SBN Coordinate System Guidelines

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Based on the 2014 SBN Coordinate Systems policy document by Michael F. A'Hearn, and with inputs provided by the SBN committee on coordinate systems: James Bauer, Tony Farnham, Ludmilla Kolokolova, Beatrice Mueller, Carol Neese, Eric Palmer, Nalin Samarasinha, Boris Semenov, and Tim Spahr.

1. Overview

In 2014, the PDS established a policy[1] requiring that coordinate systems used for PDS data archives must be defined and accepted by the International Astronomical Union (IAU), or follow the guidelines established by the IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE)[2]. The same year, working with the WGCCRE, the PDS Small Bodies Node (SBN) developed an SBN policy document[3] to help guide small bodies missions in meeting this policy, to specify how SBN expects the coordinate systems to be documented, and to provide some of the history behind the policy.

These policies and documents present a complex picture for missions trying to adhere to PDS policy while defining and documenting their coordinate systems. The purpose of this Guidelines document is to provide clear and simple guidelines and examples for the definition and documentation of small body coordinate systems for PDS archives, while referencing the applicable documents for full information. It is specific to SBN and to small bodies, which present unique challenges in the definition and documentation of coordinate systems. The intended audience includes small body mission archive teams, SBN personnel running coordinate system peer reviews and checking liens, and SBN peer reviewers.

“The coordinate system” referred to in this guidelines document, which is the subject of PDS policy and which is subject to peer review, is the body-fixed coordinate system tying the body surface latitudes and longitudes or other types of surface coordinates specified in the data or its metadata to specific points on the body surface. PDS has an interest in ensuring the useability of PDS-archived data, and in this interest places requirements on the coordinate systems (and their documentation) used in archived data. Data/metadata which don’t reference coordinates on the body surface can be archived without documentation of a coordinate system. Coordinate systems which are not used (or have not yet been used) to define the latitudes and longitudes in data to be submitted for peer review and archiving are not subject to the PDS policies and requirements described here.

We recognize the potential complications that can sometimes arise with defining and documenting a coordinate system meeting PDS requirements, and these cannot all be addressed in these guidelines. This document outlines the overall purpose of the coordinate system requirements and provides guidelines and examples for the most common cases. Data providers are encouraged to contact the SBN to resolve any concerns or questions.

2. PDS coordinate system peer review

To be used in PDS archived data, coordinate systems must meet two requirements: (a) that they conform to the PDS policy, and (b) that they are adequately documented. These two requirements are treated in more detail in sections 3 and 4.

If the coordinate system to be used in archival data is one explicitly defined by the IAU WGCCRE, a peer review is not needed and the definition of the IAU coordinate system can be referenced without the need for a separate defining document. For a new (or updated) coordinate system, a PDS peer review is held to ensure compliance with the two requirements. The review panel usually consists of two external reviewers with expertise in small body coordinate systems, and PDS representatives. (The WGCCRE itself does not normally peer-review coordinate systems but rather looks at the results of external peer review, either in journal articles or in PDS reviews.) The PDS coordinate system review is focussed on the two requirements of following the IAU WGCCRE guidelines for coordinate systems, and adequate documentation. Any liens from the review will be resolved by the data provider, and the resulting coordinate system document will be archived, for a mission usually as part of the mission bundle. The coordinate system documentation must be accepted and publicly released to the PDS archive (or otherwise published in the peer reviewed literature) before data using that coordinate system can be archived.

For missions**,** time is often short and teams are busy during the time of approach to the target body when the initial coordinate system to be used in the first archive deliveries is developed. It is suggested to coordinate with the PDS node (SBN) during the development of the coordinate system and its documentation to make sure the process goes as smoothly as possible.

3. PDS requirements for defining coordinate systems

The PDS standards require that coordinate systems in archival products follow internationally accepted standards. The prevailing international authority for the coordinates on the small bodies of the solar system is the IAU WGCCRE. This body issues a report approximately every third year, a report that is initiated during the triennial General Assembly of the IAU and published prior to the next General Assembly. The WGCCRE maintains a web page[4] where one can find references and links to all reports.

It is important to realize that the WGCCRE has different guidelines for, on the one hand, the major planets and their satellites, and on the other hand, the small bodies of the solar system

(asteroids, comets, Pluto, TNOs, etc.). For small bodies coordinate systems, the right hand rule is used, with a positive and a negative pole (rather than a north pole and a south pole) and with longitude increasing by the right hand rule. The concepts of north and south are not used, nor are the concepts of prograde and retrograde, since all cases are handled by the right hand rule. Thus coordinate systems archived by SBN typically follow guidelines different from those relevant to other nodes of PDS.

If the archival products use a coordinate system explicitly recommended by the IAU WGCCRE, the archive documentation can just note that fact with a reference to the definition (usually a table in one of the reports of the WGCCRE). The coordinate system should also be identified, with an appropriately abbreviated definition, in the product labels. In this case a separate coordinate system document is not needed.

