

**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 inconsistencies in definitions and implementations in software.
- Ephemerides from different providers can differ significantly, as do Z -axis orientations from surveyed software libraries.
- We present recommendations to improve the precision and reproducibility of these calculations and reduce effort duplication by missions.

13 **Abstract**

14 In space physics, acronyms for coordinate systems (e.g., GEI, GSM) are commonly used;
 15 however, differences in their definitions and implementations can prevent reproducibility.
 16 In this work, we compare definitions in online resources, software packages, and frequently cited journal articles and show that implementation differences can lead to trans-
 17 formations between same-named coordinate systems and ephemerides values from dif-
 18 ferent data providers to differ significantly. Based on these comparisons and results, and
 19 to enable reproducibility, we recommend that (a) a standard for acronyms and defini-
 20 tions for coordinate systems is developed; (b) a standards body develops a citable database
 21 of reference data needed for these transforms; (c) a central authority maintains the SPICE
 22 (Spacecraft, Planet, Instrument, C-matrix, Events) kernels used by space physics space-
 23 craft missions to generate data products in different coordinate systems; and (d) soft-
 24 ware developers provide explicit comparisons of their implementations with the results
 25 of (b) and documentation on implementation choices. Additionally, we provide recom-
 26 mendations for scientists and metadata developers to ensure that sufficient information
 27 is provided to enable reproducibility if these recommendations are not implemented.

29 **1 Introduction**

30 In space physics, journal articles, software, and online resources, the definition of
 31 a coordinate system is typically given by citing a reference that describes it. This work
 32 stems from a project to develop a standard for terms and descriptions for coordinate sys-
 33 tem acronyms such as GEI, GSE, GSM, and their commonly used variations, e.g., GEI_J2000,
 34 GEI_MOD; see Appendix A for definitions and Russell (1971), Hapgood (1992), Fränz and
 35 Harper (2002), and Laundal and Richmond (2016) for additional details. The objective
 36 is that, given a statement such as “the vector measurements in ABC were transformed
 37 into XYZ,” a scientist with measurements in ABC would be able to reproduce the trans-
 38 formation with the only uncertainty being due to rounding errors associated with float-
 39 ing point precision.

40 As documented in this work, comparing data transformed with different software
 41 is complicated by the fact that transform implementations are not unique, introducing
 42 unknown uncertainty. In the early era of space physics, uncertainty due to implemen-
 43 tation differences was much smaller than measurement uncertainty. Here, we argue that,
 44 in some applications, these differences matter and that implementation uncertainty poses
 45 an unnecessary impediment to reproducibility and intercomparison of data. In addition,
 46 as a matter of scientific practice, terms and definitions should be precise.

47 Our background research revealed additional issues that must be addressed to meet
 48 the objective of reproducibility in the sense defined above. First, implementing a given
 49 coordinate system given a general description requires making implementation choices.
 50 Therefore, terms and definitions for reference implementations are also needed. In sec-
 51 tions 2, we note that in astronomy and the earth sciences, this has been recognized and
 52 addressed, and we describe their terminology and conventions.

53 Second, the standard for terms and descriptions must address their existing am-
 54 biguity. Examples of ambiguity are given for the GEI coordinate system in section 3. The
 55 general conclusion is that in space physics, there is no agreed-upon standard for coor-
 56 dinate system acronyms, and descriptions generally lack key implementation details.

57 To quantify the impact of ambiguity in definitions and implementations, we give
 58 examples that demonstrate the reported ephemerides for spacecraft in the same-named
 59 reference systems can significantly differ depending on the data source in section 4.1. In
 60 section 4.2 we demonstrate that software that transforms a vector between two coordi-
 61 nate systems exhibits smaller, but possibly significant, differences.

Having summarized the problems arising from ambiguity in definitions and implementations, we next consider how spacecraft missions compute transforms. To meet the objective of reproducibility, we must understand how calculations are performed in practice and account for this in our recommendations. In section 5, we describe how missions develop data products in different coordinate systems, which may explain the differences observed in the ephemeris results in section 4.1.

In section 6, we provide a set of recommendations that address definition issues described in section 3, the results in section 4, and the description in section 5. These recommendations address ambiguity in terminology and definitions, how software for transforms is created and tested, and how missions compute transformed data products.

2 Coordinate Systems, Reference Systems, and Reference Frames

Thus far, we have used the term “coordinate system” consistent with common usage in space physics as described in section 2.1. In section 2.2, 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.

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, with coordinate values expressed in a coordinate system such as Cartesian, cylindrical, or spherical.

This usage, which “coordinate system” has two meanings, 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 in astronomy is the International Celestial Reference System (ICRS) (Petit & Luzum, 2010). No unique reference frame is associated with this reference system because creating (or, equivalently, “realizing” or “implementing”) one requires measurements for computing reference system model parameters. The International Celestial Reference Frame (ICRF) is the general name for realizations of

108 the ICRS that are agreed upon by a standards body and are updated as new measure-
 109 ments and model versions become available. There are three versions of the ICRF (Charlot
 110 et al., 2020).

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

118 Thus, what space physicists call a “coordinate system” (e.g., **GEI**, **GSM**) is analo-
 119 gous to an “ideal reference system” because it only has a general definition for their axes
 120 orientation and origin. There are no standards for the constants, models, or algorithms
 121 required to transform between observable quantities, which are necessary to define a ref-
 122 erence system, nor for the model parameters needed to define a reference frame. For ex-
 123 ample, the **GSE** reference frame requires a vector from the center of Earth to the center
 124 of the Sun — Russell (1971) gives a Fortran program provided through private commu-
 125 nication; Hapgood (1992) uses equations from Doggett et al. (1990); and Fränz and Harper
 126 (2002) uses equations from Seidelmann et al. (1992). All three cases can be regarded as
 127 unique **GSE** reference frames for the **GSE** reference system.

