Choice of Coordinate Systems for Planetary Mapping by the Europa Clipper Project

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Overview

The establishment of a coordinate system for planetary mapping is in some regards an arbitrary decision. **To date, the Galilean satellites have been mapped using a planetographic coordinate system with a west-positive longitude.** Data from the Voyager and Galileo missions are stored in the Planetary Data System using these conventions. As new missions prepare to map the Jovian system, **a proposal has been made to change the mapping convention to a planetocentric coordinate system with east-positive longitude.** This white paper will describe the differences between the two mapping conventions, document the historical coordinate systems used for the Galilean satellites in more detail, provide rationale to support a switch to an east-positive coordinate system, and consider some of the implications and implementation details of the proposed change.

Background on coordinate systems

The definition of a coordinate system is of utmost importance when mapping the surface of a planet or satellite, yet the establishment of a coordinate system is, initially, somewhat arbitrary. The reference system used to define the orientation of the planets and their satellites is shown in Figure 1. The north pole lies on the north side of the invariable plane of the Solar System and is specified by the value of its right ascension, α_0, and declination, δ_0. The two intersection points of the body's equator and the International Celestial Reference Frame (ICRF) equator are $\alpha_0 \pm 90°$. Defining the intersection at $\alpha_0 + 90$ as node Q and the intersection of the prime meridian with the body's equator as node B, the angle, W, measured between these nodes varies linearly with time. If W increases with time, the planet has a prograde rotation, and, if W decreases with time, the rotation is retrograde. In Cartesian planetary coordinate systems, the *Z*-axis is pointed at the north pole, with perpendicular *X*- and *Y*-axes spanning the equatorial plane. The *X*-axis is defined as pointing at the prime meridian.

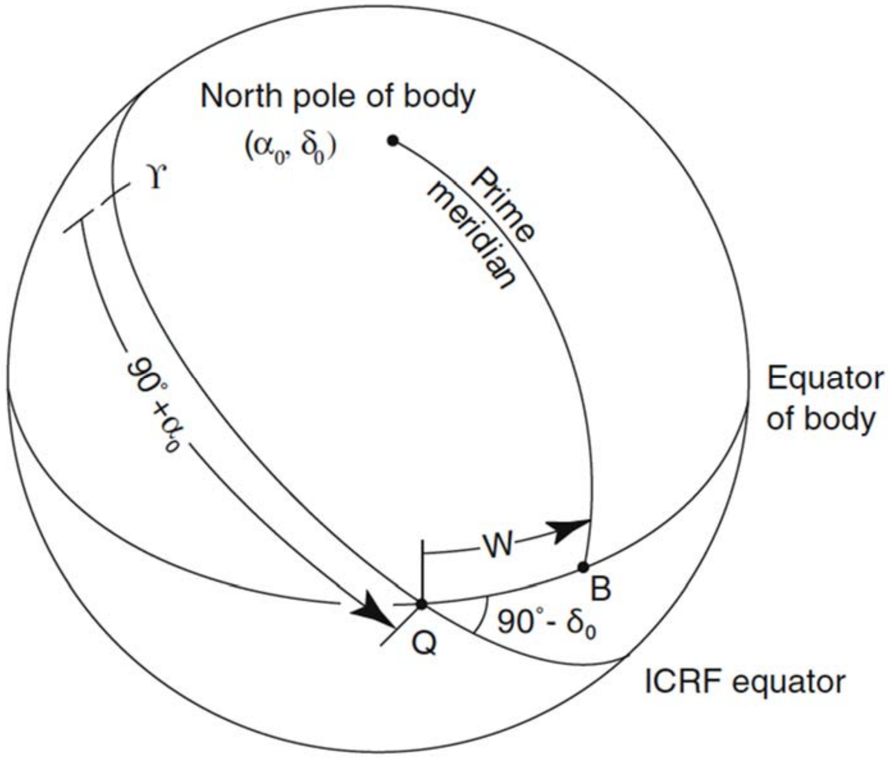


Figure 1: Reference system illustration (adopted from Archinal et al., 2010)

