Supporting information for "*PlanetMag:* Software for evaluation of outer planet magnetic fields and corresponding excitations at their moons"

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Introduction

This supplement contains a detailed description of the frames implemented in *PlanetMag* and definitions of their associated coordinate systems.

S1. Frames and coordinate systems

Below, we describe the IAU frames and those considered in past work for comparison. All frames described here are implemented in *PlanetMag* via a custom frames kernel for use with SPICE. Past studies have typically used $\phi\Omega$ coordinate systems (e.g., Zimmer et al., 2000) or spherical coordinates in the System III frame (SPRH) of the parent planet (Seufert et al., 2011; Arridge & Eggington, 2021) for evaluating the excitation moments. Although $\phi\Omega$ and SPRH coordinate systems are preferable for modeling and analysis of magnetospheric plasmas, neither is fixed to the surface of the moon. Because all large moons in our solar system rotate synchronously, the IAU axes can be approximated by one or more 90° rotations from SPRH or $\phi\Omega$ coordinates. However, the exact rotations vary throughout the orbital and true anomaly periods by up to several degrees, which introduces artifacts to the excitation spectrum.

In every case where a direction is specified from one body to another, or reference is made to a body's center, the center of mass is implied for each.

S1.1. IAU, System III, and SPRH frames

Parameterizations for IAU frames are adopted by resolution at an IAU General Assembly and described in reports of the IAU Working Group on Cartographic Coordinates and Rotational Elements, which we call the CCWG. IAU frames are defined for all major planetary objects in the solar system and are body-fixed and planetocentric, with the origin at the body center. In these frames, which are built-in to SPICE, the $\hat{z}$ axis is always directed along the rotation axis of the body, on the north side of the invariable plane—defined by the net angular momentum vector of the entire solar system. The northward normal of the invariable plane defines the $\hat{z}$ direction for International Celestial Reference System (ICRF), an inertial frame used in evaluating planetary ephemerides (the ICRF $\hat{x}$ direction is through the Earth equator at the vernal equinox at J2000).

For all planets and large moons except those in the Uranus system and Triton (which orbits Neptune in a retrograde direction), the IAU $\hat{z}$ axis is directed along the angular momentum vector of the body relative to its parent. For the Uranus system and Triton, $\hat{z}$ is in the opposite direction. The $\hat{x}$ direction is orthogonal to $\hat{z}$, directed from the body center toward the plane containing an arbitrary feature used to define the 0° (prime meridian) longitude for the body. For all moons, this is a feature intended to direct $\hat{x}$ approximately toward the parent planet. For all planets, this is a feature intended to face a particular direction at a particular epoch (Section S1.1.1). The $\hat{y}$ direction completes a right-handed coordinate system, approximately along the orbital velocity vector relative to the parent planet for the uranian moons and Triton and opposite the orbital velocity vector for all other large moons. The IAU x axis tracks the 0° longitude feature, and so moves with the surface of the body.

For the giant planets, which generally lack stable surface features, the IAU frame typically rotates at the same rate as the System III frame (Archinal et al., 2018a), which is defined by periodicity in the magnetic field of the planet or features tied to the magnetic field. These features are believed to be fixed to the motion of the deep interior of the planet. The System III frame always has the $\hat{z}$ direction along the angular momentum vector of the planet and 0° longitude along the direction of the IAU prime meridian. SPRH, a coordinate system sometimes used in spacecraft data analysis, is a spherical representation of the System III frame.

For Jupiter and Saturn, the IAU and System III frames are identical. For Uranus, the IAU frame has $\hat{y}$ and $\hat{z}$ reversed from the System III frame. For Neptune, the IAU frame was changed in the 2015 CCWG Report (Archinal et al., 2018b) to be a System II frame, which rotates along with stable atmospheric features. This definition has not yet been implemented in SPICE as of planetary constants kernel (PCK) `pck00010.tpc` and the IAU frame is not used for Neptune in *PlanetMag*. The latest PCK available, `pck00011.tpc`, implements this System II frame for Neptune, which differs from that used to derive the available magnetic field models for Neptune. We continue to use `pck00010.tpc` in *PlanetMag* for this reason. A more detailed description of the definitions of the IAU frames for the giant planets follows.

