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 from different providers can differ significantly (∼0.3°), as do Z–axis orientations from surveyed software libraries (∼0.03°).
- There is duplication of effort by spacecraft missions related to coordinate system transform calculations.

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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 enable reproducibility, we recommend that (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 (Spacecraft, Planet, Instrument, C-matrix, Events) kernels used by transforms by space physics spacecraft 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 provide recommendations for scientists and metadata developers to ensure that sufficient reproducibility–enabling information is provided in the absence of these recommendations being implemented.

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 terms in the remainder of this article.) This work stems from a project to develop a standard for ideal reference system acronyms such as `GEI`, `GSE`, `GSM`, and their commonly used variations, e.g., `GEI_J2000`, `GEI_MOD`; see the section 7 for definitions. 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 4.1, we give an example that demonstrates that the reported ephemeris for spacecraft 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 exhibits smaller, but possibly significant, differences.

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 *arbitrary* set of three orthogonal vectors and an origin. Common coordinate systems are Cartesian, cylindrical, and spherical. In the space physics literature, a coordinate system is generally meant as a *specific* set of three orthogonal vectors and an origin in which coordinate values can be specified using coordinate system such as Cartesian, cylindrical, or spherical; 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 involving analysis of data from the OGO (Orbiting Geophysical Observatory; NASA (1970)) 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 US Naval Observatory (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."

The terms "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 (or, equivalently, "implementing" or "realizing") one requires measurements for computing reference system model parameters. The "International Celestial Reference Frame (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 (in the sense that 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" in this quote should be interpreted not as meaning "preferred" but rather in the sense of "idealized model", or a model that has practical or important attributes omitted to simplify its description.

Thus, what space physicists call "coordinate systems" (e.g., `GEI`, `GSM`) 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 system 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) uses 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 (Spacecraft, Planet, Instrument, C-matrix, Events; 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” refers 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

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`; Satellite Situation Center System and Services (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 them and the center of mass of Earth. 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, that is, the orientation of the ecliptic and Earth’s rotation axis is averaged such that nutation variation is removed. If nutation variation is not averaged out, 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. (An exact reference date and time is referred to as epochs in the sense of a time instant rather than a period of time.)

Two basic categories of `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 following summary of `GEI`–related reference systems and frames below, we have ignored this technicality.

The objective of the following summary is to demonstrate the diversity in the terms and definitions used for `GEI`–related reference systems and to motivate the need for the standard recommended in section 6.

- `J2000` – Used by Satellite Situation Center System and Services (2025c) to refer to a frame with its origin at Earth’s center of mass and in SPICE to refer to a system with origin at the solar system barycenter (Acton (1997); NAIF (2025)).

  Satellite Situation Center System and Services (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 [$2.\overline{7}\cdot 10^{-5}$ 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."

- GEI2000 – Satellite Situation Center System and Services (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 (Mumford et al., 2024) with supporting definition of "A coordinate or frame in the Geocentric Earth Equatorial (GEI) system."
- GCRS – Used in AstroPy (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$_{\mathrm{J2000}}$ – Fränz and Harper (2002) state that GEI$_{\mathrm{J2000}}$ 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 "... with those of the J2000 (aka EME2000) reference frame". Satellite Situation Center System and Services (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 SpacePy (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."

  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).

4 Comparisons

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

1. From datasets provided to a data archive (e.g., NASA's Coordinated Data Analysis Web (CDAWeb) and ESA's Cluster Science Archive (CSA)) with vector measurements in different coordinate systems; in this case, the scientist selects a dataset in a needed coordinate system, if available.

2. Using data services that provide vector measurements in different coordinate systems. For example, SSCWeb provides ephemeris values for spacecraft in various coordinate systems as a function of time (Satellite Situation Center System and Services, 2025c) and a calculator that takes an input of a geocentric position in a given reference system at a specific time and outputs the position in other reference systems (Satellite Situation Center System and Services, 2025a).

3. Using 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.

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 ...".