128 Terminology related to reference systems and frames also varies in other fields. For
 129 example, SPICE (Spacecraft, Planet, Instrument, C-matrix, Events; NAIF (2023)) states
 130 “a reference frame (or simply ‘frame’) is specified by an ordered set of three mutually
 131 orthogonal, possibly time-dependent, unit-length direction vectors; this definition does
 132 not include an origin. In robotics, the term “coordinate frame” refers to a set of three
 133 orthogonal axes and an origin relative to a different coordinate frame (Murray et al., 1994).

134 3 Examples of Definition Ambiguity

135 In the previous section, examples were given of general issues with the terminol-
 136 ogy used to describe reference systems and frames. For specific reference systems or frames
 137 in space physics, there are additional ambiguities.

138 For example, we **GEI**. The **GEI** ideal reference frame has **Z** aligned with Earth’s ro-
 139 tation axis with positive northward, **X** as the intersection of Earth’s equatorial plane with
 140 the plane of Earth’s orbit around the Sun (the ecliptic plane), with positive in the di-
 141 rection from the Earth to the Sun at the time of the vernal equinox, and **Y** = **Z** × **X**.
 142 The line of intersection of Earth’s equatorial plane with the ecliptic, or the time that it
 143 is computed, is sometimes referred to as “the equinox,” and whether a line or time is meant
 144 must be determined from context.

145 First, there is no consistency in the expansion of the acronym **GEI**. Russell (1971)
 146 and Hapgood (1992) associate **GEI** with “Geocentric Equatorial Inertial System”. Fränz
 147 and Harper (2002) and Mumford et al. (2025) associate **GEI** with “Geocentric Earth Equa-
 148 torial”. Another ambiguity is in **GCI**; Satellite Situation Center System and Services (2025c)
 149 notes “Geocentric Inertial (**GCI**) and Earth-Centered Inertial (**ECI**) are the same as **GEI**.”,
 150 which implicitly defines **GCI** as “Geocentric Inertial”, in contrast to Russell (1971) and
 151 NASA (1970), which use “Geocentric Celestial Inertial”.

152 When reporting positions for **GEI**, the origin is taken as the center of mass of Earth.
 153 To establish this as a reference system as defined in section 2.2, Earth’s rotation axis,
 154 center, and the ecliptic plane must be specified, along with the models used to compute
 155 them. To define a **GEI** reference frame, the model parameters must be specified.

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 nutation variation is estimated and removed. If nutation variation is not removed, the term "true epoch-of-date" or "true-of-date" is used (Hapgood, 1995). If the **X** and **Z** orientations are time independent, an abbreviation for a reference date and time is specified, e.g., J2000.0 (2000-01-01T12:00 Terrestrial Time), at which they were determined. The reference date and time is referred to as an "epoch" in the sense of a reference 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 its 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 6.1. Similar diversity also exists in terminology and definitions in other commonly used reference systems in space physics, further motivating.

- **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 by 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 [$2.7 \cdot 10^{-5}$ 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., 2025) 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).²⁰⁵
- 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 “... 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 the 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.²¹⁸²¹⁹

220 4 Comparisons

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

- 223 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 reference systems; in this case, a dataset in a needed reference frame is selected, if available.
- 227 2. Using data services that provide vector measurements in different reference frames. For example, SSCWeb provides ephemerides for spacecraft in various reference frames 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).
- 233 3. Using software packages that have coordinate transform functions. For example, in Python, **Astropy** (Price-Whelan et al., 2022), **SunPy** (Mumford et al., 2025), **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.

238 It is sometimes argued that, although reference-frame implementations may yield
239 different results, this uncertainty is small relative to measurement uncertainty. For ex-
240 ample, Hapgood (1995) notes that “The attitude error that arises from an error in the
241 epoch used to compute GEI is 0.036°, which is small compared to the angular resolution
242 of most space plasma measurements ...”.

243 Although this statement was made thirty years ago, based on the results in this
244 section, it appears the convention in space physics is that differences at this level are con-
245 sidered negligible. That is, we find angular differences in the ephemerides from differ-
246 ent providers of ∼0.3° and coordinate transforms from different software packages of ∼0.03°,
247 and this uncertainty is not discussed in the documentation, suggesting that it is consid-
248 ered small enough to be ignored.

249 Although the convention for determining which uncertainties are considered neg-
 250 ligible may have been appropriate at one time, we suggest revisiting these assumptions.
 251 First, spacecraft constellations now have a nearest separation of 7 km (NASA, 2016). This
 252 separation was achieved for the MMS constellation when the spacecraft were at a radial
 253 distance of $\sim 8.9 R_E$ from Earth's center. At this radial distance, the angular separation
 254 between two points 7 km apart is 0.007° . Second, having different data providers or soft-
 255 ware libraries compute transforms in different ways can impede validation, for example,

- 256 • In an attempt to develop a 3D visualization program that returns the region of
 257 geospace (e.g., plasma sheet, interplanetary medium, plasmasphere) given an ar-
 258 bitrary position, we implemented the models used by SSCWeb (Satellite Situa-
 259 tion Center System and Services, 2025c) and attempted to validate our work by
 260 comparing our predicted regions at the positions provided by its web service for
 261 spacecraft. Although our predictions were generally consistent, we were unable
 262 to reproduce the exact time at which a spacecraft crossed from one region to an-
 263 other. After a search for errors in our model implementation failed to explain the
 264 differences, we realized that the discrepancies were due to the software that we
 265 used for reference-frame transformation differing from that used by SSCWeb.
- 266 • Not all global magnetosphere simulation models are executed in the same refer-
 267 ence frame. To compare two models, the solar wind input must be transformed
 268 to the simulation reference frame, and simulated variables from both models must
 269 be transformed into the same reference frame for comparison. The uncertainty as-
 270 sociated with this transformation must be known to determine the difference in
 271 the model output attributable to the simulation algorithm.

