

**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.
- Spacecraft positions from different providers can differ significantly, as do Z -axis orientations from surveyed software libraries.
- We present recommendations to improve reproducibility 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 position values from different
 18 data providers to differ significantly. Based on these comparisons and results, and to enable
 19 reproducibility, we recommend that (a) a standard for acronyms and definitions for
 20 coordinate systems is developed, similar to equivalents in astronomy or earth sciences;
 21 (b) a standards body develops a citable database of reference data needed for these transforms;
 22 (c) a central authority maintains the SPICE (Spacecraft, Planet, Instrument, C-
 23 matrix, Events) kernels used by space physics spacecraft missions to generate data products
 24 in different coordinate systems; and (d) software developers provide explicit com-
 25 parisons of their implementations with the results of (b) and documentation on imple-
 26 mentation choices. Additionally, we provide recommendations for scientists and meta-
 27 data developers to ensure that sufficient information is provided to enable reproducibil-
 28 ity.

29

30 **1 Introduction**

31 In space physics, coordinate systems are usually referenced by an acronym. The
 32 coordinate system's definition is typically assumed or given by citing a reference that de-
 33 scribes it. This work stems from a project to develop a standard for terms and descrip-
 34 tions for coordinate system acronyms such as GEI, GSE, GSM, and their commonly used
 35 variations, e.g., GEI_J2000, GEI_MOD; see Appendix A for definitions and Russell (1971),
 36 Hapgood (1992), Fränz and Harper (2002), and Laundal and Richmond (2016) for ad-
 37 ditional details. The objective is that, given a statement such as “the vector measure-
 38 ments in ABC were transformed into XYZ,” a scientist with measurements in ABC would
 39 be able to reproduce the transformation with the only uncertainty being due to round-
 40 ing errors associated with floating point precision.

41 Currently, this is not possible due to the lack of standards. At present, the best
 42 that can be achieved is a citation to the definition in one of the papers above, but this
 43 is not sufficient for reproducibility – in this work we show that how a given coordinate
 44 frame definition can be implemented in different ways, leading to different data providers
 45 giving different locations for a spacecraft and different software libraries giving differ-
 46 ent answers for a the transformation a vector from one coordinate system to another.

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

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

60 Second, the standard for terms and descriptions must address their existing am-
 61 biguity. Examples of ambiguity are given for the GEI coordinate system in section 3. The

62 general conclusion is that in space physics, there is no agreed-upon standard for coordinate system acronyms, and descriptions generally lack key implementation details.
 63

64 To quantify the impact of ambiguity in definitions and implementations, we give
 65 examples that demonstrate the reported positions for spacecraft in the same-named ref-
 66 erence systems can significantly differ depending on the data source in section 4.1. In
 67 section 4.2 we demonstrate that software that transforms a vector between two coordi-
 68 nate systems exhibits smaller, but possibly significant, differences.

69 Having summarized the problems arising from ambiguity in definitions and imple-
 70 mentations, we next consider how spacecraft missions compute transforms. To meet the
 71 objective of reproducibility, we must understand how calculations are performed in prac-
 72 tice and account for this in our recommendations. In section 5, we describe how missions
 73 develop data products in different coordinate systems, which may explain the differences
 74 observed in the position results in section 4.1.

75 In section 6, we provide a set of recommendations that address definition issues de-
 76 scribed in section 3, the results in section 4, and the description in section 5. These rec-
 77 ommendations address ambiguity in terminology and definitions, the creation and test-
 78 ing of software for transforms, and how missions compute transformed data products.

79 2 Coordinate Systems, Reference Systems, and Reference Frames

80 Thus far, we have used the term “coordinate system” consistent with common us-
 81 age in space physics as described in section 2.1. In section 2.2, we note that “ideal ref-
 82 erence system”, “reference system”, or “reference frame” is more consistent with liter-
 83 ature outside of space physics and will use these terms in the remainder of this article.

84 2.1 Coordinate Systems

85 In geometry, introductory physics, and mathematics textbooks, coordinate values
 86 in a “coordinate system” uniquely identify spatial positions relative to an *arbitrary* set
 87 of three orthogonal vectors and an origin. Common coordinate systems are Cartesian,
 88 cylindrical, and spherical. In the space physics literature, a coordinate system is gener-
 89 ally meant as a *specific* set of three orthogonal vectors and an origin, with coordinate
 90 values expressed in a coordinate system such as Cartesian, cylindrical, or spherical.

91 This usage, which “coordinate system” has two meanings, dates back to at least
 92 early documentation of the NASA shuttle program (Davis, 1974) and has been consis-
 93 tently used in frequently cited literature related to space physics reference frames (Russell
 94 (1971); Hapgood (1992); Hapgood (1995); Laundal and Richmond (2016)). (However,
 95 an earlier work involving analysis of data from the OGO (Orbiting Geophysical Obser-
 96 vatory; NASA (1970)) satellite used only “system” for the central noun, e.g., GCI sys-
 97 tem, instead of GCI coordinate system.)

98 2.2 Reference Systems and Frames

99 In astronomy, the terms “reference system” and “reference frame” are used; from
 100 US Naval Observatory (2025):

101 “A reference system is the complete specification of how a celestial coordinate sys-
 102 tem is to be formed. It defines the origin and fundamental planes (or axes) of the co-
 103 ordinate system. It also specifies all of the constants, models, and algorithms used to trans-
 104 form between observable quantities and reference data that conform to the system. A
 105 reference frame consists of a set of identifiable fiducial points on the sky (specific astro-
 106 nomical objects), along with their coordinates, that serves as the practical realization
 107 of a reference system.”

