

Article

Operational Absolute Radiometric Calibration of CAS500-1

Sun-Hwa Kim ^{1,*}, Youn-Young Choi ² , Jae-Heon Jeong ², Jihyun Choi ¹, Jeong Eun ¹  and Inkwon Baek ¹

¹ PERPIXEL Inc., Incheon 21984, Republic of Korea; sally0@perpixel.co.kr (J.C.); eun2@perpixel.co.kr (J.E.); aaron77@perpixel.co.kr (I.B.)

² Satellite Ground Station R&D Division, Korea Aerospace Research Institute, Daejeon 34133, Republic of Korea; choiyoyo@kari.re.kr (Y.-Y.C.); jjh583@kari.re.kr (J.-H.J.)

* Correspondence: sunhk@perpixel.co.kr; Tel.: +82-32-811-7639

Highlights

What are the main findings?

- Quality-controlled vicarious calibration and Sentinel-2 cross-calibration supported consistent operational radiometric calibration of CAS500-1.
- The 2024 field campaigns achieved combined uncertainties of 4.59–7.77%, with greater temporal variability observed in the NIR band.

What are the implications of the main findings?

- Integrating uncertainty assessment and independent validation strengthens decisions on annual operational calibration updates.
- Long-term PICS monitoring is required to distinguish sensor-response changes from field- and calibration-related variability.

Abstract

Maintaining radiometric consistency throughout the mission lifetime is essential for the quantitative application of high-resolution optical satellite imagery, particularly for sensors without onboard absolute radiometric calibration systems. This study presents an operational absolute radiometric calibration framework for the Compact Advanced Satellite 500-1 (CAS500-1) based on repeated field campaigns conducted during 2023–2024. Reflectance-based vicarious calibration was performed independently for the summer (TDI 1) and winter (TDI 2) operating modes using ground-measured surface reflectance, quality-controlled atmospheric observations, sensor viewing geometry, and MODTRAN6 radiative transfer simulations. Annual gain and offset coefficients were derived through band-wise linear regression between simulated top-of-atmosphere (TOA) radiance and CAS500-1 digital numbers (DN). The reliability of the calibration was evaluated through campaign-specific uncertainty assessment, independent cross-calibration with Sentinel-2A/B over Libya-4 and RadCalNet sites, and operational image-based validation. The 2024 calibration showed strong linear relationships between simulated TOA radiance and CAS500-1 DN, with campaign-specific combined uncertainties ranging from 4.59% to 7.77%. Sentinel-2 cross-calibration provided independent support for the field-derived coefficients in the visible bands, although the agreement varied with spectral band, site, and operating mode. Image-based validation showed that negative TOA radiance occurred at low proportions for most images and was primarily concentrated over low-radiance surfaces when elevated values occurred. Repeated observations over a stable asphalt reference site showed generally consistent temporal behavior in the visible bands, whereas the NIR band exhibited greater absolute variability that was also present in the original DN measurements. The results demonstrate that operational radiometric calibration should be managed through



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an integrated framework combining field calibration, uncertainty quantification, independent cross-calibration, and product-level validation. Continued PICS and reference-site monitoring is required to further distinguish long-term sensor-response changes from calibration-related variability.

Keywords: CAS500-1; absolute radiometric calibration; vicarious calibration; reflectance-based calibration; uncertainty assessment; cross-calibration; Sentinel-2; operational calibration

1. Introduction

The rapid advancement of optical Earth observation satellites has transformed satellite imagery from a qualitative visualization tool into a quantitative source of geospatial information. Satellite observations are now widely used for precision agriculture, environmental monitoring, land-cover mapping, urban planning, disaster response, and national geospatial services, where reliable radiometric measurements are essential for deriving biophysical and geophysical parameters. As these quantitative applications continue to expand, maintaining radiometric consistency has become a fundamental requirement for ensuring the accuracy, comparability, and long-term usability of satellite-derived products [1–4].

Absolute radiometric calibration establishes the relationship between the digital numbers (DNs) recorded by an optical sensor and the corresponding top-of-atmosphere (TOA) radiance. It provides the basis for subsequent processing, including atmospheric correction, surface reflectance retrieval, analysis ready data (ARD) generation, vegetation index calculation, land-cover classification, and quantitative change detection. Because uncertainties introduced during radiometric calibration propagate throughout the processing chain, calibration quality directly affects the reliability of downstream products and applications [2–5]. The increasing availability of sub-meter- and meter-class imagery has further strengthened the need for systematic calibration and validation (Cal/Val). Compared with medium-resolution missions, high-resolution optical sensors are more sensitive to uncertainties associated with detector response, viewing geometry, atmospheric variability, and spatial heterogeneity within calibration targets. In addition, many high-resolution optical satellites do not carry dedicated onboard radiometric calibration devices. Their post-launch radiometric performance must therefore be maintained primarily through field-based vicarious calibration, independent validation, cross-calibration, and continuous monitoring [6–9]. Consequently, post-launch calibration has evolved from the initial estimation of calibration coefficients into a long-term process of radiometric quality management throughout the mission lifetime.

Recent high-resolution satellite missions have adopted comprehensive Cal/Val strategies to address these requirements. The WorldView series combines laboratory characterization, reflectance-based vicarious calibration, pseudo-invariant calibration sites (PICS), independent quality assessment, and long-term trend analysis to maintain radiometric stability [10–12]. PlanetScope uses standardized processing, sensor characterization, and comparison with well-calibrated reference missions to improve consistency across a large number of sensors [13,14]. Similarly, China's GaoFen (GF) and ZY-3 programs employ regular field campaigns, cross-calibration, and long-term quality assessment as part of routine mission maintenance [15–19]. These examples demonstrate that radiometric calibration is no longer regarded as a single post-launch activity, but as a continuous operational process integrating field observations, quality control, independent validation, and long-term sensor monitoring. More recent studies have further extended these approaches toward continuous and automated on-orbit calibration. Han et al. [20] demonstrated the

use of RadCalNet observations at Railroad Valley Playa for radiometric calibration of a large-view-angle satellite sensor, while a recent Jilin-1 study [21] developed an automated on-orbit absolute radiometric calibration approach combining reference satellite observations, pseudo-invariant calibration regions, and radiative transfer modeling. These developments further highlight the transition from individual calibration experiments toward repeatable and operational radiometric performance management.

International efforts have further supported this transition by promoting standardized and traceable calibration practices. Through the Working Group on Calibration and Validation (WGCV), the Committee on Earth Observation Satellites (CEOS) has encouraged common calibration procedures, traceable reference measurements, and harmonized validation protocols for Earth observation missions [22–24]. The Radiometric Calibration Network (RadCalNet), for example, provides SI-traceable surface reflectance, atmospheric measurements, and simulated TOA radiance from globally distributed reference sites, enabling independent validation without dedicated field observations for every satellite overpass [9,23]. PICS such as Libya-4 are also widely used to evaluate long-term sensor stability, while cross-calibration with well-characterized missions, including Landsat-8/9 and Sentinel-2A/B, provides an additional means of assessing radiometric consistency among satellite systems [2,15,25,26]. Modern Cal/Val programs therefore increasingly integrate field-based calibration, standardized quality control, independent validation, and continuous monitoring within a unified radiometric quality management framework.

The Compact Advanced Satellite 500 (CAS500) program was initiated to establish Korea's indigenous capability for high-resolution Earth observation and to promote the transition from government-led to industry-led satellite development. CAS500-1, launched in March 2021, carries the Advanced Earth Imaging Sensor System-Compact (AEISS-C), which provides 0.5 m panchromatic and 2.0 m multispectral imagery over a 12 km swath. The satellite supports national mapping, land and resource management, environmental monitoring, disaster response, and public geospatial services. CAS500-1 does not use a dedicated onboard radiometric calibration system and therefore relies primarily on field-based vicarious calibration and independent validation to maintain post-launch radiometric accuracy. Systematic field campaigns, synchronized atmospheric observations, radiative transfer modeling, and cross-calibration with reference satellites consequently play central roles in its calibration strategy. To support these activities, the Korea Aerospace Research Institute (KARI) established a field-based Cal/Val program in 2022 using calibrated reference tarps, atmospheric measurements acquired near the satellite overpass time, radiative transfer simulations, and independent validation with international reference datasets.

The initial absolute radiometric calibration of CAS500-1 was previously investigated using reflectance-based vicarious calibration and cross-calibration with Sentinel-2/MSI, and the study successfully characterized the radiometric response of the AEISS-C sensor under representative field conditions [26]. However, the reported results included multiple calibration coefficients derived from different campaigns, imaging conditions, and sensor operation settings. Although these coefficients are valuable for characterizing sensor behavior, the study provided limited discussion on how a representative coefficient should be selected, validated, and managed for routine operational image production. In addition, its main focus was coefficient derivation and accuracy assessment rather than the practical implementation of recurring calibration activities, including field campaign planning, quality control of ground measurements, coefficient management, independent validation, uncertainty assessment, and long-term monitoring. These operational considerations are particularly important because calibration coefficients used in production systems must be supported not only by individual calibration experiments, but also by consistent decision criteria and repeated evidence of product-level performance.

This study addresses these limitations by presenting the operational absolute radiometric calibration program implemented for CAS500-1 during routine satellite operation. Rather than proposing a new calibration algorithm, it documents the complete workflow used to derive and manage representative operational calibration coefficients, including field campaign design, quality-controlled ground and atmospheric observations, reflectance-based vicarious calibration, coefficient estimation, independent cross-calibration, uncertainty assessment, operational product validation, and interannual monitoring. The study further evaluates how annual calibration results can be incorporated into the operational image production system and how their effectiveness can be assessed using both radiometric validation metrics and surface reflectance products. The operational experiences presented here provide practical guidance for establishing sustainable Cal/Val and radiometric quality management programs for high-resolution optical satellite missions that rely primarily on ground-based post-launch calibration.

2. Materials and Methods

2.1. CAS500-1 Sensor and Operational Calibration Context

The Compact Advanced Satellite 500-1 (CAS500-1), also known as the National Land Satellite of Korea, is the first satellite in the CAS500 series developed by the Korea Aerospace Research Institute (KARI). The satellite was designed to provide high-resolution optical imagery for national geospatial applications based on a standardized 500-kg-class satellite platform [27]. CAS500-1 is equipped with a domestically developed high-resolution electro-optical payload with a mass of approximately 150 kg and dimensions of approximately 1.0 m in diameter and 1.6 m in height [27]. CAS500-1 was successfully launched in March 2021 and carries the Advanced Earth Imaging Sensor System-Compact (AEISS-C), which provides 0.5 m panchromatic and 2.0 m multispectral imagery with a swath width of approximately 12 km [27,28]. The principal specifications of the satellite platform and optical sensor are summarized in Table 1 [28].

Table 1. Specifications of the CAS500-1 satellite and AEISS-C sensor.

Category	Specification
Satellite	CAS500-1
Orbit Type	Sun-synchronous orbit
Orbit Altitude	497.8 km
Payload	AEISS-C (Advanced Earth Imaging Sensor System-Compact)
TDI Operating Mode	TDI 1 (April–September); TDI 2 (October–March)
Spectral Bands	Panchromatic and four multispectral bands (Blue, Green, Red, and NIR)
Spectral Range	450–900 nm
Spatial Resolution (Nadir)	0.5 m (PAN); 2.0 m (MS)
Swath Width	12 km
Radiometric Resolution	12 bits
Launch Date	22 March 2021

To support operational image production, CAS500-1 routinely generates Level-1 products through the standard image preprocessing pipeline. The absolute radiometric calibration coefficients generated through the operational calibration program are subsequently applied to produce Level-2A surface reflectance products and higher-level Level-3 products. Because the satellite is not equipped with an onboard radiometric calibration subsystem, the radiometric calibration coefficients are periodically updated through field-based vicarious calibration, independent validation, and operational calibration management. This operational strategy is consistent with those adopted for many commercial and na-

tional high-resolution optical satellites, including WorldView, PlanetScope, GaoFen, and ZY-3 [10–19].

Since 2022, KARI has operated a field-based absolute radiometric calibration program for the routine maintenance of CAS500-1 radiometric performance. The program consists of annual field campaigns, standardized reference tarps, synchronized atmospheric observations, reflectance-based vicarious calibration, cross-calibration with Sentinel-2/MSI, independent validation, and long-term calibration management. Rather than being conducted as an isolated field experiment, radiometric calibration is implemented as a continuous operational process that supports the generation, validation, selection, and maintenance of calibration coefficients used in routine image production. The operational calibration workflow adopted for CAS500-1 is described in the following sections.

2.2. Operational Absolute Radiometric Calibration Framework

To ensure the long-term radiometric consistency of CAS500-1 imagery, KARI established an operational absolute radiometric calibration framework that integrates field campaign planning, standardized ground measurements, reflectance-based vicarious calibration, independent validation, cross-calibration, and calibration management into a unified operational workflow. Unlike conventional calibration studies that primarily focus on deriving calibration coefficients from individual field experiments, the proposed framework was designed to support both routine calibration operations and long-term sensor performance management throughout the mission lifetime. The overall operational calibration workflow adopted in this study is illustrated in Figure 1.

