### OLI Sensor Alignment Calibration Algorithm

#### Background/Introduction

The OLI sensor alignment calibration algorithm uses a time sequence of the LOS model alignment trending results generated by the LOS model correction algorithm (see the LOS Model Correction ADD (6.2.3) for details) to estimate the orientation of the OLI coordinate system relative to the spacecraft attitude determination coordinate system. This spacecraft -to-OLI alignment is one of the fundamental geometric calibration parameters stored in the CPF. Analyzing time sequences of measured alignment results makes it possible to smooth out random scene-to-scene pointing errors to estimate, and correct for, any underlying systematic alignment errors. The OLI sensor alignment calibration algorithm is inspired by the ALI sensor alignment algorithm used in ALIAS. Its implementation will be different, in that the ALIAS code was set up to operate on individual scene results. The heritage logic takes the precision solution output, converts it to apparent alignment errors, and then blends the individual scene results with the current best estimate of the alignment state using a Kalman filter. This approach required the scenes to be processed in time order and did not provide a view of how the apparent alignment errors varied with time, which would have made it easier to detect systematic (e.g., seasonal) effects. By retrieving and analyzing groups of individual alignment results, the OLI algorithm will make it possible to select an appropriate time window and take all the data from that window into account when deriving the alignment calibration for that time.

#### Dependencies

The OLI sensor alignment calibration algorithm assumes that the LOS model correction algorithm has populated the geometric trending database with LOS model alignment trending results.

#### Inputs

The OLI sensor alignment calibration algorithm uses the inputs listed in the following table. The user inputs define the parameters of a query used to retrieve the desired alignment trending data created by the LOS model correction algorithm.

|  |
| --- |
| **Algorithm Inputs** |
| LOS Model Correction Alignment Trending Data (from trending DB)  |
|  Precision correction reference date/time (year, day of year, hours, minutes, seconds) |
|  Roll-pitch-yaw alignment angles (in microradians) |
|  Ephemeris position corrections (in meters) |
|  Alignment covariance matrix |
|  Across- and along-track RMS GCP fit solution quality metrics (in meters) |
|  Control type used (GLS or DOQ) |
|  Number of control points used |
|  GCP outlier threshold used |
|  GCP RMS fit (in meters) |
|  Off-nadir angle (in degrees) |
|  Geometric characterization ID (of trended scene) |
|  Work Order ID (of trended scene) |
|  WRS Path/Row |
| User Inputs |
|  Trending Data Query Date Range |
|  Calibration Effective Date Range |
|  Control Type Selection (GLS, DOQ, Both) |
|  Control Type Weights (if Both are used) (see note 2) |
|  Maximum off-nadir angle (in degrees) (see note 5) |
|  Alignment Trending Flag (1 = save results) |
|  Calibration Parameter File Name |
|  Output Report File Name |

#### Outputs

|  |
| --- |
| OLI Alignment Report (see Table 6‑26 for details) |
|  Standard report header fields |
|  Control type/GCP source selected |
|  Number of scenes analyzed |
|  Retrieved data date range |
|  Estimated alignment angles (roll, pitch, yaw) |
|  Measured alignment angle RMS residuals (roll, pitch, yaw) |
|  OLI Alignment Calibration Parameters |
|  Alignment effective date range |
|  ACS to OLI rotation matrix |
|  Table of alignment trending results returned |
| OLI Alignment Characterization Database Output |
|  Processing date |
|  Processing site |
|  Maximum off-nadir angle used |
|  Control type/GCP source selected |
|  DOQ vs. GLS scene weights used |
|  Number of scenes analyzed |
|  Retrieved data date range |
|  Estimated alignment angles (roll, pitch, yaw) |
|  Measured alignment angle RMS residuals (roll, pitch, yaw) |
|  Alignment effective date range |
|  ACS to OLI alignment matrix |

#### Options

Control Source Selection (GLS or DOQ or Both)

Alignment Calibration Trending On/Off Switch

#### Prototype Code

Inputs to the executable are an ODL parameter file, an ODL CPF, and an ASCII text file that emulates the IAS trending database; outputs are an ASCII report file, an ASCII ODL-formatted CPF fragment, and trending data written to the stdout and captured in an ASCII log file.

