

DIVISION A AND F / WORKING GROUP CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS

MEMBERSHIP

B. A. Archinal (Chair), A. Conrad (Vice-Chair),
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

TRIENNIAL ACTIVITIES REPORT TO THE IAU FOR 2021–2024

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 and frames. The agreed-upon recommendations are produced approximately 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).

2. Main Report

Our efforts to compile the next version of that report have progressed more slowly than we would like. During 2023 and early 2024 this was due to our work to provide information on the cartographic lunar reference frame, as described below. However, we plan to return to doing our main report in 2024. We expect to include routine updates (Archinal and WG, 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, the Moon, Mars, Jupiter, Saturn, the Saturnian satellites, Ceres, 67P/Churyumov–Gerasimenko, Arrokoth, Bennu, and Ryugu. We also expect to clarify the (geodetic) usage of the terms “system” and “frame” and comment further on the usage of planetographic vs. planetocentric coordinates.

Lunar Cartographic Coordinates Overall: Starting in 2023 March, we began hearing from various personnel at the U. S. National Geospatial–Intelligence Agency (NGA) and NASA, that they and others from ESA were planning to use a principal axis (PA) system-based reference frame for the Moon as part of their work to develop a lunar reference system (Garner, 2022). We are not aware of any published proposals or explanation for such an action, although Gramling (2023) did indicate the PA system would be used for the proposed LunaNet navigation system. Such a change would not follow past practice where all lunar cartographic products throughout history have always been placed in a mean Earth/polar axis (ME) system reference frame, as previously recommended by the WG. The maximum difference between the two systems amounts to a quite significant 875 meters on the lunar surface. We have communicated with those involved to try to understand their plans and rationale for such a change. The WG has presented at four different meetings on this topic (Archinal and WGCRE, 2023b, 2023c, 2024; Archinal et al., 2023b). Archinal was also asked (independent of the WG) by the NASA Lunar Exploration Analysis Group to lead a white paper on this topic (Archinal et al., 2023a). We have recommended that a description of the desired changes and the need for them be published so they could be considered by the international lunar community. We are concerned about such a large change and hope that it could be avoided. If it moves forward, such a transition would require many, if not all, existing lunar data and mapping products to be converted at great cost in both funding and personnel time, with no improvement to the fundamental quality of the

products. Alternatively, its possible products could remain in the current coordinate system. Significant confusion could arise (including for navigation near the lunar surface) due to the likely resulting simultaneous use of the two systems. We are aware that in 2023 November the NASA Planetary Science Advisory Committee recommended (PAC, 2023) the continued use of the ME system for mapping, following the recommendations of Archinal et al. (2023a). The NASA Federated Board has also created a working group to consider this issue by 2024 May. (Ferguson, 2024).

Lunar Cartographic Coordinates Update: Meanwhile, the WG has been considering whether an update should be made to our recommendations regarding lunar orientation. There have been various recommendations (e.g., by the Artemis III Science Definition Team (2020), the Joint LEAG–MAPSIT SAT (2021), and the LEAG white paper (Archinal et al., 2023a)) to make an update based on a newer Jet Propulsion Laboratory (JPL) lunar ephemeris, and in preparation for upcoming missions. Abstracts and presentations on this topic have been made by the WG (Archinal and WGCCRE, 2022, 2023a, 2023b, 2023c, 2024; Archinal et al., 2023b). Such a change would result in an approximately meter level change in lunar coordinates, approaching the pixel scale of nearly all published data sets.

Mars Orientation Update: For Mars, the orientation model currently recommended by the WG (based on Kuchynka et al. (2014)) could be updated to a newer model based on Konopliv et al. (2016), or that of Yseboodt et al. (2023). However, a separate issue is that these models appear to have an offset (at least in Mars longitude at J2000.0) of about 100 m from what the WG had previously recommended (Archinal et al., 2011). Separately from the WG, D. Mayer and Archinal (of the USGS) have been looking into this issue and are in contact with the authors of Yseboodt et al. in order to consider whether a longitude correction is needed and if so of what size. Once some path forward is identified, it could be considered for recommendation by the WG.

Given the importance and urgency of updating both the lunar and Mars orientation models, the WG may consider separately publishing an abbreviated “main” report addressing those models, and then returning to doing a longer main report covering the rest of the Solar System.

3. Membership

The WG began operation in 1976. In recognition of the continued need for the WG, it became a “Functional Working Group” of the IAU in 2016, with an institutional scope and purpose in providing a service that naturally extends beyond the IAU triennial cycle (IAU Executive Committee, 2016). The WG currently comprises 15 members from 5 countries, with membership lengths from 6 to 48 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 is always looking for volunteers to join, particularly to help with each new report. Some individuals have expressed an interest in joining the WG, but we have been delayed (and apologize to them for those delays) in having them join the WG. After this report is prepared, we plan to follow up with those who have inquired about membership. However, additional members are also welcome. Our membership is open to all who wish to help with our work. We hope to increase our membership, expertise, and available time to work on our main report and respond to community requests and inquiries.

