# Geolocation

The DSCOVR spacecraft will be inserted into the L1 liberation point between the Earth and the Sun and from this point will view the Earth through the Earth Polychromatic Imaging Camera (EPIC) at a distance of about 1.5 million kilometers.

Earth image pixels from DSCOVR's EPIC instrument must be geolocated so that separate images may be assembled into a single product. This is because the earth and the spacecraft are in motion, and each camera pixel generally will not view the same geographic region in successive images. For each pixel, the geolocation procedure computes the geodetic latitude and longitude of the earth region illuminating the pixel. Pixels from multiple images corresponding to an arbitrary geographic area may then be identified because they share the same unique geodetic coordinates. DSCOVR lunar image pixels are assigned selenographic coordinates in an analogous process. Lunar images are required for radiometric calibration of the EPIC instrument.

The position of the spacecraft at the instant of image exposure is first computed in a geocentric coordinate system from ephemerides provided outside the procedure. The pointing angle of the EPIC camera at the moment of exposure is also computed in the same coordinate system from observations provided outside the procedure. By approximating the earth's surface as an oblate spheroid, the problem is largely reduced to computing the intersection of the camera optical pointing axis with the spheroid and then computing the geodetic coordinates of the intersection.

The coarse angular orientation of DSCOVR will be provided by the spacecraft attitude and control system. The pointing accuracy can be improved, however, by using a centroid algorithm, to locate the center of the Earth or moon disk in each image.

Because the Earth's diurnal rotation places a different geographic region beneath the spacecraft at any arbitrary instant, the angular position of the earth at the moment of exposure must be computed to determine the geodetic latitude and longitude of the image pixels. The lunar location method is similar, but is further complicated by the effects of gravitational coupling on the moon's rotation.

The location program operates in "normal", "lunar calibration", and "star field" modes. In normal mode, the EPIC instrument points toward the center of the Earth, and latitude and longitude values are generated in a grid for each pixel illuminated by the Earth. Occasionally, the Moon will also be in view and in this case a second selenographic grid is generated. When in lunar calibration mode, EPIC will be pointed at the Moon and the Earth will not be in view because this mode is only engaged when the Moon is more than ten degrees from the Earth-Sun line. When in star field mode, EPIC will be pointed in the direction of selected stars for instrument alignment and the Earth or Moon will generally not be in view.

In summary, the Geolocation procedure reads spacecraft position and attitude, and solar and lunar ephemerides and interpolates these data to the instant of image exposure. Locating the center of the disk image enhances the spacecraft attitude knowledge. The Earth's angular position is determined and the latitude and longitude of each pixel is computed from geometrical considerations.

## 1 Coordinate Systems

The spacecraft position and attitude and solar and lunar position vectors must all be placed in a common reference coordinate system before computing the geodetic coordinates of EPIC pixels. The Julian 2000.0 Standard Inertial System used here is an Earth-centered, inertial Cartesian system with the z-axis pointing north along the Earth's rotational axis, the x-axis in the direction of the Vernal Equinox and the y-axis completing the orthogonal triad.

**Error! Reference source not found.**1 shows the spacecraft body and star tracker Cartesian coordinate systems in the J2000 reference. For clarity, the coordinate systems are shown with origins at the center and behind the cylinder representing the spacecraft. In fact, the origins are displaced because the star tracker and the EPIC instruments are mounted on the sides of the spacecraft. When the large distance between the spacecraft and the Earth or Moon is considered, these translations have no practical consequence. The EPIC coordinate system is shown in 2.

