IAU Division A
Fundamental astronomy – Astronomie Fondamentale

Annual report for 2022

Daniel Hestroffer (Paris obs.,Paris, FR) – president
Bonnie Steves (GCU, Glasgow, UK) – vice president

April 2022

The steering committee of Division A (2021-2024) is composed of:

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Bonnie Steves (Vice-President)	UK
Norbert Zacharias (Advisor)	US
Christopher S. Jacobs (Commission A1 President)	USA
Zinovy M. Malkin (Commission A2 President)	RU
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Commissions and Working Groups

The Division webpage https://www.iau.org/science/scientific_bodies/divisions/A/info/ lists various information together with the Division Commissions and Working groups. There are currently five Commissions with respective working groups, including one cross division commission, and six Working groups including interdivision ones. The Division's Commissions and functional Working Groups have been renewed for a 6 years term.

Commission A1 Astrometry
Commission A2 Rotation of the Earth
Commission A3 Fundamental Standards
Inter-Division A-F Commission Celestial Mechanics and Dynamical Astronomy
Cross-Division A-F Commission Solar System Ephemerides

The following are division's WGs that are *functional* working groups, with tasks achieved regularly, and one inter-division WG; all have been renewed.
Division A WG Numerical Standards in Fundamental Astronomy (NSFA)
Division A WG Standards of Fundamental Astronomy (SOFA)
Division A WG Time Metrology Standards
Inter-Division A-F WG Cartographic Coordinates & Rotational Elements

Inter-Division A-F WG Near Earth Objects membership has been revised; this *functional* WG is now associated to Division A too, as an inter-division WG.

as have been renewed for three years the Working group
WG Astrometry by Small Ground-Based Telescopes

Division A WG Multi-waveband International Celestial Reference Frame (optical+VLBI) has been established in 2021, taking over two former WGs third realization of the ICRF and Multi-waveband realization of the ICRS.

Commission A2 'Rotation of Earth' has also two (joint) working groups:
- Joint IAU-IAG (International Association of Geodesy) - Improving Theories and Models of the Earth's Rotation (ITMER);
- Joint IAU-IAG-IERS on the Consistent Realization of TRF, CRF and EOP

Commission A1 has shown many activities and developments in astrometry from ground and space, global and differential, at optical/IR and radio wavelengths, advantageously pushed at radio wavelengths by the Very Long Baseline Inter- ferometry (VLBI) technique and at optical wavelengths by Gaia.

All of our cross-division and inter-division entities (Comm, WG) are shared with Division F; several WGs are joint WGs with the IAG (International Association of Geodesy), the IERS (International Earth Rotation System), and the IVS (International VLBI Service for Geodesy and Astrometry), or connected to COSPAR, to UNOOSA, or other Services for Standards and Units (BPM, CCU, CCTF, …). Some WGs have services or local webpages - that are hosted by external partner institutions (USGS, UKHO, IMCCE, …)

As already mentioned in previous reports, it is reminded that the SOFA Board is looking for a new Chair (Catherine Hohenkerk has been in post since 2010) to take SOFA forward.

Functional inter-division working group WGCCRE is looking forward to include new members, with complementary expertise, in part to be able to respond to the increased needs and inquiries from the community. Indeed, the WG notes the increasing number and complexity of community inquiries, in particular questions about the coordinate systems for the Moon and Mars. Brent Archinal is proposing to have an actual operational service—with associated functional support—in order to perform the community support functions and other tasks of the WG.

Commissions and Working Groups in particular are looking forward to hold again business meetings during General Assemblies.

GA 2021 Business meetings

The GA 2021 business sessions were held on 23 & 26 August 2021, with among others, putting in place the new Executive Committee and new Steering Committees for the next triennium, terminating or initiating IAU Working Groups, and voting for resolutions B1 to B4. Resolution B1 "in support of the protection of geodetic radio astronomy against radio frequency interference" was proposed by the IAU Commission A2 (Rotation of the Earth) and the IAU Commission A1 (Astrometry) both from Division A ; Resolution B2 on "improvement of the Earth's Rotation Theories and Models" was proposed by the IAU Commission A2 (Rotation of the Earth) ; Resolution B3 "On the Gaia Celestial Reference Frame" was proposed by the IAU Division A WG « Multi-waveband Realizations of the International Celestial Reference System ».

Membership

Division A has a total of 1872 individual members, of which about 10% are junior members. Let us welcome to the new members of the year, most of them being junior members. Having a yearly call for individual membership and junior membership is profitable to attract younger colleagues. Some colleagues have also passed away, sadly, we will honour the deceased members' memory during the Division days at the General Assembly.

PhD Prizes

Since its creation in 2015, the number of candidates under Division A to the PhD prize has always been rather low when compared to the other divisions. Members of Division A are strongly encouraged to disseminate the information and call, and motivate young PhDs to candidate. Selection for year 2021 and 2022 has been made with the entire SC, it happens that both subjects are related to General Relativity.

year 2021: E. Savalle (Paris observatory, France) with his PhD on " Testing General Relativity with clocks in space and exploring new ways to detect dark matter with cold atoms in space and in the laboratory".

year 2022: C. Hamilton (Univ. Cambridge, UK now at Princeton, NJ, USA) with his PhD on "Secular Dynamics of Binaries in Stellar Clusters "

Symposia and Focus meetings

Some commissions or groups would prefer to have an IAU label for holding regular meetings connected to commission tasks

The Symposium IAUs364 "Multi-scale (time and mass) dynamics of space objects" selected for 2020 was at its final steps of preparation just before the corona virus pandemic situation; it was hence postponed and has been hold as an hybrid symposium (Iasi, Romania) in October 2021 https://www.math.uaic.ro/~IAU_S364 (see summary below). It was supported by Division A and Commission A4.
The proposed Symposium "Complex Planetary Systems II" proposed in Namur could not be hold in 2022 because of agenda conflict with the postponed AG scientific sessions of the General Assembly.

The GA2021 scientific sessions will now be held in hybrid mode (Busan, Corea) in August 2022. Division A is coordinating two focus meetings: FM7 « Astrometry for the 21st Century » [chair A. Brown], FM10 « Synergy of small telescopes and large surveys » [chair A. Ivantsov] and is secondary for one Symposium "Astronomical Hazards for life on Earth" (chair G. Tancredi) and one FM "Planetary Astronomy via Telescopic and Microscopic Approaches" (chair H-K Moon).
The Division days will have sessions for presentation of PhD prizes, presentations of Commissions and Working Groups, and sessions dedicated to "Gaia eDR3 and DR3" and "Reference Frames and Rotations".

For the edition of year 2023, Division A has supported three symposia proposals as coordinating or secondary division "Dynamical Masses of Local Group Galaxies", "Active Galactic Nuclei and the Celestial Reference Frame AGNCRF", and Complex Planetary Systems II (CPS II) : Latest methods for an interdisciplinary approach » to be discussed for selection at EC107.

IAU label. As a reminder, some commissions or groups would like to have an IAU label for holding regular meetings, schools, or colloquium, with no particular funding requested from IAU, instead of proposing an IAU symposium. This would help keeping the IAU visibility when organising events closely connected to commission or WG tasks, and can be done at a Division level. The symposium format is not always adapted to the need of the community to discuss and work on specific tasks and science progress.

Symposium IAUs 364 short report

[C. Gales & A. Celletti]

The IAU Symposium 364 took place from October 18 to 22, 2021, in hybrid form, in which locals attended the event in person, while all other participants participated remotely. The event was organized with the support from IAU, Division A Fundamental Astronomy and

Commission A4 – Inter-Division A-F Celestial Mechanics and Dynamical Astronomy, Al. I Cuza University of Iasi, University of Rome Tor Vergata and the Romanian National Committee for Astronomy.

The objective of this Symposium was to address the recent advances in the multi-scale dynamics of natural and artificial space objects from various perspectives: modelling, development of new methods and tools to analyse the dynamics, stability analysis, exploration and exploitation of minor bodies. In fact, the IAU Symposium 364 covered the following key topics:

1. Large-scale body dynamics: planets and exoplanets;
2. Medium-scale body dynamics: asteroids, comets, NEOs, natural satellites;
3. Small-scale body dynamics: dust particles, rings and space debris;
4. Perturbation methods and long-term evolution of space objects;
5. Numerical and analytical methods for resonances and chaos;
6. Exploration and exploitation of space objects.

