Algorithm Theoretical Basis Document

Geometric Algorithms – Level 1 products

V1.2

Updated: 13 March 2025

farearth
FOR SMALLSATS

Contents

1 Introduction

This document describes the geometric algorithms used to calibrate and characterise an Earth Observation sensor using the *FarEarth* system. It is intended as a summary of the algorithms used and not as an in-depth description of the full process. Some flowcharts are provided showing the processing chains.

A short description of the terminology specific to the *FarEarth* system is given below:

Term	Description
Calibration Parameter File (CPF)	File containing information on the physical sensor properties, band descriptions and the geometric calibration coefficients
Tiepoints	Salient features on both the satellite image and the reference image which matches the satellite image coordinates to the reference image coordinates
Systematic/Precision	Orthorectification and band alignment may be performed using either a systematic or precision model. A systematic model is constructed using only the geometric calibration coefficients and the satellite's NavAtt data, while a precision model is a refined model using tiepoints. For orthorectification, tiepoints to an absolute geometric reference image are used, and for band-alignment, relative tiepoints between bands are used

2 Geometry

The geometric algorithms are used to:

- Determine the boresight alignment rotation matrixes required to align the sensor with the satellite's pose (attitude) and the line-of-sight polynomial coefficients required to project each detector/pixel to the Earth.
- Process the sensor's RAW data to band-aligned, orthorectified and map projected images.
- Validate the quality of the geometric products against reference imagery.

2.1 Geometric calibration

In-orbit geometric calibration consists of two main parts:

1. Boresight alignment calibration, and
2. Line-of-sight (LoS) calibration

In both cases, reference orthorectified imagery is used:

