DIVISION A
COMMISSION 8

ASTROMETRY
ASTROMÉTRIE

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1. Introduction

Commission 8 has regularly published triennial reports in the past and the current OC therefore voted to adopt a traditional format also for this special Legacy issue of the IAU Transactions. The outgoing President is grateful for the support of many Commission members who contributed to this report. Our contribution consists of 3 parts: 1) this introduction, providing a general overview and highlights of recent research in astrometry, 2) a summary of the astrometry business & science meeting at the 2015 IAU General Assembly, and 3) the activity report of our Commisson covering the mid-2012 to mid-2015 period.

Astrometry is about to be revolutionized by the European Space Agency (ESA) Gaia mission. Regular survey operations began mid-2014. The first data release is expected by mid-2016 and the final catalog by about 2020, depending on the lifetime of the mission, currently expected to be over 5 years. Gaia will provide an optical reference frame with positions, proper motions and parallaxes in the 10 to 300 micro-arcsecond (μas) range (depending on brightness) down to almost 21st magnitude, which will soon make most current optical reference star catalogs obsolete.

Radio astrometry continues to provide the defining celestial reference frame by VLBI observations of compact, extragalactic sources. The 2nd version of the International Celesctial Reference Frame (ICRF2) was adopted by the IAU in 2009, and observations and reductions are in progress for the ICRF3, scheduled to be adopted by the next IAU GA in 2018. The link between the Gaia (optical) and the ICRF (radio) coordinate systems is being investigated currently, however only a small number of sources seem to be in common and optical structure of AGNs is posing a possible challenge. ALMA in Chile now coming on-line will be very valuable for astrometry in the coming decade.

Another highlight in recent astrometry is the ability to obtain micro-arcsec parallaxes from radio interferometry (VLBI and the Japanese VERA project). Of particular importance was the distance estimate of Pleiades stars (Melis *et al.* 2014) which agrees with earlier ground-based results and our current understanding of stellar evolution models, while suggesting that the Hipparcos parallax of the Pleiades is in error by more than previously expected.

The 4th and final US Naval Observatory (USNO) CCD Astrograph Catalog was published in 2012, providing a dense, accurate reference frame on the ICRF at optical wavelenghts. A deeper and even more accurate star catalog, the USNO Robotic Astrometric

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Catalog was published in 2015. This likely concludes the long history of such ground-based endeavors to provide an optical reference frame in light of the upcoming Gaia 1st data release. The future large synoptic survey telescope (LSST) will utilize the Gaia reference frame and go much deeper than Gaia with high frequency of sky coverages and multiple bandpasses. PanSTARRS operated successfully throughout the last couple of years as precursor to LSST, providing unique astrometric data for objects fainter than UCAC4 or URAT.

The long anticipated textbook, *Astrometry for Astrophysics* (Ed. W. van Altena) was published in 2013 by Cambridge University Press. This is a community effort with many participating authors explaining methods, models and applications of our science to the next generation of astronomers.

2. Summary of the Commission 8 meeting at the 2015 GA

A total of 4 hours were graciously allocated for the Commission 8 meeting, that included several science presentations preceded by a traditional business meeting of the Commission. This meeting was attended by about 30 people and all presentations are available from the Commission's web sites at www.ast.cam.ac.uk/ioa/iau_comm8/ and www.iau.org .

2.1. *Business meeting*

The outgoing President, Norbert Zacharias presented an overview about the re-organization of the IAU Divisions and Commissions. All current Commissions were dissolved and new Commissions established. Following the recommendation of the Organizing Committee (OC) of the Astrometry Commission, a proposal was assembled by Anthony Brown, Dafydd Evans and Norbert Zacharias to establish a "new" Commission with the same name and with the same goals as the old Commission. This proposal was accepted by the IAU and assigned the designation "CA.1" to indicate its parent Division A.

The incoming President is Anthony Brown (Netherlands) and the elected new Vice-President (VP) is Jean Souchay (France). Alexandre Andrei (Brazil), Yoshiyuki Yamada (Japan), and Stephen Unwin (USA) are the elected new members of the OC. The co-proposer of the new Astrometry Commission, Dafydd Evans (UK) serves again on the OC as well as Norbert Zacharias ex officio.

The Commission membership has increased to 283 as of July 20, 2015. The following deceased members of our Commission were honored by a moment of silence: Donald Backer (Univ. California, Berkeley), Hans-Heinrich Bernstein (Heidelberg), Arkadiy Kharin (Main Astronomical Observatory Ukraine), Evgenia Khrutskaya (Pulkovo Observatory), Vasile Mioc (Astronomy Inst. Romanian Academy of Sciences), Naufal Rizvanov (Kazan State University), and Haruo Yasuda (Tokyo).