108 The terms “reference system” and “reference frame” are also used in the same sense
 109 in terrestrial geodesy (Seitz et al., 2014).

110 A fundamental reference system in astronomy is the International Celestial Ref-
 111 erence System (ICRS) (Petit & Luzum, 2010). No unique reference frame is associated
 112 with this reference system because creating (or, equivalently, “realizing” or “implement-
 113 ing”) one requires measurements for computing reference system model parameters. The
 114 International Celestial Reference Frame (ICRF) is the general term for realizations of
 115 the ICRS that are adopted by a standards body and updated as new measurements and
 116 model versions become available. There are three versions of the ICRF (Charlot et al.,
 117 2020).

118 In the earth sciences, an example of a fundamental reference system is the World
 119 Geodetic System 1984 (WGS 84), used to represent latitude, longitude, and altitude loca-
 120 tions relative to Earth (National Geospatial-Intelligence Agency (2014)). A standard
 121 for expressing machine-readable reference frame implementation details that facilitates
 122 reproducibility is also available (Open Geospatial Consortium, 2023).

123 In the earth sciences, Kovalevsky and Mueller (1981) and Mueller (1985) use the
 124 term “ideal reference system” to refer to reference frames with definitions that are in-
 125 complete in the sense that only fundamental planes, axes, and an origin are specified:
 126 “The term ‘ideal’ indicates the conceptual definition only and that no means are pro-
 127 posed to actually construct the system”. Note that the term “ideal” in this quote should
 128 be interpreted not as meaning “preferred” but rather means ideal in the sense of “ide-
 129 alized model”, or a model that has practical or important attributes omitted to simplify
 130 its description.

131 Thus, what space physicists call a “coordinate system” (e.g., GEI, GSM) is analo-
 132 gous to an “ideal reference system” because it only has a general definition for their axes
 133 orientation and origin. There are no standards for the constants, models, or algorithms
 134 required to transform between observable quantities, which are necessary to define a ref-
 135 erence system, nor for the model parameters needed to define a reference frame. For ex-
 136 ample, the GSE reference frame requires a vector from the center of Earth to the center
 137 of the Sun — Russell (1971) gives a Fortran program provided through private commu-
 138 nication; Hapgood (1992) uses equations from Doggett et al. (1990); and Fränz and Harper
 139 (2002) uses equations from Seidelmann et al. (1992). All three cases can be regarded as
 140 unique GSE reference frames for the GSE reference system.

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

147 3 Examples of Definition Ambiguity

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

151 For example, consider GEI. The GEI ideal reference frame has **Z** aligned with Earth’s
 152 rotation axis with positive northward, **X** as the intersection of Earth’s equatorial plane
 153 with the plane of Earth’s orbit around the Sun (the ecliptic plane), with positive in the
 154 direction from the Earth to the Sun at the time of the vernal equinox, and **Y** = **Z** × **X**. The line of intersection of Earth’s equatorial plane with the ecliptic, or the time that

156 it is computed, is sometimes referred to as “the equinox,” and whether a line or time is
 157 meant must be determined from context.

158 First, there is no consistency in the expansion of the acronym **GEI**. Russell (1971)
 159 and Hapgood (1992) associate **GEI** with “Geocentric Equatorial Inertial System”. Fränz
 160 and Harper (2002) and Mumford et al. (2025) associate **GEI** with “Geocentric Earth Equa-
 161 torial”. Another ambiguity is in the expansion of **GCI**; Satellite Situation Center Sys-
 162 tem and Services (2025c) notes “Geocentric Inertial (**GCI**) and Earth-Centered Inertial
 163 (**ECI**) are the same as **GEI**”, which implicitly defines **GCI** as “Geocentric Inertial”, in con-
 164 trast to Russell (1971) and NASA (1970), which use “Geocentric Celestial Inertial”.

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

169 Common variations of **GEI** depend on whether precession and nutation of Earth’s
 170 rotation axis and precession of the ecliptic plane are accounted for (Davis (1974); Hapgood
 171 (1995); Fränz and Harper (2002)). The term “mean epoch-of-date” (or mean-of-date)
 172 is used when only precession is accounted for, that is, the nutation variation is estimated
 173 and removed. If nutation variation is not removed, the term “true epoch-of-date” or “true-
 174 of-date” is used (Hapgood, 1995). If the **X** and **Z** orientations are time independent, an
 175 abbreviation for a reference date and time is specified, e.g., J2000.0 (2000-01-01T12:00
 176 Terrestrial Time), at which they were determined. The reference date and time is referred
 177 to as an “epoch” in the sense of a reference time instant rather than a period of time.

178 Two basic categories of **GEI**-related reference frames and systems are commonly
 179 used: inertial and non-inertial. The list of acronyms later in this section is associated
 180 with an inertial reference system: an idealized system that is not rotating with respect
 181 to the distant stars, i.e., stars at an effectively infinite distance from its origin, and with
 182 an origin that translates with a constant velocity (NAIF, 2023). Note that if the origin
 183 is specified as Earth’s center (usually its center of mass rather than its centroid is im-
 184 plied but not stated; see also Dong et al. (2003)), **GEI** is non-inertial by definition. How-
 185 ever, in the bulleted list summary of **GEI**-related reference systems and frames below,
 186 we have ignored this technicality.

187 The objective of the following summary is to demonstrate the diversity in the terms
 188 and definitions used for **GEI**-related reference systems and to motivate the need for the
 189 standard recommended in section 6.1. Similar diversity also exists in terminology and
 190 definitions in other commonly used reference systems in space physics, providing further
 191 motivation.

