Tandem Reconnection And Cusp Electrodynamics Reconnaissance Satellites (TRACERS)

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Tandem Reconnection And Cusp Electrodynamics Reconnaissance Satellites (TRACERS)

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Revision	**Release Date**	**Description/Changes**	**Change Action #**
-	2021-05-13	Initial release.	n/a
A	See watermark	Updated sensor coordinate systems to reflect the change from deployable booms to rigid brackets which caused a rotation in orientation of MAG, MSC, and MAGIC sensors.	TRACERS-SE-CCA-204

Table of Contents

Table of Exhibits

1 SCOPE

This document describes the TRACERS mission coordinate systems. The physical, mounted instrument, Level 0 data coordinate systems are detailed in this document with their reference to the single satellite coordinate system. Calibration coefficients can be found in individual instrument calibration documents. Transformations in the form of SPICE frame kernels are available outside of this document.

2 REFERENCE DOCUMENTS

2.1 TRACERS Documents

TRACERS-SE-REQ-001: TRACERS Level 1 Requirements (Program Level Requirements Appendix (PLRA)

TRACERS-SE-REQ-002: TRACERS Level 2 Mission Definition Requirements Agreement (MDRA)

TRACERS-SE-INT-015: TRACERS S/C Bus to TIS Mechanical Interface/Installation Control Drawing (MICD)

3 INTRODUCTION

3.1 TRACERS Science

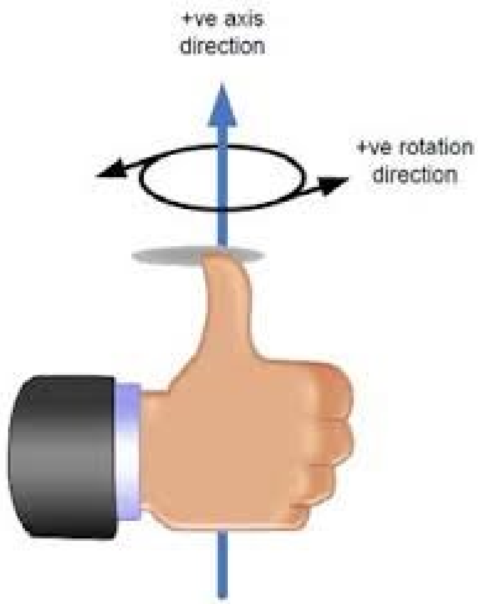
TRACERS consists of two identical spinning satellites TS1 & TS2. TS1 & TS2 are in the same LEO circular Sun synchronous orbit (SSO) that achieves science closure. The time-lag between TS1 & TS2 is 10-120s. The two satellites cross 60-85°N magnetic latitudes to encounter the magnetospheric cusp Region of Interest (ROI), with the satellite spin axes coarsely aligned to the magnetic field in the center of the cusp (Local Aggregate B-Field; LABF). Each satellite gathers ROI science data for ~7 min/orbit. Each satellite utilizes identical integrated instrument suites to achieve the science objectives. The TRACERS Instrument Suite (TIS) provides a robust set of observations tightly coupled to the science objectives and is comprised of:

- Analyzer for Cusp Ions (ACI) to measure ion energy-angle distributions at 3 distributions/second
- Analyzer for Cusp Electrons (ACE) to measure electron energy-angle distributions at 20 distributions/seconds.
- 3-axis fluxgate Magnetometer (MAG) to measure the background field, currents, and low frequency waves at 128 samples/second.
- 2-axis Electric Field Instrument (EFI) to determine the E x B flow velocity at 128 samples/second and measure higher frequency waves.
- 3-axis Magnetic Search Coil (MSC) to measure magnetic field fluctuations up to 1 kHz.

3.2 Convention

All spatial reference frames are right-handed orthogonal, and rotations follow the righthand grip rule (thumb follows the positive direction of the axis, fingers curl in the direction of positive rotation.

Exhibit 3-1: Righthand Grip Rule



3.3 Orbits and Rotation

3.3.1 Earth Orbit

The Earth's orbit around the Sun is nearly circular—but not quite. It is actually an ellipse whose average distance from the Sun is one AU (150 million kilometers). Its closest point to the Sun (147 million kilometers) happens to occur in January; its farthest point (152 million kilometers) occurs in July. This ellipse also defines the ecliptic plane. The ecliptic is the apparent annual path of the Sun against the background stars. It is along this plane that we find the constellations of the Zodiac.

3.3.2 Earth's Inclination

Earth rotates on its axis once every sidereal day (23h 56m 4s). This axis of rotation is inclined (tilted) away from a line perpendicular to the ecliptic by about 23½°. It is this tilt that is responsible for our seasons. In June, the Earth's northern hemisphere is tilted 23½° toward the Sun. In December, the Earth's southern hemisphere is tilted 23½° toward the Sun. This variation of solar angle in our skies accounts for the difference in solar heating at the Earth's surface – hence, the seasons. Incidentally, the Earth's tilts contribute more to seasonal changes than does the variation of the Earth's distance to the Sun.

3.3.3 Sun's Inclination

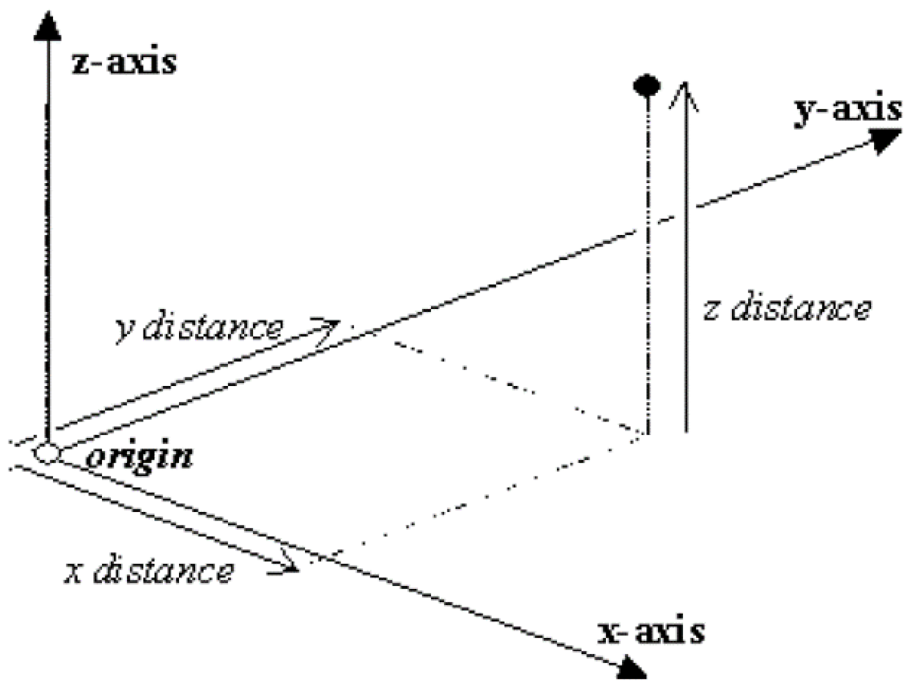
The Sun also rotates on its axis, and it rotates in the same sense as the Earth revolves about the Sun – that is, counterclockwise as viewed from the north side of the ecliptic plane. Recall that the Sun does not rotate as a solid body. The solar equator rotates faster – it takes 25 days to complete a rotation around the solar axis. The poles, on the other hand, take up to 35 days to rotate around the axis. The Sun's axis of rotation is inclined away from a line perpendicular to the ecliptic by about 7¼°. The tilt direction results in our being able to best view the Sun's North Pole in September and its South Pole in March.

4 COORDINATE SYSTEMS

4.1 Cartesian Coordinate System

To identify a general position anywhere in three-dimensional space (or the components of a vector), we can use Cartesian coordinates. The diagram below shows how we use three variables (in this case X, Y, and Z) in this coordinate system to locate a point in reference to an origin.

Exhibit 4-1: Cartesian Coordinates

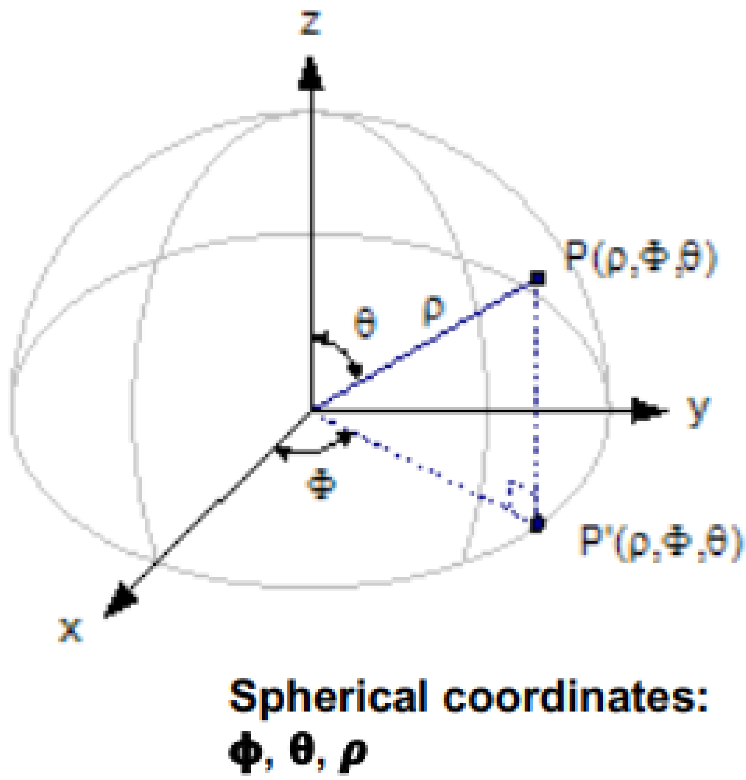


4.2 Spherical Polar Coordinate System

Another common way to identify a point in 3-dimensional space is with spherical polar coordinates. The figure below shows the coordinates for a vector to a point P, and how they relate to the three Cartesian axes. The radial coordinate r is the measure of the distance of the point from the origin of the coordinate system (i.e., the length of the vector to P). The polar coordinate q measures the angle between the z axis of the coordinate system and the vector to P. The azimuthal coordinate F measures the angle, in the right-hand sense, between the x axis and the projection of the vector to P onto the X-Y plane.

The quantity q is also known as the colatitude in some contexts, which follows from the identification of 90 – q as the latitude. Similarly, the quantity F is also referred to as the longitude in some contexts.

Exhibit 4-2: Spherical Polar Coordinates



4.3 Altitude and Elevation

Altitude is distance above a reference datum (surface). There exist many datums used for altitude, one example is Mean Sea Level (MSL), which is a geocentric sphere with a specified radius. However, the more common datum today is the ellipsoid surface WGS84, which is commonly used with GPS. TRACERS may have occasion to use either altitude definition, but in either case MSL or WGS84 will be clearly stated. In the case of MSL, a radius of 6371.2 km will be used as the MSL datum. Elevation is mainly used when referring to points on the Earth's surface relative to WGS84.

5 REFERENCE COORDINATE SYSTEMS

Many geophysical reference coordinate system definitions derive from Russell, C. T., Geophysical Coordinate Transformations, Cosmic Electrodynamics, 2 , pp. 184-196, 1971. However, some of the coordinate system definitions below have subtle differences from Russell, to make them more compatible with SPICE or with current usage. Other coordinate systems below have been defined specifically for TRACERS, although most are inspired by equivalent or similar coordinate systems defined for other missions.