The prototype code was compiled with the following options when creating the test data files:

 -g -Wall –O2 -march=nocona -m32 –mfpmath=sse –msse2

The code units of the prototype implementation are briefly described here. Additional details are provided below for units that perform core algorithm processing logic.

aligncal.c – Main driver of the OLI sensor alignment calibration process. Also includes a utility unit to format dates as text.

get\_aligncal\_parms.c – Reads the input ODL parameter file and passes processing parameters back to the main procedure.

query\_dummy.c – A dummy unit that takes the place of a trending database query function. The dummy processes an input ASCII file called alignment\_table.dat, which takes the place of the trending database.

delta\_date.c – Calculates the difference, in seconds, between two dates specified as year, day of year, second of day.

prec\_align\_to\_obs.c – Processes a single trended alignment calibration record (generated by the oliprecision process) using the covariance information to combine the observed attitude and position biases into an integrated alignment error estimate.

aligncal\_output.c – Subprocedure that controls the generation of the report, CPF ODL fragment, and trending data outputs.

write\_report.c – Generates the output ASCII report file.

output\_header.c – Creates the standard (tailored for this application) report header.

calculate\_alignment\_matrix.c – Constructs the attitude control system to OLI rotation matrix corresponding to a set of input roll-pitch-yaw alignment angles.

write\_alignment\_matrix\_ODL.c – Generates the CPF ODL fragment containing the newly computed attitude-to-OLI rotation matrix.

trending\_dummy.c – A dummy unit that writes the trending output from this procedure to stdout, taking the place of a trending database insertion function.

#### Procedure

The purpose of the sensor alignment algorithm is to use a sequence of LOS model correction solutions, including both correction parameter estimates and estimated covariance information, to estimate the underlying ACS frame to OLI instrument frame alignment. A weighted least-squares batch filter implementation is used to isolate the systematic alignment trend from the scene-to-scene variability of the attitude and ephemeris precision correction errors.

Unlike the other geometric correction, characterization, and calibration algorithms, the operational implementation of this algorithm will rely upon an interactive user interface that queries the geometric characterization database to retrieve a user-specified (based on date range and/or control source) set of LOS model correction alignment characterization results. The prototype implementation emulates this process by providing query parameters in an ODL parameter file and using them to filter (query) a static ASCII text file that emulates the trending database.

The algorithm uses the individual scene results returned from the database to estimate updates to the OLI alignment angles. The LOS model correction algorithm generates apparent OLI-to-ACS alignment angles each time it runs, whether on L1T product scenes using Global Land Survey (GLS) 2000 control, or on calibration scenes using digital orthophoto quadrangle (DOQ) control, based on the attitude corrections it estimates from the ground control measurements. The sensor alignment calibration algorithm analyzes these results over multiple scenes to detect the systematic trends that are used to update the ACS-to-OLI alignment estimate used in the CPF.

The sensor alignment calibration algorithm consists of five steps:

1. Allow the user to specify the date range, control source(s), and maximum off-nadir angle defining the desired range of LOS model correction alignment results.
2. Query the geometric characterization database to retrieve results meeting the specified criteria.
3. Determine the best-fit alignment angles from the individual scene results using a least squares procedure.
4. Allow the user to review the results, edit the list of input scenes used and rerun the solution, and accept or reject the result.
5. If the result is accepted by the user, generate an output report including the list of input scenes used and the final best-fit alignment parameters, compute the corresponding ACS to OLI alignment matrix, and write out a calibration parameter group containing the alignment matrix in the format used by the CPF.

The sensor alignment calibration algorithm procedure is depicted in Figure 6‑47.



