### Solar and View Angle Generation Algorithm

#### Background/Introduction

Landsat 8/9 Level 1T (and 1GT) products (henceforth referred to as L1T products) provide radiometrically and geometrically corrected geolocated image samples for each spectral band. These samples are 16-bit fixed point numbers that can be related to either at-sensor radiance or reflectance using parameters provided in the product metadata. The L1T samples are also precisely registered to a UTM (or polar stereographic) map projection grid which makes it straightforward to construct pixel ground coordinates from the product corners.

For some applications additional information about the scene geometry is needed, including elevation, slope/aspect, sensor viewing angles (elevation and azimuth), and/or solar illumination angles. This algorithm provides a method for generating per-pixel sensor viewing and solar illumination angles for L1T products by providing enhanced metadata, containing selected information from the geometric model and resampling grid, and associated logic for using the new metadata to compute the required angles.

The Operational Land Imager (OLI) and Thermal InfraRed Sensor (TIRS) payloads on the Landsat 8/9 mission are both pushbroom imagers with focal planes that span the full Landsat swath width. Full swath coverage is achieved by using multiple sensor chip assemblies (SCAs) across-track, with sufficient overlap between adjacent SCAs to avoid coverage gaps. This SCA-to-SCA overlap is achieved by displacing alternate SCAs along-track so that adjacent SCAs can cover overlapping portions of the across-track field of view. For the OLI, which uses 14 SCAs to cover the full swath, the 7 odd SCAs (1 through 13) are arranged to point slightly forward of nadir and the 7 even SCAs (2 through 14) are arranged to point slightly aft. Similarly for TIRS, the central SCA-C points forward while the outboard SCAs (A and B) point aft. The layout of the OLI focal plane is shown in Figure 6‑17 below.



Figure 6‑17 OLI Focal Plane Layout

Figure 1 raises a problem of terminology. Ball Aerospace uses the term SCA for just the detector and ROIC chips (without filters) and refers to the complete unit as a focal plane module (FPM). The TIRS developers used SCA to refer to the entire assembly, while the FPM acronym had an entirely different meaning. The Cal/Val team decided to adopt SCA as the standard terminology for both instruments.

A key challenge in analyzing the viewing geometry for both the OLI and TIRS sensors is the along-track offset between adjacent SCAs as this focal plane geometry leads to discontinuities in the viewing geometry at SCA boundaries. The view angle changes occasioned by the alternating even/odd SCA geometry would make it difficult to fit a simple function to the not-very-smooth angle patterns. This argues for generating and storing the view angles for each pixel. On the other hand, the along-track distribution of the spectral bands, also shown in figure 1, ensures that the viewing angles will be different for each spectral band. Explicitly representing the angles for each pixel in each band would thus be space prohibitive as the angle file would be larger than the L1T product. These considerations led to a compromise solution, described herein, that uses multiple rational polynomial functions to model the viewing geometry for each band on each SCA. These functions are implemented in an exploitation tool that uses scene-specific parameters, stored in enhanced metadata, to generate viewing angles on demand.

The algorithm is thus implemented in two parts. The first part, intended to run in the IAS/LPGS environment at product generation time, uses the geometric model and grid files used to create the L1T product, to build an additional “enhanced” metadata file that accompanies the product. This new file captures the elements of the scene geometry needed to subsequently calculate the solar illumination and sensor viewing angles for each active (i.e., those that contain OLI or TIRS image data) product pixel. The second part of the algorithm uses the new enhanced metadata file to compute these angles. This part is intended to be implemented as a standalone software tool that would be provided to the user community. Two versions of this tool are provided: an experimental version that supports multiple processing options and a simpler operational prototype that provides only basic angle generation capability.

#### Dependencies

The angle generation algorithm assumes that the standard L1T geometric modeling algorithms have run successfully and that the geometric model, geometric grid, and calibration parameter files used to create the L1T product are available. The angle computation algorithm can optionally use an input elevation model for improved accuracy. If provided, this model must match the scene frame (corners, projection, pixel size) of the L1T product multispectral bands.

#### Inputs

The solar and view angle generation algorithm and its component sub-algorithms use the inputs listed in the following table.

|  |
| --- |
| **Algorithm Inputs – Enhanced Metadata Generation** |
| Geometric Grid File |
|  Scene Framing Information: |
|  Scene corner coordinates |
|  Scene map projection information: |
|  Projection GCTP code: 1 = UTM, 6 = Polar Stereographic |
|  UTM zone number (1-60) |
|  GCTP map projection parameters |
|  Datum and spheroid codes (WGS84) |
| Geometric Model File |
|  WRS path and row (orbital, for use in output file name construction) |
|  Image times |
|  Spacecraft ephemeris (position vs. time) |
| Calibration Parameter File |
|  Earth model parameters |
|  WGS84 ellipsoid parameters |
|  Earth orientation parameters (UT1-UTC offset, pole wander) |
|  Leap second table |
| NOVAS solar ephemeris (sun ECITOD direction vs. time) |
|  |
| **Algorithm Inputs – Angle Computation** |
| Enhanced Metadata File – see output table below for contents |
| DEM File (optional) |
|  WGS84 ellipsoid height (in meters) for each 30-meter pixel in the L1T product |
| Subsampling Factor (optional) |

#### Outputs

The solar and view angle generation algorithm outputs are shown in the following table. See Table 1 below for more detail contents of the output enhanced metadata file.