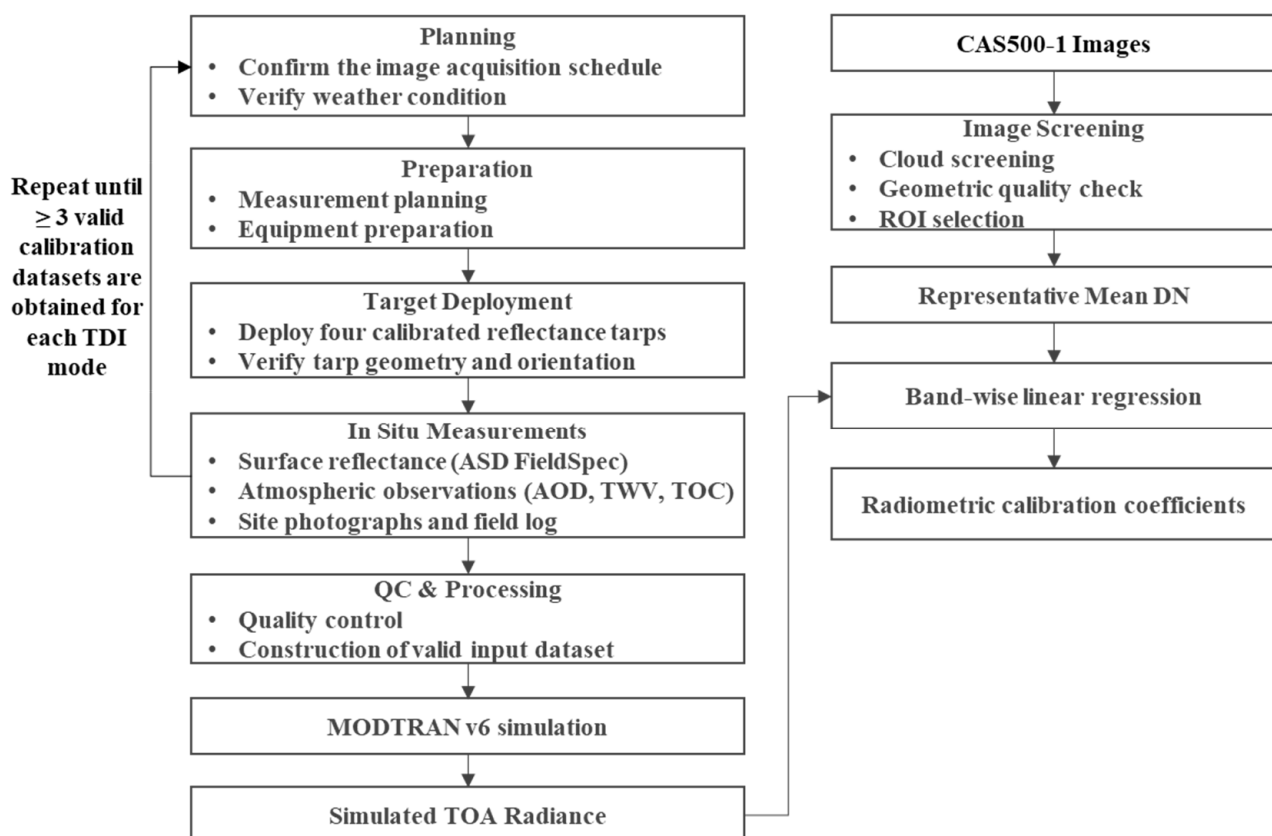


Figure 1. Overall workflow of the operational absolute radiometric calibration of CAS500-1.

The workflow begins with annual calibration campaign planning, during which observation schedules, tarp installation sites, reference targets, satellite acquisition opportunities, and atmospheric conditions are comprehensively evaluated. Tarp installation sites are

selected to satisfy the radiometric requirements of reflectance-based vicarious calibration, including spatial homogeneity, temporal stability, sufficient target size, and minimal adjacency effects. During satellite overpasses, standardized field observations are conducted following predefined operational procedures, including surface reflectance measurements, atmospheric characterization, meteorological observations, and geometric verification of the reference tarps. All field observations are subsequently subjected to a dedicated quality-control (QC) procedure before radiometric calibration processing.

Following quality control, absolute radiometric calibration coefficients are derived using the reflectance-based vicarious calibration method by comparing simulated top-of-atmosphere (TOA) radiance with satellite digital numbers. The resulting coefficients are independently evaluated through cross-calibration with Sentinel-2/MSI and consistency assessments using repeated observations acquired under different environmental conditions. Calibration coefficients, together with ancillary observations, quality-control records, uncertainty estimates, and validation results, were systematically documented and accumulated throughout the calibration campaigns to enable the interannual comparison of calibration results and the assessment of sensor radiometric stability. Temporal changes in sensor responsivity are evaluated using the accumulated calibration results to determine whether coefficient updates are required, thereby supporting consistent radiometric performance throughout routine satellite operations.

Each component of this framework is described in detail in the following sections, including the field campaign design (Section 2.3), quality control (Section 2.4), radiative transfer modeling (Section 2.5), calibration coefficient estimation (Sections 2.6 and 2.7), and independent validation and calibration management (Section 2.8).

2.3. Operational Field Campaign

To support the operational absolute radiometric calibration of CAS500-1, KARI established a standardized field campaign protocol covering campaign planning, field measurements, operational documentation, and data management. The protocol was established in 2023 and subsequently applied during the calibration campaigns conducted in 2024, providing a consistent framework for synchronized surface and atmospheric observations with satellite acquisitions. A summary of the field campaigns, satellite images, and observation conditions used in this study is provided in Table 2 [29,30].

Prior to each campaign, an Annual Observation Plan was established based on the CAS500-1 acquisition schedule, seasonal solar geometry, and forecast weather conditions. For each satellite acquisition, a Field Campaign Plan was subsequently prepared, specifying the observation site, tarp installation locations, personnel assignments, instrument configuration, measurement sequence, equipment checklist, and contingency procedures. Following each campaign, observation records, field notes, environmental conditions, measurement metadata, and photographs were compiled into a standardized Field Campaign Report to ensure complete traceability of all calibration activities [29,30]. This standardized documentation procedure provided consistent operational practices across all calibration campaigns.

Field campaigns were conducted under cloud-free conditions whenever possible. Four calibrated reflectance tarps with nominal reflectance values of approximately 50%, 30%, 20%, and 5% were individually deployed, each measuring 15 m × 15 m (Figure 2a). The four reflectance levels were selected to provide a broad radiometric dynamic range for calibration of the multispectral sensor. The tarps were aligned parallel to the nominal CAS500-1 ground track using a predefined reference direction and were sufficiently separated to minimize adjacency effects and mixed pixels. Before the measurements, the installation status,

target surface condition, illumination environment, and instrument readiness were verified according to the operational field manual [29,30].

Table 2. Summary of the field calibration campaigns used for annual calibration coefficient estimation.

Date	Site	Latitude (°N)	Longitude (°E)	Sun Zenith Angle (°)	Off-Nadir Angle (°)	TWV (gcm ⁻²)	TOC (atm-cm)	AOD (550 nm)	Calibration Year
9 May 2023	Daejeon-1	36.374	127.353	26.953	22.338	0.987	334.390	0.562	2023
25 May 2023	Daejeon-1	36.374	127.353	24.819	−19.843	1.440	517.925	0.363	2023
9 June 2023	Daejeon-1	36.374	127.353	23.681	16.741	1.854	406.080	0.312	Excluded (QC)
12 October 2023	Daejeon-1	36.374	127.353	47.685	17.308	1.155	353.900	0.288	2023
21 October 2023	Jeju	33.563	126.774	47.673	−3.554	0.781	358.887	0.117	2023
26 October 2023	Daejeon-2	36.385	127.357	50.181	3.855	1.048	343.000	0.628	Excluded (QC)
23 November 2023	Daejeon-1	36.374	127.353	58.584	20.768	0.654	336.440	0.453	Excluded (QC)
20 March 2024	Daejeon-1	36.374	127.353	43.564	5.851	0.298	510.400	0.234	Excluded (QC)
25 April 2024	Daejeon-2	36.385	127.357	30.998	11.029	1.007	415.497	0.528	Excluded (QC)
16 May 2024	Jeonju	35.827	127.052	25.584	6.244	0.943	523.800	0.259	2024
27 September 2024	Daejeon-1	36.374	127.353	41.829	10.252	2.021	381.845	0.237	Excluded (QC)
12 October 2024	Daejeon-1	36.374	127.353	48.128	23.222	1.009	393.533	0.334	2024
12 November 2024	Daejeon-1	36.374	127.353	57.363	18.642	0.952	356.687	0.201	Excluded (QC)
18 November 2024	Daejeon-1	36.374	127.353	57.836	17.058	0.187	351.337	0.096	2024
19 December 2024	Daejeon-1	36.374	127.353	62.693	14.307	0.226	390.577	0.162	2024

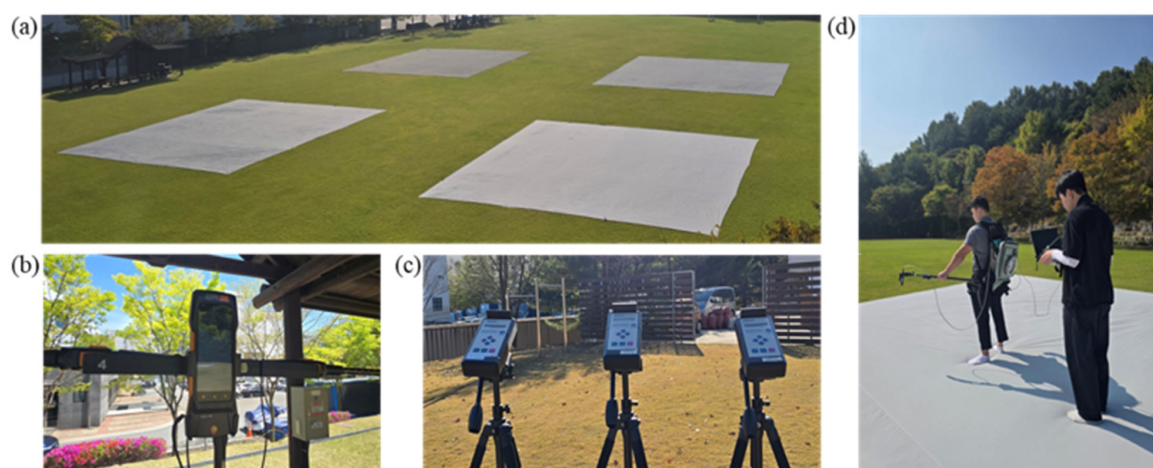


Figure 2. Field calibration campaign and measurement setup. (a) Deployment of four calibration tarps. (b) Automatic Weather Station (AWS) for continuous meteorological monitoring, (c) simultaneous atmospheric observations using three MICROTOPS II instruments, and (d) surface reflectance measurements over the calibration tarps using an ASD FieldSpec spectroradiometer.

Ground observations consisted of surface reflectance measurements, atmospheric observations, meteorological monitoring, and target positioning. Surface reflectance was measured using an ASD FieldSpec 4 Hi-Res (FS4H2000) spectroradiometer (Malvern Panalytical, Inc., Malvern, UK) following a standardized nine-point sampling strategy over each

calibration target (Figure 2d). The averaged reflectance spectrum was used to represent the target reflectance. White-reference measurements were repeatedly acquired throughout the observation sequence to compensate for temporal variations in illumination. During the target measurements, the observer was positioned approximately 90° relative to the solar azimuth direction to minimize directional effects, including specular reflection and observer shadowing. Atmospheric parameters were measured using Model 540 MICROTOPS II[®] Sunphotometers for aerosol optical depth (AOD) and total column water vapor (TWV), and Model 521 MICROTOPS II[®] Ozonometers for total column ozone (TOC) (Solar Light Company, Inc., Glenside, PA, USA). Meteorological variables were continuously recorded using an automatic weather station (AWS; Testo 400, Testo SE & Co. KGaA, Titisee-Neustadt, Germany) (Figure 2b). GPS measurements were also acquired using a GPS 73 (Garmin, Olathe, KS, USA) to determine the precise locations of the calibration targets. Detailed descriptions of the measurement procedures, instrument configurations, and atmospheric data-processing methods have been previously reported [29], whereas this study emphasizes their operational implementation within the CAS500-1 calibration framework.

To ensure temporal consistency with satellite acquisitions, atmospheric observations were continuously performed from approximately one hour before to one hour after the CAS500-1 overpass, while surface reflectance measurements were completed as close as possible to the satellite imaging time. Throughout each campaign, field measurements, instrument settings, environmental conditions, observation logs, and ancillary photographs were systematically documented together with the corresponding planning and reporting documents. These operational records ensure complete traceability of each calibration campaign and provide the basis for the quality-control procedures, radiative transfer simulations, calibration coefficient estimation, and independent validation described in the following sections [29–31].

2.4. Quality Control and Construction of Valid Input Datasets

Ground measurements acquired during each field campaign were subjected to a systematic quality-control (QC) procedure before being used as inputs to the radiative transfer simulations. The overall QC workflow is illustrated in Figure 3. The objective of the QC procedure was to construct a representative and physically consistent dataset by systematically identifying and excluding observations that could degrade the accuracy of the radiative transfer simulations and calibration coefficient estimation. The workflow comprised cloud screening, ancillary data verification, temporal consistency analysis, surface reflectance quality assessment, and construction of the final valid input dataset. The QC criteria for atmospheric observations were developed based on the AERONET quality-assurance procedures and adapted to the operational characteristics of the CAS500-1 calibration program [31].

Cloud contamination was first evaluated using the temporal variation of atmospheric parameters measured by the MICROTOPS II instruments. Since thin clouds and rapidly changing atmospheric conditions can introduce substantial uncertainties into radiative transfer simulations, the temporal behavior of AOD, TWV, and TOC was carefully examined throughout each field campaign. Measurements exhibiting abrupt fluctuations or inconsistent temporal trends were excluded from further processing. Clear-sky conditions were further confirmed using ancillary observations, including field photographs, MODIS cloud products, GEMS atmospheric products, nearby AERONET and SKYNET observations, and meteorological records collected during the satellite overpass [29,30].