Figure 6‑47. Sensor Alignment Calibration Algorithm Architecture

##### Step 1: Define the Data

The user provides a start and stop date to define the desired range of acquisition dates for the returned characterization data, a control type selection that makes it possible to use scenes processed with either DOQ or GLS control, or both, and a maximum off-nadir angle, in degrees, to include or exclude off-nadir acquisitions from the calibration process. The start/stop dates are inclusive. If the start date is not provided, all data acquired on or before the stop date are used. If the stop date is not provided, all data acquired on or after the start date are used. If no dates are provided, all dates are included. The DOQ/GLS/Both control selection defaults to DOQ. The maximum off-nadir angle is provided as an absolute value, i.e., only scenes between +MAXANG and -MAXANG would be included if MAXANG is the specified limit. The off-nadir angle limit defaults to 0.1 degrees to exclude off-nadir images.

##### Step 2: Retrieve the Data

The date range and control selection defined in step 1 are used to construct a database query to retrieve the desired scene records from the LOS model correction alignment table in the characterization database (see Table 6-26 in the LOS Model Correction ADD (see 6.2.3)). All fields in this table are returned and all but the full alignment covariance matrix are displayed to the user (in step 4 below). Only the diagonal elements and the roll-Y and pitch-X elements of the covariance are displayed. The fields returned include the following:

1. Work order ID,
2. Geometric Characterization ID,
3. WRS path,
4. WRS row,
5. Control type,
6. Off-nadir angle,
7. Number of GCPs used,
8. GCP outlier threshold used,
9. Root-mean-square (RMS) ground control point (GCP) fit (solution quality metric),
10. Acquisition date (year, day of year) and time (hours, minutes, seconds),
11. Measured roll alignment,
12. Measured pitch alignment,
13. Measured yaw alignment,
14. Measured ephemeris (orbital) X correction,
15. Measured ephemeris (orbital) Y correction,
16. Measured ephemeris (orbital) Z correction,
17. Alignment covariance matrix:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Covroll-roll | Covroll-pitch | Covroll-yaw | Covroll-X | Covroll-Y | Covroll-Z |
| Covpitch-roll | Covpitch-pitch | Covpitch-yaw | Covpitch-X | Covpitch-Y | Covpitch-Z |
| Covyaw-roll | Covyaw-pitch | Covyaw-yaw | Covyaw-X | Covyaw-Y | Covyaw-Z |
| CovX-roll | CovX-pitch | CovX-yaw | CovX-X | CovX-Y | CovX-Z |
| CovY-roll | CovY-pitch | CovY-yaw | CovY-X | CovY-Y | CovY-Z |
| CovZ-roll | CovZ-pitch | CovZ-yaw | CovZ-X | CovZ-Y | CovZ-Z |

Note that the covariance matrix can be subdivided into four 3x3 blocks:

|  |  |
| --- | --- |
| **A** | **B** |
| **BT** | **C** |

Where: **A** is the covariance of the attitude correction parameters, **C** is the covariance of the ephemeris correction parameters, **B** is the cross-covariance of the attitude and ephemeris parameters, and **BT** is the transpose of the cross-covariance.

This formulation of the covariance matrix will be used below in combining the measured alignment and ephemeris corrections.

##### Step 3: Compute the Alignment

Computing the least squares estimate of the underlying alignment trends from the retrieved sequence of individual scene alignment measurements is complicated by the correlation between the measured angular alignment corrections and the measured ephemeris corrections. Although we do not expect to detect any systematic offset in the position bias terms (x, y, and z), they are included because of their high correlation with the attitude biases. This is reflected in the observation covariance matrix where significant off-diagonal terms will exist for X-pitch and Y-roll. Any particular LOS model correction solution will resolve the correlation between the parameters by allocating the along-track and across-track errors between the ephemeris and attitude parameters based on their a priori weights. Thus, some of the systematic alignment bias could end up allocated to the ephemeris correction terms. Over multiple precision correction solutions, the net ephemeris bias should be very close to zero. Therefore, we use the covariance information to combine the ephemeris terms with the alignment terms to create consolidated along- and across-track corrections. In practice, since accurate GPS-derived ephemeris will be available, most of the correction will be allocated to the attitude terms in the LOS model correction solutions anyway.

