Algorithm Theoretical Basis Document

Radiometric Algorithms – Level 1 products

V1.2

Updated: 13 March 2025

farearth
FOR SMALLSATS

Contents

1 Introduction

This document describes the radiometric 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. This document is applicable to products up to Level 1 and visible to near-infrared (VNIR) imagery.

Flowcharts are provided showing the processing chains.

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

Term	Description
Radiometric Parameter File (RPF)	File containing information on the radiometric sensor properties, band spectral ranges and the radiometric calibration coefficients
Detectors/pixels	"Detector" is used when referring to the physical single element of a sensor array, while "pixel" is used when referring to a subgroup of detectors, which can be achieved by binning and/or time delay integration (TDI). E.g., an image sensor which has 4096 x 3072 (column x row) individual detectors, with bands using 2 x 2 binning and TDI = 4, will combine 16 detectors per pixel.

2 Radiometry

Radiometric algorithms are used to:

- Determine the calibration coefficients required to convert the sensor's RAW Digital Number (DN) values to top-of-atmosphere (TOA) radiance or reflectance values
- Process the sensor's RAW DN values to TOA radiance or reflectance
- Validate the quality of the radiometric processing by comparison to reference sensors

2.1 Radiometric calibration

Radiometric calibration of an Earth Observation sensor is performed in three steps:

1. Dark signal non-uniformity (DSNU) calibration
2. Photo response non-uniformity (PRNU) calibration
3. Absolute radiometric calibration

For in-orbit calibration, the radiometric calibration consists of these three steps and is schematically shown below:

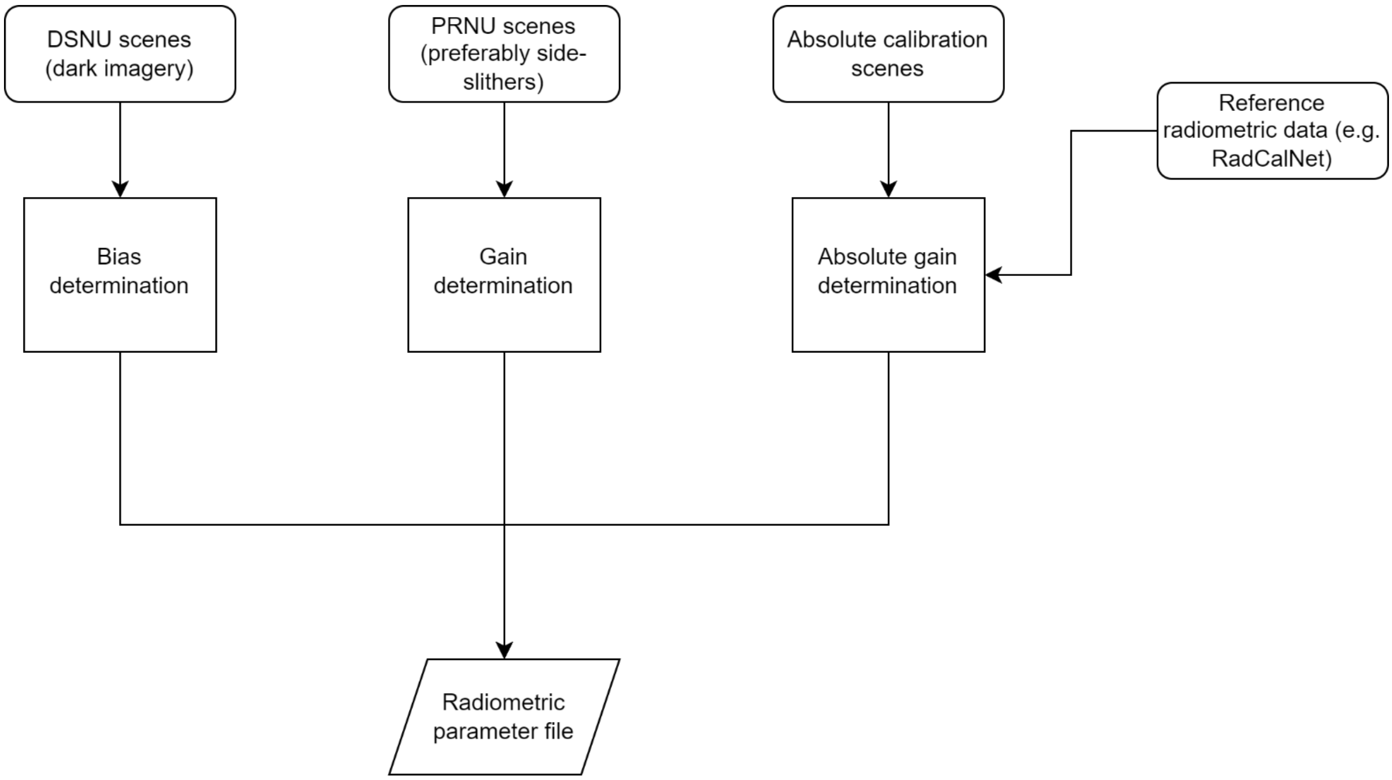

Figure 1: Radiometric calibration overview

2.1.1 Dark signal non-uniformity (DSNU) calibration

Dark signal non-uniformity calibration (DSNU) is the determination of the dark signal/current that is present on the sensor when there is no light falling on the sensor.

Pre-launch, this bias can be determined using datasets obtained in a dark room with no light incident on the sensor. In-orbit, this can be determined using dark images over the South Pacific Ocean when the sun and moon are below the horizon.

Dark images are evaluated for use by examining the RAW DN values and checking for sun and moon elevation angles. Preferred dark images are acquired during a new moon. The dark current bias coefficients are determined and stored in the radiometric parameter file (RPF) for later use during image processing.

2.1.2 Photo response non-uniformity (PRNU) calibration

The photo response non-uniformity (PRNU) calibration is the determination of the non-uniformity between detectors/pixels when light is incident on the sensor. After bias correction, there is still a non-uniformity between the sensor detectors/pixels due to differences in sensitivity and defects across the sensor.

The PRNU calibration can be performed pre-launch in the laboratory using a uniform target such as an integrating sphere, or in-orbit using acquisitions taken over uniform sites as recommended by CEOS.

The preferred method is to use side-slither acquisitions where the imagery is taken with the satellite turned by approximately 90° (yaw). This results in the detectors/pixels per row passing over the same location. The pixels are precisely aligned such that all horizontal detectors/pixels are of the same point on Earth. The uniformity across the image is assessed and areas which do not meet minimum uniformity criteria are excluded from use for calibration.

The bias-corrected DN values in the uniform areas are then compared across the sensor to determine the PRNU coefficients. This is stored as a gain coefficient per detector/pixel in the RPF for future use during processing.

Figure 2: Example of side-slither image after rotation/refinement

2.1.3 Absolute radiometric calibration

Absolute radiometric calibration entails determining the coefficients required to convert the DSNU- and PRNU-corrected DNs to TOA radiance or reflectance. Absolute calibration of a sensor is important to provide reliable measurements for quantitative analysis, intercomparison with other sensors, and more. Additionally, for satellites with an optical payload that has a multi-sensor design, it is important to ensure that the sensors have equalised radiometric responses.

Absolute radiometric calibration can be performed pre-launch in the laboratory using a reference, such as an integrating sphere with known spectral radiance. In orbit, the absolute radiometric calibration can be performed using measurements over CEOS-approved Radiometric Calibration Network (RadCalNet) sites which provide reference measurements. Bottom-of-atmosphere (BOA), Top-of-Atmosphere (TOA) reflectance, and atmospheric conditions are provided.

Acquisitions over RadCalNet sites are evaluated for suitability based on several criteria, including weather conditions, sensor performance, and satellite NavAtt. Images should preferably be acquired near-nadir (off-nadir < 5°) to avoid errors due to atmospheric modelling.

The steps followed are:

1. The raw data is processed to DSNU- and PRNU-corrected DN using the bias and gains determined previously.

2. The mean of the corrected DN values over the RadCalNet site is determined for each band using a RadCalNet region of interest (ROI).
3. The bottom-of-atmosphere (BOA) spectral reflectance and atmospheric conditions of the site obtained from RadCalNet are interpolated to the time of the acquisition.
4. The RadCalNet BOA spectral reflectance is converted to TOA spectral reflectance using a radiative transfer model given the specific satellite incidence angle and atmospheric conditions. For validation purposes, this is compared to the TOA reflectance values provided by RadCalNet.
5. The TOA spectral reflectance is convolved with the relative spectral response functions of the sensor bands and normalised to determine the bands' TOA reflectance.
6. The mean effective exo-atmospheric solar irradiance (or ESUN) value of each band is determined by convolving the Thuillier reference solar irradiance spectrum with the band's relative spectral response.
7. The TOA radiance is determined from the TOA reflectance, ESUN value, solar zenith angle and the earth-sun distance (ESD).
8. The TOA radiance is then compared to the mean corrected DN value for each band to determine the absolute gain coefficients.