During the past triennium a total of 10 newsletters were issued to all members of the Commission to inform about highlights and news in our field of research, related meetings, and relevant IAU activities. The following key projects and programs were mentioned: the Gaia mission, work on the ICRF3, the URAT1 catalog, Standards Of Fundamental Astronomy (SOFA), PanSTARRS, Skymapper, LSST, VERA, WG Astrometry by Small Ground-based Telescopes, LQAC3, and SDSS DR12. No questions or additions from the audience were received at the conclusion of the business meeting.

2.2. *Science presentations*

Jean-Eudes Arlot, on behalf of Marcelo Assafin, reported on the activities of the WG Astrometry by Small Ground-based Telescopes. This WG is under Division A and its

continuation is recommended to coordinate research efforts and assist in astrometric education and training.

Jean-Eudes Arlot presented a talk about astrometry of solar system objects after Gaia. He domonstrated that a long time span of moderately accurate observations is more beneficial to accurate ephemerides of natural satellites than a short period of extremely accurate data.

George Kaplan (USNO contractor) investigated the algorithms used for predicting the relative positions of binary star components, given a previously determined orbit. He developed new computational code that incorporates several geometric effects that have not previously been taken into account; these effects can be important for certain binary systems, especially as observational accuracy improves. He also suggested that some conventions relating to how orbits are defined should be established for future work.

Norbert Zacharias, on behalf of Erik Hoeg gave a talk about absolute astrometry in the next 50 years. Erik Hoeg proposes a 2nd Gaia-type space mission to fly in roughly 20 years from now to significantly improve the accuracy of proper motions and possibly go into the near infra-red to better penetrate galactic dust.

This talk was followed by Anthony Brown's report on a recent meeting regarding next steps towards future space astrometry missions, see also camd08.ast.cam.ac.uk/ Greatwiki/GaiaScienceMeetings/FutureAstrometryJul15 .

Norbert Zacharias presented some evidence for astrophysical offsets between the radio and optical centers of emissions of compact, extragalactic sources (AGNs) which are envisioned as link objects between the Gaia and ICRF reference frames. At this point it is not clear if just the exclusion of some sources with large structure will be sufficient or if a general problem exists on the few mas level which would render the accuracy of the radio-optical link much worse than currently expected (Zacharias & Zacharias 2014).

Nathan Secrest reported on identifying about 1.4 million sources of the WISE catalog as very likely being AGNs. This large pool of sources will be valuable for QSO research in general and for enhancing the Gaia to ICRF link of reference frames.

3. Report 2012 − 2015

3.1. *Almanac and near Earth*

The 3rd edition of the Explanatory Supplement to the Astronomical Almanac was published (Urban *et al.* 2012). The US Naval Observatory's Nautical Almanac Office and Her Majesty's Nautical Almanac Office (UK) updated all solar system computations, incorporating JPL's DE430 ephemeris for the major bodies, using JPL's Horizons ephemerides for minor planets and Ceres, and utilizing the value of the astronomical unit consistent with the IAU 2012 resolution. A paper explaining why the Meridian of Greenwich moved was published (Malys *et al.* 2015).

A new idea for determining atmospheric refraction has been developed by utilizing differential measurements with double fields of view. In 2013 a prototype telescope with double fields of view was developed and observations performed at very large zenith distances (Yong *et al.* 2015).

The OAFA (Astronomical Observatory Felix Aguilar) performed satellite observations. At the UNI (National Engineering University, Peru) the occultation of Mars by the Moon was observed at the AFARI Observatory.

A collaboration between Tang Zheng Hong, Qi Zhao Xiang and Guo Sufen (Shanghai Observatory - China), A. Andrei, E. Nogueira and J.L. Penna (Nacional Observatory RJ Brazil) and R. Teixeira, M. Fiencio, M. Voelske and O. Rodrigues (IAG/USP UNICSUL

Brasil) began an observational program of satellite debris at the Valinhos Observatory. The Space Surveillance Telescope (SST) mainly used for space debris detection also has some photometric and astrometric potential (Monet *et al.* 2013).

From 2012 onward several initiatives combining the fields of Space Debris and Navigation Satellites have been started. At the Observatory of Tarija, Bolivia, a program of observation of space debris continued in collaboration with ISON (International Scientific Optical Network). In Venezuela a combined program between the ABAE (Bolivarian Agency for Space Activities) and the CIDA (Astronomy Research Center) was started aiming to track geostationary satellites and space debris (Lacruz *et al.* 2015). In Brazil, fostered by the SHAO/CAS (Shanghai Astronomical Observatory of the Chinese Scientific Academy) 2 programs are running, one for space debris through ON (National Observatory) and USP (University of So Paulo), and the other for navigation of satellites from the BEIDOU system at ON (National Observatory). The Chilean telescope sites naturally harbor several such programs, as TAROT (French collaboration) and MODEST (University of Michigan collaboration). Several of these programs are associated with Time & Frequency research, as for instance at the ONBA (Naval Observatory of Buenos Aires) and the IGNA (National Geographic Institute of Argentina), in Argentina, and also at the ON (National Observatory) in Brazil.

