LSDS-1691
Version 1.0

Department of the Interior
U.S. Geological Survey

LANDSAT THEMATIC MAPPER (TM) AND ENHANCED THEMATIC MAPPER PLUS (ETM+) SOLAR AND VIEW ANGLE GENERATION ALGORITHM DESCRIPTION DOCUMENT (ADD)

Version 1.0

November 2018

science for a changing world

LANDSAT
THEMATIC MAPPER (TM) AND
ENHANCED THEMATIC MAPPER PLUS (ETM+)
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ALGORITHM DESCRIPTION DOCUMENT (ADD)

November 2018

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Executive Summary

This Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) Solar and View Angle Generation Algorithm Description Document (ADD) defines the algorithm used for the generation of solar and view angle bands, which are contained within the Landsat Collection 1 Level 1 (L1) data products created at the U.S. Geological Survey (USGS) Earth Resource Observation and Science (EROS) Center.

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Document History

Document Number	Document Version	Publication Date	Change Number
LSDS-1691	Version 1.0	November 2018	CR 13255

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Section 1 Introduction

1.1 Background

Landsat 4-7 Collection 1 Level 1 (L1) 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 L1 samples are also registered to a Universal Transverse Mercator (UTM) (or Polar Stereographic (PS)) 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 solar illumination angles. This algorithm provides a method for generating per-pixel sensor viewing and solar illumination angles for L1 products by providing an angle coefficient file, containing selected information from the geometric model and resampling grid, and associated logic for using the new pixel-level metadata to compute the required angles.

A key challenge in analyzing the viewing geometry for both the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors is the along-scan geometric differences between adjacent scans as this scanning geometry leads to discontinuities in the viewing geometry at scan boundaries. The view angle changes, occasioned by the alternating forward/reverse scan geometry, make it difficult to fit a simple function to the uneven angle patterns. This argues for generating and storing the view angles for each pixel. Explicitly representing the angles for each pixel in each band would be space prohibitive as the angle file would be larger than the L1 product. These considerations led to a compromise solution, described herein, that uses multiple rational polynomial functions to model the viewing geometry for each band and for the forward/reverse scans of each band. These functions are implemented in an exploitation tool that uses scene-specific parameters, stored in the angle coefficient file, to generate viewing angles on demand.

The algorithm is thus implemented in two parts. The first part, intended to run in the Image Assessment System (IAS) / Landsat Product Generation System (LPGS) environment at product generation time, uses the geometric model and grid files used to create the L1 product, to build an additional "angle coefficient" 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 TM or ETM+ image data) product pixel. The second part of the algorithm uses the new angle coefficient 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.

The angle coefficient generation algorithm and its process is applied to radiometrically corrected Level 1 Reformatted (L1R) and the radiometrically and geometrically corrected Level 1 Terrain (Corrected) (L1TP), Level 1 Systematic (Corrected) (L1G), and Level 1 Systematic Terrain (Corrected) (L1GT) products. The term L1X is used to refer to these L1 geometrically corrected products or the L1T, L1G, and L1GT products. The algorithm and process also discuss the option of being able to incorporate a Digital Elevation Model (DEM) in the calculations. Due to the possible mis-registration between the TM L1G and the DEM, it is recommended that this option (use of a DEM) not be used with this product type of the TM sensor. All other product types for the ETM+ and TM instruments can be used with the DEM option of generating the sun and sensor viewing angles.

1.2 Purpose

The primary purpose of this document is to provide technical details and information on the Landsat 4-5 TM and Landsat 7 ETM+ Solar and View Angle Generation Algorithm.

1.3 Document Organization

This document contains the following sections:

- Section 1 introduces the Landsat 4-5 TM and Landsat 7 ETM+ Solar and View Angle Generation Algorithm.
- Section 2 provides technical details on the inputs, outputs, and procedures.
- Section 3 provides details pertaining to pre-release development and testing.
- Appendix A provides a list of acronyms.
- The References section contains a list of reference documents and supporting webpages.

Section 2 Dependencies, Inputs, Outputs

2.1 Dependencies

The angle generation algorithm assumes that the standard L1X geometric modeling algorithms have run successfully and that the geometric model, geometric grid, and calibration parameter files used to create the L1X product are available. The angle computation algorithm can optionally use an input elevation model for improved accuracy. If provided, this elevation model must match the scene frame (corners, projection, pixel size) of the L1X product multispectral bands.

2.2 Algorithm Inputs

Table 2-1 lists the Solar and View Angle Generation Algorithm and its component sub-algorithms.

Algorithm Inputs – Angle Coefficient File Generation
Geometric Grid File
Scene Framing Information:
Scene corner coordinates
Scene map projection information:
Projection General Cartographic Transformation Package (GCTP) code: 1 = UTM, 6 = Polar Stereographic
UTM zone number (1-60)
GCTP map projection parameters
Datum and spheroid codes (World Geodetic System 1984 (WGS84))
Geometric Model File
Worldwide Reference System (WRS) path and row
Image times
Spacecraft ephemeris (position vs. time)
Calibration Parameter File (CPF)
Earth model parameters
WGS84 ellipsoid parameters
Earth orientation parameters (UTC Corrected (UT1)-Universal Time Code (UTC) offset, pole wander)
Leap second table
Naval Observatory Vector Astrometry Software (NOVAS) solar ephemeris - sun Earth Centered Inertial True of Date (ECITOD) direction vs. time
Algorithm Inputs – Angle Computation
Angle Coefficient File – see output table below for contents
DEM File (optional)
WGS84 ellipsoid height (in meters) for each 30-meter pixel in the L1X product
Subsampling Factor (optional)

Table 2-1. Solar and View Angle Generation Algorithm Inputs

2.3 Algorithm Outputs

Table 2-2 shows the Solar and View Angle Generation Algorithm outputs.