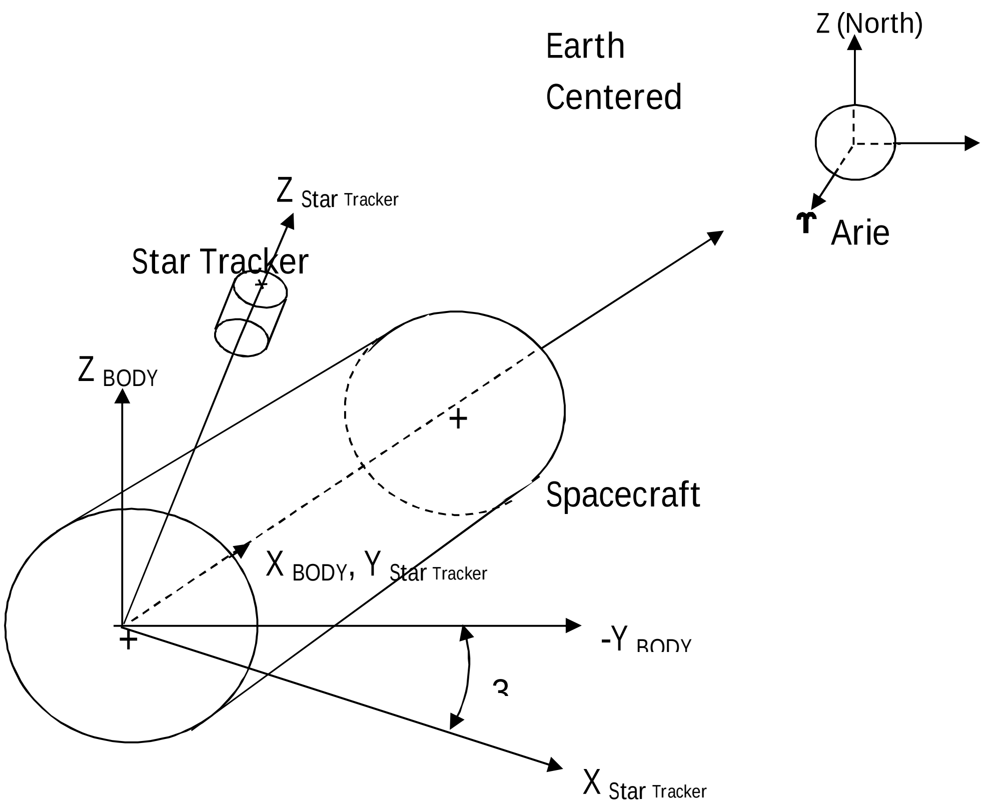


Figure 1 shows the spacecraft body and star tracker Cartesian coordinate systems in the J2000 reference. For clarity, the coordinate systems are shown with origins at the center and behind the cylinder representing the spacecraft. In fact, the origins are displaced because the star tracker and the EPIC instruments are mounted on the sides of the spacecraft. When the large distance between the spacecraft and the Earth or Moon is considered, these translations have no practical consequence.

## Attitude Matrix Computation

The Star Tracker instrument mounted on the spacecraft generates coarse attitude information. The Star Tracker examines the star field and computes its orientation in J2000 Coordinates. The spacecraft Attitude and Control System corrects the orientation for stellar aberration and other effects and generates attitude data referencing the spacecraft body. These data are expressed as quaternions in the spacecraft downlink. Quaternions are hyper-imaginary (in this case normalized) numbers expressed as a 4-tuple. Each quaternion may be written as an equivalent attitude matrix.

The required attitude matrix describes the orientation DSCOVR EPIC instrument optical sensing array in J2000 Coordinates. The problem here is to construct, from the quaternions, an attitude matrix mapping the optical array coordinates to J2000.

### *Quaternion Interpolation*

DSCOVR traces a Lissajous orbit about the L1 Lagrangian point every 6 months, and because thermal management requires a specific orientation with respect to the Sun, the spacecraft also rotates approximately two degrees each day. Because the spacecraft is in constant motion, the quaternion just before the image exposure and the quaternion just after the exposure are interpolated to the instant of exposure to give the best attitude estimate. The interpolation approach taken here is to compute the Euler Angle between the two quaternions and interpolate this scalar quantity to the instant of exposure

If :

$q(t_1)$ is the quaternion at a time just before the image exposure and ,
$q(t_2)$ is the quaternion at a time just after the image exposure,

then

$$q(t_2) = q(t_1 \to t_2) \circ q(t_1)$$

and

$$q(t_2) \circ q(t_1)^{-1} = q(t_1 \to t_2)$$

where $q(t_1 \to t_2)$ is a quaternion expressing the rotation from $q(t_1)$ to $q(t_2)$ and “ $\circ$ ” is the quaternion multiplication operator. The negative superscript indicates the quaternion inverse.