Some of the coordinate system definitions in this section depend upon the position of the spacecraft. As such, there are distinct implementations of these coordinate systems for each spacecraft. These distinctions are made by prepending “TS#_” to the generic coordinate system acronym, where “#” is either “1” or “2”, for the corresponding spacecraft.

5.1 Geocentric Equatorial Inertial Coordinate System (GEI)

The geocentric equatorial inertial coordinate system has its X-axis pointing from the Earth towards the first point of Aries (the position of the Sun at the vernal equinox). This direction is the intersection of the Earth's equatorial plane and the ecliptic plane, and thus this X-axis lies in both planes. The Z-axis is parallel to the rotation axis of the Earth and Y completes the right-handed orthogonal set ($Y = Z \times X$). The origin of the coordinate system is the origin of the center of mass of the Earth. This is the system commonly used in astronomy and satellite orbit calculations. [Russell, 1971]

The equinox is subject to both precession and nutation. Precession is the cyclic movement of the first point of Aries about the celestial sphere, which has a period of roughly 26,000 years. Superimposed on this is what is called the nutation of the equinox, which are higher order oscillations which cause deviations off of the mean. Depending on how precession and notation are accounted for, different variants of GEI are defined.

5.1.1 GEI2000

For a coordinate system to be truly inertial, you must define the first point of Aries and the rotation axis for a specific epoch. The SPICE built-in inertial coordinate system J2000 (see exhibit 5-1) is a utilization of this concept, using the J2000 epoch. Depending on the time system used, the J2000 epoch is defined as any of: Julian date 2451545.0 TT (Terrestrial Time), 2000-01-01T12:00:00 TT, 2000-01-01T11:59:27.816 TAI or 2000-01-01T11:58:55.816 UTC. For TRACERS, the GEI2000 coordinate system is aliased to this J2000 coordinate system. Note that this coordinate system is also known as EME2000 and ECI2000.

This is the primary inertial coordinate system for TRACERS orbital and attitude reference purposes, and thus will be the coordinate system used for TRACERS ephemerides and LABF pointing vectors.

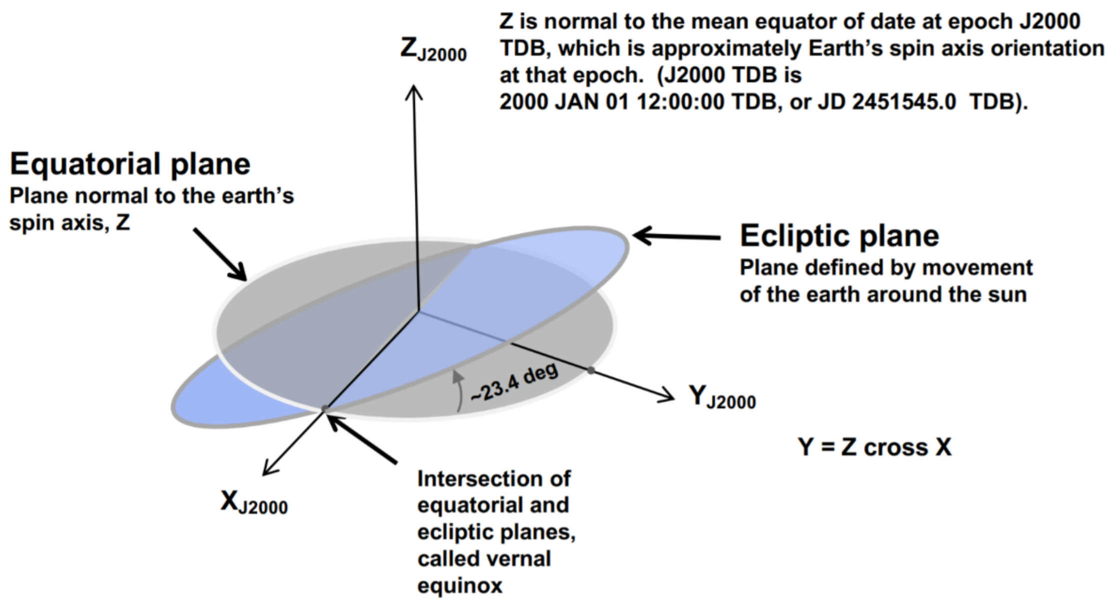
5.1.2 GEI_MOD

The term 'Mean-of-date' refers to a coordinate system where only precession is considered. GEI_MOD is the GEI coordinate system in that case.

5.1.3 GEI_TOD

The term 'True-of-date' adds on the nutation and is the actual best representation for the first point of Aries at any given epoch. GEI_TOD is the GEI coordinate system in that case.

Exhibit 5-1: J2000 Earth Centered Inertial



5.2 Geographic Coordinate System (GEO)

The geographic reference coordinate system, also known as Earth-Centered Earth-Fixed (ECEF, ECF) is defined so that its X-axis is in the Earth's equatorial plane, fixed with the rotation of the Earth so that it passes through a reference meridian (nominally the Greenwich meridian) at 0° longitude. Its Z-axis is parallel to the rotation axis of the Earth, and its Y-axis completes a right-handed orthogonal set ($Y = Z \times X$). The origin of the GEO coordinate system is the center of mass of the Earth. [Russell, 1971]

The geographic coordinate system (GEO) facilitates describing the position of things located on the surface of the spherical Earth.

The SPICE system provides a high-precision coordinate system fixed to the Earth's body, called ITRF93, in the form of a binary PCK file that is updated at least twice a week. For TRACERS, the GEO coordinate system is aliased to this ITRF coordinate system.

5.2.1 GEO-based Longitudes

5.2.1.1 Geocentric Longitude

The longitude shown in Exhibit 4-2 by F is the east-west angular distance measured from a prime meridian, which is a predetermined north-south line of origin that rotates with the coordinate system.

On the Earth the International Earth Rotation and Reference System (IERS) Reference Meridian is that prime meridian (formerly, it was the Greenwich Meridian). Longitude is usually measured toward the east from 0° to 360°, although sometimes it is measured east or west from the meridian and then designated as such. For example, longitudes of 100° and 200° are equivalent to 100°E and 160°W, respectively.

5.2.1.2 Geodetic Longitude

Geodetic longitude is very similar to geocentric longitude, except that it is based on a reference datum instead of an ideal sphere, as shown in Exhibit 5-1. Geodetic longitude is the angle in the equatorial plane between the line ‘a’ that connects the Earth's center with the prime meridian and the line ‘b’ that connects the center with the meridian on which the point P lies. A meridian is a direct path on the surface of the datum that is the shortest distance between the poles.

5.2.2 GEO-based Latitudes

5.2.2.1 Geocentric Colatitude

For GEO, the colatitude shown in Exhibit 4-2 by q is the angular distance from the geographic North pole. The earth’s north and south poles mark the rotational axis of the planet; the equator is equidistant between the poles. Colatitude is the angle between +Z-axis and position vector (0 to 180).

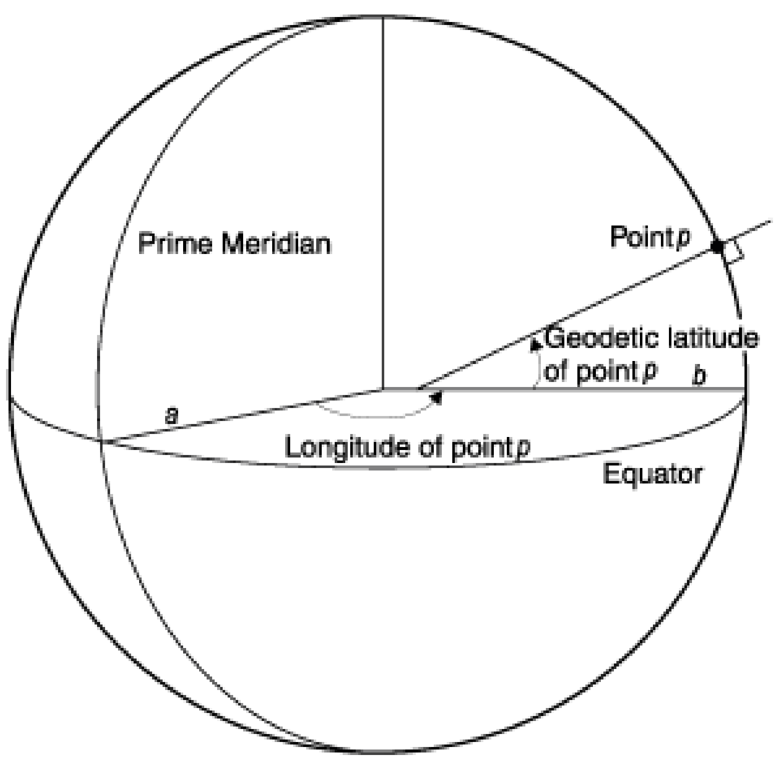
5.2.2.2 Geocentric Latitude

Geocentric latitude (in degrees) is 90 minus geocentric colatitude.

5.2.2.3 Geodetic Latitude

Geodetic latitude of a point P is the angle between the equatorial plane and the line that is normal to the datum at that point on the surface of the Earth, as shown in Exhibit 5-2. Note that this line does not in general intersect the Earth’s center because of the ellipsoidal shape of the datum.

Exhibit 5-2: Geodetic Latitude Angles



5.3 Geocentric Solar Ecliptic Coordinate System (GSE)

The geocentric solar ecliptic coordinate system has its X-axis pointing from the Earth towards the Sun and its Y-axis is chosen to be in the ecliptic plane pointing towards dusk (thus opposing planetary orbital motion). Its Z-axis is parallel to the ecliptic pole. The origin of the coordinate system is the origin of the GEO coordinate system. Relative to an inertial system this system has a yearly rotation. The SPICE definition of GSE used by TRACERS is:

- X is the direction of true_of_epoch, geometric, vector from the Earth to the Sun.
- Z is the direction of $X_{GSE} \times$ Sun_from_Earth_velocity_vector, with the latter being the true_of_epoch, geometric velocity vector of the Sun as seen from the Earth. Result is that Z_{GSE} is perpendicular to the instantaneous ecliptic, pointing northward.
- Y is the $Z_{GSE} \times X_{GSE}$ direction. The +Y direction is thus pointing opposite the direction of the Earth's orbital motion, in the plane of the ecliptic (in general).

This is a true-of-epoch coordinate system, as it uses the Earth-Sun position and velocity at the epoch of calculation. This assumes that the Sun and Earth ephemerides provided by SPICE incorporate both precession and nutation (and whatever other small motion the ecliptic may have with time).

This system has been used to display satellite trajectories, interplanetary magnetic field observations, and solar wind velocity data. Longitude, as with the geographic coordinate system, is measured in the X-Y plane from the X-axis toward the Y-axis and latitude is the angle out of the X-Y plane, positive for positive Z components. [Russell, 1971].

5.4 Geomagnetic Coordinate System (MAG)

The geomagnetic reference coordinate system is defined so that its Z-axis is parallel to the centered dipole axis of the Earth's magnetic field. The orientation of this axis, and thus the geographic coordinates of the north and south magnetic poles, are defined by the International Geomagnetic Reference Field (IGRF) model, and are a function of time. The Y-axis of this system is perpendicular to the geographic poles such that if D is the vector along the north axis of the dipole and S is vector from the center of the Earth to the south geographic pole, then $Y=D\times S$. Finally, the X-axis completes a right-handed orthogonal set. The origin of the coordinate system is the origin of the GEO coordinate system.