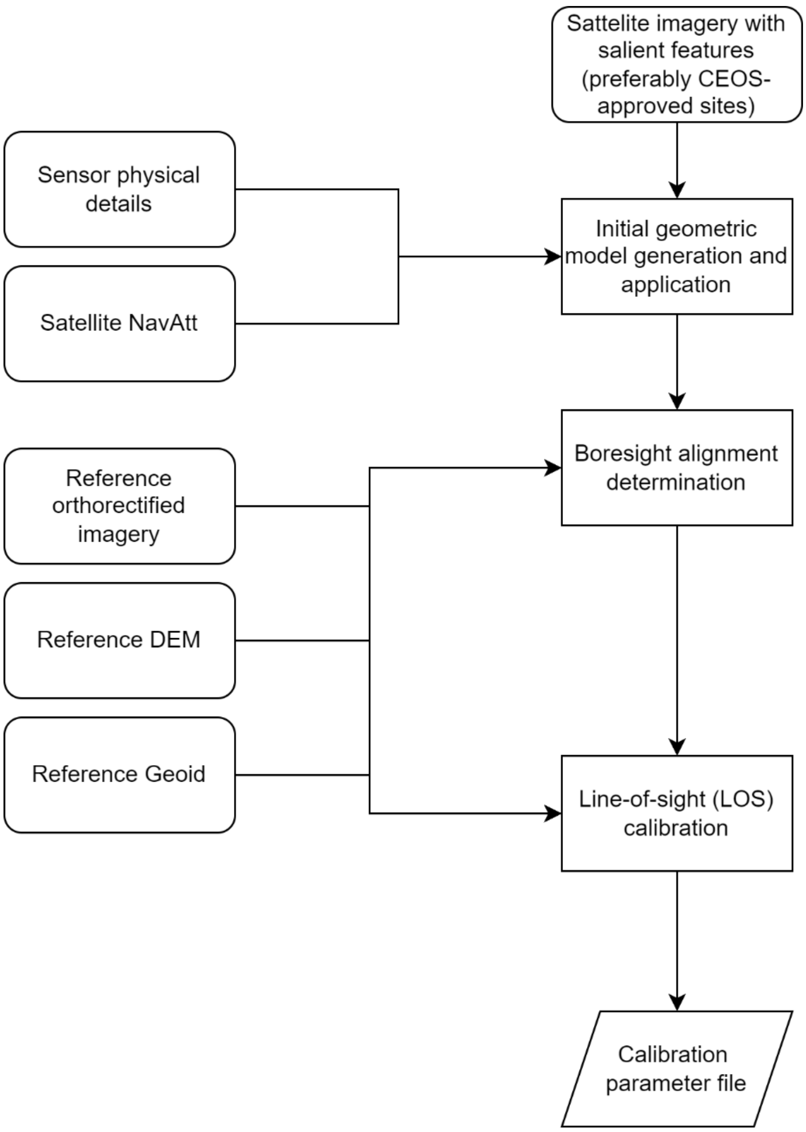

Figure 1: Geometric calibration overview

2.1.1 Boresight alignment calibration

Boresight alignment is the process of aligning the imaging sensor's frame to the attitude frame of the satellite. In most cases, the primary imaging sensor on a telescope is mechanically aligned to have the same pointing orientation as the satellite attitude determination and control system (ADCS). The satellite's attitude frame is therefore often closely aligned with the imaging sensor frame. However, there might be a misalignment bias between these two frames, either intentionally by design, or because of sensor and/or ADCS alignment inaccuracies during the manufacturing or assembly process, or due to launch shock, outgassing, etc.

Boresight alignment calibration is the determination of a 3D Euler rotation matrix which will be applied to bring the imaging sensor and satellite attitude frames in line.

Initially, boresight alignment is performed by systematically projecting a scene (preferably over a CEOS-approved geometric calibration site) onto the Earth using a geometric sensor model based on physical parameters. These parameters include:

- The along and across sensor instantaneous field of view (per detector)
- Sensor along and across detector counts
- A perfect alignment between the telescope and the ADCS (identity Euler rotation matrix)

Only a single band close to the sensor's centre is used for boresight calibration. After the image is systematically projected to the Earth, tiepoints around the centre of the image are collected against a reference orthorectified image (e.g., Sentinel-2 L1C image). The reference orthorectified image is an image of the same area which is cloud-free and temporally close to the satellite image.

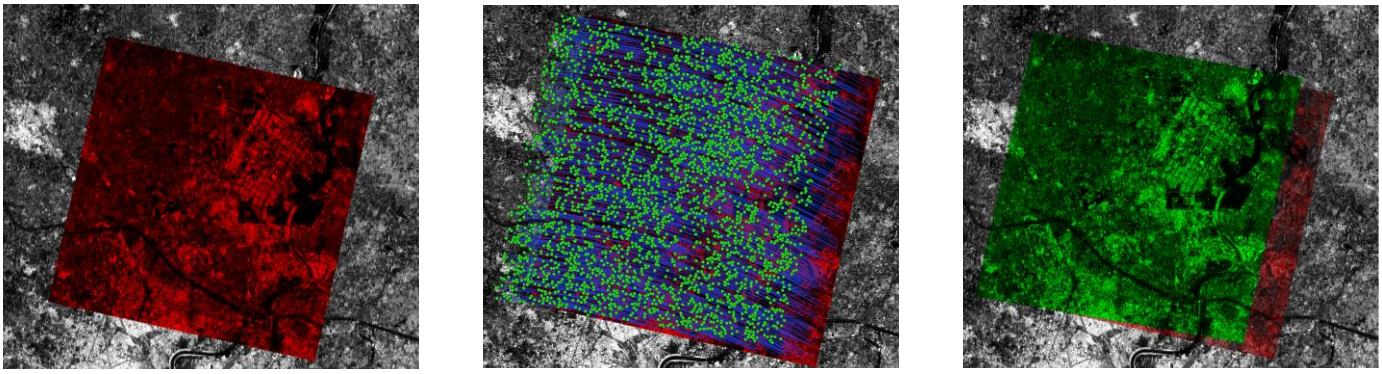

Figure 2: Example of boresight alignment of the central band of a sensor (red) to a reference Sentinel-2 orthorectified image (grey). The initial systematically projected (left), the tiepoints between the central band and reference image (centre), and the before (red) and after (green) boresight-aligned central band is shown (right).

From these tiepoints, a 3D Euler rotation matrix ($M_{boresight}$) is determined. An example boresight alignment matrix is shown below.

$$M_{boresight} = \begin{bmatrix} 0.9988 & 0.0479 & -0.0004 \\ -0.0479 & 0.9988 & 0.0049 \\ 0.0006 & -0.004 & 0.9999 \end{bmatrix}$$

This matrix is stored in the calibration parameter file (CPF) for future use.