S1.1.1. IAU frame definitions for the giant planets

Jupiter — System III (1965): This frame is described well by P. Seidelmann and Divine (1977), and was adopted by the CCWG by the time of their first report (Davies et al., 1980). The rotation rate was selected based on many years of radio observations. It was revised in the 2000 report (P. K. Seidelmann et al., 2002) to be more precise based on recent work, but reverted in the 2009 report (Archinal et al., 2011) due to subsequent challenges raised against the updated rotation rate. The prime meridian is defined such that System III (1957.0) longitudes, which used a slightly different rotation period, coincide with System II longitudes at the 1957.0 epoch. However, a mistake in evaluating System II at 1957-01-01 00:00:00.000 UTC instead of the same time TDB (Coordinated Universal Time vs. Barycentric Dynamical Time, a difference of about 41.2 s) in calculating the observed central meridian longitude means the agreement is only approximate. Jupiter System II revolves with the mid-latitude atmospheric rotation rate (Dessler, 2002). Ultimately, the System III prime meridian is arbitrary and since the frame has seen widespread adoption in magnetic modeling, it is sufficient to use the J2000 definition as a reference.

Saturn — System III: This frame was defined by Desch and Kaiser (1981) as the Saturn Longitude System (SLS) and was adopted by the CCWG in the 1982 report (Davies et al., 1983), with the planetary rotation period revised in a private communication from M. L. Kaiser to M. E. Davies. Also referred to as L1 in Voyager 1/2 data hosted on the Planetary Data System (PDS). The prime meridian is selected to coincide with the Saturn ascending node of the planet's orbit on its equator at the 1980.0 epoch, 1980-01-01 00:00:00.000 UTC. The 1982 report (Davies et al., 1983) contains expressions for the prime meridian location relative to the J2000 epoch, which remain unchanged in the latest CCWG report (Archinal et al., 2018a). Axisymmetry of the Saturn magnetic moments (no moments are even reported for $m \neq 0$ in the literature) mean that the prime meridian definition does not impact modeling of the internal field, but the same is not true of the external current systems (Andrews et al., 2019). Subsequent research has resulted in alternative systems, namely SLS2 (Kurth et al., 2007) and SLS3 (Kurth et al., 2008). These systems vary the rotation rate to maintain an observed peak in radio intensities at 100° subsolar longitude. The varying rotation rate implies that these coordinate systems may not rotate with the deep interior of the planet, and the SLS system remains that preferred by the CCWG.

Uranus — System III: The first CCWG report defined the prime meridians of Saturn, Uranus, and Neptune to coincide with the ICRF x axis (direction of Earth vernal equinox from the solar system barycenter) at the J1950 epoch, 1950-01-01 00:00:00 TDB. Uranus is the only planet that still retains this definition in the latest report (Archinal et al., 2018a). The rotation rate was updated in the 1985 report (Davies et al., 1986) based on preliminary analysis from Voyager 2, with the prime meridian being briefly (and perhaps accidentally) set to the ICRF x direction at J2000 for this report only. The rotation rate, based on Desch, Connerney, and Kaiser (1986), has not been updated since the 1986 report. The z axis for the IAU frame is opposite to the rotation direction, because the angular momentum vector is greater than 90° away from the z axis of the ICRF frame, and IAU convention stipulates this condition. This frame is not typically used in analysis of magnetic data, primarily because of the ubiquity of spherical coordinates with the polar axis aligned to the angular momentum vector, in opposition to the IAU definition.