272 The fact that different software libraries provide different options for reference frames
 273 is indirect evidence that differences can matter. For example, **SpacePy** (Morley et al.,
 274 2024) provides multiple options for computing the **MAG** system, which have angular dif-
 275 ferences of $\sim 0.01^\circ$, and **SunPy** (Mumford et al., 2025) has options for how the **GEI** frame
 276 is computed. A general finding is that differences in transform results within a single li-
 277 brary, with different options for the transform, are on the order of, or smaller than, dif-
 278 ferences in transform results between two different software libraries. As a result, im-
 279 provements in how a transform is computed within a single library are lost when com-
 280 paring data computed with a different library.

281 Even if the uncertainty associated with how a given reference frame was implemented
 282 is small relative to that of the measurements, we suggest that it is illogical for two data
 283 providers to report the location of a spacecraft that differs by more than what is expected
 284 due to numerical precision unless the reason for differences is clearly documented and
 285 ideally evident in the name of the dataset, e.g., by including the word “preliminary”. A
 286 recommendation for addressing this is given in section 6.4.

287 4.1 Ephemerides

288 In this section, we give examples showing how ephemerides values from data providers
 289 can differ. We quantify the differences in terms of three quantities:

- 290 • $|\Delta\mathbf{r}|/R_E$, the magnitude of the difference in position vectors relative to an Earth
 291 radius, with $R_E \equiv 6378.16$ km, which is the value used by SSCWeb;
- 292 • $|\Delta\mathbf{r}|/\bar{r}$ the magnitude of the difference in position vectors relative to the average
 293 of the magnitudes of the position vectors; and
- 294 • $\Delta\theta$, the angular difference between position vectors.

295 Angular differences can be compared to:

1. The average angular change in Earth's dipole Z axis of $\sim 0.04^\circ$ per year (from 1970–2025, computed using the libraries used in section 4.2).
2. The precession, also referred to as luni–solar precession, of Earth's rotation axis (also the GEI_Z reference system axis), which 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).

Figure 1 shows the ephemerides of the Geotail spacecraft from 2021–11–25 through 2021–12–05 from the SSCWeb web service and the `GE_OR_DEF` dataset in CDF (Common Data Format, 2025) files from CDAWeb. SSCWeb provides ephemerides for scientific space–craft in reference systems that include `GEI`, `J2K`, `GSE`, `GSM`, and `GM` (frequently referred to as `MAG`). The `GE_OR_DEF` dataset has ephemerides values in `GCI`, `GSE`, and `GSM`.

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 12 minutes while the CDAWeb Geotail dataset is 10-minutes. In the time interval displayed in Figure 1, values from the datasets are only shown when they have the same timestamps in the time interval shown.

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 $\bar{r} = 20R_E$, this corresponds to an uncertainty due to the precision of the data of $\Delta\theta \simeq 20 \cdot (180/\pi) \cdot 10^{-10}$ degrees $\simeq 10^{-7}$ degrees.

In Figure 1(a), and 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` ephemerides difference to be near $\simeq 10^{-7}$ degrees, assuming both data sources use the same definition of `GEI`. The average angular difference between position vectors is $\Delta\theta \sim 0.3^\circ$, 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 average geocentric distance, $|\Delta\mathbf{r}|/\bar{r}$ is 1/187, or 0.5%.

In Figure 1(b), there is a much closer match between SSCWeb/`J2K` and CDAWeb/`GCI` ephemerides, with an average angular difference in the position vector of $\sim 0.001^\circ$ 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 ephemerides is much closer to SSCWeb/`J2K` ephemerides than SSCWeb/`GEI`, which is unexpected given the SSCWeb documentation that notes `GCI` and `GEI` are equivalent. Although the CDAWeb/`GCI` ephemerides is a better match to the SSCWeb/`J2K` ephemerides, the differences are not explained by the numerical precision of the reported values. They may be due to whether or how precision and nutation in items 2.–4. listed above were accounted for.

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

344 In Figure 1(d), a comparison is made for the **GSM** reference system. A vector in the
 345 GSE reference system is transformed to **GSM** by an angle that depends on the orientation
 346 of the North geomagnetic pole (Russell (1971); Hapgood (1992)). The primary uncer-
 347 tainty is how the orientation of the North geomagnetic pole, which has an average yearly
 348 change of $\sim 0.04^\circ$, is computed. If both SSCWeb and CDAWeb computed the **GSM** ephemerides
 349 based on a transform from **GSE**, we could conclude that the observed $\Delta\theta$ are due to the
 350 use of different locations of the North geomagnetic pole. However, the maximum $\Delta\theta \simeq$
 351 0.37° is much larger than the average yearly angular change in Earth's dipole *Z* axis of
 352 $\sim 0.04^\circ$.

353 In Figure 2, a comparison is made between data from SSCWeb, CDAWeb, and the
 354 JPL Horizons web service (JPL, 2022), which provides ephemerides for some of the space-
 355 craft available from SSCWeb. The CDAWeb dataset is **MMS2_EPD-EIS_SRVY_L2_ELECTRONENERGY**.
 356 The JPL Horizons web service provides ephemerides in the **ICRF** reference frame (the
 357 version of **ICRF** is not documented), and **SunPy** is used to transform it to other reference
 358 frames.