Following cloud screening, the temporal consistency of the atmospheric observations was evaluated to identify representative atmospheric conditions during the satellite acquisition. All MICROTOPS II measurements acquired before and after the satellite overpass

were examined to assess temporal stability, and representative values of AOD, TWV, and TOC were calculated from the filtered observations. The detailed QC procedures applied to the MICROTOPS II measurements, including triplet stability tests, temporal variability analysis, air-mass constraints, and uncertainty assessment, have been described in our previous study [31] and were directly adopted in the present operational calibration framework.

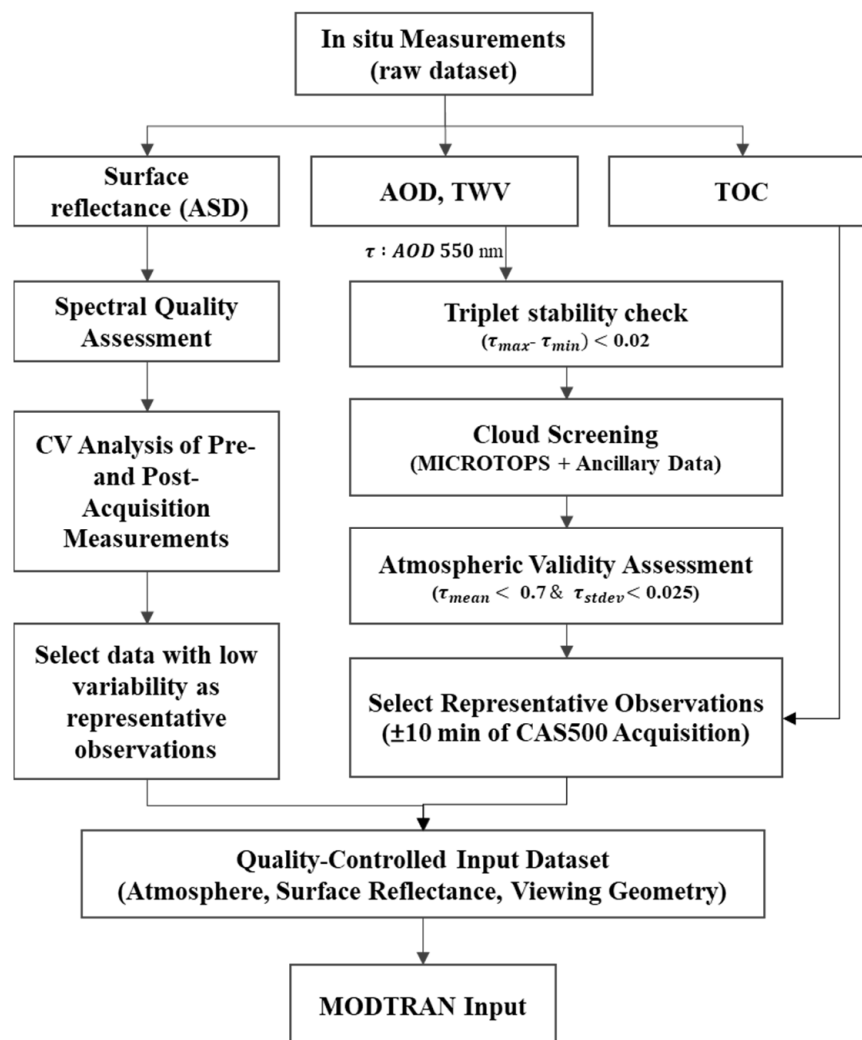


Figure 3. Quality-control workflow for field measurements and satellite data.

Surface reflectance measurements acquired according to the standardized field protocol were subsequently subjected to quality assessment before radiative transfer modeling. Individual spectra affected by instrument instability, improper white-reference calibration, shadow contamination, or abnormal spectral responses were discarded. Spectral consistency among repeated measurements over each calibration target was then evaluated, and the remaining observations were averaged to obtain representative reflectance spectra for each target. To improve the robustness of the regression analysis across a wider reflectance range, homogeneous natural surface targets were additionally included together with the four calibrated reflectance tarps (5%, 20%, 30%, and 50%) [29,30].

After completion of the QC procedure, only datasets satisfying both atmospheric and surface measurement quality requirements were retained to construct the final valid input dataset for MODTRAN6 (Spectral Sciences, Inc., Burlington, MA, USA) simulations. The resulting dataset consisted of synchronized atmospheric observations, representative surface reflectance spectra, viewing geometry, and satellite acquisition information. This quality-controlled dataset served as the standardized input for the operational ra-

diative transfer simulations and the subsequent derivation of the absolute radiometric calibration coefficients.

2.5. Radiative Transfer Modeling

The quality-controlled field measurements described in Section 2.4 were used to simulate top-of-atmosphere (TOA) radiance for the reflectance-based absolute radiometric calibration of CAS500-1. Atmospheric radiative transfer was modeled using MODTRAN6, which simulates atmospheric absorption, scattering, and transmission under user-defined atmospheric and observation conditions [26]. The principal MODTRAN configuration adopted in this study is summarized in Table 3.

Table 3. MODTRAN6 simulation configuration.

Parameter	Configuration/Input
Radiative Transfer Solver	Band Model (MODTRAN)
Multiple Scattering	DISORT (8 streams)
Atmosphere Profile	U.S. Standard 1976
TWV, TOC, AOD550 nm	Observed (MICROTOPS II)
Carbon Dioxide	420 ppm
Cloud Model	None
Aerosol Model	Urban
Surface Type/Reflectance	Lambertian Surface/ASD Field Measurements
Solar Irradiance	Thuillier et al. [32]
Observation Geometry	Satellite Image Metadata

The MODTRAN simulations incorporated two groups of input parameters: (1) quality-controlled field measurements and (2) predefined model configuration parameters. Field-derived inputs included surface reflectance measured by the ASD FieldSpec spectroradiometer; AOD, TWV, and TOC obtained from the quality-controlled MICROTOPS II observations; and acquisition-specific parameters extracted from the CAS500-1 image metadata, including solar zenith angle, solar azimuth angle, sensor viewing angle, acquisition time, and target elevation. These parameters represent the actual atmospheric, surface, and observation conditions at the time of satellite acquisition. All field-derived inputs were obtained exclusively from the valid input dataset established through the quality-control procedure described in Section 2.4 [29,30].

Model configuration parameters were selected based on the operational calibration procedure established for CAS500-1 and the standard MODTRAN configuration. The U.S. Standard Atmosphere 1976 was adopted as the atmospheric profile, while the Urban Aerosol model was used to characterize aerosol scattering over the calibration sites. The extraterrestrial solar irradiance spectrum reported by Thuillier et al. [32] was employed as the incident solar source. The hyperspectral radiance simulated by MODTRAN was subsequently convolved with the spectral response function (SRF) of each CAS500-1 panchromatic and multispectral band. This process generated band-integrated TOA radiance directly comparable to the sensor observations [26,29,30].

The simulated TOA radiance was subsequently paired with the corresponding digital number (DN) values extracted from the CAS500-1 imagery. The resulting TOA radiance–DN pairs constituted the calibration dataset used to estimate the absolute radiometric calibration coefficients, as described in the following section.

2.6. Satellite DN Extraction

Digital numbers (DNs) were extracted from CAS500-1 Level-1R (L1R) imagery acquired on the same dates as the field campaigns. Image processing and DN extraction were

performed using ENVI 5.7 (Environment for Visualizing Images, L3Harris Geospatial Solutions, Broomfield, CO, USA). The L1R products, which had undergone standard geometric correction and basic preprocessing, were spatially subset around the calibration site prior to analysis. A representative false-color composite image of the calibration site, including the deployed calibration tarps, is presented in Figure 4.

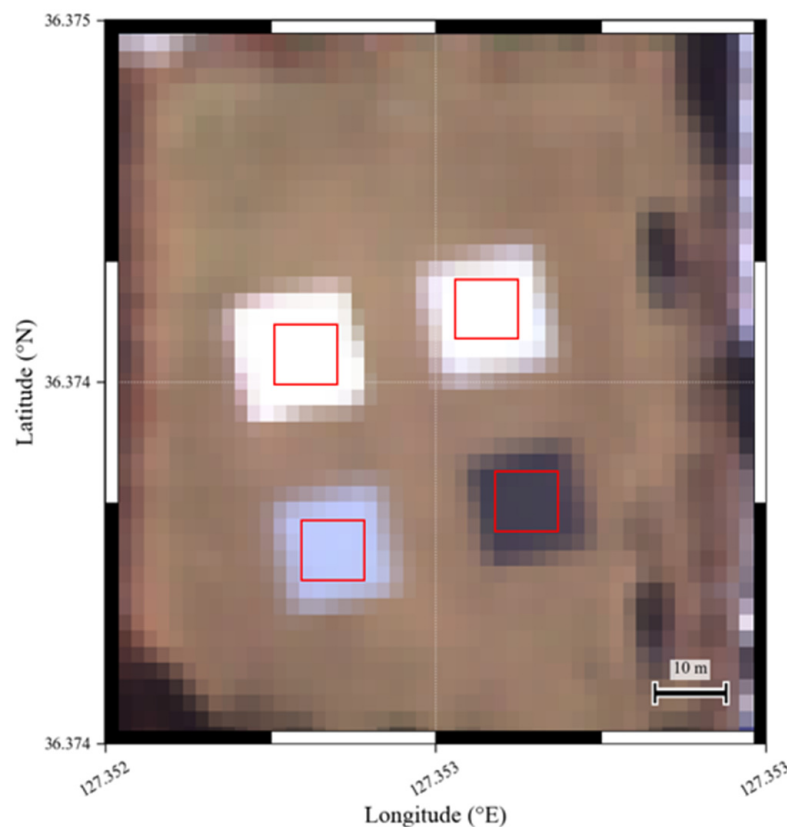


Figure 4. Example of the regions of interest (ROIs) used for DN extraction over the calibration tarps in a CAS500-1 image. Red squares denote the interior ROIs used to calculate the representative mean DN values.

Regions of interest (ROIs) were manually delineated based on the locations of the four calibrated reflectance tarps installed during each field campaign. Each tarp measured 15 m × 15 m, corresponding to approximately 49 pixels in the 2 m multispectral imagery and 784 pixels in the 0.5 m panchromatic imagery. To minimize adjacency effects and mixed-pixel contamination, pixels located along the tarp boundaries were excluded, and only interior pixels were retained as valid calibration pixels. Consequently, approximately 25 interior pixels were used for each multispectral band and 400 interior pixels for the panchromatic band. This interior-pixel strategy minimizes edge effects caused by geolocation uncertainty, point spread function (PSF), and mixed-pixel contamination, thereby improving the reliability of the extracted DN values.

For each ROI, the mean DN and standard deviation were calculated for every spectral band. Spatial homogeneity was evaluated using the coefficient of variation (CV), defined as:

$$CV(\%) = \frac{\sigma(DN)}{\mu(DN)} \times 100 \quad (1)$$

where $\mu(DN)$ and $\sigma(DN)$ denote the mean and standard deviation of the extracted DN values, respectively. The CV provides a quantitative measure of target uniformity, with lower values indicating greater spatial homogeneity and reduced mixed-pixel influence.

Following the operational quality-control criteria adopted for CAS500-1 calibration, only ROIs with CV values below the operational threshold of 1.5% (typically 0.3–1.5%) were accepted for subsequent calibration analysis.

Finally, the representative mean DN values extracted from the accepted ROIs were paired with the corresponding TOA radiance simulated by MODTRAN6. The resulting DN–radiance pairs served as the calibration dataset for estimation of the absolute radiometric calibration coefficients, as described in the following section.

2.7. Operational Calibration Coefficient Estimation

The absolute radiometric calibration coefficients of CAS500-1 were estimated using a reflectance-based vicarious calibration approach. Calibration coefficients were derived by establishing a linear relationship between the top-of-atmosphere (TOA) radiance simulated using MODTRAN6 and the corresponding digital numbers (DNs) extracted from the CAS500-1 imagery. The calibration procedure was conducted annually using quality-controlled field observations to generate updated calibration coefficients for the CAS500-1 image processing system [26,29,30].

For each calibration campaign, the band-integrated TOA radiance simulated in Section 2.5 was paired with the representative mean DN extracted from the corresponding calibration targets described in Section 2.6. In addition to the four absolute calibration tarps, homogeneous natural and artificial reference surfaces measured during the field campaigns were incorporated to expand the radiometric dynamic range and improve the robustness of the regression analysis. Only datasets satisfying the quality-control criteria described in Section 2.4 were included in the calibration dataset [29–31].

Calibration coefficients were estimated independently for each multispectral band and the panchromatic band using the following first-order linear regression model:

$$L_{TOA} = G \times DN + O \quad (2)$$

where L_{TOA} is the simulated TOA radiance, DN is the mean digital number extracted from the satellite imagery, G is the calibration gain, and O is the calibration offset. In this study, the term “gain” refers to the multiplicative radiometric calibration coefficient used in the operational CAS500-1 radiometric conversion equation, consistent with the convention adopted in previous CAS500-1 calibration studies [26]. The DN values used in the regression were not background-subtracted, and the offset O was estimated simultaneously with the gain coefficient as the intercept of the linear regression. Independent regression models were established for each annual calibration campaign and for each Time Delay Integration (TDI) mode to account for variations in detector operating conditions. The coefficient of determination (R^2) was used to evaluate the goodness-of-fit of each regression model, while the resulting gain and offset values constituted the calibration coefficients for each spectral band.

Following verification, the updated calibration coefficients were implemented in the CAS500-1 image processing chain and applied to the generation of Level-2A surface reflectance products and subsequent Level-3 analysis products until the next annual calibration campaign. Annual coefficient updates provide a continuous calibration management strategy that maintains long-term radiometric consistency while accommodating gradual changes in sensor response caused by sensor aging, operational configuration changes, and TDI updates [29,30]. Accordingly, the calibration coefficients reported in this study represent operational calibration parameters implemented in the CAS500-1 image production system rather than experimental calibration results.