The event gathered **199 participants**, from more than 30 countries, with a large (>50%) participation of post-docs, doctoral and master students. The scientific results obtained by the participants were disseminated through oral communications (**20 invited talks** and **65 contributed talks**) and **38 e-posters**. The technical programme included 9 sessions addressed to the above mentioned key topics, one session devoted to e-posters, a **public lecture** and a **Memorial dedicated to Andrea Milani**.

All sessions, including the *public lecture* scheduled on Wednesday afternoon, October, 20, 2021, were streamed via Zoom.

The **book of abstracts** and the videos of **recorded talks** are available on the website of the Symposium 364 at: https://www.math.uaic.ro/~IAU_S364/programme/
A number of **38 e-posters** are uploaded in the pdf format on the website of the Symposium 364 at: https://www.math.uaic.ro/~IAU_S364/posters/
A **Slack workspace**, titled *Multi-scale (time&mass) dynamics of space objects*, was created and all participants were invited to use its channels for chatting and questions and for interacting with the authors of e-posters and speakers.

Commissions and Working groups reports.

Summary. Commissions A1, A2, A3, cross-division commission X2, and inter-division commission A4 ; Working groups SOFA, WGASGBT, WGTMS, WGNSFA, inter-division WGCCRE WGNEOs have provided their annual report. Reports have different formats but all are showing scientific and programmatic activities either as functional entities, and/or as holding meetings exchanging information, and supporting IAU plan.

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COMMISSION A1 — ASTROMETRY

ASTROMETRY

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ANNUAL REPORT 2022

1. Activities of IAU Commission A1 during 2021-22

Commission A1 on Astrometry is pleased to share that the 2021–2022 year has been a year full of successes in the field of astrometry. We report here progress in both global and differential astrometry at optical/IR and radio wavelengths.

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

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

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

Ground based optical work ranging from surveys to speckle observations to Lunar Laser Ranging have added to our scientific knowledge during 2021-2022.

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

Finally, we call to your attention this year's IAU General Assembly XXXI, in Busan, Korea where Focus Meeting 7, 'Astrometry for 21st Century Astronomy,' is scheduled for 10-11 August 2022. `http://www.busan2021fm7.org`

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

2. Progress on Celestial Reference Frames

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

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

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

2.2. *VLBI radio Celestial Reference Frames*

The next generation of the IAU’s official International Celestial Reference Frame, the ICRF-3 (Charlot et al.,2020) was adopted at the 2018 IAU General Assembly and became official on 2019 Jan 01. It contains components at three wavelengths: S/X (8.4 GHz), K (24 GHz), and X/Ka (32 GHz) enabling the potential for studying the astrophysical limitations of the ICRF. Comparison of the S/X-band radio ICRF3 with the optical Gaia Celestial Reference Frame 2 does not show evidence for deformation larger than 0.03 mas between the two frames, in agreement with the ICRF3 noise level.

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

Since the cutoff for ICRF3 in 2018, the number of S/X observations has increased by 25% to 16.5 million. During the past year alone, twelve VLBA astrometry sessions at X/S band which were coordinated, scheduled and analyzed at the U.S. Naval Observatory. These observations have concentrated on improving the positions of the lesser observed X/S sources and on adding additional sources. As of March 2022, there were 5399 sources in the X/S catalog, an increase of 863 or 19% over the ICRF3 (Gordon et al, 2022). Also noteworthy is that this includes ∼400 additional ecliptic sources over ICRF3.

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

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

K band (24 GHz) ICRF work has continued with approximately monthly VLBA sessions and two HartRAO-Hobart26 (S.Africa–Australia). These were coordinated and scheduled by P.I. Alet deWitt at the South African Radio Astronomy Observatory and analyzed at the USNO. The K-band reference frame currently has 1.76 million observations, a 270% increase over the ICRF3, and has added 211 sources for a total of 1035, a 25% increase. Source precision has also improved considerably at K-band to $\sim 45, 90$ μas in $\alpha \cos\delta$, δ, respectively—approximately as precise as S/X-band (Gordon et al, 2022).

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

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

X/Ka (32 GHz) work continues with a combined NASA, ESA, and JAXA network which has now produced 0.11 million observations. Median source precision has improved considerably at X/Ka-band to $47, 69$ μas in $\alpha \cos\delta$, δ, respectively—slightly better than the ICRF3-SX. Accuracy is currently limited by a quadrupole 2,0 "magnetic" distortion in the frame of $131 \pm 19\mu$as. There are hints that accounting for the spatial and temporal correlations in the troposphere noise may reduce the quadrupole distortion. The large Z-dipole distortion seen in the ICRF3-XKa is now statistically insignificant as long as the full $\alpha - \delta$ parameter covariances are accounted for (Jacobs et al, 2022).

2.2.4. *Radio Imaging of ICRF Sources*

Now that radio astrometry is available at the sub-mas level at multiple wavelengths along with Gaia optical astrometry at similar levels of precision, inter-comparisons are revealing differences in positions that may be caused by source morphology (deWitt et al, 2022a). In order to study these differences, much needed images at various wavelengths are being produced e.g. at S/X (Hunt et al, 2021 and at K-band (de Witt et al, 2022b).

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

The Bordeaux VLBI image database has served the community for many years and now contains 7862 images spread over 1514 sources at various wavelengths including S, X, K, and Q-bands. New data is added on an ongoing basis. `http://bvid.astrophy.u-bordeaux.fr`.

Another rich collection of radio images may be found at the astrogeo web site: `http://astrogeo.org/vlbi_images/` The Astrogeo VLBI FITS image database contains 111,396 brightness distributions of 17432 compact radio sources—mainly Active Galactic Nuclei (AGN)—generated by analyzing Very Long Baseline Interferometry (VLBI) surveys. This database is updated as more data become available.

FRIDA: The USNO has a searchable, interactive radio image database called the Fundamental Reference Image Data Archive (FRIDA) covering epochs from 1992 to 2017 and frequencies from 2.3 to 43 GHz. (`https://crf.usno.navy.mil/FRIDA`). USNO has spent the last two years working improving the user interface, increasing the total number images, as well as providing image quality metrics. New data will be added on an ongoing basis.

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

2.3. *Dynamical Frame: Ephemerides DE440 and DE441*

The next-generation, general-purpose JPL planetary and lunar ephemerides called DE440/ DE441 were delivered in 2020 (Parks et al, 2021). DE440 covers the years 1550-2650 while DE441 is tuned to cover a time range of -13,200 to +17,191 years. Ongoing work continues to add new radio and optical data to improve dynamical models and data calibration.

3. Space astrometry

3.1. *Gaia mission*

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

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

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

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

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

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

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

3.3. *Anomalous Quasar Proper Motions*

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

3.4. *Voyage 2050 Near-Infrared mission*

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

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

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

3.5. *JASMINE mission*

In Japan the development of the JASMINE mission continues with the goal of launch in the mid-2020s. Small-JASMINE is a space mission (Gouda, 2021) to provide astrometric data with high precision (20 μas level) in a near infrared band for stars in the Galactic central regions. The primary scientific objective is to carry out the Galactic Center Archeology and Galacto-seismology by exploring the Galactic nuclear bulge and the Galactic plane, which lead to the elucidation of the formation histories of the Galaxy and the supermassive black hole at the center, and the Galactic Habitable Orbits which are necessary for life to be created and maintained. Furthermore, we plan to observe other specific astronomical objects such as the transit observations to search for Earth-type planets in the habitable zone around M-type stars. Small-JASMINE was selected in May 2019 as the unique candidate for the competitive 3rd Medium-class science satellite mission by ISAS/JAXA.