### Centroid Algorithm

The spacecraft Attitude and Control System will provide the angular orientation of DSCOVR. The pointing accuracy can be improved, however, by using a centroid algorithm to examine the image pixels and locate the center of the earth or moon disk in each image. The procedure uses an intensity threshold to distinguish the earth disk limb from the dark cosmic background

Conceptually, the algorithm constructs spokes radiating from the center of a nominal ellipse computed to be the approximate size and shape of the Earth image. Then algorithm determines the segment length along each spoke between the edge of the Earth disk and the ellipse. The location of the ellipse center is adjusted in iterative steps to minimize the differences in segment lengths. This minimal point is the

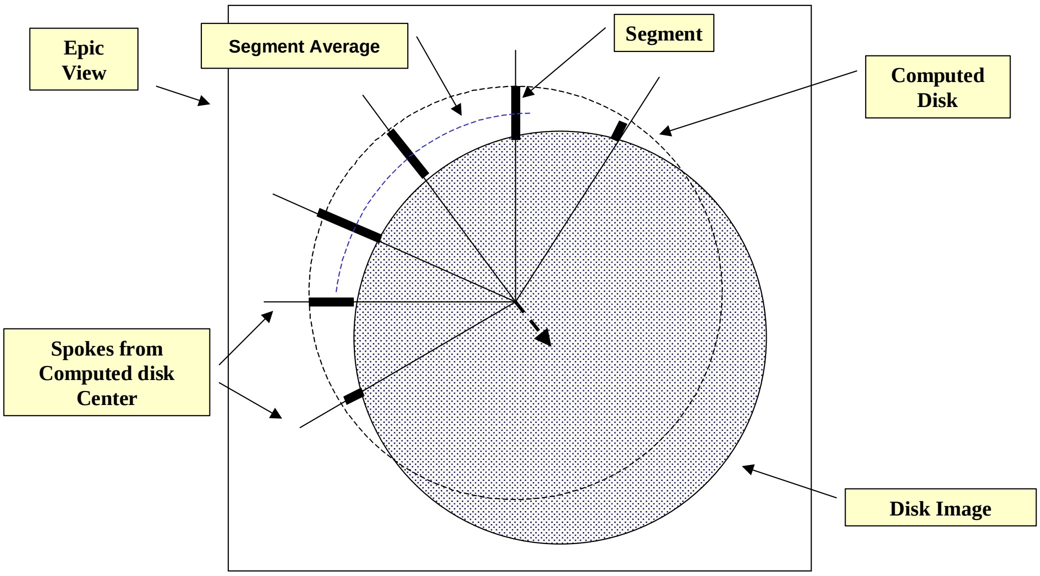


**Figure 2 Centroid Method**

center of the disk image.

Because the DSCOVR will generally be between 4 and 15 degrees away from the Earth Sun line, the spacecraft will view the terminator and therefore see a gibbous Earth. Also, occasionally, the Moon will be visible on the earth limb. These regions of distortion in the earth image must be removed from consideration when computing the image center and are determined from solar and lunar ephemeris files.

#### *Centroid Procedure*

The procedure searches spokes radiating from the center of the centroid ellipse and determines the segment along each spoke between the edge of the Earth disk and the ellipse. The edge is detected by searching the spoke in sets of 2 X 2 pixel squares. If a pixel is above a threshold and the diagonal pixel is below the threshold, then the edge is detected.

The spokes lie within the list of arcs where the Earth limb is expected to be undistorted by the gibbous effect or lunar occlusion. For each spoke, the x and y deviation from the arithmetic mean of all segments is computed. The mean of all x deviations and the mean of all y deviations are used to adjust the location of the ellipse in iterative steps to minimize the differences in segment lengths. This minimal point is the center of the disk image. See Fig 3.

