IAU Commission A1 - Astrometry

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Annual Report 2019

Progress on the Celestial Reference Frame

The last few years saw the completion and adoption of the new generation of IAU official International Celestial Reference Frame. The ICRF-3 was adopted at the 2018 IAU general assembly and became official as of 2019 Jan 01. 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 about 5000 sources.

At K-band (24 GHz) observations have continued in the far south with 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 adds the new dimension of full polarization observations and increased sensitivity. Information can be found in https://ui.adsabs.harvard.edu/abs/2019aerr.confE...2D/ abstract and in (De Witt et al.,2019).

X/Ka (32 GHz) work continues with both NASA's Deep Space network and ESA's Malargüe, Argentina station. The big news is that the Japanese space agency (JAXA) is building a 54-m at Misasa near Usuda which will join the X/Ka effort. First fringes at X-band were achieved with the 54m in December. 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 at Ka-band.

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 Kilometre 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 50 000 Gaia counterparts was proposed.

Space astrometry

2.1 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 recently. It was executed without problem and is 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 will be 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 will go back to normal in the summer of 2020.

The estimated end-of-life for Gaia (when the micro-propulsion fuel runs out) is still end-2024. The process of extending the mission for the period 2023-2025 (thus covering end-of-life) started on February 27 with a technical review of the status of the spacecraft and payload. In June 2020 we hope to get the confirmation for the extension 2021-2022 and preliminary approval for 2023-2025.

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 (α, δ), parallaxes, and proper motions] for more than 1.3 billion sources, with a limiting magnitude of $G = 21$ and a low limit at $G \approx 3$. 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 finished and the release is being validated. The release date is unknown at the moment due to the Covid-19 crisis. This release will feature improved astrometry (positions, parallaxes, proper motions) and photometry (integrated G, G_BP,G_RP). For convenience the radial velocities from Gaia DR2 will be included as well. Many new data products will become available with Gaia DR3 in the second half of 2021. As listed on https://www.cosmos.esa.int/web/gaia/release

- 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 at best 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 10 000 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)

2.2 Jasmine mission

In Japan the development of JASMINE missions (Gouda 2011) has been continued. ISAS (science division of JAXA) has selected a mission candidate JASMINE, NIR astrometry mission into the central part of our galaxy that will reveal the evolution history of our galaxy, for a M-class slot. ISAS is determined to proceed to budget request for JASMINE to be launched in mid-2020s. Its capacity is also suited for detecting exo-planet in habitable zones of low mass stars. The conclusion and the plan have been notified to a governmental committee that oversees the space science activity in Japan on May 21. JASMINE has also been listed as one of large research program in 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: 1.1~1.7 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. The survey will be performed with a single beam telescope with 30 cm diameter of the primary mirror (Yano et al. 2011). JASMINE is discussing with a USA team led by USNO about their contribution to the development of the detector box unit. We are also discussing with ESA their ground station contribution for science data down-link. The JASMINE Consortium, responsible for data analysis (Yamada et al. 2017) and science activities, was organized and a kick-off meeting was held in September 2019. We welcome the international

partners to join the consortium in near future. Development of data analysis software starts as an activity of consortium, and also international collaboration with ZAH-ARI. As one of the consortium's working groups, the team for investigating detecting exo-planet is organized.
A larger mission to observe the entire bulge region with infrared was planned. This plan is considered to require international collaborations.

2.3 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 (~ 1.7 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.

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 deg, down to magnitudes H=19.0 a,d K=18.4. Observations have largely finished for the K-band survey, and the H-band survey is well under way. By end of June 2018 the USNO Robotic Astrometric Telescope (URAT) concluded observing at Cerro Tololo Interamerican Observatory (CTIO). An internal catalog was produced in early 2019, based on 159,000 URAT exposures over 3years. Results for bright stars (-1.5 to 4.5 Mag) were extracted and combined with UBAD observations and Hipparcos epoch data for a new solution of all 5 astrometric parameters (March 2020).

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 radiosources, 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) continues its infrared parallax program, targeting brown dwarfs, on the 1.55 m Strand astrometric telescope at NOFS. Limited observations continue on the USNO Bright Star Astrometric Database (UBAD), a survey of bright ($V < 3$, $I < 3.5$) northern hemisphere stars, also with the Strand astrometric telescope. After an initial UBAD catalog was produced in 2019, a final catalog is expected in 2020.

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.

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, we intent 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.

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 one. Its first aim is to give the 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 592 809 quasars. This represents roughly a 34% increase with respect to the number of 443 725 objects recorded in the previous version, the LQAC-4 (Gattano et al.,2018). Among them, 398 697 objects were found in common with the Gaia DR2, within a 1" search radius. That corresponds to 67.26% of the whole population of the compilation. This is considerably more than the 248 788 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.

Miscellaneous studies dealing with astrometry

- 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 556 869 sources in Gaia-DR2 obtained from a positional cross-match with the ICRF3 and AllWISE 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.

- 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 lits 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 they except AGB stars and stars in binaries systems, which shows significant discrepancies, they 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.

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