A planet's spin-axis poles and equator can be used to map lines of latitude, using well-defined conventions which yield 0° latitude at the equator and 90° at the poles. Which pole is the north pole, and which is the south, depends on the rotation direction of the planet or satellite and its orbital plane and direction around its primary body (or the Sun), and can be an arbitrary distinction. In addition, the establishment of a prime meridian, the zero point of longitude, can also be arbitrary (such as in the case of Greenwich, England) but in the planetary context is typically set based on orbital dynamics. In the case of the Jovian system, the sub-Jupiter point is close to the zero longitude point for Europa – this definition is usually applied to tidally-locked satellites. However, the direction of longitude, whether it is positive eastward or positive westward, and whether longitude uses a range of -180° to +180° or a range of 0° to 360°, can all vary from world to world and in some cases from map to map.

While the poles and equator are relatively easy to establish, the determination of latitude depends on whether planetographic or planetocentric coordinates are used. Planetocentric latitudes are computed based on the angle between the equator and a vector between the planet's center and the surface normal, while a planetographic latitude is computed via the intersection of the surface normal vector with the equatorial plane (Figure 2). For a spherical body, the planetographic and planetocentric latitudes are identical, but as a body becomes more oblate, the difference between the two latitudes increases. In the planetographic coordinate system, the difference between circles of latitudes is proportional to the distance along the surface.

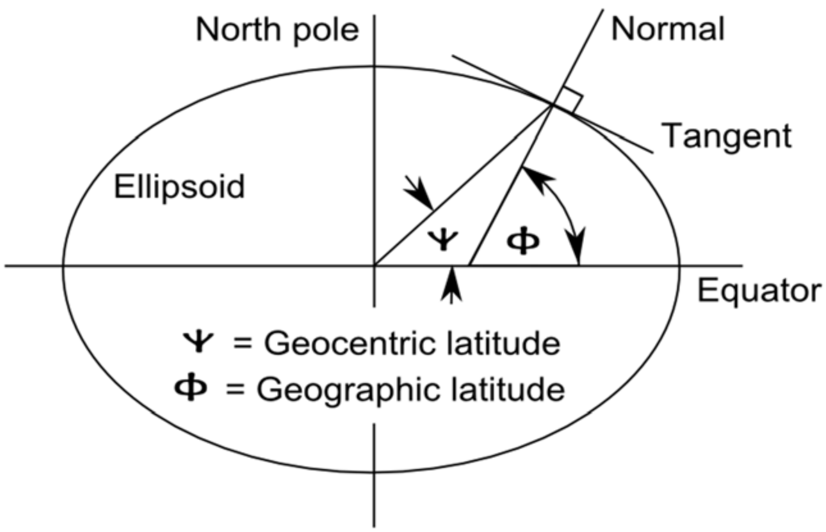
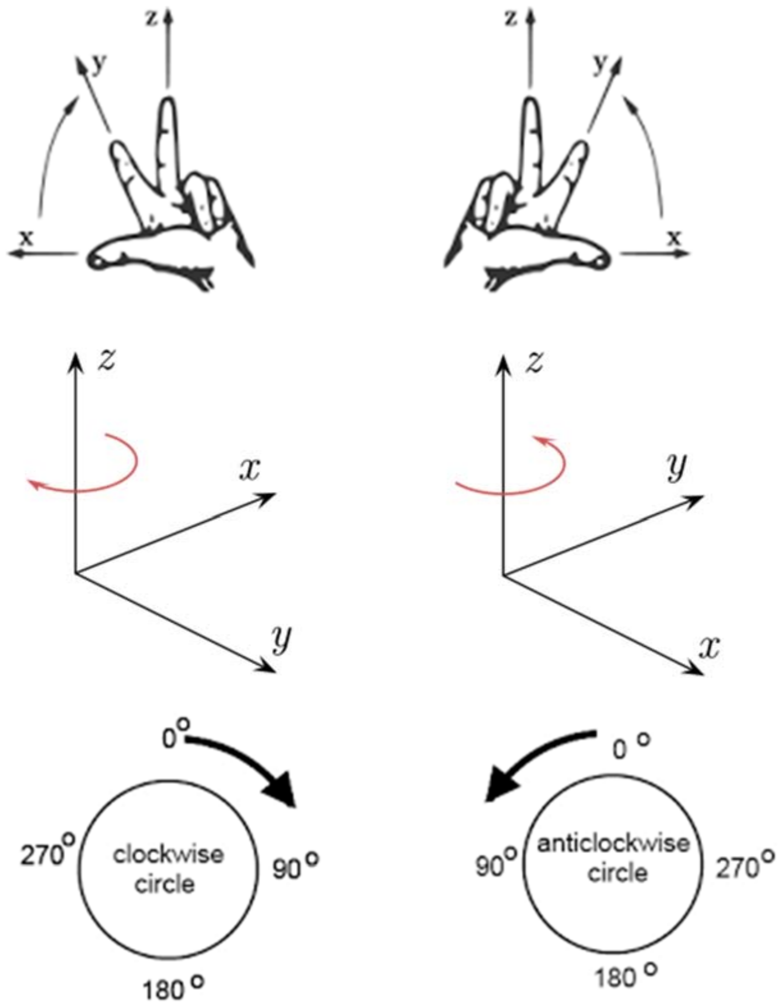