Algorithm Outputs – Angle Coefficient File Generation
Angle Coefficient File
File Header
Angle Coefficient file name
Satellite ID
WRS path and row
Mode (Scan Line Corrector (SLC) on/off)
First scan direction
Number of bands
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
L1X product projection corners
Ephemeris Data
UTC epoch (year, day of year, seconds of day)
Number of ephemeris points
Time from epoch for each point
Earth Centered Earth Fixed (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
Scan Time Polynomial
Number of scan time polynomial coefficients
Number of scan time directions
Mean active scan time (one for each scan direction)
Mean scan end of line length (one for each scan direction)
Scan time polynomial coefficients (one set of coefficients for each scan direction)
Rational Polynomial Coefficient Data for each Band
Lines per scan
Number of directions
Number of lines and samples in L1X product
Number of lines and samples in L1R input (full scene)
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 L1X 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 scan directions in current band
Rational Polynomial Coefficient Data for each scan direction
Mean height in scan direction
Mean L1R line/sample coordinates in scan direction
Mean L1X line/sample coordinates in scan direction
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 L1X pixel (unless subsampled)
Viewing azimuth angle for each L1X 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 (Band Sequential (BSQ))
Projection information
Projection type (UTM or PS)
UTM zone/PS projection parameters
Pixel size
Upper Left (UL) corner coordinates
Solar Angle File for each Band
Solar zenith angle for each L1X pixel (unless subsampled)
Solar azimuth angle for each L1X 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 (Environment for Visualizing Images (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
Pixel size
UL corner coordinates

Table 2-2. Solar and View Angle Generation Algorithm Outputs

2.3.1 Angle Computation Options

Angle computation can work with or without elevation data input. The output angle “bands” can be optionally subsampled.

Section 3 Procedure

The primary tasks performed by the Solar and View Angle Generation Algorithm are as follows:

1. At product generation time, create an angle coefficient 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 L1G/T data product.
2. On demand for the user, use the angle coefficient file to generate solar illumination and sensor viewing angles that correspond to the L1G/T product pixels.

3.1 Phase 1: Generate Angle Coefficient File

Central to the ability to compute the satellite viewing or solar illumination geometry for a particular L1X 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 sun angles can be calculated.

The key to mapping output product image pixels to imaging time is to reconstruct the relationship between the resampled L1X product pixels and the un-resampled L1R calibrated detector samples from which they are derived, because there is a simple linear relationship between L1R line number and time.

The L1R to L1X mapping can be calculated from the geometric model. To facilitate efficient L1X product generation, this relationship is stored in the geometric grid file for an array of points spanning the image bounds. The goal is to formulate a set of equations that represent, in a compact form, the input space L1R line/sample to output space (L1 Product) line/sample mappings contained in the geometric grid file.

Experimentation has shown that sub-pixel accuracy in the L1X line/sample to L1R line/sample mapping can be achieved using rational polynomial functions of the following form:

$$\begin{aligned} L1R_{Line} &= L1R_{MeanLine} \\ &+ \frac{(a_0 + a_1 * L1X_L + a_2 * L1X_S + a_3 * Hgt + a_4 * L1X_L * L1X_S)}{(1 + b_1 * L1X_L + b_2 * L1X_S + b_3 * Hgt + b_4 * L1X_L * L1X_S)} \qquad (1) \end{aligned}$$

$$\begin{aligned} L1R_{Sample} &= L1R_{MeanSample} \\ &+ \frac{(c_0 + c_1 * L1X_L + c_2 * L1X_S + c_3 * Hgt + c_4 * L1X_L * L1X_S)}{(1 + d_1 * L1X_L + d_2 * L1X_S + d_3 * Hgt + d_4 * L1X_L * L1X_S)} \end{aligned}$$

Where:

$L1X_{L} = L1X_{Line} – L1X_{MeanLine}$

$L1X_{S} = L1X_{Sample} – L1X_{MeanSample}$

$Hgt = Height – Height_{Mean}$

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 scan direction using the information in the geometric grid file. For TM and ETM+, there are 23 coefficients / band / number scan directions. 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 scene area covered by the functions. This helps provide numerical stability in the least squares solution for the model coefficients.

3.1.1 Calculate Scan Time Polynomials

Scan times for each scan direction are treated differently by fitting a polynomial for the starting scan time of all the scans for a given scan direction, determining the average number of pixels acquired for each scan direction (average active scan line length), and determining the average active scan time for each scan.

Time for a given pixel is found by, for a given scan direction and L1R pixel, calculating the starting scan time using the scan time polynomial and calculating within the scan time based on the average active scan line length, the average active scan time, and the L1X sample number:

1. For a given scan direction, store start scan times, active scan line length, and active scan line length.
2. For a given scan direction, solve for a scan time polynomial using least squares fit and data assembled in step 1.
3. For a given scan direction, determine the mean active scan line length and time.

3.1.2 Calculate the Model Coefficients

The geometric grid file contains a set of three-dimensional arrays of L1R to L1X pixel mappings, one for each band. The array axes are L1R line, L1R sample, and height, with each array point corresponding to one L1R line / L1R sample / height triplet (see Figure 3-1).

The L1X line/sample location corresponding to each triplet is computed using the Line-of-Sight (LOS) projection model and the selected output L1X scene frame. The results are stored in the grid structure for subsequent use during image resampling. The grid provides the information required to solve for the rational polynomial model coefficients.