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 (e.g., plasma sheet, interplanetary medium, plasmasphere) given an arbitrary position, we implemented the models used by (Satellite Situation Center System and Services, 2025c) and attempted to validate our work by comparing our predicted regions at the positions provided by its web service for spacecraft. Although our predictions were generally consistent, we were unable to reproduce the exact time when a spacecraft 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 mismatch 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, `SpacePy` (Morley et al., 2024) provides multiple options for computing the `MAG` system, which have angular differences of $\sim$0.01°, and `SunPy` (Mumford et al., 2024) has options for how the `GEI` frame is computed (see section 4.2). A general finding is that the differences in the transform results using a single library but with different options for the transform 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 with 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 is illogical for two data providers to report the location of a spacecraft 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 dataset, e.g., by including the word "preliminary").

4.1 Ephemeris

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

In Figure 1, the ephemeris of the Geotail spacecraft from `2021-11-25` through `2021-12-05` is shown from the Satellite Situation Center System and Services (2025c) web service and CDF (Common Data Format, 2025) files in from CDAWeb. SSCWeb provides the ephemeris for scientific spacecraft 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, $\overline{r}$, from the two providers and errors relative to an Earth radius, $R_E \equiv 6378.16$ 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 Geotail data is 2 minutes while the CDAWeb Geotail dataset is at a 10–minute cadence. In the time interval displayed in Figure 1, values from the datasets are only used when they had the same timestamps in the time interval shown.

Based on the documentation for Satellite Situation Center System and Services (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 between their position vectors is $\Delta\theta \sim 0.3°$, and the average error relative to an Earth radius, $|\Delta\mathbf{r}|/R_E \sim 0.16$, or 16%. The maximum error relative to the radius, $|\Delta\mathbf{r}|/\overline{r}$ 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 $|\Delta r|/R_E \simeq 10^{-10}$ 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 $\overline{r} = 20R_E$, this corresponds to an uncertainty due to the precision of the data of $\Delta\theta \simeq 20 \cdot (180/\pi) \cdot 10^{-10}$ degrees $\simeq 10^{-7}$ degrees.

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 ∼0.002° and an average error relative to an Earth radius of ∼0.05%.

Angular differences can be compared to:

1. The average angular change in Earth's dipole Z axis of ∼0.04° per year (from 1970–2025, computed using the libraries considered in section 4.2).
2. The precession (also referred to as luni–solar precession) of Earth's rotation axis (also the $\texttt{GEI}_Z$ axis), which drifts by $\simeq 0.006°$ per year (Hapgood, 1995).
3. The one–year change in angle due to nutation of Earth's rotation axis of $\simeq 0.0025°$ per year (Hapgood, 1995).
4. The precession of the ecliptic (planetary precession) of $\Delta\theta \simeq 0.000014°$ per year (Hapgood, 1995).

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 numerical precision of the reported values 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 $\texttt{GEI}_X$ to align Earth's equator with the ecliptic plane and a rotation around the $\texttt{GEI}_Z$ axis (as it is after the first rotation) to orient $\texttt{GEI}_X$ towards the center of the Sun. 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 on the 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 $\sim 0.04°$, is computed. If both SSCWeb and CDAWeb computed the `GSM` ephemeris based on a transform from `GSE`, we could conclude that the observed $\Delta\theta$ are due to the use of different locations of the North geomagnetic pole. However, the maximum $\Delta\theta \simeq 0.37°$ is much larger than the average yearly angular change in the dipole Z axis of $\sim 0.04°$.

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 documented), and `SunPy` is used to transform it to other reference frames.

Figure 2a shows that the $\Delta\mathbf{r}$ between `GSE` locations from CDAWeb and SSCWeb match to within ~ 3 km, which is much larger than expected by numerical precision 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 $\sim 1°$ instead of 0.003° found in the comparison of SSCWeb and CDAWeb in Figure 2a. A similar conclusion is made by a comparison of Figure 2b and Figure 2d. A possible explanation for the sharp increase in $\Delta\theta$ near 11:00 is a thruster firing – the raw JPL Horizons web service output notes that "The spacecraft may be maneuvered frequently. Therefore, the JSpOC TLE-based [Joint Space Operations Center Two–Line Element] 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.".