Figure 2: Definition of latitude in planetocentric and planetographic coordinate systems.

Planetographic longitudes can also be defined for a body which does not have equatorial symmetry, i.e., an ellipsoid with different extent along the *X*- and *Y*-axes. Planetographic coordinate systems are fundamentally left-handed and longitudes are incremented clockwise. When the rotating planet is viewed from a distance, the longitudes on the surface seem to increase as the body rotates. This convention was adopted for historical maps of Mars, Mercury, and the Galilean Satellites. It is *not*, however, the mathematical convention.

By contrast, a planetocentric coordinate system is a fundamentally right-handed system, in which longitudes are incremented counter-clockwise. This system follows the familiar right-hand rule of physics (Figure 3) and complies with mathematical conventions; thus, this system currently favored by geophysicists. In a planetocentric coordinate system, the longitude is always measured positive to the east. This convention is currently used for Mars, Moon, Mercury, and Vesta. The change to a planetocentric coordinate system for Mars and Mercury was urged by the scientists, notably geophysicists, who worked with improved data for these bodies.

One issue with planetographic coordinates is that they are not easily converted into Cartesian coordinates. Thus, it can be difficult to use these coordinates to measure lengths or to calculate the distance between two points. In some instances, a combination of the two conventions has been used in cartography, for example, a single map might use a planetographic longitude system with planetocentric latitudes.



Planetographic Coordinates (left column)

Planetocentric Coordinates (right column)

Figure 3: Progression of positive longitude in planetographic (left column) and planetocentric (right column) coordinate systems.

Historical coordinate systems used for the Galilean Satellites

The difference in usage of planetocentric and planetographic coordinate systems and of associated longitude conventions is primarily based on astronomical tradition. While the definition of a planetocentric coordinate system is fundamentally mathematical, the planetographic coordinate system is defined based on guiding principles from the XIVth General Assembly of the International Astronomical Union (IAU) from 1970. These state that:

1) The rotational pole of a planet or satellite which lies on the north side of the invariable plane will be called north, and northern latitudes will be designated as positive.
2) The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial system, will increase with time. The range of longitudes shall extend from 0 to 360 degrees (Davies et al., 1996).

Using this planetographic convention, longitude is measured west-positive if rotation is prograde, and east-positive if rotation is retrograde. However, because of astronomical tradition, Earth, Sun, and Moon do not follow this convention – in all three of these cases, their rotations are prograde, and longitudes are labeled both east and west 180° instead of a global 360°.