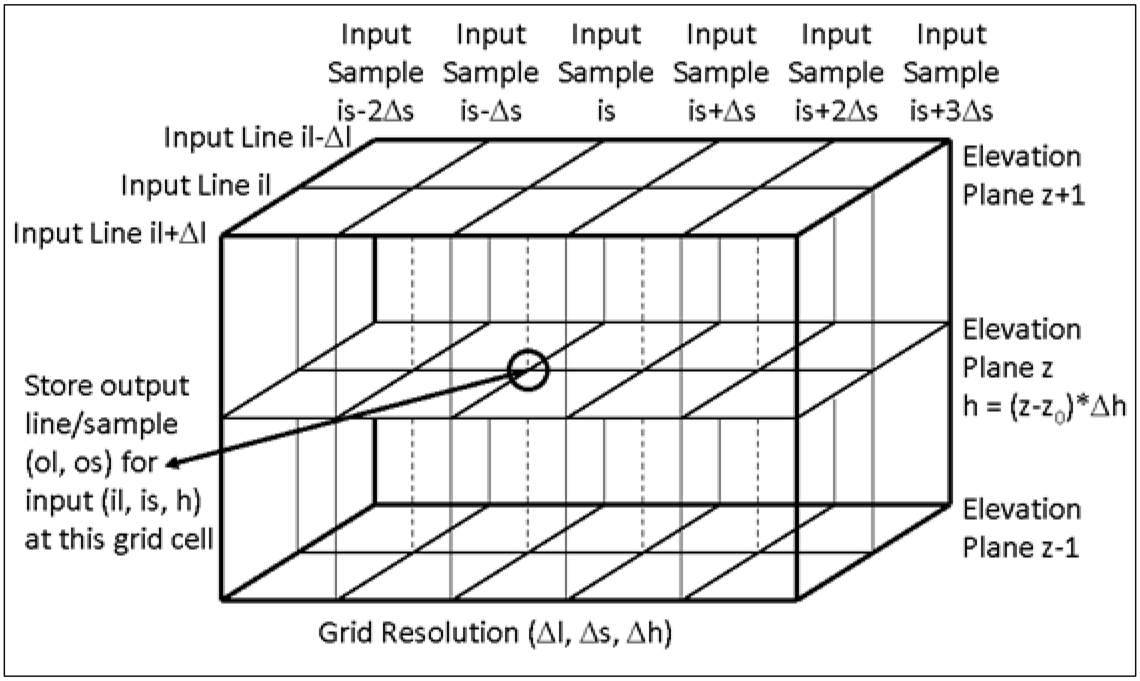

Figure 3-1. Geometric Grid Structure

All grid points for a given band/scan direction are used to solve for the model coefficients for that band/scan direction. Calculating the mean L1R line, L1R sample, L1X line, L1X sample, and height values is straightforward; the model coefficients are determined by a least squares solution. To accomplish this task, the rational functions are linearized by multiplying the denominator by the Left-Hand Side (LHS) and rearranging terms as follows:

$$L1R_L = (a_0 + a_1 * L1X_L + a_2 * L1X_S + a_3 * Hgt + a_4 * L1X_L * L1X_S) - (b_1 * L1X_L * L1R_L + b_2 * L1X_S * L1R_L + b_3 * Hgt * L1R_L + b_4 * L1X_L * L1X_S * L1R_L) \tag{3}$$

$$L1R_S = (c_0 + c_1 * L1X_L + c_2 * L1X_S + c_3 * Hgt + c_4 * L1X_L * L1X_S) - (d_1 * L1X_L * L1R_S + d_2 * L1X_S * L1R_S + d_3 * Hgt * L1R_S + d_4 * L1X_L * L1X_S * L1R_S) \tag{4}$$

Where:

$L1R_L = L1R_{Line} – L1R_{MeanLine}$

$L1R_S = L1R_{Sample} – L1R_{MeanSample}$

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.

3.1.3 Construct the Angle Coefficient File

The sequence of activities required to assemble the information required to build the angle coefficient file is as follows:

1. Open and read the input data files:
    a. Load the geometric model from the LOS model file.
    b. Load the geometric grid from the grid file.
    c. Load the Earth model parameters from the CPF.
2. Initialize the Earth model:
    a. Initialize the IAS time conversion library functions using the leap seconds.
    b. Store the World Geodetic System 1984 (WGS84) ellipsoid semi-major and semi-minor axes from the CPF in the angle coefficient file data structure.
3. Get path/row, ephemeris, and sun vector information from the geometric model.
    a. Store the Worldwide Reference System (WRS) path and row from the model in the angle coefficient file data structure.
    b. Extract ephemeris data covering the current scene from the geometric model.
        i. Determine ephemeris start and end times from scan times.
        ii. Allocate ephemeris based on start time, end time, and sample time of ephemeris angle coefficient file data structure.
        iii. Extract or interpolate angle coefficient file ephemeris from geometric model ephemeris based on angle coefficient file data structure sample times.
    c. Use Naval Observatory Vector Astrometry Software (NOVAS) to compute Earth Centered Earth Fixed (ECEF) sun vectors at the ephemeris sample times.
        i. Initialize the NOVAS solar ephemeris package.
        ii. For each ephemeris point:
            1. Construct the full Universal Time Code (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 Earth Centered Inertial (ECI) true-of-date solar direction vector at the specified Julian day.
            5. Use angle coefficient library routines to convert the Earth Centered Inertial True of Date (ECITOD) sun vector to ECI of epoch J2000 (by applying nutation and precession models).
            6. Use angle coefficient library routines to convert the ECIJ2000 sun vector to ECEF, including the pole wander and UTC Corrected (UT1)-UTC corrections from the geometric model.
            7. Load the time and ECEF solar unit vector into the angle coefficient file data structure.
        iii. Shut down the NOVAS package.
4. Get map projection and scene corner information from the geometric grid.
    a. Load the projection code, units, zone, spheroid, datum, and General Cartographic Transformation Package (GCTP) map projection parameter

    fields from the grid into the angle coefficient file data structure. These parameters are needed to convert map X/Y to geodetic latitude/longitude.
    b. Load the scene corner map projection coordinates from the grid into the angle coefficient file data structure. The corners are needed to convert L1X line/sample to map projection X/Y.
5. Initialize the IAS library map projection logic.
    a. Pre-establishing this transformation makes subsequent map projection conversion computations easier.
6. Calculate scan direction specific time polynomials.
    a. The least squares matrices for determining starting scan times take the form of:

$$[A][SP] = [Y]$$

$$\begin{bmatrix} 1 & \vdots & line_0{}^n \\ \cdots & \cdots & \cdots \\ 1 & \vdots & line_M{}^n \end{bmatrix} \begin{bmatrix} SP_0 \\ \vdots \\ SP_n \end{bmatrix} = \begin{bmatrix} start\_scan\_time_0 \\ \vdots \\ start\_scan\_time_m \end{bmatrix}$$

