frontiers | Frontiers in Remote Sensing

TYPE Editorial
PUBLISHED 09 July 2025
DOI 10.3389/frsen.2025.1585494

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 28 February 2025
ACCEPTED 25 April 2025
PUBLISHED 09 July 2025

CITATION
Ruddick KG, Bialek A, Brando VE, Dogliotti AI, Doxaran D and Goyens C (2025) Editorial: Optical radiometry and satellite validation.
Front. Remote Sens. 6:1585494.
doi: 10.3389/frsen.2025.1585494

Editorial: Optical radiometry and satellite validation

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KEYWORDS

optical radiometry, satellite validation, measurement networks, reflectance, hyperspectral

Editorial on the Research Topic
Optical radiometry and satellite validation

Introduction

This Research Topic gathers 21 state of the art papers on the Research Topic of Optical Radiometry and Satellite Validation.

This Editorial and all included papers are focussed on water and land surface reflectance measurements. Validation of other measurands, including end-user products derived from satellite reflectance, e.g. chlorophyll *a* concentration in water or vegetation indices on land, are outside the scope of this Research Topic.

Motivation

Strict quality control is essential to ensure that the satellite data products routinely used for environmental monitoring of water and land surfaces are fit for purpose. A crucial step in this process is the validation of the water and land surface reflectance, from which the final end-user products are derived. The topic of radiometric validation is growing rapidly in importance both because of the advent of operational satellite missions for routine environmental monitoring and because of the rapid expansion in the number of satellite missions, including CubeSat constellations with limited calibration/validation resources. This enhanced need for radiometric validation data covering a wide VIS/NIR/SWIR range (e.g., 380–2,400 nm), preferably with a hyperspectral resolution, must be met by new techniques and hardware, particularly ground-based automated radiometry.

Summary

The following subtopics are covered in papers from this Research Topic and are summarised in the following sections:

- Measurement networks and validation strategy
- Radiometer design, calibration, characterisation and comparison
- Data processing, quality control and measurement uncertainty
- Differences in angular and spatial characteristics of satellite and *in situ* measurements
- Examples of use of *in situ* measurement water and land surface reflectance measurements for satellite calibration and validation

A few other single-paper subtopics are addressed and some "missing" subtopics, not covered by this Research Topic, are highlighted for future work.

Measurement networks and validation strategy

Measurement networks with a common data portal for users have proven to be most effective as a source of data for satellite validation. Until now, the main source of *in situ* measurements for satellite radiometric validation over water and satellite calibration have been the AERONET-OC (Zibordi et al., 2009; Zibordi et al., 2021) and RadCalNet (Bouvet et al., 2019) networks.

The AERONET-OC network is based on deployment of a multispectral instrument system at a federated network of sites, typically on offshore platforms in coastal waters. The instruments have common hardware, calibration, data processing and quality control. This network has grown from a single prototype site in 2002 to 14 active sites (and 31 currently inactive sites) at the time of writing and is the main source of *in situ* measurements for radiometric validation of operational ocean colour missions such as VIIRS and Sentinel-3/OLCI as well as many other satellite missions.

The RadCalNet network federates various instrument systems, typically mounted on masts and deployed at land sites with optimal conditions for vicarious calibration, including low spatial variability. Instrumentation may be multispectral or hyperspectral and processing to surface reflectance may be performed in different ways. Data is unified by traceability to the SI units with corresponding measurement uncertainties. Acceptance of a site in the network is subject to approval of documents describing the measurement method and uncertainty analysis. This network has grown to 5 active sites at the time of writing and is used as one of the calibration methods for optical missions including Sentinel-2.

This Research Topic gathers papers from 2 new emerging networks, HYPERNETS and HYPERNAV.