3.6. *Square Kilometer Array*

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

4. Ground-based optical astrometry

4.1. *USNO Bright Star Catalog:*

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

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

4.2. *USNO VLBI Spectroscopic Catalog*

USNO has developed a catalog of optical spectroscopic parameters (emission line fluxes, widths, etc.) for objects in ICRF3. This is the first such catalog to be developed, and will allow for astrometric quantities of interest to be compared with AGN spectral parameters. This catalog, the USNO VLBI Spectroscopic Catalog (UVSC), uses an updated version of the Bayesian spectral fitting code developed specifically for AGNs and quasars that fits all spectral components such as AGN/stellar continua and emission lines simultaneously, using a Markov Chain Monte Carlo sampler to obtain robust parameter posterior distributions. In addition to fit spectral parameters, the UVSC also contains derived parameters where possible, such as estimates of the black hole masses, AGN bolometric luminosities, and Eddington ratios. The catalog will appear in Sexton et al. (2022, in review). Currently, the included spectroscopic data come entirely from SDSS/BOSS, but the catalog will be expanded to include archival spectroscopic data found elsewhere. The catalog will also be extended to include VLBI sources not currently in the ICRF, such as those in the recent USNO global solutions, and in VLBI source compilations such as OCARS (Malkin, 2018). Once published, the catalog will be hosted on VizieR (`https://vizier.u-strasbg.fr`) and the USNO CRF webpage (`https://crf.usno.navy.mil`).

4.3. *USNO Deep South Telescope*

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

4.4. *UKIRT Hemisphere Survey*

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

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

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

(WDS) which has grown by 30% (8%) in the number of measures (systems) since IAU-GA XXX (Vienna). We have also stood up a new Supplement to the WDS which consists of pairs that are typically wider and fainter and comes primarily from large astrometric surveys (such as Gaia). This catalog known as the WDSS is already 5.2(15.7) times larger in the number of measures (systems) than the WDS. We also continue to maintain both the Visual Orbit Catalog as well as the Linear Elements Catalog. The most current versions of these catalogs are accessible at our new website `https://crf.usno.navy.mil` under the IAU Double Star Center/WDS pages. Observing in support of all of these catalogs continues to be conducted with the USNO 26” telescope in Washington, DC, the Navy Precision Optical Interferometer (NPOI) in Flagstaff, AZ, and through collaborative relationships the SOAR telescope as well as both the Gemini North and South telescopes. Sections 4.1 to 4.5 on USNO optical work are due to Cigan et al (2022).

4.6. *LSST*

The Vera C. Rubin Observatory is an almost completed ground based observatory which will survey the entire southern sky every few nights for ten years thus carrying out the Legacy Survey of Space and Time (LSST). Planned to start in 2024, the Rubin LSST is a unique facility that combines high spatial resolution, high cadence, and high sensitivity thus contributing to nearly all fields of astronomy with an unprecedentedly rich data set (see e.g. Li et al. 2022). While the survey’s main focus is photometry, the astrometry provided will encompass an enormous dataset with billions of objects measured, including many background galaxies. Besides many classic astrometric applications of such a data base, we highlight here the possibility of measuring H0 directly from galaxy parallax. Specifically, galaxy parallax shifts due to Earth’s motion with respect to the CMB frame may be detected by Rubin LSST (Croft, 2021).

4.7. *Speckle observations:*

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

5. LLR astrometry

Since 1969, Lunar Laser Ranging (LLR) data have been collected by various observatories and analysed by different analysis groups. In recent years, observations with bigger telescopes (APOLLO) and at infra-red wavelength (OCA) have been carried out, resulting in a better distribution of precise LLR data over the lunar orbit and the observed retro-reflectors on the Moon. Biskupek et al (2021) report estimates of relativistic parameters characterizing the temporal variation of the gravitational constant $\dot{G}/G_0 = (-5.0 \pm 9.6) \times 10^{-15}/yr$
the equivalence principle with $\Delta(m_g/m_i)EM = (-2.1 \pm 2.4) \times 10^{-14}$
and the PPN parameters: $\beta - 1 = (6.2 \pm 7.2) \times 10^{-5}$, $\gamma - 1 = (1.7 \pm 1.6) \times 10^{-4}$
The results show a significant improvement in the accuracy of the various parameters,

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

6. Bar and Spiral Structure Legacy (BeSSeL) Survey

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

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

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

7. Surveys of AGN and quasars

7.1. *VLBA Calibrator Surveys*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Acknowledgments:

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

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

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

Christopher S. Jacobs
Jet Propulsion Laboratory, Calfornia Institute of Technology
President of the Commission
2022 April 04

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IAU Commission A2 Rotation of the Earth
Annual report for 2021

Organizing Committee:
Zinovy M. Malkin (President)
Alberto Escapa (Vice-President)
Laura I. Fernandez (Secretary)
Florian Seitz (Advisor – Past President)
Shuanggen Jin
Jolanta Nastula
David A. Salstein
Hadia Hassan Selim
Jean Souchay
Robert Heinkelmann (IAG Representative)
Daniela Thaller (IERS Representative)
Oleg A. Titov (IVS Representative)

Organization

IAU Commission 19 began its history with the birth of the IAU at the Brussels Conference in 1919, where Standing Committee 19 on Latitude Variations was established. At the first IAU General Assembly in 1922, Standing Committee 19 became Commission 19 "Variation of Latitude". Later, as the topic of the Commission was expanded to include observations and the theory of Earth rotation and interconnection between Earth rotation and geophysical phenomena, in 1964 it was renamed Commission 19 "Rotation of the Earth". In 2015, Commission 19 was renewed as Commission A2 "Rotation of the Earth" (CA2) with the same functions. In 2021, CA2 was renewed for the next 6-year term. Among its scientific rationale, CA2 helps linking the astronomical community to other scientific organizations such as the International Association of Geodesy (IAG), International Earth Rotation and Reference Systems Service (IERS), and space geodesy technique services largely contributed to the monitoring and investigation of the Earth's rotation, such as International VLBI Service for Geodesy and Astrometry (IVS), International GNSS Service (IGS), International Laser Ranging Service ILRS), and International DORIS Service (ILRS).

Election of CA2 officers for the term 2021–2024 took place in April 2021. Alberto Escapa was elected as the new CA2 Vice-President. Three new CA2 OC members were elected: Laura Fernandez, David Salstein, and Jean Souchay. Second term CA2 OC members are Hadia Hassan Selim, Shuanggen Jin, and Jolanta Nastula.

Three non-voting Representatives to CA2 OC from other organizations were appointed by the new CA2 OC and confirmed by corresponding organizations: Robert Heinkelmann (IAG Representative), Daniela Thaller (IERS Representative), and Oleg Titov (IVS Representative).

Laura I. Fernandez was appointed by the CA2 OC as the new Commission Secretary.

The Commission currently joints 111 members.

The CA2 webpage is https://www.iau.org/science/scientific_bodies/commissions/A2/info/ .

General activity

CA2 proposed an IAU Resolution on Improvement of the Earth's Rotation Theories and Models, which was approved by the IAU GA 2021 as IAU Resolution B2 http://www.iau.org/static/archives/announcements/pdf/ann21040b.pdf .

CA2 together with CA1 proposed an IAU Resolution in support of the protection of geodetic radio astronomy against radio frequency interference, which was approved by the IAU GA 2021 as IAU Resolution B1
http://www.iau.org/static/archives/announcements/pdf/ann21040a.pdf .

A. Escapa, R. Heinkelmann, J. M. Ferrandiz, F. Seitz, and R. Gross prepared an article for IAU Catalyst on these two IAU Resolutions including their detailed description and explanation.

Scientific meetings

A proposal for IAU GA 2021 Symposium "Reference systems and their ties with the rotation of the Earth and other Solar System bodies" jointly prepared by IAU Commissions A1, A2 (lead), and Inter-Division A/F WG on Cartographic Coordinates and Rotational Elements (WGCCRE) https://www.iau.org/static/science/scientific_bodies/commissions/a1/info/meetings/a1-symposium-proposal.pdf was submitted, but was not approved by the IAU EC. The CA2 OC decided to work on a new IAU Symposia proposal, together with other IAU Commissions having interest in the CA2 topics.