359 Figure 2a shows that the $\Delta\mathbf{r}$ between **GSE** locations from CDAWeb and SSCWeb
 360 match to within ~ 3 km, which is much larger than expected by numerical precision but
 361 smaller than the closest separation distance of MMS spacecraft of ~ 7 km (NASA, 2016).
 362 Figure 2b shows that there are larger differences for **GSM**.

363 In Figure 2c, much larger differences are shown to exist between SSCWeb and JPL
 364 than between SSCWeb and CDAWeb, with the maximum angular difference being up
 365 to $\sim 1^\circ$ instead of 0.003° found in the comparison of SSCWeb and CDAWeb in Figure 2a.
 366 A similar conclusion is made by a comparison of Figure 2b and Figure 2d. A possible
 367 explanation for the sharp increase in $\Delta\theta$ near 11:00 is a thruster firing – the raw JPL
 368 Horizons web service output notes that “The spacecraft may be maneuvered frequently.
 369 Therefore, the JSpOC TLE-based [Joint Space Operations Center Two-Line Element]
 370 trajectory provided here may at times depart from the actual trajectory. This can hap-
 371 pen because TLEs do not model thruster firings; the TLE trajectory solutions must be
 372 reinitialized after each event.”

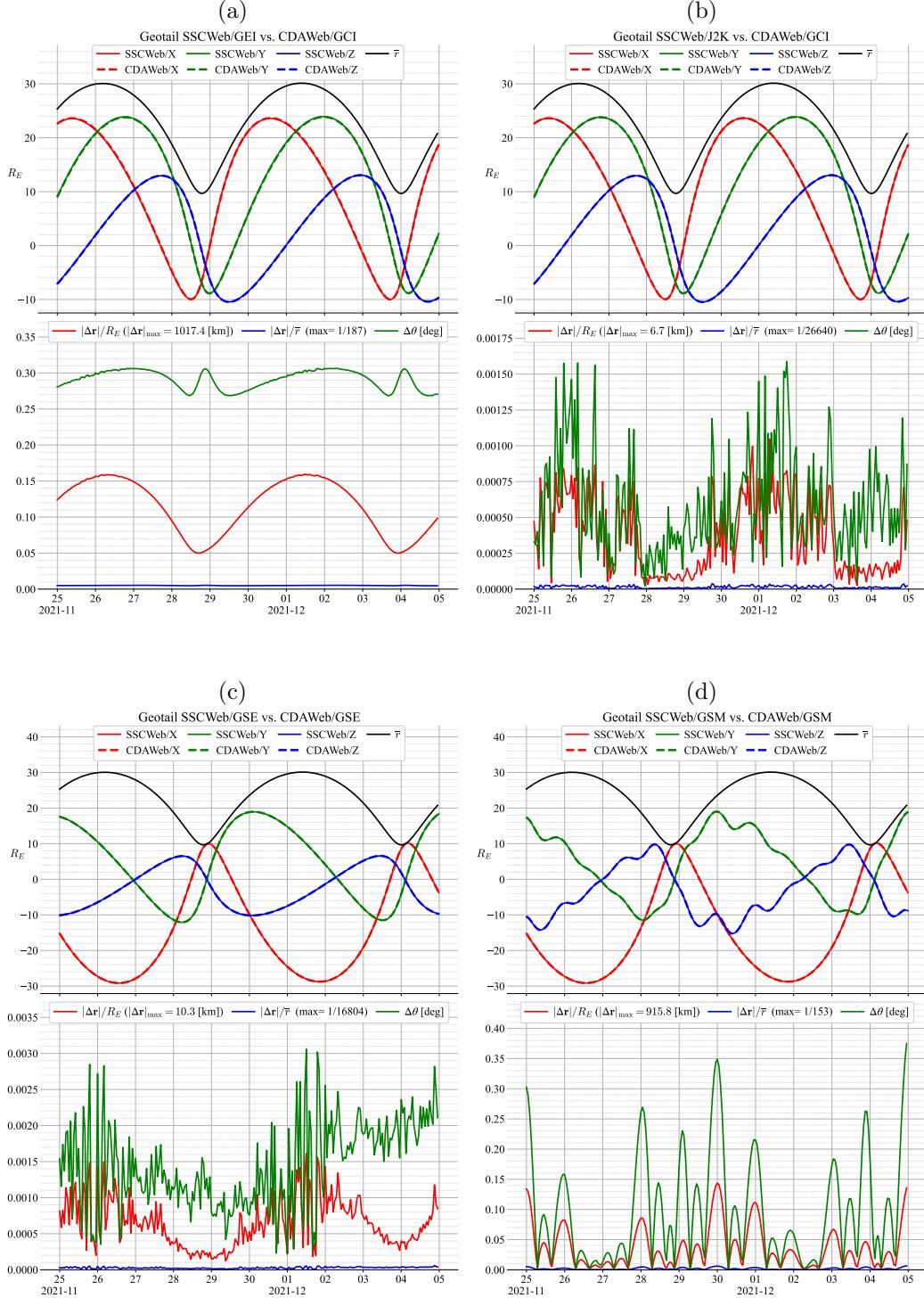


Figure 1: Comparison of ephemerides values for the Geotail spacecraft from SSCWeb and CDAWeb in four different reference systems. The top panel in each subplot displays the X , Y , and Z values from each provider (on this scale, differences are not visible) and the average radial distance, \bar{r} , between the two providers. The bottom panel of each subplot shows relative differences in the position vector $\Delta\mathbf{r}$ and the angular difference in the position vectors, $\Delta\theta$.