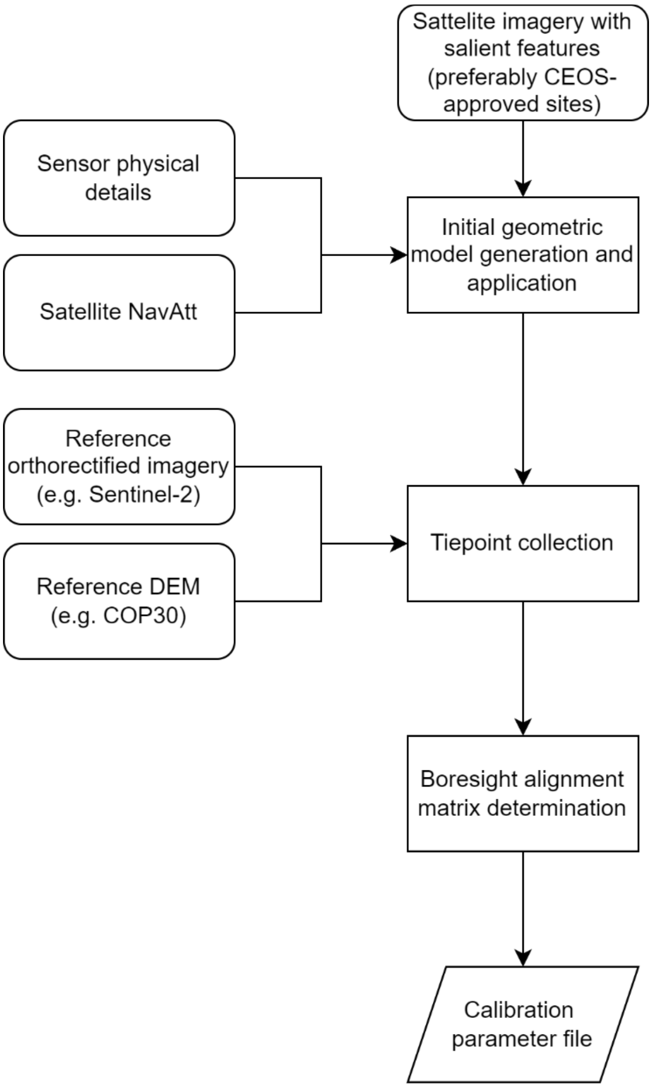

Figure 3: Boresight alignment calibration flowchart

2.1.2 Line-of-sight (LOS) calibration

Line-of-Sight (LOS) calibration provides a model that describes a pointing vector for each detector within each band. The goal of line-of-sight (LOS) calibration is to estimate the best polynomial coefficients for the along- and across-scan pointing vectors. The LOS vectors are 3D pointing vectors projected from the detectors/pixels to the Earth. Each band has a model that generates the pointing vector for each detector. Generally, the LOS_x and LOS_y components of the LOS vector are expressed as linear functions.

Therefore, the LOS vector model has the structure of:

$$LOS(d) = \begin{cases} \sum_{i=0}^{n_x} c_{xi} * d^i \\ \sum_{i=0}^{n_y} c_{yi} * d^i \\ 1 \end{cases} = \begin{cases} LOS_x \\ LOS_y \\ LOS_z \end{cases}$$

$$LOS^* = |LOS|$$

where:

n_x and n_y are the polynomial orders for LOS_x and LOS_y
c_x and c_y are the polynomial coefficients for LOS_x and LOS_y
d is the normalised detector index

LOS calibration is the process of estimating the coefficients c_x and c_y.

To determine the two coefficient sets c_x and c_y, tiepoints are collected between the satellite images incorporating the boresight alignment and the reference orthorectified images (e.g. Sentinel-2). The same reference selection criteria are used as for the boresight calibration.

Using these tiepoints the best LOS coefficients are determined that minimize the geolocation disparities of the geometric sensor model.

The final LOS models are determined per band at a specific sensor row and stored in the CPF for future use.