If the archival products use a coordinate system which is not explicitly recommended by the IAU but is consistent with IAU WGCCRE guidelines and is already defined in a paper published in the peer reviewed literature, a separate coordinate system document may not be required if the coordinate system meets the PDS policy and is adequately documented in the published paper, which is then cited in the data archive documentation and metadata. The PDS coordinate system review will confirm whether the requirements are met or if anything else is needed.

If the data provider is defining a new coordinate system, whether the first system for a particular body or a refinement (e.g., for higher precision) of an older system, there will be additional requirements on the definition of the coordinate system. In addition to the IAU guidelines for a new small body coordinate system, if the coordinate system is for a body for which coordinate systems have been previously defined, particularly via any fixed surface features, the recommendations of the WGCCRE for updating a previously defined coordinate system should be followed.

For full details of the IAU WGCCRE guidelines see the current Report (they are usually updated triennially), to be found on their website[4]. SBN is available to advise in implementing the guidelines.

4. SBN guidelines for documenting coordinate systems

4.1 Purpose and scope of the archive coordinate system document

As part of its standard requirements of archive usability, SBN requires that a coordinate system used in data submitted for archiving be adequately documented. Unless the coordinate system is already adequately documented by the IAU or in the published literature, this is normally accomplished with a coordinate system document which is included in the document collection of the Mission Information bundle. The intended purpose of the coordinate system document is to demonstrate that the coordinate system adheres to PDS policy, and to make sure the data user can fully understand the coordinate system used for the archived data, can translate correctly and reliably between positions specified by latitude/longitude (or other types of surface coordinates) and points on the body, and can understand the uncertainties involved. If the coordinate system

is adequately documented in the published literature, a document with a brief description of the coordinate system with references to the applicable papers would take the place of the more detailed description needed for a new coordinate system.

A new or updated coordinate system may be defined in many ways depending on the characteristics of the target body and the state of knowledge about it. These guidelines don't try to anticipate every possible type of coordinate system and rigorously specify the parameters that must be documented in all cases. Rather, the most common cases are treated with suggestions how to extend to other more complex cases.

4.2 Contents of the coordinate system document

To meet the goal of enabling the data user to understand and use the coordinate system with the data, the documentation for a typical coordinate system for a principal axis (PA) rotator should include the definition of the polar axis orientation in J2000 α, δ, with associated uncertainties, the rotation rate and its uncertainty, and a short discussion of how these were determined. The document should also include a discussion of the definition of longitude, specifically showing a figure of the feature that is used to define the zero point of longitude (whether it is at 0° longitude or not) along with the date/time for which it is defined, and a projected map of the body with the zero point identified, the defining feature identified, and whatever other information would be useful to a scientist in understanding the coordinate system, such as the orientations of the principal axes. The defining feature should be identified in a way which allows the data user to reliably find and identify it in the data images. The document should also provide, to the extent known, the value of w0, the parameter defining the orientation of the zero point of longitude at epoch J2000.0 (or other specified epoch). The date/time or time range of the data used to define these parameters should be specified. The document should specify the precision of all relevant parameters of the model. Note that more complex features such as changing rotation rate may complicate this picture and result in a need for additional information to fully document the coordinate system.

If a SPICE text PCK file implementing the rotation model values is archived in the PDS, it is recommended to reference this PCK in the document.

In the case of non-principal axis (NPA) or other excited state rotator, or in cases where the rotation state is not well known, the definition of the coordinate system may diverge significantly from this and the parameters documented must be changed appropriately to enable the user to understand and make use of the coordinate system. Note that the WGCCRE has not treated cases of excited state rotation in their Report. Coordinate systems in such cases might be defined without reference to the rotation state, or possibly in reference to other rotation parameters (see Appendix). Although the document is not expected to define the rotation state of the body beyond what is needed to define the coordinate system, it should specify, in so far as known, the type of rotation state such as PA or NPA.

If the coordinate system is for a body for which coordinate systems have been previously defined, particularly via any fixed surface features, the document should also show how the

improved system follows the recommendations of the WGCCRE for updating coordinate systems. This can be best accomplished by identifying in a figure and a map any feature(s) previously used to define the zero point of longitude and showing that the new definition is consistent with that definition.

If desired, the coordinate system document may include additional information about the rotation state or other properties of the body, the plans for updating the coordinate system in the course of the mission, or any other relevant information deemed useful to the end data user. Information additional to that needed to meet PDS and SBN requirements is not required, but can potentially result in a more useful document.

4.3 Updating the document

In the course of mission operations at the target body, the coordinate system may be refined and updated. If an updated version of the coordinate system is to be used in data submitted to PDS for archiving, the updated coordinate system and its documentation will be peer reviewed to ensure that the two requirements, conforming to PDS policy and being adequately documented, are met. The updated document will supersede the earlier version, so all information about the earlier version(s) of the coordinate system are retained, and documentation of the updated coordinate system versions are added, resulting in a comprehensive document that can be used to understand all archived versions of the coordinate system. The peer review process is similar to the initial one. The updated document must have passed peer review and be released to the public archive before data using the updated coordinate system can be archived in PDS.