Neptune — System II: Following the Voyager 2 flyby of Neptune, a radio-derived rotation period based on Warwick et al. (1989) was adopted by the IAU. The 1950.0 ICRF x axis definition for the prime meridian was retained until the current System II definition was adopted in the 2015 report (Archinal et al., 2018b) based on observations of remarkably stable cloud features reported by Karkoschka (2011). The System II definition uses the rotation period inferred from the South Polar Feature and South Polar Wave identified by Karkoschka (2011), and the prime meridian is located at the average of the longitudes of both features. This meridian is stated to coincide with the System III (1950.0) meridian at 1989-08-03 12:00:00 UTC. The System II frame is not yet implemented in the latest recommended version of the SPICE planetary constants kernel, `pck00010.tpc`.

S1.2. Frames for planetary field models

Each intrinsic field model implemented in *PlanetMag* is evaluated using the coordinates specified in the peer-reviewed publication that describes the model. Generally, these coordinates match those in which the available spacecraft measurements are reported for the planet. Current sheet models often use unique coordinate systems, but these are referenced to the same standard systems. All models for a particular planet use a single coordinate system, as follows.

Jupiter: System III (1965), implemented as the `IAU_JUPITER` frame in SPICE.

Saturn: Saturn Longitude System (SLS), also known as S1, implemented as the `IAU_SATURN` frame in SPICE.

Uranus: Uranus Longitude System (ULS), also known as U1, as defined by Ness et al. (1986) and named by Herbert (2009). $\hat{z}$ is aligned with the planet's angular momentum vector, the prime meridian is arbitrarily defined using the Voyager 2 trajectory, and the frame rotates along with the intrinsic magnetic moments. This frame is obtained by inverting the z axis of the `IAU_URANUS` frame and rotating to set the Voyager 2 position at 1986-01-24 18:00:00, about 1 s from closest approach (CA), to be 302°W in the ULS frame. From the most up-to-date SPICE kernel reconstructing the Voyager 2 trajectory, `vgr2.ura111.bsp`, and the `pck00010.tpc` planetary constants kernel, the IAU longitude of the spacecraft at this time was about 225.3°E. The ULS frame is a constant offset from the IAU frame and thus rotates with the IAU frame. The Voyager 2 magnetic measurements and trajectory from the Uranus flyby are reported in ULS coordinates.

Neptune: Neptune Longitude System (NLS), as defined by Connerney, Acuña, and Ness (1992). $\hat{z}$ is aligned with the planet's angular momentum vector, defined by Connerney et al. (1992) to have right ascension $\alpha_0 = 298.90°$ and declination $\delta_0 = 42.84°$, which we assume to be in reference to the ICRF frame at J2000. The prime meridian orientation is defined using 167.7°W at 0356 spacecraft event time (SCET, equivalent to UTC in this case) on day-of-year 237 (August 25) of the year 1989. The Voyager 2 trajectory determined from the latest SPICE kernels (`vg2_nep097.bsp`) in this frame does not match the data reported in PDS (volume VG2-N-MAG-4-SUMM-NLSCOORDS-12SEC-V1.0). We have implemented the frame defined by Connerney et al. (1992) as `NLS_RADEC` and a second frame, `NLS`, that is equivalent to the `IAU_NEPTUNE` frame implemented in SPICE based on the 2009 CCWG report (Archinal et al., 2011) but rotated to place Voyager 2 at a planetocentric west longitude of 167.7°, a rotation of 12.0140°. The `NLS` frame much more closely approximates the Voyager 2 trajectory detailed in this frame along with the magnetic data on PDS, but some systematic offset is still present from an unknown source. See Figure S1 for a comparison of the NLS trajectory against that reported in the PDS data.