Where:
SP is the scan time polynomials for a given scan direction.
M = number of scans for a given scan direction.
Start_scan_time = starting scan time for a given scan direction.

The values for SP are then found using a least-squares fit.

The equation for time is then calculated from:
Time = SP_0 + SP_1 * line + … + SPn * line^n + mean_active_scan_time * (sample) / mean_end_of_line
Where:
Line = L1R line location
Sample = L1R sample location

The steps for determining the polynomials and mean values are then as follows:

a. For each scan direction.
    i. For each scan associated with current scan direction:
        1. Determine scan start times for each scan. Store values in array Y.
        2. Determine mid scan line. Store line number values according to the number of coefficients that fit in array A.
        3. Sum end-of-line locations for each scan.
        4. Sum active scan time for each scan.
    ii. Determine mean end-of-line location for current scan direction:

mean_end_of_line = sum_end_of_line / number of scans for direction

        iii. Determine mean active scan time for current scan direction.

mean_active_scan_time = sum_active_scan_times / number of scans for direction

        iv. Determine polynomial coefficients.

$$[SP] = [A]^{-1}[Y]$$

7. Assemble the band-specific angle coefficient fields for each band.
    a. Load the band number, number of scan directions, number of L1X lines/samples, and pixel size from the grid into the angle coefficient file data structure.
    b. Load the number of L1R lines/samples, band start time, and line increment time (sampling time) from the geometric model into the angle coefficient file data structure.
    c. For each scan direction, record the scan direction in the angle coefficient file data structure and calculate the coefficients of the L1X-to-L1R RPC model.
        i. Compute the mean height of the grid points as:
        Mean_hgt = (num_Zplanes – 1 – 2*zeroplane)*Zspacing/2
        ii. Compute the mean L1R line and sample values by cycling through the grid in_lines and in_samps arrays.
        iii. Compute the mean L1X line and sample values by cycling through the grid point out_lines and out_samps arrays.
        iv. Loop through all the points in the grid for this band/scan direction 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:
            $X_L^T\theta_L = Y_L$ $X_S^T\theta_S = Y_S$

            Where:

$$X_L = \begin{bmatrix} 1 \\ L1X_L \\ L1X_S \\ Hgt \\ L1X_L * L1X_S \\ -L1R_L * L1X_L \\ -L1R_L * L1X_S \\ -L1R_L * Hgt \\ -L1R_L * L1X_L * L1X_S \end{bmatrix} \quad \theta_L = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} \quad Y_L = [L1R_L]$$

$$X_S = \begin{bmatrix} 1 \\ L1X_L \\ L1X_S \\ Hgt \\ L1X_L * L1X_S \\ -L1R_S * L1X_L \\ -L1R_S * L1X_S \\ -L1R_S * Hgt \\ -L1R_S * L1X_L * L1X_S \end{bmatrix} \quad \theta_S = \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} \quad Y_S = [L1R_S]$$

2. Each observation of each type (line or sample) contributes to the normal equations:

   $N_L\theta_L = L_L$ and $N_S\theta_S = L_S$

   Where the N and L matrices are accumulated as:

   $N_L \mathrel{+}= X_L X_L^T$ $\qquad$ $L_L \mathrel{+}= X_L Y_L$

   $N_S \mathrel{+}= X_S X_S^T$ $\qquad$ $L_S \mathrel{+}= X_S Y_S$

v. Once the observation contributions from all of the grid points are collected into the normal equation matrices, solve for the unknown rational polynomial coefficient vectors θ_L and θ_S:

   $\theta_L = N_L^{-1} L_L$ $\qquad$ $\theta_S = N_S^{-1} L_S$

vi. This procedure generates a set of L1X-to-L1R RPCs for each scan direction 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 L1X 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 L1X 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 L1X 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.

3.1.4 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-scan direction L1X-to-L1R rational functions, because they must account for the scan-to-scan discontinuities. This is achieved by including both L1X and L1R input terms in the formulation. The RPC model equation for the satellite viewing unit vector X component is:

$$Sat_X = Sat_{XMean} + \frac{Num_x(L1X_L, L1X_S, Hgt, L1R_L, L1R_S)}{Den_x(L1X_L, L1X_S, Hgt, L1R_L, L1R_S)} \qquad (5a)$$

$$\begin{aligned} Num_x(L1X_L, L1X_S, Hgt, L1R_L, L1R_S) \\ = a_0 + a_1 * L1X_L + a_2 * L1X_S + a_3 * Hgt + a_4 * L1R_L + a_5 * L1X_L \\ * L1X_L + a_6 * L1X_L * L1X_S + a_7 * L1X_S * L1X_S + a_8 * L1R_S * L1R_L \\ * L1R_L + a_9 * L1R_L * L1R_L * L1R_L \qquad (5b) \end{aligned}$$

$$\begin{aligned} Den_x(L1X_L, L1X_S, Hgt, L1R_L, L1R_S) \\ = 1 + b_1 * L1X_L + b_2 * L1X_S + b_3 * Hgt + b_4 * L1R_L + b_5 * L1X_L \\ * L1X_L + b_6 * L1X_L * L1X_S + b_7 * L1X_S * L1X_S + b_8 * L1R_S * L1R_L \\ * L1R_L + b_9 * L1R_L * L1R_L * L1R_L \qquad (5c) \end{aligned}$$

Where:

$L1X_L = L1X_{Line} – L1X_{MeanLine}$
$L1X_S = L1X_{Sample} – L1X_{MeanSample}$
$Hgt = Height – Height_{Mean}$
$L1R_L = L1R_{Line} – L1R_{MeanLine}$
$L1R_S = L1R_{Sample} – L1R_{MeanSample}$
a_0 to a_9, and b_1 to b_9, are the RPC model coefficients.