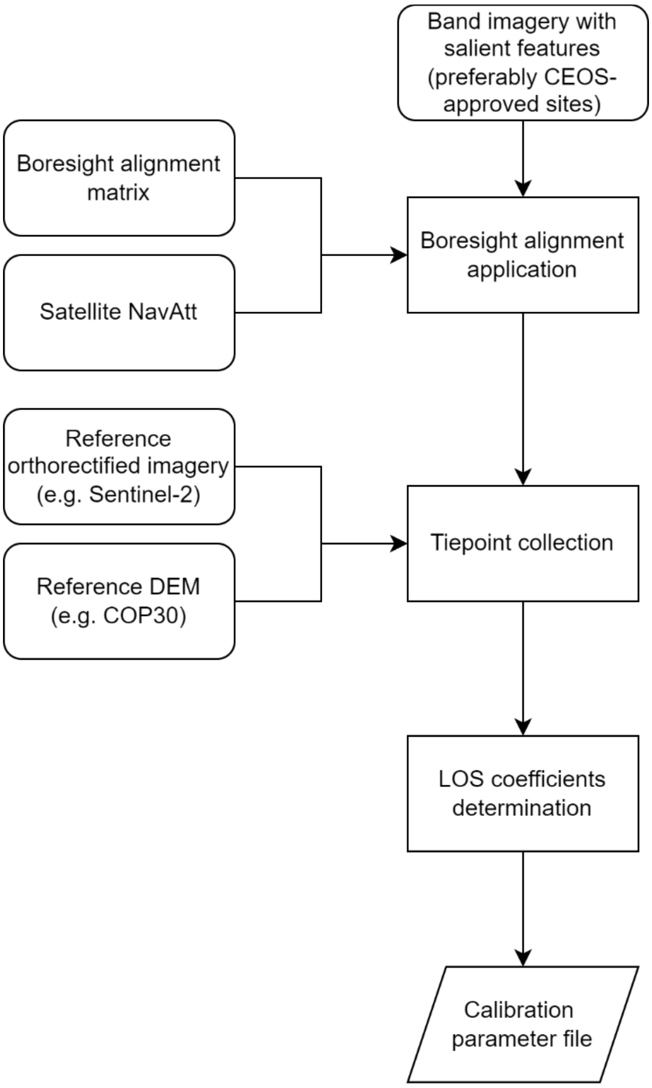

Figure 4: Line-of-sight (LOS) calibration flowchart

2.2 Geometric processing – product generation

During image processing, the satellite image is geometrically corrected to be accurately located on the Earth and the images from individual sensor bands are aligned to each other. The steps are:

1. RAW to L0: no geometric processing applied
2. L0 to L1A: systematic geolocation model is generated for all bands
3. L1A to L1B: either a systematic or precision (if possible) orthorectification and band alignment model is generated. The band alignment model (systematic or precision) is applied.
4. L1B to L1C: orthorectification model (systematic or precision) is applied and geometric quality assessment is performed using GVerify.

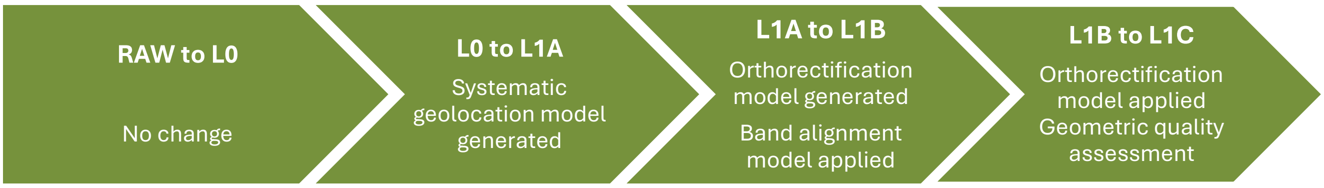

Figure 5: Geometric processing steps

2.2.1 Systematic alignment

Boresight alignment is performed by applying the rotation as defined by the boresight alignment matrix contained in the satellite's CPF.

For a given scanline, each detector is projected onto the Earth. Using the attitude and ephemeris (ATT & EPH) associated with the scanline, the LOS projection is performed. The algorithm casts a ray for each detector from the satellite onto the Earth using the LOS coefficients contained in the satellite's CPF.

The Earth model used is WGS84 (World Geodetic System). The projection traces the intersection point of the LOS ray onto the Earth's ellipsoid, or if an elevation model is used, the ray is traced until the desired height above the ellipsoid is found. The WGS84 model is an Earth-Centred Earth Fixed (ECEF) model; thus, the EPH data must be transformed into an ECEF reference frame to be compatible.

The ATT is transformed into the satellite's Local-Vertical Local-Horizontal (LVLH) reference frame so the orientation can be directly mapped from the satellite.

2.2.2 Precision alignment

After systematic alignment, tiepoints are collected between the sensor's most-central band and an orthorectified reference image, similar to what was done during the calibration process. This is used to refine the geometric model of the central band.

