

Coordinate Systems and Transforms in Space Physics: Terms, Definitions, Implementations, and Recommendations for Reproducibility

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Key Points:

- Reproducing coordinate system transforms is difficult due to variations in definitions and implementations.
- Ephemeris datasets from different data providers can differ significantly ($\sim 0.3^\circ$), as do Z-axis orientations from surveyed software libraries ($\sim 0.03^\circ$).
- There is duplication of effort by spacecraft missions related to coordinate system transform calculations.
- Recommendations are given to make reproducibility easier and reduce duplication of effort.

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Abstract

In space physics, acronyms for coordinate systems (e.g., **GEI**, **GSM**) are commonly used; however, differences can exist in their definitions and implementations that prevent reproducibility. In this work, we compare definitions in frequently cited journal articles, online resources, and software packages and show that implementation differences can lead to transformations between same-named coordinate systems to differ significantly. Based on these comparisons and results, and to improve reproducibility, we recommend (a) a standard for acronyms and definitions for coordinate systems is developed; (b) a central authority maintains a citable database of reference data needed for these transforms; (c) a central authority maintains the SPICE kernels for transforms if by space physics **satellite** missions to generate data products in different coordinate systems; and (d) software developers provide explicit comparisons of their implementations with the results of (b) and documentation on implementation choices. In addition, we also provide recommendations for scientists and metadata developers to provide sufficient information that will enable reproducibility in the absence of implementation of these recommendations.

1 Introduction

In space physics journal articles and software, the definition of a coordinate system is typically given by citing a reference that describes it. (Thus far, we have used the term “coordinate system” consistent with common usage in space physics. In section 2, we note that “ideal reference system”, “reference system”, or “reference frame” is more consistent with literature outside of space physics and will use these term in the remainder of this article.)

This work stems from a project to develop a standard for ideal reference system acronyms (e.g., **GEI**, **GSE**, **GSM**, and their commonly used variations, e.g., **GEI_J2000**, **GEI_MOD**, etc.). The motivation was that, given a statement such as “the vector measurements in **ABC** were transformed into **XYZ**,” a scientist with measurements in **ABC** would be able to reproduce the transformation with the only uncertainty being due to round-off error at the level of floating point precision.

The primary challenge with this task is that implementing a given reference system requires making implementation choices, and therefore, definitions of reference implementations are also needed (in section 3, we refer to an implementation of a reference system as a “reference frame”). As a result, developing a list of acronyms and associated definitions for reference systems does not address the fundamental problem of reproducibility – implementations of the same reference system will not necessarily be the same because implementations rely on models, and there are both independent models and multiple versions of the same model that can be used. In section 4, we give examples where different databases and software produce significantly different results based on transforms.

In section 5, we describe how missions develop data products in different reference systems. In section 6, we provide a set of recommendations based on the example in section 3, results in section 4, and description in section 5.

2 Coordinate Systems, Reference Systems and Reference Frames**2.1 Coordinate Systems**

In geometry, introductory physics, and mathematics textbooks, coordinate values in a “coordinate system” uniquely identify spatial positions relative to **an origin**. Common coordinate systems are **Cartesian**, cylindrical, and spherical. In the space physics literature, **however**, a coordinate system is generally meant as a set of three orthogonal

vectors and an origin (e.g, the GCI coordinate system); this usage dates back to at least early documentation of the NASA shuttle program (Davis, 1974) and has been consistently used in frequently cited literature related to space physics reference frames (Russell (1971); Hapgood (1992); Hapgood (1995); Laundal and Richmond (2016)). (However, an earlier work for analysis of data from the OGO satellite used only “system” for the central noun, e.g., GCI system, instead of GCI coordinate system.)

2.2 Reference Systems and Frames

In astronomy, the terms “reference system” and “reference frame” are used; from USNO (2025): “A reference system is the complete specification of how a celestial coordinate system is to be formed. It defines the origin and fundamental planes (or axes) of the coordinate system. It also specifies all of the constants, models, and algorithms used to transform between observable quantities and reference data that conform to the system. A reference frame consists of a set of identifiable fiducial points on the sky (specific astronomical objects), along with their coordinates, that serves as the practical realization of a reference system.”

“Reference system” and “Reference frame” are also used in the same sense in terrestrial geodesy (Seitz et al., 2014).

A fundamental reference system is the International Celestial Reference System (ICRS) (Petit & Luzum, 2010). No unique reference frame is associated with this reference system because creating (equivalently, “implementing” or “realizing”) one requires measurements for computing reference system model parameters. The “International Celestial Reference System (ICRF)” is the general name for realizations of the ICRS that are agreed upon by a standards body and are updated as new measurements and model versions become available. There are three versions of the ICRF (Charlot et al., 2020).

Kovalevsky and Mueller (1981) and Mueller (1985) use the term “ideal reference system” to refer to reference frames with definitions that are incomplete (only fundamental planes, axes, and an origin are specified): “The term ‘ideal’ indicates the conceptual definition only and that no means are proposed to actually construct the system”. The term “ideal” should be interpreted not as meaning “preferred” but rather in the sense of “idealized model”, or a model that has practical or important effects omitted to simplify its description.

Thus, what we call “coordinate systems” (e.g., GEI, GSE) in space physics are analogous to “ideal reference systems” because they have definitions for their orientation and origin; however, there are no standards for the constants, models, and algorithms required to transform between observable quantities, which are necessary to define a “reference system”. For example, the GSE reference frame requires a vector from the center of Earth to the center of the sun. Russell (1971) gives a Fortran program provided through private communication; Hapgood (1992) uses equations from Doggett et al. (1990), and Fränz and Harper (2002) use equations from Seidelmann et al. (1992). All three cases can be regarded as unique GSE reference frames for the GSE reference system.