Each retrieved scene provides a vector of six correction measurements:



where:

roll = roll alignment angle, in microradians (μrad);

pitch = pitch alignment angle (μrad)

yaw = yaw alignment angle (μrad)

X = along-track orbit position error in meters (m)

Y = cross-track orbit position error (m)

Z = radial orbit position error (m)

**x** = the roll-pitch-yaw 3x1 sub-vector

**y** = the X-Y-Z 3x1 sub-vector

The corresponding covariance matrix is also retrieved (see the LOS Model Correction ADD (see 6.2.3) for a description of how these characterization data are created). It has the following structure:



Comparing this to the A-B-C decomposition shown above, note that the "**A**" portion of the covariance matrix contains the attitude/attitude terms, the “B” portion of the matrix contains the attitude/ephemeris terms, and the "**C**" portion of the matrix contains the ephemeris/ephemeris terms.

The alignment and ephemeris corrections are combined as follows:

**x**' = **x** - **BC-1y**

where: **x**' = the consolidated along- and across-track alignment vector

 **x** = the input alignment corrections

 **y** = the input ephemeris corrections

 **B** and **C** are the 3x3 covariance sub-matrices defined above.

Thus, the six LOS model correction measurements retrieved for each scene are reduced to three equivalent alignment angle observations for each scene. Consolidating the results for each scene in this manner yields a sequence of alignment angle observations:

**x'j** where: j = 1 to N with N being the number of scenes retrieved.

Each scene observation is also assigned a (scalar) weight, wj, based upon its control source. The DOQ and GLS weights are editable by the user, and are initially populated with default values (e.g., 50% for DOQ scenes and 50% for GLS scenes). Note that these weights are only relevant if both GLS and DOQ controlled scenes are used at the same time. The logic that enables the user to edit the weights should ensure that only numbers between 0 and 100% are allowed.

The new alignment estimate is the weighted average of these observations:



Compute the RMS residuals:







The corresponding orientation matrix is:



Take the transpose of the **M**OLI2ACS matrix to compute the ACS to OLI alignment matrix used in the CPF, **M**ACS2OLI.

##### Step 4: Review the Results

The user is presented with a scrollable table of the individual scene results as well as the summary roll, pitch, and yaw alignment values (r, p, and y) and the roll-pitch-yaw RMS residuals. The scene results table's columns include, in addition to the fields identified in step 2 above, the weight value, and the consolidated roll'-pitch'-yaw' values computed in step 3. The Landsat 7 Bumper Mode User Interface (BUI) is a good model for this display.

Each row in the table includes a check box or button (e.g., the BUI "Select" column) that the user can select to remove that scene/row from the alignment calculation. The user may choose to exclude scenes, based on the off-nadir angle or RMS GCP fit metrics, for example. The user can also press a button to recalculate the average alignment based on the current selection of rows. The user should be able to adjust the selected scene list and recompute the average alignment as many times as desired.

A capability to plot each alignment angle is desirable but not required (see note #1). If provided it should allow the user to select which axis (roll, pitch, or yaw) to plot and then plot the corresponding consolidated angles for each selected scene on the Y axis with scene acquisition date on the X axis. It should also show the mean alignment value for that axis as a solid horizontal line or other easily identifiable symbol.

Once the user is satisfied with the alignment solution, or is ready to give up, he or she presses either the "Accept" button or the "Quit" button. The "Accept" button advances the process to step 5. The "Quit" button terminates the algorithm.

##### Step 5: Generate the Output

The sensor alignment calibration algorithm creates either two or three outputs depending upon the setting of the "Alignment Trending Flag.” In all cases, a report file is generated using the input file name specified by the user, and an ODL file fragment is written out containing the ATTITUDE\_PARAMETERS CPF group including the newly calculated ACS-to-OLI rotation matrix. Characterization database output is only created if the alignment trending flag is set to "Yes.” The user input effective date ranges for the output calibration parameters (the ACS-to-OLI sensor alignment matrix) are embedded in the automatically generated file name used for the output ODL CPF fragment. The calibration parameter effective date range need not match the original query date range as it is often desirable to include extra data from outside the calibration time window to ensure continuity in the calibration parameters from time to time period.