3.2. *Solar System*

A set of astrometric solutions were developed (Qi & Yu 2015a) of the pointing and tracking of celestial objects for the Lunar-based Ultraviolet Telescope (LUT), an astronomical instrument aboard Change 3, the lunar probe of Chinas Lunar Exploration Program that was successfully landed on the northern part of the Moons Mare Imbrium in late 2013. Feasibility was first shown with experiments done from Earth, and then confirmed with actual LUT observations from the Moons surface.

The Naval Observatory Flagstaff Station (NOFS) continued their long-term program with the Flagstaff Automated Scanning Transit Telescope (FASTT) monitoring Uranus, Neptune, Pluto and the bright satellites of Jupiter through Neptune for ephemerides improvement with about 300 observations per year. 5700 bright asteroids are monitored with FASTT for ephemerides improvement and for occultation predictions, with about 25,000 obs/year. NOFS works with JPL to observe a few NASA targets with the 61-inch telescope for spacecraft navigation purposes. Observations of Pluto and a sample of other bright Kuiper Belt Objects were performed with the 61-inch telescope for occultation predictions.

2358 CCD Astrometric observations of the 5 major Uranian satellites were made between 1998 and 2007 near Beijing and Shanghai and compared with theory (Qiao *et al.* 2013) showing an accuracy of between 50 and 200 mas per observation. Digitization and reduction of old astronomical plates of natural satellites began at the Chinese Academy of Sciences using a commercial scanner.

Triton's orbit was determined with the use of a revised pole model (Qiao, R.C. *et al.* 2014) using the 3108 Earth-based astrometric observations from the Natural Satellite Data Center (NSDC) covering the time span of 1975 to 2006. A revised model for Neptune's pole was derived.

1095 astrometric positions of Triton were observed between 2007 and 2009 (Zhang *et al.* 2014a) using 3 telescopes in China. Comparison to ephemerides show residuals between 30 and 50 mas and significant differences between various ephemerides.

Since 2011, the Jinan University group led by Q. Peng has been working on the geometric distortion (GD) solution for a CCD frame and its application. This method was applied to CCD images from the 1-m and 2.4-m telescope at Yunnan Observatory for

open clusters (Peng *et al.* 2012), the saturnian satellite Phoebe (Peng *et al.* 2015), and the near-Earth asteroid Apophis (Wang et al. 2015), improving the positional accuracy by about a factor of 2.

Differential VLBI was used to improve the ephemerides of Mars and Saturn (Jones *et al.* 2015), and to track numerous spacecraft. Most notably the MSL lander, Curiosity, in August 2012 was tracked with 1 nrad (200 μas) accuracy.

A remarkable success was obtained by the international group that includes several institutions of various South American and other countries for observation and interpretation of occultations when rings around the asteroid Chariklo were observed at LaSilla, Chile by Brazilian astronomers.

3.3. *Solar Neighborhood*

The Research Consortium on Nearby Stars (RECONS) lead by T. Henry, Georgia State Univ., continued their effort to obtain parallaxes and photometry of nearby stars. About 150 M dwarfs could be added to the sample of stars within 25 pc of the Sun (Finch *et al.* 2014, Riedel *et al.* 2014).

Trigonometric parallaxes and proper motions of young stellar objects and brown dwarfs were obtained by C. Ducourant and J.F. Le Campion (Bordeaux Observatory - France) and R. Teixeira, P.A.B. Galli, A. Krone-Martins and A.C. Ferreira (IAG/USP - Brazil), see Galli *et al.* 2013, Ducourant *et al.* 2014, Teixeira *et al.* 2014. This research aims at determining membership and the study of properties like ages and masses of stars as part of Fundamental Astronomy.

A number of parallax programs were also concluded using the VLBA for star-forming regions (Zhang *et al.* 2014b, Wu *et al.* 2014) and in the infrared for brown dwarfs (Smart *et al.* 2013, Marocco *et al.* 2013).

NOFS continues the 61-in parallax observing program of red dwarfs and white dwarfs which began about 20 years ago with papers in preparation. Evaluation of the URAT data (see below) to obtain parallaxes of nearby stars began. NOFS has observed northern bright stars (magnitudes 0-6) for a comparison with Gaia astrometry of bright targets.