- 192 • J2000 – Used by Satellite Situation Center System and Services (2025c) to refer
 193 to a frame with its origin at Earth’s center of mass and by SPICE to refer to a
 194 system with origin at the solar system barycenter (Acton (1997); NAIF (2025))
 195 using the reference epoch J2000.0 (2000 January 1 noon Terrestrial Time).

196 Satellite Situation Center System and Services (2025c) provides the definition:

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

203 NAIF (2025) notes that J2000 is “generally used in SPICE to refer to the **ICRF**";
 204 “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).”
- GEIJ2000 – Fränz and Harper (2002) state that GEIJ2000 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 (Niekof 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.

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

250 `SpacePy` (Morley et al., 2024), and `PySPEDAS` (Angelopoulos et al., 2024a). Other
 251 libraries include `cxftransform` (Boller & Santiago, 2025) in C, and `Geopack` (Tsyganenko,
 252 2008) and `IRBEM` (Boscher et al., 2022) in Fortran.

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

258 Although this statement was made thirty years ago, based on the results in this
 259 section give below, it appears the convention in space physics is that differences at this
 260 level are considered negligible. That is, we find angular differences in spacecraft posi-
 261 tions from different providers of $\sim 0.3^\circ$ and coordinate transforms from different software
 262 packages of $\sim 0.03^\circ$, and this uncertainty is not discussed in the documentation, suggest-
 263 ing it is considered small enough to be ignored.

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

- 271 • In an attempt to develop a 3D visualization program that returns the region of
 272 geospace (e.g., plasma sheet, interplanetary medium, plasmasphere) given an ar-
 273 bitrary position, we implemented the models used by `SSCWeb` (Satellite Situa-
 274 tion Center System and Services, 2025c) and attempted to validate our work by
 275 comparing our predicted regions at the positions provided by its web service for
 276 spacecraft. Although our predictions were generally consistent, we were unable
 277 to reproduce the exact time at which a spacecraft crossed from one region to an-
 278 other. After a search for errors in our model implementation failed to explain the
 279 differences, we realized that the discrepancies were due to the software that we
 280 used for reference-frame transformation differing from that used by `SSCWeb`.
- 281 • Not all global magnetosphere simulation models are executed in the same refer-
 282 ence frame. To compare two models, the solar wind input must be transformed
 283 to the simulation reference frame, and simulated variables from both models must
 284 be transformed into the same reference frame for comparison. The uncertainty as-
 285 sociated with transformations must be known to determine the difference in the
 286 model output attributable to the simulation algorithm.

287 The fact that different software libraries provide different options for reference frames
 288 is indirect evidence that differences can matter. For example, `SpacePy` (Morley et al.,
 289 2024) provides multiple options for computing the `MAG` system, which have angular dif-
 290 ferences of $\sim 0.01^\circ$, and `SunPy` (Mumford et al., 2025) has options for how the `GEI` frame
 291 is computed. A general finding is that differences in transform results within a single li-
 292 brary, with different options for the transform, are on the order of, or smaller than, dif-
 293 ferences in transform results between two different software libraries. As a result, im-
 294 provements in how a transform is computed within a single library are lost when com-
 295 paring data computed with a different library.

296 Even if the uncertainty associated with how a given reference frame was implemented
 297 is small relative to that of the measurements, we suggest that it is illogical for two data
 298 providers to report the location of a spacecraft that differs by more than what is expected
 299 due to numerical precision unless the reason for differences is clearly documented and

300 ideally evident in the name of the dataset, e.g., by including the word “preliminary”. A
 301 recommendation for addressing this is given in section 6.4.

302 4.1 Spacecraft Positions

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

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

310 All vectors in these quantities have an origin at the center of Earth.

311 Angular differences can be compared to:

- 312 1. The average angular change in Earth’s dipole Z axis of $\sim 0.04^\circ$ per year (from 1970–
 313 2025, computed using the libraries used in section 4.2).
- 314 2. The precession, also referred to as luni–solar precession, of Earth’s rotation axis
 315 (also the GEI_Z reference system axis), which drifts by $\simeq 0.006^\circ$ per year (Hapgood,
 316 1995).
- 317 3. The one–year change in angle due to nutation of Earth’s rotation axis of $\simeq 0.0025^\circ$
 318 per year (Hapgood, 1995).
- 319 4. The precession of the ecliptic (planetary precession) of $\Delta\theta \simeq 0.000014^\circ$ per year
 320 (Hapgood, 1995).
- 321 5. The angular separation for the reported closest separation ever of any multi-spacecraft
 322 formation (NASA, 2016) of 4.5 miles (7.24 km), which corresponds to $\sim 0.008^\circ$.

323 Figure 1 shows the position of the Geotail spacecraft from 2021-11-25 through 2021-12-05
 324 from the SSCWeb web service and the **GE_OR_DEF** dataset in CDF (Common Data For-
 325 mat, 2025) files from CDAWeb. SSCWeb provides positions for scientific spacecraft in
 326 reference systems that include **GEI**, **J2K**, **GSE**, **GSM**, and **GM** (frequently referred to as **MAG**).
 327 The **GE_OR_DEF** dataset has position values in **GCI**, **GSE**, and **GSM**.