S1.3. Frames for magnetic investigation of moons

Past investigations have primarily used $\phi\Omega$ frames. These frames are common in analysis of plasma flow and moon–plasma interactions because the axes rotate along with the moon as it orbits and the xy plane is coplanar with that of the planet's System III frame, related by a rotation about $\hat{z}$. In $\phi\Omega$ frames, the $\hat{z}$ direction is aligned to the parent planet's spin angular momentum vector, $\hat{x} = -\hat{r} \times \hat{z}$, where $\hat{r}$ is the direction from the parent planet to the moon, and $\hat{y}$ completes the right-handed set. $\hat{y}$ is approximately toward the parent planet, $\hat{x}$ is in the corotation direction—approximately along the orbital velocity vector, and $\hat{z}$ is approximately along the moon's angular momentum vector in the case of natural moons that orbit near the planet's spin equator. Because each moon's orbit is elliptical, the axes rotate in a non-uniform fashion, faster near periapsis and slower near apoapsis. A comparison between the IAU frame, which is fixed to the body surface, and the $\phi\Omega$ frame for Europa, E$\phi\Omega$, is shown in Figure S2. In *PlanetMag*, we have implemented $\phi\Omega$ frames only for the moons of Jupiter, to facilitate comparison to past studies. These frames are available in *PlanetMag* as `IO_PHI_O`, `EUROPA_PHI_O`, etc. Note also that the above descriptions of these frames may vary for retrograde orbits, as in the case of Triton.

S1.4. Additional frames for evaluation of models in the literature

For convenience and comparison to prior work, we have also implemented the following frames, all of which are centered on the planet:

Planet–Sun–Orbit: $\hat{x}$ is directed toward the Sun. $\hat{y}$ is directed along the component of the Sun's instantaneous inertial velocity vector, as seen from the planet, that is normal to $\hat{x}$, and $\hat{z}$ completes the right-handed set. Available in *PlanetMag* as `JSO`, `KSO`, `USO`, and `NSO` for Jupiter, Saturn, Uranus, and Neptune, respectively.

Planet–Sun–Magnetic: $\hat{x}$ is directed toward the Sun. $\hat{y}$ is along $\hat{\mathbf{M}} \times \hat{x}$, where $\mathbf{M}$ is the instantaneous magnetic dipole moment vector. $\hat{z}$ completes the right-handed set. A model must be selected for the orientation of the dipole moment. These frames are available in *PlanetMag* with the following model dipole orientations: `JSM` — O4 (Acuña & Ness, 1976), used in magnetosphere shape calculations in KS2005 model (Khurana & Schwarzl, 2005); `KSM` — Cassini 11 (Dougherty et al., 2018); `USM` — Offset, tilted dipole (OTD) (Ness et al., 1986), used in magnetopause field calculations of Arridge and Eggington (2021); `NSM` — O8 (Connerney et al., 1992). Originally defined by Acuña and Ness (1976) and given this name in Bagenal and Wilson (2016, `https://lasp.colorado.edu/home/mop/files/2015/02/CoOrd_systems12.pdf`).