3.4. *Double Stars*

Speckle astrometric studies of binaries have been carried out with the PISCO camera at Merate (Scardia *et al.* 2015) and lucky imaging of Luhman 16AB (Mancini, *et al.* A&A in press). The result of Kaplan's investigation (see above) prompted a revision of algorithms used in many orbital solutions e.g. the Washington Double Star program.

Work on the Washington Double Star catalog (WDS) continued which now contains 1,276,937 mean positions of 132,600 pairs. The USNO speckle interferometry observing program primarily consists of observations obtained with the 0.67 m refractor in Washington, DC (Mason *et al.* 2013, Hartkopf *et al.* 2015). Over the triennium 7367 observations were made resulting in 3607 mean positions. Collaborations continue with Tokovinin (CTIO), Roberts (JPL), and others to obtain measures of pairs inaccessible with the USNO refractor (Tokovinin *et al.* 2015). For details on the double cataloging and observing programs of the USNO please see the Commission 26 Triennial Report.

The CHARA optical interferometer can perform astrometric observations of binary systems with high angular resolution (ten Brummelaar, Tuthill & Van Belle, 2013, Farrington *et al.* 2014). It continues to work on spectroscopic binary stars, Be Stars, separate fringe packet objects and the detection and imaging of faint companions to many classes of objects. Gail Schaefer at CHARA, continues a binary star orbit program using the Adaptive Optics system at the Keck Observatory.

3.5. *Star Catalogs*

The final release of the Carlsberg Meridian Catalogue series (CMC15) was published (Muinos & Evans 2014). It is the last of the series and comprises all the observations made between March 1999 and March 2011 with the Carlsberg Automatic Meridian Circle in El Roque de los Muchachos Observatory on the island of La Palma (Spain). The catalogues CMC12, CMC13, and CMC14 are superseded by this one. CMC15 contains more than 122 million observations in the magnitude range of $9 \leqslant r' \leqslant 17$ and declination range of $-40° \leqslant \delta \leqslant +50°$. The catalogue internal errors in astrometry are below 30 mas in both coordinates for stars brighter than $r'=13$, reaching 60 mas for $r'=16$. The internal magnitude error is below 0.020 mag for stars brighter than $r'=13$, and about 0.090 mag for $r'= 16$. The instrument has been decommissioned and will go into a museum. Work continued on the SST (Space Surveillance and Tracking) field with the Telescope Fabra-ROA at Montsec (TFRM).

The USNO CCD Astrograph Catalog project concluded with the release of the final, 4th catalog, the UCAC4 (Zacharias *et al.* 2013). This all-sky astrometric survey covers stars between about R = 7 and 16 with 20 to 70 mas positional accuracy depending on magnitude.

A complete re-design of the USNO "redlens" astrograph (which also was used for the UCAC project) utilizes a 28 sq.deg. focal plane consisting of 4 STA1600 CCDs with 10,560 by 10,560 pixels each. The resulting USNO Robotic Astrometric Telescope (URAT) project operated for 3 years (April 2012 to June 2015) from NOFS. A first data release, the URAT1 catalog (Zacharias *et al.* 2015) provides accurate positions of over 220 million stars between about Dec = +90 and −15 deg and about R = 4 to 18.5 mag. The large number of observations per star (average 24) results in small random errors with an estimated systematic error floor of about 10 mas. The URAT data also allow to derive parallaxes of all nearby stars in that area of sky, the largest survey of this kind since the Hipparcos program. URAT was relocated to CTIO in mid 2015 and began a southern hemisphere survey aiming mainly at the brightest stars where Gaia's capabilities are not well understood at this time.

The UNC (National University of Cordoba, Argentina) established a catalog of the ecliptic area. At the CIDA (Astronomy Research Center, Venezuela), a combined astrometric catalogue is being compiled using Carte du Ciel and Carlsberg-CAMC fields.

Several investigations and comparisons of large astrometric catalogs of positions and proper motions were performed (Vityazev & Tsvetkov 2014). An updated version, the XPM2 catalog was constructed (Fedorov, Akhmetov, & Shulga 2014) based on Super-COSMOS data of Schmidt plate scans and linked to extragalactic sources. Vector spherical harmonics algorithms were developed for astrometric catalog analysis (Mignard & Klioner 2012).

A new catalog of absolute proper motions and updated positions was presented (Qi & Yu 2015b), derived from the Space Telescope Science Institute digitized Schmidt survey plates utilized for the construction of Guide Star Catalog II. As special attention was devoted to high accuracy by the removal of position, magnitude, and color dependent systematic errors through the use of both stars and galaxies, this release is solely based on plate data outside the galactic plane $|b| \geqslant 27°$.