|  |
| --- |
| **Algorithm Outputs – Enhanced Metadata Generation** |
| Enhanced Metadata File |
|  File Header  |
|  Enhanced metadata file name |
|  Satellite ID |
|  WRS path and row (orbital) |
|  List of bands included |
|  Projection Information |
|  Ellipsoid parameters |
|  Projection type/code |
|  Projection units (meters) |
|  Projection spheroid and datum (WGS84) |
|  UTM zone number |
|  GCTP projection parameters |
|  L1T product projection corners |
|  Ephemeris Data |
|  UTC epoch (year, day of year, seconds of day) |
|  Number of ephemeris points |
|  Time from epoch for each point |
|  ECEF X, Y, and Z position for each point |
|  Solar Vector Data |
|  UTC epoch (year , day of year, seconds of day) |
|  Number of solar vectors provided |
|  Time from epoch for each vector |
|  ECEF X, Y, and Z directions for each vector |
|  Rational Polynomial Coefficient Data for each Band |
|  Number of SCAs |
|  Number of lines and samples in L1T product |
|  Number of lines and samples in L1R input (full scene) |
|  L1T pixel size (in meters) |
|  Image start time relative to ephemeris epoch |
|  Image line time (time between lines) |
|  Mean height in scene |
|  Mean L1R line/sample coordinates in scene |
|  Mean L1T line/sample coordinates in scene |
|  Mean satellite viewing vector components (local east-north-vertical coordinates) |
|  Rational polynomial numerator coefficients for the viewing vector X component |
|  Rational polynomial denominator coefficients for the viewing vector X component |
|  Rational polynomial numerator coefficients for the viewing vector Y component |
|  Rational polynomial denominator coefficients for the viewing vector Y component |
|  Rational polynomial numerator coefficients for the viewing vector Z component |
|  Rational polynomial denominator coefficients for the viewing vector Z component |
|  Mean solar illumination vector components (local east-north-vertical coordinates) |
|  Rational polynomial numerator coefficients for the solar vector X component |
|  Rational polynomial denominator coefficients for the solar vector X component |
|  Rational polynomial numerator coefficients for the solar vector Y component |
|  Rational polynomial denominator coefficients for the solar vector Y component |
|  Rational polynomial numerator coefficients for the solar vector Z component |
|  Rational polynomial denominator coefficients for the solar vector Z component |
|  List of SCAs in current band |
|  Rational Polynomial Coefficient Data for each SCA |
|  Mean height in SCA |
|  Mean L1R line/sample coordinates in SCA |
|  Mean L1T line/sample coordinates in SCA |
|  Rational polynomial numerator coefficients for L1R line coordinate |
|  Rational polynomial denominator coefficients for L1R line coordinate |
|  Rational polynomial numerator coefficients for L1R sample coordinate |
|  Rational polynomial denominator coefficients for L1R sample coordinate |
|  |
| **Algorithm Outputs – Angle Computation** |
| Satellite Viewing Angle File for each Band |
|  Viewing zenith angle for each L1T pixel (unless subsampled) |
|  Viewing azimuth angle for each L1T pixel (unless subsampled) |
|  Zenith and azimuth “bands” are sequential |
|  Zenith and azimuth angles are stored as 16-bit integers scaled to units of 0.01 degrees |
| Satellite Viewing Angle (ENVI) Header File (one per angle file)  |
|  Number of lines and samples in angle file |
|  Number of bands in angle file (2) |
|  Data type (signed 16-bit integer) |
|  Interleaving type (BSQ) |
|  Projection information |
|  Projection type (UTM or PS) |
|  UTM zone/PS projection parameters |
|  Output angle file pixel size (in meters) = L1T pixel size \* subsampling factor |
|  UL corner coordinates |
| Solar Angle File for each Band |
|  Solar zenith angle for each L1T pixel (unless subsampled) |
|  Solar azimuth angle for each L1T pixel (unless subsampled) |
|  Zenith and azimuth “bands” are sequential |
|  Zenith and azimuth angles are stored as 16-bit integers scaled to units of 0.01 degrees |
| Solar Angle (ENVI) Header File (one per angle file)  |
|  Number of lines and samples in angle file |
|  Number of bands in angle file (2) |
|  Data type (signed 16-bit integer) |
|  Interleaving type (BSQ) |
|  Projection information |
|  Projection type (UTM or PS) |
|  UTM zone/PS projection parameters |
|  Output angle file pixel size (in meters) = L1T pixel size \* subsampling factor |
|  UL corner coordinates |

#### Options

Angle computation can work with or without elevation data input.

The output angle “bands” can be optionally subsampled.

#### Procedure

The primary tasks performed by the solar and view angle generation algorithm are to:

1. At product generation time: create an enhanced metadata file that contains all of the information a user needs to calculate per-pixel solar illumination and sensor viewing angles for each band in the L1GT/T data product.
2. On demand for the user: use the enhanced metadata file to generate solar illumination and sensor viewing angles that correspond to the L1GT/T product pixels.

**Phase 1: Generate Enhanced Metadata File**

Central to the ability to compute the satellite viewing or solar illumination geometry for a particular L1T image pixel is the ability to associate that pixel with its time of observation. Once the time is known, it can be used to calculate the spacecraft position, from which the sensor viewing geometry is derived, and the solar direction, from which we calculate sun angles. The key to mapping output product image pixels to imaging time is to reconstruct the relationship between the resampled L1T product pixels and the unresampled L1R calibrated detector samples from which they are derived, since there is a simple linear relationship between L1R line number and time. The L1R to L1T mapping can be calculated from the geometric model. To facilitate efficient L1T product generation, this relationship is stored in the geometric grid file for an array of points spanning the image bounds. The goal here is to formulate a set of equations that represent, in a compact form, the input space (Level 1R) line/sample to output space (Level 1T) line/sample mappings contained in the geometric grid file. Experimentation has shown that sub-pixel accuracy in the L1T line/sample to L1R line/sample mapping can be achieved using rational polynomial functions of the following form:

Where:

 L1TL = L1TLine – L1TMeanLine

 L1TS = L1TSample – L1TMeanSample

 Hgt = Height – HeightMean

 a0 to a4, b1 to b4, c0 to c4, and d1 to d4 are model coefficients.

One set of rational polynomial coefficients (RPCs) is computed for each band on each SCA using the information in the geometric grid file. For the OLI, there are thus 23 model parameters (18 polynomial coefficients plus 5 mean offsets) per band/SCA. With 14 SCAs and 9 bands, this results in a total of 2898 model constants per scene. For the TIRS, there are 23 model parameters / band / SCA \* 3 SCAs \* 2 bands for a total of 138 additional model constants. This is a large but manageable number. Note that five model parameters; the mean values of the input and output coordinates; are added to reference the rational polynomial formulation to the center of the band/SCA area covered by the functions. This helps provide numerical stability in the least squares solution for the model coefficients.