4. Community Inquiries

The WG Chair and many of the WG members spend significant time answering questions from NASA, the NASA Planetary Data System, missions, mission instrument teams, journal editors, individual researchers, and the public, on various issues related to planetary coordinate systems. As already noted, there are ongoing open questions about the coordinate systems for the Moon and Mars. Some of our members have provided information to international archiving organizations such as the European Space Agency’s Planetary Science Archive, the Japan Aerospace Exploration Agency’s and Russian Space Research Institute’s archiving arms, as well as the International Planetary Data Alliance. We have also provided information to planning organizations such as the NASA Mapping and Planetary Spatial Infrastructure Team (MAPSIT) analysis group. The WG cooperates with other IAU components, such as IAU Commissions A1 Astrometry and A3 Fundamental Standards and the X2 Cross-Division A–F Commission Solar

System Ephemerides. We have also interacted in the past with the International Association of Geodesy (IAG) of the International Union of Geodesy and Geophysics. WG members also have often been asked to review papers and plans for data archives regarding coordinate system issues.

5. Concern About Support as a Functional WG

We repeat our past comments, in that in recent years the WG has been concerned that it is becoming over-extended, 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 have (as noted above) planned to address this partly by increasing membership, especially as experienced personnel retire. However, it also may be necessary to consider whether an actual service (perhaps analogous to the International Earth Rotation and Reference Systems Service) 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 for the WG to seek additional support, perhaps from other 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).

6. Publications and Meetings

The WG has continued to make its efforts and activities known via its website (<https://www.usgs.gov/centers/astrogeology-science-center/science/iau-wgocre>) and by various publications and community presentations. Specifically:

- In 2024 we plan to publish our main report to the planetary community, or as noted above publish an interim report with lunar and Mars orientation recommendations and then our main report in 2025.
- 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) and in 2022 for Division A, and have submitted an abstract for the 2024 meetings (Archinal and the WGCCRE, 2024b).
- 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 herein for examples of those submissions and presentations.
- The WG has collaborated on and supported a proposal for an IAU Symposium in 2025 on Advancing Reference Systems, Ephemeris, and Standards which will provide an opportunity for a focused discussion and agreement on lunar, Mars, and other planetary reference system recommendations moving forward.

7. Closing remarks

Our highest priority is to add new members and complete the next version of our main report. 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. However, we are open to and see a need to consider other possibilities regarding the long-term operation of the WG, such as some new organizational structure with a similar purpose.

References

- Archinal, B. A. et al. (2011). “Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009,” CMDA 109, 101–135, <https://doi.org/10.1007/s10569-010-9320-4>.
- Archinal, B. A., et al. (2018). “Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015,” CMDA, 130, 22, <https://doi.org/10.1007/s10569-017-9805-5>.
- Archinal, B. A., et al. (2019). “Correction to: Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015,” CMDA, 131, 12, <https://doi.org/10.1007/s10569-019-9925-1>.
- Archinal, B. A., et al. (2020). “Coordination of Planetary Coordinate System Recommendations by the IAU Working Group on Cartographic Coordinates and Rotational Elements – Status and Future,” ISPRS Arch. Photog. Rem. Sen. & Spat. Inf., XLIII–B3–2020, 1091–1097, <https://doi.org/10.5194/isprs-archives-XLIII-B3-2020-1091-2020>.
- Archinal, B., and the IAU WGCCRE (2020a). “Update for 2020 from the IAU Working Group on Cartographic Coordinates and Rotational Elements,” LPS XI, Abstract #2385. <https://www.hou.usra.edu/meetings/lpsc2020/pdf/2385.pdf>.
- Archinal, B., and the IAU WGCCRE (2020b). “Planetary Coordinate System Recommendations by the IAU Working Group on Cartographic Coordinates and Rotational Elements Status and Future,” 43rd COSPAR Scientific Assembly, 2021 January 28–February 4, Sydney, Australia. <https://www.cospar-assembly.org/user/download.php?id=27192&type=abstract§ion=congressbrowser>.
- Archinal, B., and the IAU WGCCRE (2021a). “Coordination of Planetary Coordinate System Recommendations by the IAU Working Group on Cartographic Coordinates and Rotational Elements An Update,” 5th PDW and 2nd PSIDA meeting, June 28 July 2. <https://www.hou.usra.edu/meetings/planetdata2021/pdf/7051.pdf>. Video at <https://www.youtube.com/watch?v=ye0RJFULSgU>.
- Archinal, B., and the IAU WGCCRE (2021b). “Report from Working Group on Cartographic Coordinates and Rotational Elements,” presentation to the IAU Division F Planetary Systems and Astrobiology Business Meeting, August 24.
- Archinal, B., and the IAU WGCCRE (2021c). “International Coordination of Planetary Coordinate System Recommendations and the IAU Working Group on Cart. Coordinates and Rotational Elements,” Abs. of the Inter. Cart. Assoc., 3, 30th Inter. Cart. Conf., 1418 Dec, Florence, Italy. <https://www.abstr-int-cartogr-assoc.net/3/9/2021/>.
- Archinal, B., and the IAU WGCCRE (2022). “Lunar Reference Frame Status and Possible Updates,” Planetary Science Informatics and Data Analytics, June 21–23, Villanueva de la Cañada, Spain. Abstract and poster at <https://www.cosmos.esa.int/web/psida-2022/conference-programme> (last entry on page).
- Archinal, B., and the IAU WGCCRE (2023a). “Considerations On Updating the Lunar Reference Frame,” LPS LIV, Abstract #2305. Poster at <https://lpsc2023.ipostersessions.com/default.aspx?s=68-FA-6C-24-D5-C1-58-83-3A-BB-25-67-C9-C2-97-A6>.
- Archinal, B., and the IAU WGCCRE (2023b). “Updating the Lunar Reference Frame,” EGU General Assembly 2023, April 23–28, Vienna, Austria. Abstract #EGU23–9136. <https://meetingorganizer.copernicus.org/EGU23/EGU23-9136.html>.
- Archinal, B., and the IAU WGCCRE (2023c). “Lunar Reference Frame Considerations,” 6th Planetary Data Workshop, June 26–28, Flagstaff, AZ. <https://www.hou.usra.edu/meetings/planetdata2023/pdf/7095.pdf>.
- Archinal, B., et al. (2023a). “Continued Use of the Mean Earth Coordinate System for the Moon,” a white paper produced at the request of the NASA Lunar Exploration Analysis Group. https://www.lpi.usra.edu/leag/reports/ME-White-Paper_Final.pdf.
- Archinal, B., et al. (2023b). “The Cartographic Lunar Reference Frame,” Journees 2023: Time and General Relativity, September 11–12, Nice, France. Abstract <https://journees2023.sciencesconf.org/file/984838>. Paper submitted.
- Archinal, B., and the IAU WGCCRE (2024a). “Updating the Cartographic Lunar Reference Frame,” LPS LV, Abstract #1696, <https://www.hou.usra.edu/meetings/lpsc2024/pdf/1696.pdf>. Poster at <https://lpsc2024.ipostersessions.com/?s=3F-79-38-C5-7D-41-8F-C0-FE-9D-65-4C-35-45-0F-B2>.

