

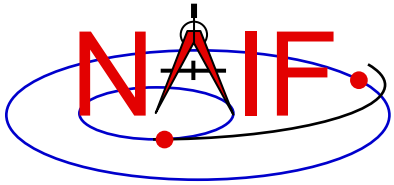


---

Navigation and Ancillary Information Facility

# Fundamental Concepts

January 2020

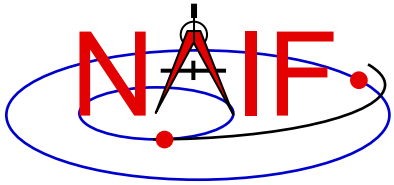


# Topics

---

Navigation and Ancillary Information Facility

- **Preface**
- **Time**
- **Reference Frames**
- **Coordinate Systems**
- **Positions and States**
- **Aberration Corrections**



# Preface

---

Navigation and Ancillary Information Facility

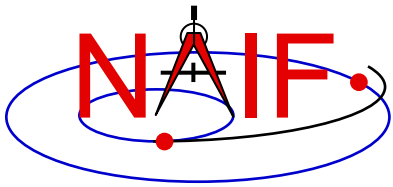
- **This tutorial introduces terminology and concepts used in the later SPICE tutorials.**
- **Some of this material is more difficult than what follows in later presentations.**
  - A complete understanding of this material is *not* essential in order to use SPICE.
- **Still, we think this information may be helpful, so... on we go!**



# Time

Navigation and Ancillary Information Facility

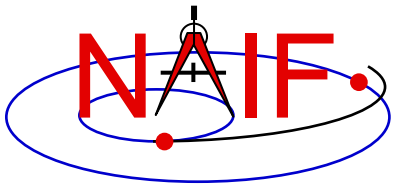
- **An epoch is an instant in time specified by some singular event**
  - Passage of a star across your zenith meridian
  - Eclipse of a spacecraft signal as it passes behind a solid body
- **Clocks**
  - Clocks count epochs specified by events such as: “regular” oscillations of a pendulum, quartz crystal, or electromagnetic radiation from a specified source, measured from an agreed upon reference epoch.
  - Careful specification of epochs using clocks requires reference to the particular clock and the location of that clock.
- **Time Systems**
  - Are agreed upon standards for “naming” epochs, measuring time, and synchronizing clocks



# Atomic Time and UTC

Navigation and Ancillary Information Facility

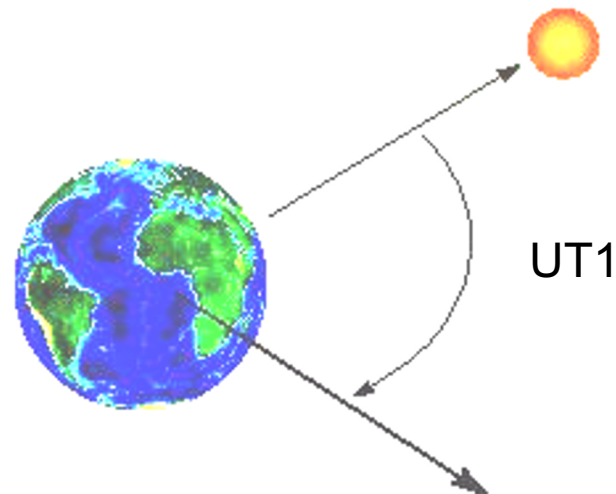
- **International Atomic Time (TAI)**
  - **Statistical time scale**
    - » **Based on data from ~200 atomic clocks in over 50 national laboratories**
  - **Maintained by Bureau International des Poids et Mesures (BIPM)**
  - **Unit is the SI (System International) second**
    - » **duration of 9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom**
  - **TAI is expressed as a count of atomic seconds past the astronomically determined instant of midnight 1 Jan 1958 00:00:00**
- **Coordinated Universal Time (UTC)**
  - **Civil Time at Greenwich England (~GMT)**
  - **Usual Calendar Formats plus Hour:Minute:Second.fraction**
- **Relationship between TAI and UTC**
  - **UTC + 10 seconds + number of leap seconds = TAI**
    - » **Valid only after Jan 01, 1972**

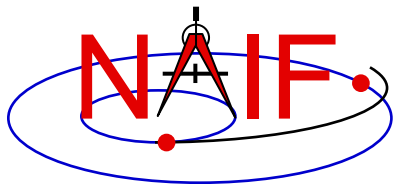


# Astronomical Time – UT1

Navigation and Ancillary Information Facility

- **Astronomical Time (UT1) is an hour representation of the angle between the Greenwich zenith meridian and the location of the “computed mean sun.”**
- **Used prior to atomic time for civil time keeping**

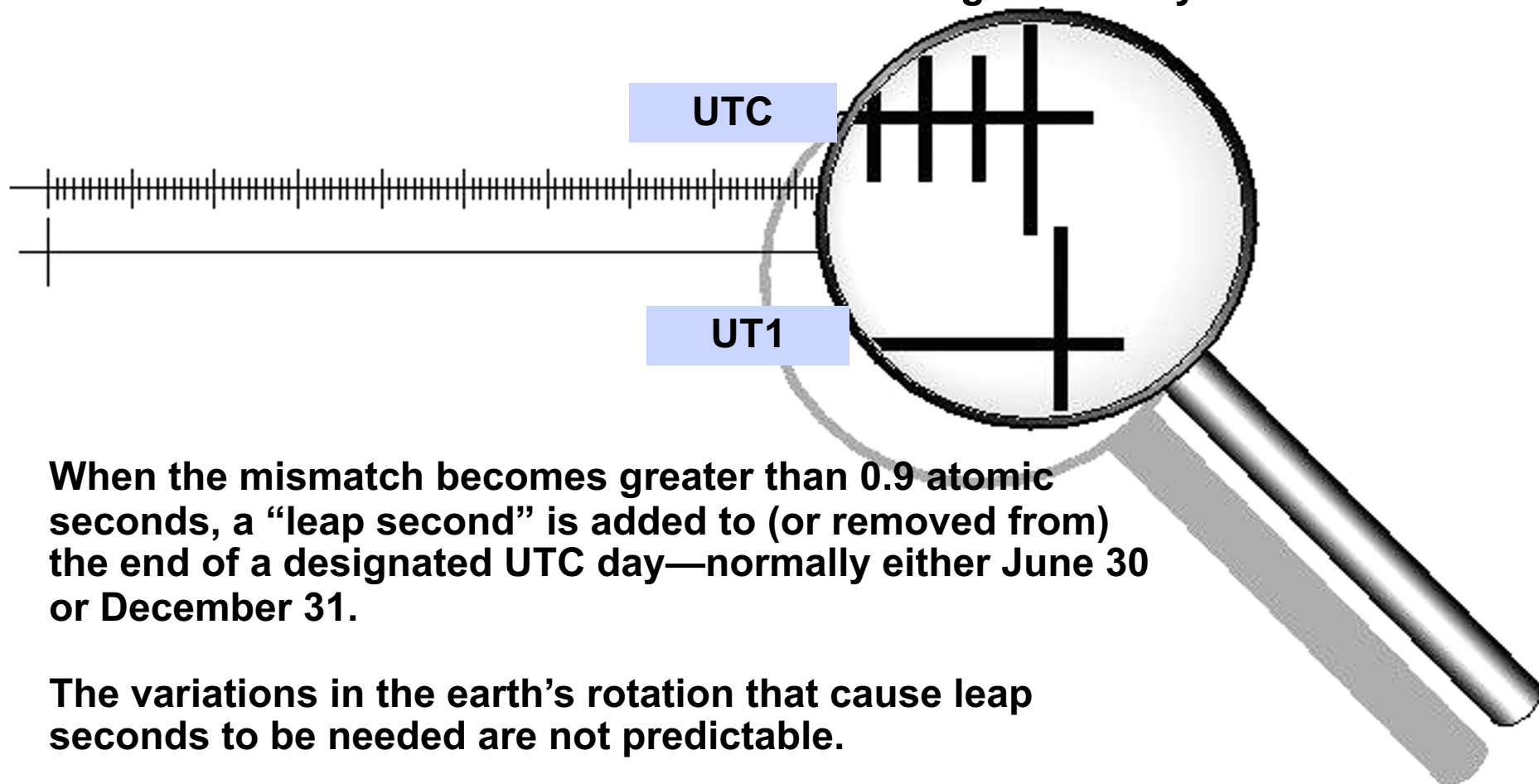




# Tying UTC to Earth's Rotation (UT1)

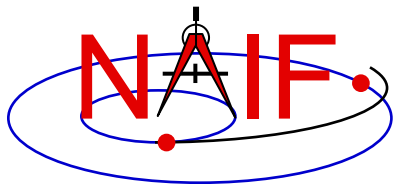
Navigation and Ancillary Information Facility

Ideally, UTC noon and astronomical noon at Greenwich (UT1) should occur simultaneously. However, the earth's rotation is not uniform. Eventually, UTC noon and astronomical noon at Greenwich get out of sync.



When the mismatch becomes greater than 0.9 atomic seconds, a “leap second” is added to (or removed from) the end of a designated UTC day—normally either June 30 or December 31.

The variations in the earth's rotation that cause leap seconds to be needed are not predictable.



# Leapseconds (+ and -)

Navigation and Ancillary Information Facility

- **“Normal” sequence of UTC time tags**

- 1998 Dec 31 23:59:58.0
- 1998 Dec 31 23:59:59.0
- 1999 Jan 01 00:00:00.0
- 1999 Jan 01 00:00:01.0

Leap seconds complicate the task of finding the duration between two UTC epochs:

- You need to know when past leap seconds occurred to compute durations defined by pairs of past UTC epochs.
- Durations defined by pairs of future UTC epochs are indeterminate if leap seconds could occur in the interim.