Absolute astrometry was obtained from PanSTARRS data in collaboration with USNO (Makarov *et al.* 2015). The accuracy of the obtained proper motions matches the simulations while the observed positional accuracy of pre-public release data is significantly worse than expected. A major public release of PanSTARRS data is expected by end of 2015. Future astrometry with LSST was further investigated (Ivezic *et al.*

2013). The Palomar Transient Factory 2nd data release became public in August 2015 (http://www.ptf.caltech.edu/iptf). Its image processing and data archive is explained in Laher *et al.* 2014.

3.6. *Proper Motions and our Milky Way Galaxy*

NOFS completed a deep proper motion survey in the SDSS imaging area (Munn *et al.* 2014) with a followup paper in preparation on the white dwarfs in the survey.

Various projects for the determination of proper motions from ground-based, wide-field imagers (Libralato *et al.* 2014, 2015) the Hubble Space Telescope (Bedin *et al.* 2014, Massari *et al.* 2015) and photographic plates (Qi & Yu 2015b) have been concluded. The kinematics of our Milky Way X-shaped bulge was analyzed using proper motion observations (Vásquez *et al.* 2013).

The absolute proper motions of 3 globular clusters (NGC 6397, 6626 and 6656) were measured based on Southern Proper Motion (SPM) material (Casetti-Dinescu *et al.* 2013). Extensive use of the SPM4 catalog was made to select OB-type candidate stars and then study these spectroscopically. Recent results indicate the existence of such stars at the edge of the Galactic disk, likely formed recently due to the interaction between the Magellanic Clouds and the disk of the Milky Way (Casetti-Denescu *et al.* 2012). SPM4 proper motions were used to study some 8000 RR Lyrae stars from the recent Siding Springs catalog. An RR Lyrae overdensity was found towards the inner regions of the Milky Way that is kinematically distinct from the Milky Way stellar populations (Casetti-Dinescu *et al.* 2015). Proper motions indicate the overdensity has a net vertical motion away from the Galactic plane. The possibility that this overdensity is debris from Omega Centauri's parent galaxy was explored but no definite conclusion can be drawn at this time.

Possible systematic errors in the Sloan Digital Sky Survey (SDSS) proper motions were investigated by comparing them with proper motions from the Kapteyn Selected Area (SA) survey in order to estimate the accuracy of the absolute proper motion zero point. Results from 22 SA fields indicate that the SDSS zero point has an uncertainty of about 1 mas/yr in fields with low reddening, while in fields with large reddening errors are of a few mas/yr (Ahn *et al.* 2012).

The Visible and Infrared Survey Telescope (VISTA) was used to study high proper motion objects in the galactic plane (Smith *et al.* 2014, Kurtev *et al.* 2015). The Hubble Space Telescope was used for a dedicated proper motion project (HSTPROMO) reaching globular clusters (Bellini *et al.* 2014, Watkins *et al.* 2015) and members of the local group of galaxies (Platais *et al.* 2015). The proper motion of the Large Magellanic Cloud was also obtained from ground-based observations using the SPM catalog (Vieira *et al.* 2014).

3.7. *International Celestial Reference Frame (ICRF)*

The journal paper about the second realization of the International Celestial Reference Frame (ICRF2) by Very Long Baseline Interferometry (VLBI) was published (Fey *et al.* 2015).

The ICRF3 working group was reformed in 2012 after a 3-year hiatus following ICRF2. The 2012-2015 triennium focussed on assessing the needs and initiating observations to address those needs, aiming at adoption of the ICRF3 by the IAU GA in 2018. VLBA S/X Cal Survey II (VCS-II) was carried out under David Gordon's leadership. About 2400 sources were detected and precision improved almost by a factor of 4. The K-band CRF became full-sky and is being densified under the leadership of PI Alessandra Bertarini. The X/Ka-band became full-sky in 2012. In 2015 its precision surpassed that of the ICRF2. In late 2012 the X/Ka CRF work expanded to incorporate a collaboration

with ESA and their 35-m antenna in Malargue Argentina. Observational programs were put in place to increase the number of radio sources with optically bright counterparts (V ⩽ 18 mag) for an improved Gaia to ICRF reference frame tie. Observations are now underway at S/X, K, and X/Ka-bands.

A new combined catalog of radio source positions was computed (Sokolova & Malkin, 2014). Impact of correlations between radio source coordinates in VLBI-based catalogs on the orientation angles between two CRF realizations was estimated (Sokolova & Malkin, 2012). Apparent and proper motions of ICRF radio sources were further studied (Voronkov & Zharov 2013, Zharov *et al.* 2014).

The affect of Galactic aberration on the ICRS realization and on the Earth orientation parameters (EOP), which refer to the ICRS were investigated (Liu *et al.* 2012, Liu, Xie & Zhu 2013). Although the effect is small (few microarcseconds) it is being considered by several IAU working groups of Division A. Impact of the Galactic aberration on proper motions of the celestial reference frame was further investigated (Liu *et al.* 2012, Malkin 2012, 2014, 2015).