Terminology related to reference systems and frames also varies in other fields. For example, SPICE (NAIF, 2023) states “a reference frame (or simply ‘frame’) is specified by an ordered set of three mutually orthogonal, possibly time dependent, unit-length direction vectors.”. (This definition does not include an origin.) In robotics, the term “coordinate frame” is used to refer to a set of three orthogonal axes and an origin relative to a different coordinate frame (Murray et al., 1994).

3 Examples of Definition Ambiguity

In this section, we provide an example of the diversity of definitions and usage of GEI-related ideal reference frames to motivate recommendation (a) in the abstract. Similar ambiguities exist for other ideal reference frames used in space physics.

First, there is no consistency in the expansion of the acronym “GEI”. Russell (1971) and Hapgood (1992) associate GEI with “Geocentric Equatorial Inertial System”. Fränz and Harper (2002) and Mumford et al. (2024) associate GEI with “Geocentric Earth Equatorial”. Another ambiguity is in GCI; SSCWeb (2025c) notes “Geocentric Inertial (GCI) and Earth-Centered Inertial (ECI) are the same as GEI.”, which implicitly defines GCI as “Geocentric Inertial”, in contrast to Russell (1971) and NASA (1970), which use “Geocentric Celestial Inertial”.

In general, the GEI ideal reference frame has \mathbf{Z} aligned with Earth’s rotation axis with positive Northward, \mathbf{X} as the intersection of Earth’s equatorial plane with the plane of Earth’s orbit around the Sun (the ecliptic plane), with positive in the direction from the Earth to the sun at the time of the vernal equinox, and $\mathbf{Y} = \mathbf{Z} \times \mathbf{X}$. (The line of intersection of Earth’s equatorial plane with the ecliptic, or the time that it is computed, is sometimes referred to “the equinox”.) When reporting positions, the origin is taken as the center of mass of Earth. To establish this as a reference system as defined in section 2.2, Earth’s rotation axis and the ecliptic plane must be specified, along with a model used to compute it. ~~If the definition includes the origin as Earth’s center of mass, a corresponding model is needed.~~ Common variations of GEI depend on whether precession and nutation of Earth’s rotation axis and precession of the ecliptic plane are accounted for (Davis (1974); Hapgood (1995); Fränz and Harper (2002)). The term “mean epoch-of-date” (or mean-of-date) is used when only precession is accounted for, meaning the orientation of the ecliptic and Earth’s rotation axis vary with time using an average orientation near a date. If these orientations account for nutation, the term “true epoch-of-date” (or true-of-date) is used (Hapgood, 1995). If the orientations are time independent, an abbreviation for a reference date and time is specified, e.g., J2000.0. (These exact reference date and times are referred to as epochs in the sense of a time instant rather than a period of time.)

Two basic categories of the GEI-related reference frames and systems are commonly used: inertial and non-inertial. The following acronyms are associated with an inertial reference system, an idealized system that is not rotating with respect to the distant stars (i.e., stars at an effectively infinite distance from its origin) and with an origin that translates with a constant velocity (NAIF, 2023). Note that if the origin is specified as Earth’s center (usually its center of mass rather than centroid is implied but not stated), GEI is non-inertial by definition. However, in the list of reference systems and frames below, we have ignored this technicality.

- J2000 – Used by SSCWeb (2025c) to refer to a frame with its origin at Earth’s center of mass and in SPICE to refer to as a system with origin at the solar system Barycenter (Acton (1997); NAIF (2025)).

SSCWeb (2025c) provides the definition “Geocentric Equatorial Inertial for epoch J2000.0 (GEI2000), also known as Mean Equator and Mean Equinox of J2000.0 (Julian date 2451545.0 TT (Terrestrial Time), or 2000 January 1 noon TT, or 2000 January 1 11:59:27.816 TAI or 2000 January 1 11:58:55.816 UTC.) This system has X-axis aligned with the mean equinox for epoch J2000; Z-axis is parallel to the rotation axis of the Earth, and Y completes the right-handed orthogonal set.”

NAIF (2025) notes that J2000 is “generally used in SPICE to refer to the ICRF”; “The rotational offset between the J2000 frame and the ICRS has magnitude of under 0.1 arcseconds [$2.7 \cdot 10^{-5}$ degrees].”; “The ICRF frame is defined by the

adopted locations of 295 extragalactic radio sources.”; “The J2000 (aka EME2000) frame definition is based on the earth’s equator and equinox, determined from observations of planetary motions, plus other data.”; and “The realization of ICRF was made to coincide almost exactly with the J2000 frame.”

The Van Allen Probes mission used the SPICE implementation of J2000 for GEI.

- GEI2000 – SSCWeb (2025c) identifies this as equivalent to J2000 by a parenthetical statement in the definition of J2000: “Geocentric Equatorial Inertial for epoch J2000.0 (GEI2000)”.
- GeocentricEarthEquatorial – Used by SunPy with supporting definition of “A coordinate or frame in the Geocentric Earth Equatorial (GEI) system.”
- GCRS – Used by Price-Whelan et al. (2022) with supporting definition “A coordinate or frame in the Geocentric Celestial Reference System (GCRS). GCRS is distinct from ICRS mainly in that it is relative to the Earth’s center-of-mass rather than the solar system Barycenter. That means this frame includes the effects of aberration (unlike ICRS).”
- GEI_{J2000} – Fränz and Harper (2002) state that GEI_{J2000} is realized through the ICRF (this is ambiguous today, because there are now three ICRF versions (Charlot et al., 2020)).
- EME2000 – Earth Mean Equator and Equinox J2000.0; defined in NAIF (2025) via “aka J2000”. SSCWeb (2025c) defines as “Mean Equator and Mean Equinox of J2000.0” in its definition of J2000.
- ECI2000 – Earth Centered Inertial for J2000 epoch; used in (Niehof et al., 2022).
- ECI – Earth Centered Inertial; used in NASA (2024) with note “GEI/J2000 – Earth-Centered Inertial (ECI). To fully specify the system the equinox must be defined. This system uses the mean equinox at the J2000 epoch.” Also used by the PUNCH MOC.
- GCI – Geocentric Celestial Inertial; used in OGO satellite data analysis (NASA, 1970) and stated in Russell (1971) as equivalent to GEI.
- ECLIPJ2000 Mean ecliptic and equinox of J2000 (NAIF, 2025).
- M50 – Mean of 1950 (or Aries-mean-of-1950). This frame is defined in a manner similar to J2000, except that the mean equator and equinox are taken at the start of the Besselian year 1950 (Davis, 1974).