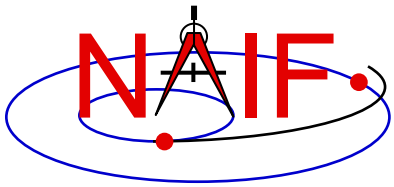
- **Sequence with a Positive Leapsecond**

- 1998 Dec 31 23:59:58.0
- 1998 Dec 31 23:59:59.0
- 1998 Dec 31 23:59:60.0
- 1999 Jan 01 00:00:00.0
- 1999 Jan 01 00:00:01.0

- **Sequence with a Negative Leapsecond**

- 1998 Dec 31 23:59:57.0
- 1998 Dec 31 23:59:58.0
- 1999 Jan 01 00:00:00.0
- 1999 Jan 01 00:00:01.0





# Barycentric Dynamical Time

---

Navigation and Ancillary Information Facility

- **Barycentric Dynamical Time (TDB) and Ephemeris Time (ET) are synonyms in SPICE documentation.**
- **TDB is**
  - a mathematical ideal used in the equations of motion.
  - used as the independent time variable for many SPICE subroutine interfaces.
  - related to Barycentric Coordinate Time (TCB) by an offset and a scale factor.
  - TDB advances on average at very close to the same rate as TAI---the difference is nearly periodic.

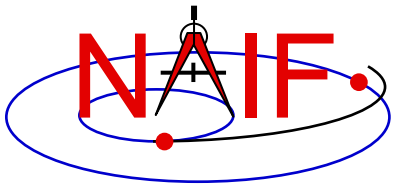


# Terrestrial Dynamical Time

---

Navigation and Ancillary Information Facility

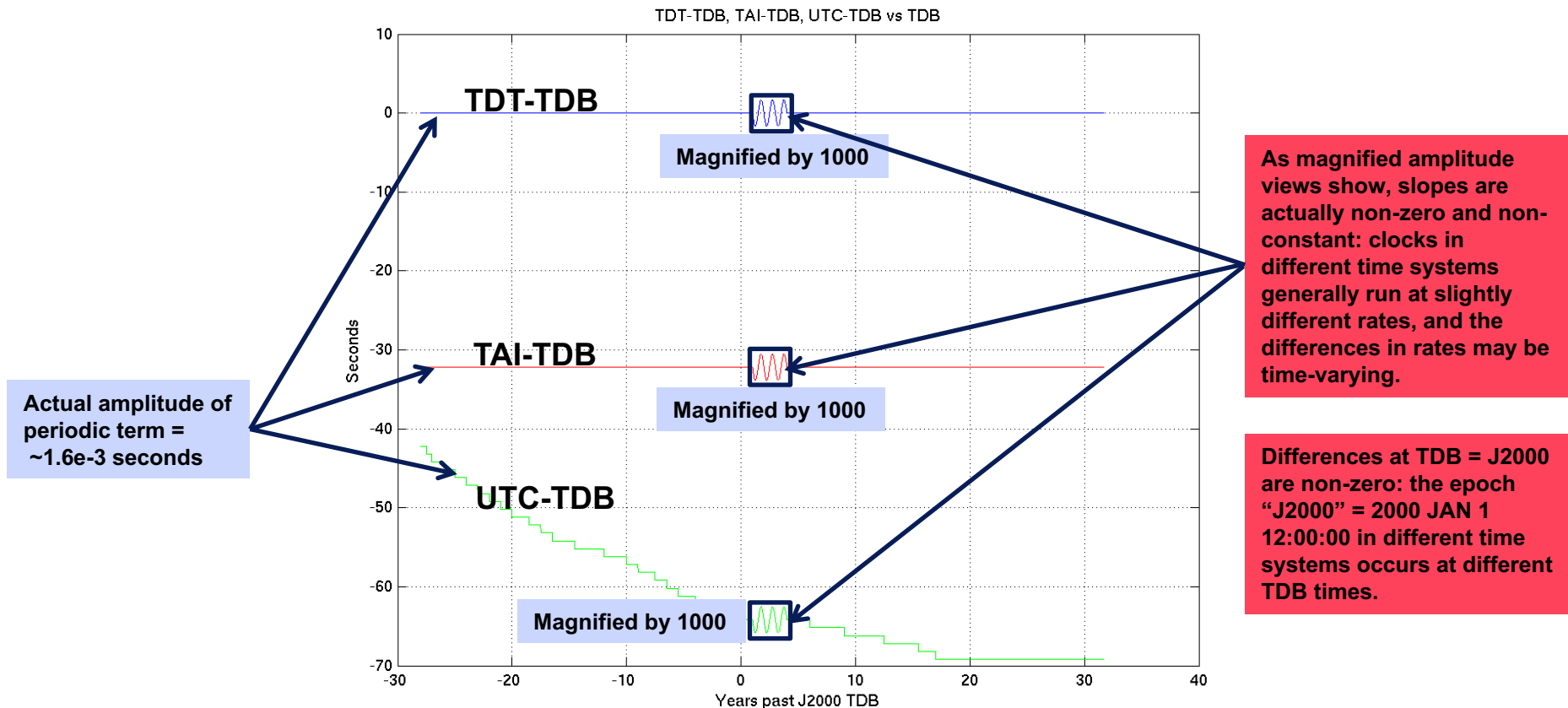
- **Terrestrial Dynamical Time (TDT)**
  - TDT is the Ideal Time (proper time) on Earth at sea level
  - $\text{TDT} = \text{TAI} + 32.184 \text{ seconds}$
  - The IAU has adopted the name “Terrestrial Time” (TT)
    - » But this is called TDT throughout SPICE documentation
- **TDB and TDT have nearly the same reference epoch (approximately 1 Jan 2000, 12:00:00 at Greenwich England), called “J2000.”**
- **TDB and TDT advance at different rates.**
  - Variations are small:  $\sim 1.6$  milliseconds
  - Variations are almost periodic with a period of 1 sidereal year (to first order)
  - Variations are due to relativistic effects
    - »  $\text{TDB} = \text{TDT} + 0.001657 \sin(E + 0.01671 \sin(E))$
- **Use of TDT in the SPICE system is quite limited.**
  - SCLK kernels
  - Duration computations involving UTC



# Offsets between Time Systems

Navigation and Ancillary Information Facility

**Difference between seconds past J2000 in a given time system and TDB seconds past J2000 TDB. Systems used for comparison are TDT, TAI, and UTC:**

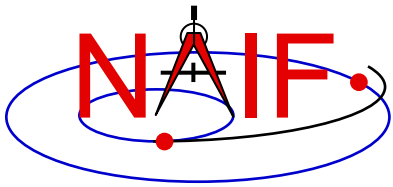




# Spacecraft Clocks

Navigation and Ancillary Information Facility

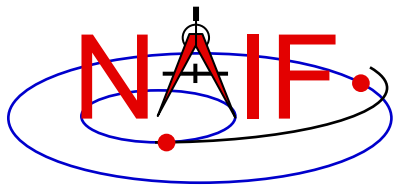
- **Spacecraft have onboard clocks to control scheduling of observations, maneuvers, attitude adjustments, etc.**
- **Used to time stamp data**
- **Fundamental unit of time is the “tick”**
  - Smallest increment possible for a spacecraft clock
  - Nominal tick duration is spacecraft clock dependent
- **Spacecraft clock time is a count of ticks since some reference tick.**
- **The duration of the tick drifts with respect to other time systems because spacecraft clocks are not very stable**



# More about Spacecraft Clocks

Navigation and Ancillary Information Facility

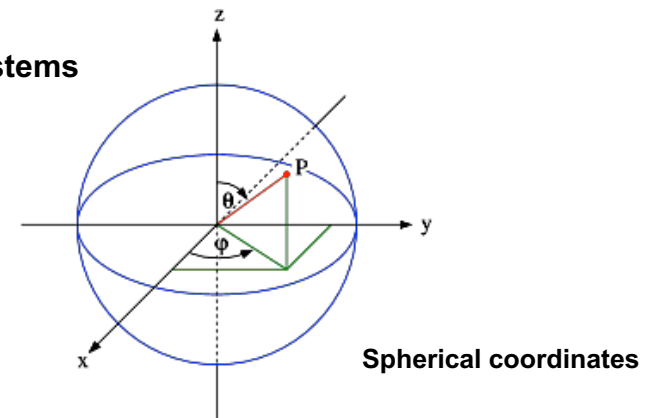
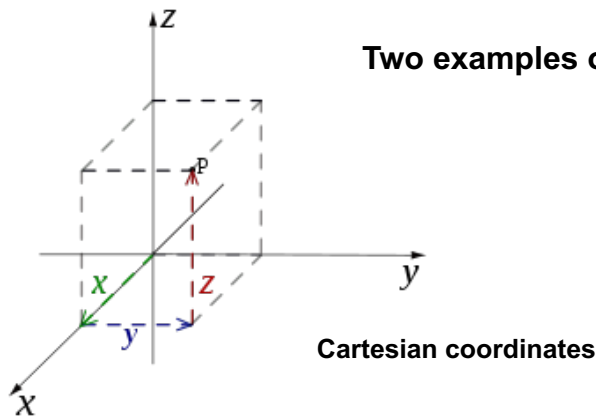
- **SCLK string formats vary from one spacecraft clock to the next.**
  - **Cassini: Maximum reading for partition 1 = 1/4294967295.255**
    - » **Partition number:** 1
    - » **Seconds:** 4294967295
    - » **Ticks (for Cassini, unit = 1/256 second):** 255
  - **Galileo: Maximum reading for partition 1 = 1/16777215:90:09:07**
    - » **Partition number:** 1
    - » **"RIM" count (unit = 60 2/3 seconds):** 16777215
    - » **"Mod 91" count (unit = 2/3 second):** 90
    - » **"RTI" count (unit = 1/15 second):** 9
    - » **"Mod 8" count (unit = 1/120 second):** 7
- **The format of spacecraft clock and the relationship between tick count and other time systems (usually UTC) is captured in a SPICE SCLK kernel**

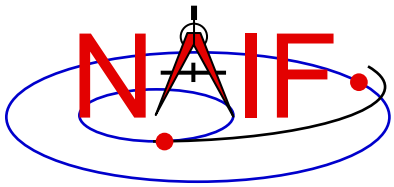


# SPICE Definitions: Reference Frames & Coordinate Systems

Navigation and Ancillary Information Facility

- A **reference frame** is an ordered set of three mutually orthogonal (possibly time dependent) unit-length direction vectors, coupled with a location called the frame's "center" or "origin."
  - SPICE documentation frequently uses the shorthand "frame" instead of "reference frame."
  - The ordered set of axes of a reference frame is also called a "basis."
- A **coordinate system** specifies the method of locating a point within a reference frame.