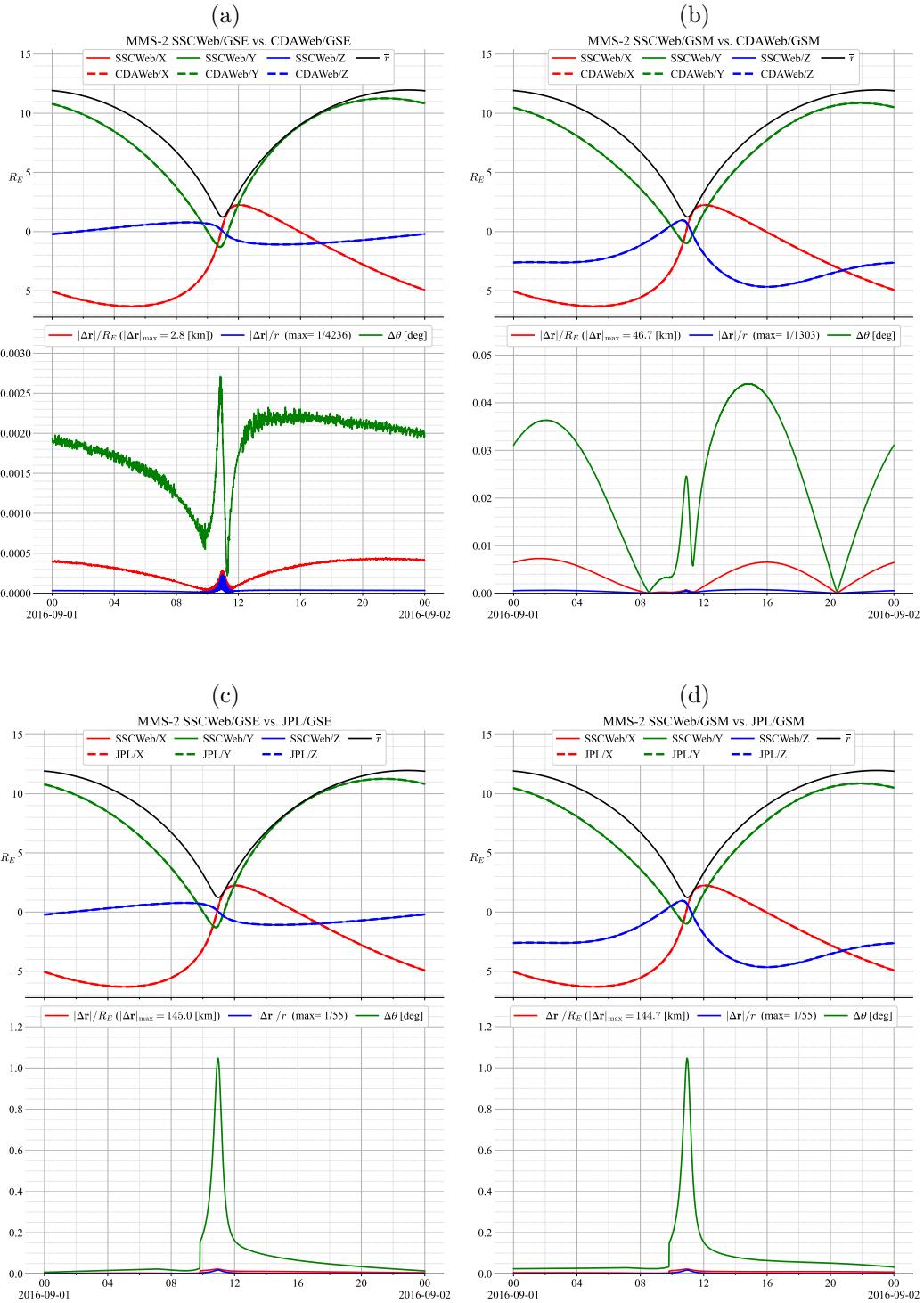


Figure 2: Comparison of ephemerides values for the MMS-2 spacecraft from (a)–(b) SSCWeb and CDAWeb; (c)–(d) SSCWeb and JPL Horizons in two different reference systems.

373 **4.2 Software**

374 In this section, we compare reference frame calculations using the following soft-
 375 ware packages.

- 376 • **Geopack-2008** double precision (Tsyganenko (2008); labeled as `geopack_08_dp` in
 377 the figures in this section), a Fortran library that was upgraded from earlier ver-
 378 sions to support calculations using 64-bit floating point values.
- 379 • **PySPEDAS** 1.7.28, which uses transformation code derived from the IDL version of
 380 PySPEDAS (Angelopoulos et al., 2024b), which in turn used code from the **ROCTLIB**
 381 Fortran (CDPP/IRAP, 2025) library, which was used for data from the Cluster
 382 spacecraft mission (Robert, 1993).
- 383 • **SpacePy** 0.0.6, which has an option to use the **IRBEM** Fortran library (Boscher et
 384 al. (2022); labeled as `spacepy-irbem`) or an alternative and native Python imple-
 385 mentation (`spacepy`) of the transforms.
- 386 • **SpiceyPy** 6.0.0 is a Python wrapper for the SPICE toolkit. Two versions of SPICE
 387 kernel files were used, indicated by `spicey1` and `spicey2`. `spicey1` was used
 388 for reference frame transforms for the Van Allen Probes mission. `spicey2` had
 389 an update to the MAG frame, which used a more recent version of the IGRF model
 390 (Alken et al., 2021) to determine the Earth's magnetic dipole orientation.
- 391 • **SunPy** version 7.0.0, which extends the AstroPy coordinates framework to include
 392 space physics reference frames.