The ICRS product center of the IERS evaluates the consistency of celestial reference frames produced at different IVS analysis centers by re-analysis of full VLBI observational database on a yearly basis. This evaluation is done through the modelling of the coordinate difference between the ICRF2 defining source coordinates in both the individual catalogs and the ICRF2. Results are shown in the successive annual reports of the IERS (see http://www.iers.org/IERS/EN/ Organization/ProductCentres/ICRSCentre/icrs.html).

3.8. *Radio-Optical Reference Frame Link*

Offsets between the centers of emission as observed in the radio and optical were found for ICRF sources (Zacharias & Zacharias 2014), see also above (section GA business meeting). Staff from the Paris Observatory, as part of the ICRS product Center of the IERS, were deeply involved in the monitoring of the ICRF sources observed in VLBI, the study of their optical counterparts and the compilation of all the recorded quasar names in the Large Quasar Astrometric Catalogue (LQAC).

An observing campaign is under way using the T-1m class telescopes with automation (TAROT). They are observing regularly a selected sample of AGNs well suited for the radio-optical link between the ICRF2 and the future Gaia catalogue. In particular studies of correlations between astrometric positions and flux variations as well as very regular photometric time series have been undertaken (Taris *et al.* 2011, 2013). Statistical analysis of these series will be performed to determine periodic signatures due to astrophysical processes.

Due to the drastic increase of the number of discovered quasars, mainly from the SDSS catalog updates, 2 new releases of the LQAC, respectively the LQAC2 (Souchay *et al.* 2012) and the LQAC3 (Souchay *et al.* 2015) were delivered, the last one including 321,957 objects. In addition to giving the information obtained from the original catalogues as redshift and multi-bandpass magnitudes, the LQAC contains new or improved data from re-calculations of quasar coordinates, estimated absolute magnitudes and determination of morphology indexes. Moreover some statistical and physical studies have been performed using the LQAC2 catalogue, including an estimate of about 1 million for the number of quasars expected to be detected by the Gaia mission (Gattano *et al.* 2014).

3.9. *VERA extragalactic Radio Astrometry*

The Mizusawa VLBI Observatory of NAOJ continued the operation of VERA (VLBI Exploration of Radio Astrometry), which is a dedicated array for maser astrometry. To date, parallaxes and proper motions have been obtained for 40 Galactic maser sources,

namely, star-forming regions or late-type stars. Recent results of VERA have been published in the VERA special issue of PASJ in 2014 Vol. 66-6 and 2015 Vol. 67-4. Highlights are the discussion of systematic deviations of source motions from the Galactic rotation in terms of the density-wave spiral-arm model (Sakai *et al.* 2015), and the calibration of period-luminosity relation of Miras based on accurate distances measured with VLBI (Nakagawa *et al.* 2014). The determination of Galactic fundamental constants is reported (Honma *et al.* 2012) based on 52 star-forming regions for which accurate astrometric results were available, showing that R0 = 8.05 ± 0.45 kpc and Theta_0 = 238 ± 14 km/s. By combining the results of VERA, VLBA (Very Long Baseline Array) and EVN (European VLBI Network), VLBI maser astrometry has been obtained for more than 100 sources (Reid & Honma 2014).

The Japanese astronomical community established the Japan Square Kilometre Array Consortium (SKA-JP) in 2008, then the SKA-JP Astrometry Working Group in 2009. This WG activated real astrometry demonstrations at the low frequency band (1.6 GHz) since 2013. The first successful detection of a trigonometric parallax was announced in the autumn meeting of the Astronomical Society of Japan (H. Imai and the SKA-JP Astrometry Working Group, 2015 September). This result suggests the high potential of high precision radio astrometry (10 micro-arcsecond level) at the low frequency bands covered with the SKA (SKA1-MID Band-2, SKA1 System Baseline Design, 2013 March). The WG has provided a core member of the SKA VLBI Working Group (established in 2015 August) for realizing the SKA specification available to high precision radio astrometry with the SKA. The WG presented its idea of future radio astrometry with the SKA at the 1.6 GHz band for exploring the dynamical structure of the Milky Way and the Local Group (e.g. Imai *et al.*, in the Asia-Pacific Radio Science Conference 2013).

The KVN and VERA array (KaVA) has been partly opened as an open-use array toward Japanese, Korean and Taiwanese communities since 2013. Compared to the VERA array, KaVA has an advantage for observations of faint and extended sources. Regarding the astrometry capability of KaVA, evaluations and test observations are currently conducted to open the KaVA astrometry mode by March 2016 or later.

3.10. *Other Reference Frame Topics*

The direct distance determination process using trigonometric parallaxes was reviewed in light of physical assumptions (Lindegren 2013).