Implementing the MAG coordinate system is SPICE is non-trivial because there is no mechanism to directly incorporate the time-dependent coefficients of the IGRF model. TRACERS overcomes this by first using the IGRF coefficients to calculate the time-varying geographic location of the north MAG pole, and then tabulating quaternions that transform from GEO to MAG. These quaternions are then encoded into a SPICE CK (i.e., attitude) kernel, which allows transform between MAG and all other SPICE coordinate systems.

The MAG system is often used for defining the position of magnetic observatories. Also, it is a convenient system in which to do field line tracing when current systems, in addition to the Earth's internal field, are being considered. [Russell, 1971]

5.4.1 Magnetic Latitude

Magnetic latitude is the MAG equivalent of the GEO latitude described in 5.2.2.2. As such, it is a measure of the angle between X-Y MAG plane and the vector from the center of the Earth to a point P, with positive angles north of the plane and negative ones south of it.

5.5 Geocentric Solar Magnetospheric Coordinate System (GSM)

For the geocentric solar magnetospheric coordinate system, the X-axis points from the Earth to the Sun, and has the same definition as the X_{GSE} axis. The Y-axis is defined to be perpendicular to the Earth's magnetic dipole (i.e., to the $+Z_{MAG}$ axis) so that the X-Z GSM plane contains the dipole axis. The positive Z-axis is chosen to be in the same sense as the northern magnetic pole. The origin of the coordinate system is the origin of the GEO coordinate system. The difference between the GSM coordinate system and the GSE one is simply a rotation about the X-axis.

This coordinate system is useful for displaying magnetopause and shock boundary positions, magnetosheath and magnetotail magnetic fields and magnetosheath solar wind velocities because the orientation of the magnetic dipole axis alters the otherwise cylindrical symmetry of the solar wind flow. [Russell, 1971]

5.6 Solar Magnetospheric Coordinate System (SM)

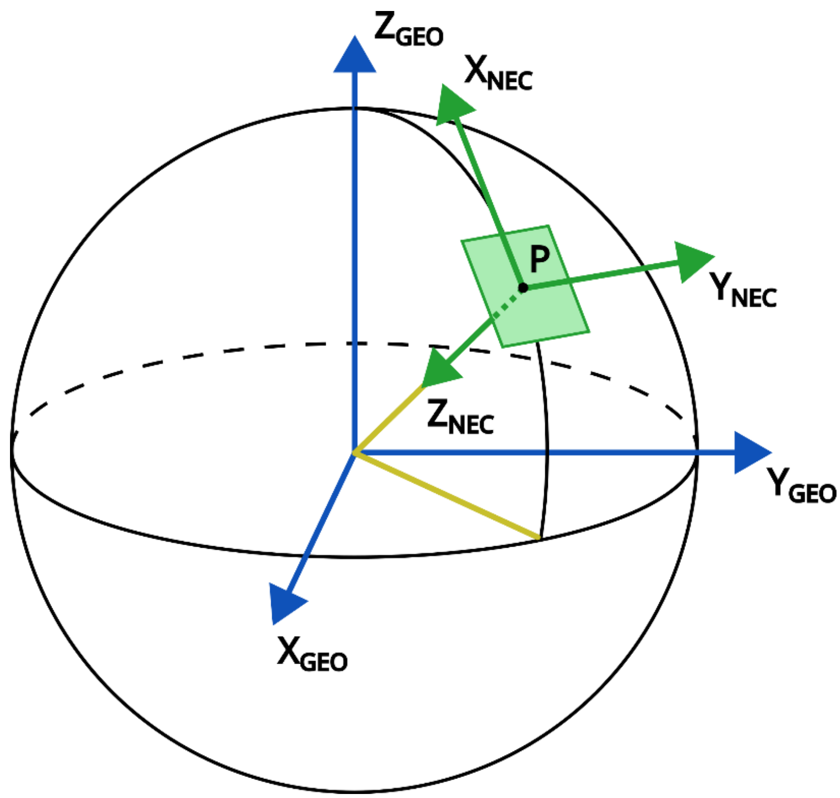
The solar magnetospheric coordinate system has the Z-axis along the north axis of the Earth's magnetic dipole (i.e., $+Z_{SM}$ is the same as $+Z_{MAG}$) as the primary axis. The Y-axis is then defined to be perpendicular to the Earth-Sun line, oriented towards dusk., and is the same as the Y_{GSM} axis. The X-axis completes the X=Y×Z triad, and is in the plane defined by the Earth-Sun line and the dipole axis. The SM coordinate system only differs from the GSM coordinate system by a rotation around the Y-axis by an angle equal to the Earth's dipole tilt angle. The origin of the coordinate system is the origin of the GEO coordinate system.

5.7 North East Center Coordinate System (TS#_NEC)

The north east center coordinate system is an implementation of a coordinate system that is locally tangent to the Earth-centered sphere intersecting the measurement point P. The coordinate system uses the spacecraft-to-Earth vector (defining +Z) as the primary defining vector and the Z_{GEO} axis as the secondary defining vector. The origin of the coordinate system is the origin of the TSCS coordinate system (section 6.2).

- Z is the spacecraft-to-Earth direction.
- Y is eastward, in the direction $Z_{NEC} \times Z_{GEO}$.
- X is northward, completing the X=Y×Z triad.

Exhibit 5-3: North East Center (NEC) Coordinate System



5.7.1 Local Magnetic Coordinates

Geomagnetic field vectors are often expressed in the NEC coordinate system, using one of two systems to deconstruct the vector (see Exhibit 5-4). The first simply uses Cartesian coordinates:

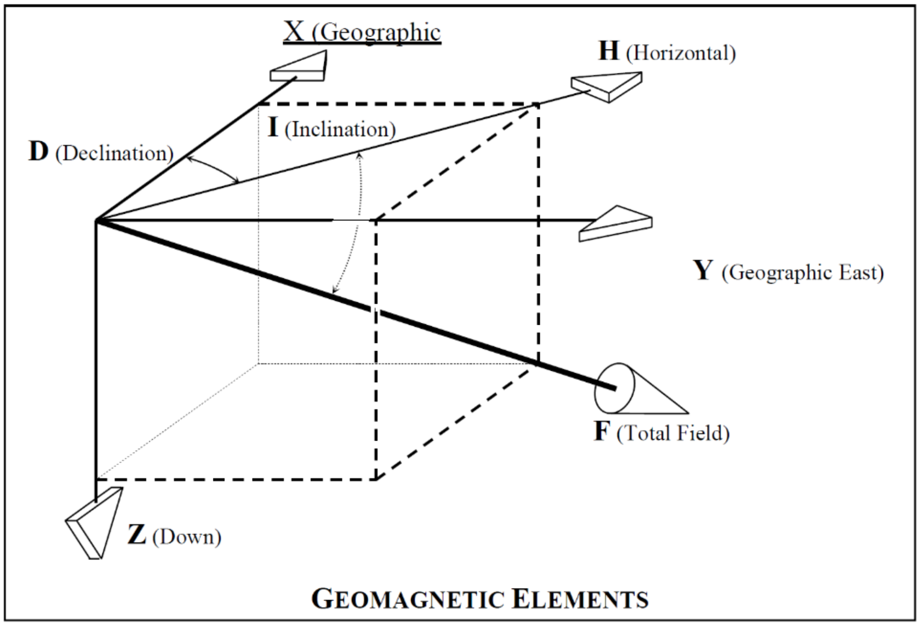
- X is the northward (geographic) component of the magnetic field (in nT).
- Y is the eastward (geographic) component of the magnetic field (in nT).
- Z is the local vertical (downward) component of the magnetic field (in nT).

The second uses a form of spherical polar coordinates:

- F is the total field strength (i.e., magnitude of the magnetic field vector) (in nT).
- H is the horizontal (in NEC X-Y plane) strength of the magnetic field (in nT).
- D is the declination of the magnetic field, the angle between geographic north (XNEC direction) and H (in degrees).
- I is the inclination of the magnetic field, the "dip" angle, or the angle between the horizontal (NEC X-Y) plane and the field vector. (in degrees). I is measured positive downward (along the +ZNEC axis.

5.7.2 Geomagnetic Elements

Exhibit 5-4: Geomagnetic Elements



5.8 Field Aligned Coordinates Coordinate System (TS#_FAC)

The field aligned coordinates coordinate system uses the IGRF model magnetic field vector at the spacecraft location as the primary defining direction and the Earth-to-spacecraft vector as the secondary defining direction. The origin of the coordinate system is the origin of the TSCS coordinate system (section 6.2).

- Z is along the IGRF model magnetic field direction at the spacecraft location.
- Y is in the direction of ZFAC × Earth-to-spacecraft_vector. This will be in an easterly direction.
- X completes the X=Y×Z triad.

5.9 Field Velocity Coordinates Coordinate System (TS#_FVC)

The field velocity coordinates coordinate system uses the IGRF model magnetic field vector at the spacecraft location as the primary defining direction and the spacecraft velocity vector as the secondary defining direction. The origin of the coordinate system is the origin of the TSCS coordinate system (section 6.2).

- Z is along the IGRF model magnetic field direction at the spacecraft location.
- Y is in the direction of ZFVC × spacecraft_velocity_vector.
- X completes the X=Y×Z triad.

5.10 TRACERS Field Sun Coordinate System (TS#_TFS)

The TRACERS field Sun coordinate system uses the IGRF model magnetic field vector at the spacecraft location as the primary defining direction and the spacecraft-to-Sun vector as the secondary defining direction. The origin of the coordinate system is the origin of the TSCS coordinate system (section 6.2).

- Z is along the IGRF model magnetic field direction at the spacecraft location.
- Y is in the direction of ZTFS × spacecraft-to-Sun_vector, with the latter being the true_of_epoch, geometric vector from the spacecraft to the Sun.
- X completes the X=Y×Z triad. The +XTFS direction points roughly sunward.

When the spacecraft is in the TRACERS Region of Interest, and the spin axis is aligned with the LABF vector, the TFS and TSS (section 5.11) coordinate systems will be very similar. This will not be true in general, though.

5.11 TRACERS Spin Sun Coordinate System (TS#_TSS)

The TRACERS spin Sun coordinate system uses the spacecraft spin axis as the primary defining direction and the spacecraft-to-Sun vector as the secondary defining direction. The origin of the coordinate system is the origin of the TSCS coordinate system (section 6.2).

- Z is along the spin axis of the spacecraft. In practice, it is identical to ZTSCS.
- Y is in the direction of ZTSS × spacecraft-to-Sun_vector, with the latter being the true_of_epoch, geometric vector from the spacecraft to the Sun.
- X completes the X=Y×Z triad. The +XTSS direction points roughly sunward.