393 The top subplots in Figure 3 show the angles between the Z axis of four coordi-
 394 nate frame pairs. The angle between the Z axis in frame A and the Z axis in frame B ,
 395 $\angle(Z_A, Z_B)$, was computed by transforming the Z axis in frame A into frame B , and the
 396 angle was computed between this transformed axis and the Z axis in frame B .

397 The middle subplots in Figure 3 show the difference of the angles between the Z
 398 axes for each library with respect to that for `geopack_08_dp`. The choice of library to
 399 use as the baseline for this comparison is arbitrary; in general, we are interested in the
 400 maximum differences among the libraries, which are shown in the lower panel of each
 401 subplot. The maximum absolute values range from $4 \cdot 10^{-9}$ degrees for `pyspedas` in Fig-
 402 ure 3(a) to $1 \cdot 10^{-2}$ degrees for `spicey1` in Figure 3(c); the values for each library are
 403 given in the legend in the middle panel of each subplot.

404 The bottom panels of Figure 3 shows that across all libraries, the maximum ab-
 405 solute value of lines in the middel panel are $\sim 0.01^\circ$ for **GEO/GSE**, $\sim 0.03^\circ$ for **GEO/GSM**,
 406 $\sim 0.04^\circ$ for **GSE/GSM**, and $\sim 0.03^\circ$ for **GSE/GSM**, all of which are comparable to the aver-
 407 age angular change in Earth's dipole Z axis of $\sim 0.04^\circ$ per year.

408 We have also performed coordinate transforms using the Satellite Situation Cen-
 409 ter System and Services (2025a) coordinate calculator web service. However, this ser-
 410 vice outputs values only to two decimal places, leading to angular differences of 0.3° . These
 411 values are not plotted so that the other library differences are clearly visible.

412 The range of the maximum absolute differences, 0.001° - 0.04° , shown in the bot-
 413 tom panels of the subplots in Figure 3 is smaller than the range, 0° - 1° , of angular dif-
 414 ference in spacecraft position vectors in the same coordinate system from two different
 415 data providers found in section 4.1. The position vectors can differ for two reasons: dif-
 416 ferences in the source of the ephemerides data and differences in the data providers' soft-
 417 ware libraries, if a transformation is needed. To determine the magnitude of each requires
 418 analyzing the source code used to generate the ephemerides, which is not readily avail-
 419 able.

420 In summary, in this section, we have shown that differences in library implemen-
 421 tations of reference frames range from 0.001° to 0.04° for the chosen set of coordinate

422 frames and comparison axis. This range of differences is comparable to the range of an-
423 gles identified in section 4.1, which includes the average angular change in Earth's dipole
424 Z -axis over the past 45 years, the precession of Earth's rotation axis, changes in nuta-
425 tion of Earth's rotation axis over one year, and the precession of the ecliptic. The im-
426 plication is that inter-comparison of measurements transformed with different libraries
427 may require an analysis of the differences in the transform implementations if the dif-
428 ferences in the measurements are not significantly larger than these differences. This type
429 of analysis is challenging because it requires access to the transform software, which may
430 not be maintained or available, and because calculations are needed to quantify differ-
431 ences due to transform implementation choices.