4 Comparisons

Space physics researchers and analysts have several options for obtaining data in different coordinate frames or transforming between them.

1. It is common for space physics missions to provide datasets to a data archive (e.g., NASA/CDAWeb, ESA/CSA) with vector measurements in different coordinate systems; in this case, the scientist selects a dataset in a needed coordinate system, if available.
2. There exist data services that provide vector measurements in different coordinate systems. For example, SSCWeb provides ephemeris values for satellites in various coordinate systems as a function of time (SSCWeb, 2025c) and a calculator that takes an input position in a given coordinate system at a specific time and produces the transformed position in other coordinate systems (SSCWeb, 2025a).

Although the calculator requires positions $> 1R_E$, a non-positional vector can be scaled and entered as a position to determine its value in a different coordinate frame.

- Many software packages have coordinate transform functions. For example, in Python, Astropy (Price-Whelan et al., 2022), SunPy (Mumford et al., 2024), SpacePy (Morley et al., 2024), and PySPEDAS (Angelopoulos et al., 2024a). Other libraries include (Boller & Santiago, 2025) in C, and Geopack (Tsyganenko, 2008) and IRBEM (Boscher et al., 2022) in Fortran.

In section 4.1, we give an example that demonstrates that the reported ephemeris for satellites in same-named reference systems can significantly differ depending on the source. In section 4.2 we demonstrate that software that transforms a vector between two reference frames exhibit smaller, but possibly significant, differences. The software used to generate the results and the values for the plots are available in (Weigel et al., 2025).

It is sometimes argued that, although reference frame implementations may give different results, this uncertainty is small compared to measurement uncertainty. For example, Hapgood (1995) notes that “The attitude error that arises from an error in the epoch used to compute GEI is 0.036° , which is small compared to the angular resolution of most space plasma measurements ...”. However, having different data providers or software libraries compute GEI in different ways can lead to issues, for example,

- In an attempt to develop a 3D visualization program that returns the region of geospace given an arbitrary position, we implemented the models used by (SSCWeb, 2025c) and attempted to validate our work by comparing our predicted regions at the positions provided by its web service for satellites. Although our predictions were generally consistent, we were unable to reproduce the exact time when a satellite crossed from one region into another. After a search for errors in our model implementation failed to explain the differences, we realized that the errors were due to the software used for reference frame transformation differing from that used by SSCWeb.
- Not all global magnetosphere simulation models are executed in the same reference frame. To compare the models, their variables must be transformed into the same coordinate frame, and the uncertainty associated with this transformation must be known to accurately identify the true difference in the model output. In addition, if the two models should, but do not, match to numerical precision at certain locations or under certain conditions, it is difficult to determine the cause of the mis-match when different transforms were used (Thomas et al., 2025).

The fact that different software libraries provide different options for reference frames is indirect evidence that differences can matter. For example, Morley et al. (2024) provides multiple options for computing the MAG system, which have angular differences of $\sim 0.01^\circ$ degrees, and Mumford et al. (2024) has options for how the GEI frame are computed (see section 4.2). A general finding is that the differences in the transform results using a single library are on the order of, or smaller than, the difference in transform results found when comparing two different software libraries. As a result, the value of improvements in how a transform is computed with a single library is lost when a comparison is made using data computed using a different library.

Even if the uncertainty associated with how a given coordinate frame was implemented is small relative to that of the measurements, we suggest that it does not make sense for two data providers to report the location of a satellite that differs by more than what is expected due to numerical precision (unless the reason for differences is clearly

documented and ideally evident in the name of the data set, e.g., by including the word “preliminary”).

4.1 Ephemeris

In this section, we give examples of how ephemeris values from data providers can differ.

In Figure 1, the ephemeris of the Geotail satellite from 2021-11-25 through 2021-12-05 is shown from the SSCWeb (2025c) web service and CDF files in NASA (2025a). SSCWeb provides the ephemeris for scientific satellites in reference systems that include GEI, J2K, GSE, GSM, and GM (frequently referred to as MAG). The GE_OR_DEF dataset has ephemeris values in GCI, GSE, and GSM.

In Figure 1, the average distance, \bar{r} , from the two providers and errors relative to an Earth radius, $R_E = 6378.16$ km, which is the value used by SSCWeb. We used the SSCWeb option to return data as a fraction of R_E with 10 fractional digits. The CDAWeb dataset stores values with units of km as IEEE-754 64-bit floats, and the metadata indicates a recommended display precision of 10 fractional digits. The cadence of the SSCWeb data is 12-minutes while the CDAWeb data is at a 10-minutes cadence. In the time interval displayed in Figure 1, values for the 240 common time stamps are shown.