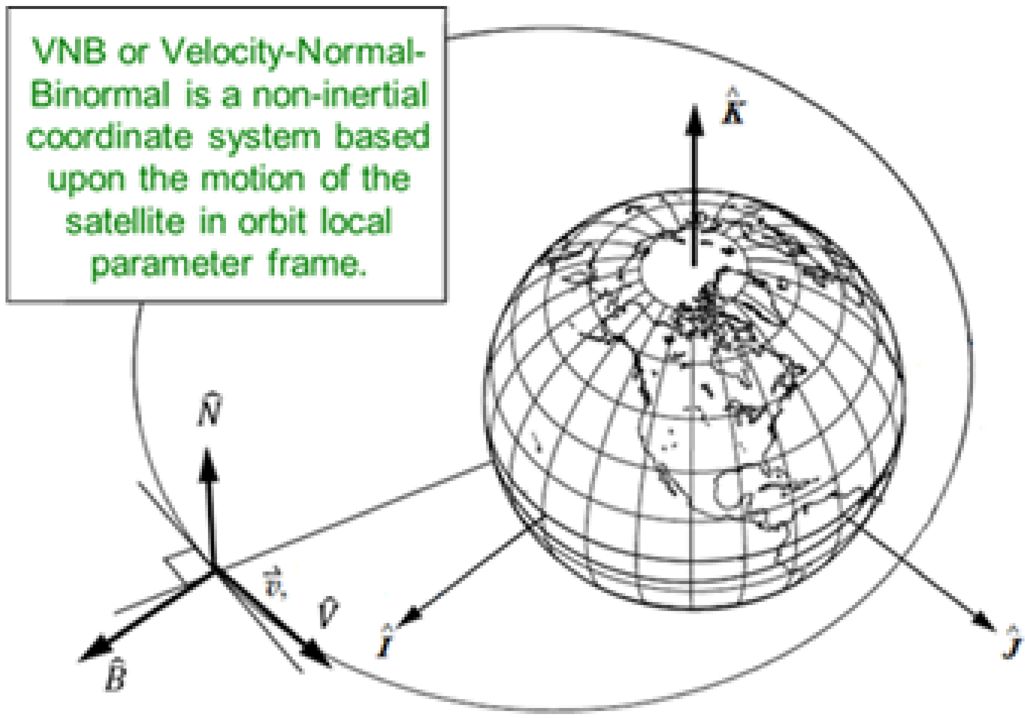
When the spacecraft is in the TRACERS Region of Interest, and the spin axis is aligned with the LABF vector, the TFS (section 5.10) and TSS coordinate systems will be very similar. This will not be true in general, though.

For a nominal TRACERS orbit, it looks like TSS will be quite similar to the GSE coordinate system, but with a 180 degree rotation around X_{GSE}. This follows from the LABF direction (nominal spin-axis direction) being primarily in the -Z direction in the GSE coordinate system. There will be variation however, depending on the actual LABF direction for any given day.

5.12 Intersatellite Spatial/Temporal Relationship and COLA Definition Coordinate System (Velocity-Normal-Binormal)

Non-inertial reference coordinate system based upon the motion of the satellite in orbit local parameter coordinate system. Relevant for inter-satellite lateral separation and collision avoidance specification and verification definition and assessments. The V-N-B origin is nominally the center of mass of the satellite, for any configuration under consideration. The Velocity (V) unit vector points in the direction of the Satellite's on-orbit velocity; The Normal (N) unit vector points in the direction normal to the orbit plane such that VxN, in a right-handed reference coordinate system convention, results in a predominantly earth zenith-disposed Binormal (B) unit vector.

Exhibit 5-5: Velocity Normal Binormal Reference Coordinate System



6 TRACERS SPACECRAFT COORDINATE SYSTEMS

6.1 Distinction Between Individual Spacecraft

The two TRACERS spacecraft are designed and built to be identical. As such, the definitions, rotations, and translations given for each coordinate system in the sections below are identical for each spacecraft. The only difference between spacecraft for each coordinate system is in the designation/acronym used. This distinction is made by prepending "TS#_" to the generic coordinate system acronym, where "#" is either "1" or "2", for the corresponding spacecraft.

6.2 TRACERS Satellite Coordinate System (TS#_TSCS)

TRACERS Satellite Coordinate System for a single "on orbit" TRACERS Satellite. All other secondary coordinate systems will reference and transform to/from this reference coordinate system. The origin of the TSCS is at the geometric [theoretical zero error] center of the launch vehicle adaptor ring on the separation interface plane. The Theoretical Design Separation plane physical referenced to the Motorized LightBand (MLB) attachment datum plane and offset away from that plane by 26.67 mm. The $+Z_{TSCS}$ axis originates from this origin and is directed through the Satellite along the center line of the theoretical [zero error] "spin-axis" and is operationally disposed [approximate] in the Northern Cusp +B-Field (precipitation) direction. The $+X_{TSCS}$ axis lies along a line projecting, orthogonal to $+Z_{TSCS}$, from the origin in the separation plane co-incident with the theoretical [zero error] deployed Electric Field Investigation 1 (EFI1) sensor and the $+Y_{TSCS}$ axis completes a right-handed Cartesian coordinate system. The X-Y plane constitutes a theoretical [zero error] "spin plane".

Exhibit 6-1: TRACERS Satellite Coordinate System

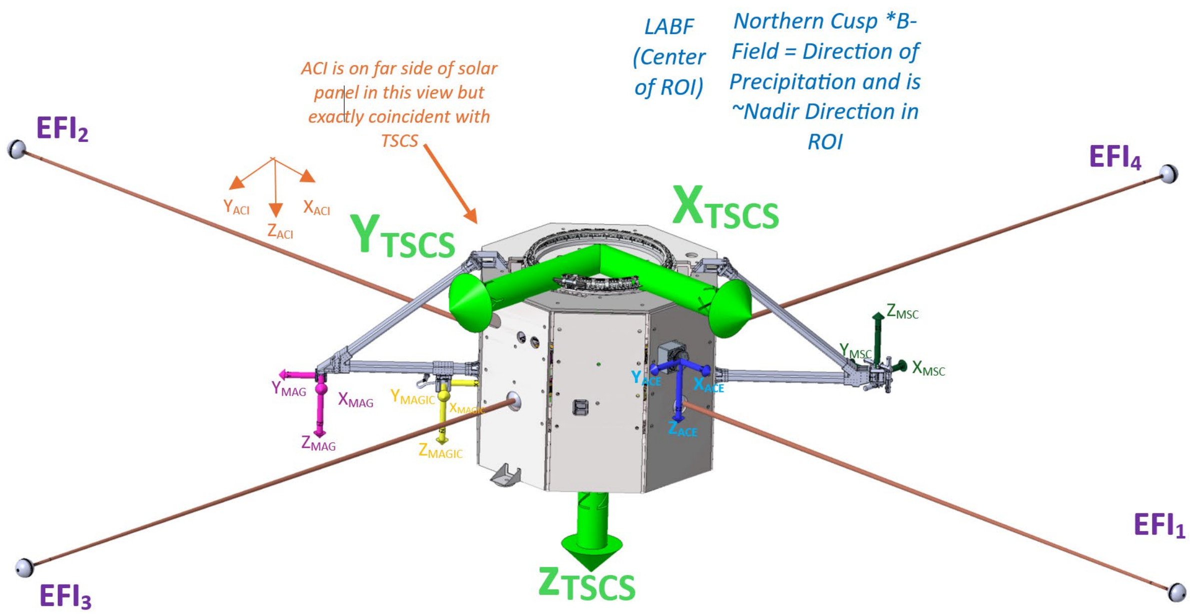


Exhibit 6-2: TRACERS Satellite Coordinate System Definition

Type	Name	Designation
Cartesian	TRACERS SATELLITE COORDINATE SYSTEM	TS#_TSCS
Rationale	Coordinate System for a single "on orbit" TRACERS Satellite	
Definition		
+X	Axis lies along a line projecting, orthogonal to $+Z_{TSCS}$, from the origin in the separation plane co-incident with the theoretical [zero error] deployed Electric Field Investigation 1 (EFI1) sensor.	
+Y	Will be along an orthogonal theoretical EFI boom centerline; It is labeled sensor EFI3, completes a right-handed Cartesian coordinate system.	
+Z	Is geometrically centered along Satellite theoretical spin axis, In the ROI, the magnetic field will generally be aligned to th**e +Z axis (this is roughly Nadir zone)**	
Origin	At the geometric [theoretical zero error] center of the launch vehicle adaptor ring on the separation interface plane and zero error spin axis.	
Transformation	-	
Translation	-	
Rotation	-	
Formula	-	

6.3 TRACERS Instrument Local Body-Referenced Standard Spherical Coordinate System

As part of a locally-referenced-to-an instrument sensor Standard Spherical Coordinate System, the term "polar" angle relates to parameters of an instrument that specify angular range measurement requirements and has its NADIR zero-reference as the $+Z_{TSCS}$ axis theoretical [zero error] direction. The term "azimuth" angle relates to parameters that specify angular range measurement requirements about the polar axis as projected onto the $+X_{TSCS}$ -to- $+Y_{TSCS}$ theoretical [zero error] "spin plane" with zero-reference emanating from $+X_{TSCS}$; azimuth angle increases from the $+X_{TSCS}$ as you rotate toward $+Y_{TSCS}$.

6.4 TRACERS Instrument Field-Referenced Measurement Terms

The term pitch angle of a charged particle is the angle between the particle's velocity vector (direction) and the local (instantaneous) magnetic field vector (direction). Pitch angle relates solely to the B-field at the point where the particle is being measured even though TRACERS body attitude may vary, relative to the local B-field line. TRACERS also favors measurement of particle trajectories as they travel towards the Satellite body in the precipitation direction (motion of a charged particle along the magnetic B-field and toward the Earth) which can be termed "incoming" for the ROI in the chosen northern cusp. This is accomplished by eliminating/minimizing physical body obstructions of the incoming particles which are intended to enter the plasma instrument apertures. Additionally, ion outflow emissions occur (motion of a charged particle along the magnetic B-field and away from the Earth) and TRACERS strives to minimize physical body obstruction of these outflow particle trajectories, although on a lower relative priority than the favored precipitating ion trajectories. Particle flux, gyro-radius and pitch angle vary, based on particle type and energy, per the field synopsis description in the TRACERS-SE-REQ-005 (TRACERS Environmental Requirements Document).

6.5 TRACERS Instrument Coordinate Systems

6.5.1 Unit Reference Feature (URF)

Each instrument has a defined Unit Reference Feature (URF). The URF is the physical datums that properly locate the instrument. The TRACERS Mechanical Interface/Installation Control Drawing (MICD) (TRACERS-SE-INT-015) defines how the instrument URF relates to the Instrument reference coordinate system.

6.5.2 Position and Orientation Specification Convention

Each sensor reference coordinate system is characterized by a vector $\boldsymbol{o}$ and a direction cosine matrix $\boldsymbol{R}$. $\boldsymbol{o}$ gives the location of the sensor coordinate system origin with respect to the TSCS coordinate system. $\boldsymbol{R}$ transforms vectors from the TSCS coordinate system to the sensor coordinate system. For example, consider a vector $\boldsymbol{x}_t$ represented in the TSCS coordinate system. To express this vector in a sensor reference coordinate system ($\boldsymbol{x}_s$) with given $\boldsymbol{R}$ and $\boldsymbol{o}$, the following operation would be performed:

$$\boldsymbol{x}_s = \boldsymbol{R}(\boldsymbol{x}_t - \boldsymbol{o})$$

6.5.3 ACE Sensor Coordinate System (TS#_ACE)

To orient ACE to its desired B field measurement aspect, the ACE X-axis is radial outward from the satellite deck while the ACE Z-axis is approximately parallel to the ambient magnetic field +B in the ROI, or LABF. The ACE physical orientation is specified with respect to the satellite spin axis. The +LABF roughly corresponds to ~nadir in the northern cusp. The following exhibit shows the relationship between the ACE sensor coordinate system, the ACE FOV, and its desired unobstructed glint zone.