2.8. Calibration Validation and Uncertainty Assessment

The operational calibration coefficients derived in Section 2.7 were evaluated through independent cross-calibration, uncertainty assessment, and image-based validation to assess their radiometric consistency, temporal stability, and suitability for operational implementation. Cross-calibration was performed using CAS500-1 and Sentinel-2A/B image pairs acquired over pseudo-invariant calibration sites (PICS) and RadCalNet sites. The image pairs used for cross-calibration are summarized in Table 4. The spectral response functions (SRFs) of CAS500-1 and Sentinel-2A/B are compared in Figure 5, with the CAS500-1 SRFs adopted from the previously reported AEISS-C spectral response characteristics [28]. The overall cross-calibration procedure is illustrated in Figure 6.

Table 4. Summary of image pairs used for cross-calibration.

Date	CAS500-1 Acquisition (UTC)	Sentinel-2 Acquisition (UTC)	Δt (min)	Reference Sensor	Off-Nadir Angle (°)	Sun Zenith Angle (°)
17 April 2023	09:04:29	08:55:59	8	Sentinel-2B	13.77	26.53
27 April 2023	09:04:16	08:55:59	8	Sentinel-2B	13.32	23.78
7 May 2023	09:03:59	08:55:59	8	Sentinel-2B	12.50	21.96
12 May 2023	09:04:05	08:56:01	8	Sentinel-2A	13.25	20.98
22 May 2023	09:04:33	08:56:01	8	Sentinel-2A	14.68	20.04
16 June 2023	09:06:07	08:55:59	10	Sentinel-2B	19.16	19.80
15 July 2024	08:46:48	08:56:01	9	Sentinel-2A	9.14	23.54
22 July 2024	08:49:33	08:55:59	6	Sentinel-2B	1.30	23.94
25 July 2024	08:52:10	08:56:01	3	Sentinel-2A	6.24	24.41
4 August 2024	08:57:46	08:56:01	1	Sentinel-2A	21.39	25.38

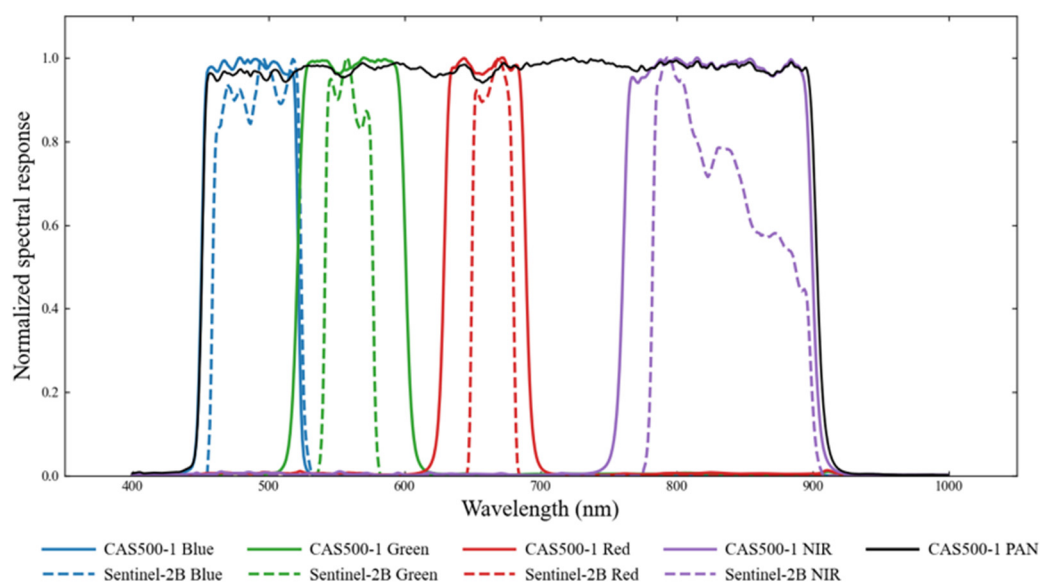


Figure 5. Spectral response functions of CAS500-1 and Sentinel-2B.

Sentinel-2A/B Level-1C imagery was adopted as the reference dataset because of its well-established radiometric calibration performance. Its relatively high spatial resolution was also advantageous for reducing spatial-representativeness uncertainty when matching observations with the high-resolution CAS500-1 imagery. Image pairs were selected considering acquisition time difference, cloud conditions, viewing geometry, and target homogeneity. The PAN band was excluded from the Sentinel-2 cross-calibration because Sentinel-2 does not provide a spectrally comparable panchromatic channel. To compensate

for differences in the spectral responses of CAS500-1 and Sentinel-2A/B, a Spectral Band Adjustment Factor (SBAF) was calculated using the SRFs of both sensors and 746 spectra from the USGS Spectral Library (splib06a), representing man-made materials, rocks, soils, vegetation, and other surface types [33]:

$$SBAF = \frac{\int_0^\infty \rho(\lambda) RSR_{Sentinel-2}(\lambda) d\lambda}{\int_0^\infty \rho(\lambda) RSR_{CAS500-1}(\lambda) d\lambda} \quad (3)$$

where $\rho(\lambda)$ is the target reflectance spectrum and $RSR(\lambda)$ represents the relative spectral response of each sensor. The band-effective reflectance corresponding to a given spectral response was calculated as:

$$RSR = \frac{\int_0^\infty SRF(\lambda) \rho(\lambda) d\lambda}{\int_0^\infty SRF(\lambda) d\lambda} \quad (4)$$

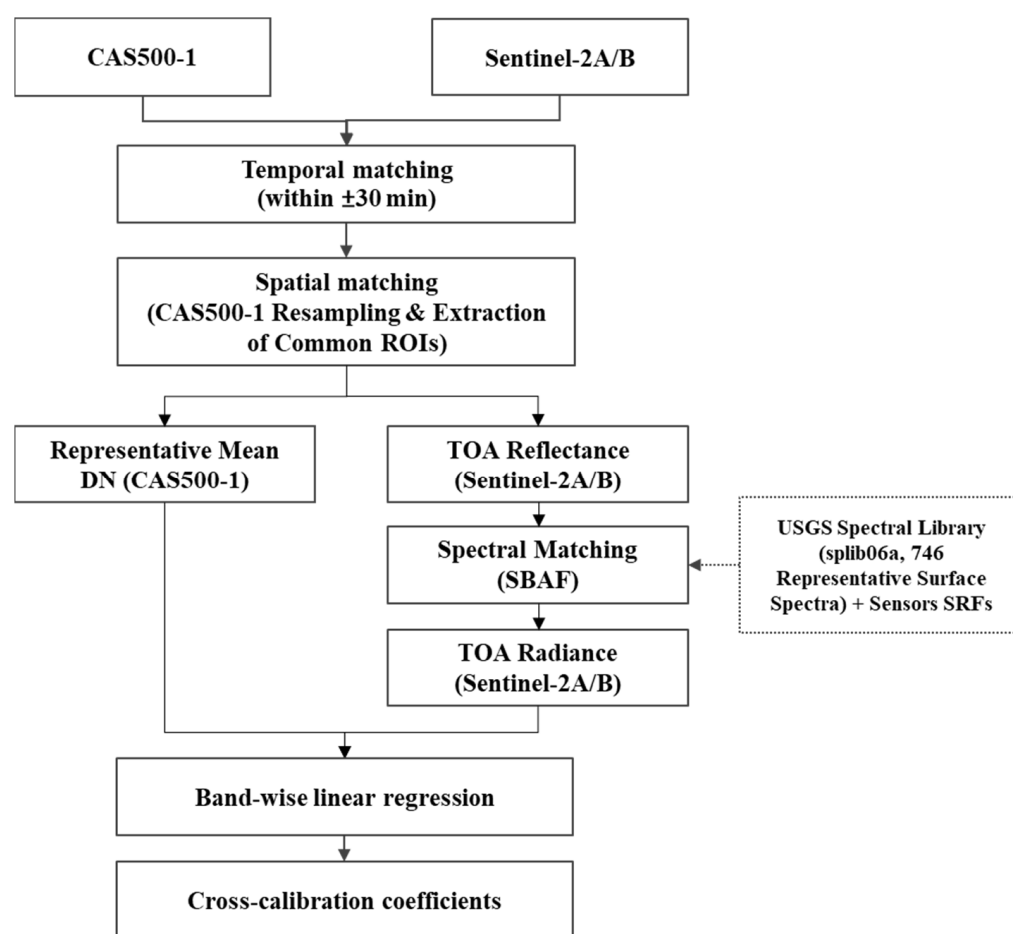


Figure 6. Workflow of the cross-calibration procedure.

The resulting SBAF was applied to the Sentinel-2 TOA reflectance to account for the spectral-response differences between Sentinel-2 and the corresponding CAS500-1 multi-spectral bands prior to the regression analysis. The SBAF-corrected Sentinel-2A/B TOA reflectance was subsequently converted to TOA radiance and paired with the corresponding representative mean digital numbers (DNs) extracted from the CAS500-1 imagery.

Band-wise linear regression between CAS500-1 DN and the reference TOA radiance was then performed to derive independent cross-calibration gain and offset coefficients. These coefficients were compared with the field-derived calibration coefficients to evaluate the radiometric consistency of the operational calibration results.

The uncertainty associated with the field-based calibration procedure was assessed by identifying the principal uncertainty sources throughout the calibration chain, from field surface-reflectance measurement and atmospheric characterization to radiative transfer simulation and satellite-image DN extraction. The individual uncertainty components considered included uncertainties associated with ground reflectance measurement, atmospheric parameters (AOD, TWV, and TOC), radiative transfer modeling, solar irradiance, image DN extraction, and surface- and geometry-related effects. The uncertainty associated with spectroradiometer temperature sensitivity was not determined from a dedicated temperature-characterization experiment for the ASD instrument used in this study. Instead, a value of 1.0% was adopted as a literature-based estimate based on the experimental temperature-sensitivity analysis of field spectroradiometers reported by Ma et al. [34]. The wavelength dependence of temperature sensitivity was not separately characterized for the ASD instrument used in this study; therefore, the 1.0% value was applied as a wavelength-independent uncertainty component in the present uncertainty budget. The individual components were quantitatively evaluated according to their respective uncertainty sources and subsequently propagated to obtain the combined relative standard uncertainty.

For uncertainty components derived from repeated measurements, Type A evaluation was performed in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM; JCGM 100:2008) and KOLAS-Gc01:2022. For a set of N repeated observations, the sample standard deviation was calculated as:

$$U = \sqrt{\frac{\sum_{i=1}^N (x_i - \mu)^2}{N - 1}}, \quad (5)$$

where x_i is an individual observation, μ is the arithmetic mean of the repeated observations, and N is the number of observations. The Type A standard uncertainty of the mean was then calculated as:

$$U(x_i) = \frac{U}{\sqrt{N}}. \quad (6)$$

Field reflectance measurement uncertainty was evaluated using the Type A uncertainty derived from repeated ASD surface-reflectance measurements acquired during each calibration campaign, together with the bias relative to the certified reference-panel reflectance. Because the Type A component was derived independently for each campaign, the resulting uncertainty varied according to the observed within-campaign measurement variability.

For uncertainty components expressed relative to their measured or reference quantity, the relative standard uncertainty was calculated as:

$$U(\%) = \frac{U(x_i)}{\mu} \quad (7)$$

Assuming that the individual uncertainty components were independent, the combined relative standard uncertainty of the calibration procedure was obtained by the root-sum-of-squares method:

$$U_c = \sqrt{\sum_{i=1}^M U(x_i)^2} \quad (8)$$

where U_c is the combined relative standard uncertainty, $U(x_i)$ is the relative standard uncertainty associated with the i -th uncertainty component, and M is the total number of uncertainty components considered. The resulting combined uncertainty was used to characterize the reliability of the calibration datasets and to assess the uncertainty associated with the derived annual calibration coefficients.

For the temporal evaluation of operational calibration performance, repeated CAS500-1 observations were analyzed over an asphalt reference site in Uiwang, Korea (37.315°N,

126.955°E) [35], where surface reflectance was periodically measured using an ASD spectro-radiometer. The CAS500-1 datasets used for the temporal variability analysis, together with the independent images used for the negative TOA radiance assessment, are summarized in Table 5. Prior to the satellite time-series analysis, the temporal stability of the reference surface was evaluated using repeated ASD surface reflectance measurements acquired during 2023–2024 (Figure 7). CAS500-1 DN, TOA reflectance, and surface reflectance were subsequently evaluated on a band-by-band basis over the same reference site and compared with the ASD observations to assess temporal and interannual radiometric consistency.

Table 5. CAS500-1 datasets used for negative TOA radiance assessment and temporal variability analysis.