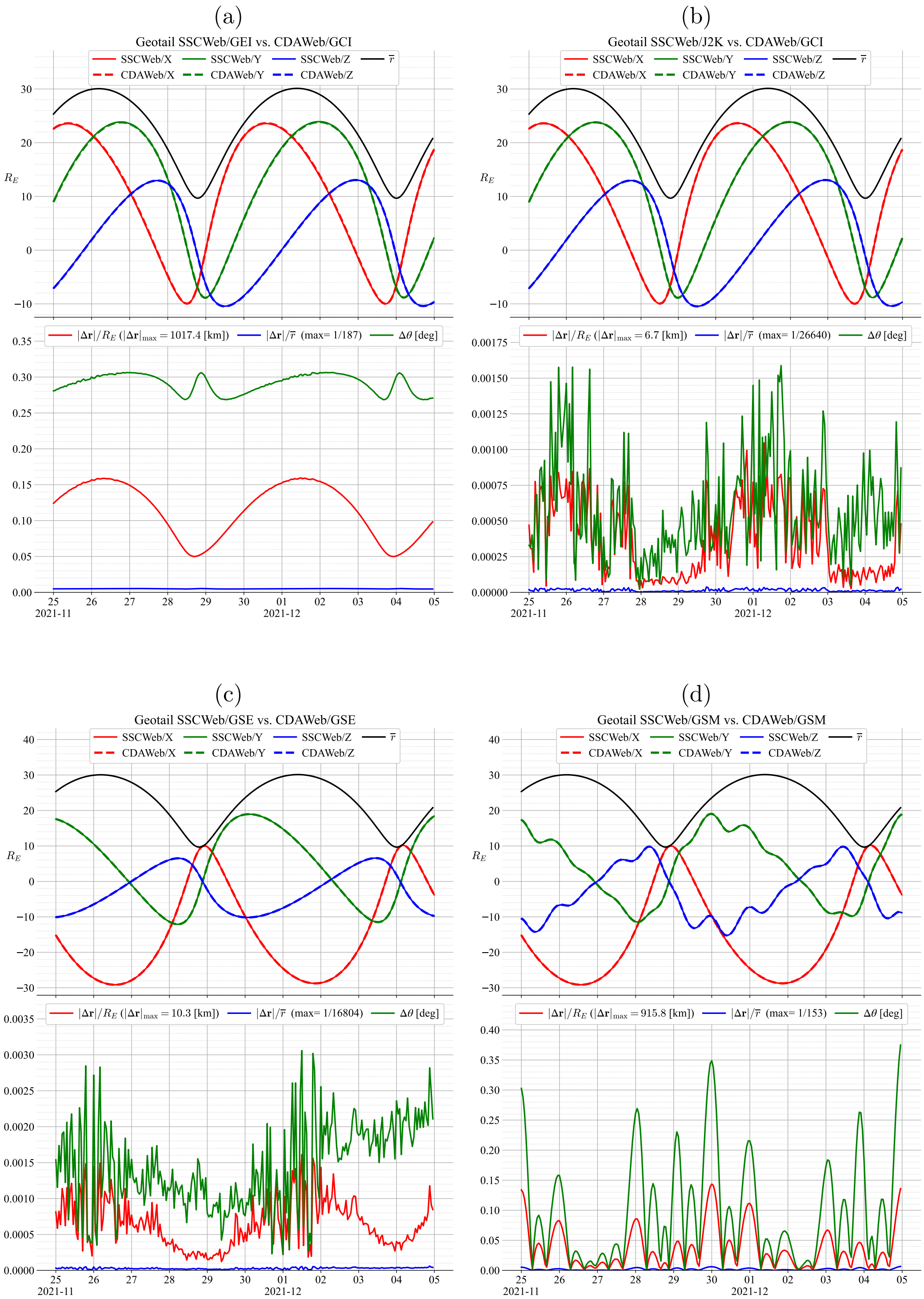

Figure 1: Comparison of ephemeris values from SSCWeb and CDAWeb in four different reference systems.