*Calculating the Model Coefficients*

 The geometric grid file contains a set of three-dimensional arrays of L1R to L1T pixel mappings, one for each band on each SCA. The array axes are L1R line, L1R sample, and height, with each array point corresponding to one L1R line / L1R sample / height triplet. This is depicted in figure 2. The L1T line / sample location corresponding to each triplet is computed using the line-of-sight projection model and the selected output L1T scene frame, and the results are stored in the grid structure for subsequent use during image resampling. The grid thus provides all of the information required to solve for the rational polynomial model coefficients.



**Figure 2: Geometric Grid Structure**

All of the grid points for a given band/SCA are used to solve for the model coefficients for that band/SCA. Calculating the mean L1R line, L1R sample, L1T line, L1T sample, and height values is straightforward. The model coefficients are determined by a least squares solution. To accomplish this, the rational functions are linearized by multiplying the denominator by the left hand side and rearranging terms as follows:

 (3)

 (4)

Where:

 L1RL = L1RLine – L1RMeanLine

 L1RS = L1RSample – L1RMeanSample

One pair of equations of this form can be constructed for each grid point. Standard least squares techniques are used to solve for the nine coefficients in each equation.

*Constructing the Enhanced Metadata*

The sequence of activities required to assemble the information required to build the enhanced metadata file is as follows:

1. Open and read the input data files:
	1. Load the geometric model from the LOS model file.
	2. Load the geometric grid from the grid file.
	3. Load the Earth model parameters from the CPF.
	4. All of these operations are accomplished using standard IAS library input/output modules.
2. Initialize the Earth model:
	1. Initialize the IAS time conversion library functions using the leap second table read from the CPF.
	2. Store the WGS84 ellipsoid semi-major and semi-minor axes from the CPF in the enhanced metadata (EMETA) structure.
3. Get path/row, ephemeris, and sun vector information from the geometric model.
	1. Store the WRS path and row from the model in the EMETA structure.
	2. Extract ephemeris data covering the current scene from the geometric model.
		1. Using the ephemeris start time (UTC epoch) as a reference, calculate the time offsets to the first and last line in each band by invoking the ias\_math\_get\_time\_difference utility.
		2. Determine the earliest band start time (this will normally be the TIRS bands) and latest band end time.
		3. Subtract 8 seconds from the earliest start time and add 8 seconds to the latest end time to get the target time bounds for extracting ephemeris data to cover the scene.
		4. Find the index of the first ephemeris point with a time after the target start time and the index of the last ephemeris point with a time before the target end time.
		5. Establish a new ephemeris epoch at the time of the first sample to be extracted.
		6. Load the time (adjusted for the new epoch) and ECEF position fields for the selected ephemeris points from the model into the EMETA structure.
	3. Use NOVAS to compute ECEF sun vectors at the ephemeris sample times.
		1. Initialize the NOVAS solar ephemeris package.
		2. For each ephemeris point:
			1. Construct the full UTC time by adding the point’s time offset to the ephemeris UTC epoch.
			2. Convert the UTC year and day of year to month and day.
			3. Use the year, month, day, and seconds of day to compute the Julian day required by NOVAS.
			4. Invoke NOVAS to compute the ECI true-of-date solar direction vector at the specified Julian day.
			5. Use IAS library routines to convert the ECITOD sun vector to ECI of epoch J2000 (by applying nutation and precession models). Note that the IAS library ECEF/ECI coordinate transformation routines also invoke NOVAS.
			6. Use IAS library routines to convert the ECIJ2000 sun vector to ECEF, including the pole wander and UT1-UTC corrections from the geometric model.
			7. Load the time and ECEF solar unit vector into the EMETA structure.
		3. Shut down the NOVAS package.
4. Get map projection and scene corner information from the geometric grid.
	1. Load the projection code, units, zone, spheroid, datum, and GCTP map projection parameter fields from the grid into the EMETA structure. These parameters are needed to convert map X/Y to geodetic latitude/longitude.
	2. Load the scene corner map projection coordinates from the grid into the EMETA structure. The corners are needed to convert L1T line/sample to map projection X/Y.
5. Initialize the IAS library map projection logic.
	1. Construct a map projection structure using the parameters loaded in the EMETA structure, by invoking the ias\_geo\_set\_projection module.
	2. Construct a geodetic projection structure to produce latitude/longitude coordinates in radians, using the ias\_geo\_set\_projection module.
	3. Construct a projection transformation that converts map X/Y to geodetic latitude/longitude using the structures from a. and b. above, and the ias\_geo\_create\_proj\_transformation module.
	4. Pre-establishing this transformation will make subsequent map projection conversion computations easier.
6. Assemble the band-specific enhanced metadata fields for each band.
	1. Load the band number, number of SCAs, number of L1T lines/samples, and pixel size from the grid into the EMETA structure.
	2. Load the number of L1R lines/samples, band start time, and line increment time (sampling time) from the geometric model into the EMETA structure.
	3. For each SCA, record the SCA number in the EMETA structure and calculate the coefficients of the L1T-to-L1R RPC model described above.
		1. Compute the mean height of the grid points as:

Mean\_hgt = (num\_Zplanes – 1 – 2\*zeroplane)\*Zspacing/2

* + 1. Compute the mean L1R line and sample values by cycling through the grid in\_lines and in\_samps arrays.
		2. Compute the mean L1T line and sample values by cycling through the grid point out\_lines and out\_samps arrays.
		3. Loop through all the points in the grid for this band/SCA to construct the normal equations:
			1. The form of the observations is shown in equations (3) and (4) above. Each grid point yields one line and one sample observation, expressed in matrix/vector notation:

Where:

* + - 1. Each observation of each type (line or sample) contributes to the normal equations:

 and

Where we have accumulated the N and L matrices as:

* + 1. Once the observation contributions from all of the grid points are collected into the normal equation matrices, we solve for the unknown rational polynomial coefficient vectors L and S:

* + 1. This procedure generates a set of L1T-to-L1R RPCs for each SCA in the band.