Based on the documentation for SSCWeb (2025c), which has the statement “Geocentric Inertial (GCI) and Earth-Centered Inertial (ECI) are the same as GEI.”, we expect the SSCWeb/GEI and CDAWeb/GCI to be identical to the level of precision of the data, assuming both data sources use the same definition of GEI. The result is shown in Figure 1(a). The average angular difference in the position vector is $\Delta\theta \sim 0.3^\circ$, and the average error relative to an Earth radius, $|\Delta\mathbf{r}|/R_E \sim 0.1$, or 10%. The maximum error relative to the radius, $|\Delta\mathbf{r}|/\bar{r}$ is $1/187$, or 0.5%.

Based on the precision of the data, and if both providers use the same definition of GEI, we expect $|\Delta\mathbf{r}|/R_E \simeq 10^{-10}$ given that the SSCWeb values are reported in R_E to 10 fractional digits and the CDAWeb values are recommended for display with 10 fractional digits. For $\bar{r} = 20R_E$, this corresponds to an uncertainty due to the precision of the data of $\Delta\theta \simeq 20 \cdot (180/\pi) \cdot 10^{-10} \simeq 10^{-7}$ degrees.

Angular differences can be compared to:

1. The average angular change in the dipole Z axis of $\sim 0.04^\circ$ per year (from 1970–2025, computed using the libraries considered in section 4.2).
2. The precession of Earth’s rotation axis (luni-solar precession), the GEI_Z axis drifts by $\simeq 0.006^\circ$ per year (Hapgood, 1995).
3. The one-year change in angle due to nutation of Earth’s rotation axis of $\simeq 0.0025^\circ$ per year (Hapgood, 1995).
4. The precession of the ecliptic (planetary precession) of $\Delta\theta \simeq 0.000014^\circ$ per year (Hapgood, 1995).

In Figure 1(b), there is a much closer match between SSCWeb/J2K and CDAWeb/GCI, with an average angular difference in the position vector of $\sim 0.002^\circ$ and an average error relative to an Earth radius of $\sim 0.05\%$.

In summary, Figure 1(a) and (b) show that what is labeled as GCI in the CDAWeb ephemeris is much closer to SSCWeb/J2K ephemeris than SSCWeb/GEI, which is unexpected given the SSCWeb documentation that notes GCI and GEI are equivalent. Although the CDAWeb/GCI ephemeris is a better match to the SSCWeb/J2K ephemeris, the differences are not explained by the precision and may be due to if and how items 2–4. above were accounted for.

In Figure 1(c), a comparison is made for the **GSE** reference system. To transform a vector from a **GEI** reference system to **GSE**, two rotations are required: a rotation around **GEI_X** to align Earth’s equator to the ecliptic plane and a rotation around the **GEI_Z** axis (as it is after the first rotation). These two angles are the obliquity of the ecliptic and the ecliptic longitude of the Sun, respectively (Hapgood (1992)).

In Figure 1(d), a comparison is made for the **GSM** reference system. A vector in the **GSE** reference system is transformed to **GSM** by an angle that depends orientation of the North geomagnetic pole (Russell (1971); Hapgood (1992)). The primary uncertainty is how the orientation of the North geomagnetic pole, which has an average yearly change of 0.04° , is computed. If both SSCWeb and CDAWeb computed the **GSM** ephemeris based on a transform from **GSE**, we could conclude that the observed differences in $\Delta\theta$ are due to the use of different locations of the North geomagnetic pole. However, the maximum $\Delta\theta \simeq 0.37^\circ$ is much larger than the average yearly angular change in the dipole Z axis of $\sim 0.04^\circ$.

In Figure 2, a comparison is made between data from SSCWeb, CDAWeb, and the JPL Horizons web service (JPL, 2022), which provides ephemeris for some of the spacecraft available from SSCWeb. The JPL Horizons web service provides ephemeris in the **ICRF** reference frame (the version of **ICRF** is not stated), and SunPy is used to transform it to other reference frames.

Figure 2a shows that the $\Delta\mathbf{r}$ in **GSE** from CDAWeb and SSCWeb match to within ~ 3 km, which is much larger than expected by round-off but smaller than the closest separation distance of MMS spacecraft of ~ 7 km. Figure 2b shows that there are larger differences for **GSM**.

In Figure 2c, much larger differences are shown to exist between SSCWeb and JPL than SSCWeb and CDAWeb, with the maximum angular difference being up to $\sim 1^\circ$ instead of 0.003° found in the comparison of SSCWeb and CDAWeb in Figure 2a. A similar conclusion is made by comparison of Figure 2b and Figure 2c. A possible explanation for the differences was found by inspecting the raw JPL Horizons web service result that was used by SunPy, in which it is noted that “The spacecraft may be maneuvered frequently. Therefore, the **JSpOC** TLE-based trajectory provided here may at times depart from the actual trajectory. This can happen because TLEs do not model thruster firings; the TLE trajectory solutions must be reinitialized after each event.”.