Purpose	Data Product	Date	Site
Negative TOA radiance assessment	CAS500-1 L2A TOA Radiance	10 April 2023 16 October 2023 23 January 2024 16 May 2024	Suwon, Gyeonggi-do Uiwang, Gyeonggi-do Yongin, Gyeonggi-do Iksan, Jeollabuk-do
Temporal variability analysis	CAS500-1 L2A TOA Reflectance	8 August 2023 7 September 2023 16 October 2023 2 November 2024 8 December 2024	Uiwang asphalt reference site (37.315°N, 126.955°E)

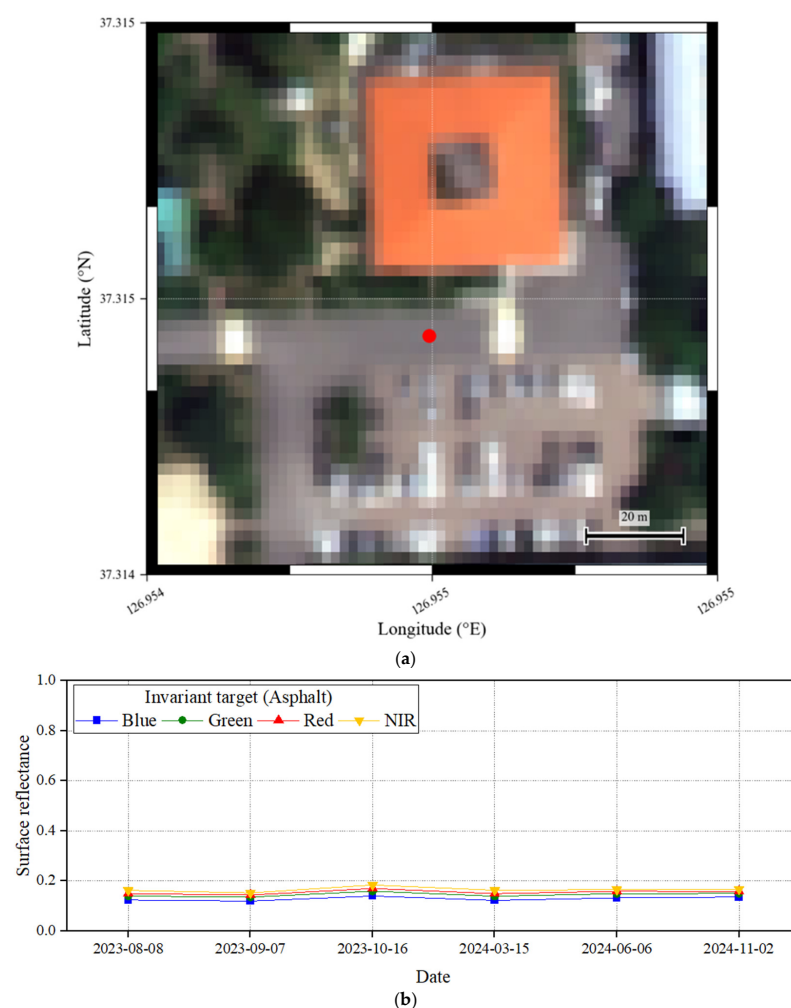


Figure 7. Uiwang asphalt reference site (37.315°N, 126.955°E): (a) CAS500-1 image acquired on 8 August 2023 and (b) time-series ASD surface reflectance measurements.

In addition, the operational applicability of the annual calibration coefficients was evaluated using independent CAS500-1 images acquired over different regions and operating conditions (Table 5). For each image, the proportion and spatial distribution of pixels exhibiting negative TOA radiance after application of the annual gain and offset coefficients were examined for each spectral band. This analysis was used as a practical diagnostic of calibration behavior in the low-signal range, particularly over low-radiance surfaces such as water bodies and terrain-shadowed areas. Together with the Sentinel-2 cross-calibration and uncertainty assessment, these image-based evaluations provided complementary measures of the radiometric consistency, temporal stability, and operational applicability of the annually updated CAS500-1 calibration coefficients.

3. Results

3.1. Field Campaign Results

A total of fifteen field campaigns were conducted during 2023–2024. Following the QC procedure described in Section 2.4, only observations satisfying the predefined atmospheric and surface-measurement quality criteria were retained for calibration coefficient estimation, as summarized in Table 2.

Figure 8 compares the representative reflectance spectra of the calibration tarps measured during the 2023 and 2024 field campaigns. The calibration tarps used in 2023 were replaced with newly manufactured tarps prior to the 2024 campaigns after repeated field deployment. Small interannual differences were observed in the measured reflectance spectra, particularly in the blue wavelength region. However, the measured spectra remained close to the nominal reflectance levels (5%, 20%, 30%, and 50%), and the observed differences were within the manufacturer-specified tolerance and were therefore considered acceptable for radiometric calibration.

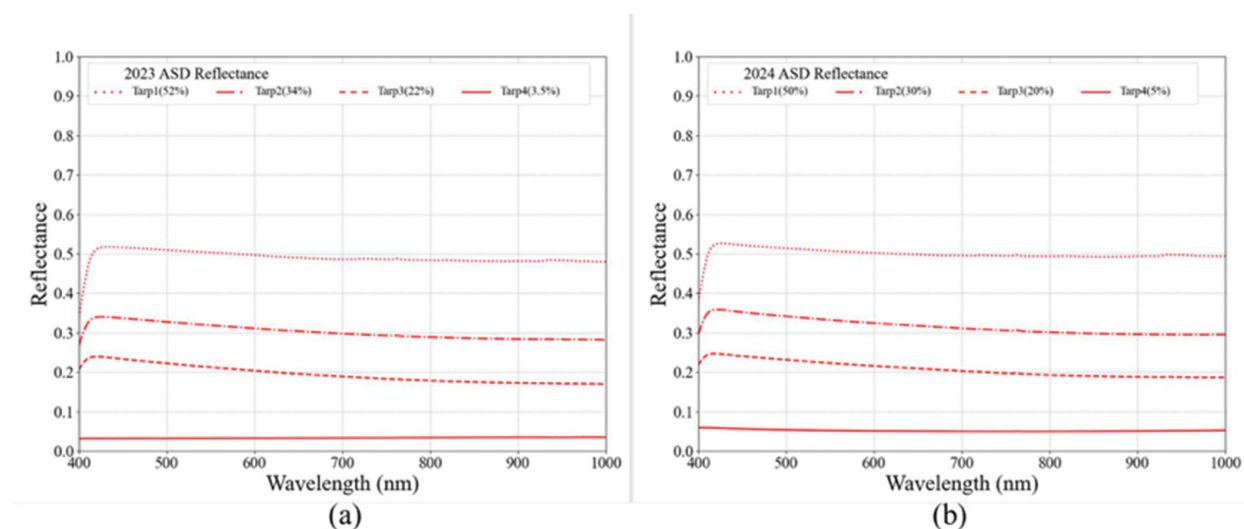


Figure 8. Representative reflectance spectra of the calibration tarps used for the 2023 (a) and 2024 (b) field campaigns.

For each field campaign, ASD measurements acquired before and after the satellite overpass were independently evaluated to identify the most representative surface reflectance observation. The uncertainty of each ASD observation was estimated by combining the temporal variability of repeated spectral measurements with the bias relative to the nominal reflectance of the corresponding calibration tarp. The observation with the lower combined uncertainty was selected as the representative surface reflectance for radiative transfer modeling. The uncertainty comparison between the pre- and post-overpass ASD

measurements is summarized in Table 6, together with the observation selected for the subsequent calibration process.

Table 6. Uncertainty assessment of ASD measurements acquired before and after the satellite overpass for representative spectrum selection.

Date	Before Uncertainty (%)	After Uncertainty (%)
9 May 2023	2.521	2.088
25 May 2023	2.810	2.223
9 June 2023	2.824	2.070
12 October 2023	2.426	2.286
21 October 2023	3.333	4.995
26 October 2023	1.887	5.541
23 November 2023	1.923	4.234
20 March 2024	1.607	1.959
25 April 2024	-	1.396
16 May 2024	-	1.582
27 September 2024	-	4.607
12 October 2024	1.400	2.695
12 November 2024	4.048	5.601
18 November 2024	2.636	3.204
19 December 2024	11.310	2.170

The temporal behavior of the MICROTOPS II atmospheric measurements was also evaluated during the QC procedure. As illustrated in Figure 9, rapid fluctuations in AOD coincided with periods of increased cloud fraction identified from the GeoKOMPSAT-2 AMI Cloud Fraction (CF) product, indicating that cloud contamination significantly affected the atmospheric observations. After applying the QC procedure described in Section 2.4, cloud-contaminated observations were removed, resulting in substantially reduced temporal variability of AOD (Figure 10). The quality-controlled atmospheric parameters agreed well with the independent reference observations, yielding correlation coefficients greater than 0.82 for AOD with RMSE values of 0.009–0.015, while TWV and TOC achieved correlation coefficients of 0.974 and 0.952, respectively [31]. The processed atmospheric parameters listed in Table 2 were subsequently used as inputs to the MODTRAN simulations.

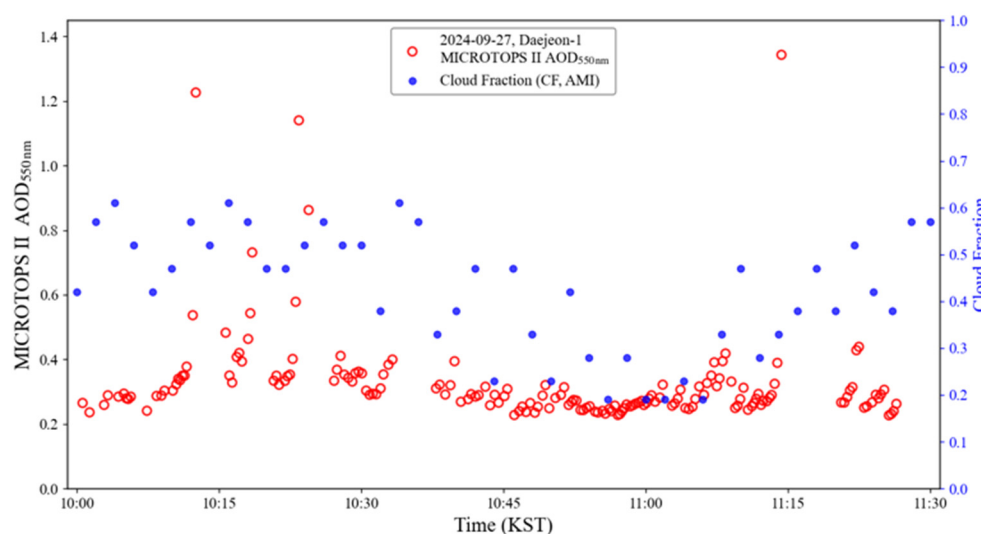


Figure 9. Identification of cloud-contaminated periods using the AMI Cloud Fraction (CF) and corresponding variations in MICROTOPS II AOD measurements.

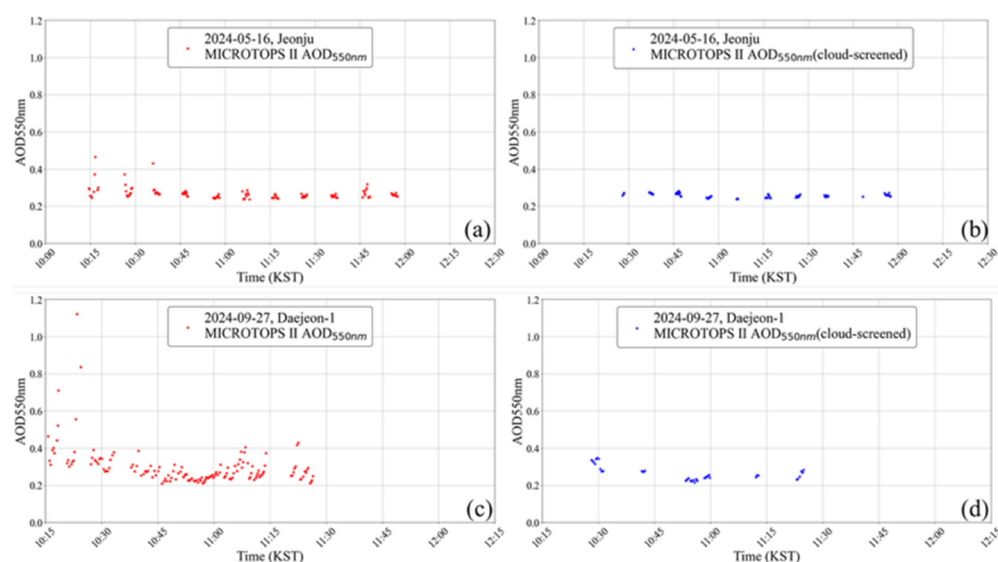


Figure 10. Temporal variation of MICROTOPS II AOD measurements before and after quality control (QC): (a) before QC in 2023, (b) after QC in 2023, (c) before QC in 2024, and (d) after QC in 2024, illustrating the reduced variability after quality control.

3.2. Radiometric Calibration Coefficients

Following the quality assessment of the field measurements, annual radiometric calibration coefficients were independently derived for each spectral band under the summer (TDI 1) and winter (TDI 2) operating modes using the reflectance-based vicarious calibration procedure described in Section 2.7. For each valid field dataset, the measured tarp reflectance, quality-controlled atmospheric parameters, satellite observation geometry, and sensor spectral response functions were used as inputs to MODTRAN6 to simulate band-integrated top-of-atmosphere (TOA) radiance. Linear regression between the simulated TOA radiance and the corresponding mean DN extracted from the calibration-tarp ROIs was then used to estimate the gain and offset coefficients. Only datasets satisfying the predefined quality-control criteria were included in the regression analysis.

Figures 11 and 12 present the band-specific regression relationships obtained from the 2023 and 2024 calibration campaigns, respectively, and Table 7 summarizes the resulting gain and offset coefficients. In 2023, the coefficients of determination ranged from 0.910 to 0.987 for TDI 1 and from 0.868 to 0.973 for TDI 2. The lowest values were obtained for the TDI 1 NIR band and the TDI 2 panchromatic band. In 2024, the regression performance generally improved, with R^2 values ranging from 0.965 to 0.994 for TDI 1 and from 0.973 to 0.998 for TDI 2. The improved linearity in 2024 indicates that the quality-controlled field and atmospheric measurements provided more internally consistent inputs for coefficient estimation. However, the 2024 TDI 2 coefficients were derived from eight valid observations and should therefore be interpreted in consideration of the smaller sample size.