Because of COVID-19 pandemic, there were no scientific meetings co-organized by IAU CA2 in 2021. Meanwhile, during 2021, CA2 members actively participated in organization of many scientific meetings of CA2 interest, such as 25th Working Meeting of the European VLBI Group for Geodesy and Astrometry (virtual, 15–18 March 2021), European Geoscience Union General Assembly (virtual, 19-30 April 2021), IAG Scientific Assembly (Beijing, China, 28 June – 5 July 2021, Beijing, China), AGU Fall meeting (New Orleans, LA, USA, 13–17 December 2021.

Working Groups under IAU Commission A2

Joint IAU-IAG-IERS WG Consistent Realization of TRF, CRF and EOP (JWG CRTCE)
Chair: Robert Heinkelmann, Co-Chair: Manuela Seitz
The main objectives of this WG are:

- to compute multi-technique CRF-TRF solutions together with EOP in one step,
- to quantify the consistency of the current conventional reference frames and EOP,
- assess the consistency of reprocessed and predicted EOP.

Joint IAU-IAG WG Improving Theories and Models of the Earth’s Rotation (JWG ITMER)
Chair: Jose Ferrándiz, Co-Chair: Richard Gross
The main purpose of this WG is to propose consistent updates of the Earth rotation theories and models, and their validation. The associated tasks will thus contribute to the implementation of the 2018 IAU Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames, and the 2019 IAG Resolution 5 on Improvement of the Earth’s Rotation Theories and Models.

The Working Groups publish their reports at https://www.iau.org/publications/iau/wg_reports/

IAU Commission A3 - Fundamental Standards
Annual Report 2021

Susan G. Stewart, Jose M. Ferrándiz, Steven A. Bell, Agnès Fienga, Demetrios N. Matsakis, Wendy K. Puatua, Antonia J. Wilmot

IAU Division A Commission A3 (CA3) strives to fill an important and necessary role in the IAU and wider astronomical research community by identifying, coordinating, researching and communicating fundamental astronomical standards. The Commission is entering its third triennium and currently has 101 members. In 2021, four new members joined the CA3 Organizing committee. The primary mission of the CA3 Organizing Committee is to:

1) Identify emerging standards
2) Coordinate the investigation and implications of emerging standards
3) Gather feedback from standards organizations, A3 members and the astronomical community
4) Communicate recommended and IAU-endorsed standards

These primary goals of CA3 are achieved by maintaining two lines of communication. As such, both incoming and outgoing communication are of great importance to the success of CA3. The Commission seeks to keep strong ties and enhance communication with our standards partner organizations: Global Geodetic Observing System Bureau of Products and Standards (GGOS BPS), Consultative Committee on Time and Frequency (CCTF), Consultative Committee for Units (CCU) and International Earth Rotation and Reference Systems Service (IERS). We also seek strong coordination with IAU standards partners: Standards of Fundamental Astronomy (SOFA) and the Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE). We have improved the outgoing communication the past two years through the development of and updates to the CA3 website: https://iau-a3.gitlab.io/ (Susan Stewart, webmaster). In this effort, CA3 has now taken over the responsibility for the future upkeep of the end product of the Numerical Standards for Fundamental Astronomy (NSFA) Working Group which dissolved at the conclusion of the last triennium. Past President of CA3 James Hilton wrote the final triennial report for the NSFA WG this past year and it is posted on the CA3 website. Commission leadership participated in the virtual GA business meeting in August and communicated with members regarding support for resolutions in relation to the importance of fundamental standards.

Commission A3 is currently organizing for the hybrid General Assembly in August 2022. Preparations have revolved around reaching out to standards organizations and discussions concerning the agenda of the CA3 business meeting and presentation at the Division Days. Recently we have organized our committee discussion topics which include consideration of virtual workshop, a social media account to elevate CA3 communication of standards, and evaluating our list of emerging standards. We have asked the IAU Communications committee their opinion of the social media platform and other ideas for broader communication.

31 Mar 2022

Inter-Division A-F Commission A4 “Celestial Mechanics and Dynamical Astronomy”

PRESIDENT: Christos Efthymiopoulos

VICE-PRESIDENT: Giovanni Federico Gronchi

ADVISOR: Alessandra Celletti (past President)

ORGANIZING COMMITTEE MEMBERS:
Alexandre C. M. Correia, Romina Paula Di Sisto, Silvia M. Giuliatti Winter, Ireneusz Wlodarczyk, Li-Yong Zhou.

ANNUAL REPORT 2021-2022

The IAU Inter-Division A-F Commission A4 “Celestial Mechanics and Dynamical Astronomy” presently unites 202 members. The main goal of the commission is to co-ordinate and support the activities of IAU members working in these two broad fields. These activities include: treatments of the mathematical, physical and computational aspects of planetary theory, perturbation theory, resonance models, chaos and diffusion, stability criteria, orbital and space mechanics, ring systems, tidal models, galactic dynamics, non-gravitational forces, and computer languages for analytical developments.

1. The **IAU Symposium 364 on "Multi-Scale (Time and Mass) Dynamics of Space Objects"** was held in dual form in Iasi, Romania, from October 18 to 22, 2021. The Symposium was proposed by the previous organizing committee (2018-2021) in 2019, but it was postponed due to the COVID events. The symposium was a major event which gathered together about 200 participants, out of whom 98 speakers (20 invited) in the following topics: Large-scale body dynamics: planets and exoplanets, medium-scale body dynamics: asteroids, comets, NEOs, natural satellites, perturbation methods and long-term evolution of space objects, exploration and exploitation of space objects, small-scale body dynamics: dust particles, rings and space debris & numerical and analytical methods for resonances and chaos. Most contributions are included in the corresponding IAU volume of proceedings (A. Celletti (co-chair), C. Galeş (co-chair), C. Beaugé, and A. Lemaitre (eds), Cambridge University Press). More information about the content of the Symposium can be found at the symposium's webpage: https://www.math.uaic.ro/~IAU_S364/.

2. One of the main goals of the IAU Commission A4 (see *https://www.iau.org/science /scientific_bodies/commissions/A4/*) is to "promote the periodic holding of a Summer School aiming to train young researchers on the most important current topics in Celestial Mechanics and Dynamical Astronomy. Such schools can take place before major scientific meetings, such as the celebrated CELMEC conferences.”

This year, the **Advanced Study School on "Celestial Mechanics -Theory and Applications"** (CELTA ASI) 2022 will be held from 15 to 27 August 2022 at Inverness & Skye, Scotland. The school is under the patronage of the IAU Commission A4, and it will include lectures by 16 Invited Speakers. The school is organized jointly with the 77th Scottish Universities Summer School in Physics, under the direction of Prof. Bonnie Steves (Glasgow Caledonian University). The school will precede the **Eighth International Meeting on Celestial Mechanics (CELMEC VIII)** which will take place at the University of Rome Tor Vergata during the period 5-9 September 2022 (Organizing/Scientific committee: A. Celletti, G.F. Gronchi, C. Lhotka, U. Locatelli, G. Pinzari, S.

Terracini). The format will be hybrid, and there will be 203 participants (including 24 invited talks). CELMEC has reached an agreement with the international journal "Celestial Mechanics and Dynamical Astronomy", to allow the publication of original papers presented at the meeting. The papers will be organised in two Topical Collections, under the titles: a. Innovative computational methods in Dynamical Astronomy, and b. Variational and perturbative methods in Celestial Mechanics.