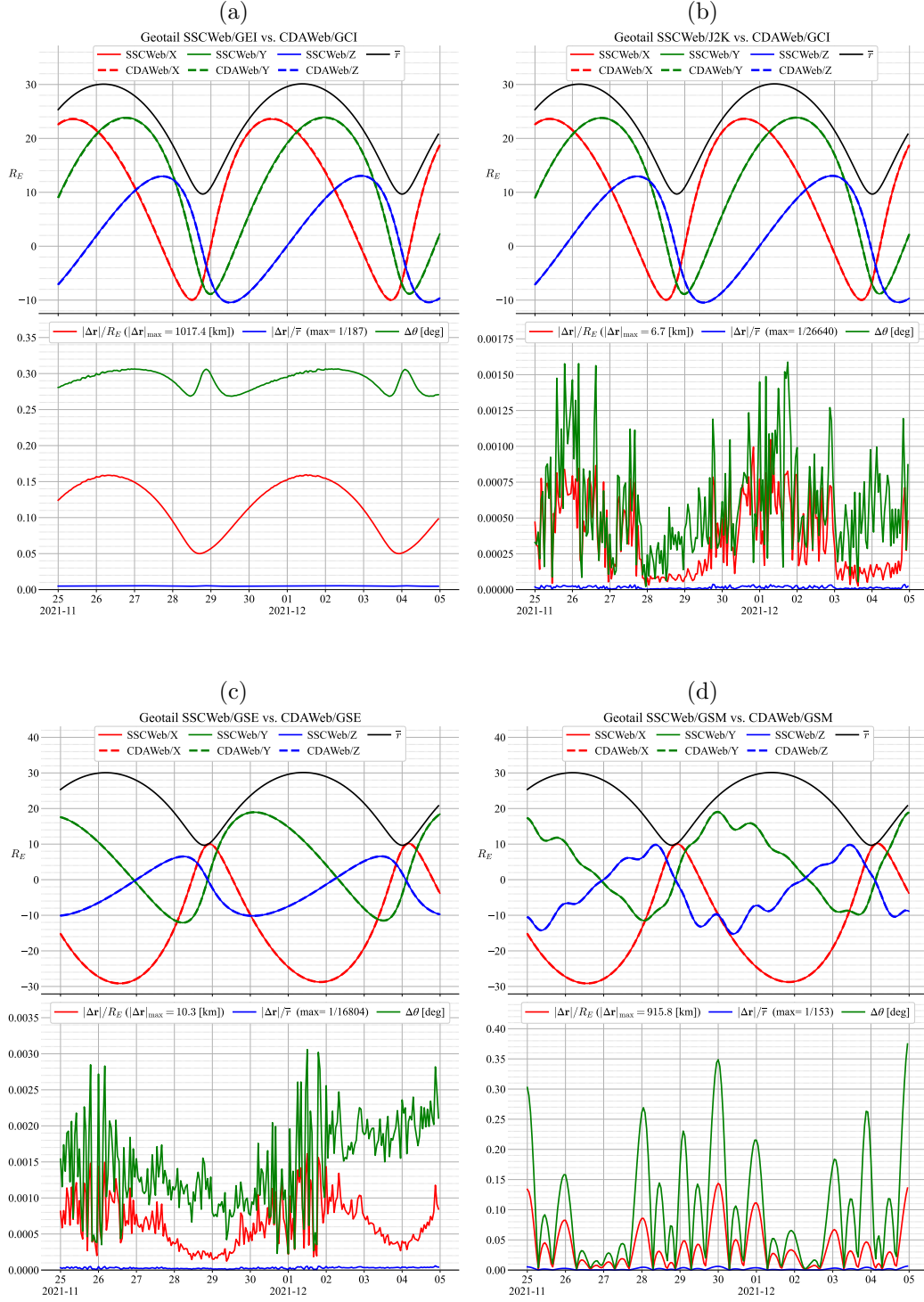


Figure 1: Comparison of ephemeris values from SSCWeb and CDAWeb in four different reference systems.