The multi-wavelength catalogues of 2MASS, WISE, and AKARI are used to calculate the position of the Galactic plane (Ding, Zhu & Liu 2015). The parameters for the direction of the North Galactic pole and the Galactic center are given which can be used to redefine the Galactic coordinate system by IAU in the future. The definition and use of the ecliptic in modern astronomy was reviewed (Capitaine & Soffel 2015).

After more than 10 years since its adoption by the IAU in 2006 the precession model was studied again (Liu & Capitaine 2015) using new solutions of the Earth-Moon Barycenter (EMB) motion, new theoretical contribution to the precession rates, and a revised J2 long-term variation obtained from Satellite Laser Ranging (SLR).

3.11. *JASMINE*

JASMINE is an acronym for Japan Astrometry Satellite Mission for Infrared Exploration. Three satellites are planned as a series of JASMINE projects, as a step-by-step approach, to overcome technical issues and promote scientific results (Gouda 2011, Gouda 2012). These are Nano-JASMINE, Small-JASMINE and (medium-sized) JASMINE. Nano-JASMINE is a nano-size satellite of 50 cm size that weights about 35 kg (Hatsutori *et al.* 2011). The diameter of the primary mirror is 5 cm. A fully depleted

CCD is located at the focal plane of the telescope (Kobayashi *et al.* 2010). The flight model of the Nano-JASMINE satellite was fabricated in Oct. 2010. Nano-JASMINE will operate in the zw-band (0.6 to 1.0 micron). The target accuracy of parallaxes is about 3 mas at zw = 7.5 mag (Kobayashi *et al.* 2011). Experimental evaluation of radiation damage has been performed (Kobayashi *et al.* 2012). Moreover high-accuracy proper motions (0.1 mas/year) can be obtained by combining the Nano-JASMINE catalogue with the Hipparcos catalogue (Michalik *et al.* 2012). The observing strategy and methods used in the data analysis for Nano-JASMINE will be similar to what is planned for Gaia. Hence the use of Nano-JASMINE data is useful to check algorithms that are to be used in the Gaia data analysis, and the algorithms of Gaia data analysis can be applied to Nano-JASMINE (Yamada *et al.* 2012). Economic and political issues prevented an early launch by a Ukraine-Brazil launch service. Nano-JASMINE is expected to be launched into a Sun-synchronized orbit with an altitude of about 650 to 800 km in late 2017.

Small-JASMINE will determine positions and parallaxes accurate to about 10 to 20 μas for stars towards a region around the Galactic nuclear bulge and other small regions that include scientifically interesting target stars (e.g. Cyg X-1), brighter than Hw=11.5 mag (1.1 to 1.7 micron). Thus it will be complementary to Gaia. Proper motions of between 10 and 50 μas/year are expected. The survey will be done with a single beam telescope of which the diameter of the primary mirror is about 30 cm (Yano *et al.* 2011). The target launch date is around 2021. The basic designs of Small-JASMINE and technical problems have been investigated mainly at the JASMINE project office of the National Astronomical Observatory of Japan in collaboration with JAXA, Kyoto University and other institutes (Utsunomiya *et al.* 2014).

The main scientific objective of Small-JASMINE is to clarify the dynamical structure of the Galactic nuclear bulge and search for observational relics of a sequential merger of multiple black holes to form the supermassive black hole at the Galactic center. In particular, Small-JASMINE's primary purpose well be to provide an understanding of the past evolution process of the supermassive black hole and the prediction of future activities of our Galactic center using the knowledge of the gravitational potential in the Galactic nuclear bulge. This understanding can contribute to a better understanding of the co-evolution of the supermassive black holes and bulges in external galaxies.

(Medium-sized) JASMINE is an extended mission of Small-JASMINE, which will observe towards almost the whole region of the Galactic bulge with accuracies of 10 μas in Kw-band (1.5 to 2.5 micron). The target launch date is the 2030s. Merging with other future missions like WFIRST or post-Gaia ESA mission is under consideration.

3.12. *Gaia*

The ESA Gaia mission was launched on 19 December 2013, and after a 6-month commissioning period started its routine science observations in July 2014. The main scientific aim of Gaia is to reveal the structure and kinematics of our Galaxy. The science requirements deduced from the main goal and amended by many other science cases have resulted in a mission conducting an astrometric, photometric and spectroscopic survey of the full sky. Gaia is anticipated to detect and measure more than 1 billion objects astrometrically (Lindegren *et al.* 2012) and photometrically. In addition, spectroscopy will provide radial velocities for an estimated 150 million stars.