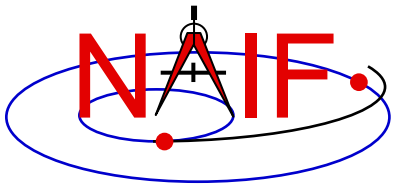




# Reference Frame Center

Navigation and Ancillary Information Facility

- **A reference frame's center is an ephemeris object whose location is coincident with the origin (0, 0, 0) of the frame.**
  - The center of the IAU\_<body> frame is center of mass of <body>.
  - The center of any inertial frame is (in SPICE) the solar system barycenter.
    - » True even for frames naturally associated with accelerated bodies, such as MARSIAU.
- **A frame's center plays little role in specification of states**
  - Origin cancels out when doing vector arithmetic
    - » Whether positions of objects A and B are specified relative to centers C1 or C2 makes no difference:
$$(A - C1) - (B - C1) = (A - C2) - (B - C2) = A - B$$
  - But the center *is* used in computing light time to centers of non-inertial frames
    - » When the aberration-corrected state of Titan as seen from the Cassini orbiter is computed in the body-fixed IAU\_Titan frame, light time is computed from Titan's center to the Cassini orbiter, and this light time is used to correct both the state and orientation of Titan.
    - » (Light time and aberration corrections are discussed later on.)

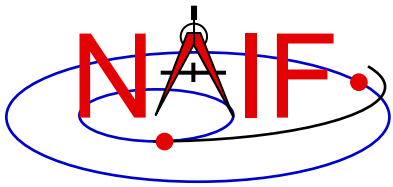


# Types of Reference Frames

Navigation and Ancillary Information Facility

- **Inertial**
  - **Non-rotating**
    - » With respect to fixed stars
  - **Non-accelerating origin**
    - » Velocity is typically non-zero; acceleration is negligible
  - **Examples:**
    - » J2000 (also called ICRF), B1950
- **Non-Inertial**
  - **Examples**
    - » **Body-fixed**
      - Centered at body center
      - Topocentric
    - » **Instrument**
    - » **Dynamic frames**
      - For example, frames defined by time-dependent vectors

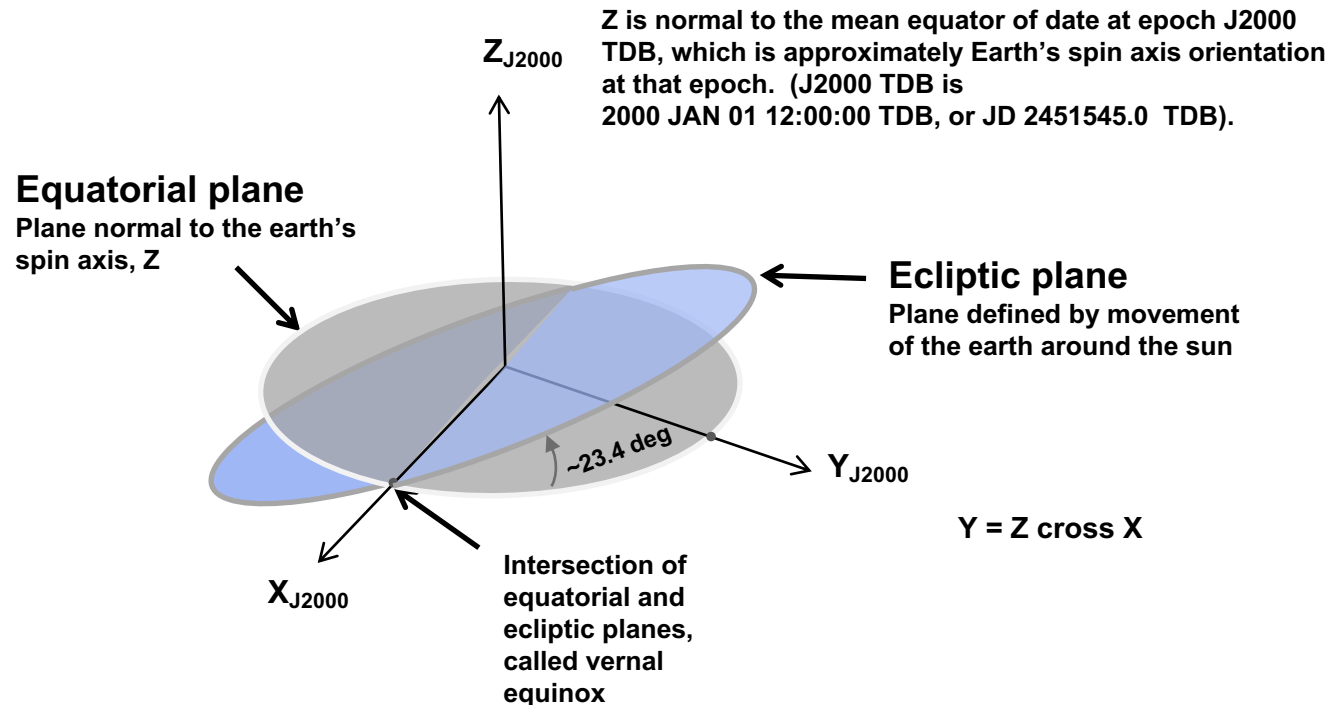




# J2000 Frame

Navigation and Ancillary Information Facility

- The J2000\* (aka EME2000) frame definition is based on the earth's equator and equinox, determined from observations of planetary motions, plus other data.



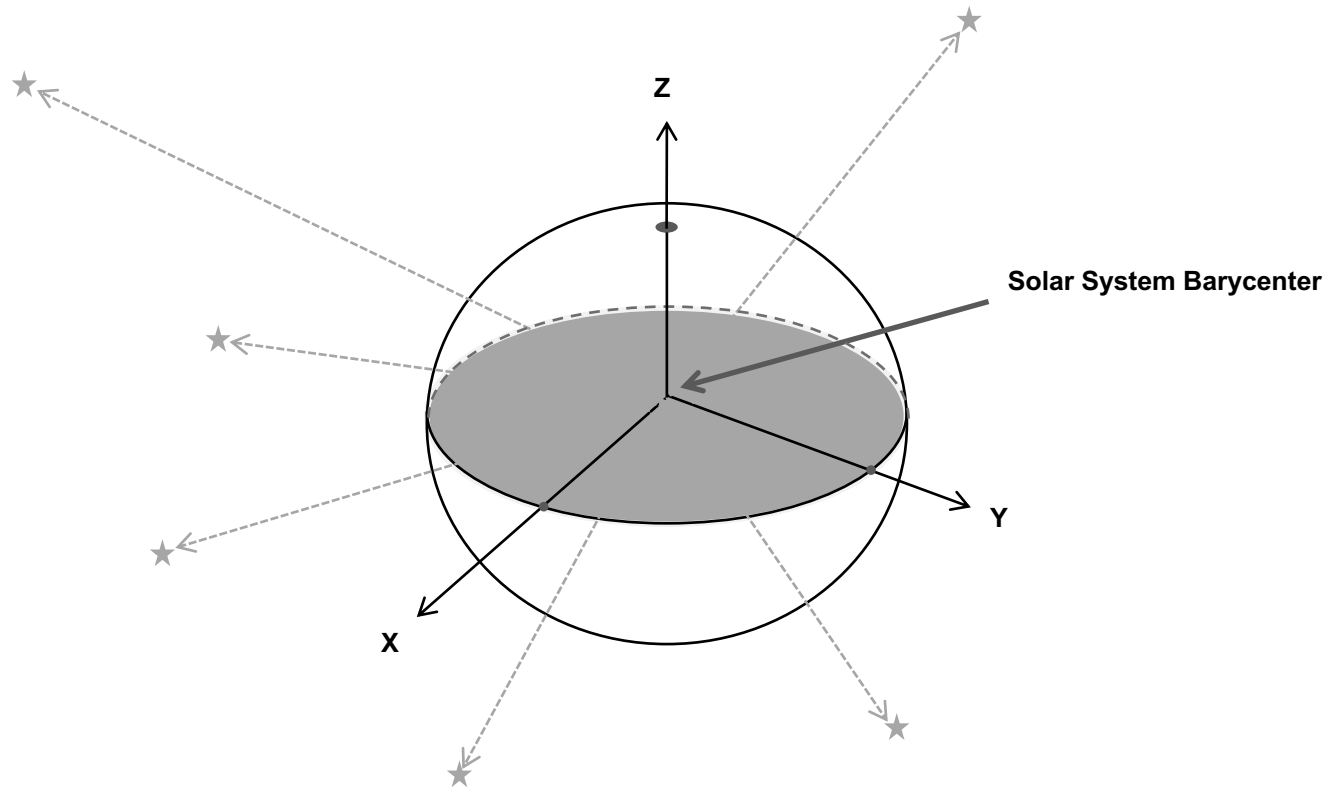
\*Caution: The name "J2000" is also used to refer to the zero epoch of the ephemeris time system (ET, also known as TDB).