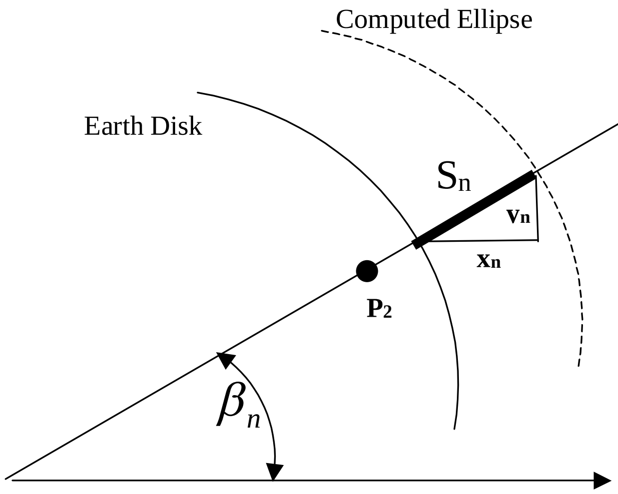


Figure 3 Along each spoke, n, with an angle $\beta_n$, beginning with point P1 and ending at point P2, the spoke is searched for the Earth limb. See **Error! Reference source not found.**. The Earth limb may be on either side of the computed ellipse. If the limb is not found, then the spoke is not considered further. Otherwise, the segment is included in the average:

The Attitude and Control System provides DSCOVR's attitude aboard the spacecraft. However, the knowledge of pointing accuracy can be improved if the EPIC disk image center is known. This is because the spacecraft position is accurately determined by ranging methods and the position vector must pass through the Earth at the point in the image center.

The earth's diurnal rotation presents a different geographic region to the EPIC instrument at any arbitrary instant. To compute the geodetic coordinates of an image pixel, the earth's angular orientation must be computed for the moment of exposure. The rotation angle is measured from the Greenwich Meridian to a point on the background of fixed stars called the First Point of Aries. The earth's rotation is not constant. Gravitational coupling with the sun causes the rotation axis to wander (precession) in a circle over a period of about 26,000 years. In the same way, lunar gravitational coupling causes the earth's rotation axis to "nod" (nutation) over a period of about 18.6 years. Further, the First Point of Aries is not truly fixed or inertial; it shifts slowly westward. The rotation model must consider these motions.

From the angular orientation of the DSCOVR EPIC axis provided by the attitude matrix and the spacecraft position, the location algorithm determines the intersection of the EPIC axis with an oblate spheroid approximation to the earth (or lunar surface). Essentially, this involves solving a quadratic equation for the distance along the scanner axis to the spheroidal surface.

**Grid Generation**

The latitude and longitude grid is generated by first computing the centroid-corrected attitude matrix and rotating it to Earth-fixed or lunar-fixed coordinates. A similar transform converts the spacecraft position to the appropriate coordinate system and the spacecraft attitude matrix and position are used to initialize the osition are used to initialize the geolocation procedure. The geodetic locations are computed by line and pixel in a nested loop by converting these raster coordinates to angular displacements and then calling the geolocation procedure.

## Conversion To Selenographic Coordinates

DSCOVR lunar image pixels are assigned selenographic coordinates in a process analogous to geolocation. The spacecraft position is first translated from geocentric to selenographic coordinates. The required lunar ephemerides are provided externally. A lunar rotation model replaces the Earth rotation model. Gravitational coupling constrains the moon to present the same general face to the Earth, but the moon also wobbles and these fluctuations or librations must be considered.

**Program Description**

The geodetic and lunar location software is a single executable program for generating Earth and Lunar grids of DSCOVR EPIC images. The program is designed to execute under ITOS but may be invoked manually or by a script supplying the required command line parameters. With each execution, the program reads a calibrated a calibrated DSCOVR EPIC image file, several metadata files and generates a grid file for the Earth.

The program command line provides values for those parameters expected or likely to change between program executions. A configuration file enables some parameters to be modified without re-compiling the program. Each execution also generates a log file containing status information useful for isolating anomalies. Status information is written to the ITOS operator's log through the ITOS event mechanism and an exit code is returned to ITOS.