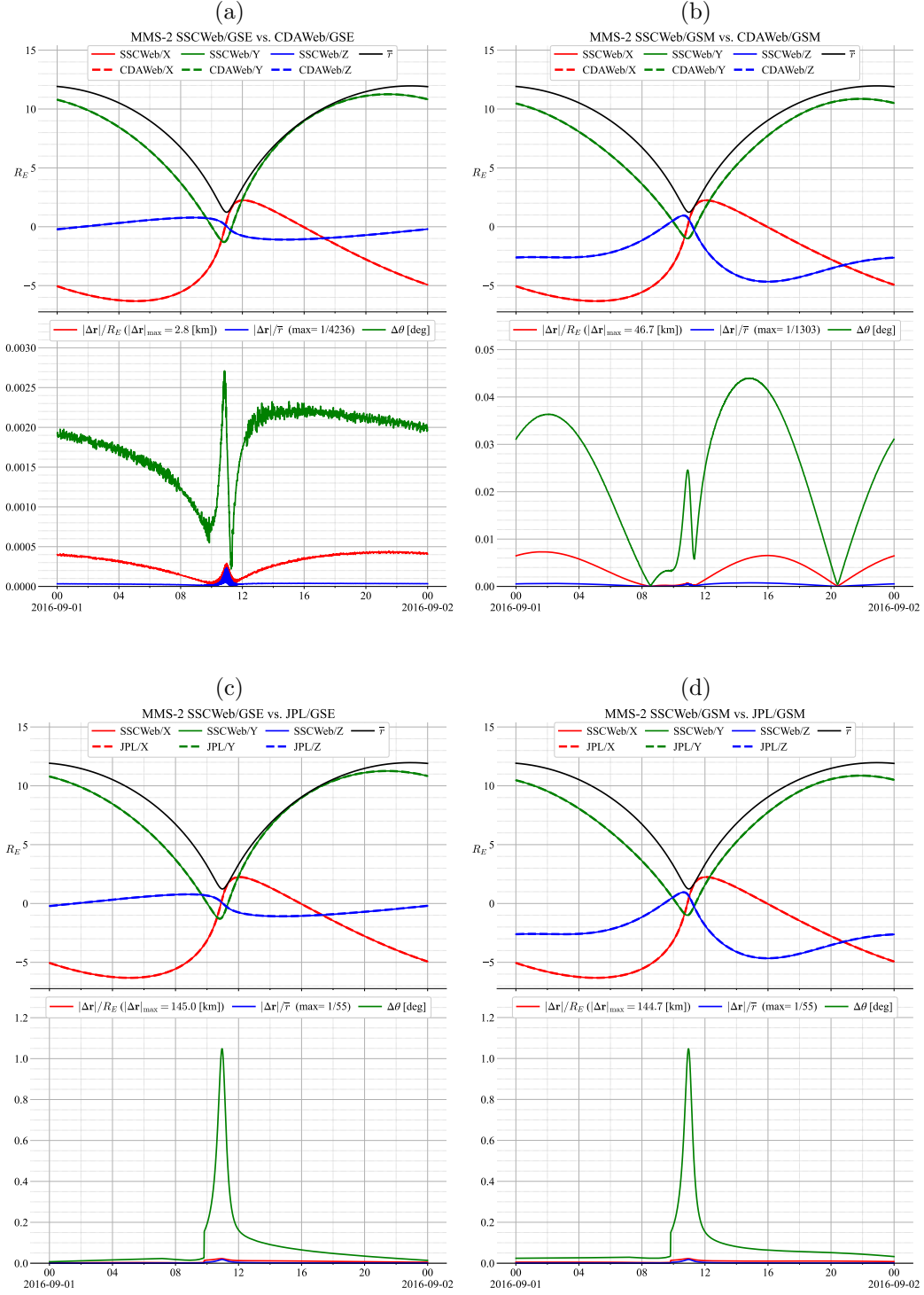


Figure 2: Comparison of ephemeris values from SSCWeb and CDAWeb (panels (a) and (b)) and SSCWeb and JPL Horizons in two different reference systems.

4.2 Software

In this section, we compare reference frame calculations using the following software packages.

- Geopack-2008 double precision (Tsyganenko (2008); labeled as `geopack_08_dp`), a Fortran library that was upgraded from earlier versions to support calculations using 64-bit floating point values.
- SpacePy 0.0.6, which has an option to use the IRBEM Fortran library (Boscher et al. (2022); labeled as `spacepy-irbem`) or a native Python implementation (`spacepy`) of the transforms.
- SpicePy 6.0.0 is a Python wrapper for the SPICE toolkit. Two versions of SPICE kernel files were used, indicated by `spicepy1` and `spicepy2`. `spicepy1` was used for reference frame transforms for the Van Allen Probes mission. `spicepy2` had an update to the MAG frame, which used a more recent version of the IGRF model to determine the Earth’s magnetic dipole orientation.
- SunPy version 7.0.0
- PySPEDAS 1.7.28, which uses transformation code derived from the IDL version of PySPEDAS (Angelopoulos et al., 2024b), which in turn used code from the ROCOTLIB Fortran (CDPP/IRAP, 2025) library, which was used for data from the Cluster spacecraft mission (Robert, 1993).

Figure 3 compares the angles between the Z axis of select coordinate system pairs. The average of the absolute value of the differences with respect to `geopack_08_dp` ranges from $4 \cdot 10^{-7}$ to $9 \cdot 10^{-2}$ degrees. These values can be used as a rough uncertainty estimate when comparing data transformed using different software libraries.

In general, the differences found here are smaller than those found when comparing ephemeris values in section 4.1. (The choice of which library to use as a baseline for this comparison is arbitrary; in general, we are interested in the overall variability among the libraries, which is displayed in the lower panel of each subplot.)

The maximum annual difference of 0.009° degrees is approximately one-quarter of the the average yearly angular change in the dipole Z axis of $\sim 0.04^\circ$ (from 1970–2025) and 1.5 times the average precession of Earth’s rotational axis ($\sim 0.006^\circ$ per year).

We have also performed coordinate transforms using the (SSCWeb, 2025a) web service. However, this system only outputs values to two decimal places, which leads to angular differences of 0.3° . These values are not plotted so that the library differences are clearly visible (but are available in (Weigel et al., 2025)).