# The ICRF Frame

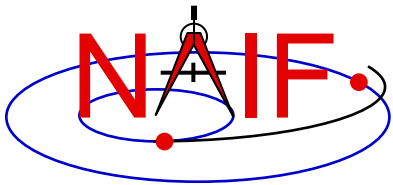
Navigation and Ancillary Information Facility

- The ICRF\* frame is defined by the adopted locations of 295 extragalactic radio sources



\*ICRF = International Celestial Reference Frame

The ICRF is managed by the International Earth Rotation Service (IERS)

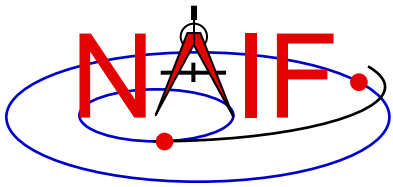


# J2000 vs. ICRF

Navigation and Ancillary Information Facility

- **The realization of ICRF was made to coincide almost exactly with the J2000 frame.**
  - The difference is very small—a rotation of less than 0.1 arc second
  - These two frame names are treated synonymously in SPICE
    - » In reality, any SPICE data said to be referenced to the J2000 frame are actually referenced to the ICRF frame
    - » For historical and backwards compatibility reasons, only the name “J2000” is recognized by SPICE software as a frame name—not “ICRF”
- **No transformation is required to convert SPICE state vectors or orientation data from the J2000 frame to the ICRF.**

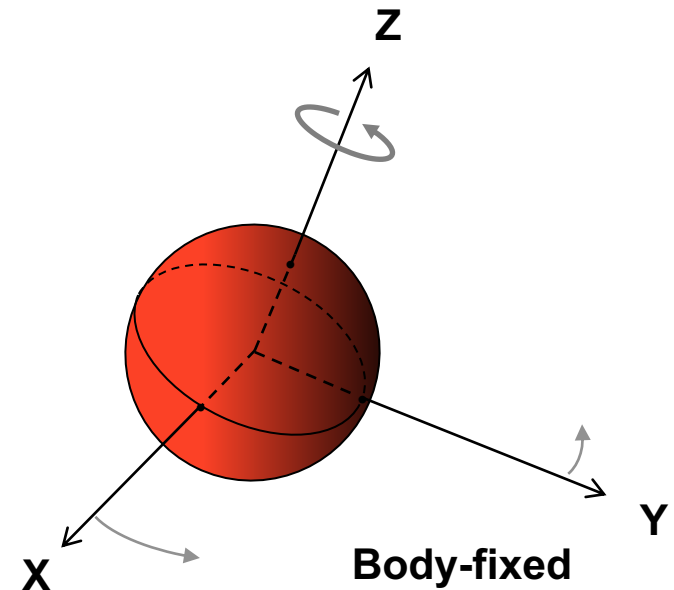
ICRF = International Celestial Reference Frame, defined by the IERS  
IERS = International Earth Rotation Service

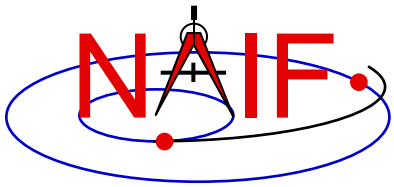


# Body-fixed Frames

Navigation and Ancillary Information Facility

- **Body-fixed frames are tied to a named body and rotate with it**
  - The most common names, those for planets, satellites, the sun, and a few asteroids and comets, are hard-coded in SPICE software
    - » Frame name style is “IAU\_body name”
      - Examples: IAU\_MARS, IAU\_SATURN
    - » To see all such names, see:
      - Frames Required Reading document, or
      - Latest generic PCK file
  - The rotation state (the orientation at time  $T$ ) is usually determined using a SPICE text PCK containing data published by the IAU
  - The earth and moon are special cases!
    - » IAU\_EARTH and IAU\_MOON both exist but generally should NOT be used
    - » See the SPICE tutorial named “lunar-earth\_pck-fk” for the best frames to be used for those bodies
  - On very rare occasions a CK is used to provide a body’s rotation state

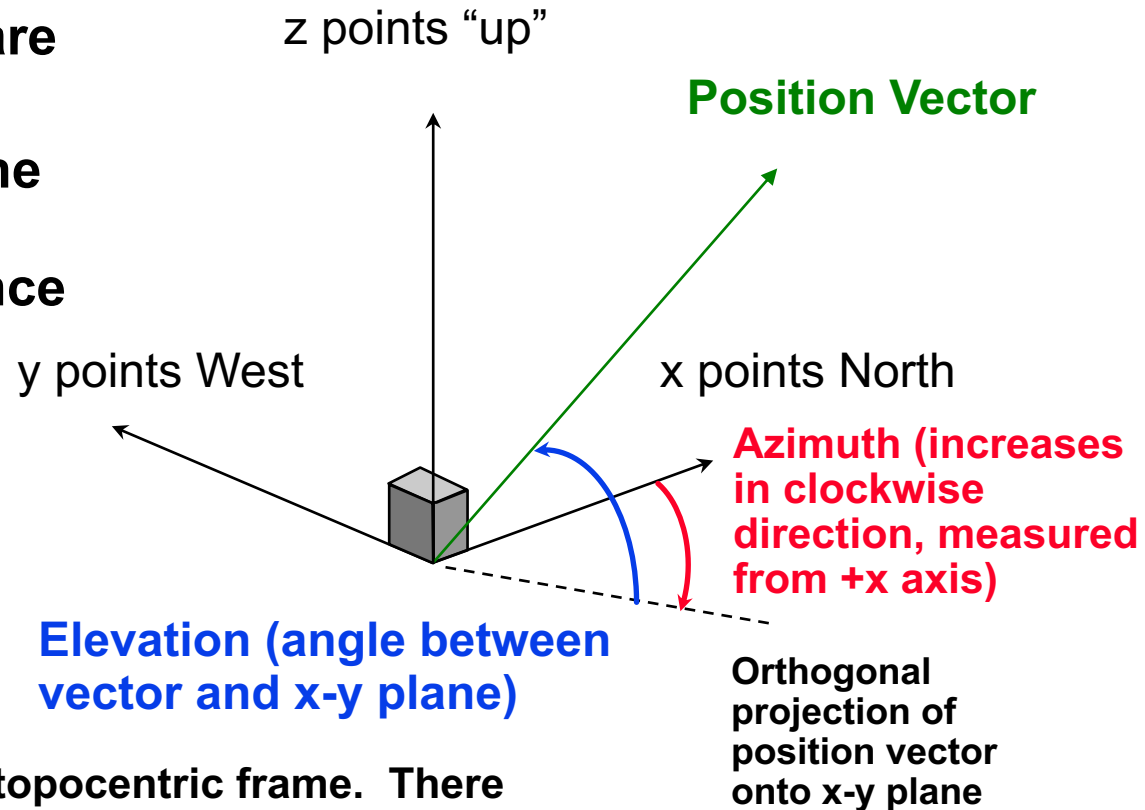




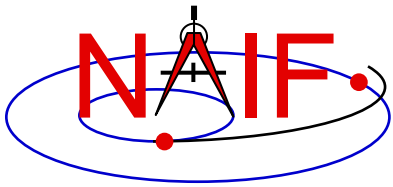
# Topocentric Frames

Navigation and Ancillary Information Facility

- Topocentric frames are attached to a surface
- Z-axis is parallel to the gravity gradient or orthogonal to reference spheroid



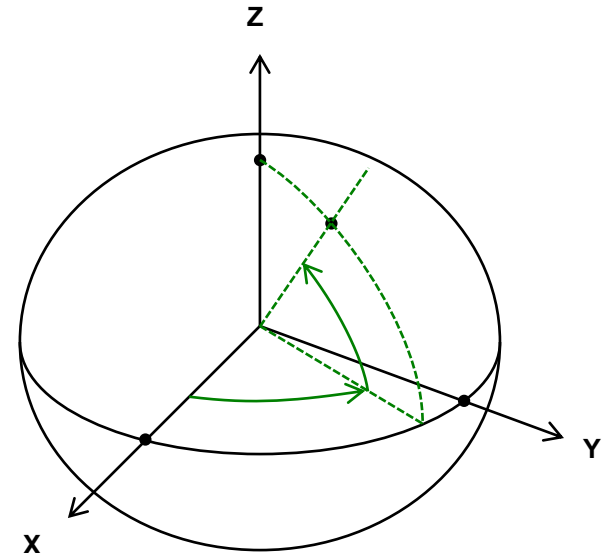
One example of a topocentric frame. There are other types of topocentric frames: for example, the z-axis could point down, the x-axis North, and the y-axis East.