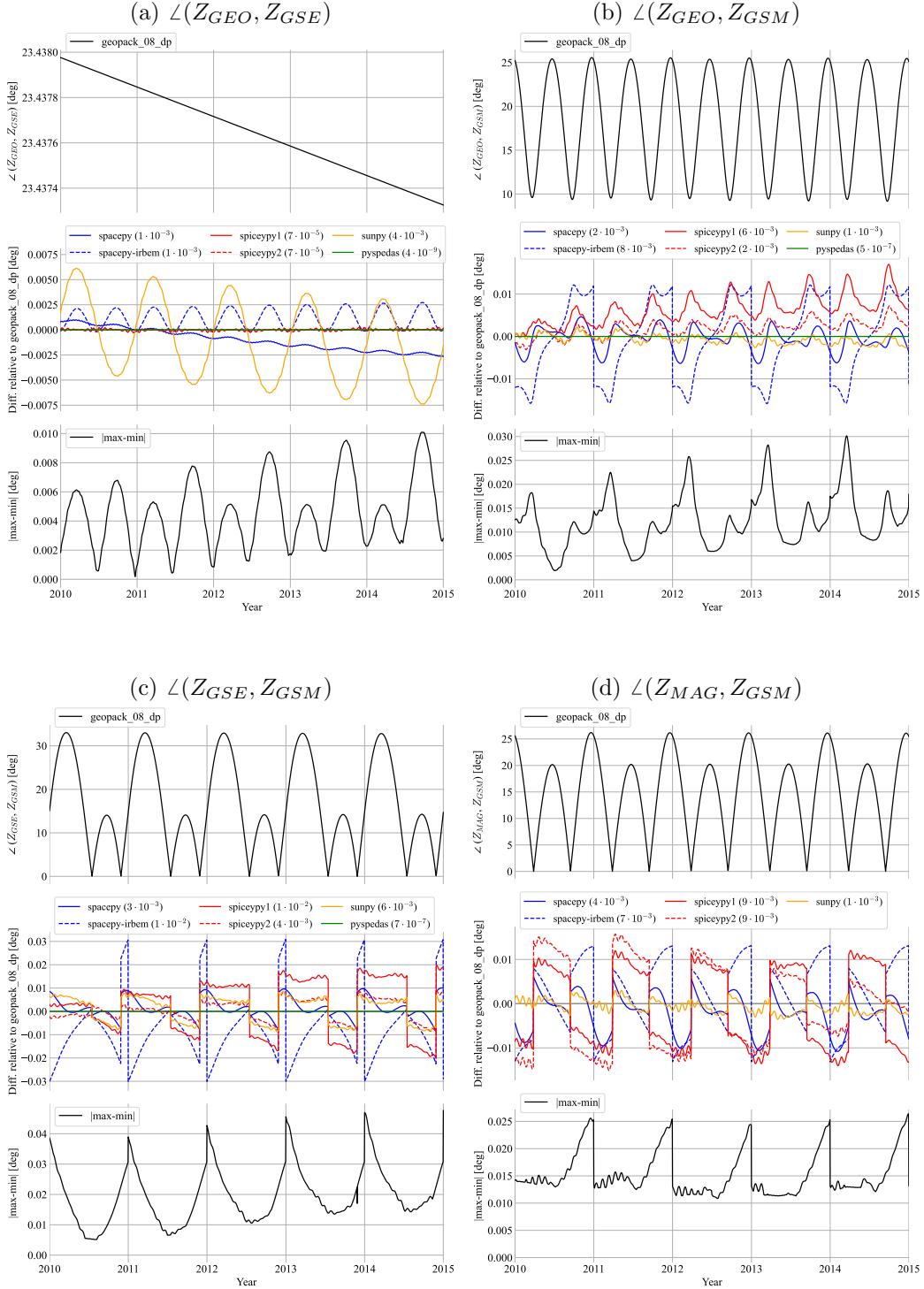


Figure 3: Angles between Z axes in select coordinate frames as computed by different software packages. In the top panels of each subplot, the notation $\angle(Z_A, Z_B)$ means the angle between the Z axis of coordinate frame A and the Z axis of coordinate frame B computed using `geopack_08_dp`. The middle panel of each subplot shows the difference between $\angle(Z_A, Z_B)$ computed using `geopack_08_dp` and that computed using the library indicated in the legend; the maximum of the absolute value of each line is shown in parentheses. The bottom panels show the maximum absolute differences in the middle panel.

432 5 How transform information is created for spacecraft missions

433 Archival data for space physics spacecraft missions typically include vector mea-
 434 surements in multiple reference frames. For NASA missions, archival data products are
 435 delivered to the Space Physics Data Facility (NASA, 2025). Modern missions typically
 436 take one of two approaches for transforms: (a) A mission operations team develops SPICE
 437 kernels for select space physics reference frames, and SPICE software is used for the trans-
 438 forms; or (b) A non-SPICE software library is used for the transforms, for example, ROCOTLIB
 439 and SpacePy.

440 There is significant overlap in effort across missions; typically, a scientist familiar
 441 with space physics reference systems but not with their implementation options will use
 442 available software or SPICE kernels and develop tests. As noted in the conclusions, this
 443 effort to develop and verify transform calculations would not be necessary if either a database
 444 of transform matrices or versioned SPICE kernels were available that were accepted as
 445 a community standard.

446 For the SSCWeb data service (Satellite Situation Center System and Services, 2025c),
 447 which provides spacecraft ephemerides, three approaches have been taken in order of pri-
 448 ority (see Satellite Situation Center System and Services (2025b) for a table indicating
 449 which approach was taken and provenance):

- 450 1. Mission-developed SPICE kernels for ephemerides are obtained from the mission
 451 team periodically and archived. The GEI ephemerides-related SPICE kernel in-
 452 formation is used to generate the J2000 ephemerides. Then, International Solar-
 453 Terrestrial Physics-era (ISTP; International Solar Terrestrial Physics (2025)) soft-
 454 ware is used to compute ephemerides in different coordinate frames, including GEI,
 455 GEO, GM, GSE, GSM, and SM. The ISTP software uses proprietary information needed
 456 for the reference frames, such as the position of the Sun, calculated by GSFC's
 457 Flight Dynamics Facility (FDF). This approach is only used on ISTP-era missions,
 458 i.e., ACE, Polar, Wind, and Geotail.
- 459 2. A GEI ephemerides-related variable in archival data files that was computed by
 460 the mission is then used to compute orbit and attitude data in different reference
 461 frames; only data in the GEI-related frame is used. This is a possible source of the
 462 differences shown in Figure 1 if the mission computed the ephemerides in the archival
 463 data products by transforming GEI using different software than SSCWeb. Dif-
 464 ferences can also occur if the mission uses a different definition of GEI than SS-
 465 CWeb.
- 466 3. If SPICE kernels or other mission-computed GEI ephemerides-related values are
 467 not available, TLE (Two-Line Element) files are obtained from NORAD (North
 468 American Aerospace Defense Command), and a translation of the C NORAD li-
 469 brary to Pascal (Brodowski, 2002) is used to compute ephemerides in TEME (True
 470 Equator, Mean Equinox). Often, TLEs are used at the start of the mission, and
 471 a switch is made to approaches 1. or 2. as information becomes available. This
 472 switching has implications for reproducibility that are discussed in section 6.4 be-
 473 cause previous versions of ephemeris are not retained.

474 6 Summary and Recommendations

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

477 **6.1 Standards for Reference System and Frame Definitions**

478 As defined in section 2, an *ideal reference system* is a general description of a ref-
 479 erence frame that lacks key details necessary for its implementation. Examples were pro-
 480 vided in which the GEI acronym had different expansions, and different acronyms were
 481 identified as equivalent.

482 The next level of specificity relative to an ideal reference system is a *reference sys-*
 483 *tem*, which defines constants, models with free parameters, and algorithms for transform-
 484 ing between observable quantities and reference data.