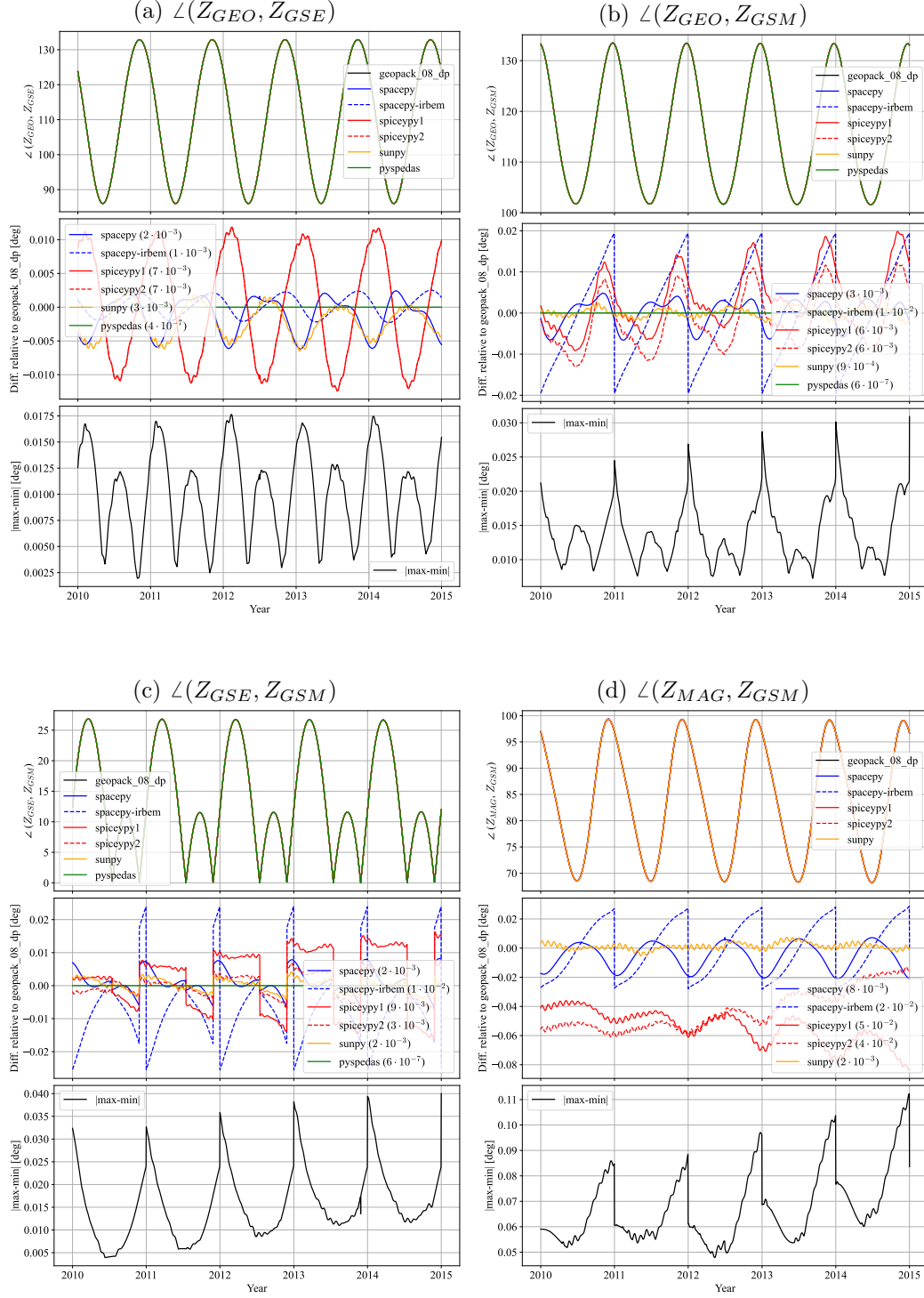


Figure 3: Angles between Z axes in select coordinate frames. In the top panels of each subplot, the notation $\angle(Z_A, Z_B)$ means the angle between the Z axis of coordinate frame A in coordinate frame B and the Z axis of coordinate frame B . The middle panel of each subplot shows the difference in the computed angles in the top panel with respect to `geopack_08_dp`. The bottom panels show the maximum absolute value of the differences in the middle panel.

5 How transform information is created for spacecraft missions

Archival data for space physics satellite missions typically include vector measurements in multiple reference frames. For NASA missions, the archival data products are delivered to the Space Physics Data Facility (NASA, 2025b). Modern missions typically take one of two approaches:

1. A mission operations team develops SPICE kernels for ephemeris and select space physics reference frames, and SPICE software is used to process ephemeris data and vector data in select coordinate frames for archival data products.
2. The variables are computed by the mission team. Examples of software used for this include ROTOLIB, SpacePy, and SPICE. There is a significant overlap in effort – typically, a scientist familiar with space physics reference systems, but not their many options for implementation, will use available software and develop tests.

~~As recommended in the conclusions,~~ this effort to develop transforms for variables into different reference frames would not be needed if either a database of transform matrices or SPICE kernels were available.

For the SSCWeb data service (SSCWeb, 2025c), which includes spacecraft ephemeris, three approaches have been taken in order of priority (see SSCWeb (2025b) for a table indicating which approach was taken):

1. Mission-developed SPICE kernels for ephemeris are ingested and archived. The GEI ephemeris-related SPICE kernel information is used to generate the J2000 ephemeris. Then ISTP-era software is used to compute ephemeris in different coordinate frames, including GEI, GEO, GM, GSE, GSM, and SM. The ISTP software uses proprietary information needed for the reference frames (such as the position of the sun) calculated by GSFC's Flight Dynamic Facility, FDF.
2. A GEI ephemeris-related variable in archival CDF files ingested from the mission database is used. ISTP-era software is used to compute ephemeris in different coordinate frames,
3. TLE (two-line element) files are obtained from NORAD and a translation of the C NORAD library to Pascal (Brodowski, 2002) is used to compute ephemeris in TEME. If an existing SPICE kernel has reference frame information, it is not used, and if the CDF files have ephemeris in different coordinate systems, they are not used.

Bobby - Is the last item correct? If so, why is the approach taken?

6 Conclusions and Recommendations

In this section, we provide recommendations to address the issues identified in this article. No single recommendation will address all of the problems or satisfy all of the use cases.

6.1 Standards for Reference Frame Definitions

As defined in section 2, an *ideal reference system* is a general description of a reference frame without key details needed for its implementation. In that section, examples were provided where the GEI acronym had different expansions, and different acronyms were identified as equivalent to one another.

The next level of specificity to an ideal reference system is a *reference system*, which defines constants, models, and algorithms used to transform between observable quantities and reference data. Each ideal reference system should have at least one associated reference system; if multiple reference systems are in common use, they should have their definition and way of being referred to.

Finally, a *reference frame* is a realization of a reference system based on measurements that are used to determine the free parameters in a reference system model. At least one reference frame should be defined as a part of the standard.

6.2 Reference Frame Reference Dataset

For a given transform between reference frames, a transformation matrix at an instant in time (or one or two rotation angles) relative to a base reference frame is needed. We also note that implementing transforms requires technical expertise in software and maintenance (for example, updating IGRF coefficients). Although providing a software version allows for reproducibility in principle, in practice, not all users will be familiar with the cited software, and in the long term, the software may not be maintained, or it may be difficult to install and use.

Based on this, we recommend that a reference dataset is developed with a long-term plan to keep it up-to-date. Each record in the dataset will consist of a timestamp and a matrix (or rotation angles) that are required to transform from a given coordinate system to a reference coordinate system. The records should be at 1-second cadence or less and be made in a standard scientific file format. A parsimonious alternative to providing 9 transform matrix values is to define only one or two angles that are needed to compute the matrix values.