There are similar models for Sat_Y, Sat_Z, Sun_X, Sun_Y, and Sun_Z.

The terms included in these equations were determined by experimentation to minimize the rational polynomial model fit residuals. To use these models, it is necessary to first evaluate the L1X-to-L1R RPC model to determine the values for $L1R_L$ and $L1R_S$.

The final steps in the assembly of the angle coefficient file are to compute these “angle” rational polynomial model coefficients, using a procedure much like that described in Section 3.1.3 step #7 above, and to write out the angle coefficient Object Description Language (ODL) file:

1. Calculate the direct angle RPCs for each band.
    a. Calculate the satellite viewing vector and the solar illumination vector in the local vertical coordinate system at each point in the geometric grid.

i. Extract the height (from the grid Z-plane), L1R line/sample, and L1X line/sample for the current point from the grid structure.

ii. Use the L1X corners and pixel size to convert L1X line/sample to map X/Y:
$X = upleft\_X + L1X_S * pixel\_size$
$Y = upleft\_Y – L1X_L * pixel\_size$
This assumes a projection of north-up for the L1X products. This could be made more elaborate to support path-oriented products if necessary because all four scene corners are included in the angle coefficient file.

iii. 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.

iv. 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 instrument LOS Projection/Grid Generation Algorithm Description Document (ADD). This yields the ground point ECEF vector G_{ECEF}.

v. Calculate the local vertical coordinate system basis vectors from the latitude and longitude:

$$H_x = \begin{bmatrix} -\sin(lon) \\ \cos(lon) \\ 0 \end{bmatrix}$$

East in ECEF

$$H_y = \begin{bmatrix} -\sin(lat) * \cos(lon \\ -\sin(lat) * \sin(lon) \\ \cos(lat) \end{bmatrix}$$

North in ECEF

$$H_z = \begin{bmatrix} \cos(lat) * cos\ (lon) \\ \cos(lat) * \sin(lon) \\ \sin(lat) \end{bmatrix}$$

Up in ECEF

vi. Calculate the time of observation from the L1R line/sample:
Time = Scan Polynomial (line) + sample * (mean active scan time / mean end of scan).

vii. 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 S_{ECEF}.

viii. Calculate the ground-to-space viewing vector:

$V_{ECEF} = S_{ECEF} - G_{ECEF}$

 ix. Project the ECEF viewing vector into the local vertical coordinate system:

$$V_{LV} = \begin{bmatrix} H_x^T \\ H_y^T \\ H_z^T \end{bmatrix} V_{ECEF}$$

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

 x. 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.

 xi. 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 S_{LV}.

b. As each grid point is processed, accumulate the sums of and then calculate the average of values for the height, L1R line, L1R sample, L1X line, L1X sample, view vector X, Y, Z coordinates, and sun vector X, Y, Z coordinates.

c. For each component of the viewing vector V_{LV} and the sun vector S_{LV}, compute the coefficients of an RPC model of the form shown above in equations 5a, 5b, and 5c.

 i. 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:

$$X_{Satx}^T \theta_{Satx} = Y_{Satx}$$

Where:

$$X_{Satx} = \begin{bmatrix} 1 \\ L1X_L \\ L1X_S \\ Hgt \\ L1R_L \\ L1X_L * L1X_L \\ L1X_L * L1X_S \\ L1X_S * L1X_S \\ L1R_S * L1R_L * L1R_L \\ L1R_L * L1R_L * L1R_L \\ -Sat_X * L1X_L \\ -Sat_X * L1X_S \\ -Sat_X * Hgt \\ -Sat_X * L1R_L \\ -Sat_X * L1X_L * L1X_L \\ -Sat_X * L1X_L * L1X_S \\ -Sat_X * L1X_S * L1X_S \\ -Sat_X * L1R_S * L1R_L * L1R_L \\ -Sat_X * L1R_L * L1R_L * L1R_L \end{bmatrix} \qquad \theta_{Satx} = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \\ a_9 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \\ b_8 \\ b_9 \end{bmatrix}$$

$$Y_{Satx} = [Sat_X]$$

All of the L1X, L1R, height, and vector component inputs above are offset by the means as shown in equation (5).

2. Each observation contributes to the normal equations:

$$N_{Satx}\theta_{Satx} = L_{Satx}$$

Where the N and L matrices are accumulated as:

$$N_{Satx} += X_{Satx}X_{Satx}^T \qquad L_{Satx} += X_{Satx}Y_{Satx}$$

ii. Once the observation contributions from all of the grid points are collected into the normal equation matrices, solve for the unknown rational polynomial coefficient vectors θ_L and θ_S:

$$\theta_{Satx} = N_{Satx}^{-1}L_{Satx}$$

d. This procedure runs 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 L1X-to-angle RPCs for the band.

Load the angle RPC model coefficients into the angle coefficient file data structure.