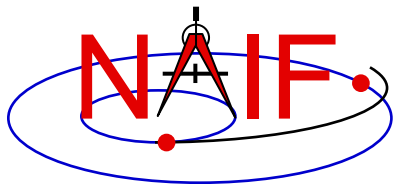
# Coordinate System Conventions - 1

Navigation and Ancillary Information Facility

- **Planetocentric coordinate systems (also known as latitudinal)**
  - For planets and their satellites the +Z axis (+90 LAT) always points to the north side of the invariable plane (the plane whose normal vector is the angular momentum vector of the solar system)
    - » Planetocentric longitude increases positively eastward
    - » Planetocentric latitude increases positively northward
  - Dwarf planets\*, asteroids and comets spin in the right hand sense about their “positive pole.”
    - » What the IAU now calls the “positive pole” is still referred to as the “north pole” in SPICE documentation.
    - » The “positive pole” may point above or below the invariable plane of the solar system (see above).
    - » This revision by the IAU Working Group (2006) inverts what had been the direction of the north pole for Pluto, Charon and Ida.
  - Planetocentric routines are RECLAT/ LATREC, RADREC/RECRAD, DRDLAT/DLATDR



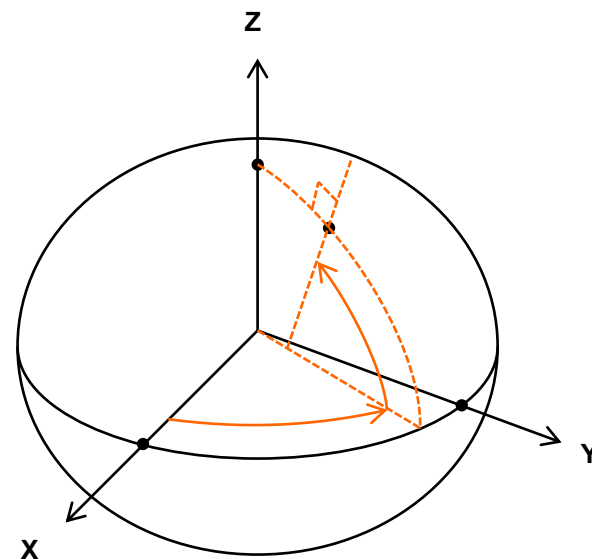
\*The dwarf planets are: Ceres, Eris, Haumea, Makemake, Pluto

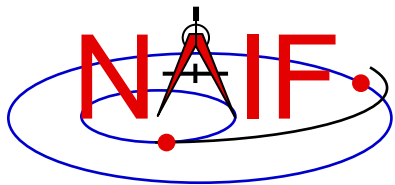


# Coordinate System Conventions - 2

Navigation and Ancillary Information Facility

- **Planetodetic coordinate systems**
  - Planetodetic longitude is planetocentric longitude
    - » increases positively eastward
  - Planetodetic latitude
    - » Tied to a reference ellipsoid
    - » For a point on a reference ellipsoid, the angle measured from the X-Y plane to the surface normal at the point of interest. For other points, equals latitude at the nearest point on the reference ellipsoid
    - » Latitude increases positively in the +Z direction
      - +Z is defined the same as for planetocentric coordinates
  - Planetodetic routines are **RECGeo/GEOREC**, **DRDGeo/DGEODR**

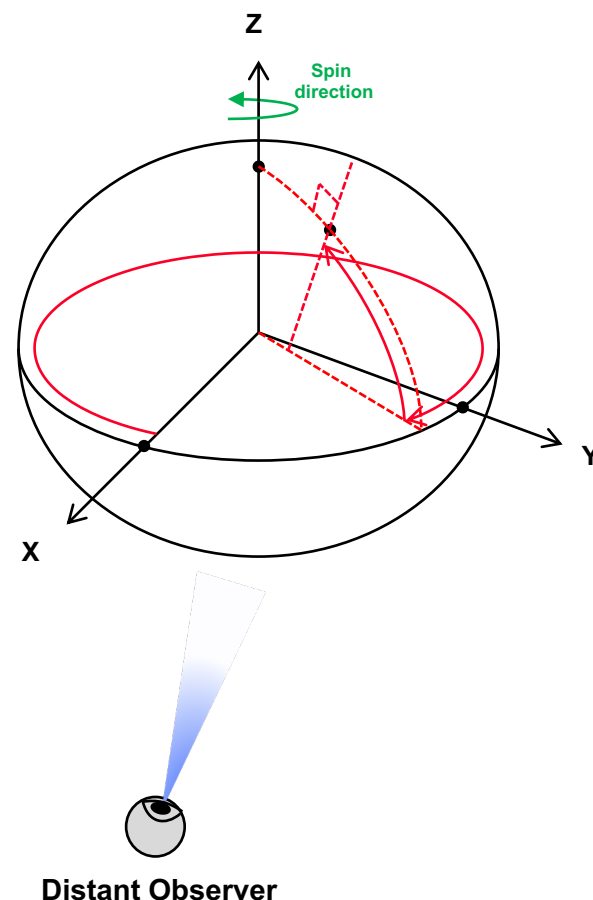




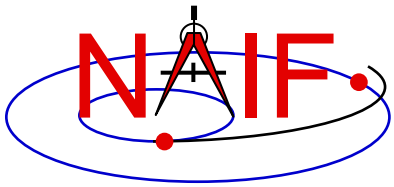
# Coordinate System Conventions - 3

Navigation and Ancillary Information Facility

- **Planetographic coordinate systems**
  - **For planet and satellite planetographic coordinate systems:**
    - » Planetographic latitude is planetodetic latitude
    - » Planetographic longitude is usually defined such that the sub-observer longitude increases with time as seen by a distant, fixed observer in an inertial reference frame
      - The earth, moon and sun are exceptions; planetographic longitude is positive east by default
      - Planetographic routines are PGRREC/RECPGR
  - **For dwarf planets, asteroids and comets:**
    - » There are multiple, inconsistent standards! (USNO, IAU, PDS)
    - » NAIF strongly suggests you use only planetocentric or planetodetic coordinates
      - Planetocentric routines are RECLAT/ LATREC, RADREC/RECRAD, DRDLAT/DLATDR
      - Planetodetic routines are RECGEO/GEOREC, DRDGEO/DGEODR







# State Vectors

Navigation and Ancillary Information Facility

- **The state of an object is its position and velocity relative to a second object**
  - In SPICE, these objects are often referred to as “target” and “observer” or “center”
  - E.g. Saturn relative to Saturn barycenter; Titan relative to Huygens probe
  - A state is always given in the TDB time system (also known as ET)
- **In the SPK subsystem a state is a six dimensional vector**
  - First three components are Cartesian position:  $x, y, z$
  - Second three components are Cartesian velocity:  $dx/dt, dy/dt, dz/dt$
  - Units are km, km/sec
- **A state is specified relative to a reference frame**

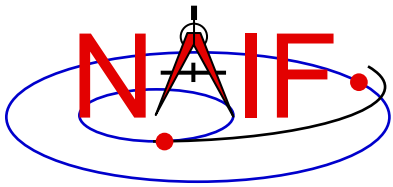


# Transforming States

Navigation and Ancillary Information Facility

- To perform algebraic operations on states they must be in the same reference frame.
- Position-only frame transformations require only a rotation\* matrix given as a function of time.
  - »  $P_B(t) = R_{A \text{ to } B}(t) P_A(t)$
- Position and velocity frame transformations require that we differentiate the above equation
  - »  $dP_B(t)/dt = dR_{A \text{ to } B}(t)/dt P_A(t) + R_{A \text{ to } B}(t) dP_A(t)/dt$
- We can use a 6x6 matrix to combine these two transformations into a single equation

\* Assuming both frames are right-handed



# Transforming States

Navigation and Ancillary Information Facility

$$\mathbf{S}_B(t) = \mathbf{T}_{A \text{ to } B}(t) \mathbf{S}_A(t)$$

where

$$\mathbf{S}_i(t) = \begin{pmatrix} \mathbf{P}_i(t) \\ d\mathbf{P}_i(t)/dt \end{pmatrix} \quad i = A \text{ or } B$$

and

$$\mathbf{T}_{A \text{ to } B}(t) = \left( \begin{array}{c|c} \mathbf{R}_{A \text{ to } B}(t) & \mathbf{0} \\ \hline d\mathbf{R}_{A \text{ to } B}(t)/dt & \mathbf{R}_{A \text{ to } B}(t) \end{array} \right)$$

The SPICELIB routines SXFORM and PXFORM return state transformation and position transformation matrices respectively.

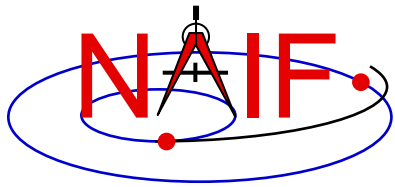


# Aberration Corrections: Introduction

---

Navigation and Ancillary Information Facility

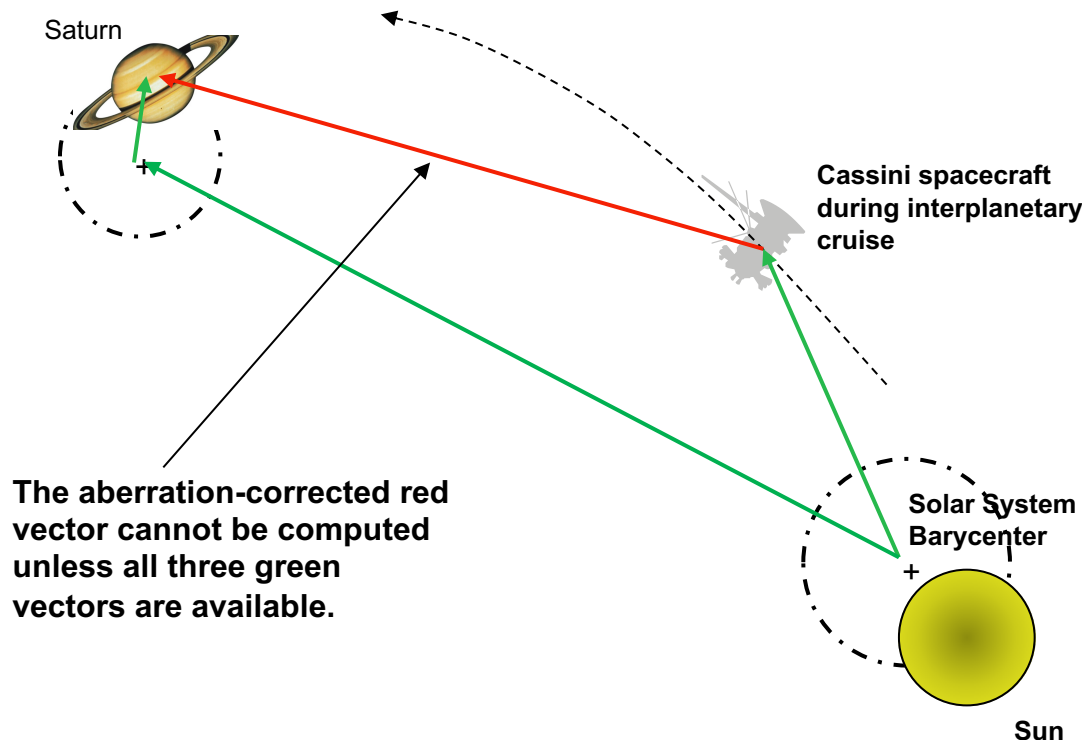
- **Within the SPICE system, “aberration corrections” are adjustments made to state vectors and time-dependent reference frames to accurately reflect the apparent—as opposed to the actual—state and attitude of a target object as seen from a specified observer at a specified time.**
  - Actual, uncorrected states from an ephemeris are called “geometric” states.
  - When computing state vectors, SPICE users may request geometric or aberration-corrected states.
- **Aberration corrections are needed to accurately answer questions such as:**
  - In which direction must a remote sensing instrument be pointed to observe a target of interest?
  - For a given pointing direction and observation time, what target body surface location would be observed by a remote sensing instrument?
  - In which direction must an antenna be pointed to transmit a signal to a specified target?