Exhibit 6-3: ACE Coordinate System

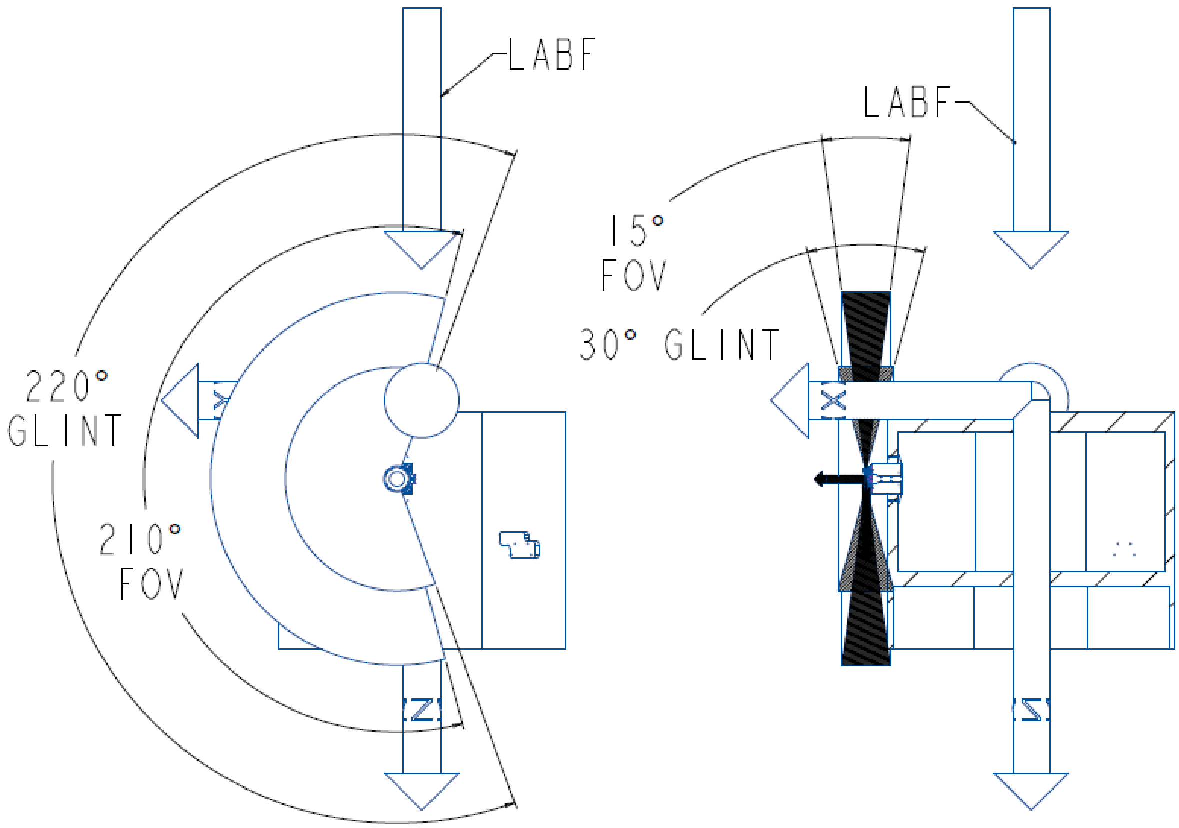
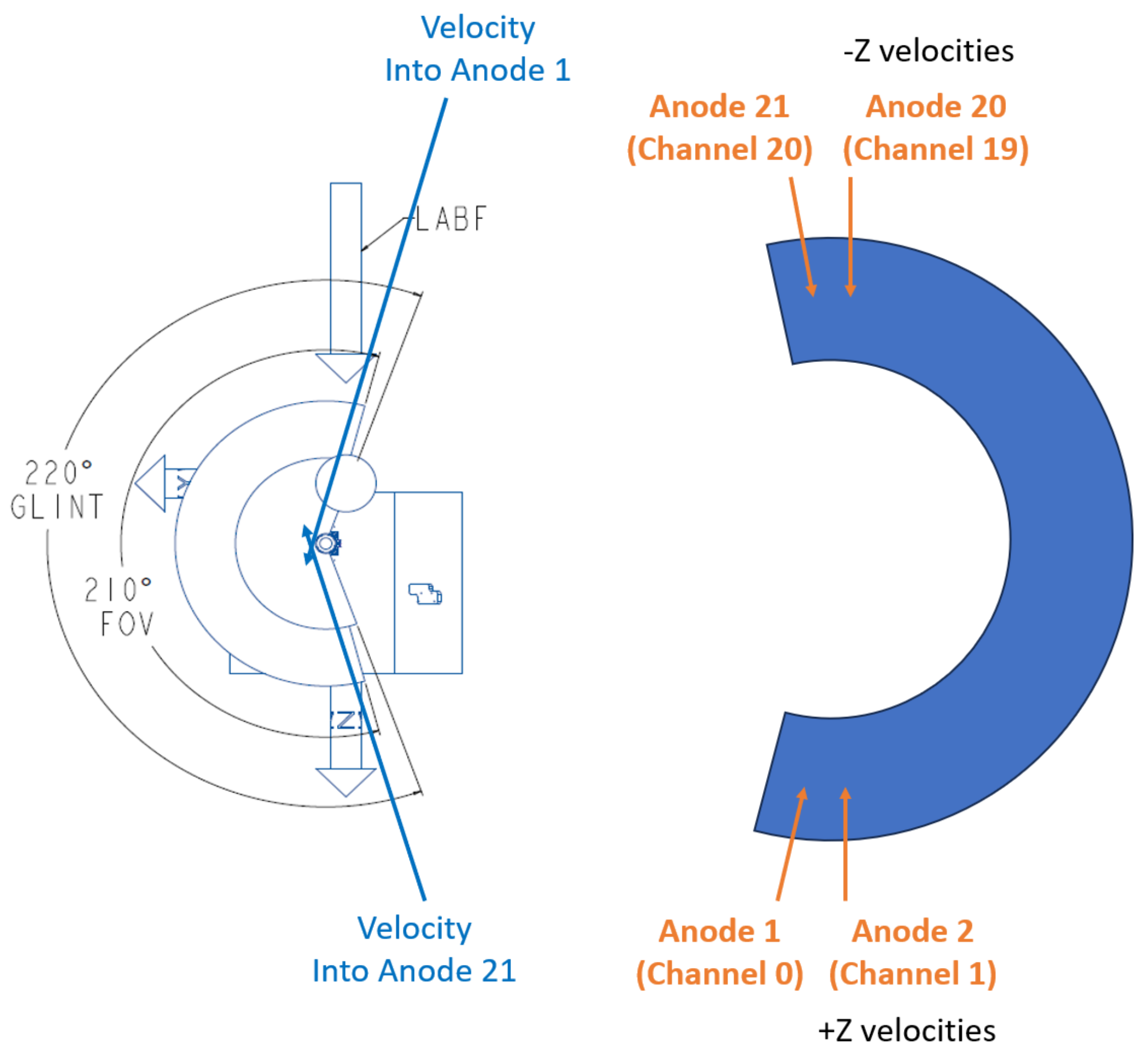


Exhibit 6-4: ACE Coordinate System Definition

Type	Name	Designation			
Cartesian	ACE COORDINATE SYSTEM	TS#_ACE			
Definition					
+X	Identical to TSCS Axes	1	0	0	0.563
+Y		0	1	0	0.085
+Z		0	0	1	0.268
Origin	-				
Rationale	-				
Transformation	1 0 0				
	0 1 0				
	0 0 1				
Translation (m)	(X) = 0.563				
	(Y) = 0.085				
	(Z) = 0.268				
Rotation	-				
URF	SEE MICD TRACERS-SE-INT-015				

Exhibit 6-5: ACE Anode Velocity Alignment



6.5.4 ACI Sensor Coordinate System (TS#_ACI)

The ACI coordinate system aligns directly with the TSCS reference coordinate system, see Exhibit 5-5. The ACI Polar Angle is zero at $-Z_{ACI}$ and increases from Y_{ACI} to Z_{ACI}. The ACI Azimuthal Angle follows the spacecraft rotation. The primary target for ACI is precipitating ions. These enter ACI from the $-Z_{ACI}$ direction.

To orient ACI to its desired B field measurement aspect, the ACI X-axis is radial inward from the satellite deck while the ACI Z-axis is approximately parallel to the ambient magnetic field +B in the ROI, or LABF. The ACI physical orientation is specified with respect to the satellite spin axis. The +LABF roughly corresponds to ~nadir in the northern cusp. The following exhibit shows the relationship between the ACI sensor reference coordinate system and the ACI FOV. Ion gyro-radii are sufficiently larger than the satellite characteristic size such that their interaction is uniform and does not need to be explicitly specified.