If this refinement process is successful the product's orthorectification is flagged as “PRECISION”, while if it cannot be performed due to a lack of cloud-free reference imagery or an inability to collect tiepoints (e.g., due to cloudy satellite imagery), the orthorectification is flagged as “SYSTEMATIC”.

For precision band alignment, tiepoints are collected between the different bands of the sensor. The disparities between the bands are determined and the most suitable alignment paths between bands are used to align the bands to the central band.

Similar to the orthorectification flags, if this band alignment refinement process was successful, the product's band alignment is flagged as “PRECISION”, and “SYSTEMATIC” otherwise.

2.2.3 Processing summary

The flowcharts below show the geometric processing performed during product generation:

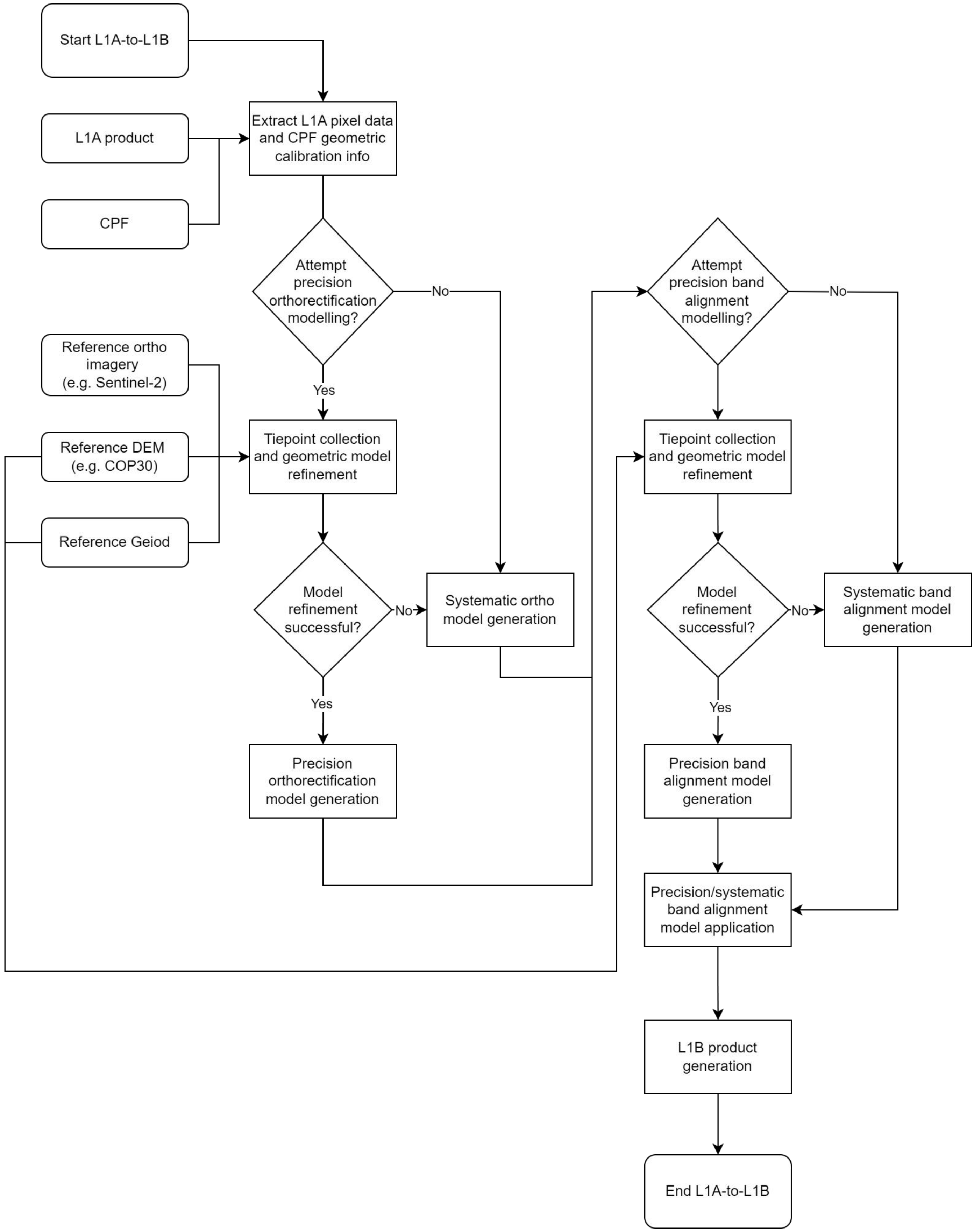

Figure 6: L1A to L1B processing flowchart

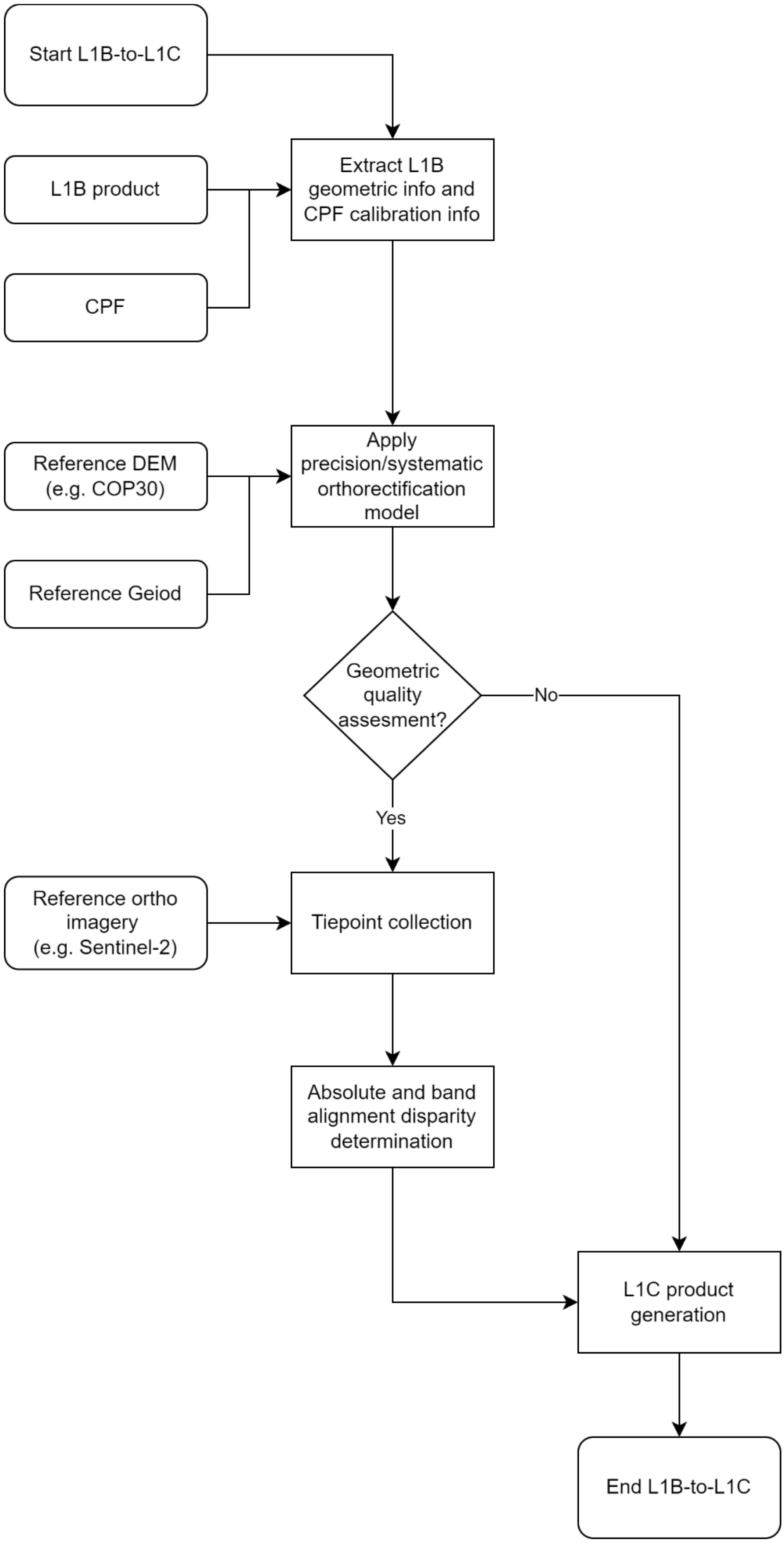

Figure 7: L1B to L1C processing flowchart

2.3 Geometric validation

Geometric validation is performed to determine the geometric quality of the generated products using GVerify.