The procedure described thus far provides everything necessary to support the computation of the required view and sun angles: a mechanism for relating L1T product line/sample to L1R line/sample which yields time of observation; the ECEF position of the spacecraft as a function of time; the ECEF direction to the sun as a function of time; and the scene framing and projection information needed to convert L1T line/sample to map X/Y, then to geodetic (optionally including height from an input DEM), and finally to ECEF. Though feasible, this approach requires the application of multiple complex coordinate transformations for every pixel in the L1T product. Experiments with this approach to generating view and sun angles demonstrated that, while angle accuracies of 1 arc-minute or better can be achieved if terrain data are included, the required computations are rather time consuming. On the IAS development platform, generating satellite viewing and solar illumination zenith and azimuth angles for every imaged pixel in all bands required 40-45 minutes of processing time. In an effort to reduce this processing time, a more computationally efficient alternative was developed.

*Rapid Angle Computation*

In the alternate approach, a second-tier rational polynomial model is fitted directly to the satellite and sun unit viewing vectors making it possible to compute them directly. This circumvents the need for complex map projection and geodetic computations involving trigonometric functions. Unit vector components, rather than the angles themselves, are fitted to avoid the +/-180 degree azimuth discontinuity.

The second-tier “angle” rational polynomial functions, one set per band, are more complicated than the first-tier per-SCA L1T-to-L1R rational functions, because they must account for the SCA-to-SCA discontinuities. This is achieved by including both L1T and L1R input terms in the formulation. The RPC model equation for the satellite viewing unit vector X component is:

Where:

 L1TL = L1TLine – L1TMeanLine

 L1TS = L1TSample – L1TMeanSample

 Hgt = Height – HeightMean

 L1RL = L1RLine – L1RMeanLine

 L1RS = L1RSample – L1RMeanSample

a0 to a9, and b1 to b9, are the RPC model coefficients.

There are similar models for SatY, SatZ, SunX, SunY, and SunZ.

The terms included in these equations were determined by experimentation to minimize the rational polynomial model fit residuals. Note that in order to use these models it is necessary to first evaluate the L1T-to-L1R RPC model to determine the values for L1RL and L1RS.

The final steps in the assembly of the enhanced metadata file are to compute these “angle” rational polynomial model coefficients, using a procedure much like that described in step #6 above, and to write out the enhanced metadata ODL file:

1. Calculate the direct angle RPCs for each band.
	1. Calculate the satellite viewing vector and the solar illumination vector in the local vertical coordinate system at each point in the geometric grid.
		1. Extract the height (from the grid Z-plane), L1R line/sample, and L1T line/sample for the current point from the grid structure.
		2. Use the L1T corners and pixel size to convert L1T line/sample to map X/Y:

X = upleft\_X + L1TS \* pixel\_size

Y = upleft\_Y – L1TL \* pixel\_size

Note that this assumes projection north-up products, which all L8/9 L1T products currently are. This could be made more elaborate to support path-oriented products if necessary since all four scene corners are included in the enhanced metadata.

* + 1. Use the (already initialized) map projection transformation to convert map X/Y to latitude/longitude using IAS library functions. These functions implement the map projection algorithms documented in, “Map Projections – A Working Manual” by John P. Snyder, USGS Professional Paper 1395, U.S. Government Printing Office, Washington, DC, 1987.
		2. Convert geodetic latitude, longitude, and height (from the grid) to ECEF X, Y, Z using IAS library functions. The details of the geodetic to ECEF transformation are described in the OLI Line-of-Sight Projection/Grid Generation Algorithm Description Document. This yields the ground point ECEF vector GECEF.
		3. Calculate the local vertical coordinate system basis vectors from the latitude and longitude:

 East in ECEF

 North in ECEF

 Up in ECEF

* + 1. Calculate the time of observation from the L1R line:

Time = Band Start Time + L1RL \* Line Time

* + 1. Interpolate the spacecraft ECEF X, Y, Z position at the time of observation using 4 point Lagrange interpolation. This is implemented using IAS library functions, and yields the spacecraft ECEF vector SECEF.
		2. Calculate the ground-to-space viewing vector:

VECEF = SECEF - GECEF

* + 1. Project the ECEF viewing vector into the local vertical coordinate system:

This is equivalent to taking the dot product of the ECEF viewing vector with each of the local vertical system basis vectors.

* + 1. Interpolate the ECEF sun direction vector at the time of observation using 4 point Lagrange interpolation. This is the same functionality used for the ephemeris data.
		2. Project the sun direction ECEF vector into the local vertical coordinate system as was done in step ix above, to yield the local vertical sun direction vector SLV.
	1. As each grid point is processed, accumulate the sums of and then calculate the average values for the height, L1R line, L1R sample, L1T line, L1T sample, view vector X, Y, Z coordinates, and sun vector X, Y, Z coordinates.
	2. For each component of the viewing vector VLV and the sun vector SLV, compute the coefficients of a RPC model of the form shown above in equations 5a, 5b, and 5c.
		1. Loop through all the vectors (each corresponding to a point in the grid) for this band to construct the normal equations:
			1. The form of the observations is shown in equations (5a), (5b), and (5c) above. Each grid point yields one observation, expressed in matrix/vector notation:

Where:

Note that all of the L1T, L1R, height, and vector component inputs above are offset by the means as shown in equation (5).

* + - 1. Each observation contributes to the normal equations:

Where we have accumulated the N and L matrices as:

* + 1. Once the observation contributions from all of the grid points are collected into the normal equation matrices, we solve for the unknown rational polynomial coefficient vectors L and S:
	1. This procedure is run six times, on the X, Y, and Z components of the view vector (Satx, Saty, and Satz) and on the X, Y, and Z components of the sun vector (Sunx, Suny, and Sunz). This generates a set of L1T-to-angle RPCs for the band.
	2. Load the angle RPC model coefficients into the EMETA structure.
1. Write the EMETA structure to an output ODL formatted enhanced metadata file.
	1. Construct the output file name from the path, row, and date. This will need to be enhanced to include ground station ID and version number for operational use.
	2. Write the FILE\_HEADER group containing the file name, satellite ID, path, row, number of bands and band list.
	3. Write the PROJECTION group containing the ellipsoid parameters, projection, units, datum, spheroid, and zone codes, the GCTP projection parameters, and the scene corner coordinates.
	4. Write the EPHEMERIS group containing the ephemeris data start UTC epoch, the number of points, and the time from epoch, ECEF X, Y, and Z coordinates (in meters) for each point.
	5. Write the SOLAR\_VECTOR group containing the start UTC epoch, the number of points, and the time from epoch, ECEF X, Y, and Z directions for each point. The times will match the ephemeris data so those values are somewhat redundant.
	6. Write an RPC\_BANDnn group for each band containing the number of SCAs, SCA list, number of L1T lines and samples, number of L1R lines and samples, pixel size, band start UTC epoch and line time increment, mean height, mean L1T line/sample, mean L1R line/sample, mean view vector components, view vector RPC model coefficients, mean sun vector components, and mean sun vector RPC model coefficients.
		1. For each SCA in the band, write the mean height, mean L1T line/sample, mean L1R line/sample, and the L1T-to-L1R RPC model coefficients.