485 Finally, a *reference frame* is a realization of a reference system based on measure-
 486 ments used to determine the free parameters in its models.

487 A community-developed standard should be created for acronyms and definitions.
 488 The standard should provide abbreviation/definition pairs for commonly used space physics
 489 ideal reference frames. Associated with each ideal reference frame definition, there should
 490 be at least one reference system abbreviation/definition pair. If multiple reference sys-
 491 tems are in common use, their definitions and referencing conventions should be spec-
 492 ified. For each reference system, at least one reference frame should be defined.

493 **6.2 Reference Frame Standard Dataset**

494 For a given transform between reference frames, a transformation matrix at a spe-
 495 cific instant in time (or, equivalently, rotation angles or quaternions) relative to a base
 496 reference frame is required. We also note that implementing transforms requires tech-
 497 nical expertise in software and maintenance, including updating free parameters in reference-
 498 frame models, verifying calculations, and documenting changes. Although providing a
 499 software version enables reproducibility in principle, in practice, not all users will be fa-
 500 miliar with or want to use the cited software, and in the long term, the software may not
 501 be maintained or may be difficult to install and use.

502 Based on this, we recommend that a standards body develop a standard dataset
 503 with a long-term plan to keep it up-to-date. Each record in the dataset should consist
 504 of a timestamp and a transform matrix that relates a coordinate frame to a reference
 505 coordinate frame. The records should be made available in a standard scientific file for-
 506 mat and from a web service API (Application Programming Interface). A parsimonious
 507 alternative to providing 9 transform matrix values is to define only one or two angles (and
 508 associated rotation axes) from which the matrix can be computed.

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

513 Many software libraries do spot checks of transforms. For example, SunPy’s unit
 514 tests (Mumford et al., 2025) involve a comparison with a table from Fränz and Harper
 515 (2002) at several time instants; `cxf orm` (Boller & Santiago, 2025) tests its implemen-
 516 tation by comparing the ephemeris in GSE of one year of data from three spacecraft from
 517 Satellite Situation Center System and Services (2025c); a comparison is also made with
 518 a table in Fränz and Harper (2002). With the proposed reference database, a software
 519 library developer could make a more comprehensive comparison, allowing users to es-
 520 timate uncertainties associated with coordinate transforms directly. An additional ad-
 521 vantage of this dataset is that software developers can use it for more comprehensive test-
 522 ing of their implementations.

523 We also suggest that this dataset contains common time representations. Each record
 524 should be a UTC timestamp along with values for UT1, TAI, TT, and ET (McCarthy (2011);

see section Appendix A for definitions). Although these time relationships are simple, some require a leap second table, and to perform the computation, one needs to parse (and update if required) the leap second table.

The advantage of the standard dataset over software libraries is that the latter require continual upgrades, and not all users perform their analysis the language in which the library is implemented. Although software that automatically updates IGRF coefficients and leap-second information may work now, it is not guaranteed to be maintained and usable indefinitely. 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, in principle, the package developers can maintain reproducibility, doing so requires significant effort. The proposed standard 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 standard dataset described in section 6.2 or an evaluation of the differences between transforms using these SPICE kernels and the standard dataset would be provided as documentation.

We also recommend using modern version control systems for the SPICE kernels. At present, kernels can be found on various websites, and kernel versions are sometimes indicated in the file name, but prior versions are not always provided, thereby inhibiting reproducibility. Storing kernels in a source code repository, which provides versioning and simplifies change tracking, will improve this. Additionally, we recommend assigning unique identifiers, such as DOIs, to kernels to facilitate their citation.

6.4 Versioning and Documenting Ephemerides

In this work, we have been primarily interested in the problem of transforming a vector from one reference frame to another. In the case of ephemerides 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 — the source of the ephemerides. 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), the Deep Space Network (DSN), NAIF, and NORAD to produce the ephemerides for the mission. Section 4.1, we show an example where the ephemerides 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.

To address this, we suggest that data providers indicate how their ephemerides were obtained. We also suggest that if two data providers provide ephemerides for the same

spacecraft, they document how and why their results may differ, if applicable. We also recommend that the metadata indicate the uncertainty in the locations. Often, data providers will modify the ephemerides values when more accurate calculations become available. This makes reproducibility difficult. Ideally, for reproducibility, old versions of ephemerides would be made available. Often, this is impractical, so an alternative is to include version information in the metadata.

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 standard dataset described in section 6.2 for a transform, only the standard dataset is needed for reproducibility. Similarly, if one or more SPICE kernels are used, each with 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 version of the SPICE software library 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. Additional software citation recommendations are given in Jackson (2012) and Smith et al. (2016).
- Data providers should ensure that metadata associated with ephemerides and variables that are transformed include details about the software version used for the transforms or the data used for the transform, such as SPICE kernels. The metadata description should be validated by having a third party assess whether it contains sufficient information to re-implement the transform.
- Paper authors include the version of software, a DOI for that version if available, and options passed to the transform function. If SPICE kernels are used, they should be provided as supplementary material if they are not otherwise citable and online, or posted to a general repository (e.g., Zenodo).

Appendix A Definitions

- ACE – Advanced Composition Explorer (spacecraft mission)
- CDAWeb – Coordinated Data Analysis Web (NASA data archive)
- CD – Centered Dipole (reference frame). Same as GM and MAG if they use a model dipole with an origin of Earth’s center of mass.
- 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 (reference 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
- MAG – Geomagnetic (reference frame). Also referred to as Centered Dipole (CD) and GM.
- MMS – Magnetospheric Multiscale Mission
- 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)
- TME – True Equator, Mean Equinox (reference system)
- UT1 – Universal Time 1 (time standard)

Open Data

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

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