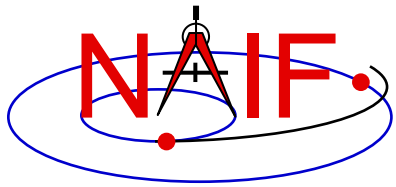


# Computing Aberration-corrected States

Navigation and Ancillary Information Facility

- In order to compute an aberration-corrected state, the state vectors used in the computation must all be chained back to the Solar System Barycenter



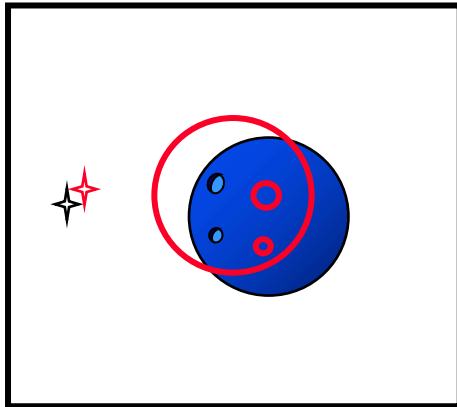


# Example: Predicted vs Actual Photo

## Navigation and Ancillary Information Facility

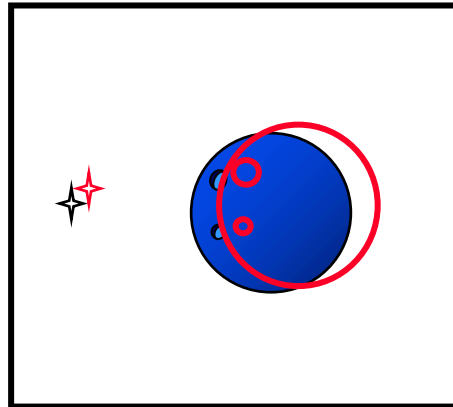
We compare the predicted appearance of a photograph from an optical camera against the actual photograph. We show three predictions derived using different aberration corrections: NONE, LT ("light time only"), and LT+S ("light time plus stellar aberration").

For each prediction, we use red overlays to indicate the expected location in the photo of the images of an extended target body (for example, a natural satellite), of features on the surface of the target body, and of a star.



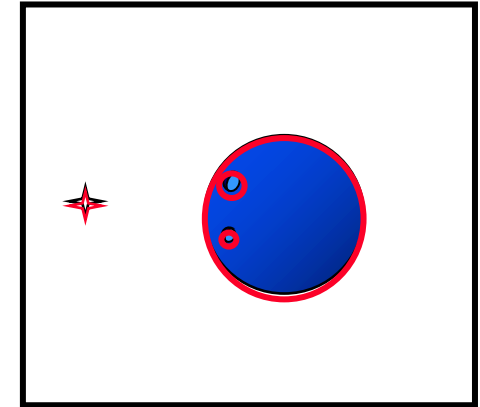
NONE

Predicted images using uncorrected target position and orientation and uncorrected star direction vector



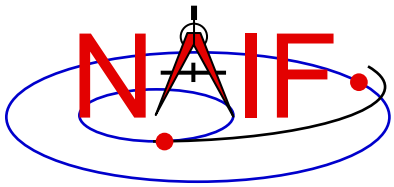
LT

Predicted images using light time-corrected target position and orientation and uncorrected star direction vector



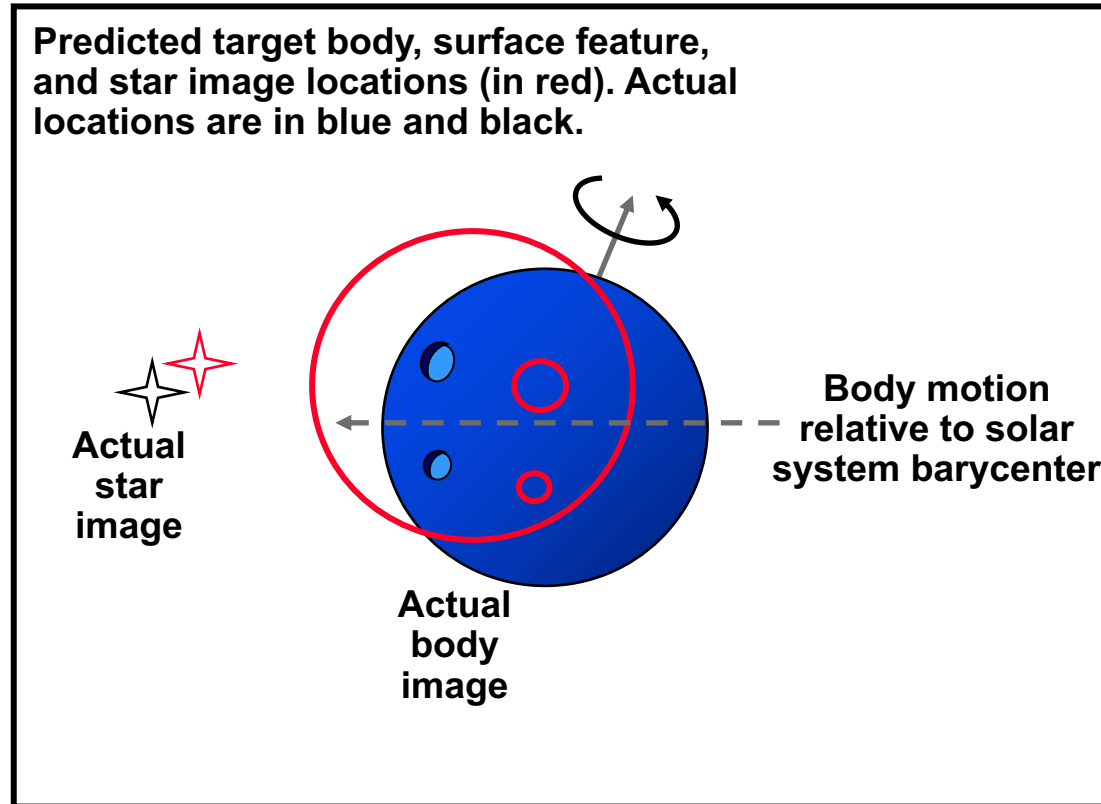
LT+S

Predicted images using light time and stellar aberration-corrected target position, light time-corrected target orientation, and stellar aberration-corrected star direction vector