- Archinal, B., and the IAU WGCCRE (2024b). “Report from the Division A & F Working Group on Cartographic Coordinates and Rotational Elements,” Division A and F sessions, IAU General Assembly, August 6–15, Cape Town, South Africa. Submitted.
- Artemis III Science Definition Team (2020). “Artemis III Science Definition Team Report: A Bold New Era of Human Discovery,” NASA/SP-20205009602, December 7. <https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf>.
- Ferguson, R. (2024). “Lunar Reference Frame Update,” MAPSIT Town Hall meeting, March 12. Slides no. 20-22 at https://www.lpi.usra.edu/mapsit/meetings/archive/mapsit_town_hall_2024-03-12_combined_reduced.pdf.
- Garner, T. (2022). “Developing a Lunar Reference System for Navigation Safety,” ION Int. Tech. Mtg., <https://www.ion.org/itm/abstracts.cfm?paperID=10769>.
- Gramling, C. (2023) “Defining a Global Lunar Position, Navigation, and Timing System,” oral presentation, Cislunar Security Conference.
- IAU Executive Committee (2016). “Summary of IAU Executive Committee Meeting in May 2016,” Available as <https://www.iau.org/static/archives/announcements/pdf/ann16029a.pdf>.
- Konopliv, A. S., et al. (2016). “An improved JPL Mars gravity field and orientation from Mars orbiter and lander tracking data,” *Icarus* 274, August, 253–260, <https://doi.org/10.1016/j.icarus.2016.02.052>.
- Kuchynka, P., et al. (2014). “New constraints on Mars rotation determined from radiometric tracking of the Opportunity Mars Exploration Rover,” *Icarus* 229, February, 340–347, <https://doi.org/10.1016/j.icarus.2013.11.015>.
- A Joint LEAG–MAPSIT SAT (2021). “Final Report of the Lunar Critical Data Products Specific Action Team,” September. Released 2022 January 11. https://www.lpi.usra.edu/mapsit/reports/leag_mapsit_report_2022-01-11.pdf.
- Planetary (Science) Advisory Committee (2023). “PAC Findings/Recommendations Meeting: November 13-14, 2023,” Finding 7, <https://smd-cms.nasa.gov/wp-content/uploads/2023/12/pac-findings-nov-2023-final.pdf>.
- Paganelli, F., et al. (2020). “The Need for Recommendations in Support of Planetary Bodies Cartographic Coordinates and Rotational Elements Standards,” submitted to the Planetary Science and Astrobiology Decadal Survey White Paper 2023–2032, <https://is.gd/WGCCRE2020wp>.
- Yseboodt, M., et al., (2023). “Mars orientation and rotation angles,” *CMDA*, 135, 50. <https://doi.org/10.1007/s10569-023-10159-y>,