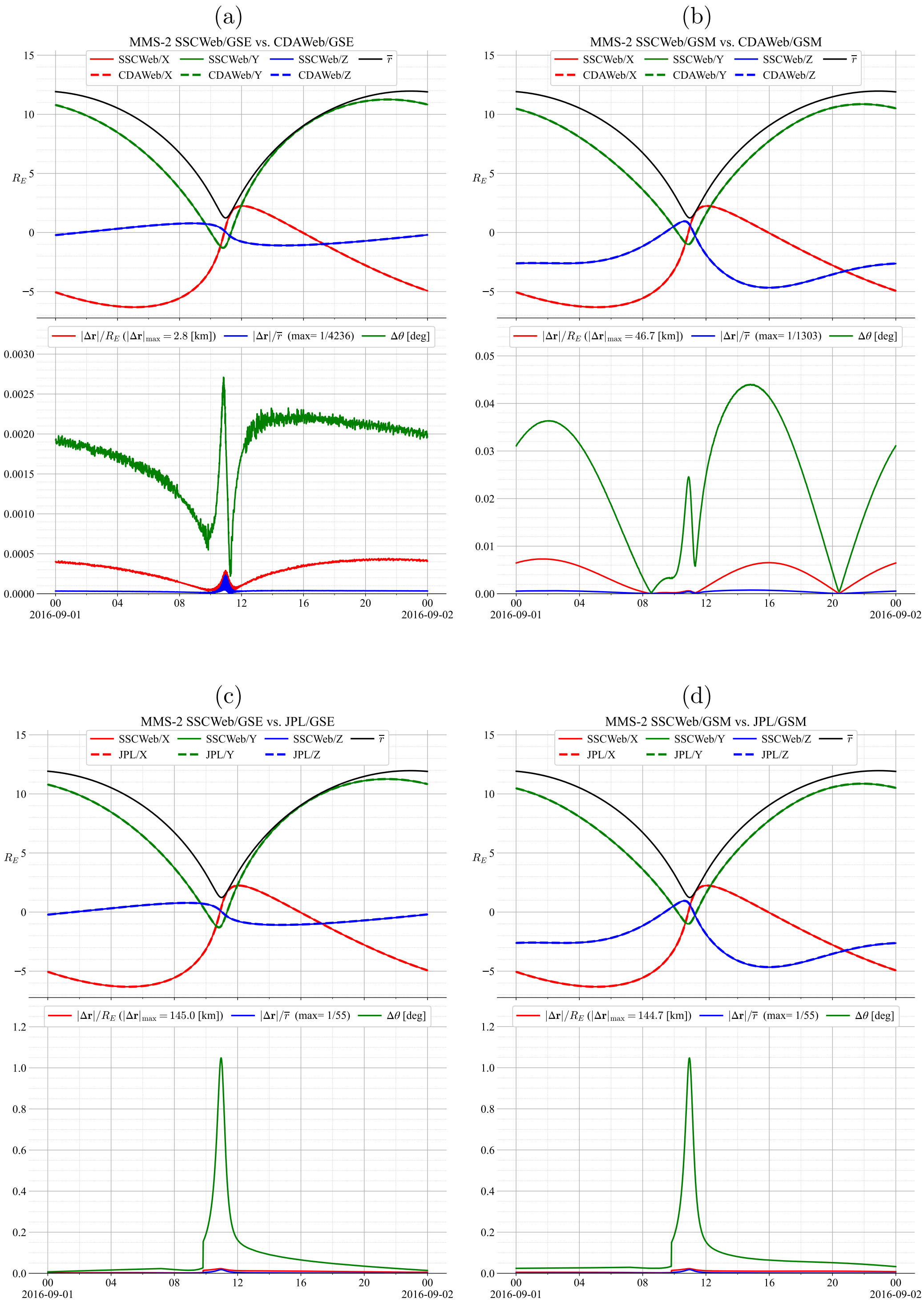

Figure 2: Comparison of ephemeris values from SSCWeb and CDAWeb (panels (a) and (b)) and SSCWeb and JPL Horizons in two different reference systems.