Exhibit 6-6: ACI Coordinate System

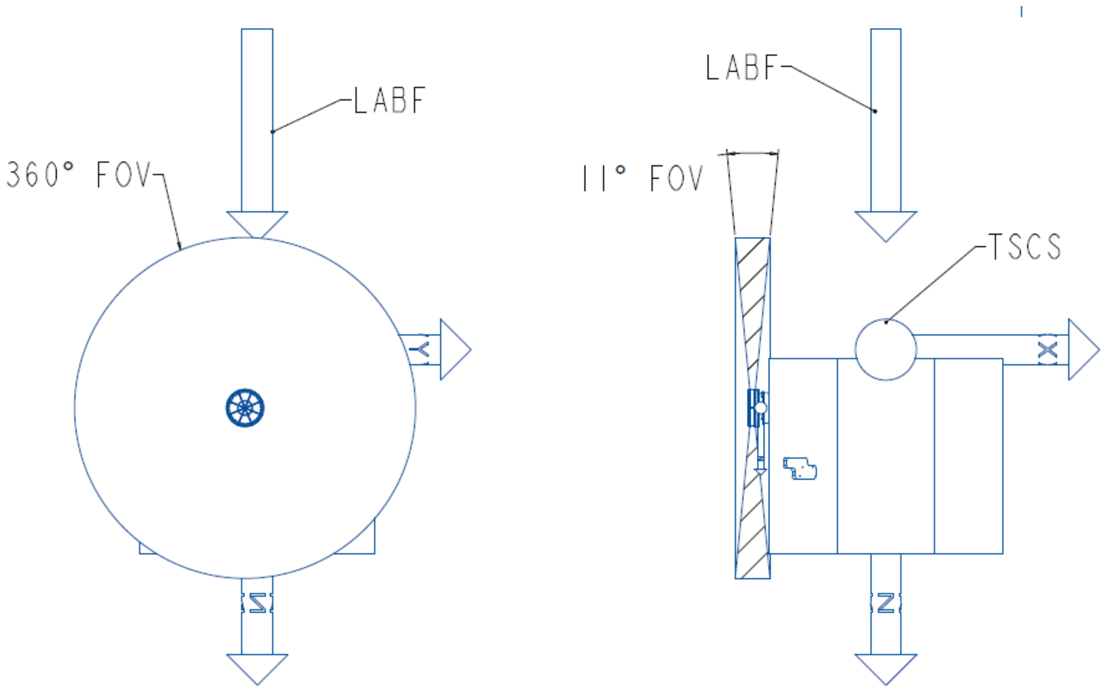
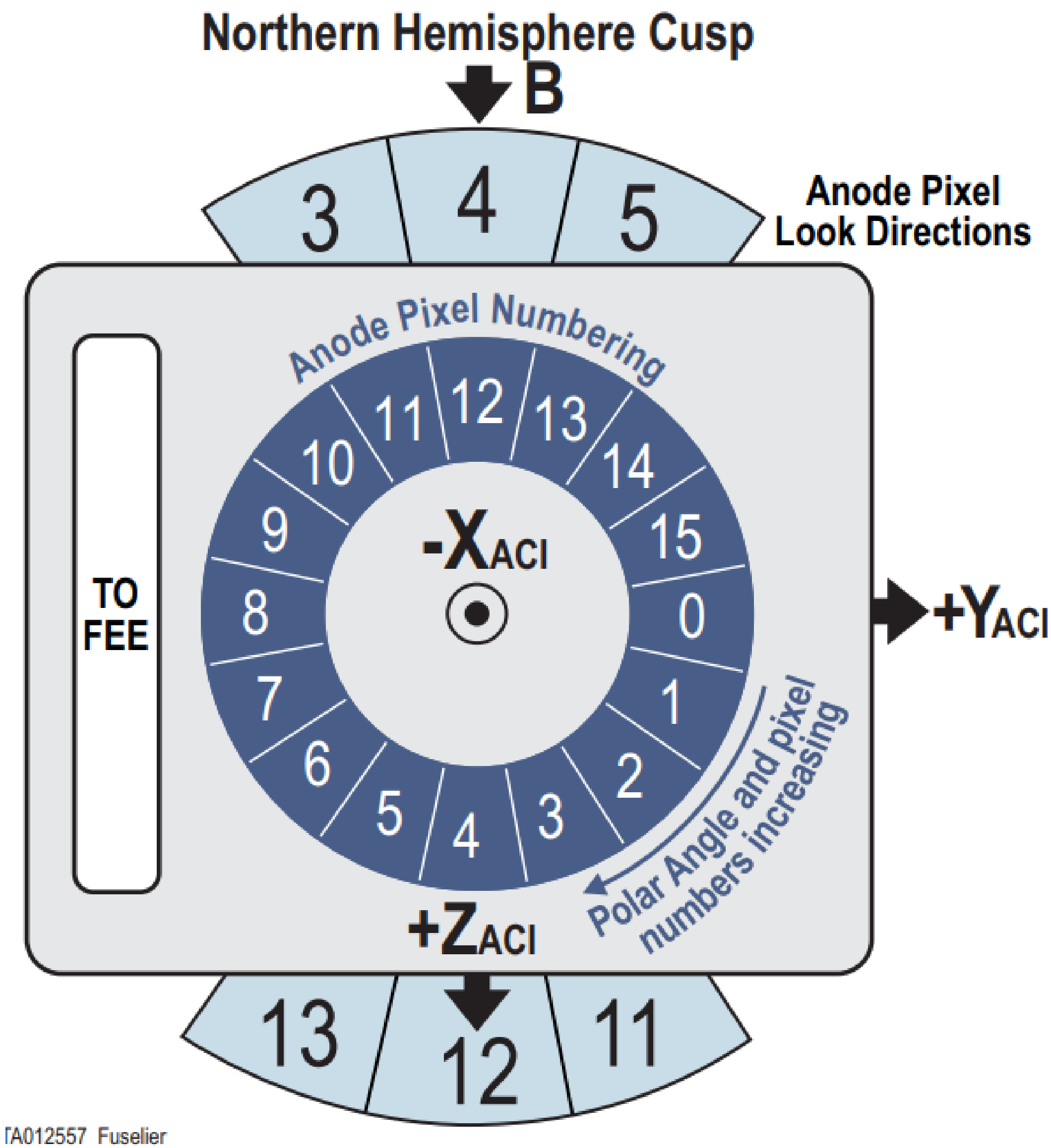


Exhibit 6-7: ACI Coordinate System Definition

Type	Name	Designation			
Cartesian	ACI COORDINATE SYSTEM	TS#_ACI			
Definition					
+X	Identical to TSCS	1	0	0	-0.521
+Y		0	1	0	-0.052
+Z		0	0	1	-0.243
Origin	-				
Rationale	-				
Transformation	1 0 0				
	0 1 0				
	0 0 1				
Translation (m)	(X) = -0.521				
	(Y) = -0.052				
	(Z) = -0.243				
Rotation	-				
URF	SEE MICD TRACERS-SE-INT-015				

Exhibit 6-8: ACI Anode Velocity Alignment (Note: Anode 4 Velocity Direction is +Z)



6.5.5 MAG Sensor Coordinate System (TS#_MAG)

The following exhibit shows the zero-error placement of the MAG sensor with the boom in the deployed state.

Exhibit 6-9: MAG Coordinate System, As-Mounted

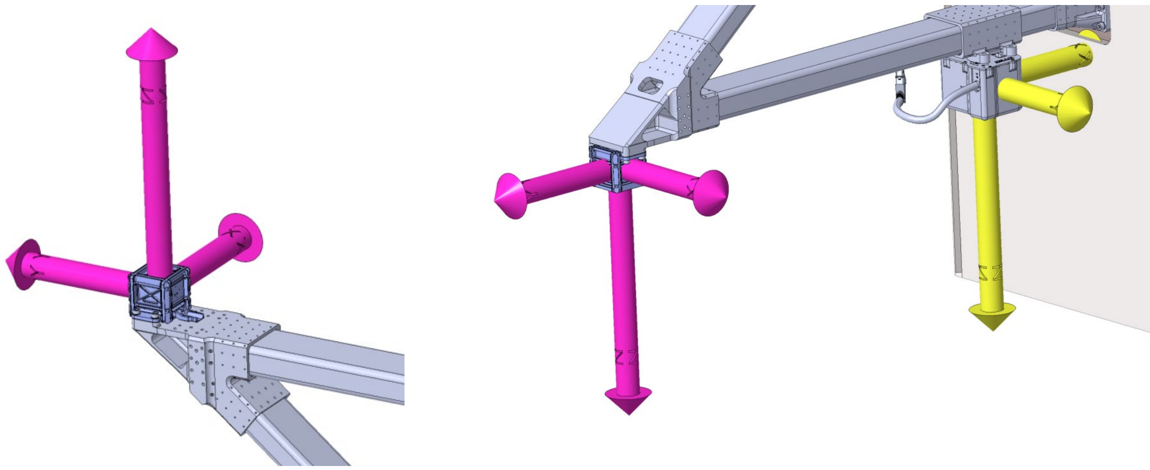


Exhibit 6-10: MAG Instrument, As-Mounted

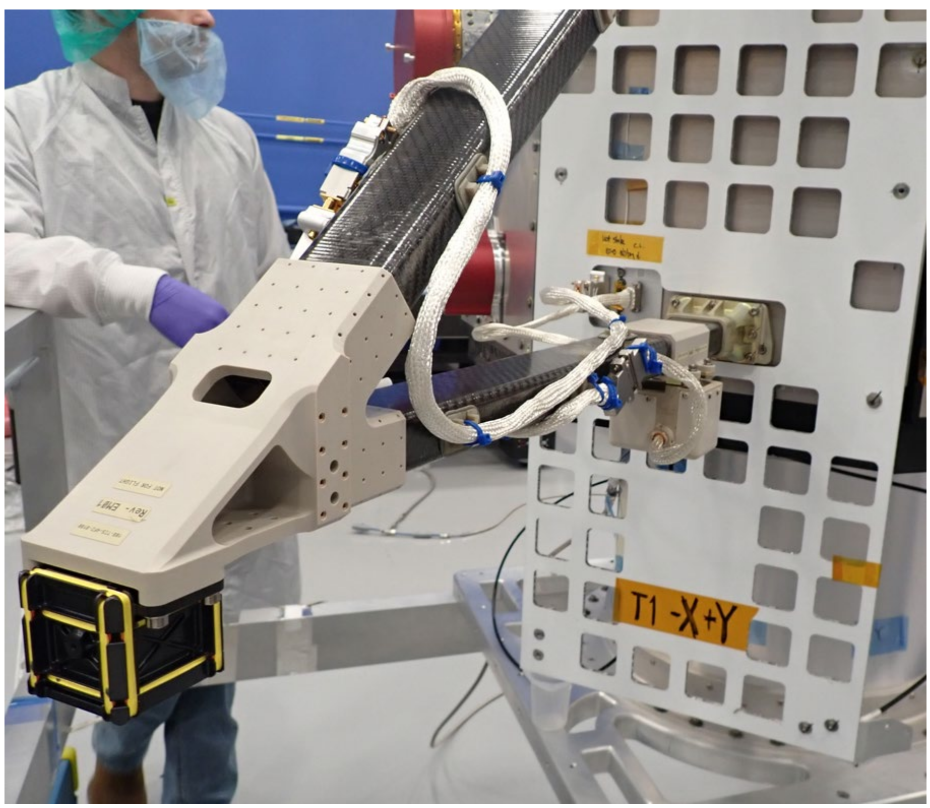


Exhibit 6-11: MAG Coordinate System Definition

Type	Name	Designation			
Cartesian	MAG COORDINATEY SYSTEM	TS#_MAG			
Definition					
+X	Rotated +45° about TSCS Z-axis	0.707	-0.707	0	-0.792
+Y		0.707	0.707	0	0.825
+Z		0	0	1	0.539
Origin	-				
Rationale	-				
Transformation	$\frac{1}{\sqrt{2}} \quad -\frac{1}{\sqrt{2}} \quad 0$				
	$\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0$				
	$0 \quad 0 \quad 1$				
Translation (m)	(X) = -0.792				
	(Y) = 0.825				
	(Z) = 0.539				
Rotation	-				
URF	SEE MICD TRACERS-SE-INT-015				

6.5.6 MSC Sensor Coordinate System (TS#_MSC)

The following exhibit shows the zero-error placement of the MSC sensor with the boom in the deployed state.