A schematic representation of how the absolute gain coefficients are determined using RadCalNet data is given below.

Alternatively, the calibration can also be performed using cross-calibration imagery from reference sensors with similar characteristics over CEOS-approved Pseudo-Invariant Calibration Sites (PICS).

The absolute gain coefficients, ESUN values and relative spectral responses are stored in the RPF for future use during processing.

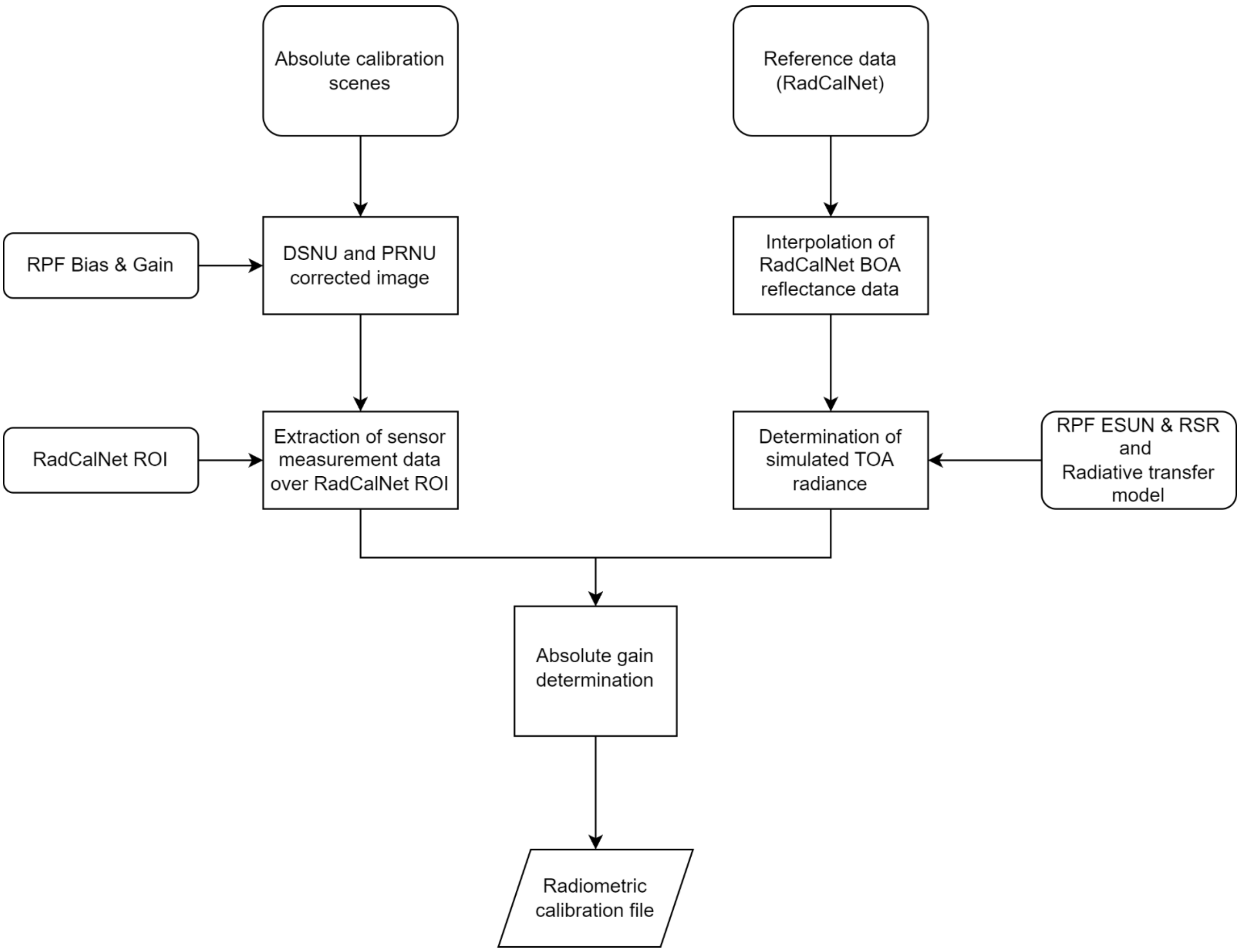

Figure 3: Schematic of absolute radiometric calibration

2.2 Radiometric processing – product generation

During image processing in *FarEarth* the sensor's RAW DN values are corrected and converted to TOA radiance or reflectance using the DSNU, PRNU and Absolute calibration coefficients as determined during the radiometric calibration process.