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` in the figures in this section), a Fortran library that was upgraded from earlier versions to support calculations using 64–bit floating point values.
- `PySPEDAS` 1.7.28, which uses transformation code derived from the IDL version of ~~Py~~`SPEDAS` (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).
- `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.
- `SpiceyPy` 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 (Alken et al., 2021) to determine the Earth's magnetic dipole orientation.
- `SunPy` version 7.0.0

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 an uncertainty estimate when comparing data transformed using different software libraries.

In general, the differences in Figure 3 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 maximum differences among the libraries, which is displayed in the lower panel of each subplot.)

The maximum annual difference of 0.009° is approximately 1/4 of the average yearly angular change in the dipole Z axis of ∼0.04° (from 1970–2025) and 1.5 times the average precession of Earth's rotational axis (∼0.006° per year).

We have also performed coordinate transforms using the (Satellite Situation Center System and Services, 2025a) web service. However, this web service 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.

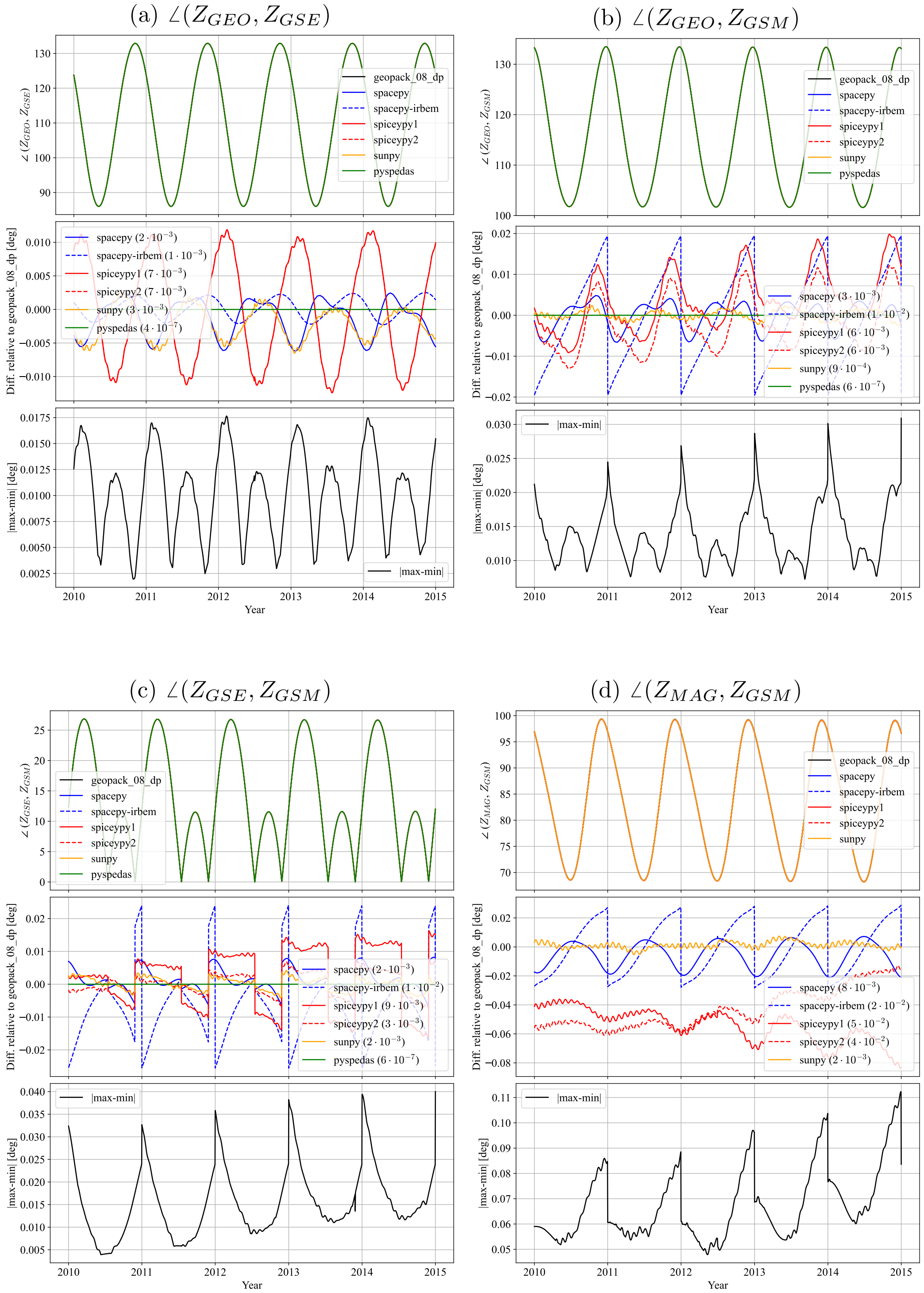

Figure 3: Angles between Z axes in select coordinate frames. In the top panels of each subplot, the notation $\angle(Z_A, Z_B)$ means the angle between the Z axis of coordinate frame A in coordinate frame B and the Z axis of coordinate frame B. The middle panel of each subplot shows the difference in 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 spacecraft 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, 2025). Modern missions typically take one of two approaches: (a) A mission operations team develops SPICE kernels for select space physics reference frames, and SPICE software is used for the transforms; or (b) A non–SPICE software library is used for the transforms, for example, `ROCOTLIB` and `SpacePy`.

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 or SPICE kernels and develop tests.

As noted in the conclusions, this effort to develop and verify transforms for variables into different reference frames would not be necessary if either a database of transform matrices or versioned SPICE kernels were available that were accepted as a community standard.

For the SSCWeb data service (Satellite Situation Center System and Services, 2025c), which provides spacecraft ephemeris, three approaches have been taken in order of priority (see Satellite Situation Center System and Services (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 its `J2000` ephemeris. Then International Solar-Terrestrial Physics–era (ISTP; International Solar Terrestrial Physics (2025)) 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 Dynamics Facility, FDF. This approach is only used on ISTP–era missions, e.g., ACE, Polar, Wind, and Geotail.

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; if the CDF files contain ephemeris in reference frames other than the `GEI`–related frame, they are not used.