Exhibit 6-12: MSC Coordinate System, As-Mounted

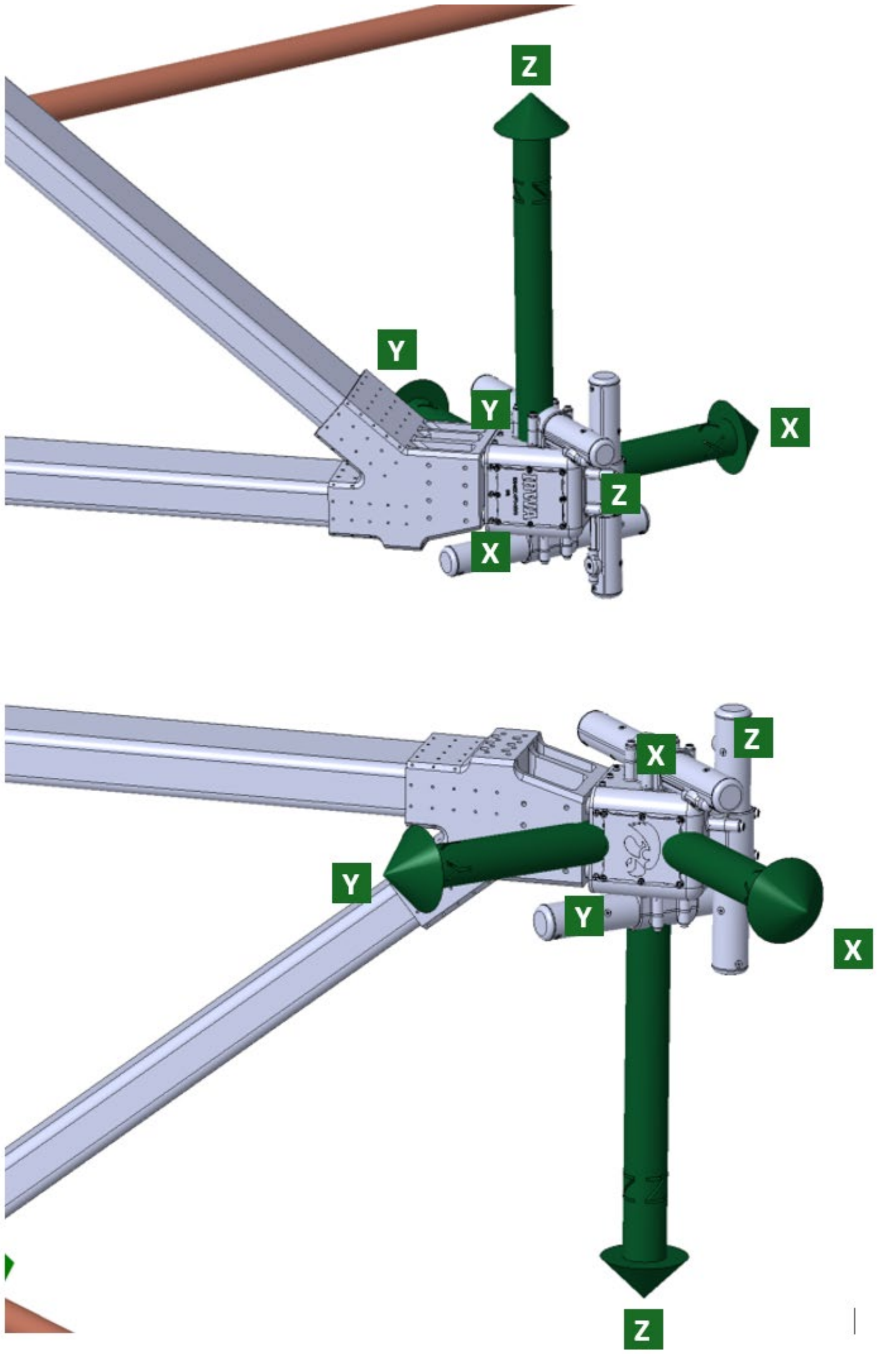


Exhibit 6-13: MSC Instrument, As-Mounted

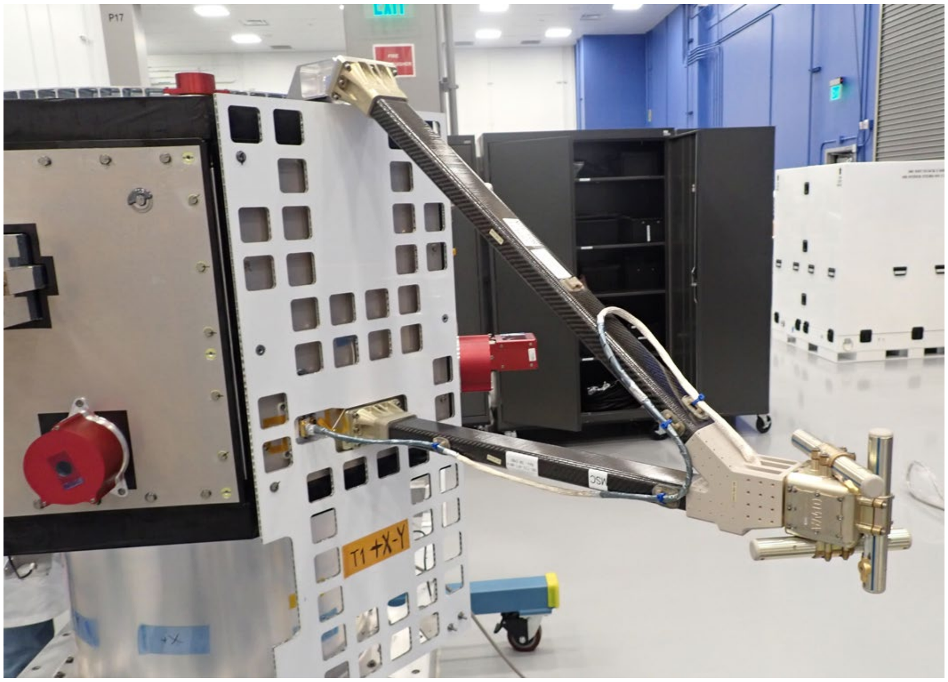


Exhibit 6-14: MSC Coordinate System Definition

Type	Name	Designation			
Cartesian	MSC COORDINATE SYSTEM				
Definition					
+X	Rotated 180° about TSCS Z-Axis	0	-1	0	0.816
+Y		-1	0	0	-0.829
+Z		0	0	-1	0.491
Origin	-				
Rationale	-				
Transformation	$\mathbf{0} \quad \mathbf{-1} \quad \mathbf{0}$				
	$\mathbf{-1} \quad \mathbf{0} \quad \mathbf{0}$				
	$\mathbf{0} \quad \mathbf{0} \quad \mathbf{-1}$				
Translation (m)	(X) = 0.816				
	(Y) = -0.829				
	(Z) = 0.491				
Rotation	-				
URF	SEE MICD TRACERS-SE-INT-015				

6.5.7 EFI Sensor Coordinate System (TS#_EFI)

The EFI opposing sensor pairs define the EFI X and EFI Y coordinate axis. The EFI1 and EFI2 sensors are parallel to TSCS X-axis and project through the satellite spin axis. The EFI3 and EFI4 sensors are parallel to the TSCS Y-axis and project through the satellite spin axis.

Exhibit 6-15: EFI Coordinate System Definition

Type	Name	Designation			
Cartesian	EFI COORDINATE SYSTEM	TS#_EFI			
Definition					
+X	Identical to TSCS Axes	1	0	0	0
+Y		0	1	0	0
+Z		0	0	1	0.5
Origin	-				
Rationale	-				
Transformation	1 0 0				
	0 1 0				
	0 0 1				
Translation (m)	(X) = 0				
	(Y) = 0				
	(Z) = 0.5				
Rotation	-				
URF	SEE MICD TRACERS-SE-INT-015				

6.5.8 MAGIC Sensor Coordinate System (TS#_MAGIC)

The following exhibit shows the zero-error placement of the MAGIC sensor with the boom in the deployed state.