GVerify uses a similar process compared to the geometric calibration and precision alignment processes mentioned above. Tiepoints are collected between the product's central band image and a reference orthorectified image which covers the central band's spatial extent, is temporally close to the acquisition date, and is cloud-free. This is used to estimate the absolute geometric accuracy compared to the reference image (e.g. Sentinel-2). Similarly, tiepoints are collected between bands to estimate the band alignment precision.

GVerify metadata and images of the tiepoints' disparities overlayed on the images are generated and published with the products. The disparities are colour-coded to indicate the level of severity (see below). The disparities can be used to determine the Mean Error and Circular Error with a 95 % probability (CE95), which is given in the L1C product reports together with scatter plots.

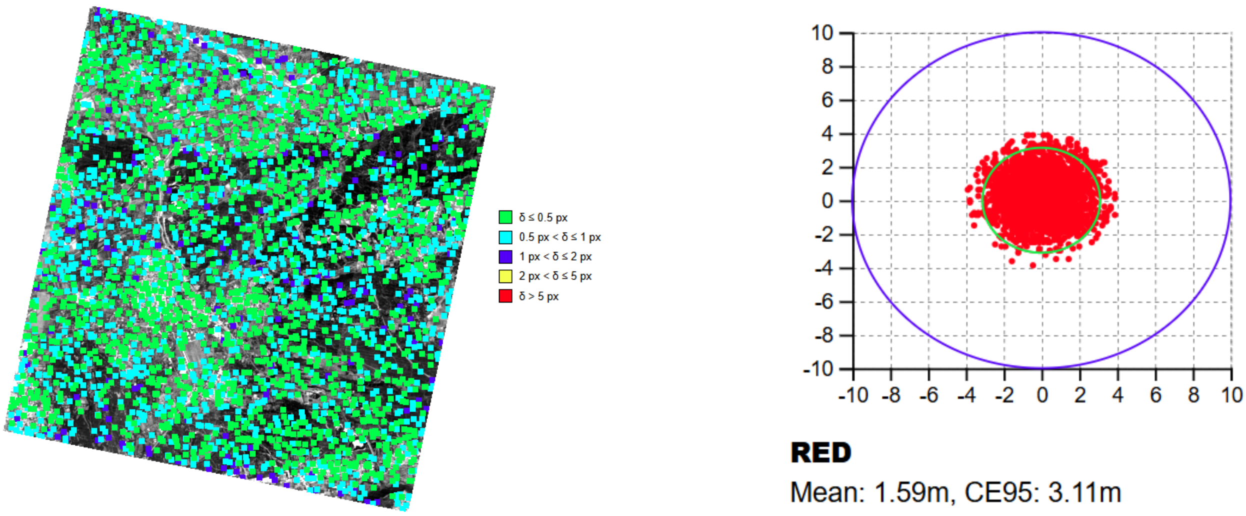

Figure 8: Examples of an absolute geometric validation GVerify image (left) and CE95 scatter plot (right) provided with L1C products. The scatter plot shows the tiepoints (red points), the GSD of the satellite image (green circle), GSD of the reference image (blue circle), and CE95 (red circle – below the green circle),

If the results of the geometric quality assessment reveal any drift or abnormal behaviour, the geometric calibration can be updated using more recently acquired imagery.

2.4 Uncertainty characterisation

Although a full uncertainty evaluation is not performed, the GVerify process gives an indication of the accuracy and precision of the geometric performance by providing a comparison to reference orthorectified imagery.

The following factors may influence the geometric uncertainty:

- Any inaccuracies in the ATT&EPH data, especially with the ATT data from the spacecraft's ACDS, can result in poor pointing accuracy. These inaccuracies or random noise may need to be addressed explicitly, e.g. smoothing of the ATT, and will contribute to the geometric uncertainty.
- Issues with the boresight alignment due to inaccuracies in determining tiepoints between the sensor image and the reference ortho image.
- Issues with determining the LOS polynomials. The quality of the LOS polynomials is influenced by
  - Too low/high order LOS polynomials
  - Insufficient number of tiepoints or insufficient accuracy of tiepoints
  - Uneven distribution of tiepoints across the image
- Uncertainty due to the misalignment between sensors when a multi-sensor design is employed.