Previous maps of Mars (from Mariners 4, 6, 7, and 9 and Viking), Mercury (from Mariner 10), and the Galilean satellites all used a planetographic latitude convention. Maps of the Jupiter system from Galileo and Voyager used a planetographic coordinate system with a west-positive longitude. The data is stored in the Planetary Data System (PDS) using this coordinate system. For example, the current global basemap of Europa (USGS, 2002) uses a west-positive longitude convention, with a planetographic latitude system. The Europa prime meridian is defined such that the crater Cilix is located at 182°W.

Suggested future coordinate system convention for the Galilean satellites

Although previous mapping of the Galilean satellites has used a planetographic coordinate system with west-positive longitude, the Europa Clipper project proposes to use from its onset a planetocentric coordinate system with east-positive longitude.

It is recognized that a switch of this kind could cause some short-term disruption, requiring translation of existing maps and data products to the new coordinate system and convention. However, we suggest that in the long run, such a switch will produce more consistent scientific results that can be integrated with current digital mapping techniques.

Current conventions:
PDS Galileo & Voyager datasets: planetographic coordinates with west positive longitude

Suggested future conventions:
Europa Clipper: planetocentric coordinates with east positive longitude

The Europa Clipper Project prefers the planetocentric east-positive longitude coordinate system for four important reasons:

1) **Europa Clipper will perform geophysical investigations, and the geophysical sciences traditionally use the east-positive longitude convention.** Geophysics-based disciplines

apply fundamental mathematical and geometric principles, which natively use a planetocentric, east-positive coordinate system. For example, gravitational potential calculations and spacecraft navigation use a spherical coordinate system, which is identical to a planetocentric coordinate system. Such a system would facilitate application of tools and techniques for studying Earth to studying the Galilean satellites.

2) **The east-positive planetocentric system has a mathematical basis, whereas the west-positive planetographic system does not.** In conjunction with point (1) above, using a coordinate system with an inherently mathematical basis allows ease of computation in this age of digital cartography, such as with GIS-based software. Longitude increases in the right-handed direction. Again, this is consistent with direct application of tools and techniques for studying Earth to studying the Galilean satellites.
3) **In planetographic coordinate systems, latitudes of surface features change when the reference ellipsoid is updated.** In contrast, the latitudes of surface features in planetocentric coordinate systems are fixed and do not change as the reference ellipsoid continues to be updated or the height of a point above or below that ellipsoid changes. As the shapes of the Galilean satellites become better described by future missions, this will become increasingly relevant.
4) **Consistency with the ESA JUICE mission.** For the reasons above, the European Space Agency (ESA) has already made the decision that the upcoming JUpiter ICy Moons Explorer (JUICE) mission will adopt a planetocentric east-positive coordinate system for mapping the surfaces of Europa and other Galilean satellites. The Europa Clipper and JUICE missions will both be active in the Jovian system in the same era; to ease scientific collaboration, to avoid confusion, and, most important, to prevent targeting and analysis errors, it is imperative that both missions share identical coordinate system definitions.

The IAU is the international governing body responsible for ensuring consistency in mapping and naming within astronomical and planetary contexts. The IAU Working Group on Cartographic Coordinates does not currently give preference to either the geodetic or the geocentric coordinate system, which for planets correspond to planetographic or planetocentric coordinate systems, respectively (Archinal et al., 2010). Previous IAU recommendations do state that a longitude convention be used in which the longitude of the central point on the surface, when viewed from a distant fixed point, increases over time. (Davies et al., 1996).

With the advent of digital mapping techniques, the coordinates of each pixel in a map or other data product can be specified in metadata files or image backplanes. Thus, the mapping process no longer requires relation of observations to a global reference sphere. Instead, using digital cartography, the latitude, longitude, and radius can be specified separately and individually for each pixel. Moreover, the USGS ISIS software package, which is the standard used for planetary image processing, can now work with datasets using either planetocentric or planetographic latitude, as well as data labeled in either east- or west-positive longitude (Duxbury et al., 2002).