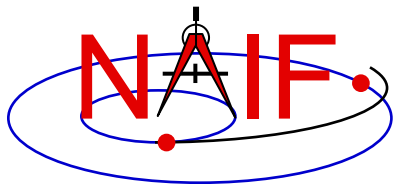


# Prediction Without Corrections

Navigation and Ancillary Information Facility

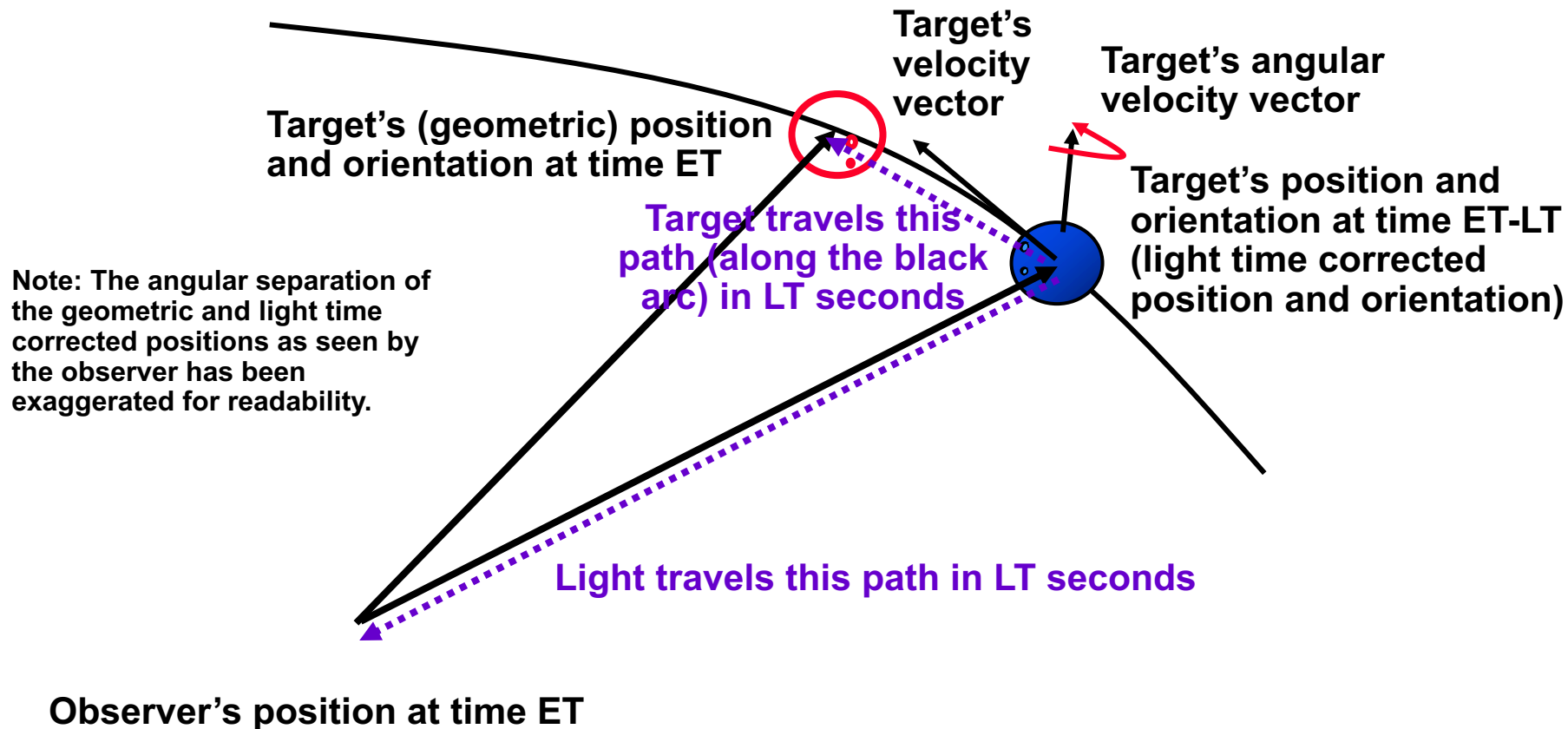


Using geometric target positions, target images in photos or other remote-sensing observations don't appear at their predicted locations.



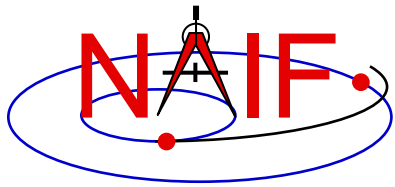
# Light Time Corrections

Navigation and Ancillary Information Facility



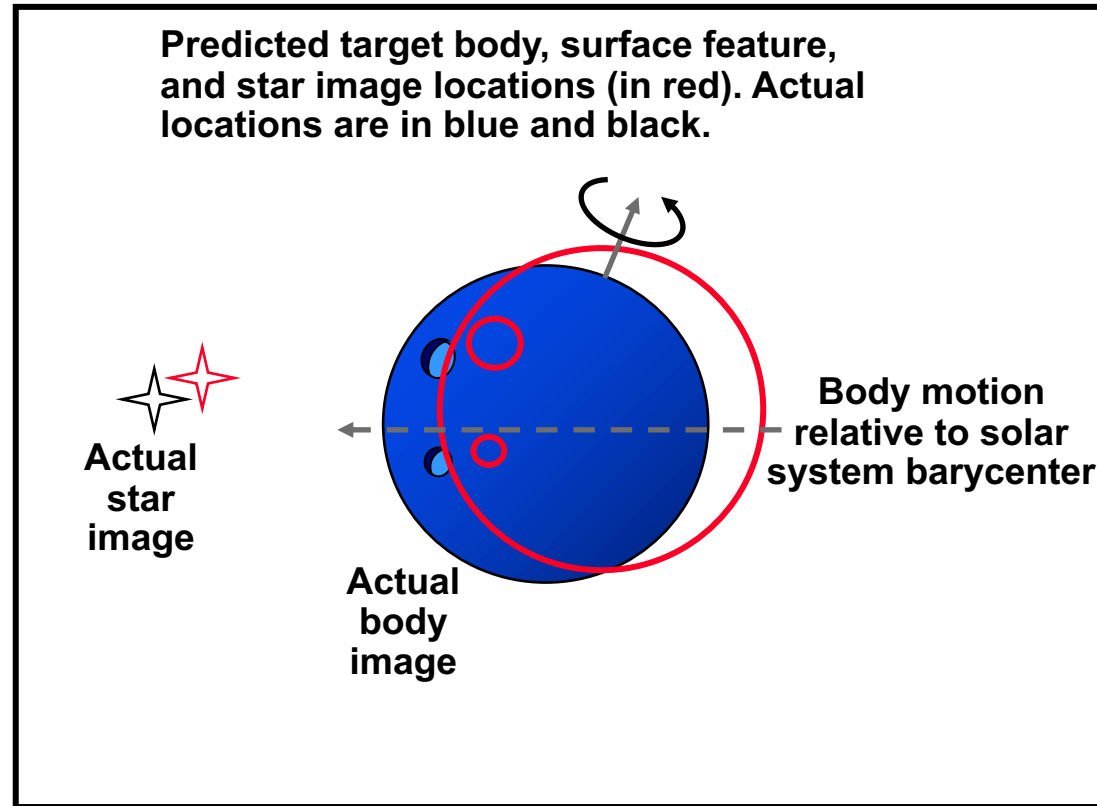
At time ET, the observer's camera records photons emitted from the target at time ET-LT, where LT is the one-way light time. The camera "sees" the target's position and orientation at ET-LT.



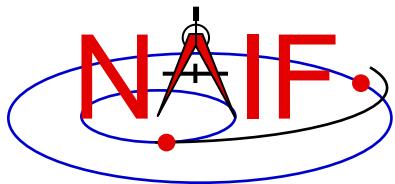


# Prediction Using Light Time Corrections

Navigation and Ancillary Information Facility

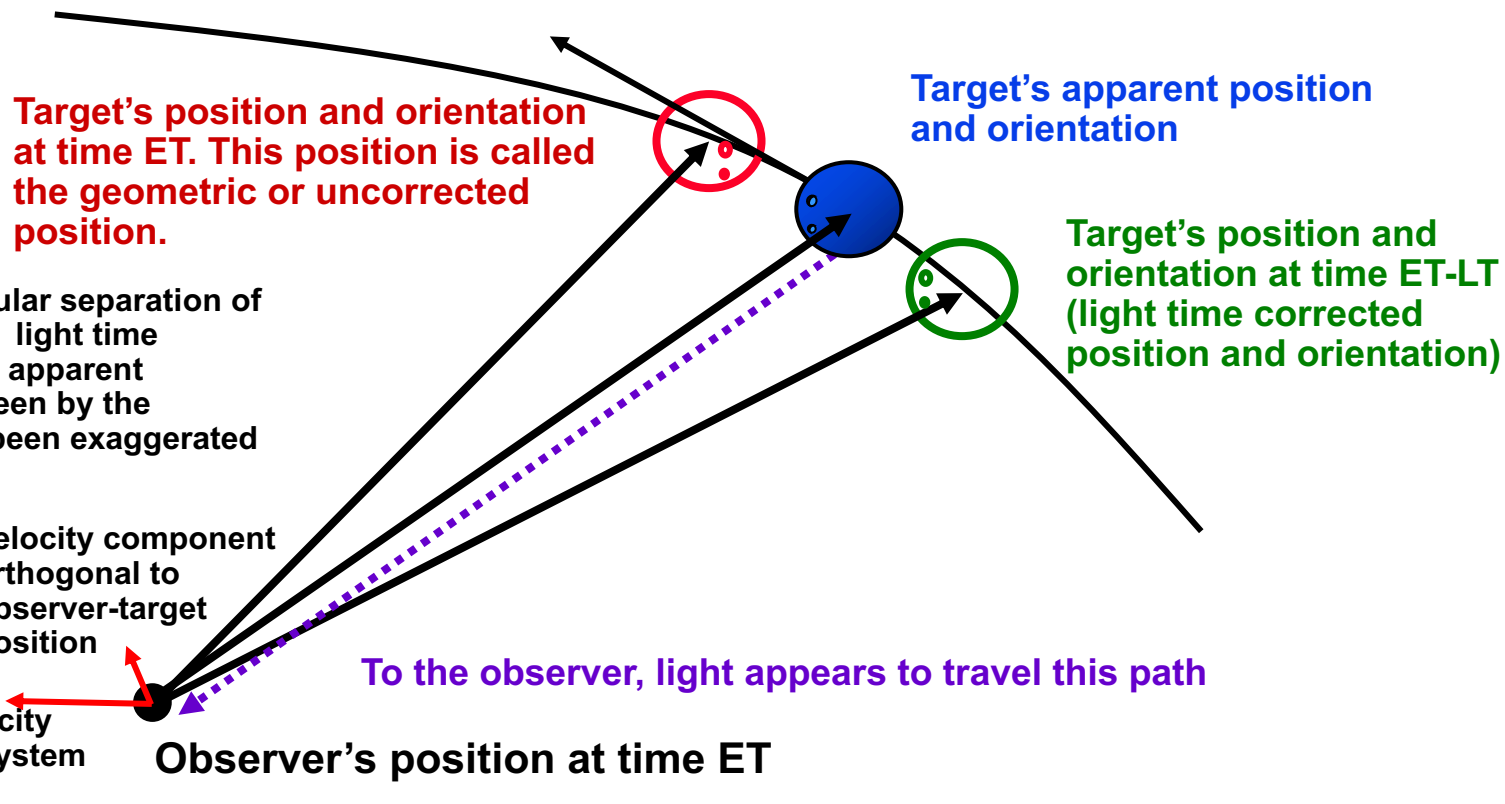


Using the light time corrected target position and orientation, the predicted locations in the photo of the target image and surface features have changed, but the accuracy of the prediction may still be poor.