3. The past-president of the A4 organising committee (A. Celletti) is chief editor of the journal Celestial Mechanics and Dynamical Astronomy, and many members of our commission participate in the editorial board (see https://www.springer.com/journal/10569/editors). Besides regular articles, the journal publishes topical collections which provide a continuous update on the most important advances in celestial mechanics, astrodynamics and space mechanics, as well as broader topics within the field of dynamical astronomy. In the period 2021-2022, the following topical collections were published by the journal:

- Dynamics of Space Debris and NEO
  Xiyun Hou, Massimiliano Vasile and Alessandra Celletti (eds)

- Exoplanet Dynamics
  Alessandro Morbidelli, Kleomenis Tsiganis and Alessandra Celletti (eds)

X2 – Cross-Division A-F Commission Solar System Ephemerides

During this period, optical observers and data processing centers (MPC, NASA, ESA, NEODyS) consolidated the adoption of the ADES format, which was approved by Commission 20 at the 2015 IAU General Assembly. The transition process is on-going, but important applications are already in place such as the NEO Confirmation Page targets data processing for JPL-Scout and NEODyS-NEOScan computations. The next major challenge is preparing to process the increased flow of astrometric data due to the start of big surveys such as the Vera Rubin Telescope, the NEO Surveyor mission, and the Fly-Eye Telescope. The data flow is expected to increase by up to two orders of magnitude relative to the current data flow, which primarily comes from the operational surveys. In view of this increased data volume, the Minor Planet Center is making the necessary preparations and major software and data flow architecture reviews are undergoing. Similar adaptations are necessary for the other data processing centers. On the planetary side, the next-generation, general-purpose planetary and lunar ephemerides called DE440/DE441 were delivered in 2020 by JPL. Compared to the previous general-purpose ephemerides DE430, seven years of new data have been added with improved dynamical models and data calibration.

Since 2016, three new versions of INPOP planetary and lunar ephemerides have been delivered by the IMCCE team: INPOP17a, INPOP19, and INPOP21a. They benefit from an improved modeling of the Moon rotation and orbit (INPOP17a), the introduction of Bayesian methods for the asteroid mass determination and the regular inputs of Juno, Mars Express and ExoMars data (INPOP19a, INPOP21a). Perturbations by TNOs have been included since 2020 after the introduction of recently analyzed Cassini observations. Constraint on the size of the Moon core has been obtained, INPOP21a gave a better description of the distribution of the mass for the outer solar system and new constraints on dilaton and graviton theories have been published using INPOP19a and INPOP20a.

In 2021 the IAA - Russian Academy of Sciences released a new version of planetary ephemerides, EPM2021, after 4 years since last release.

In 2021 the JPL-Sentry team announced the implementation of a new impact monitoring method that replaces the Line-of-Variations method. This development is important because the new method is fully independent of the previous ones, thus improving the reliability of the results and of the cross-check validation with NEODyS and ESA.

Annual Report 2021/2022
IAU Division A Working Group
Astrometry by Small Ground-Based Telescopes

Chair	Anatoliy Ivantsov
Co-Chair	Marcelo Assafin
Members	Alexandre Humberto Andrei,
	Jean-Eudes Arlot,
	Goran Damljanovic,
	Christine Ducourant,
	Charlie Thomas Finch,
	Wenjing Jin,
	Nadiia Maigurova,
	Jose L. Muinos Haro,
	Dan Pascu,
	Thierry Pauwels,
	Yuri Protsyuk,
	Olexander Shulga,
	Richard Smart,
	Jean Souchay,
	Magdalena Stavinschi,
	Zheng Hong Tang,
	Francois Taris,
	Ramachrisna Teixeira,
	William Thuillot,
	William Van Altena,
	Roberto Vieira Martins,
	Norbert Zacharias

Jean-Eudes Arlot (IMCCE, Paris Observatory, France) reports on the observation of mutual events of the Galilean satellites which provide high-quality data allowing to reach an unprecedented resolution in the satellites' dynamical models. A worldwide campaign of observations of the mutual events of the Galilean satellites was conducted by IMCCE, Paris, France and Sternberg Astronomical Institute, Moscow University, Moscow, Russian Federation in 2021. The magnitude of the Galilean satellites is sufficiently bright to allow observations with very small telescopes that increases the possibility of their observations. 37 observers from 18 different sites of observation observed 85 phenomena in spite of many difficulties: the campaign must be conducted only during the occurrence of the events (when the Earth and the Sun pass through the equatorial plane of Jupiter) and during the opposition of Jupiter as seen from the Earth. Unfortunately, the maximum of events occurred during the conjunction of Jupiter with the Sun. A publication of the results is in preparation.

Jean-Eudes Arlot reports on the ongoing digitizing project of photographic plates at IMCCE, Paris Observatory, France. From 1890 to 1990, astronomical observations were taken mostly using photographic plates at small telescopes with apertures from 30 cm-refractors to 2 m-telescopes. The project will consider some of these plates, reduction of them using new accurate star catalogues such as GAIA for astrometry, so it will be possible to measure the past observations with today's accuracy. The works conducted at the present time are related to natural satellites astrometry and Be stars spectroscopy.

Marcelo Assafin and Roberto Vieira-Martins report on the astrometric and photometric use of the T0.6m and T1.6m telescopes at the Observatorio do Pico dos Dias (OPD), Brazil. Dozens of nights at each telescope were used to observe small bodies, mostly TNOs, dwarf planets and natural satellites of Jupiter and Uranus, but also Jupiter Trojan asteroids. TNO observations were dedicated for the prediction and observation of stellar occultations. The Uranus system was observed with the technique of mutual approximations between the main satellites (Santos-Filho et al., 2019). Astrometry of Jupiter irregular satellites was also made. They attempted also observation of all 15 mutual events of the Galilean satellites plus Amalthea and Thebe that were visible at OPD for the 2021 season.

Charlie Thomas Finch (U.S. Naval Observatory, USA) reports that astrometric and photometric observations continue with the Deep South Telescope (DST) after a long pause in 2020 due to the COVID-19 pandemic with 10,298 exposures taken in 2021. The main goal is to monitor a select list of extragalactic celestial reference frame sources (AGN, QSOs) in hopes of better understanding the radio-optical position offsets. The principal instrument (Sophia 4K CCD) has been down for repairs and a stop gap CCD camera (Marana) has been installed. The Sophia 4K is planned to be reinstalled on DST within a few months. An IR camera is planned for the optical IR port on DST supporting an ICRF photometric characterization and monitoring effort, as well as southern-sky priorities for infrared-bright objects. A USNO Bright Star Catalog paper has been submitted to the Astronomical Journal using data obtained from both the USNO Robotic Astrometric Telescope (URAT) and UBAD project using the 1.55-meter telescope at the Naval Observatory Flagstaff Station.

Thierry Pauwels and Peter De Cat (Royal Observatory of Belgium, Belgium) report that in 2017 the dome of the Ukkel Schmidt Telescope (main mirror 1.2 m, diaphragmed to 85 cm) has been restored, and during that period no observations were possible. After the telescope was available for observations again, the number of still to be discovered asteroids in the range of our equipment (mag limit 20-20.5 in the best case) had decreased too much to justify the cost of the maintenance and to motivate the observers. There are no plans for the moment to resume the observations. They provided a summary of the achievements of the RUSTICCA project (Revalorising the Ukkel Schmidt Telescope by Installing a Ccd CAmera), which started in 1993, and was operational 1996—2016. 24531 astrometric positions of asteroids and 71 astrometric positions of comets have been published in the MPCs, with a few hundred still waiting to be published. 217 asteroids, including 1 PHA and 3 Trojans, have been discovered by the equipment, with another 10-20 on the waiting list to be recognized as such. 300 astrometric positions of minor planets (NEOs) and comets have been published in the Minor Planet Electronic Circulars. Also, 29 light curves of mutual phenomena of the Galilean satellites of Jupiter (1997, 2003, 2009, 2014, and 2015), and 9 light curves of mutual phenomena of an asteroid and its satellite (2006—2008) have been recorded, and precise timings of disappearance and reappearance of 8 stellar occultations by asteroids have been derived. In total, the archive contains 30967 images and films.

William Thuillot (IMCCE, Paris Observatory, France) reports on the activity related to astrometry by small ground-based telescopes, focused on monitoring Gaia alerts for solar system objects (SSOs). As soon as Gaia detects an uncatalogued mobile source, an alert is triggered via a public website to the Gaia-FUN-SSO network. At the time of writing, about 300 uncatalogued SSOs, either newly detected or with imprecise orbits, have been observed and their astrometry provided to the IAU Minor Planet Center. These observations were made by telescopes of one meter diameter or less at the Las Cumbres Global Telescope, Observatoire de Haute-Provence, C2PU at Calern-OCA, Terskol, Kyiv Comet Station, Odessa-Mayaki, Abastumani (Carry et al., 2021).