2. Write the angle coefficient file data structure to an output ODL formatted angle coefficient file.
    a. Construct the output file name from the path, row, and date. This needs to be enhanced to include ground station ID and version number for operational use.
    b. Write the FILE_HEADER group containing the file name, satellite ID, path, row, number of bands, and band list.
    c. Write the PROJECTION group containing the ellipsoid parameters, projection, units, datum, spheroid, zone codes, GCTP projection parameters, and the scene corner coordinates.
    d. 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.
    e. 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 match the ephemeris data, so those values are somewhat redundant.
    f. Write an RPC_BAND group for each band containing the number of scan directions, scan direction list, number of L1X lines and samples, number of L1R lines and samples, pixel size, band start UTC epoch and line time increment, mean height, mean L1X 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.
        i. For each scan direction in the band, write the mean height, mean L1X line/sample, mean L1R line/sample, and the L1X-to-L1R RPC model coefficients.

The output angle coefficient 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 L1X product pixel.

3.2 Phase 2 – Compute Satellite Viewing and Solar Illumination Angles

The Phase 2 angle generation portion of the algorithm provides two options for performing the angle computations. Both methods use the L1X-to-L1R RPC models to calculate the L1R coordinates that correspond to a given L1X pixel. Both methods also retrieve the pixel height from an input DEM, if provided. Otherwise, the mean elevation for the band, from the angle coefficient file, is used. Having been given the L1X line/sample and determined the corresponding L1R line/sample and height, the first “rigorous” method follows the procedure described above in step 8a 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 angle coefficient file.

There are some subtleties to the use of the L1X-to-L1R RPCs that deserve elaboration. Although the rational polynomial functions generate L1R line and sample coordinates for any given L1X product pixel (and height), each scan direction has a separate set of

RPCs; therefore, it is necessary to know which scan direction the pixel falls inside to select the correct model parameters. Having only the L1X image to work with, staff know which band number to use, but not which scan direction. This was the original reason for including an L1R sample RPC model. The L1R sample coordinates for each scan direction in the current band can be evaluated to determine which scan direction or scan directions the L1X pixel came from. At most, two scan directions return L1R sample values that fall within the actual range of samples on that scan direction, thus identifying the set of rational polynomial coefficients to use to evaluate the L1R line coordinate. In scan overlap areas, two scans are valid. In the scan gap area, no valid L1X pixel may reside. Depending upon the accuracy required, either could be used to compute the time and angles. Currently, the first scan acquired is chosen.

3.2.1 Calculate Viewing and Solar Angles

The sequence of activities required to generate satellite viewing angles and solar illumination angles for each L1X pixel using the angle coefficients 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, and/or subsampling factor.
2. Initialize the angle coefficient interface using the inputs provided:
    a. Open the input angle coefficient file and load the contents into an angle coefficient file data structure.
    b. Initialize the map projection logic:
        i. Pre-establishing this transformation makes subsequent map projection conversion computations easier.
    c. Load the Geographic Tagged Image File Format (GeoTIFF) formatted DEM, if one is provided.
        i. Read the header information and store in a data structure.
        ii. Load the elevation array.
        iii. If no DEM is provided, or if the DEM does not match the image dimensions specified in the angle coefficient file, set the elevation array to NULL.
    d. Get the number of bands from the angle coefficient file data structure and return this value to the calling procedure.
3. For each band:

a. Extract the scene framing information from the angle coefficient file data structure.

    i. Extract the spectral band number, scene dimensions, map projection information (code, zone), pixel size, and upper-left corner coordinates from the angle coefficient file data structure. The projection information is used to generate the output angle image header files.

b. Calculate the size of the output angle images using the size of the L1X image and the subsampling factor:

   Angle nlines = (L1X nlines – 1) / subsample + 1

   Angle nsamps = (L1X nsamps – 1) / subsample + 1

c. Step through the L1X image pixels using the subsampling factor as a loop increment. Calculate the view and sun angles at each L1X line/sample location:

    i. Select the angle coefficients for the current band.

    ii. Calculate the subsampling relationship between the L1X image and the DEM:

        DEM subsample = (L1X nlines – 1) / (DEM nlines – 1)

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

    iii. Calculate the DEM indices that correspond to the current L1X indices by dividing by the DEM subsample factor, noting that the indices are zero-relative.

    iv. Extract the height from the DEM at the specified indices. If no DEM was provided, set the height to NULL.

    v. Calculate the angles using the selected method:

        1. Rigorous method – see the following for details.

        2. RPC method – see the following for details.

    vi. Quantize the computed angles to units of 0.01 degrees.

d. Write the angles to output band files:

    i. Calculate the angle band pixel size by multiplying the L1X pixel size by the subsampling factor.
    ii. Construct the output file names using the angle coefficient input file root name and the band number.
    iii. Write the satellite zenith and azimuth angle values, band sequentially, to the satellite angle file.
    iv. Write an ENVI-format header file for the satellite angles using the framing information extracted previously.
    v. Write the solar zenith and azimuth angles, band sequentially, to the solar angle file.
    vi. Write an ENVI-format header file for the solar angles using the framing information extracted previously.

4. Shut down the angle coefficient logic by releasing the allocated ephemeris data memory in the angle coefficient file data structure and in the map projection transformation structure.

3.2.2 Compute Angles Using the Rigorous Method

To compute the satellite viewing and solar illumination angles at a specified L1X line/sample location, given the corresponding elevation and angle coefficients, using the rigorous method:

1. If the input height is NULL, replace it with the mean height from the band RPC parameters in the angle coefficient file data structure.
2. Determine which scan(s) viewed the L1X pixel:
    a. For each scan direction for a given L1X pixel, calculate the L1R pixel location.
    b. Determine if L1R falls within L1R space.
    c. Determine if L1R line falls in a scan that corresponds to the current scan direction being checked. If true, mark as a valid mapping.
    d. If buffering scans, determine fractional distance from the scan and if L1R falls within the current scan direction being checked, mark as a valid mapping.
3. For the first valid scan found to contain the point, calculate the satellite and solar vectors:
    a. This procedure is described in Section 3.1.4 step 1.a. of the algorithm with the exception of the first sub-step (height retrieval). Here, the height is provided as an input.
4. 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
```

5. 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
   ```

3.2.3 Compute Angles Using the RPC Method

To compute the satellite viewing and solar illumination angles at a specified L1X line/sample location, given the corresponding elevation and angle coefficients, use the RPC method:

1. If the input height is NULL, replace it with the mean height from the band RPC parameters in the angle coefficient file data structure.
2. Determine which scan direction(s) viewed the L1X pixel. This procedure is the same as for the rigorous method.
3. Offset the L1X line, L1X sample, and height values by the mean values for the current band.
4. For first valid scan direction:
   a. Offset the L1R line and L1R sample coordinates by the mean values for the current band.
   b. 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.
   c. Calculate the angles corresponding to the resulting vectors using the methods described in steps 4 and 5 of the rigorous method above.