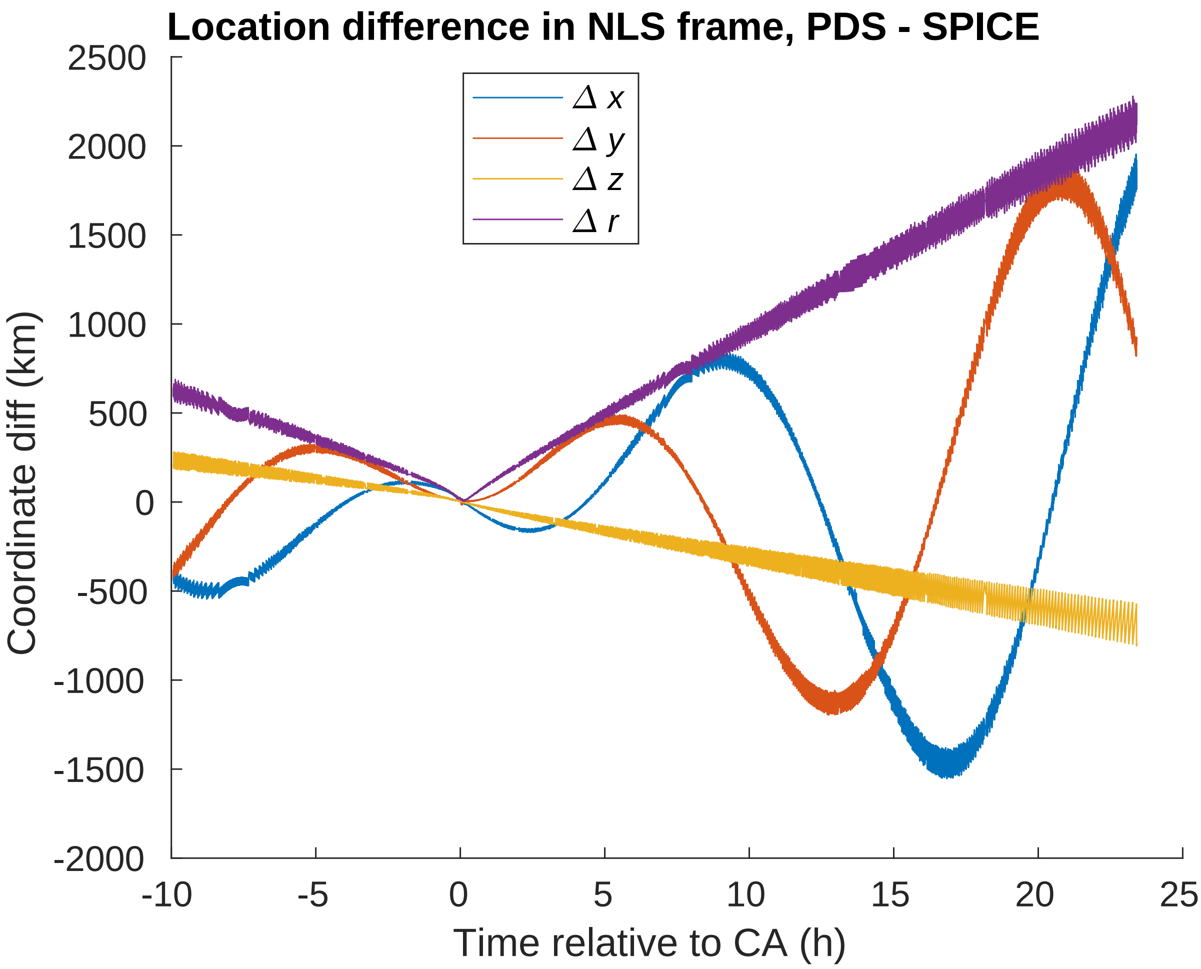

Figure S1. Comparison of the Voyager 2 trajectory in the NLS frame as reported in PDS data (volume VG2-N-MAG-4-SUMM-NLSCOORDS-12SEC-V1.0) vs. our implementation of the frame using the latest reconstruction using SPICE kernels.