The correction of DN values to account for the DSNU and PRNU of the sensor is performed during the L0 to L1A processing step, as well as the conversion to TOA radiance. Additionally, the TOA radiance is converted to TOA reflectance in the L1A to L1B step or can be kept in TOA radiance if preferred. An overview of the radiometric changes during image processing steps is shown below.

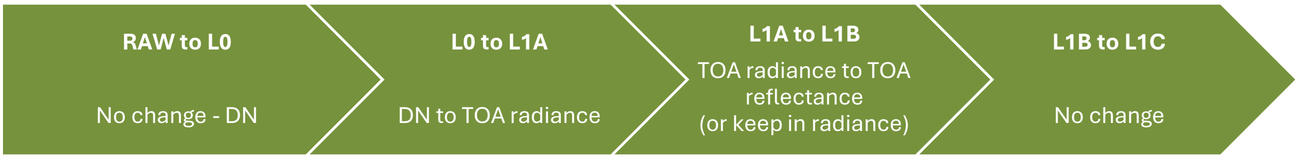

Figure 4: Radiometric processing steps

2.2.1 DSNU correction

The DSNU correction is applied in the L0 to L1A processing step by subtracting the bias from the RAW DN values. The bias is determined by extracting the detector/pixel bias coefficients from the RPF. DSNU-corrected DN values are unitless.

2.2.2 PRNU correction

The PRNU correction is also applied in the L0 to L1A processing step by multiplying the bias-corrected DN values with the detector/pixel gains. The gain is determined by extracting the gain coefficients from the RPF. PRNU-corrected DN values are unitless.

2.2.3 Absolute radiometric conversion

The conversion to TOA radiance is performed in the L0 to L1A step by multiplying the PRNU-corrected DN values with the absolute gain. The absolute gain is determined by extracting the absolute gain coefficients from the RPF. The TOA radiance is in units of watts per square meter per steradian $[\frac{W}{m^2\,sr}]$.

The conversion to TOA reflectance is performed in the L1A to L1B step by applying the following equation:

$$\rho_{TOA} = \frac{L_{TOA}\, d^2\, \pi}{E_{sun} \cos \theta_{sun}}$$

where

ρ_{TOA}	is the band TOA reflectance
L_{TOA}	is the band TOA radiance
E_{sun}	is the band ESUN value
θ_{sun}	is the solar zenith angle
d	is the earth-sun distance (ESD).

The TOA reflectance is unitless and is scaled by a factor of 10^4 for compression purposes.

2.2.4 Processing summary

Flowcharts indicating the radiometric processes during product generation are shown below:

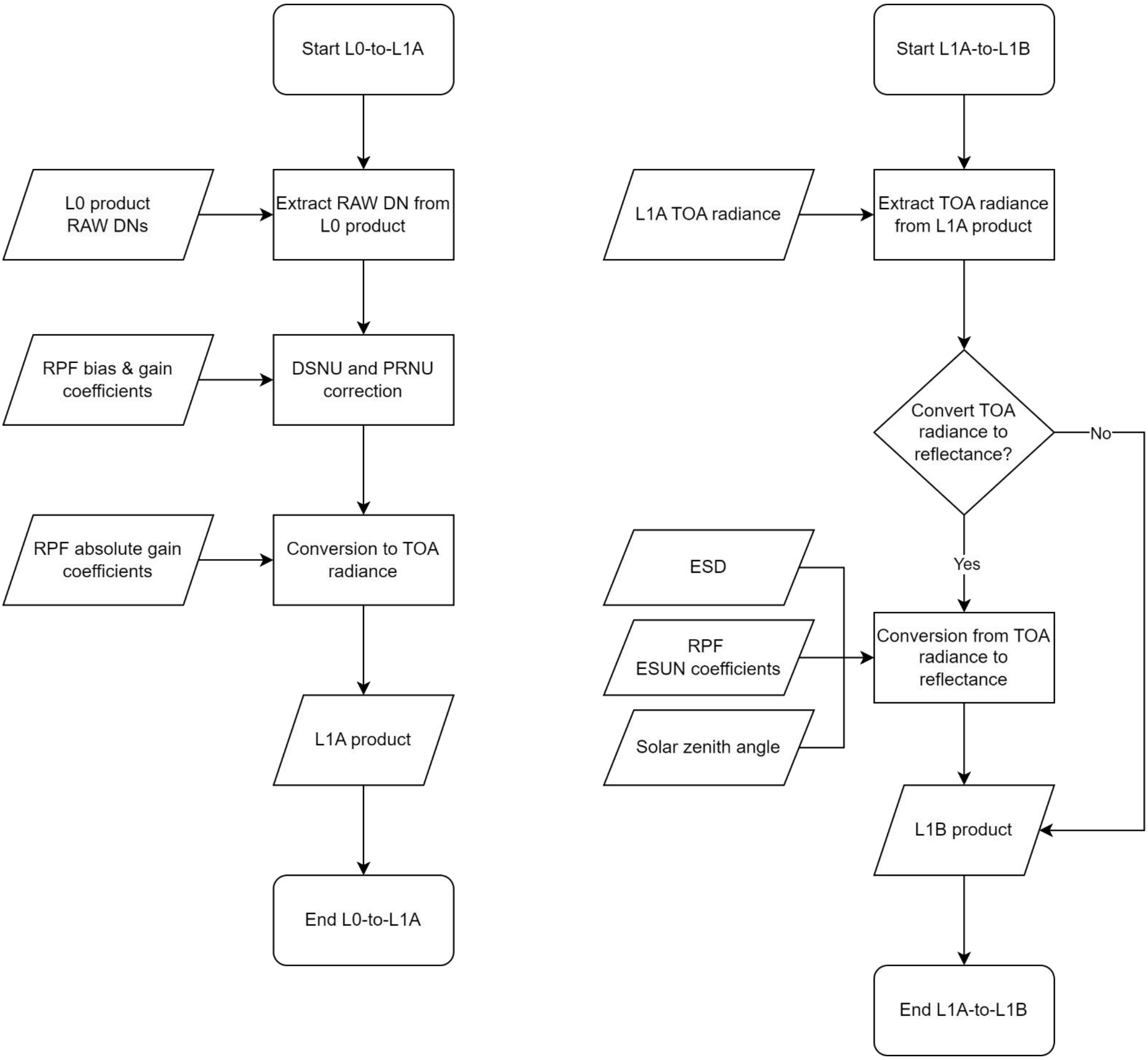

Figure 5: Radiometric processing during L0-to-L1A and L1A-to-L1B steps

2.3 Radiometric validation

Radiometric validation can be performed using the Radiometric Statistics processor in FarEarth. This process compares the radiometric data of the satellite image to a reference image. The reference image is a cloud-free image that is temporally close to the satellite image (e.g., within 5 days) and from a reference satellite (e.g., Sentinel-2 L1C). The comparison is more suitable for satellite sensors that have bands with spectral responses matching the reference satellite but can also be used for other sensors to monitor relative performance over time.

Furthermore, radiometric performance can also be evaluated over time by comparing the results from acquisitions over RadCalNet sites to the RadCalNet reference data when they become available.

2.4 Metrological traceability

Satellites for which an absolute radiometric calibration against a radiometric reference site (e.g, RadCalNet) has been performed are traceable to SI units through the calibration of ground instruments. Satellites which have been calibrated to a reference sensor will have metrological traceability through the reference sensor's traceability chain. An in-orbit calibration report documents the calibration process.

2.5 Uncertainty characterisation

Although a full uncertainty evaluation is not performed, the Radiometric Statistics processor gives an indication of the accuracy of the radiometric performance by comparing it to a reference sensor (e.g. Sentinel-2).

Contributions that influence the radiometric uncertainty include:

- Uncertainty from the calibration of DSNU and PRNU
- Uncertainty from the Absolute Gain calibration, which includes the uncertainty in the reference data, the radiative transfer model, temporal interpolation and viewing geometry
- Satellite's performance during imaging, such as NavAtt stability and timing offsets
- Radiometric noise, stray light, and crosstalk
- Differences in spectral response functions between satellite and reference
- Geometric uncertainty and resampling methods used