3.3 Angle Coefficient Output File

Table 3-1 shows the detailed contents of the angle coefficient file. Although some of the fields in the angle coefficient file duplicate information found in the standard L1X product metadata (MTA) file, this was done intentionally to make the angle coefficient file self-contained. In some cases, different parameter names are used in the angle coefficient 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 angle coefficient 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 spectral bands.

Group	Parameter	Type	Size	Contents
FILE_HEADER	FILE_NAME	char	29	The Angle Coefficient file name mimics the MTA file name with the extension “MTA” replaced by “ANG”.
FILE_HEADER	SATELLITE	char	9	Satellite identifier = LANDSAT_4, LANDSAT_5, LANDSAT_7
FILE_HEADER	WRS_PATH	int	1	Scene WRS-2 path (1-233).
FILE_HEADER	FIRST_SCAN_DIRECTION	char	1	Direction of first scan in imagery.
FILE_HEADER	WRS_ROW	int	1	Scene WRS-2 row (1-248).
FILE_HEADER	NUMBER_OF_BANDS	int	1	Number of bands contained in this ANG file, normally 11.
FILE_HEADER	BAND_LIST	int	11	List of the spectral band numbers contained in this ANGfile, normally (1,2,3,4,5,6,7,8).
PROJECTION	ELLIPSOID_AXES	float	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 are always METERS.
PROJECTION	PROJECTION_DATUM	char	5	Datum is always WGS84.
PROJECTION	PROJECTION_SPHEROID	int	1	The projection spheroid code is always 12.
PROJECTION	PROJECTION_ZONE	int	1	UTM zone number (1-60). Only northern hemisphere zones are used; therefore, this number is always positive.
PROJECTION	PROJECTION_PARAMETERS	float	15	GCTP map projection parameters. All zeros for UTM. For PS, 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	float	2	L1X upper left corner map projection coordinates (meters).
PROJECTION	UR_CORNER	float	2	L1X upper right corner map projection coordinates (meters).

Group	Parameter	Type	Size	Contents
PROJECTION	LL_CORNER	float	2	L1X lower left corner map projection coordinates (meters).
PROJECTION	LR_CORNER	float	2	L1X 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	float	1	Epoch seconds of day.
EPHEMERIS	NUMBER_OF_POINTS	int	1	Number of ephemeris points provided in following four parameter fields.
EPHEMERIS	EPHEMERIS_TIME	float	variable	Ephemeris sample time offsets (from epoch) in seconds.
EPHEMERIS	EPHEMERIS_ECEF_X	float	variable	Ephemeris sample ECEF X coordinate in meters.
EPHEMERIS	EPHEMERIS_ECEF_Y	float	variable	Ephemeris sample ECEF Y coordinate in meters.
EPHEMERIS	EPHEMERIS_ECEF_Z	float	variable	Ephemeris sample ECEF 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	float	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	float	variable	Vector sample time offsets (from epoch) in seconds.
SOLAR_VECTOR	SOLAR_ECEF_X	float	variable	Solar vector sample ECEF X direction.
SOLAR_VECTOR	SOLAR_ECEF_Y	float	variable	Solar vector sample ECEF Y direction.
SOLAR_VECTOR	SOLAR_ECEF_Z	float	variable	Solar vector sample ECEF Z direction.
SCAN_TIME_POLY	SCAN_TIME_POLY_NCOEF	int	variable	Number of coefficients in polynomial that defines starting scan times.

Group	Parameter	Type	Size	Contents
SCAN_TIME_POLY	SCAN_TIME_POLY_DIRECTIONS	int	1	Number of scan directions.
SCAN_TIME_POLY	SCAN_TIMEdd_MEAN_ACTIVESCAN	float	1	Mean active scan time for each scan direction.
SCAN_TIME_POLY	SCAN_TIMEdd_MEAN_EOL	float	1	Mean end of line length for each scan direction.
SCAN_TIME_POLY	SCAN_TIMEdd_POLY_COEFF	float	variable	Polynomial coefficients defining starting scan time.
RCP_BANDbb	LINES_PER_SCAN	Int	variable	Number of lines or detectors per scan.
RPC_BANDbb	NUMBER_OF_SCAN_DIRECTIONS	int	1	Number of scan directions.
RPC_BANDbb	NUM_L1T_LINES	int	1	Number of lines in the L1X product.
RPC_BANDbb	NUM_L1T_SAMPS	int	1	Number of samples in the L1X product.
RPC_BANDbb	NUM_L1R_LINES	int	1	Number of lines in the L1R product.
RPC_BANDbb	NUM_L1R_SAMPS	int	1	Number of samples per scan in the L1R product.
RPC_BANDbb	PIXEL_SIZE	float	1	L1X pixel size in meters.
RPC_BANDbb	START_TIME	float	1	L1R image start time in seconds from the ephemeris epoch.
RPC_BANDbb	LINE_TIME	float	1	L1R image line time increment in seconds.
RPC_BANDbb	BANDbb_MEAN_HEIGHT	float	1	Mean height offset for the RPC angle model.
RPC_BANDbb	BANDbb_MEAN_L1R_LINE_SAMP	float	2	Mean L1R line and (file) sample offsets for the RPC angle model.
RPC_BANDbb	BANDbb_MEAN_L1T_LINE_SAMP	float	2	Mean L1X line and sample offsets for the RPC angle model.
RPC_BANDbb	BANDbb_MEAN_SAT_VECTOR	float	3	Mean satellite view vector for the RPC angle model.
RPC_BANDbb	BANDbb_SAT_X_NUM_COEF	float	10	Numerator polynomial coefficients for the satellite view vector X coordinate.
RPC_BANDbb	BANDbb_SAT_X_DEN_COEF	float	9	Denominator polynomial coefficients for the satellite view vector X coordinate.