During the commissioning period a number of anomalies were encountered, in particular excess stray light entering the payload, the much larger than expected variations of the basic angle between the lines of sight of Gaia's two telescopes, and transmission degradation due to continued out-gassing (http://www.cosmos.esa.int/web/gaia/news_20140729). On-board measures were implemented to mitigate the effect of the stray light

for in particular the Radial Velocity Spectrograph (RVS). The effect of the additional stray light has been accounted for in updated performance predictions for the Gaia mission (http://www.cosmos.esa.int/web/gaia/science-performance). The transmission loss was countered by decontamination activities, the last of which took place in June 2015 (the previous one in September 2014). The contamination rate appears to be slowing. The basic angle variations are being measured to high precision with the on-board metrology system and investigations are ongoing to account for the variations in the astrometric processing through a combination of metrology measurements and self-calibration from the data (Lammers & Lindegren 2014).

Over the first year of science operations a number of results were presented that highlight the capabilities of Gaia (Brown 2015). These include the first supernova discovery, the showcasing of spectra obtained with the RVS and of spectrophotometry obtained with the prism photometers, demonstrations of the detection and observation of solar system objects, a demonstration of the excellent quality of the on-board detection and initial data treatment through observations of Einstein's cross, and two examples of how Gaia deals with crowded regions and nebulae seen in emission. At the IAU General Assembly in Honolulu a first Gaia Hertzsprung-Russell diagram, based on the so-called Tycho-Gaia Astrometric Solution, was presented. It demonstrates the overall correctness and readiness of the data processing chain, the quality of the Gaia instruments, and strengthens the confidence that the impact of the Basic Angle variations can be eliminated from the final astrometric results.

The Gaia Data Processing and Analysis Consortium (DPAC) swung into action straight after the launch and provided support to the commissioning activities through its Initial Data Treatment (IDT) and First Look (FL) pipelines as well as through the analysis of data by the DPAC payload experts. During the first year of science operations the main active DPAC systems were the IDT/FL pipelines, the Astrometric Verification Unit's basic angle monitor and astrometric instrument model pipelines, the RVS processing pipelines provided by the DPAC payload experts, the photometric processing pipeline, and the Astrometric Global Iterative Solution system, responsible for the core astrometric data processing. In parallel a number of the advanced processing pipelines (variable stars, astrophysical parameters, solar system objects, non-single stars) were exercised on the data collected over the special Ecliptic Pole scanning period during the first month of science observations. Throughout the period since launch the ground based optical tracking of Gaia took place through regular observations of the spacecraft from the 2.0-m Liverpool Telescope on La Palma, ESO's 2.6-m VST on Paranal, and the Las Cumbres telescopes. These observations will be included in the very demanding orbit determination for the Gaia spacecraft.

At the time of writing this report ESA and DPAC are gearing up toward the first Gaia data release in 2016.

3.13. *Gaia related*

Gaia data will allow to test aspects of fundamental physics like gravitational deflection of light, energy flux of gravitational waves and Local Lorenz Invariance (Klioner 2014). The astrometric exoplanet detection capability with Gaia was investigated (Perryman *et al.* 2014).

Many astronomers in Europe, including but by far not limited to astrometrists, are involved in Gaia supporting activities, particularly the data processing centers. For more details see the ESA Gaia web pages.

3.14. *Other Space Missions*

The following astrometry related space missions are in the planning stages: the gravitation astrometric measurement experiment (Gai *et al.* 2012a), interferometric stratospheric astrometry for solar system obects (Gai *et al.* 2012b) and the production of the Fine Guidance Star Catalog for Euclid in collaboration with Thales-Alenia (Bucciarelli *et al.* 2015).

Erik Hoeg is proposing a 2nd Gaia-type mission to significantly improve the proper motions (Hoeg 2015). Ideally such a mission would fly about 20 years after Gaia and moving the bandpass into the IR is under consideration.

3.15. *Teaching*

A collaboration between R. Teixeira, J.P. Delicato, D. Miranda and M. Fidencio (IAG/ USP Brazil) started a teaching program about the use of the concept of space in science education, science fiction setting in teaching Astronomy and activity book for remote observations with educational purposes.

3.16. *Meetings*

The Journées meeting scientific developments from highly accurate space-time reference systems, was held at Paris Observatory in September 2013. The IAU-sponsored conference Journées 2014, organized in cooperation with the Paris Observatory was held in Pulkovo Observatory in September 2014. The 2 most recent ADeLA (Dynamical Astronomy in Latin America) meetings took place in Argentina (2012, 5th meeting) and Chile (2014, 6th meeting). Volume 46 of RMxAA is dedicated to the proceedings of ADeLA 6. IAU Symposium 298 (Setting the scene for Gaia and LAMOST) was held at Lijang, China in May 2013. Proceedings of the IAU Symposium 289 (Advancing the Physics of Cosmic Distances) was published in 2013.

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