Transitions between coordinate systems have been successfully accomplished in the past. For example, although Mariner 10 observations at Mercury were archived with planetographic, west-positive coordinates, the MESSENGER project chose a planetocentric, east-positive coordinate system for this planet, in order to facilitate geodetic analyses of Mercury's topography and gravity, as well as its cartography. For backwards compatibility, a standard transformation was defined between the new MESSENGER coordinate set and the pre-existing Mariner 10 dataset, which used the IAU standard coordinates (Archinal et al., 2010).

Similarly, the Mars Global Surveyor mission defined a planetocentric, east-positive coordinate system, which was used successfully in combination with data from the Mariner and Viking missions as represented in the previous planetographic west-positive (IAU standard) coordinate system. A major reason stated for this change was that it eliminates updates to the planetographic latitudes of surface features whenever the Mars reference ellipsoid is updated. Since switching to a planetocentric coordinate system, the latitudes of surface features have been fixed (Duxbury et al., 2002). This argument does not apply to Europa to the same degree, because Europa's shape is much more than spherical than Mars, and the reference surface for Europa is currently a sphere, but such may well change for Europa and the other Galilean satellites upon future detailed examination.

Following the adoption of a planetocentric, east-positive coordinate system for Mars by the Mars Global Surveyor project, the Mars Odyssey, Mars Exploration Rover, and Mars Express missions adopted this coordinate system, and it is anticipated that future Mars missions will do so as well. In response, the USGS formally proposed to NASA to make all future digital and paper Mars maps consistent with this coordinate system (Duxbury et al., 2002). The coordinate system convention proposed for Mars has also been adopted internationally (e.g., Gehrke et al., 2003.

For the many reasons above, the Europa Clipper Project and Science Team recommend the use of a planetocentric coordinate system with east-positive longitude for Europa and the other Galilean satellites.

Implementation / Implications

The adoption of a new longitude convention and coordinate system for Europa would affect Europa Clipper mission design and data archiving and would also have implications for data sets currently archived in the PDS.

Moving forward, the Europa Clipper project would update the locations of features on Europa's surface to the adopted coordinate system and would use these conventions for future trajectory analysis, landform location, and other aspects of mission planning that require absolute locations on the surface.

Retroactively, coordinate system transformations for Galileo and Voyager images of Europa, and likely of other Galilean satellites, currently stored in the PDS would need to be generated.

Galileo and Voyager imaging data are stored in the PDS is in .img format, which does include initial spacecraft and viewing geometry in detached label (.lbl) files. The following is an example for a Viewing Geometry label block of an image stored in PDS3 format:

```
/* Viewing Geometry */
/* Note: These viewing geometry parameters are best estimates */
/* at the time this picture label was generated. */
POSITIVE_LONGITUDE_DIRECTION = WEST

/* Spacecraft Geometry */
TARGET_CENTER_DISTANCE = 3.968076e+03
CENTRAL_BODY_DISTANCE = 6.722434e+05
SUB_SPACECRAFT_LATITUDE =   -1.038
SUB_SPACECRAFT_LONGITUDE =  340.155
SUB_SPACECRAFT_LINE = -6701.040
SUB_SPACECRAFT_LINE_SAMPLE = 15156.391
SUB_SPACECRAFT_AZIMUTH =  334.302
```

The label contains a “positive longitude direction” flag, which could be used to differentiate between a west-positive and east-positive version of the same image in the archive. This flag, together with the subsequent descriptions of spacecraft geometry and camera and lighting geometry (not shown), are processed by programs such as ISIS to establish the initial pointing and image geometry information. The Europa Clipper data will be archived in PDS4 format, which allows for similar descriptors.

If and when such a change to coordinate system and longitude convention is approved, the PDS could consider creating new versions of affected archived data products using the new coordinate system, or providing a script or a software tool to transform images into the new coordinate system.

As an interim or perhaps even a permanent solution, maps and other data products could be labeled with both east- and west-longitude conventions on their longitude axes. This is currently done for some Mars maps from USGS. Moving forward, such a change should also be documented in papers, maps, and other materials. In addition to updating reference maps and cartographic products, a coordinate system change would also require the IAU nomenclature database to be updated with the new coordinates of surface features on Europa.

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