Exhibit 6-16: MAGIC Coordinate System, As-Mounted

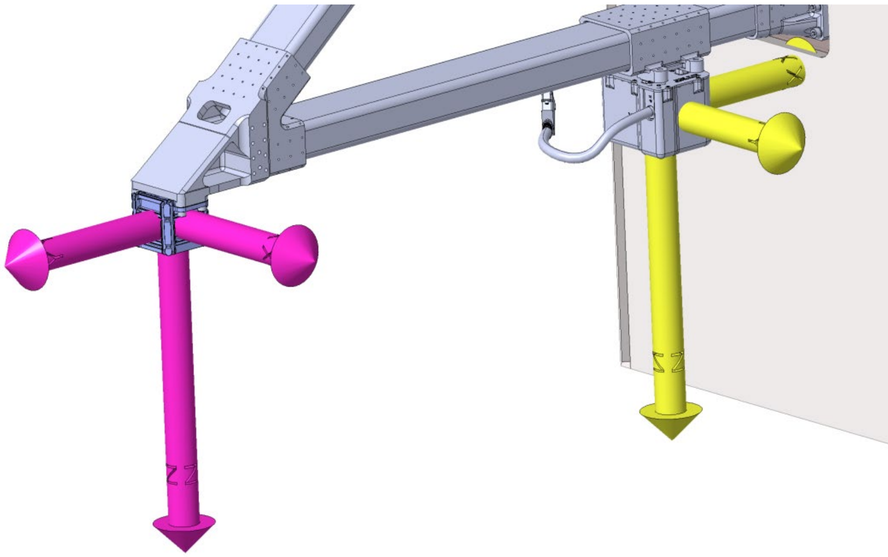


Exhibit 6-17: MAGIC Instrument, As-Mounted

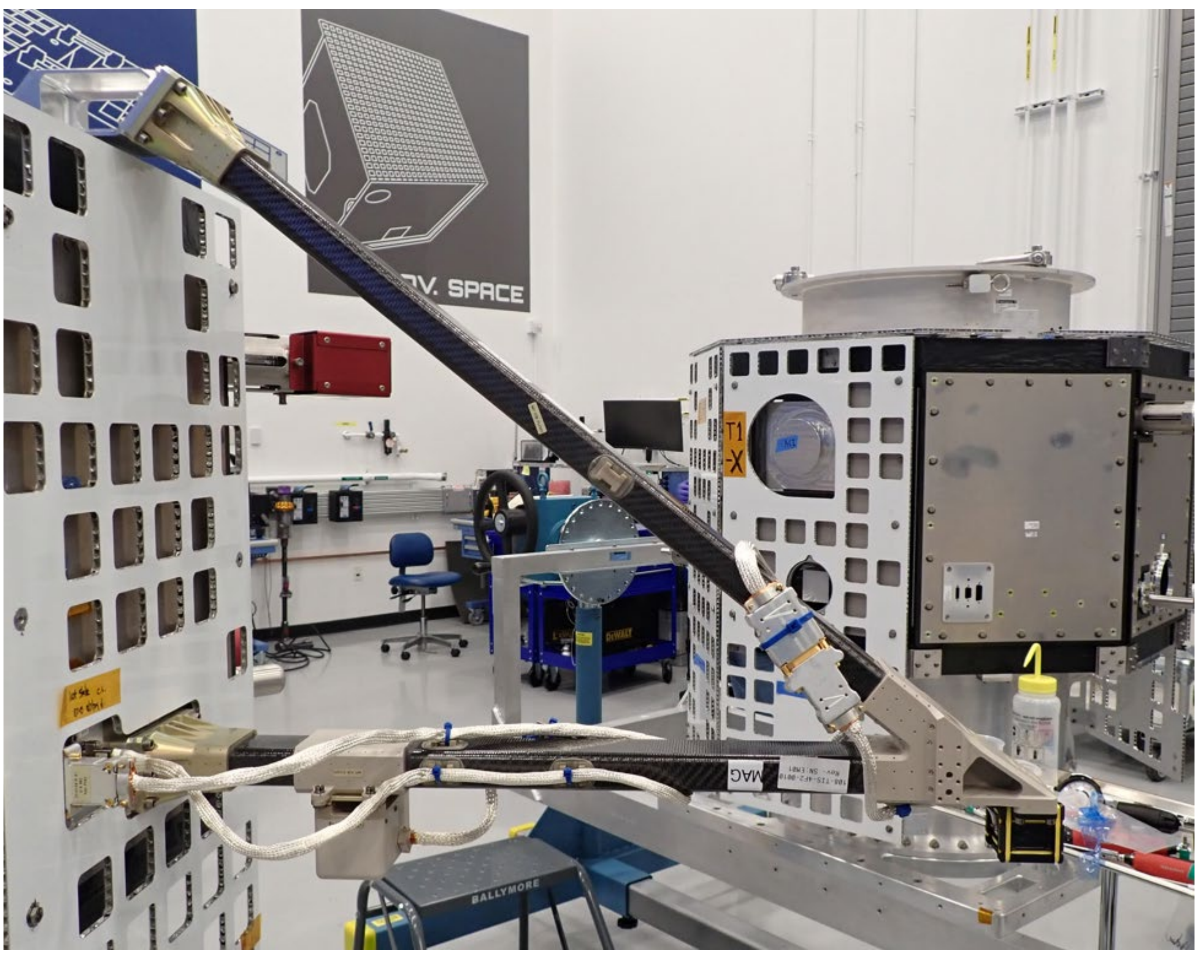


Exhibit 6-18: MAGIC Coordinate System Definition

<table>
<tr><th>Type</th><th>Name</th><th colspan="4">Designation</th></tr>
<tr><td>Cartesian</td><td>MAGIC COORDINATE SYSTEM</td><td colspan="4">TS#_MAGIC</td></tr>
<tr><th colspan="6">Definition</th></tr>
<tr><td>+X</td><td rowspan="3">Rotated -45° about TSCS Z-Axis</td><td>0.707</td><td>0.707</td><td>0</td><td>-0.426</td></tr>
<tr><td>+Y</td><td>-0.707</td><td>0.707</td><td>0</td><td>0.471</td></tr>
<tr><td>+Z</td><td>0</td><td>0</td><td>1</td><td>0.555</td></tr>
<tr><td>Origin</td><td colspan="5">-</td></tr>
<tr><td>Rationale</td><td colspan="5">-</td></tr>
<tr><td>Transformation</td><td colspan="5">$\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0$</td></tr>
<tr><td></td><td colspan="5">$-\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0$</td></tr>
<tr><td></td><td colspan="5">0 0 1</td></tr>
<tr><td>Translation (m)</td><td colspan="5">(X) = -0.426</td></tr>
<tr><td></td><td colspan="5">(Y) = 0.471</td></tr>
<tr><td></td><td colspan="5">(Z) = 0.555</td></tr>
<tr><td>Rotation</td><td colspan="5">-</td></tr>
<tr><td>URF</td><td colspan="5">SEE MICD TRACERS-SE-INT-015</td></tr>
</table>

6.5.9 TRACERS GNC Coordinate System

The GNC coordinate system is coincident with the TSCS in that attitude control inputs and outputs are given in the TSCS coordinate system. Dynamics are propagated using the moments of inertia taken with respect to a reference coordinate system that is aligned with the TSCS coordinate system and has origin at the center of mass. Note that this coordinate system is not necessarily aligned with the principal axes of inertia so there are off diagonal terms in the inertia matrix. The thruster torque matrix is computed using the vector from the TSCS origin to the center of mass. The thruster positions and thrust vector directions are expressed in the TSCS coordinate system.

Exhibit 6-19: TRACERS GNC Coordinate System

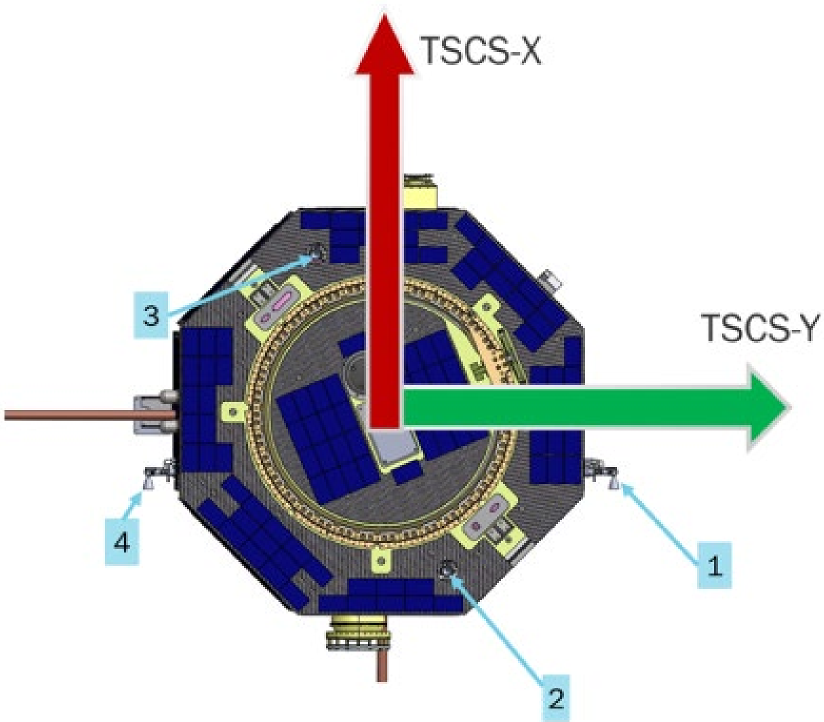


Exhibit 6-20: Thruster Positions and Unit Thrust Vectors in Body Coordinate System

Thruster	Pos X (m)	Pos Y (m)	Pos Z (m)	Thrust Vector X	Thrust Vector Y	Thrust Vector Z
#1	-.1854	.5898	.1918	1	0	0
#2	-.3810	.1588	0.0361	0	0	1
#3	.3810	-.1588	0.0361	0	0	1
#4	-.1854	-.5898	.5093	1	0	0

6.6 TRACERS Launch Stack System (S-System)

TS1 (lower) Satellite Theoretical Design Separation Plane is $S_Z = 0$ origin, which contains S_X and S_Y. at the geometric [theoretical zero error] center of the launch vehicle adaptor ring on the separation interface plane and zero error spin axis. The Theoretical Design Separation plane physical referenced to the MLB per Section 6.2.

Exhibit 6-21: Launch Stack System

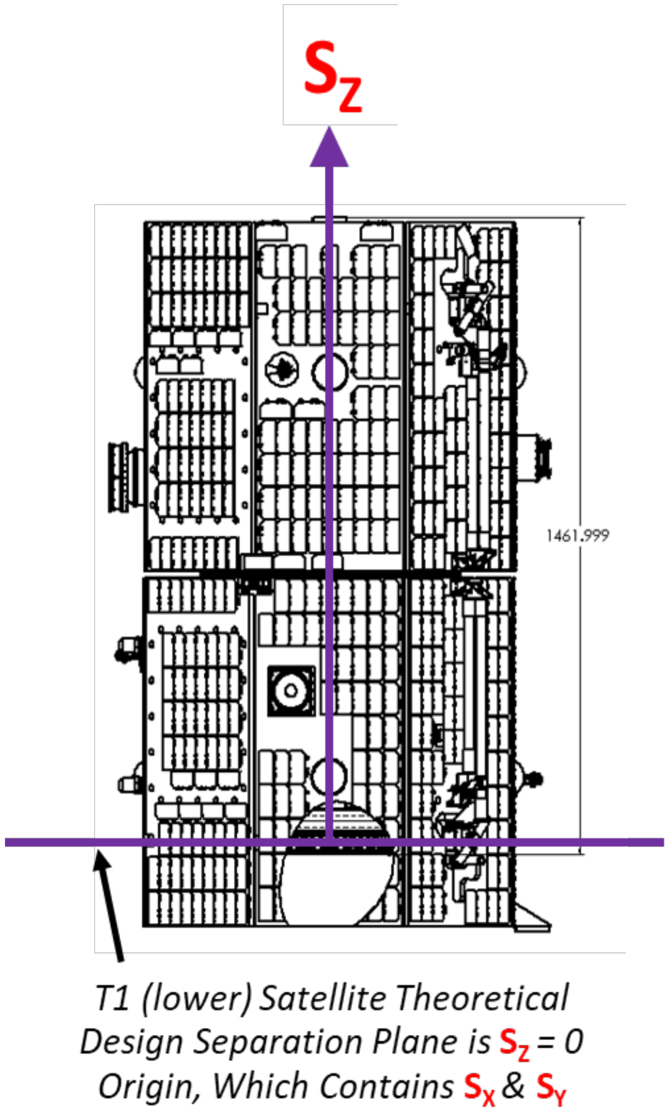
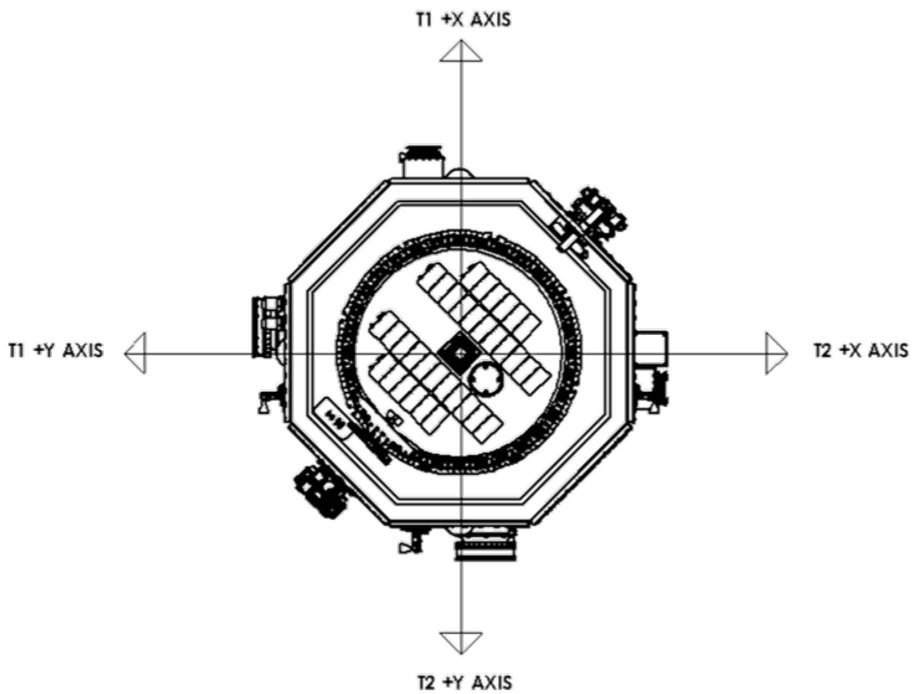


Exhibit 6-22: Launch Stack System (top view)



7 TIME

Refer to TRACERS-SE-REQ-002 TRACERS Level 2 Mission Definition Requirements Agreement (MDRA) section 1.2.28 for the time standards utilized and anticipated use cases.

8 POINTING AND CONTROL PLACEMENT, B-FIELD DEFLECTION & "BSOFF" ERRORS

Refer to TRACERS-SE-REQ-002 TRACERS Level 2 Mission Definition Requirements Agreement (MDRA) 4.9.2 (Satellite Placement, Alignment & Stability) for the specific limits and contributing constituents' budgets.

8.1 Cusp B-Field Deflection

The angle between a given orbit's B-Field vector under consideration and the Satellite body-axis (theoretical perfect spin axis), evaluated when the Satellite is at the center of the Cusp.

8.2 B-Field-to-Spin Axis Offset (BSOff)

The BSOff is the sum of the Cusp B-Field Deflection and the Satellite-LABF Attitude Placement. The following exhibit shows the contributors to the overall offset error between the B-Field and spin axis offset.

Exhibit 8-1: B-Field and Spin Axis Offset