The output enhanced metadata file contains all of the information needed by the phase 2 portion of the algorithm to generate satellite viewing and solar illumination angles for each L1T product pixel.

**Phase 2: Compute Satellite Viewing and Solar Illumination Angles**

The phase 2 experimental angle generation portion of the algorithm (simple\_view) provides two options for performing the angle computations. Both methods use the L1T-to-L1R RPC models to calculate the L1R coordinates that correspond to a given L1T pixel. Both methods will also retrieve the pixel height from an input DEM, if provided. Otherwise, the mean elevation for the band, from the enhanced metadata file, is used. Having been given the L1T line/sample and determined the corresponding L1R line/sample and height, the first, “rigorous”, method follows the procedure described above in step 7a of the phase 1 algorithm. The second, “RPC”, method applies equation (5) above using the parameters of the angle RPC model for the current band, stored in the enhanced metadata file. The simpler operational prototype version (l8\_angles) supports only the RPC and no-DEM options.

There are some subtleties to the use of the L1T-to-L1R RPCs that deserve some elaboration. Although the rational polynomial functions will generate L1R line and sample coordinates for any given L1T product pixel (and height), each SCA has a separate set of RPCs, so it is necessary to know which SCA the pixel falls inside to select the correct model parameters. Having only the L1T image to work with, we will know which band number to use, but not which SCA. This was the original reason for including an L1R sample RPC model. We can evaluate the L1R sample coordinates for each SCA in the current band to decide which SCA, or SCAs, the L1T pixel came from. At most 2 SCAs will return L1R sample values that fall within the actual range of samples on that SCA, thus identifying the set of rational polynomial coefficients to use to evaluate the L1R line coordinate. In SCA overlap areas two SCAs will be valid. Depending upon the accuracy required, either could be used to compute the time and angles. In practice, both are evaluated and averaged, since overlapping pixels are averaged when the L1T products are generated.

*Calculating Viewing and Solar Angles*

The sequence of activities required to generate satellite viewing angles and solar illumination angles for each L1T pixel using the enhanced metadata is as follows:

1. Capture the input command line parameters to determine which processing options to apply: RPC or rigorous computation, DEM input or mean height, subsampling factor.
2. Initialize the enhanced metadata interface using the inputs provided:
	1. Open the input enhanced metadata file and load the contents into an EMETA data structure.
	2. Initialize the map projection logic:
		1. Construct a map projection structure using the parameters loaded in the EMETA structure, by invoking the ias\_geo\_set\_projection module.
		2. Construct a geodetic projection structure to produce latitude/longitude coordinates in radians, using the ias\_geo\_set\_projection module.
		3. Construct a projection transformation that converts map X/Y to geodetic latitude/longitude using the structures from a. and b. above, and the ias\_geo\_create\_proj\_transformation module.
		4. Pre-establishing this transformation will make subsequent map projection conversion computations easier.
	3. Load the GeoTIFF formatted DEM, if one is provided.
		1. Read the header information and store in a data structure.
		2. Load the elevation array.
		3. If no DEM is provided or the DEM does not match the image dimensions specified in the enhanced metadata, set the elevation array to NULL.
	4. Get the number of bands from the EMETA structure and return this value to the calling procedure.
3. For each band:
	1. Extract the scene framing information from the EMETA structure.
		1. Extract the spectral band number, scene dimensions, map projection information (code, zone), pixel size, and upper-left corner coordinates from the EMETA structure. The projection information will be used to generate the output angle image header files.
	2. Calculate the size of the output angle images using the size of the L1T image and the subsampling factor:

Angle nlines = (L1T nlines – 1) / subsample + 1

Angle nsamps = (L1T nsamps – 1) / subsample + 1

* 1. Step through the L1T image pixels using the subsampling factor as a loop increment. Calculate the view and sun angles at each L1T line/sample location:
		1. Select the enhanced metadata for the current band.
		2. Calculate the subsampling relationship between the L1T image and the DEM:

DEM subsample = (L1T nlines – 1) / (DEM nlines – 1)

This is needed to properly index the DEM elevations when processing the panchromatic band.

* + 1. Calculate the DEM indices that correspond to the current L1T indices by dividing by the DEM subsample factor, noting that the indices are zero-relative.
		2. Extract the height from the DEM at the specified indices. If no DEM was provide, set the height to NULL.
		3. Calculate the angles using the selected method:
			1. Rigorous method – see below for details.
			2. RPC method – see below for details.
		4. Quantize the computed angles to units of 0.01 degrees.
	1. Write the angles to output band files:
		1. Calculate the angle band pixel size by multiplying the L1T pixel size by the subsampling factor.
		2. Construct the output file names using the EMD input file root name and the band number.
		3. Write the satellite zenith and azimuth angle values, band sequentially, to the satellite angle file.
		4. Write an ENVI-format header file for the satellite angles using the framing information extracted previously.
		5. Write the solar zenith and azimuth angles, band sequentially, to the solar angle file.
		6. Write an ENVI-format header file for the solar angles using the framing information extracted previously.
1. Shut down the enhanced metadata logic by releasing the allocated ephemeris data memory in the EMETA structure and in the map projection transformation structure.