328 We used the SSCWeb option to return data as a fraction of R_E with 10 fractional
 329 digits. The CDAWeb dataset stores values in km as IEEE-754 64-bit floats, and the meta-
 330 data indicates a recommended display precision of 10 fractional digits. The cadence of
 331 the SSCWeb Geotail data is 12 minutes while the CDAWeb Geotail dataset is 10 min-
 332 utes. In the time interval displayed in Figure 1, values from the datasets are only shown
 333 when they have the same timestamps in the time interval shown.

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

339 In Figure 1(a), and based on the documentation for Satellite Situation Center Sys-
 340 tem and Services (2025c), which has the statement “Geocentric Inertial (**GCI**) and Earth-
 341 Centered Inertial (**ECI**) are the same as **GEI**”, we expect the SSCWeb/**GEI** and CDAWeb/**GCI**
 342 positions differences to be near $\simeq 10^{-7}$ degrees, assuming both data sources use the same
 343 definition of **GEI**. The average angular difference between position vectors is $\Delta\theta \sim 0.3^\circ$,
 344 and the average error relative to an Earth radius, $|\Delta\mathbf{r}|/R_E \sim 0.16$, or 16%. The max-
 345 imum error relative to the average geocentric distance, $|\Delta\mathbf{r}|/\bar{r}$ is 1/187, or 0.5%.

346 In Figure 1(b), there is a much closer match between SSCWeb/J2K and CDAWeb/GCI
 347 positions, with an average angular difference in the position vector of $\sim 0.001^\circ$ and an
 348 average error relative to an Earth radius of $\sim 0.05\%$.

349 In summary, Figure 1(a) and (b) show that what is labeled as GCI in the CDAWeb
 350 positions is much closer to SSCWeb/J2K positions than SSCWeb/GEI, which is unex-
 351 pected given the SSCWeb documentation that notes GCI and GEI are equivalent. Although
 352 the CDAWeb/GCI positions are a better match to the SSCWeb/J2K positions, the dif-
 353 ferences are not explained by the numerical precision of the reported values. They may
 354 be due to whether, or how, precision and nutation in items 2–4 listed above were accounted
 355 for.

356 In Figure 1(c), a comparison is made for the GSE reference system. To transform
 357 a vector from GEI to GSE, two rotations are required: a rotation around GEI_X to align
 358 Earth’s equator with the ecliptic plane and a rotation around the GEI_Z axis (as it is af-
 359 ter the first rotation) to orient GEI_X to point to center of the Sun. These two angles are
 360 the obliquity of the ecliptic and the ecliptic longitude of the Sun, respectively (Hapgood
 361 (1992)).

362 In Figure 1(d), a comparison is made for the GSM reference system. A vector in the
 363 GSE reference system is transformed to GSM by an angle that depends on the orientation
 364 of the North geomagnetic pole (Russell (1971); Hapgood (1992)). The primary uncer-
 365 tainty is how the orientation of the North geomagnetic pole, which has an average yearly
 366 change of $\sim 0.04^\circ$, is computed. If both SSCWeb and CDAWeb computed the GSM po-
 367 sitions based on a transform from GSE, we could conclude that the observed $\Delta\theta$ are due
 368 to the use of different locations of the North geomagnetic pole. However, the maximum
 369 $\Delta\theta \simeq 0.37^\circ$ is much larger than the average yearly angular change in Earth’s dipole Z
 370 axis of $\sim 0.04^\circ$.

371 In Figure 2, a comparison is made between data from SSCWeb, CDAWeb, and the
 372 JPL Horizons web service (JPL, 2022), which provides positions for some of the space-
 373 craft available from SSCWeb. The CDAWeb dataset is MMS2_EPD-EIS_SRVY_L2_ELECTRONENERGY.
 374 The JPL Horizons web service provides positions in the ICRF reference frame (the ver-
 375 sion of ICRF is not documented), and SunPy is used to transform it to other reference
 376 frames.