The annual coefficients exhibited systematic differences between the 2023 and 2024 campaigns. The 2024 gain coefficients were higher than the corresponding 2023 values for all bands and both TDI modes, while the magnitude and direction of the offset changes varied by band. The gain increases ranged from approximately 13% to 30% for TDI 1 and from 17% to 28% for TDI 2. The largest relative gain differences occurred in the TDI 1 NIR band and the TDI 2 panchromatic band. These differences may reflect a combination of changes in field measurement quality, atmospheric characterization, calibration-target condition, and the number and distribution of valid calibration observations. Accordingly, the coefficient differences alone should not be interpreted as direct evidence of sensor degradation.

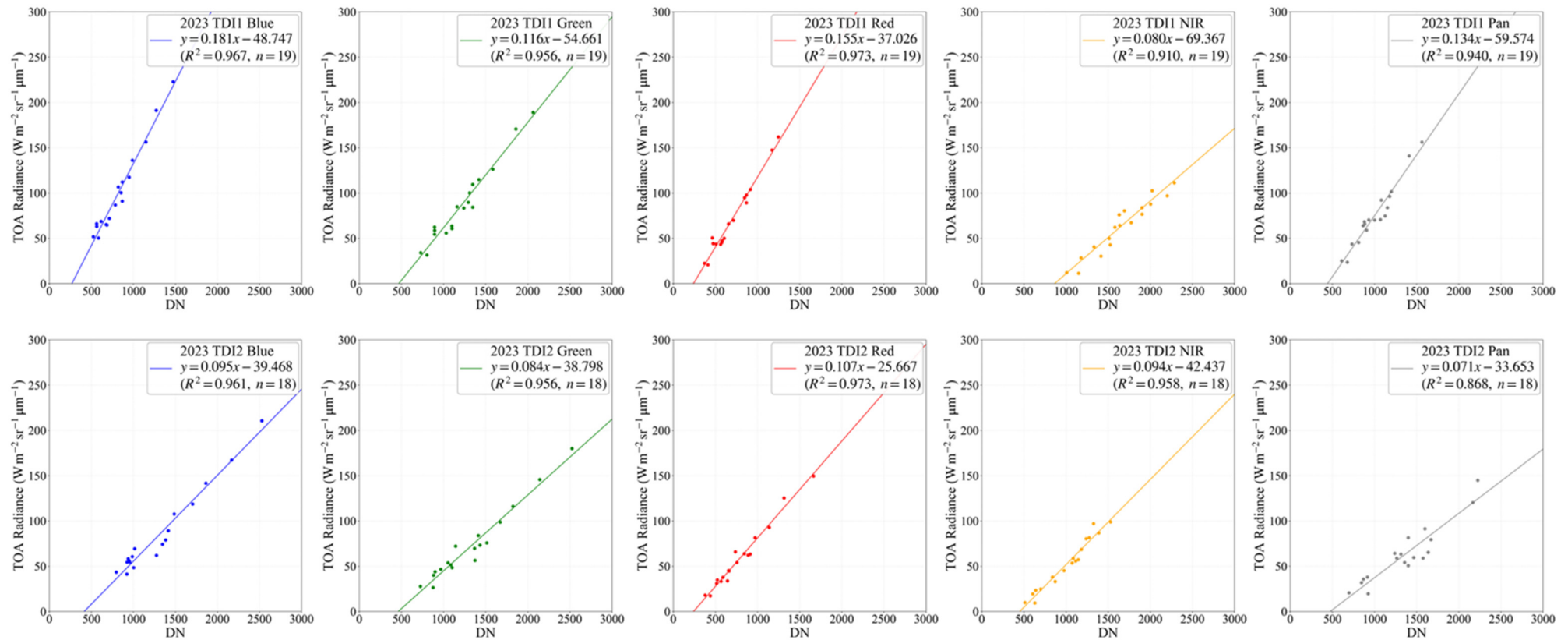


Figure 11. Relationships between the simulated top-of-atmosphere radiance and CAS500-1 DN values for the 2023 calibration campaign: TDI 1 mode in the upper row and TDI 2 mode in the lower row.

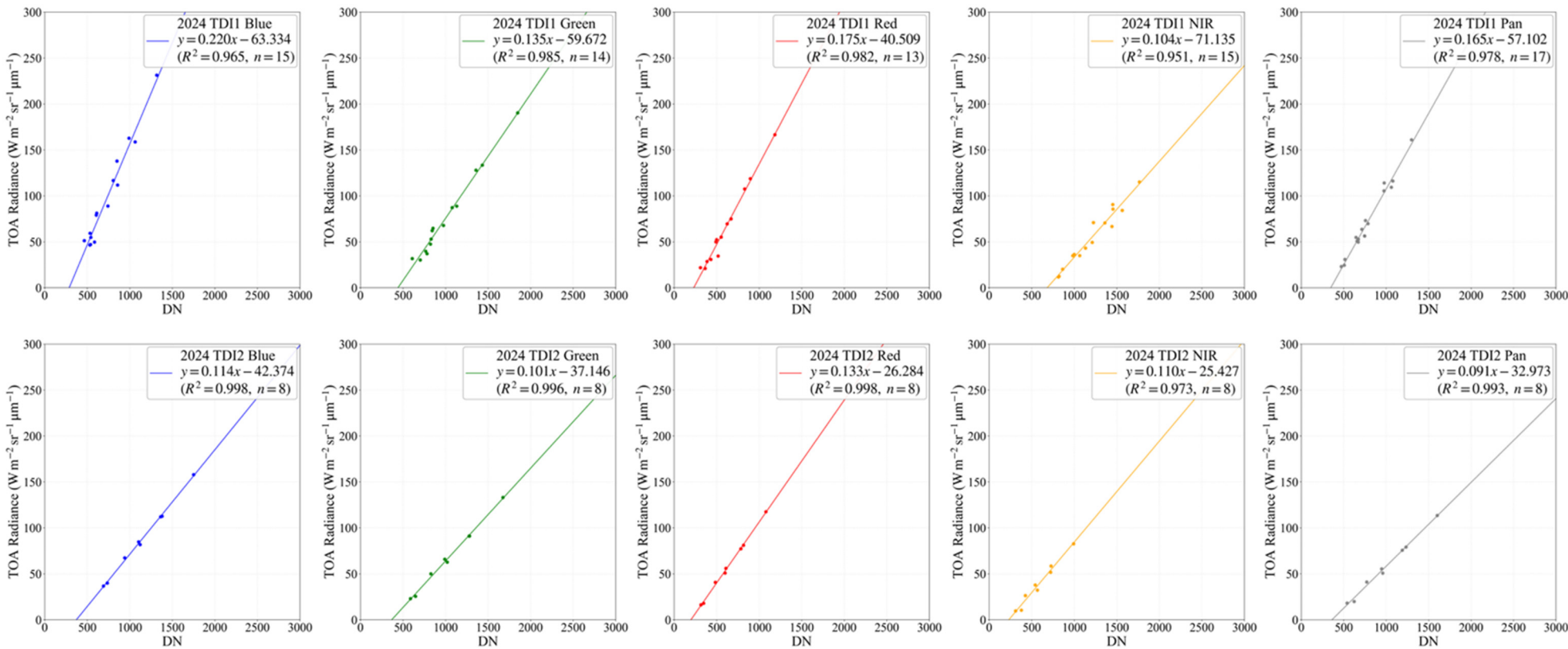


Figure 12. Relationships between the simulated top-of-atmosphere radiance and CAS500-1 DN values for the 2024 calibration campaign: TDI 1 mode in the upper row and TDI 2 mode in the lower row.

Table 7. Comparison of the CAS500-1 radiometric calibration coefficients derived from field-based vicarious calibration and Sentinel-2 cross-calibration over Libya PICS and RVUS.

Year /Mode	Method	Field-Based Vicarious Calibration					Sentinel-2 Cross-Calibration							
		Band	Gain	Offset	R^2	n	Libya PICS				RVUS			
							Gain	Offset	R^2	n	Gain	Offset	R^2	n
2023 (TDI 1)	Blue	0.181	−48.747	0.987		19	0.185	−58.843	0.870	35	-	-	-	-
	Green	0.116	−54.661	0.956			0.117	−81.714	0.831		-	-	-	
	Red	0.155	−37.026	0.973			0.144	−52.293	0.784		-	-	-	
	NIR	0.080	−69.367	0.910			-	-	-		-	-	-	
	Pan	0.135	−59.574	0.940			-	-	-		-	-	-	
2023 (TDI 2)	Blue	0.095	−39.468	0.961		18	-	-	-	-	-	-	-	-
	Green	0.084	−38.798	0.957			-	-	-		-	-	-	
	Red	0.107	−25.667	0.973			-	-	-		-	-	-	
	NIR	0.094	−42.437	0.958			-	-	-		-	-	-	
	Pan	0.071	−33.653	0.868			-	-	-		-	-	-	
2024 (TDI 1)	Blue	0.220	−63.334	0.965		16	0.197	−68.457	0.794	20	0.182	−29.070	0.983	16
	Green	0.135	−59.672	0.985			0.123	−89.712	0.904		0.117	−41.999	0.985	
	Red	0.175	−40.509	0.982			0.135	−30.060	0.897		0.185	−61.206	0.976	
	NIR	0.104	−71.435	0.986			-	-	-		0.090	−60.392	0.939	
	Pan	0.165	−57.102	0.994			-	-	-		-	-	-	
2024 (TDI 2)	Blue	0.114	−42.374	0.998		8	0.113	−82.678	0.879	20	0.111	−100.950	0.760	16
	Green	0.101	−37.146	0.996			0.091	−94.119	0.886		0.102	−115.620	0.912	
	Red	0.133	−26.284	0.998			0.123	−97.727	0.832		0.123	−70.799	0.976	
	NIR	0.110	−25.427	0.973			-	-	-		0.110	−88.399	0.945	
	Pan	0.091	−32.973	0.993			-	-	-		-	-	-	

Note: “-” indicates that no cross-calibration coefficient was derived. For the NIR band at Libya-4, the correlation between CAS500-1 DN and Sentinel-2 TOA radiance did not satisfy the acceptance criterion ($r < 0.5$). The PAN band was excluded because Sentinel-2 does not provide a corresponding panchromatic band.

The annual coefficient comparison demonstrates the importance of periodically updating the operational calibration parameters using quality-controlled field observations. The coefficients derived from the annual campaigns were implemented in the CAS500-1 image-processing system for operational radiometric conversion and the subsequent production of higher-level surface-reflectance and analysis-ready products. Continued annual calibration and independent temporal validation are required to distinguish changes arising from calibration-input conditions from actual variations in sensor radiometric response.

3.3. Validation Results

3.3.1. Independent Cross-Calibration

The field-derived operational calibration coefficients were independently evaluated through cross-calibration with Sentinel-2A/B using observations acquired over the Libya-4 PICS and the RadCalNet RVUS site. Table 7 compares the gain and offset coefficients obtained from the field-based vicarious calibration with those independently derived from the Sentinel-2 cross-calibration. Cross-calibration coefficients were retained only when sufficient correlation was obtained between CAS500-1 DN and the corresponding Sentinel-2

TOA radiance. For the NIR band, reliable coefficients could not be derived from the Libya-4 dataset because the correlation coefficient was below the acceptance criterion ($r < 0.5$), which was attributed to limitations in the quality of the CAS500-1 NIR DN imagery. In contrast, NIR coefficients were successfully derived from the 2024 RVUS observations. The PAN band was excluded from cross-calibration because Sentinel-2 does not provide a corresponding panchromatic band.

For the 2023 TDI 1 mode, cross-calibration was available only for the Libya-4 PICS. The cross-calibration gains for the Blue, Green, and Red bands were 0.185, 0.117, and 0.144, respectively, compared with the corresponding field-derived gains of 0.181, 0.116, and 0.155. The relative gain differences were approximately 2.2%, 0.9%, and 7.1%, indicating generally close agreement between the two independent approaches for the visible bands. The corresponding cross-calibration R^2 values ranged from 0.784 to 0.870 compared with 0.956–0.987 for the field-based regressions.

For the 2024 TDI 1 mode, the Libya-4 cross-calibration gains for the Blue, Green, and Red bands were 0.197, 0.123, and 0.135, respectively, whereas the corresponding field-derived gains were 0.220, 0.135, and 0.175. The relative differences were approximately 10.5%, 8.9%, and 22.9%, with the largest discrepancy observed in the Red band. The RVUS-derived gains were 0.182, 0.117, 0.185, and 0.090 for the Blue, Green, Red, and NIR bands, respectively. Relative to the field-derived coefficients, the corresponding differences were approximately 17.3%, 13.3%, 5.7%, and 13.5%. The RVUS regressions showed high coefficients of determination, ranging from 0.939 to 0.985, whereas the Libya-4 results ranged from 0.794 to 0.904.

For the 2024 TDI 2 mode, the Libya-4 cross-calibration gains for the Blue, Green, and Red bands were 0.113, 0.091, and 0.123, respectively, compared with field-derived gains of 0.114, 0.101, and 0.133. The corresponding relative differences were approximately 0.9%, 9.9%, and 7.5%. The RVUS-derived gains were 0.111, 0.102, 0.123, and 0.110 for the Blue, Green, Red, and NIR bands, respectively, corresponding to relative differences of approximately 2.6%, 1.0%, 7.5%, and 0.0% from the field-derived values. The RVUS R^2 values ranged from 0.760 to 0.976, while the Libya-4 values ranged from 0.832 to 0.886. Overall, the TDI 2 gain coefficients showed relatively good consistency among the field-based, Libya-4, and RVUS calibration approaches.