*Computing Angles Using the Rigorous Method*

To compute the satellite viewing and solar illumination angles at a specified L1T line/sample location, given the corresponding elevation and enhanced metadata, using the rigorous method:

1. If the input height is NULL, replace it with the mean height from the band RPC parameters in the EMETA structure.
2. Determine which SCA, or SCAs, viewed the L1T pixel:
	1. If the last\_sca flag is invalid (e.g., for the first point calculated), start with the central SCA (isca = num\_sca /2), otherwise use isca = last\_sca.
	2. If the current SCA number (isca) is not valid (< 0 or >= num\_SCA), return the number of valid SCAs found so far. Otherwise, compute the L1T-to-L1R RPCs for the current SCA:
		1. Offset the input L1T line, L1T sample, and height by the mean values for this band/SCA.
		2. Evaluate L1R line and L1R sample using equations (1) and (2) above with the RPC coefficients for this band/SCA.
	3. If the computed L1R sample coordinate is between 0 and the number of L1R samples per SCA for this band.
		1. Increment the number of successful searches, ntry.
		2. If the L1R line number is between 0 and the number of L1R lines in the image:
			1. Store the calculated L1R line coordinate.
			2. Convert the L1R sample SCA coordinate to a L1R file coordinate, and store that also:

L1R\_file\_samp = L1R\_SCA\_samp + isca\*num\_samp\_per\_SCA

* + - 1. Increment the number of SCAs found.
		1. Set last\_sca = isca
		2. If we’ve found more than one SCA (ntry > 1) return the number found.
		3. If the L1R SCA sample number is below the SCA overlap threshold, decrement the current SCA index (isca) and go back to step b to test for a second overlapping SCA.
		4. If the L1R SCA sample number is within the SCA overlap threshold of the number of samples per SCA, increment the current SCA index (isca) and go back to step b to test for a second overlapping SCA.
		5. If the L1R SCA sample number is not within the potential overlap regions, return the number of SCAs found.
	1. If the L1R sample is out of range for the current SCA (i.e., the test in step c. above fails):
		1. If at least one SCA has already been found (ntry > 0) return the number found.
		2. If the L1R sample number is outside the image (< 0 for the first SCA or > number of samples for the last SCA), return the number of SCAs found.
		3. Calculate the L1R file sample number:

L1R\_file\_samp = L1R\_SCA\_samp + isca \* num\_samp\_per\_SCA

* + 1. Calculate the predicted SCA index:

isca = L1R\_file\_samp / num\_samp\_per\_SCA

isca = MAX( isca, 0 )

isca = MIN( isca, num\_SCA – 1)

* + 1. Go back to step b.
	1. This sub-algorithm returns the number of valid SCAs found and the corresponding L1R line and sample coordinates for each.
1. For each SCA found to contain the point, calculate the satellite and solar vectors:
	1. This procedure is described in step 7.a. of the phase 1 algorithm above with the exception of the first, height retrieval, sub-step. Here, the height is provided as an input.
2. Calculate the satellite and sun zenith angles corresponding to the vectors, clipping the zenith angles at the horizon (90 degrees):

if satvector.z > 0 then sat\_zenith = acos( satvector.z )

else sat\_zenith = 0

if sunvector.z > 0 then sun\_zenith = acos( sunvector.z )

else sun\_zenith = 0

1. Calculate the satellite and sun azimuth angles, setting the azimuth equal to zero if the vector is vertical:

hdist = sqrt( satvector.x\*satvector.x + satvector.y\*satvector.y )

if hdist > 0 then sat\_azimuth = atan2( satvector.x, satvector.y )

else sat\_azimuth = 0

hdist = sqrt( sunvector.x\*sunvector.x + sunvector.y\*sunvector.y )

if hdist > 0 then sun\_azimuth = atan2( sunvector.x, sunvector.y )

else sun\_azimuth = 0

1. Average the angles computed from the individual SCAs.

*Computing Angles Using the Rational Polynomial Coefficient (RPC) Method*

To compute the satellite viewing and solar illumination angles at a specified L1T line/sample location, given the corresponding elevation and enhanced metadata, using the RPC method:

1. If the input height is NULL, replace it with the mean height from the band RPC parameters in the EMETA structure.
2. Determine which SCA, or SCAs, viewed the L1T pixel. This procedure is the same as for the rigorous method and is described above. Note, however, that this sub-algorithm returns the L1R line and L1R file sample coordinates for each valid SCA. The L1R sample coordinate was not used in the rigorous method, but will be here.
3. Offset the L1T line, L1T sample, and height values by the mean values for the current band.
4. For each valid SCA:
	1. Offset the L1R line and L1R sample coordinates by the mean values for the current band.
	2. Use the offset values and the angle RPC model parameters for this band to evaluate equations (5a), (5b), and (5c) above for each component of the satellite viewing vector and each component of the solar illumination vector.
	3. Calculate the angles corresponding to the resulting vectors using the methods described in steps 4 and 5 of the rigorous method, above.
5. Average the angles computed from the individual SCAs.

*Enhanced Metadata Output File*

The detailed contents of the enhanced metadata (EMD) file are shown in Table 1 below. Note that although some of the fields in the EMD file duplicate information found in the standard L1T product metadata (MTA) file, this was done intentionally to make the EMD file self- contained. In some cases, different parameter names are used in the EMD file. In a production implementation it may be desirable to harmonize the parameter names or even combine the metadata files into one. Such decisions are beyond the scope of this algorithm.

The EMD file is ODL structure text and consists of 15 parameter groups: a file header group, a projection group, an ephemeris group, a solar vector group, and one group of RPC model parameters for each of the 11 spectral bands.