Group	Parameter	Type	Size	Contents
RPC_BANDbb	BANDbb_SAT_Y_NUM_COEF	float	10	Numerator polynomial coefficients for the satellite view vector Y coordinate.
RPC_BANDbb	BANDbb_SAT_Y_DEN_COEF	float	9	Denominator polynomial coefficients for the satellite view vector Y coordinate.
RPC_BANDbb	BANDbb_SAT_Z_NUM_COEF	float	10	Numerator polynomial coefficients for the satellite view vector Z coordinate.
RPC_BANDbb	BANDbb_SAT_Z_DEN_COEF	float	9	Denominator polynomial coefficients for the satellite view vector Z coordinate.
RPC_BANDbb	BANDbb_MEAN_SUN_VECTOR	float	3	Mean sun vector for the RPC angle model.
RPC_BANDbb	BANDbb_SUN_X_NUM_COEF	float	10	Numerator polynomial coefficients for the sun vector X coordinate.
RPC_BANDbb	BANDbb_SUN_X_DEN_COEF	float	9	Denominator polynomial coefficients for the sun vector X coordinate.
RPC_BANDbb	BANDbb_SUN_Y_NUM_COEF	float	10	Numerator polynomial coefficients for the sun vector Y coordinate.
RPC_BANDbb	BANDbb_SUN_Y_DEN_COEF	float	9	Denominator polynomial coefficients for the sun vector Y coordinate.
RPC_BANDbb	BANDbb_SUN_Z_NUM_COEF	float	10	Numerator polynomial coefficients for the sun vector Z coordinate.
RPC_BANDbb	BANDbb_SUN_Z_DEN_COEF	float	9	Denominator polynomial coefficients for the sun vector Z coordinate.
RPC_BANDbb	BANDbb_SCAN_DIRECTIONS	int	X	List of scan directions in file.
RPC_BANDbb	BANDbb_DIRECTIONdd_MEAN_HEIGHT	float	1	Mean height offset for the DIRECTIONdd L1X-to-L1R RPC model.
RPC_BANDbb	BANDbb_DIRECTIONdd_MEAN_L1R_LINE_SAMP	float	2	Mean L1R line and sample offsets for the DIRECTIONdd L1X-to-L1R RPC model.
RPC_BANDbb	BANDbb_DIRECTIONdd_MEAN_L1T_LINE_SAMP	float	2	Mean L1X line and sample offsets for the DIRECTIONdd L1X-to-L1R RPC model.
RPC_BANDbb	BANDbb_ DIRECTIONdd_LINE_NUM_COEF	float	5	Numerator polynomial coefficients for the DIRECTIONdd L1R line RPC model.
RPC_BANDbb	BANDbb_ DIRECTIONdd_LINE_DEN_COEF	float	4	Denominator polynomial coefficients for the DIRECTIONdd L1R line RPC model.
RPC_BANDbb	BANDbb_ DIRECTIONdd_SAMP_NUM_COEF	float	5	Numerator polynomial coefficients for the DIRECTIONdd L1R sample RPC model.
RPC_BANDbb	BANDbb_ DIRECTIONdd_SAMP_DEN_COEF	float	4	Denominator polynomial coefficients for the DIRECTIONdd L1R sample RPC model.

Group	Parameter	Type	Size	Contents
bb for each band present.	dd for each scan direction present.			

Table 3-1. Angle Coefficient File Detailed Contents

Appendix A Acronyms

ADD	Algorithm Description Document
BSQ	Band Sequential
CCB	Configuration Control Board
CPF	Calibration Parameter File
CR	Change Request
DEM	Digital Elevation Model
DPAS	Data Processing and Archive System
ECEF	Earth Centered Earth Fixed
ECI	Earth Centered Inertial
ECITOD	Earth Centered Inertial True of Date
ENVI	Environment for Visualizing Images
EROS	Earth Resource Observation and Science
ETM+	Enhanced Thematic Mapper Plus
GCTP	General Cartographic Transformation Package
GeoTIFF	Geographic Tagged Image File Format
IAS	Image Assessment System
L1	Level 1
L1G	Level 1 Systematic (Corrected)
L1GT	Level 1 Systematic Terrain (Corrected)
L1R	Level 1 Reformatted
L1TP	Level 1 Terrain (Corrected)
LHS	Left Hand Side
LOS	Line-of-Sight
LPGS	Landsat Product Generation System
MTA	metadata
NOVAS	Naval Observatory Vector Astrometry Software
ODL	Object Description Language
PS	Polar Stereographic
RPC	Rational Polynomial Coefficients
SLC	Scan Line Corrector
TM	Thematic Mapper
UL	Upper Left
USGS	U.S. Geological Survey
UT1	UTC Corrected
UTC	Universal Time Code
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
WRS	Worldwide Reference System

References

Please see https://landsat.usgs.gov/glossary-and-acronyms for a list of acronyms.

Visit https://landsat.usgs.gov/solar-illumination-and-sensor-viewing-angle-coefficient-file for more information.