Compared with the gain coefficients, larger differences were observed in the offset terms, particularly between the field-based and cross-calibration results. The offset is more sensitive to differences in acquisition geometry, spatial and spectral matching, surface characteristics, and residual atmospheric effects, and therefore greater variability can be expected in satellite-to-satellite cross-calibration. Nevertheless, the generally comparable gain coefficients obtained from the two independent reference sites support the radiometric consistency of the field-derived operational calibration coefficients. The remaining band- and site-dependent differences, particularly for the TDI 1 Red band and the NIR measurements, indicate that cross-calibration should be interpreted together with the uncertainty assessment and long-term temporal stability analyses when evaluating the operational validity of the annual calibration coefficients.

3.3.2. Uncertainty Assessment

The uncertainty associated with the field-based radiometric calibration was evaluated by considering the major uncertainty sources arising from surface reflectance measurements, atmospheric characterization, radiative transfer modeling, and satellite image measurements. The uncertainty budgets for the 2023 and 2024 calibration campaigns are summarized in Table 8. In 2023, uncertainty was assessed using an annual representative uncertainty budget (Table 8a), whereas a refined campaign-specific uncertainty assessment

was implemented in 2024 (Table 8b) to account for variations in field and atmospheric conditions among individual campaigns.

Table 8. Uncertainty assessment of the CAS500-1 field-based radiometric calibration: (a) annual representative uncertainty budget for 2023 and (b) campaign-specific uncertainty budgets for 2024.

(a) 2023 Annual Representative Uncertainty Budget									
Uncertainty Component		Relative Uncertainty (%)							
ASD Observation		2.10							
MODTRAN V6		2.00							
Solar Irradiance Model		1.70							
AOD		1.00							
TWV		1.00							
TOC		1.00							
Adjacency and BRDF Effects		5.00							
Overall Uncertainty		6.26							
(b) 2024 Campaign-Specific Uncertainty Budgets									
Category	Uncertainty Component	20 Mar	25 Apr	16 May	27 Sep	12 Oct	12 Nov	18 Nov	19 Dec
Ground Reflectance	Stray Light	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	Laboratory Calibration	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Instrument Degradation	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Spectrometer Temperature Sensitivity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Noise during Field Measurement	0.29	1.16	2.32	4.38	0.23	5.58	3.15	0.76
Radiative Transfer Code	Solar Irradiance Model	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	Aerosol Model	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	MODTRAN V6	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Atmospheric Characterization	AOD	6.23	1.13	1.23	3.82	1.73	2.64	1.34	1.33
	TWV	1.92	0.53	0.57	0.39	0.36	0.70	0.78	0.52
	TOC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Site Homogeneity	ROI DN Variability	0.98	1.17	1.48	1.00	1.22	2.02	1.52	1.63
	Adjacency and BRDF Effects	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Combined Uncertainty (%)		7.77	4.59	5.12	7.19	4.64	7.71	5.61	4.70

For the 2023 calibration, representative uncertainty values were assigned to the major components based on the field measurement and radiative transfer procedures, resulting in a combined relative uncertainty of 6.26%. In 2024, individual uncertainty components were evaluated separately for each field campaign, particularly those associated with field reflectance measurements, atmospheric parameters, and target DN variability. The resulting campaign-specific combined uncertainties ranged from 4.59% to 7.77%, demonstrating that the overall calibration uncertainty varied substantially depending on the surface measurement and atmospheric conditions at the time of each satellite acquisition.

The uncertainty components summarized in Table 8 were quantified using either measurement-based estimates or values adopted from previous studies, depending on the availability of campaign-specific information. For the 2023 uncertainty budget, the ASD observation uncertainty of 2.10% was estimated by root-sum-square (RSS) propagation of the major uncertainty components associated with field spectroradiometric measurements,

including laboratory calibration (2.0%), field measurement noise (<0.1%), stray light (0.3%), and instrument degradation (0.5%), following the uncertainty framework adopted from Yeom et al. [36] and the RadCalNet site uncertainty statement. The uncertainties associated with AOD, TWV, and TOC were conservatively estimated based on Yeom et al. [36]. The MODTRAN6 component represented radiative-transfer-model uncertainty, while the solar irradiance uncertainty was assigned based on the VNIR uncertainty of the adopted solar reference spectrum [32]. A conservative uncertainty of 5.0% was assigned to account for residual adjacency and non-Lambertian BRDF effects that were not explicitly corrected. For the refined 2024 assessment, field reflectance measurement uncertainty was evaluated from the Type A uncertainty of repeated ASD measurements together with the bias relative to the certified reference-panel reflectance. The uncertainties associated with atmospheric parameters were evaluated from measurement repeatability, while ROI DN uncertainty was quantified from spatial variability within each ROI using the coefficient of variation (CV). Fixed uncertainty components associated with stray light, laboratory calibration, instrument degradation, and spectroradiometer temperature sensitivity were adopted from the experimental uncertainty analysis reported by Ma et al. [34].

Several differences in the uncertainty components between 2023 and 2024 resulted from refinements to the calibration and uncertainty-assessment procedures rather than to direct changes in sensor performance. For solar irradiance, the default MODTRAN solar irradiance model based on Fontenla was used in 2023, with an assigned uncertainty of 1.7%, whereas the Thuillier et al. [32] solar irradiance spectrum adopted for the 2024 calibration had an uncertainty of 1.5%. The treatment of surface- and geometry-related uncertainties was also refined. In the 2023 uncertainty budget, the BRDF-related component included contributions associated with satellite DN variability and surface reflectance uncertainty. In 2024, these contributions were evaluated separately, including campaign-specific field measurement variability and ROI DN variability, while the remaining adjacency and BRDF effects were treated as an independent uncertainty component. Consequently, the component-level uncertainties in Table 8a,b should not be interpreted as direct year-to-year changes, but rather as reflecting the refinement of the uncertainty-assessment framework.

Among the 2024 campaigns, the combined uncertainties were 7.77%, 4.59%, 5.12%, 7.19%, 4.64%, 7.71%, 5.61%, and 4.70% for 20 March, 25 April, 16 May, 27 September, 12 October, 12 November, 18 November, and 19 December, respectively. The larger uncertainties observed for some campaigns were primarily associated with increased variability in field reflectance measurements and atmospheric characterization, particularly AOD. The datasets retained for annual calibration coefficient estimation exhibited combined uncertainties of 5.12%, 4.64%, 5.61%, and 4.70% for 16 May, 12 October, 18 November, and 19 December, respectively. These campaign-specific uncertainty estimates provided a quantitative basis for evaluating the reliability of individual calibration datasets, and together with the quality-control criteria described in Section 2.4, supported the selection of valid observations for operational calibration coefficient estimation.

3.3.3. Operational Validation After Annual Calibration Coefficients

The operational performance of the annual radiometric calibration coefficients was evaluated using independent CAS500-1 images acquired under both TDI 1 and TDI 2 operating modes. As a practical diagnostic of calibration performance, the proportion of pixels exhibiting negative top-of-atmosphere (TOA) radiance after radiometric conversion was calculated for each spectral band. Negative radiance values can occur when the measured signal is sufficiently low that the calibrated radiance approaches or falls below zero after application of the gain and offset coefficients. Therefore, the occurrence of

negative TOA radiance was examined to assess the behavior of the derived calibration coefficients, particularly in the low-signal range.

Table 9 summarizes the negative TOA radiance ratios for the validation images acquired in 2023 and 2024. For the 2023 TDI 1 image acquired on 10 April, the negative-radiance ratios ranged from 0.001% to 0.042% across the four multispectral bands. The 2023 TDI 2 image acquired on 16 October similarly exhibited low ratios in the visible bands (0.009–0.011%), although a relatively higher value of 0.250% was observed in the NIR band. The 2024 TDI 2 image acquired on 23 January also showed consistently low negative-radiance ratios, ranging from 0.007% to 0.031%. These results indicate that the annual calibration coefficients generally produced positive TOA radiance values for the vast majority of pixels in the evaluated images.

Table 9. Negative TOA radiance ratios (%) in the CAS500-1 validation images after application of the annual radiometric calibration coefficients.

Acquisition Date	TDI Mode	Blue	Green	Red	NIR
10 April 2023	TDI 1	0.001	0.034	0.028	0.042
16 October 2023	TDI 2	0.011	0.011	0.009	0.250
23 January 2024	TDI 2	0.008	0.010	0.007	0.031
16 May 2024	TDI 1	0.020	0.260	5.128	1.537

A different behavior was observed in the TDI 1 image acquired on 16 May 2024. While the negative-radiance ratios remained relatively low in the Blue (0.020%) and Green (0.260%) bands, they increased to 5.128% and 1.537% in the Red and NIR bands, respectively. Examination of the spatial distribution showed that these negative values were not uniformly distributed across the image but occurred predominantly over low-radiance features, particularly water bodies and terrain-shadowed areas in mountainous regions. Figure 13 illustrates this spatial pattern for the NIR band, in which negative-radiance pixels are highlighted in red. The concentration of negative values over dark targets suggests that their occurrence is primarily associated with the radiometric conversion behavior near the lower end of the sensor signal range rather than with a systematic scene-wide radiometric bias.

Overall, negative TOA radiance occurred only in a small fraction of pixels for most evaluated images and spectral bands, supporting the operational applicability of the annually derived radiometric calibration coefficients. However, the increased occurrence of negative radiance in the Red and NIR bands of the 16 May 2024 TDI 1 image indicates that the radiometric conversion remains sensitive to very low signal levels, particularly over water bodies and terrain-shadowed surfaces. These results highlight the importance of continued monitoring of low-radiance targets in operational CAS500-1 products as a complementary assessment to the independent cross-calibration and uncertainty analyses. Although a nominal 5% reflectance tarp was included in the field campaigns, the radiance range represented by this target may not fully characterize the extremely low-signal conditions encountered over dark water and terrain-shadowed surfaces. Future calibration campaigns should therefore include additional measurements targeting the lower end of the sensor dynamic range, together with a dedicated assessment of radiometric response linearity under low-signal conditions.

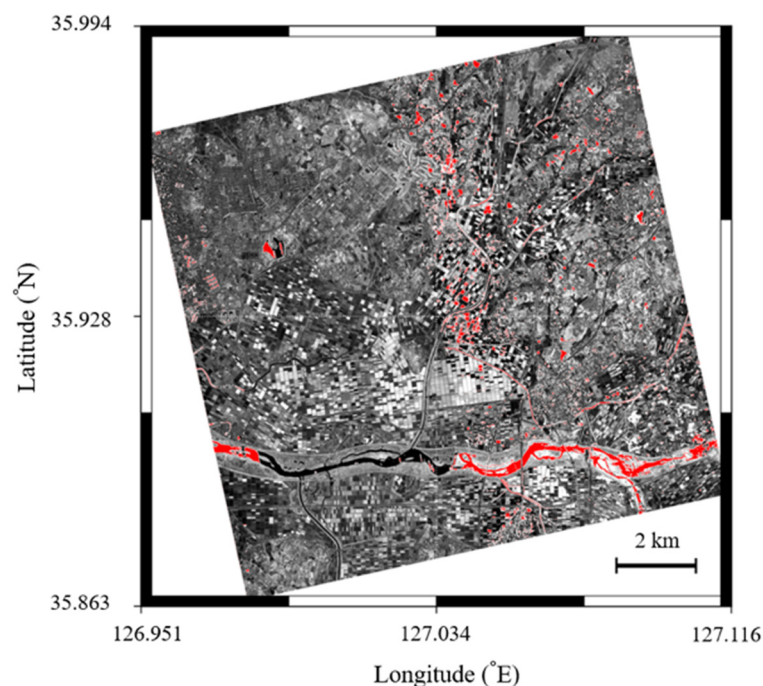


Figure 13. Spatial distribution of negative TOA radiance pixels in the NIR band of the CAS500-1 image acquired on 16 May 2024. Negative-radiance pixels, occurring predominantly over water bodies and terrain-shadowed areas, are highlighted in red.

3.4. Interannual Radiometric Stability

To evaluate the temporal radiometric stability of CAS500-1 after application of the annually updated calibration coefficients, repeated observations over the Uiwang asphalt reference site were analyzed during 2023–2024. The site was selected because repeated ASD measurements demonstrated relatively stable surface reflectance characteristics over the study period, as shown in Figure 7. Accordingly, temporal variations observed in the CAS500-1 measurements over this target were used to assess the consistency of the calibrated radiometric response across different acquisition dates and TDI operating modes.

Figure 14 shows the temporal variation in CAS500-1 L2A TOA reflectance for the Blue, Green, Red, and NIR bands. Although some temporal variation was observed among the acquisition dates, the Blue, Green, and Red bands generally exhibited similar temporal behavior, whereas the NIR band showed comparatively larger fluctuations. In particular, TOA reflectance decreased on 7 September 2023 and subsequently increased on 16 October 2023, with the NIR band exhibiting the largest temporal response. A relatively high NIR reflectance was also observed on 2 November 2024. Nevertheless, the overall temporal patterns of the visible bands remained mutually consistent across the 2023 and 2024 observations.

The band-wise statistics further demonstrate the comparatively large variability of the NIR band (Table 10). The mean TOA reflectance values calculated from the five observations were 0.125, 0.115, 0.118, and 0.178 for the Blue, Green, Red, and NIR bands, respectively, with corresponding standard deviations of 0.033, 0.034, 0.035, and 0.051. Thus, the NIR band exhibited the largest absolute temporal variability in TOA reflectance. A similar characteristic was evident in the original DN measurements: the DN standard deviations were 241.271, 173.199, 107.351, and 389.691 DN for the Blue, Green, Red, and NIR bands, respectively, with the NIR band showing substantially greater variability than the visible bands.