| **Group** | **Parameter** | **Type** | **Size** | **Contents** |
| --- | --- | --- | --- | --- |
| FILE\_HEADER | FILE\_NAME | char | 29 | The EMD file name mimics the MTA file name with the extension “MTA” replaced by “EMD”. |
| FILE\_HEADER | SATELLITE | char | 9 | Satellite identifier = LANDSAT\_9 |
| FILE\_HEADER | WRS\_PATH | int | 1 | Scene WRS-2 orbit-based path (1-233) |
| FILE\_HEADER | WRS\_ROW | int | 1 | Scene WRS-2 orbit-based row (1-248) |
| FILE\_HEADER | NUMBER\_OF\_BANDS | int | 1 | Number of bands contained in this EMD file, normally 11. |
| FILE\_HEADER | BAND\_LIST | int | 11 | List of the spectral band numbers contained in this EMD file, normally (1,2,3,4,5,6,7,8,9,10,11). |
| PROJECTION | ELLIPSOID\_AXES | double | 2 | WGS84 ellipsoid semi-major and semi-minor axes in meters. |
| PROJECTION | PROJECTION\_CODE | int | 1 | Code for map projection type: 1 = UTM, 6 = PS. |
| PROJECTION | PROJECTION\_UNITS | char | 6 | Map projection units will always be METERS |
| PROJECTION | PROJECTION\_DATUM | char | 5 | Datum will always be WGS84 |
| PROJECTION | PROJECTION\_SPHEROID | int | 1 | The projection spheroid code will always be 12. |
| PROJECTION | PROJECTION\_ZONE | int | 1 | UTM zone number (1-60). Note that only northern hemisphere zones are used so this number will always be positive. |
| PROJECTION | PROJECTION\_PARAMETERS | double | 15 | GCTP map projection parameters. All zeros for UTM. For polar stereographic this contains the ellipsoid axes, false easting and northing (both 0), latitude of true scale (+/-71 degrees) and the vertical axis longitude (0). |
| PROJECTION | UL\_CORNER | double | 2 | L1T upper left corner map projection coordinates (meters). |
| PROJECTION | UR\_CORNER | double | 2 | L1T upper right corner map projection coordinates (meters). |
| PROJECTION | LL\_CORNER | double | 2 | L1T lower left corner map projection coordinates (meters). |
| PROJECTION | LR\_CORNER | double | 2 | L1T lower right corner map projection coordinates (meters). |
| EPHEMERIS | EPHEMERIS\_EPOCH\_YEAR | int | 1 | Year of ephemeris epoch (start time). |
| EPHEMERIS | EPHEMERIS\_EPOCH\_DAY | int | 1 | Epoch day of year. |
| EPHEMERIS | EPHEMERIS\_EPOCH\_SECOND | double | 1 | Epoch seconds of day. |
| EPHEMERIS | NUMBER\_OF\_POINTS | int | 1 | Number of ephemeris points provided in following four parameter fields. |
| EPHEMERIS | EPHEMERIS\_TIME | double | variable | Ephemeris sample time offsets (from epoch) in seconds. |
| EPHEMERIS | EPHEMERIS\_ECEF\_X | double | variable | Ephemeris sample Earth Centered Earth Fixed X coordinate in meters. |
| EPHEMERIS | EPHEMERIS\_ECEF\_Y | double | variable | Ephemeris sample Earth Centered Earth Fixed Y coordinate in meters. |
| EPHEMERIS | EPHEMERIS\_ECEF\_Z | double | variable | Ephemeris sample Earth Centered Earth Fixed Z coordinate in meters. |
| SOLAR\_VECTOR | SOLAR\_EPOCH\_YEAR | int | 1 | Year of solar vector epoch (start time). This is the same as the ephemeris epoch. |
| SOLAR\_VECTOR | SOLAR\_EPOCH\_DAY | int | 1 | Epoch day of year. |
| SOLAR\_VECTOR | SOLAR\_EPOCH\_SECOND | double | 1 | Epoch seconds of day. |
| SOLAR\_VECTOR | NUMBER\_OF\_POINTS | int | 1 | Number of solar vectors provided in following four parameter fields. |
| SOLAR\_VECTOR | SAMPLE\_TIME | double | variable | Vector sample time offsets (from epoch) in seconds. |
| SOLAR\_VECTOR | SOLAR\_ECEF\_X | double | variable | Solar vector sample Earth Centered Earth Fixed X direction. |
| SOLAR\_VECTOR | SOLAR\_ECEF\_Y | double | variable | Solar vector sample Earth Centered Earth Fixed Y direction. |
| SOLAR\_VECTOR | SOLAR\_ECEF\_Z | double | variable | Solar vector sample Earth Centered Earth Fixed Z direction. |
| RPC\_BAND01 | NUMBER\_OF\_SCAS | int | 1 | Number of SCAs: 14 for OLI bands. |
| RPC\_BAND01 | NUM\_L1T\_LINES | int | 1 | Number of lines in the L1T product. |
| RPC\_BAND01 | NUM\_L1T\_SAMPS | int | 1 | Number of samples in the L1T product. |
| RPC\_BAND01 | NUM\_L1R\_LINES | int | 1 | Number of lines in the L1R product. |
| RPC\_BAND01 | NUM\_L1R\_SAMPS | int | 1 | Number of samples per SCA in the L1R product.  |
| RPC\_BAND01 | PIXEL\_SIZE | double | 1 | L1T pixel size, in meters. |
| RPC\_BAND01 | START\_TIME | double | 1 | L1R image start time in seconds from the ephemeris epoch. |
| RPC\_BAND01 | LINE\_TIME | double | 1 | L1R image line time increment in seconds. |
| RPC\_BAND01 | BAND01\_MEAN\_HEIGHT | double | 1 | Mean height offset for the RPC angle model. |
| RPC\_BAND01 | BAND01\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (file) sample offsets for the RPC angle model. |
| RPC\_BAND01 | BAND01\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the RPC angle model. |
| RPC\_BAND01 | BAND01\_MEAN\_SAT\_VECTOR | double | 3 | Mean satellite view vector for the RPC angle model. |
| RPC\_BAND01 | BAND01\_SAT\_X\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector X coordinate. |
| RPC\_BAND01 | BAND01\_SAT\_X\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector X coordinate. |
| RPC\_BAND01 | BAND01\_SAT\_Y\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector Y coordinate. |
| RPC\_BAND01 | BAND01\_SAT\_Y\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector Y coordinate. |
| RPC\_BAND01 | BAND01\_SAT\_Z\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector Z coordinate. |
| RPC\_BAND01 | BAND01\_SAT\_Z\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector Z coordinate. |
| RPC\_BAND01 | BAND01\_MEAN\_SUN\_VECTOR | double | 3 | Mean sun vector for the RPC angle model. |
| RPC\_BAND01 | BAND01\_SUN\_X\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector X coordinate. |
| RPC\_BAND01 | BAND01\_SUN\_X\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector X coordinate. |
| RPC\_BAND01 | BAND01\_SUN\_Y\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector Y coordinate. |
| RPC\_BAND01 | BAND01\_SUN\_Y\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector Y coordinate. |
| RPC\_BAND01 | BAND01\_SUN\_Z\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector Z coordinate. |
| RPC\_BAND01 | BAND01\_SUN\_Z\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector Z coordinate. |
| RPC\_BAND01 | BAND01\_SCA\_LIST | int | 14 | List of SCAs in this band. For OLI bands this is: (1,2,3,4,5,6,7,8,9,10,11,12,13,14) |