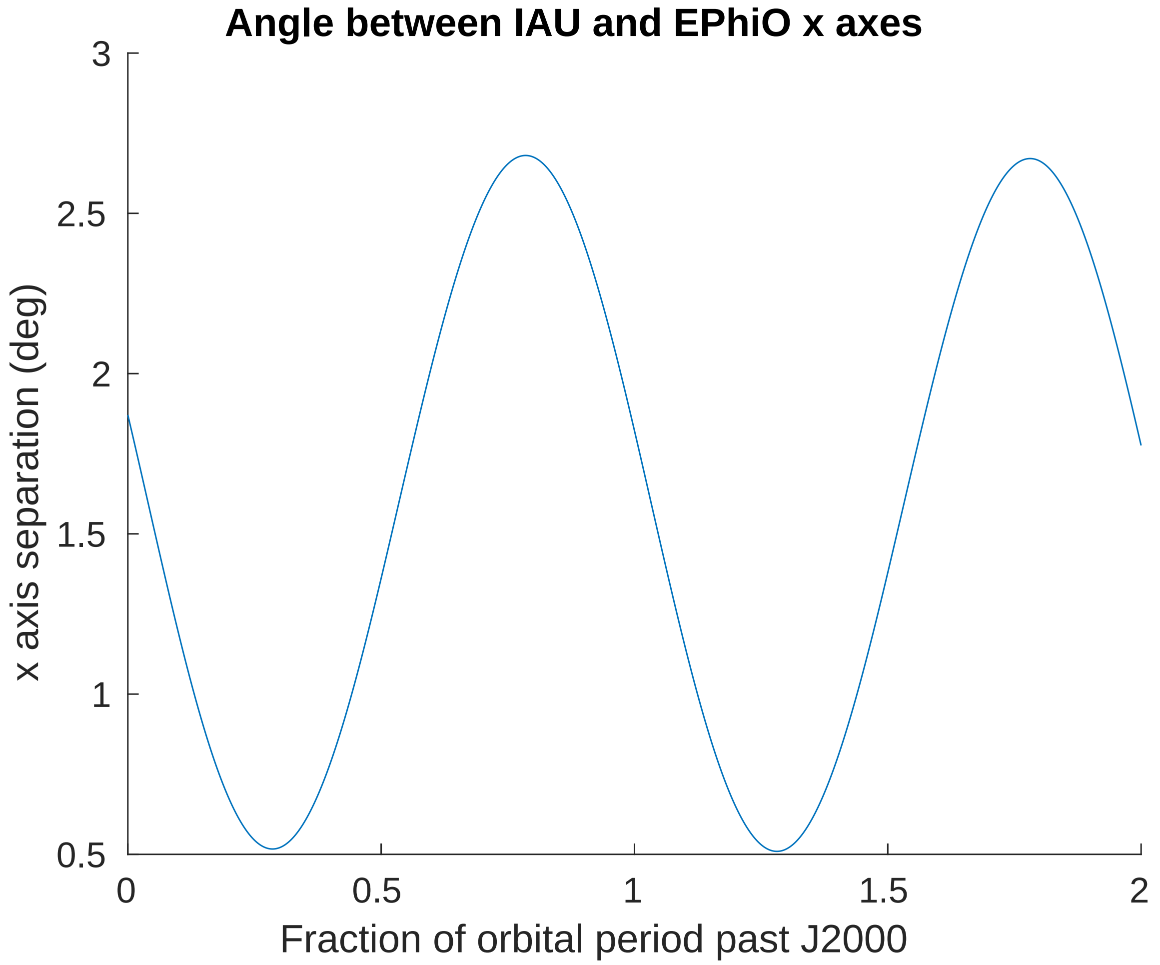

Figure S2. Angle between $\hat{x}$ for the IAU frame for Europa and the E$\phi\Omega$ coordinate system commonly used in past magnetic sounding investigations throughout the first 2 orbital periods following the J2000 epoch. The IAU frame is fixed to the body surface; the E$\phi\Omega$ axes vary throughout Europa's orbital period as it librates.

Planet–Dipole–Solar–Zenith: $\hat{z}$ is directed toward the Sun. $\hat{y}$ is along $\hat{\mathbf{M}} \times \hat{z}$, where $\hat{\mathbf{M}}$ is along the dipole moment vector and the same models are selected as in the Planet–Sun–Magnetic frames. $\hat{x}$ completes the right-handed set, approximately antiparallel to $\hat{\mathbf{M}}$. Available in *PlanetMag* as `JDSZ`, `KDSZ`, `UDSZ`, and `NDSZ`. This frame is described in application to Jupiter by Alexeev and Belenkaya (2005), but not named therein. Used in Arridge and Eggington (2021) magnetopause model based on shape defined by Shue et al. (1997), for which this frame makes evaluation simple.

Solar–Magnetic–Planet: $\hat{z}$ is along $\hat{\mathbf{M}}$ as defined in the models selected for the Planet–Sun–Magnetic frames. $\hat{y}$ is along $\hat{r}_{\mathrm{Sun}} \times \hat{z}$, where $\hat{r}_{\mathrm{Sun}}$ is directed toward the Sun. $\hat{x}$ completes the right-handed set. The xy plane of this frame is the magnetic dipole equator, and $\phi = 0$ in spherical coordinates in this frame coincides with the sub-solar longitude. Available in *PlanetMag* as `SMJ`, `SMK`, `SMU`, and `SMN`.

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