processed with high order astrometric solutions. A final product is expected by early 2021.

8. Miscellaneous studies dealing with astrometry

This report cannot mention all the countless studies whether they deal fully with astrometric measurements or which are related to astrometric data. In the following we select some of these studies representing the large variety of topics dealing with astrometry. But we are aware that this list is far from being exhaustive.

- A careful investigation of 3413 ICRF3 extragalactic radio-loud sources was done (Makarov et al., 2019) with accurate positions determined by very long baseline interferometry in the S/X band, cross-matched with DR2 sources to study the radio-optical offsets. The distribution of normalized offsets was shown to be non-Rayleigh. After a suitable deselection, a list of 2119 radio-loud quasars of prime astrometric quality was published. Dependence on redshift values and color were demonstrated.

- (Luri et al.2019) provided guidelines on how to use parallaxes more efficiently to estimate distances by using Bayesian methods, in particular by using DR2 data. Their conclusion is that to fully use the potential of such data it will be always necessary to pay careful attention to the statistical treatment of both parallaxes and proper motions.

- A new method SREAG (spherical rectangular equal-area grid) is proposed to divide a spherical surface into equal-area cells (Malkin,2019). It provides rectangular grid cells with latitude-and longitude-oriented boundaries, near-square cells in the equatorial rings. It is simple in construction and use and provides more uniform width of the latitudinal rings than other methods of equal-area pixelization of a spherical surface.

- A new way to estimate the distribution of the luminosity function of quasars by using the principle of Maximum Entropy was developed by (Andrei et al., 2019). The study was limited to apparent magnitude 15-19 with $z < 3$ to $I = 20.2$ at $z > 3$. They show that their results concerning the luminosity function compare well with previous works

- Geodetic / astrometric VLBI data obtained during nearly 40 yrs. has produced more than 10 million baseline delay, phase and amplitude observables. They were used by Xu et al. (2019) to study, by means of closure rms (CARMS) analysis, the intrinsic source structures and their evolution over time. The overall structure effect magnitudes for 3417 ICRF radio sources are quantified. Among them the 30 most frequently observed sources, which constitute 40% of current geodetic VLBI observables, are studied in detail

- A comparison of Gaia DR2 parallaxes of stars with VLBI astrometry was done by Xu et al. (2019). Their sample was various, ranging from young stellar objects, evolved AGB stars to other radio stars. Their conclusion is that when we except AGB stars and stars in binaries systems, which show significant discrepancies, we obtain an average, systematic parallax offset of +/- 29 μas for Gaia DR2, consistent with their estimate of a parallax zero-point between -100 and 0 μas.

- A quantitative analysis of systematic differences in the positions and proper motions of Gaia DR2 with respect to VLBI (Petrov et al.,2019) concerns 9081 sources matched between the two kinds of catalogues. According to that study the median position uncertainty is a factor of two larger than the median position uncertainty in Gaia DR2. They show both that the major contributor for significant offsets is the presence of optical jets, and that among the sources which present significant proper motions, the fraction of sources with proper motion directions parallel to the jets is a factor of three greater than on average.

- In the case of AGN targets observed assiduously by the TAROT telescopes the Allan time variance shows that the longest averaging period of the magnitudes is in the range 20?70d (Taris et al., 2018). The observation period by Gaia for a single target largely exceeds these values, which might be a problem when the magnitude variations exhibit flicker or random walk noises. Preliminary computations show that if the coordinates of the targets studied were affected by a white-phase noise with a formal uncertainty of about 1 mas (due to astrophysical processes that are put in evidence by the magnitude variations of the sources), it would affect the precision of the link at the level of 50 μas.

- A large sample of 1.36 million quasars observed by the Wide-field Infrared Survey Explorer (WISE) was used to study the large-scale anisotropy of the universe by measuring the dipole in the angular distribution of the objects (Secrest et al.,2021). The direction of the dipole calculated form the sample was shown to be similar to that of the CMB (cosmic microwave background) but its amplitude is over twice as large as expected.

- The 2020 total solar eclipse was observable in land only in South America, but it was plagued by bad sky conditions, especially in Chile. However it is worth to mention the observation of the anomalous comet C/2020X3by the cameras of SoHO and Stereo-A, which contributed to improve the parameters of its orbit (Battams and Boonplod, 2019).

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