| RPC\_BAND01 | BAND01\_SCA01\_MEAN\_HEIGHT | double | 1 | Mean height offset for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (SCA) sample offsets for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_LINE\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA01 L1R line RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_LINE\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA01 L1R line RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_SAMP\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA01 L1R sample RPC model. |
| RPC\_BAND01 | BAND01\_SCA01\_SAMP\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA01 L1R sample RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_MEAN\_HEIGHT | double | 1 | Mean height offset for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (SCA) sample offsets for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_LINE\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA02 L1R line RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_LINE\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA02 L1R line RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_SAMP\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA02 L1R sample RPC model. |
| RPC\_BAND01 | BAND01\_SCA02\_SAMP\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA02 L1R sample RPC model. |
| RPC\_BAND01 | BAND01\_SCAnn\_... |  |  | The previous seven parameters repeat for SCAs 03 through 14. |
| … |  |  |  |  |
| RPC\_BANDmm |  |  |  | The RPC\_BAND01 group parameters are repeated for bands 2 through 9. |
| … |  |  |  |  |
| RPC\_BAND10 | NUMBER\_OF\_SCAS | int | 1 | Number of SCAs: 3 for TIRS bands. |
| RPC\_BAND10 | NUM\_L1T\_LINES | int | 1 | Number of lines in the L1T product. |
| RPC\_BAND10 | NUM\_L1T\_SAMPS | int | 1 | Number of samples in the L1T product. |
| RPC\_BAND10 | NUM\_L1R\_LINES | int | 1 | Number of lines in the L1R product. |
| RPC\_BAND10 | NUM\_L1R\_SAMPS | int | 1 | Number of samples per SCA in the L1R product.  |
| RPC\_BAND10 | PIXEL\_SIZE | double | 1 | L1T pixel size, in meters. |
| RPC\_BAND10 | START\_TIME | double | 1 | L1R image start time in seconds from the ephemeris epoch. |
| RPC\_BAND10 | LINE\_TIME | double | 1 | L1R image line time increment in seconds. |
| RPC\_BAND10 | BAND10\_MEAN\_HEIGHT | double | 1 | Mean height offset for the RPC angle model. |
| RPC\_BAND10 | BAND10\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (file) sample offsets for the RPC angle model. |
| RPC\_BAND10 | BAND10\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the RPC angle model. |
| RPC\_BAND10 | BAND10\_MEAN\_SAT\_VECTOR | double | 3 | Mean satellite view vector for the RPC angle model. |
| RPC\_BAND10 | BAND10\_SAT\_X\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector X coordinate. |
| RPC\_BAND10 | BAND10\_SAT\_X\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector X coordinate. |
| RPC\_BAND10 | BAND10\_SAT\_Y\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector Y coordinate. |
| RPC\_BAND10 | BAND10\_SAT\_Y\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector Y coordinate. |
| RPC\_BAND10 | BAND10\_SAT\_Z\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the satellite view vector Z coordinate. |
| RPC\_BAND10 | BAND10\_SAT\_Z\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the satellite view vector Z coordinate. |
| RPC\_BAND10 | BAND10\_MEAN\_SUN\_VECTOR | double | 3 | Mean sun vector for the RPC angle model. |
| RPC\_BAND10 | BAND10\_SUN\_X\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector X coordinate. |
| RPC\_BAND10 | BAND10\_SUN\_X\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector X coordinate. |
| RPC\_BAND10 | BAND10\_SUN\_Y\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector Y coordinate. |
| RPC\_BAND10 | BAND10\_SUN\_Y\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector Y coordinate. |
| RPC\_BAND10 | BAND10\_SUN\_Z\_NUM\_COEF | double | 10 | Numerator polynomial coefficients for the sun vector Z coordinate. |
| RPC\_BAND10 | BAND10\_SUN\_Z\_DEN\_COEF | double | 9 | Denominator polynomial coefficients for the sun vector Z coordinate. |
| RPC\_BAND10 | BAND10\_SCA\_LIST | int | 3 | List of SCAs in this band. For TIRS bands this is: (1,2,3) |
| RPC\_BAND10 | BAND10\_SCA01\_MEAN\_HEIGHT | double | 1 | Mean height offset for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (SCA) sample offsets for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the SCA01 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_LINE\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA01 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_LINE\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA01 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_SAMP\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA01 L1R sample RPC model. |
| RPC\_BAND10 | BAND10\_SCA01\_SAMP\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA01 L1R sample RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_MEAN\_HEIGHT | double | 1 | Mean height offset for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (SCA) sample offsets for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the SCA02 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_LINE\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA02 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_LINE\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA02 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_SAMP\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA02 L1R sample RPC model. |
| RPC\_BAND10 | BAND10\_SCA02\_SAMP\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA02 L1R sample RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_MEAN\_HEIGHT | double | 1 | Mean height offset for the SCA03 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_MEAN\_L1R\_LINE\_SAMP | double | 2 | Mean L1R line and (SCA) sample offsets for the SCA03 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_MEAN\_L1T\_LINE\_SAMP | double | 2 | Mean L1T line and sample offsets for the SCA03 L1T-to-L1R RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_LINE\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA03 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_LINE\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA03 L1R line RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_SAMP\_NUM\_COEF | double | 5 | Numerator polynomial coefficients for the SCA03 L1R sample RPC model. |
| RPC\_BAND10 | BAND10\_SCA03\_SAMP\_DEN\_COEF | double | 4 | Denominator polynomial coefficients for the SCA03 L1R sample RPC model. |
| RPC\_BAND11 |  |  |  | The RPC\_BAND10 group parameters are repeated for band 11. |

**Table 1: Enhanced Metadata File Detailed Contents**