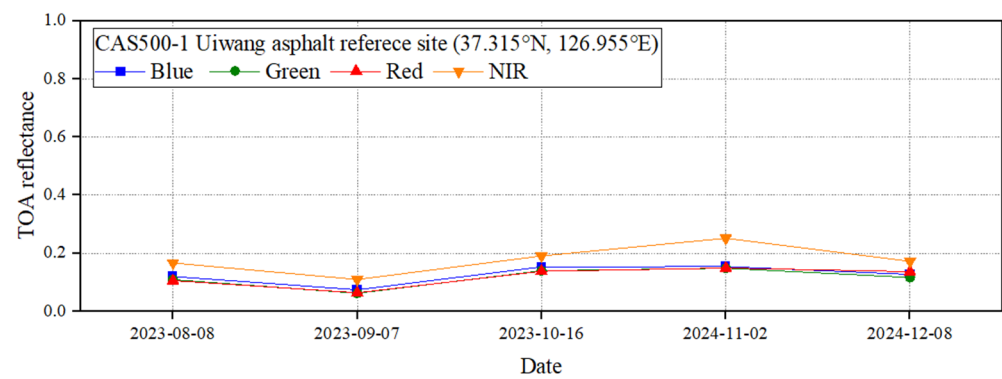


Figure 14. Temporal variation in CAS500-1 L2A TOA reflectance over the Uiwang asphalt reference site during 2023–2024.

Table 10. Temporal mean and standard deviation of CAS500-1 DN and TOA reflectance over the Uiwang asphalt reference site based on five observations acquired during 2023–2024.

Data	DN		TOA Reflectance	
	Mean	Std.	Mean	Std.
Blue	743.200	241.271	0.125	0.033
Green	856.600	173.199	0.115	0.034
Red	512.200	107.351	0.118	0.035
NIR	949.200	389.691	0.178	0.051

The relatively large temporal variability observed in the NIR TOA reflectance therefore appears to be associated, at least in part, with variability already present in the original NIR DN measurements rather than being introduced solely by the annual radiometric conversion. This interpretation is also consistent with the relatively stable surface reflectance characteristics of the asphalt reference target observed by the ASD measurements (Figure 7). The higher variability of the NIR DN suggests that the radiometric quality of the original NIR imagery may contribute to the temporal fluctuations observed after calibration. However, because the present analysis was based on a limited number of repeated observations, the contribution of sensor response, acquisition geometry, atmospheric conditions, and residual surface effects cannot be fully separated, and further observations are required to characterize the source of the NIR variability more quantitatively.

Overall, the repeated observations over the reference site indicate that the annually updated calibration coefficients provided generally consistent radiometric behavior across the 2023–2024 period, particularly for the visible bands. At the same time, the larger variability observed in the NIR band highlights the importance of considering the radiometric quality of the original DN imagery when evaluating temporal radiometric stability. Importantly, the increased NIR variability was also evident in the original DN measurements, indicating that it cannot be attributed solely to the application of the annual calibration coefficients. The available observations are insufficient to isolate the underlying mechanism, and additional investigation of the NIR response, including sensor-level behavior and acquisition-dependent effects, is required. Such characterization will be important for developing appropriate mitigation strategies if systematic NIR-specific effects are confirmed. Together with the independent cross-calibration, uncertainty assessment, and operational image validation presented in Section 3.3, these results provide complementary evidence for evaluating the temporal consistency and limitations of the operational CAS500-1 radiometric calibration framework. Given the limited number and temporal span of the available observations, the present time-series analysis should be regarded as an operational stability assessment rather than a quantitative estimate of long-term sensor degradation.

4. Discussion

4.1. Operational Vicarious Calibration and Uncertainty

This study established an operational absolute radiometric calibration framework for CAS500-1 based on repeated field campaigns, systematic quality control, reflectance-based vicarious calibration, and quantitative uncertainty assessment. Rather than deriving a single set of calibration coefficients, the framework was designed to support periodic evaluation and updating of radiometric calibration during routine satellite operations. This approach is particularly important for CAS500-1, which relies on ground-based and external reference observations for post-launch absolute radiometric calibration.

The field-based calibration showed strong linear relationships between CAS500-1 DN and MODTRAN-simulated TOA radiance for both TDI operating modes. Although the gain coefficients derived in 2024 were systematically higher than those obtained in 2023, these differences should not be interpreted directly as evidence of sensor degradation. Several aspects of the calibration procedure changed between the two years, including the condition and replacement of the calibration tarps, the quality and number of accepted observations, atmospheric characterization, the adopted solar irradiance model, and the uncertainty treatment. The improved regression performance in 2024 further suggests that refinement of the field measurements and QC procedures contributed to the differences between the annual coefficients. Consequently, the observed interannual changes likely reflect a combination of sensor response and differences in calibration inputs and methodology rather than an unambiguous change in sensor responsivity. However, the temporal density and duration of the currently available reference-site observations are insufficient to quantitatively separate long-term sensor degradation from interannual variability associated with field conditions and calibration procedures. A denser and longer-term time series based on PICS and stable reference sites will therefore be important for characterizing gradual changes in CAS500-1 radiometric responsivity throughout the mission lifetime.

The uncertainty assessment further demonstrated that the reliability of individual calibration campaigns was not uniform. In 2024, campaign-specific combined uncertainties varied according to measurement conditions, with field reflectance measurement variability and atmospheric characterization contributing substantially to the observed differences. In particular, comparison of MICROTOPS II measurements with independent cloud information showed increased AOD variability during cloud-affected periods, while the QC procedure reduced this variability by removing contaminated observations. These results highlight the importance of screening both surface and atmospheric measurements before their use in radiative transfer simulations. However, a direct comparison of individual uncertainty components between 2023 and 2024 should be made cautiously because the uncertainty framework itself was refined between the two years. Although the present uncertainty budget incorporates the major identifiable sources in the field-based calibration chain, further refinement will require more detailed characterization of sensor- and wavelength-dependent effects and their propagation into the final TOA radiance and calibration coefficients. Overall, these findings indicate that annual calibration updates should be based not only on regression performance, but also on the quality and uncertainty of the underlying calibration datasets.

The wavelength accuracy of the ASD spectroradiometer represents an additional source of uncertainty that was not independently quantified in the present study. Although the instrument was newly acquired in 2023 and showed consistent reflectance measurements during simultaneous field measurements with another ASD spectroradiometer, no independent wavelength calibration was performed prior to the campaigns. Therefore, wavelength-calibration uncertainty and its propagation into TOA radiance and the derived calibration coefficients should be quantitatively evaluated in future calibration campaigns.

4.2. Independent and Operational Validation of Calibration Performance

Independent cross-calibration with Sentinel-2 provided complementary evidence for evaluating the field-derived calibration coefficients. The visible-band gain coefficients showed generally reasonable agreement between the two calibration approaches, although the degree of agreement varied by band, reference site, and TDI mode. Differences between the Libya-4 and RVUS results demonstrate that cross-calibration performance depends not only on the radiometric response of CAS500-1, but also on the site characteristics, spectral compatibility between sensors, acquisition geometry, and image quality. Although SBAF was applied to reduce the effect of spectral-response differences between the two sensors, the residual uncertainty associated with spectral mismatch and SBAF estimation was not explicitly propagated in the present cross-calibration analysis. Therefore, residual spectral mismatch should be considered an additional uncertainty source when interpreting the cross-calibration results. In particular, a reliable NIR coefficient could not be derived from the Libya-4 observations because the correlation between CAS500-1 NIR DN and Sentinel-2 TOA radiance was insufficient. Although coarse-resolution sensors such as MODIS and VIIRS can provide valuable radiometric references over sufficiently homogeneous calibration sites, Sentinel-2 was preferred in the present study because its finer spatial resolution reduces spatial-representativeness uncertainty when matching observations with high-resolution CAS500-1 imagery. The present Sentinel-2 cross-calibration was limited to the multispectral bands because Sentinel-2 does not provide a panchromatic band spectrally comparable to the CAS500-1 PAN band. Consequently, the PAN calibration could not be independently evaluated using the same cross-calibration framework. Future validation should incorporate high-resolution reference sensors equipped with spectrally compatible panchromatic channels to provide an independent assessment of the CAS500-1 PAN calibration. These limitations emphasize the value of using multiple independent reference sites and treating cross-calibration as complementary validation rather than as a direct substitute for field-based absolute calibration.

The operational image assessment provided additional information that could not be obtained from regression statistics alone. Negative TOA radiance occurred at very low proportions in most evaluated images and spectral bands, indicating that the annual gain and offset coefficients generally produced physically reasonable radiometric conversion. The higher negative-radiance ratios observed in the Red and NIR bands for one TDI 1 image were concentrated primarily over low-radiance surfaces such as water bodies and terrain-shadowed areas rather than being distributed throughout the image. This spatial behavior suggests increased sensitivity to the offset component near the lower end of the sensor dynamic range rather than a scene-wide radiometric bias. The greater variability of the cross-calibration offsets also supports the need for the careful characterization of low-signal radiometric behavior. Future calibration campaigns could therefore benefit from additional low-reflectance targets or dedicated dark-target observations to improve constraints on the offset term.

Taken together, the Sentinel-2 cross-calibration and operational image assessment demonstrate the importance of evaluating calibration performance using multiple independent criteria. A coefficient set showing strong field-based regression does not necessarily guarantee optimal behavior across the full dynamic range of operational imagery. Cross-sensor consistency and product-level radiometric behavior therefore provide important complementary criteria when determining whether annually derived coefficients are suitable for operational implementation.

4.3. Temporal Radiometric Stability, Limitations, and Future Monitoring

Repeated observations over the Uiwang asphalt reference site provided an initial assessment of temporal radiometric consistency following application of the annual calibration coefficients. The visible bands showed generally consistent temporal behavior, whereas the NIR band exhibited greater absolute variability in both DN and TOA reflectance. Because repeated ASD measurements indicated relatively stable surface reflectance at the reference site, the larger NIR variability appears to be associated, at least in part, with variability already present in the original CAS500-1 NIR DN measurements rather than being introduced solely by the annual radiometric conversion. Nevertheless, the limited number of repeated observations prevents the effects of sensor response, atmospheric conditions, acquisition geometry, and residual surface variability from being fully separated.

An important limitation of the present study is the absence of a sufficiently long and temporally dense PICS time series for independent evaluation of CAS500-1 radiometric drift. Libya-4 was used for Sentinel-2 cross-calibration, but the available observations were primarily used to derive independent cross-calibration coefficients rather than to establish a multi-year sensor-stability record. Therefore, the differences between the 2023 and 2024 field-derived calibration coefficients cannot yet be quantitatively attributed to actual changes in sensor responsivity. This limitation is particularly relevant when interpreting the systematic differences observed between the annual gain coefficients.

Future work should therefore incorporate systematic PICS monitoring as an additional component of the CAS500-1 operational Cal/Val framework. Repeated observations over stable desert targets such as Libya-4, normalized for acquisition geometry, atmospheric conditions, and spectral-response differences, could be evaluated together with well-characterized reference sensors to establish long-term trends in relative sensor responsivity. Such PICS-based monitoring would complement annual field calibration: field campaigns provide an absolute radiometric reference under carefully characterized conditions, whereas frequent PICS observations are better suited for detecting gradual temporal trends or abrupt changes in sensor response.

Overall, the results indicate that operational radiometric calibration should be treated as a continuous quality-management process rather than solely as periodic coefficient estimation. Field-based vicarious calibration, uncertainty assessment, independent cross-calibration, operational image validation, and long-term reference-site monitoring provide complementary information on different aspects of radiometric performance. Continued accumulation of field, RadCalNet, reference-site, and PICS observations will provide a stronger basis for distinguishing calibration uncertainty from genuine sensor-response changes and for making evidence-based decisions regarding future updates of the CAS500-1 operational calibration coefficients.

5. Conclusions

This study established and evaluated an operational absolute radiometric calibration framework for CAS500-1 using field-based vicarious calibration, systematic quality control, uncertainty assessment, independent Sentinel-2 cross-calibration, and image-based validation. Annual radiometric gain and offset coefficients were independently derived for the TDI 1 and TDI 2 operating modes using quality-controlled field measurements and MODTRAN6 simulations. Strong linear relationships between CAS500-1 DN and the simulated TOA radiance were obtained across the spectral bands, demonstrating the applicability of the reflectance-based approach to routine radiometric calibration.

The results also demonstrated that annual calibration coefficients should be interpreted together with the quality and uncertainty of the calibration inputs. Differences between the 2023 and 2024 coefficients were accompanied by changes in field measurement conditions,

atmospheric characterization, calibration inputs, and uncertainty treatment and therefore cannot be attributed solely to changes in sensor responsivity. The campaign-specific uncertainty assessment implemented in 2024 yielded combined uncertainties of 4.59–7.77%, providing a quantitative basis for evaluating the reliability of individual calibration datasets and highlighting the importance of surface reflectance and atmospheric characterization in the overall calibration uncertainty.

Independent cross-calibration with Sentinel-2 generally supported the radiometric consistency of the field-derived coefficients in the visible bands, although the agreement varied with spectral band, site, and operating mode. Operational image evaluation further showed that negative TOA radiance was limited for most images and bands, while relatively large negative-radiance ratios occurred primarily over low-radiance surfaces such as water bodies and terrain-shadowed areas. Temporal observations over the Uiwang asphalt reference site showed generally consistent behavior in the visible bands, whereas the NIR band exhibited greater absolute variability, which was also evident in the original DN measurements.

Overall, the results demonstrate that reliable operational calibration of CAS500-1 requires an integrated quality-management approach combining field calibration, uncertainty assessment, independent cross-calibration, and product-level validation rather than relying solely on periodically derived calibration coefficients. A sufficiently long PICS time series was not available in this study to independently quantify long-term sensor responsivity changes. Future work will therefore focus on integrating systematic PICS monitoring with continued field and reference-site observations to distinguish actual sensor-response changes from calibration-related variability and to support evidence-based updates of the operational calibration coefficients.

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