3. If SPICE kernels or other mission–computed values are not available, TLE (Two-Line Element) files are obtained from NORAD (North American Aerospace Defense Command), and a translation of the C NORAD library to Pascal (Brodowski, 2002) is used to compute ephemeris in `TEME` (True Equator, Mean Equinox). Often, TLEs are used at the start of the mission, and a switch is made to approaches 1 or 2 as information becomes available.

6 Summary and Recommendations

In this section, we provide recommendations to address the issues identified in this article.

6.1 Standards for Reference System and Frame Definitions

As defined in section 2, an *ideal reference system* is a general description of a reference frame that lacks key details necessary for its implementation. 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 relative to an ideal reference system is a *reference system*, which defines constants, models, and algorithms used to transform between observable quantities and reference data.

Finally, a *reference frame* is a realization of a reference system based on measurements that are used to determine the free parameters the models specified in a reference system model.

A community–developed standard should be created for acronyms and definitions. The standard should provide abbreviation/definition pairs for commonly used space physics ideal reference frames. Associated with each ideal reference frame definition, there should be at least one reference system abbreviation/definition pair; if multiple reference systems are in common use, they should have their definition and way of being referred to. For each reference system, there should be at least one reference frame abbreviation/definition.

6.2 Reference Frame Reference Dataset

For a given transform between reference frames, a transformation matrix at a specific instant in time (or, equivalently, rotation angles or quaternions) relative to a base reference frame is required. We also note that implementing transforms requires technical expertise in software and maintenance, for example, updating parameters in reference frames, verifying the calculations, and documenting changes. 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 be developed with a long–term plan to keep it up–to–date. Each record in the dataset should consist of a timestamp and a matrix that is required to transform from a given coordinate system to a reference coordinate system. The records should be made available in a standard scientific file format and from a web service API (Application Programming Interface). A parsimonious alternative to providing 9 transform matrix values is to define only one or two angles (and associated rotation axes) 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 citing 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; `cxform` (Boller & Santiago, 2025) tests its implementation by comparing the ephemeris in `GSE` of one year of data from three spacecraft from Satellite Situation Center System and Services (2025c); a comparison is also made with a table in Fränz and Harper (2002). With the proposed reference database, a software library developer could make a more comprehensive comparison, allowing users to directly 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 `UT1`, `TAI`, `TT`, and `ET` (McCarthy, 2011). Although these time relationships are simple, 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 testing their implementations.