With such a dataset, if a scientist wants to allow for reproducibility, they could state, for example, “the vector measurements in ABC were transformed into reference frame XYZ,” by using ABC to REF and REF to XYZ transformation matrices in the reference dataset and to cite both the standard that defines the acronyms and the reference dataset.

We have found that many software libraries do spot checks of transforms. For example, SunPy’s unit tests (Mumford et al., 2024) involve a comparison with a table from Fränz and Harper (2002) at several time instants; (Boller & Santiago, 2025) tests its implementation by comparing the ephemeris in GSE of one year of data from three spacecraft from SSCWeb (2025c) and compares its transformed ephemeris with that of SSCWeb (2025c); a comparison is also made with a table in Fränz and Harper (2002). With the proposed database, a software library developer could make a more comprehensive comparison with the reference dataset, allowing users to estimate uncertainties associated with coordinate transforms.

We also suggest that this dataset contains common time representations. Each record should be a UTC timestamp along with values for CDF_EPOCH, CDF_TT2000, TAI, etc. Although these time relationships are much easier to compute, some require leap second tables, and to perform the computation, one needs to parse (and update if required) the leap second table. An additional advantage of this dataset is that software developers can use it for unit testing their implementations.

This database may not be usable for all applications. However, it can still be used as a reference. For example, suppose the dataset provides transforms at 1-second cadence, but software generates transforms at a millisecond cadence (and interpolation is not acceptable). The software provider (or SPICE kernel author) can validate their transforms and make a statement about the difference in their transforms with respect to values determined by interpolation of the reference dataset.

One advantage of this dataset over software libraries is that the latter require continual upgrades. Although software automatically updating IGRF coefficients and leap second information may work at present, it is not guaranteed that all software will be maintained indefinitely into the future. In addition, transform results may change as a given software package evolves. For example, consider a package that utilizes non-definitive IGRF model coefficients for **MAG** and computes a transformation. Five years later, the result will not be the same if the software now uses definitive IGRF coefficients. Although it is possible in principle for the package developers to maintain reproducibility, doing so requires significant effort. The proposed dataset could address this by defining two **MAG** reference frames. One uses only definitive IGRF coefficients. The other only uses non-definitive. We also recommend that each release of the IGRF coefficients are given its own DOI and archived in a generalized repository. (At present, it is only possible to cite descriptions of the model, e.g., Alken et al. (2021), but not a specific release.)

Having a dataset of reference frame transform matrices (or angles) will address another issue. In the development of section 4.2, we encountered significant errors in four of the libraries, even though these libraries passed their tests. (These errors were reported and a version with the corrections was used in section 4.2). If these libraries had a more comprehensive set of test matrices, these errors would have been noticed.

6.3 Database of SPICE kernels

Historically, some satellite missions have used the SPICE software and associated SPICE kernels (~~configuration data files~~) to compute ephemeris and reference frame transforms. In addition, web services such as SSCWeb (2025c), JPL (2022), and Génot et al. (2018) use SPICE and SPICE kernels, and the SPICE project (NAIF, 2024) provides a set of SPICE kernels and information on how to obtain PDS-archived SPICE kernels. NASA (2025b) provides directories SPICE data for missions that both used and provided this information to it. In all of these cases, no common directory structure or file naming convention is used, and a single interface that documents the location of all mission-related SPICE information is not available. In addition, many SPICE kernel sets have coordinate transform specifications that are found in spacecraft mission-specific SPICE kernel sets; for example, both the Van Allen Probes and **Solar Orbiter** mission SPICE kernel sets include specifications for **GEI** and **GSE**.

Ideally all mission-specific SPICE kernels would be available from a single repository, kernels related to standard space physics reference frames would be shared across missions, and these standard kernels would either be used to generate the reference dataset described in section 6.2 or an evaluation of the differences between transforms using these SPICE kernels and the reference dataset would be provided as documentation.

We also recommend that modern version control systems are used. At present, kernels can be found at various web sites and the kernel versions are sometimes indicated in the file name, but the prior versions are not always provided, which inhibits reproducibility. Storing kernels in a source code repository, which handles versioning and simplifies research of changes, will improve this. Additionally, we recommend assigning unique identifiers, such as DOIs, to kernels to facilitate their citation.

6.4 Documentation

If the above recommendations are followed, the necessary documentation for reproducibility related to coordinate transforms will be simplified. For example, if an author or software package used the reference dataset described in section 6.2 for a transform, only the reference dataset is needed for reproducibility. Similarly, if one or more SPICE kernels are used and each has a unique DOI and stored in a permanent gener-

alized repository, only the DOIs are needed to retrieve the kernels. In this case, these DOIs and the SPICE software library version used are sufficient for reproducibility.

In the absence of these options, we recommend the following.

- Software package developers provide documentation on implementation choices (e.g., model used for obliquity). If data from an external resource is used (for example, if the IGRF coefficients are dynamically downloaded), the user should have an option to view the data used easily so that if important, the values used can be documented in a publication. Software should have DOI for each version (so that version used can be referenced rather than only a top-level DOI or paper).
- Metadata associated with ephemeris and variables that are transformed should have details about the software version used for the transforms or data used for the transform such as SPICE kernels. The metadata description should be validated by having a third-party consider if there is enough information in the description for them to re-implement the transform.
- Paper authors include the version of software (or DOI for that version, if available) used for transforms and publish SPICE kernels as supplementary material (if used and not citable and online) or post to generalized repository (e.g., Zenodo).
- Papers that use transforms using a software package should provide details on the options passed to the transform function (e.g., if the transform function allows for the selection of an obliquity model). Ideally software used for paper has DOI and is public.

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