Once the solution is accepted by the user a report file is generated containing the items shown in Table 6‑26. Note that the first 11 items in Table 6‑26 constitute the standard report header, but that several of these fields are not applicable for a multi-scene algorithm such as sensor alignment calibration. Also note that the alignment matrix output is formatted as a CPF parameter group and includes the effective date range specified by the user. In addition to the standard report header information, the report file contains the summary alignment angles and RMS residuals, the CPF OLI alignment matrix and effective dates, and a comma-delimited table containing key fields from all the individual scene rows used in the alignment solution.

If the alignment trending flag is set, the subset of the items in Table 6‑26 with "Yes" in the "Database Output" column are written to the characterization database.

|  |  |  |
| --- | --- | --- |
| **Field** | **Description** | **Database Output** |
| Date and time | Date (day of week, month, day of month, year) and time of file creation. | Yes |
| Spacecraft and instrument source | Landsat 8/9 and OLI | No |
| Processing Center | EROS Data Center SVT (see notes #3) | Yes (see note #4) |
| Work order ID | Work order ID – not used for sensor alignment calibration as it operates on the results of multiple work orders. | No |
| WRS path | WRS path number - blank for sensor alignment cal | No |
| WRS row | WRS row number - blank for sensor alignment cal | No |
| Software version | Software version used to create report | No |
| Off-nadir angle | Actual maximum scene off-nadir roll angle (in degrees) | Yes |
| Acquisition Type | Earth viewing, Lunar, or Stellar (only Earth-viewing scenes are used for sensor alignment calibration) | No |
| Geo char ID | Geometric characterization trending ID – not used for sensor alignment calibration. | No |
| L1G image file | Not used for sensor alignment calibration | No |
| Acquisition date | N/A for sensor alignment calibration | No |
| GCP source | Ground control source used (GLS or DOQ or Both) | Yes |
| DOQ Weight | Weight placed on DOQ-controlled scenes (0-100%) | Yes |
| GLS Weight | Weight placed on GLS-controlled scenes (0-100%) | Yes |
| Number of scenes used | Number of scenes used in calibration | Yes |
| Data start date | Start date of data window used (query start) | Yes |
| Data stop date | Stop date of data window used (query stop) | Yes |
| Roll alignment | Best-fit roll alignment angle in microradians | Yes |
| Pitch alignment | Best-fit pitch alignment angle in microradians | Yes |
| Yaw alignment | Best-fit yaw alignment angle in microradians | Yes |
| Roll residual RMSE | RMSE of individual scene roll residuals (microradians) | Yes |
| Pitch residual RMSE | RMSE of individual scene pitch residuals (microradians) | Yes |
| Yaw residual RMSE | RMSE of individual scene yaw residuals (microradians) | Yes |
| Alignment effective date start | Start effective date of alignment calibrationReport format: Effective\_Date\_Begin = "YYYY-MM-DD" | Yes |
| Alignment effective date stop | Stop effective date of alignment calibrationReport format:Effective\_Date\_End = "YYYY-MM-DD" | Yes |
| OLI sensor alignment matrix | Best-fit ACS to OLI rotation matrixReport format:Attitude\_To\_OLI\_Matrix = (sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn,  sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn,  sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn, sn.nnnnnnnnEsnn)  where: s = sign (+/-) and n = digit | Yes |
| For each scene used in the calibration: |  |  |
| Work order ID | Work order ID that generated scene results | No |
| Geo Char ID | Geometric Characterization ID for scene | No |
| WRS path | Scene WRS path number | No |
| WRS row | Scene WRS row number | No |
| Control type | DOQ or GLS | No |
| RMS GCP fit | Root-mean-square (RMS) ground control point (GCP) fit solution quality metric | No |
| Acquisition date | Scene acquisition date | No |
| Combined roll alignment | Consolidated roll value (roll') in microradians | No |
| Combined pitch alignment | Consolidated pitch value (pitch') in microradians | No |
| Combined yaw alignment | Consolidated yaw value (yaw') in microradians | No |

Table 6‑26. Sensor Alignment Calibration Output Details

**Accessing the Sensor Alignment Characterization Database**

Though not part of the formal sensor alignment calibration algorithm, some comments regarding the anticipated methods of accessing and analyzing the sensor alignment results stored in the characterization database may assist with the design of the characterization database.