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

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

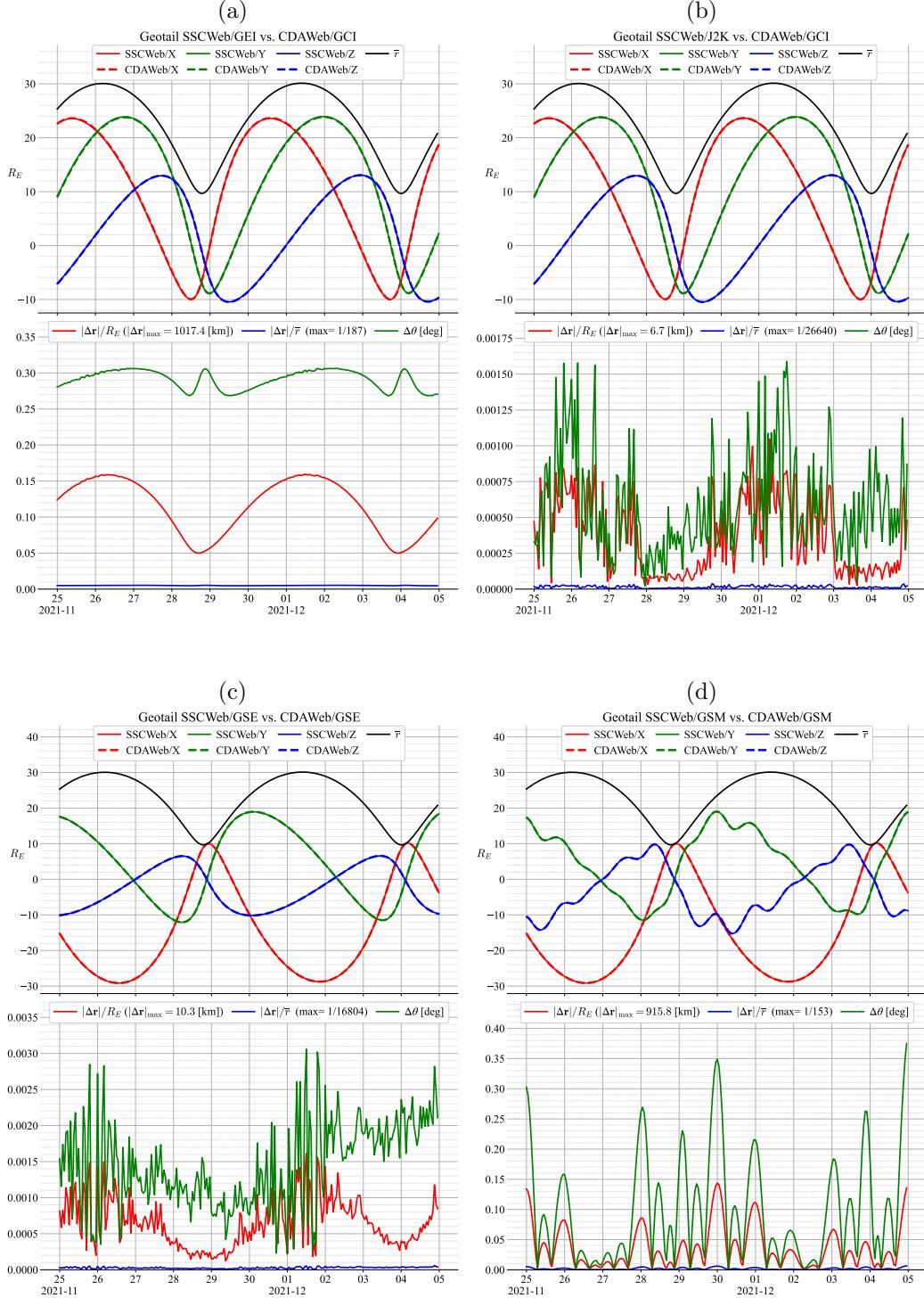


Figure 1: Comparison of position values for the Geotail spacecraft from SSCWeb and CDAWeb in four different reference systems. The top panel in each subplot displays the X , Y , and Z values from each provider (on this scale, differences are not visible) and the average radial distance, \bar{r} , between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