The command line can specify "normal", "lunarcal" or "starfield" execution modes. Normal mode assumes that the spacecraft EPIC instrument is aimed toward the Earth and is viewing a full disk image. A centroid procedure determines the Earth disk image center to improve location accuracy, and the program generates a grid file containing the geodetic coordinates for each pixel illuminated by the Earth disk. If the Moon is in view, a second grid file containing selenographic coordinates of those pixels illuminated by the moon is also generated.

Lunarcal mode assumes that the EPIC is aimed at the Moon for radiometric calibration. The centroid procedure determines the center of the lunar disk image. In this mode, the Earth is not visible and only a lunar grid file is generated.

In normal mode, the gibbous region of the Earth and any portions of the Earth limb occluded by the Moon are determined from the ephemerides. These regions are discarded and the remaining portions of an arc circumscribing the Earth or lunar disk image are passed as a list to the centroid procedure. The steps are similar in lunar mode except that the Earth will not occlude the lunar limb.

The centroid procedure improves geolocation accuracy by determining the center of the disk image. The procedure reads the calibrated image file and stores a sub sampled image map. The parameters of a centroid ellipse matching the Earth disk image are computed from the ephemerides. Because the attitude of the spacecraft is not precisely known, the centroid ellipse will not generally coincide with the disk image. Selected radii from the ellipse center are searched for intersection with the Earth limb. Radii in the gibbous region or where the Moon occludes the Earth limb are not considered. A direction is computed which reduces the deviations of the radii from an average and the process is repeated until the deviations are minimized. The computed centroid ellipse center then overlays the image center.

A correction matrix to improve the attitude knowledge of the spacecraft is computed from the image center location determined by the centroid procedure and the spacecraft position vector. The spacecraft position vector must pass through the Earth region at the disk image center; therefore the EPIC should look in a direction opposite the position vector when viewing the image center. The correction matrix is computed to make this true.

When in normal mode the DSCOVR is viewing the Earth. However, the earth's diurnal rotation presents a different geographic region to the EPIC instrument at any arbitrary instant. To compute the geodetic coordinates of an image pixel, the Earth's angular orientation or Greenwich Hour Angle must be computed for the moment of exposure, and the rotated by this amount relative to DSCOVR. This is equivalent to transforming the spacecraft position vector and attitude to Earth-fixed coordinates.

Alternatively when the program is in lunarcal mode the spacecraft is viewing the Moon, and the program is required to generate selenographic coordinates, and the spacecraft vector and attitude must be transformed to Moon-fixed, Luna centric coordinates. A somewhat complex procedure [Error! Bookmark not defined.] first computes a rotation matrix transforming J2000 coordinates to selenographic, and then the DSCOVR position vector and attitude matrix are mapped to the selenographic system.

The location procedure computes the geodetic or selenographic location of a pixel from the spacecraft position and attitude. Euler Angle rotations computed from pixel coordinates point a unit vector along the optical axis of the pixel. The unit vector is then mapped to J2000 coordinates by the attitude matrix. The intersection with the Earth modeled as an oblate spheroid is then computed in the same system.

The grid generator uses the location procedure to calculate the latitude and longitude of those pixels viewing the Earth or when performing lunar calibration, the Moon. Those pixels not viewing the Earth are set to a unique value. The grid file also includes a header containing parameters useful for reconstructing the grid.

In normal operation, the program is expected to be invoked by Integrated Test & Operations System (ITOS). ITOS is a production data process manager responsible for staging the input and output program files and calling the requisite programs during DSCOVR data acquisition and image processing. ITOS gives the program file and path names and other parameters through the command line. The program returns messages to the ITOS Operator's Log using the ITOS interface.

A status handler processes all program events. Program events must be defined before being posted. The definition optionally configures the event to write text to the ITOS Operator's log, write text to the local log, or terminate the program with a specified exit code. Posted events not terminating the program are stacked and written just prior to program termination.

The use of the geolocation program will produce all 10 wavelength channels on a common grid suitable for use in deriving geophysical quantities that require input from radiances at multiple wavelengths.