The database output from the sensor alignment calibration algorithm will be accessed only for purposes of reviewing the history of calibration operations. Unlike other calibration and characterization algorithms, no summary statistics are required since the sensor alignment calibration results are themselves summary statistics. Hence, a special tool to perform the query and retrieval is probably not necessary so long as basic database query capabilities are readily available.

The sensor alignment results would typically be queried by processing date, CPF effective dates, maximum off-nadir angle, and/or GCP source. The most common query would likely be a combination of GCP source and CPF effective date range, for example, selecting all of the DOQ-derived results effective for a given calendar year:

 GCP\_Source = "DOQ"

 Effective\_Start\_Date is between 01JAN2013 and 31DEC2013

 Effective\_Stop\_Date is between 01JAN2013 and 31DEC2013

The query results should be formatted in a set of comma-delimited records (for ease of ingest into Microsoft Excel), one record per scene. Each record would contain all of the fields written to the characterization database (items with "Yes" in the rightmost column of Table 6‑26 above). A header row containing the field names should precede the database records.

#### Maturity

Parts of the heritage ALIAS sensor alignment calibration logic were reused, but the OLI version is substantially new (but simpler).

1. A user interface to capture input from the Cal Analyst will be required, but is not provided with the prototype implementation.
2. An interface to query the geometric trending database will be required. This is emulated by a text file in the prototype implementation.
3. A capability to display the query results (as a table) to the Analyst, allowing him/her to selectively include or exclude particular entries will be required. This is not provided in the prototype implementation.
4. The updated alignment estimate computation capabilities perform the following:
	1. Merge the X and Y precision solution offsets into the pitch and roll (respectively) alignment estimates using the trended covariance information. Note that this blending was implicit in the heritage Kalman filter implementation.
	2. Fit constant (average) functions to the alignment estimates.
	3. Convert the alignment angles to the equivalent ACS-to-OLI rotation matrix for inclusion in the CPF.
5. A capability to insert the resulting alignment calibration parameters into the trending database (upon Analyst command) will also be required. This is emulated by ASCII output to stdout in the prototype implementation.

#### Notes

Some additional background assumptions and notes include the following:

1. Plotting capability that shows the individual scene alignment measurements along with the fitted constant results would also be nice.
2. Results derived from GLS control, if used at all for sensor alignment calibration, would be given lower weight than DOQ controlled scenes due to the poorer accuracy of the GLS control source as well as the additional alignment uncertainty introduced by using the SWIR1 band for GCP mensuration.
3. Configuration parameters should be provided for each installation of the algorithm implementation to convey site-specific information such as the processing center name (used in the standard report header), the number of processors available (for parallel processing implementations), etc. This takes the place of the heritage system table, which also contained certain algorithm-related parameters. Anything related to the algorithms has been moved to the CPF for Landsat 8/9. This is implemented through environment variables in the prototype.
4. Most geometric characterization trending output is performed on a scene-by-scene basis so the work order ID, geometric characterization ID, and/or acquisition date fields uniquely identify the data being characterized and provide the basis for a unique database key for the trended record. In the case of sensor alignment, many input data sets are used, so provisions for a unique database record key are somewhat different. This is primarily an implementation detail, so no unique key fields are called out in the output table or Table 6‑26 above, nor are sensor alignment calibration work order or geometric characterization IDs included in the database output. That said, the concept is that a unique sequence number would be automatically generated each time a new sensor alignment calibration record was inserted into the characterization database. In conjunction with a processing site identifier (e.g., EROS, GSFC, BATC, or SDSU), this sequence number would provide the basis for a primary key that would uniquely distinguish OLI sensor alignment calibration results generated at EROS or elsewhere.
5. Sensor alignment calibration would typically be run using the results from nadir-viewing scenes only. Since all processed scenes can produce alignment calibration results (through the LOS model correction algorithm) the user of this application needs to be able to filter the scene results based upon the off-nadir angle field.