4.4 Examples

The Asteroid Ryugu coordinate system description[5] produced by the Hayabusa2 mission in support of their PDS-archived Ryugu data, was reviewed, accepted, and archived by SBN and is a good example for the finished document for a mature coordinate system for a relatively simple case. An example document for a more complex case is that of Comet 67P/Churyumov-Gerasimenko, archived with the Rosetta data[6]. Other examples, including for more preliminary coordinate systems early in the mission, or for updates of a coordinate system near the end of the mission, are available in the PDS archive, or by request to the SBN.

5. References

1. PDS Policy on Acceptable Body-Fixed Coordinate Systems, Aug. 27, 2014. https://pds.nasa.gov/datastandards/documents/policy/PolicyOnAcceptableBodyFixedCoordinateSystems08272014.pdf
2. Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015. Celest Mech Dyn Astr (2018) 130:22 https://doi.org/10.1007/s10569-017-9805-5.

3. Coordinate Systems at PDS-SBN, April 10, 2014. https://pds-smallbodies.astro.umd.edu/data_sb/resources/CoordinateSystems-at-SBN_Final.pdf
4. IAU WGCCRE Web Page. http://astrogeology.usgs.gov/groups/iau-wgccre
5. Ryugu Coordinate System Description. https://sbnarchive.psi.edu/pds4/hayabusa2/hyb2/document/Ryugu_Coordinate_System_Description.pdf
6. Reference Frames and Mapping Schemes for Comet 67P. https://pds-smallbodies.astro.umd.edu/holdings/ro-c-multi-5-67p-shape-v1.0/document/cheops_ref_frame_v1.pdf

Appendix - Rotational States

Since some elements of the rotation state are typically used in the definition of coordinate systems, these may need to be included in the coordinate system definition. An overview of the parameters of rotation states for principal and non-principal axis rotation may be helpful. The following overview has been provided by Nalin Samarasinha in Oct. 2021.

Defining Rotational States of Small Bodies

The rotational state of a small body could be either executing a rotation around a principal axis[1] (i.e., PA rotation or simple rotation) or it could be in a non-principal-axis rotational state (i.e., NPA rotation or complex rotation; also known by the non-technical term “tumbling motion”).

All NPA rotational states are dynamically excited rotational states but not all dynamically excited rotational states are NPA rotational states. The dynamically excited PA rotation around the long principal axis and that around the intermediate principal axis are excited states. However, the PA rotation around the short principal axis is not a dynamically excited state and represents the relaxed least energy state. The NPA states can be divided into two modes and they are called Short Axis Mode (SAM) and Long Axis Mode (LAM); LAM rotational states are more energetic than SAM rotational states.

A simple (i.e., a principal-axis) rotation requires three independent parameters and an initial condition to uniquely define it; namely, (i) two parameters defining the direction of the rotational angular momentum vector, RAMV (in this case, same as the spin axis direction), (ii) the rotation period, and (iii) the orientation of a reference longitude of the small body at a specific time in an inertial frame[2]. Whereas, an NPA state requires six independent parameters[3] and two initial conditions to uniquely define it.

See the review chapter by Samarasinha et al. (2004) and references therein in the COMETS II book (University of Arizona Press) for further details on the NPA rotation.

Required Information for Uniquely Defining a Rotational State[4]:

Is the rotational state, a PA state or an NPA state?

If it is in a PA state, specify the following:
1. Direction of the Spin Axis (RA and Dec) at a specific time
2. Rotation period or rate at a specific time
3. Orientation of a reference longitude of the small body (at zero latitude) at a specific time

If the rotational state is an NPA state, is it SAM or LAM?

In addition, specify the following:
(a) If the small body can be approximated by a near-prolate or a triaxial shape,
1. Direction of the RAMV (RA and Dec)
2. Precession period of the long principal axis around the RAMV
3. Rotation (either full or back and forth) period around the long principal axis
4. Ratios between the moments of inertia for the three principal axes (I_i/I_l and I_s/I_l)
5. Euler angles φ and ψ at a specific time[5]

(b) If the small body can be approximated by a near-oblate shape,
1. Direction of the RAMV (RA and Dec)
2. Precession period of the short principal axis around the RAMV
3. Rotation (either full or back and forth) period around the short principal axis
4. Ratios between the moments of inertia for the three principal axes (I_i/I_l and I_s/I_l)
5. Euler angles φ and ψ at a specific time[6]

Note: If the rotational state is a mildly excited SAM, it may be appropriate to follow (b) even if the shape can be approximated by a near-prolate or a triaxial ellipsoid.

Footnotes:

1. Subscripts l, i, and s represent the long, intermediate, and short principal axes, respectively.

2. The inertial frame can be the body-centric equatorial frame, body-centric ecliptic frame, or the body-centric orbital frame.

3. Some of these six independent parameters could be substituted by suitable alternate parameters (e.g. instead of two independent component periods of the NPA state, the rotational kinetic energy and the magnitude of the RAMV).

4. The parameters are selected such that they represent those appropriate from an observer's perspective.

5. Euler angles are defined as in Samarasinha et al. chapter in COMETS II.

6. Euler angles are defined as in Samarasinha and Mueller (2015) [Icarus, 248, 347-356].