The Working Group besides Division A and Division B is supporting the IAU Focus Meeting 10 "Synergy of Small Telescopes and Large Surveys for Solar System and Exoplanetary Bodies Research", https://iaufm10.org, to be held at the XXXI IAU General Assembly in Busan, Republic of Korea on August 2-22, 2022. The SOC is comprised of three members of this WG (Marcelo Assafin, Anatoliy Ivantsov and William Thuillot).

Concluding Remarks

Small telescopes with apertures less than 2 m are still useful for getting accurate astrometric measurements of Small Solar System Bodies, natural satellites and extragalactic sources either through direct imaging or using photometric measurements of mutual events. The Working Group is actively facilitating the exchange of information, coordination of campaigns and setup of telescope networks. Further details are provided on the continuously updated webpage at https://iau_wgnps.imcce.fr.

Anatoliy Ivantsov & Marcelo Assafin
Chair & Co-Chair of Working Group

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IAU Working Group on Multi-waveband ICRF

Annual Report 2021-2022

P. Charlot

1. Formation of the working group

A new Division A working group entitled “Multi-waveband ICRF” has been established in 2021. This working group takes over two former working groups: (i) the working group on the “Third Realization of the International Celestial Reference Frame (ICRF3)”, terminated in 2018 with the realization and adoption of the ICRF3 (IAU Resolution B2, 2018), and (ii) the working group entitled “Multi-waveband realizations of the International Celestial Reference System (ICRS)”, terminated in 2021 after the adoption of the Gaia-CRF3 as the optical realization of the ICRS (IAU Resolution B3, 2021).

The objective of the new working group is to work toward the realization of a fully integrated multi-waveband celestial reference frame, incorporating positions in both radio and optical bands and ensuring their consistency over the various bands. Membership was established by assembling the expertise considered necessary to reach this objective, covering a wide-range of topics, from VLBI and Gaia to reference frames and active galactic nuclei. The working group comprises 18 members[1] coming from 14 institutions in 10 different countries. An overview of the work to be performed is given below.

2. Description of activities

The end goal of the working group will be to produce the next generation VLBI frames at the S/X, K, and X/Ka bands, or at any other radio band that may emerge in the coming years, to match these with the optical realization from the Gaia space mission, and to place all such positions on a common grid guaranteeing consistency of the source positions over the different bands comprised in the frame. Before this can be accomplished, a number of questions relating to the construction of such a multi-waveband frame are to be addressed. In particular, specific attention should be given to the following issues:

- **Sky distribution**
  Having a uniform distribution of sources over the celestial sphere and a uniform distribution of coordinate uncertainties is essential to limit deformations of the individual frames produced in each waveband and to properly align these on a common grid. While such properties are largely verified for the Gaia optical frame, that is less true in the radio band with ICRF3 showing a deficiency of sources in the south and asymmetries in the coordinate uncertainties. Correcting this non-uniformity goes through increasing VLBI observing in the southern hemisphere.
- **Galactic acceleration**
  The acceleration of the solar system in its motion around the Galactic center, with an amplitude of about 5 μas/yr, is now seen from the VLBI and Gaia measurements and has been integrated into the realization of ICRF3 and Gaia-CRF3, albeit with a slightly different amplitude value. As data accumulates, present estimates of this amplitude will further improve and the data will also determine precisely the direction of the acceleration vector. In order to ensure consistency, it is mandatory that Galactic acceleration is modeled identically in the radio and optical bands, adopting the most accurate vector determination (whether from Gaia or VLBI) for this purpose.

[1] The members are: Sonia Anton, Felicitas Arias, Patrick Charlot (Chair), Alet de Witt, Bryan Dorland, David Gordon, Robert Heinkelmann, Christopher Jacobs, Sergei Klioner, Hana Krásná, Sébastien Lambert, Lennart Lindegren, Valeri Makarov. Zinony Malkin, François Mignard, Elena Skurikhina, Jean Souchay, and Oleg Titov.

- **Alignment of frames**
  There is not a single way to align reference frames produced independently at different bands or with different techniques. Whether only rotations or both rotations and deformations should be considered in the alignment process, whether individual source positions should be given equal weights or weighted separately, whether all sources or only a subset of them (e.g. the so-called defining sources in the successive ICRF realizations) should be considered, is a matter of debate. In this respect, the working group should establish a common practice, to be applied for generating the proposed multi-waveband realization and any other future realizations.
- **Wavelength- and time-dependent source positions**
  The process to align reference frames at different bands may be further affected by wavelength-dependent source positions. Comparing radio and optical positions shows that these do not coincide for a significant portion of the sources. Even within the three radio bands, positions are found to differ for a fraction of the sources. Additionally, positions may show instabilities with time, as revealed by VLBI time series, and this may also be the case on the optical side when position time series are released by Gaia. In this context, the working group should propose a scheme to deal with this frequency dependence and time variability of the source positions in the alignment process.

3. Terminology

Besides constructing the frame, the working group will also work towards defining a proper terminology for referring to the individual (per wavelength) components of the multi-waveband frame. For historical reasons, the ICRF terminology, though not attached specifically to the radio band, has been associated with the VLBI realizations, simply because there was no other technique with similar capabilities until the advent of Gaia. Whether keeping this terminology, incorporating the Gaia optical realizations, or whether a new one should be defined, is a matter of debate and agreement within the community.

4. Timeline

The projected timeline for the work anticipates that the issues relating to the construction of the frame (as described above) would be addressed by the end of this triennium (2024), while the foreseen multi-waveband celestial reference frame would be generated in the period from 2024 onwards,

IAU Standards of Fundamental Astronomy (SOFA)
Annual Report 2021

SOFA Board/Working Group Members

John Bangert	United States Naval Observatory, retired
Steven Bell	HM Nautical Almanac Office, UKHO (Webmaster)
Nicole Capitaine	Paris Observatory
Maria Davis	US Naval Observatory (IERS)
Mickaël Gastineau	Paris Observatory, IMCCE
Catherine Hohenkerk	HM Nautical Almanac Office, retired (Chair)
Li Jinling	Shanghai Astronomical Observatory
Zinovy Malkin	Pulkovo Observatory, St Petersburg
Jeffrey Percival	University of Wisconsin
Wendy Puatua	United States Naval Observatory
Scott Ransom	National Radio Astronomy Observatory
Nicholas Stamatakos	US Naval Observatory
Patrick Wallace	RAL Space, retired
Toni Wilmot	HM Nautical Almanac Office (Trainee)

SOFA is a Functional Working Group of Division A. The IAU SOFA service continues its task of establishing and maintaining an accessible and authoritative set of algorithms and procedures that implement standard models used in fundamental astronomy. This is achieved via the expertise of Board members and the SOFA website (www.iausofa.org).

Currently SOFA is in a "maintenance" mode. However, during 2021 there were two major releases and one minor release. The latest release, on 2021 May 12, was the unified eighteenth release, a major release that added three new routines, two in the astrometry category, and an approximate lunar ephemeris routine to the ephemerides category. Currently the collection consists of an ANSI C and a Fortran library made up of 192 astronomy routines of which 59 are canonical that realise IAU standards. There are also 55 utility routines dealing with vectors, matrices, and angles, making a total of 247 routines.

The previous major release, the unified seventeenth release (2021 January 25), added extra defensive precautions when computing astronomical refraction at low altitudes, and μarcsecond-level improvements to the handling of polar motion, which is now rigorous. A very rare problem, which to some extent was dependent on compiler behaviour and rounding was found with the routine dealing with leap seconds during the period 1960 to 1971 before leap seconds were introduced. This issue was corrected in the minor release 17a. SOFA is grateful to the Astropy group for reporting this issue and to all users for their comments and suggestions. Many miscellaneous typographical corrections and improvements to the Cookbooks and other documents were also made. Technical queries from users still occur, which were answered by Patrick Wallace.