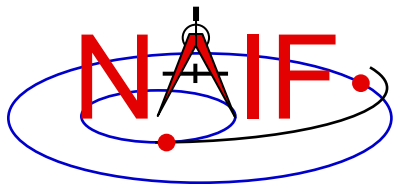
# Stellar Aberration Correction

Navigation and Ancillary Information Facility



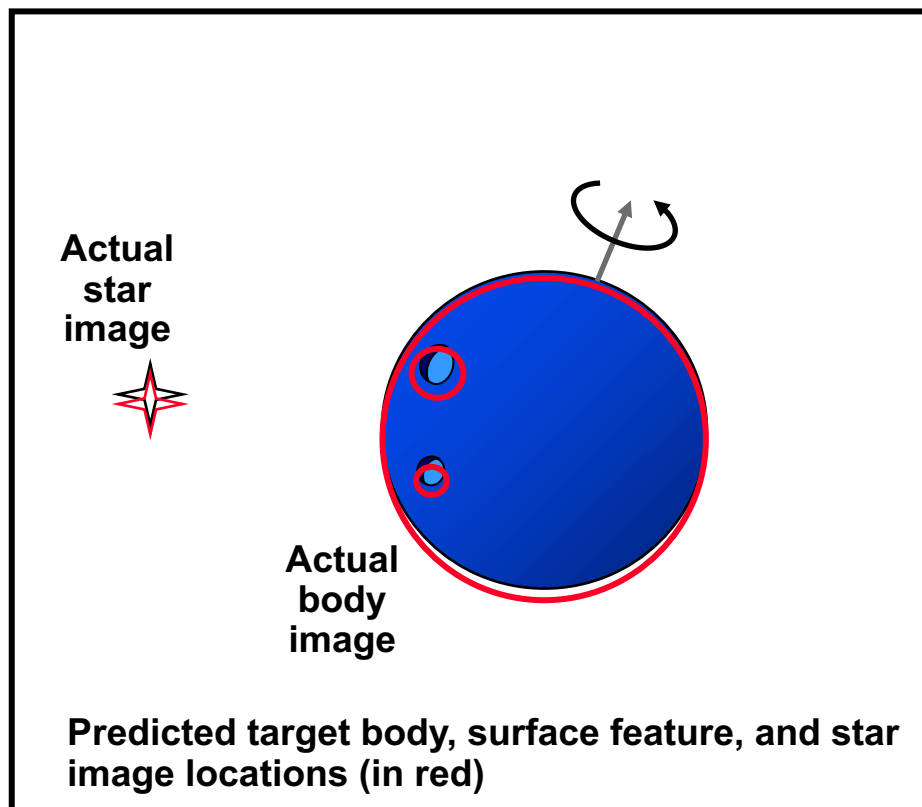
At time ET, the observer's camera records photons emitted from the target at time ET-LT, where LT is the one-way light time.

The vector from the observer at ET to the location of the target at ET-LT is displaced by a physical phenomenon called stellar aberration. The displaced vector yields the apparent position of the target.



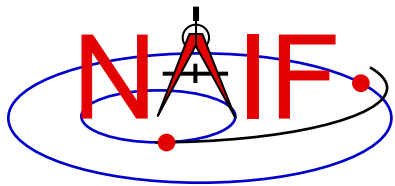
# Prediction Using "LT+S" Corrections

Navigation and Ancillary Information Facility



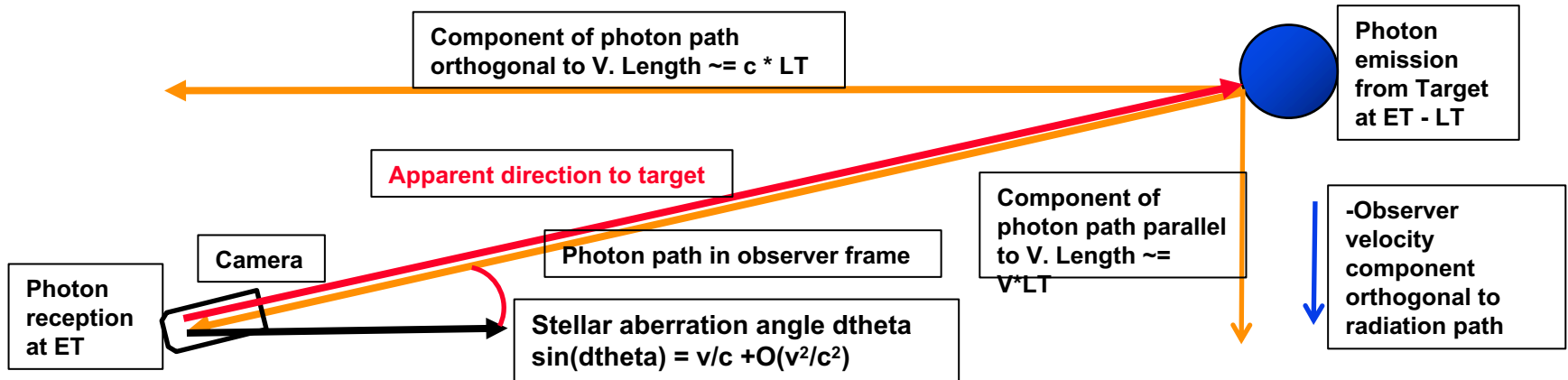
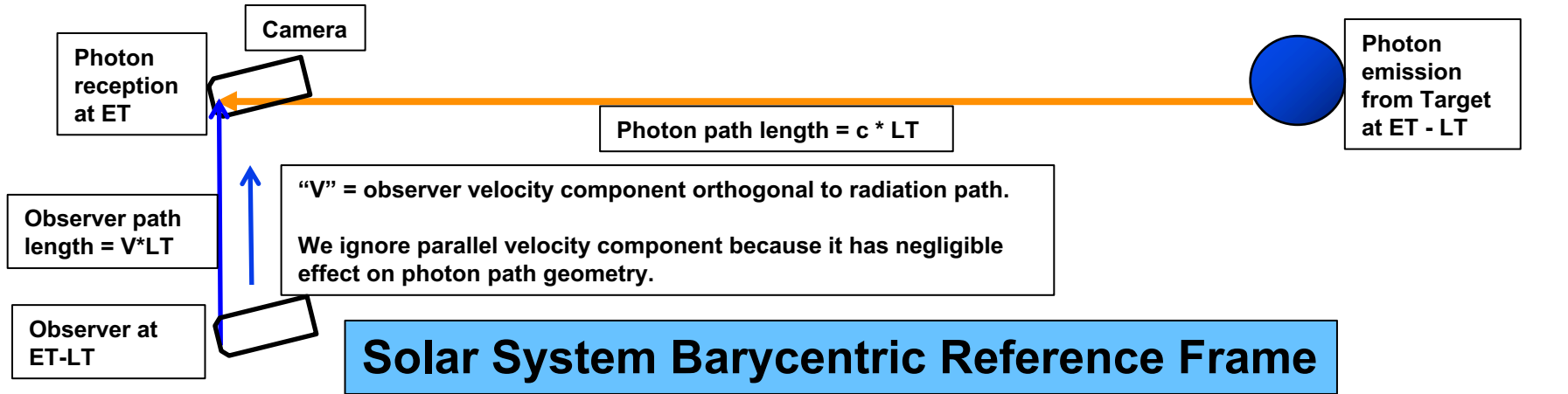
Using the light time and stellar aberration-corrected target position, light time-corrected target orientation, and stellar aberration-corrected star direction, we obtain a significantly improved image location predictions.

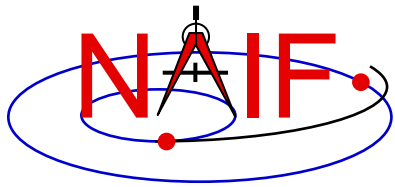
Remaining prediction errors may be due to, among other causes, pointing error, spacecraft and target ephemeris errors, and timing errors.



# Newtonian Stellar Aberration Effect

Navigation and Ancillary Information Facility



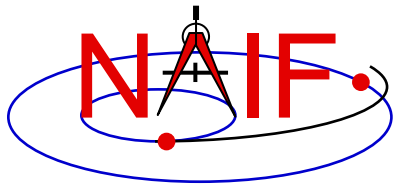


# Effect of Aberration Corrections - 1

---

Navigation and Ancillary Information Facility

- **Angular offsets between corrected and uncorrected position vectors over the time span 2004 Jan 1--2005 Jan1**
  - **Mars as seen from MEX:**
    - » **LT+S vs NONE: .0002 to .0008 degrees**
    - » **LT vs NONE: .0006 to .0047 degrees**
  - **Earth as seen from MEX:**
    - » **LT+S vs NONE: .0035 to .0106 degrees**
    - » **LT vs NONE: .0000 to .0057 degrees**
  - **MEX as seen from Earth:**
    - » **LT+S vs NONE: .0035 to .0104 degrees**
    - » **LT vs NONE: .0033 to .0048 degrees**
  - **Sun as seen from Mars:**
    - » **LT+S vs NONE: .0042 to .0047 degrees**
    - » **LT vs NONE: .0000 to .0000 degrees**



# Effect of Aberration Corrections - 2

Navigation and Ancillary Information Facility

- **Angular offsets between corrected and uncorrected position vectors over the time span 2004 Jan 1--2008 Jan1**
  - **Saturn as seen from CASSINI:**
    - » **LT+S vs NONE: .0000 to .0058 degrees**
    - » **LT vs NONE: .0001 to .0019 degrees**
  - **Titan as seen from CASSINI:**
    - » **LT+S vs NONE: .0000 to .0057 degrees**
    - » **LT vs NONE: .0000 to .0030 degrees**
  - **Earth as seen from CASSINI:**
    - » **LT+S vs NONE: .0000 to .0107 degrees**
    - » **LT vs NONE: .0000 to .0058 degrees**
  - **CASSINI as seen from Earth:**
    - » **LT+S vs NONE: .0000 to .0107 degrees**
    - » **LT vs NONE: .0000 to .0059 degrees**
  - **Sun as seen from CASSINI:**
    - » **LT+S vs NONE: .0000 to .0059 degrees**
    - » **LT vs NONE: .0000 to .0000 degrees**