One advantage of this dataset over software libraries is that the latter require continual upgrades. Although software that automatically updates IGRF coefficients and leap second information may work now, it is not guaranteed that it will be maintained and usable 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 then 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 be 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 will address another issue. In the development of section 4.2, we encountered significant errors in four of the libraries, despite these libraries passing 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 transform kernels

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 be used. At present, kernels can be found at various websites, 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 the research of changes, will improve this. Additionally, we recommend assigning unique identifiers, such as DOIs, to kernels to facilitate their citation.

6.4 Versioning of Ephemeris

In this work, we have been primarily interested in the problem of transforming a vector between reference frames. In the case of an ephemeris provided in a given reference frame, there is an uncertainty due to what is meant by that reference frame, which is addressed by the recommendation in section 6.1.

There is an additional source of uncertainty – how the ephemeris was determined. Missions have used direct GPS measurements, commercial software such as STK (Systems Tool Kit), and data from facilities such as GSFC Flight Dynamics Facility (FDF), Deep Space Network (DSN), NAIF, and NORAD.

Section 4.1, we show an example where the ephemeris for two different data providers for the same spacecraft differed in a way that was unlikely to be due to differences in how the data providers implemented the reference frame.

6.5 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 generalized 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 easily view the data used, so that, if necessary, the values used can be documented in a publication. Software should have a DOI for each version so that the 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 (and a DOI for that version, if available) used for transforms and publish SPICE kernels as supplementary material (if used and not otherwise citable and online) or post to a 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, the software used for the paper has a DOI and is public.

7 Definitions

- ACE – Advanced Composition Explorer (spacecraft mission)
- CDAWeb – Coordinated Data Analysis Web (NASA data archive)
- CDF – Common Data Format (file format for scientific data)
- DSN – Deep Space Network (NASA communications network)
- ECI – Earth-Centered Inertial (reference frame)
- EME – Earth Mean Equator (reference frame)
- ET – Ephemeris Time (time standard)
- GEI – Geocentric Equatorial Inertial (reference system)
- GEO – Geographic (reference system)
- GM – Geomagnetic (reference system, often called MAG)
- GSE – Geocentric Solar Ecliptic (reference system)
- GSM – Geocentric Solar Magnetospheric (reference system)
- GCI – Geocentric Celestial Inertial (reference system)
- GCRS – Geocentric Celestial Reference System (reference system)
- GPS – Global Positioning System
- GSFC – Goddard Space Flight Center (NASA center)
- IGRF – International Geomagnetic Reference Field (geomagnetic model)
- ISTP – International Solar-Terrestrial Physics (NASA program)
- IRBEM – International Radiation Belt Environment Modeling (software library)
- ICRF – International Celestial Reference Frame (reference frame)
- ICRS – International Celestial Reference System (refernce system)
- J2000 – Reference system with reference epoch of 2000 January 1 noon TT.
- J2000.0 – Reference epoch associated with J2000
- J2K – Abbreviation of J2000
- JPL – Jet Propulsion Laboratory
- MMS – Magnetospheric Multiscale Misson
- NAIF – Navigation and Ancillary Information Facility
- MOD – Mean of Date (reference frame modifier, precession only)

- NORAD – North American Aerospace Defense Command
- SM – Solar Magnetic (reference system)
- SPICE – Spacecraft, Planet, Instrument, C-matrix, Events (NAIF toolkit)
- SPEDAS – Space Physics Environment Data Analysis Software (software library)
- SSCWeb – Satellite Situation Center Web (NASA data service)
- STK – Systems Tool Kit (commercial orbit analysis software)
- TAI – International Atomic Time (time standard)
- TT – Terrestrial Time (time standard)
- TLE – Two-Line Element set (satellite orbital elements)
- TEME – True Equator, Mean Equinox (reference system)
- UT1 – Universal Time 1 (time standard)

8 Open Data

The software, data, and associated calculations are available in (Weigel et al., 2025). The additional software used and their versions and references is referenced in section 4.2.

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