Statistics concerning the use of SOFA has been missing in recent years due to system changes at SOFA's host organisation. However, we now have some access to some data. For the current release 936 users had registered and were informed of the 18th release. These libraries have been downloaded 3639 times, 63% ANSI C and 37% Fortran. This is an increase on the 2018 figures. It is both individual users and system managers who are installing either or both libraries on their computers. These figures do not give a measure of those who use the SOFA website to download a particular Cookbook or study an individual routine to better understand the algorithms and processes involved. There are also many users of the SOFA software via other implementations, Java from Jodrell Bank Centre for Astrophysics and C# available from the World Wide Astronomy library, and the Essential Routines for Fundamental Astronomy (ERFA) version that is bundled with Astropy in Python. We encourage all our users to acknowledge their use of SOFA.

The International Earth Rotation and Reference Systems Service (IERS) representative, Brian Luzum, has stepped down from the Board. We thank Brian for some 14 years of service to SOFA. We welcome Maria Davis of US Naval Observatory, who replaces Brian as the IERS representative. The SOFA Board also needs a new Chair to take SOFA forward.

Finally, we acknowledge and thank the members of the Board and their institutes. The Board thanks the United Kingdom Hydrographic Office for hosting the SOFA website. We also thank our users; in particular for reporting issues and making suggestions.

Catherine Hohenkerk
Chair IAU SOFA Board
2022 March 18

INTERNATIONAL ASTRONOMICAL UNION
DIVISION A AND F / WORKING GROUP
CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS

MEMBERSHIP B. A. Archinal (Chair), A. Conrad (Vice-Chair), C. H. Acton, T. Duxbury, D. Hestroffer, J. L. Hilton, L. Jorda, R. L. Kirk, S. A. Klioner, J.-L. Margot, J. Oberst, F. Paganelli, J. Ping, P. K. Seidelmann, D. J. Tholen, I. P. Williams

REPORT TO IAU FOR 2021-2022

1. Introduction

The main activity of the IAU Working Group on Cartographic Coordinates and Rotational Elements (hereafter, WG) is to make recommendations regarding the creation and maintenance of cartographic planetary coordinate systems. The agreed-upon recommendations are produced roughly in conjunction with each IAU General Assembly and are published as a report in the journal *Celestial Mechanics and Dynamical Astronomy*. Our most recent main report was published in February 2018 (Archinal et al., 2018) with corrections published in 2019 (Archinal et al., 2019).

We are beginning work to compile the next version of that report. We expect routine updates (Archinal and WGCCRE, 2021a and 2021c) to recommended orientation and size models resulting from processing or reprocessing of various planetary datasets, e.g., with improvements possible for various bodies such as Mercury, Venus, Jupiter, Saturn, the Saturnian satellites, Ceres, 67P/Churyumov–Gerasimenko, Arrokoth, Bennu, and Ryugu.

Although lunar ephemerides currently seem to provide the orientation of the Moon with an accuracy of a few meters, improved ephemerides solutions continue to be made based on new lunar laser ranging (LLR) from various groups, and recommendations have been made to NASA to update the lunar reference frame in preparation for upcoming missions (Joint LEAG-MAPSIT SAT, 2021). Therefore, changes in the lunar orientation model should be considered. Another issue is whether to finally base the mean Earth/polar axis lunar frame directly on a no-net rotation-based LLR solution for retroreflector coordinates rather than on a specific lunar ephemeris as is done currently. An abstract on this topic has been submitted to the upcoming Planetary Science Informatics and Data Analytics Conference (Archinal and WGCCRE, submitted).

For Mars, the orientation model previously recommended by the WG could be updated to a newer model. However, a separate issue is that the new models seem to have a ~100 m offset in longitude at the fundamental epoch of J2000.0 relative to the previous recommended system. Clarification is needed as to the cause of this offset and a decision must be made based on community input as to whether some correction in longitude is needed in these newer models.

2. Membership

The WG currently consists of 16 members from 5 countries, with membership lengths from 4 to 46 years. Brent Archinal (U. S. Geological Survey) serves as the current Chairman, and Al Conrad (Large Binocular Telescope Observatory) serves as the Vice-Chairman. The WG began operation in 1976. In recognition of the continued need for the WG, in 2016 it became a “Functional Working Group" of the IAU, with an institutional scope and purpose in providing a service that naturally extends beyond the IAU triennial cycle (IAU Exec. Committee, 2016).

The WG is always looking for volunteers to join, particularly to help with each new report. Our membership is open to all who wish to help with our work. Some individuals have recently expressed an interest in joining the WG and we plan to follow up with them and others likely interested, but additional members are welcome. This will help to increase our membership, expertise, and available time to work on our main report and community inquires.

3. Community Inquiries

The WG Chair and many of the WG members spend significant time answering questions from NASA, missions, mission instrument teams, journal editors, individual researchers, and the public, on various issues related to planetary coordinate systems. Because of new data and improvements in data returned from active missions, there are ongoing questions about the coordinate systems for the Moon and Mars, and other questions from various NASA Planetary Data System personnel. Some of our members have provided information to international archiving organizations such as ESA's Planetary Science Archive, JAXA's and IKI's archiving arms, as well as the International Planetary Data Alliance; and to planning organizations such as the NASA Mapping and Planetary Spatial Infrastructure Team (MAPSIT) advisory group. The WG cooperates with other IAU components, such as IAU Commission A1 Astrometry and the X2 Cross-Division A-F Commission Solar System Ephemerides. More frequently relative to coordinate system issues, WG members also have been asked to review papers and plans for data archives.

4. Concern About Support as a Functional WG

In recent years the WG has been concerned that it is becoming overextended, particularly due to the greatly increasing number and complexity of community inquiries. The time needed to respond to such inquiries have resulted in delays of our most recent reports relative to the preferred triennial schedule of IAU activities. We plan to address this partly by increasing membership, especially as experienced personnel retire and are not replaced. However, it also may be necessary to consider whether an actual service (perhaps analogous to the International Earth Rotation and Reference Systems Service, even if not initially at the same scale) is needed to perform some of the community support functions of the WG. One of us (Archinal) receives NASA funding for a portion of his work, but it may be necessary to seek additional funding and help in planning, perhaps from sources such as international space agencies, to continue to address community requests and increased demands for input. The WG is considering these issues, but community input is welcome as we proceed. A discussion of the overall issues involved has been presented as input to the NASA Planetary Science and Astrobiology Decadal Survey (Paganelli et al., 2020) and at other venues (Archinal and the WGCCRE, 2020a, 2020b, 2021a, 2021c; Archinal et al., 2020).

5. Publications and Meetings

The WG has continued to make its efforts and activities known via its website (https://astrogeology.usgs.gov/groups/IAU-WGCCRE) and by various publications and community presentations. Specifically:

- We will continue to publish our main report to the planetary community, to be published approximately triennially, following each IAU General Assembly. Since our previous report was delayed, and due to delays due to pandemic issues, we tentatively plan to issue our next report in late 2022. A separate triennial report on our activities is also prepared for the IAU (Archinal et al., 2021).
- The WG will make brief annual reports such as this to the IAU and Divisions A and F on our activities. We are also willing to continue to make oral reports at the General Assembly Division meetings, such as in 2021 for Division F (Archinal and the WGCCRE, 2021b).
- To make our work better known and encourage adherence to the recommendations in our main report, we will continue to submit abstracts to and make presentations at various planetary science meetings, describing the activities of the WG and our reports. See the various references here for examples of those submissions and presentations.

- Members of the WG and others, such as from the ICA Commission on Planetary Cartography, have worked to make our recommendations more accessible via software packages and other standards (Hare et al., submitted).

6. Closing remarks

We plan to complete a new version of our main report by late 2022. We will continue to address questions from the planetary community regarding planetary coordinate system issues and continue to further increase community awareness of our work with abstracts and presentations at appropriate scientific meetings. Inquiries from the community have increased greatly in recent years from individuals, editors, instrument teams, missions, and space agencies. We expect to accommodate this increased workload in part by moving forward with an increased WG membership.

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IAU Near-Earth Object Working Group
Inter-Division A-F, Functional
Annual Report 2021-2022

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The NEO Working Group is a functional inter-Division A-F WG. It continues its task of monitoring and participating to the international activities focused on planetary defense, of representing the IAU in international groups, such as the UN-endorsed International Asteroid Warning Network (IAWN; see: https://iawn.net). It also highly contributes to public outreach efforts, noting that NEOs and planetary defense are of high interest for the public.