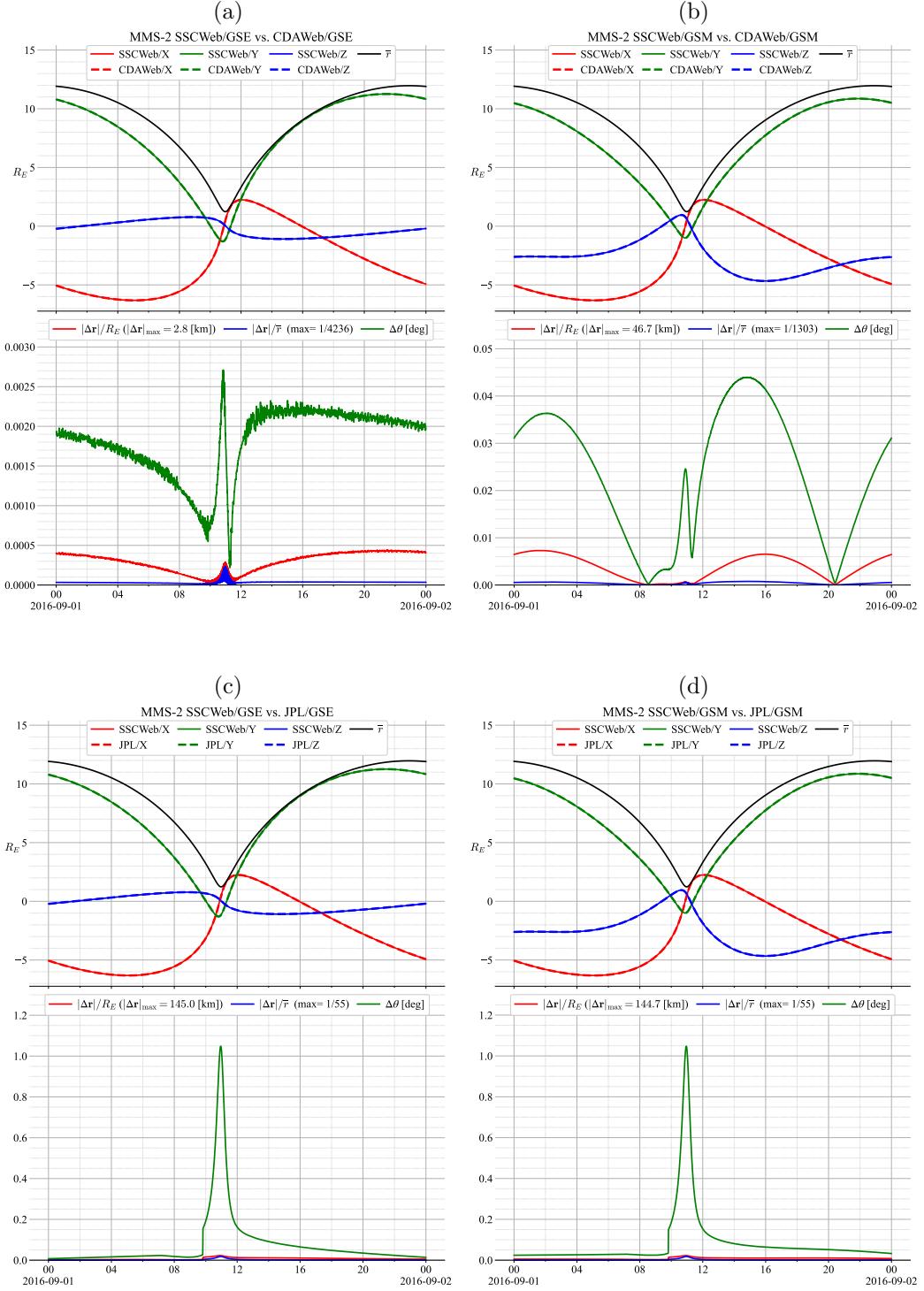


Figure 2: Comparison of position values for the MMS-2 spacecraft from (a)–(b) SSCWeb and CDAWeb; (c)–(d) SSCWeb and JPL Horizons in two different reference systems.

391 **4.2 Software**

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

- 394 • **Geopack-2008** double precision (Tsyganenko (2008); labeled as `geopack_08_dp` in
 395 the figures in this section), a Fortran library that was upgraded from earlier ver-
 396 sions to support calculations using 64-bit floating point values.
- 397 • **PySPEDAS** 1.7.28, which uses transformation code derived from the IDL version of
 398 PySPEDAS (Angelopoulos et al., 2024b), which in turn used code from the **ROCTLIB**
 399 Fortran (CDPP/IRAP, 2025) library, which was used for data from the Cluster
 400 spacecraft mission (Robert, 1993).
- 401 • **SpacePy** 0.6, which has an option to use the **IRBEM** Fortran library (Boscher et al.
 402 (2022); labeled as `spacepy-irbem`) or an alternative and native Python implemen-
 403 tation (`spacepy`) of the transforms.
- 404 • **SpiceyPy** 6.0.0 is a Python wrapper for the SPICE toolkit. Two versions of SPICE
 405 kernel files were used, indicated by `spiceypy1` and `spiceypy2`. `spiceypy1` was used
 406 for reference frame transforms for the Van Allen Probes mission. `spiceypy2` had
 407 an update to the MAG frame, which used a more recent version of the IGRF model
 408 (Alken et al., 2021) to determine the Earth's magnetic dipole orientation.
- 409 • **SunPy** version 7.0.0, which extends the AstroPy coordinates framework to include
 410 space physics reference frames.

411 The top subplots in Figure 3 show the angles between the Z axis of four coordi-
 412 nate frame pairs. The angle between the Z axis in frame A and the Z axis in frame B ,
 413 $\angle(Z_A, Z_B)$, was computed by transforming the Z axis in frame A into frame B , and the
 414 angle was computed between this transformed axis and the Z axis in frame B .

415 The middle subplots in Figure 3 show the difference of the angles between the Z
 416 axes for each library with respect to that for `geopack_08_dp`. The choice of library used
 417 as the baseline for this comparison is arbitrary, and it should not be interpreted as im-
 418 plying that this library is preferred; in general, we are interested in the maximum dif-
 419 ferences among the libraries, which are shown in the lower panel of each subplot. The
 420 maximum absolute values range from $4 \cdot 10^{-9}$ degrees for `pyspedas` in Figure 3(a) to
 421 $1 \cdot 10^{-2}$ degrees for `spiceypy1` in Figure 3(c); the values for each library are given in the
 422 legend in the middle panel of each subplot.

423 The bottom panels of Figure 3 shows that across all libraries, the maximum ab-
 424 solute value of lines in the middle panel are $\sim 0.01^\circ$ for **GEO/GSE**, $\sim 0.03^\circ$ for **GEO/GSM**,
 425 $\sim 0.04^\circ$ for **GSE/GSM**, and $\sim 0.03^\circ$ for **GSE/GSM**, all of which are comparable to the aver-
 426 age angular change in Earth's dipole Z axis of $\sim 0.04^\circ$ per year.

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

431 The range of the maximum absolute differences, 0.001° - 0.04° , shown in the bot-
 432 tom panels of the subplots in Figure 3 is smaller than the range, 0° - 1° , of angular dif-
 433 ference in spacecraft position vectors in the same coordinate system from two different
 434 data providers found in section 4.1. The position vectors can differ for two reasons: dif-
 435 ferences in the source of the position data and differences in the data providers' software
 436 libraries, if a transformation is needed. To determine the magnitude of each, one must
 437 analyze the source code used to generate the positions, which is not readily available.

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

frames and comparison axis. This range of differences is comparable to the range of angles identified in section 4.1, which includes the average angular change in Earth's dipole Z-axis over the past 45 years, the precession of Earth's rotation axis, changes in nutation of Earth's rotation axis over one year, and the precession of the ecliptic. The implication is that inter-comparison of measurements transformed with different libraries may require an analysis of the differences in the transform implementations if the differences in the measurements are not significantly larger than these differences. This type of analysis is challenging because it requires access to the transform software, which may not be maintained or available, and because calculations are needed to quantify differences due to transform implementation choices.