In 2021, the Planetary Defense Conference took place virtually on April 26-30, hosted by the United Nations Office of Outer Space Affairs (UNOOSA). Over 900 individuals registered, and total attendance included over 700 individuals, with 250 to 300 individuals participating at any given time. As described in the report of the conference (https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf), a primary outcome of the conference was unanimous attendee support for an International Year of Planetary Defense (formal name to be defined) similar to the 2009 International Year of Astronomy. The 2029 close passage of Apophis is a natural opportunity to hold the event, raise awareness about the hazard, demystify the topic, and connect current and future communities. A group has been set up to make a proposal to the UN. Also, a highlight of the conference was the Asteroid Threat Exercise. As in several previous conferences, the purpose of the asteroid threat exercise for the 2021 conference was to acquaint conference participants and decision-makers with an asteroid threat representative of the type of threat that might be possible given limitations of current discovery capabilities. The conference was then organized around several sessions covering all the topics that are relevant to planetary defense, such as the NASA mission DART that will perform the first asteroid deflection test and will carry the ASI Cubesat LICIACube to observe the impact and its early effects, the ESA Hera mission that will study the long term effects of the DART impact, results from the JAXA Hayabusa2 and NASA OSIRIS-REx missions, NEO discoveries and characterization, deflection and disruption testing, mission and campaign design, impact effects, disaster management, the decision to act, public education and communication, Apophis and others, far and near: future characterization opportunities from NEO close approach.

Highlight lectures were also given at the International Astronautical Congress (IAC) in Dubai, in October 2021, concerning the results of OSIRIS-REx and Hayabusa2. The Hayabusa2 Team was awarded the IAF World Space Award. A planetary defense special session took place titled: The Grand Planetary Defense DART/HERA missions Interactive Q&A.

The IAWN and Space Mission Planning Advisory Groups met three times, in March and October 2021, as well as in February 2022. They cover a wide range of activities, related to observations of NEOs, space missions and also legal aspects. Reports of IAWN meetings can be found here: https://iawn.net/meetings.shtml, while reports of SMPAG meetings can be found here: https://www.cosmos.esa.int/web/smpag.

2021 once again saw an increase in the discovery rate of NEOs, with a record 3090 new objects being found and having good enough orbits for provisional designations to be assigned. Although most were discovered by the big 3 surveys (PanSTARRS, Catalina and ATLAS), over 200 were found by smaller discovery efforts.

The science of NEOs also made amazing advances thanks to the different publications concerning the asteroids Bennu and Ryugu, from OSIRIS-REx and Hayabusa2 data, respectively. Both asteroids are of carbonaceous type, and one of the great discoveries is that they behave almost like cohesionless bodies, as demonstrated by the Hayabusa2 impact experiment that produced a gravity-controlled crater and the sampling mechanism (TAGSAM) of OSIRIS-REx that felt almost no resistance of the soil. This information is crucial in the framework of deflection missions. Furthermore, a preliminary investigation of samples of Ryugu brought back by Hayabusa2 showed that the density of the samples (about 1.3 g/cc on average) is much lower that the density of meteorites of the same group. Compared to the bulk density of Ryugu (1.19 g/cc), if the density of samples is representative of the density of Ryugu's material, this tells us that most of the porosity of Ryugu is microporosity and not macroporosity, which has different implications on how to deflect such a body.

One amazing highlight of 2021 is the launch of the NASA DART mission at 1:21 a.m. EST on November 24, from the Vandenberg Air Force base (California) onboard a SpaceX Falcon 9 rocket. This marvelous launch will be followed by the impact of DART on Dimorphos, the small moon of the binary asteroid Didymos, on September 26, 2022, at 6:15 pm EST. Before doing so, DART will deploy the Italian LICIACube, which will observe the impact and the minutes following it, giving us previous data on the impact and its early ejecta. On October 2024, the ESA Hera spacecraft with its two Cubesats Juventas and Milani will launch to get to Didymos at the end of 2026, providing us detailed measurements of DART impact outcome and full characterization of the asteroids, including for the first time subsurface and internal properties. The Asteroid Impact & Deflection Assessment (AIDA) international collaboration, which supports the development and data interpretation of DART and Hera, will then provide a fully documented impact experiment and deflection test at actual asteroid scale, including the impact conditions provided by DART and LICIACube, the ejecta properties provided by LICIACube, the change in the orbital period of Dimorphos provided by ground based observation, and the full characterization of the DART impact outcome and target properties by Hera and its two Cubesats.

The NEO Surveyor mission is also in development at NASA for a possible launch in 2026. It will allow making the inventory of NEOs larger than 140 meters (including direct measurement of their diameter) in about 10 years for space and therefore assessing the threat of such objects on a short-middle timescale. Other funded NEO missons include the extension of Hayabusa 2 to a flyby of 2001 CC21 in 2026 and a rendezvous with the 60-meter-sized NEO 1998 KY26 with a 10 mn spin rate in 2031, and the Destiny+ mission to the active NEO 3200 Phaethon. At an early stage of development, the NEOMIR concept is being studied at ESA. This mission survey mission would overlap with NEO Surveyor but be targeted at smaller solar elongations.

In Europe, the European Union and its Horizon 2020 program is funding two projects in the time frame 2020-2023: NEO-MAPP (Near Earth Object Modelling and Payload for Protection) that supports activities related to the Hera mission and future NEO missions (see: https://neomapp.eu) and NEOROCKS that performed studies oriented on ground based observations and characterizations of NEOs and impact predictions (see: https://neorocks.eu).

In 2022, several workshops and meetings are taking place that are relevant to NEO and planetary defense activities:

- The Apophis T-7 workshop is taking place on May 11-13, 2022 virtually and will present the activities related to this asteroid, as well as possible space mission projects (see: https://www.hou.usra.edu/meetings/apophis2022/).

- The Hera international workshop is taking place on May 30-June 3, 2022, in Nice (France) and will give an overview of the various activities and their advances regarding this mission (see: https://www.heramission.space/heraworkshop2022).

- The IAU Symposium S374 Astronomical Hazards for Life on Earth will be held at the XXXI IAU General Assembly in Busan, Republic of Korea, in the week of August 8-11, 2022 (see: http://hazards.astronomia.edu.uy)

- The IAU Focus Meeting 8 Planetary Astronomy via Telescopic and Microscopic Approaches will also be held at the XXXI IAU General Assembly in Busan, Republic of Korea, on August 2-11, 2022 (see: https://iau2021fm8.kasi.re.kr).

- A Planetary Defense session is organized at the European Planetary Science Congress (EPSC) 2022 on September 18-23, in Grenada (see: https://meetingorganizer.copernicus.org/EPSC2022/session/44648).

- A Plenary Session on Planetary Defense has been proposed for the IAC 2022 in Paris on September 18-23 (see: https://iac2022.org).

NEOs and Planetary Defense are active areas of research, and we are looking forward to the DART impact that will take place in this year.

Patrick Michel
On behalf of the NEO WG.

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IAU Division A Working Group on Time Metrology Standards
Annual Report 2021-2022

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Report

Administration

The WG TMS has 18 members and one associate. No changes in the membership occurred in the period. Communication between the members has been by e-mail only.

The future of Coordinated Universal Time (UTC)

Resolution 655 of the World Radiocommunication Conference 2015 (WRC-15) invited the relevant international organizations and scientific associations to cooperate submitting results of studies on the possible implementation of a continuous time scale. Work progressed at the Working Party 7A of the International Telecommunication Union – Radiocommunication Sector (ITU-R) on the establishment of a report on the "Content and structure of time signals to be disseminated by radiocommunication systems and various aspects of current and potential future reference time scales, including their impacts and applications in radiocommunication". The outcome of this document, will be included in a report of the Radiocommunication Bureau at the Word Radiocommunication Conference 2023.

The Working Group worked on the preparation of the texts concerning the use of UTC in astronomy, its relation to UT1 and the impact of a possible change in the definition that would make UTC continuous, at least for a long period of time. This contribution has been included in the version of the report to be discussed the meeting of the ITU-R WP7A in May 2022.