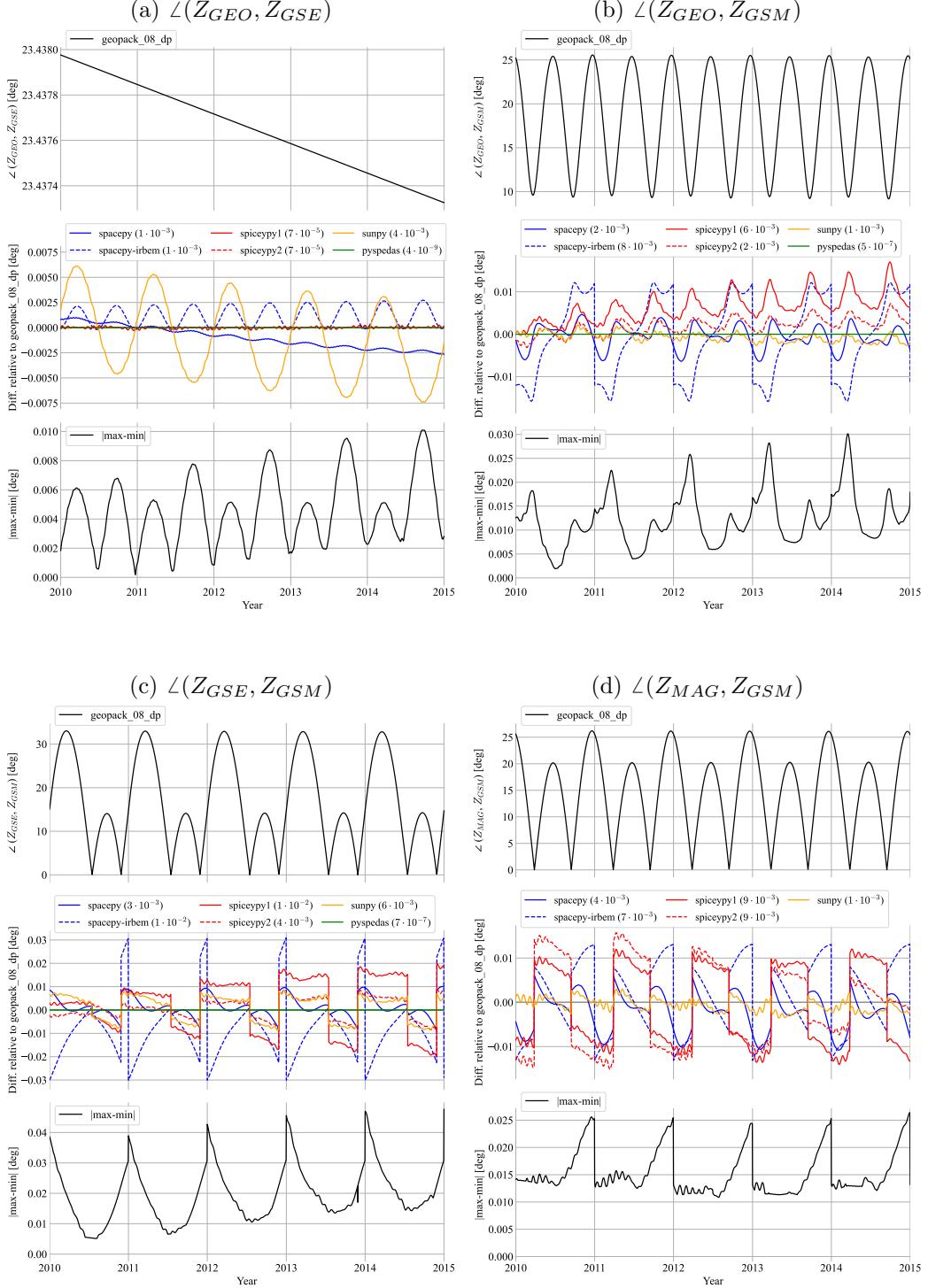


Figure 3: Angles between Z axes in select coordinate frames as computed by different software packages. In the top panels of each subplot, the notation $\angle(Z_A, Z_B)$ means the angle between the Z axis of coordinate frame A and the Z axis of coordinate frame B computed using `geopack_08_dp`. The 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.

450 5 How transform information is created for spacecraft missions

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

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

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

- 468 1. Mission-developed SPICE kernels for positions that are obtained from the mis-
 469 sion team periodically and archived. The GEI position-related SPICE kernel in-
 470 formation is used to generate the J2000 spacecraft positions. Then, software de-
 471 veloped as part of the International Solar-Terrestrial Physics program in the 1990s
 472 (ISTP; International Solar Terrestrial Physics (2025)) is used to compute positions
 473 in different coordinate frames, including GEI, GEO, GM, GSE, GSM, and SM. The ISTP
 474 software uses proprietary information needed for the reference frames, such as the
 475 position of the Sun, calculated by GSFC's Flight Dynamics Facility (FDF). This
 476 approach is only used on ISTP-era missions, i.e., ACE, Polar, Wind, and Geotail.
- 477 2. A mission-computed GEI position-related variable in archival data files delivered
 478 to SPDF is then used to compute orbit and attitude data in different reference frames;
 479 only data in the GEI-related frame is used. This is a possible source of the differ-
 480 ences shown in Figure 1 if the mission computed positions in the archival data prod-
 481 ucts by transforming GEI with software other than that used by SSCWeb. Differ-
 482 ences can also occur if the mission uses a different definition of GEI than SSCWeb.
- 483 3. If SPICE kernels or other mission-computed GEI position-related values are not
 484 available, TLE (Two-Line Element) files are obtained from NORAD (North Amer-
 485 ican Aerospace Defense Command), and a translation of the C NORAD library
 486 to Pascal (Brodowski, 2002) is used to compute positions in TEME (True Equator,
 487 Mean Equinox). Often, TLEs are used at the start of the mission, and a switch
 488 is made to approaches 1. or 2. as information becomes available. This switching
 489 has implications for reproducibility that are discussed in section 6.4 because pre-
 490 vious versions of positions are not retained.

491 6 Summary and Recommendations

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

494 6.1 Standards for Reference System and Frame Definitions

495 As defined in section 2, an *ideal reference system* is a general description of a ref-
 496 erence frame that lacks key details necessary for its implementation. Examples were pro-

497 vided in which the GEI acronym had different expansions, and different acronyms were
 498 identified as equivalent.

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

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

504 These terms are used in the astrophysics and earth science communities, and we
 505 recommend that the space physics community adopt them in place of the ambiguous term
 506 “coordinate system” (see section 3).

507 A community-developed standard for acronyms and definitions should be created.
 508 The standard should provide abbreviation/definition pairs for commonly used space physics
 509 ideal reference frames, so that data providers and paper authors can use them and re-
 510 duce ambiguity. Associated with each ideal reference frame definition, there should be
 511 at least one reference system abbreviation/definition pair. If multiple reference systems
 512 are in common use, their definitions and referencing conventions should be specified. For
 513 each reference system, at least one reference frame should be defined.

514 The reference system definitions will involve key quantities, such as the position
 515 of the sun and Earth’s dipole orientation. As a result, these key quantities will need to
 516 be precisely defined along with the model and methodology for computing them.

517 6.2 Reference Frame Standard Dataset

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

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

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

537 Many software libraries do spot checks of transforms. For example, SunPy’s unit
 538 tests (Mumford et al., 2025) involve a comparison with a table from Fränz and Harper
 539 (2002) at several time instants; `cxf orm` (Boller & Santiago, 2025) tests its implemen-
 540 tation by comparing the positions in GSE of one year of data from three spacecraft from
 541 Satellite Situation Center System and Services (2025c); a comparison is also made with
 542 a table in Fränz and Harper (2002). With the proposed reference database, a software
 543 library developer could make a more comprehensive comparison, allowing users to es-
 544 timate uncertainties associated with coordinate transforms directly. An additional ad-

vantage of this dataset is that software developers can use it for more comprehensive testing of their implementations.

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); 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 in 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 shared 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 Positions

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 positions 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 positions. Missions have used direct GPS measurements, commercial software such as STK (Systems Tool Kit), and data from facilities such as the GSFC Flight Dynamics Facility (FDF), the Deep Space Network (DSN), NAIF, and NORAD to produce the spacecraft positions for the mission. In section 4.1, we showed examples where the positions for two differ-

593 ent data providers for the same spacecraft differed in a way that was unlikely to be due
 594 to differences in how the data providers implemented the reference frame.

595 To address this, we suggest that data providers indicate how they obtained their
 596 spacecraft positions. We also suggest that if two data providers provide positions for the
 597 same spacecraft, they document how and why their results may differ, if applicable. We
 598 also recommend that the metadata indicate the uncertainty in the locations. Often, data
 599 providers will modify the position values when more accurate calculations become avail-
 600 able. This makes reproducibility difficult. Ideally, for reproducibility, old versions of po-
 601 sitions would be made available. Often, this is impractical, so an alternative is to include
 602 version information in the metadata, including a short description of the changes from
 603 the last version to the new one. The metadata for previous versions should be made avail-
 604 able so users can understand the changes from earlier versions to the current one. Fi-
 605 nally, the version number and its identifier should be included in the metadata.

606 **6.5 Documentation**

607 If the above recommendations are followed, the necessary documentation for re-
 608 producibility related to coordinate transforms will be simplified. For example, if an au-
 609 thor or software package used the standard dataset described in section 6.2 for a trans-
 610 form, only the standard dataset is needed for reproducibility. Similarly, if one or more
 611 SPICE kernels are used, each with a unique DOI and stored in a permanent generalized
 612 repository, only the DOIs are needed to retrieve the kernels. In this case, these DOIs and
 613 the version of the SPICE software library used are sufficient for reproducibility.

614 We recommend the following for general software and data documentation.

- 615 • Software package developers provide documentation on implementation choices
 616 (e.g., model used for obliquity and its parameters). If data from an external re-
 617 source is used, for example, if the IGRF coefficients are dynamically downloaded,
 618 the user should have an option to easily view the data used, so that, if necessary,
 619 the values used can be documented in a publication. Software should have a DOI
 620 for each major version, so the version used can be referenced rather than just a
 621 top-level DOI. Additional software citation recommendations are given in Jackson
 622 (2012), Smith et al. (2016), and (Stall et al., 2023).
- 623 • Data providers ensure that metadata associated with positions and variables that
 624 are transformed include details about the software version used for the transforms
 625 or the data used for the transform, such as SPICE kernels. The metadata descrip-
 626 tion should be validated by having a third party assess whether it contains suf-
 627 ficient information to re-implement the transform.
- 628 • When data are provided that have been transformed to a reference frame that de-
 629 pends on a magnetic field model (such as IGRF), data are also provided in a frame
 630 such as GEI/J2000 or ECI/J2000. The motivation is that there is variability in
 631 the implementation of the field model.
- 632 • Paper authors include the version of software, a DOI for that version if available,
 633 and the options passed to the transform function. If SPICE kernels are used, they
 634 should be permanently publicly accessible and citable with a version-specific iden-
 635 tifier.

636 **Appendix A Definitions**

- 637 • ACE – Advanced Composition Explorer (spacecraft mission)
- 638 • CDAWeb – Coordinated Data Analysis Web (NASA data archive)
- 639 • CD – Centered Dipole (reference frame). Same as GM and MAG if they use a model
 640 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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