The HYPERNETS network has been designed similarly to the AERONET-OC federated model and is based on the newly-developed HYPSTAR® radiometer system (Kuusk et al.), and the PANTHYR radiometer system (Vansteenwegen et al., 2019) based on the mature TRIOS/RAMSES instrument. Both systems are hyperspectral with common radiometer calibration and characterisation, data processing, quality control and (future) data distribution portals. An overview of the HYPERNETS network is given by (Ruddick et al.), covering user needs, measurement method, instrumentation and validation site considerations and some first results. HYPERNETS is composed of subnetworks for water (WATERHYPERNET) and land surface reflectance (LANDHYPERNET). The WATERHYPERNET is described in detail by (Ruddick et al.), including demonstrations of validation for Sentinel-2 and Sentinel-3/OLCI and use of data for phytoplankton monitoring.

The strategy of the HYPERNAV network is outlined in (Barnard et al.) for the purposes of satellite system vicarious calibration (SVC). A newly designed radiometric system is integrated with an autonomous profiling float to be deployed from ships at multiple locations. The overview of the data portal and network logistics are complemented by discussion of governance and funding considerations. The selection of HYPERNAV sites is described by (Chamberlain et al.) with an approach estimating the cost per validation matchup, taking account of logistics and the need to reposition floats which have drifted far from the initial location using simulations of deployments.

Brewin et al. proposes to reach out to wealthy citizen scientists with superyachts and an active interest in environmental monitoring. A pilot study is described where the Archimedes superyacht was used to mount radiometers with data processing using the open source HyperInSPACE software (https://github.com/nasa/HyperCP). This approach may help fill gaps in remote ocean areas not routinely covered by research vessels or ships-of-opportunity.

Radiometer design, calibration, characterisation and comparison

Kuusk et al. describe the design of a HYperspectral Pointable System for Terrestrial and Aquatic Radiometry (HYPSTAR®) to provide automated, *in situ* multiangular reflectance measurements of land and water targets. The radiometer covers 380–1,020 nm spectral range at 3 nm spectral resolution for water targets with an extension of the spectral range to 1,680 nm at 10 nm spectral resolution for land targets. The radiometer is mounted on a two-axis pointing system with 360° range of free movement in both axes and incorporates a stable light emitting diode as a light source, used for monitoring the stability of the radiometric calibration during the long-term unattended field deployment. This radiometer has been tested and used in the HYPERNETS network at 10 water and 11 land sites.

Vabson et al. describes laboratory calibrations and characterizations on a set of 37 hyperspectral field radiometers representative of those most used by the ocean colour community. The study covers radiometric responsivity, long-term stability, the accuracy of the spectral scale, non-linearity and accuracy of integration times, spectral stray light, angular response of irradiance sensors in air, dark signal, thermal sensitivity, polarization sensitivity, and signal-to-noise ratio. This work contributes to establishing consistent correction of biases and procedures for uncertainty analysis of *in situ* data obtained from different instruments and measurement models.

Barnard et al. describe the design and field verification results of an *in situ* radiometric system, called HyperNav, integrating dual upwelling radiance heads coupled to individual spectrometers, with spectral resolution of ~2.2 nm (full width, half-maximum) across 320–900 nm, integrated shutter systems for dark measurements, and integrated tilt and

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pressure sensors. This radiometric system is mounted on an autonomous float for surface and under water profiling measurements and is used for system vicarious calibration of satellites (Barnard et al.).

Melin et al. compare water remote sensing reflectance and aerosol optical thickness data from a 5.5 years time series of two autonomous pointable photometers deployed together at the Acqua Alta Oceanographic Tower. Uncertainty tree diagrams are used to illustrate all error sources and uncertainty cone diagrams are used to compare uncertainty estimates with matchup comparison statistics across their range of values. The mathematical theory developed here showed that the centred root-mean-square difference between data collected by two systems is a conservative estimate of the uncertainty associated with these data (excluding systematic contributions) if these data show a good agreement and if their uncertainties can be assumed similar with errors moderately correlated.

Data processing, quality control and measurement uncertainty

De Vis et al. describes the processing algorithm and software for the HYPSTAR® *in-situ* hyperspectral data products from both land and water sites of the HYPERNETS network. Radiance and irradiance data are acquired at the measurement sites following standardised measurement protocols, and are calibrated, processed and quality controlled to give reflectance data products for distribution to users, annotated by anomaly and quality flags, where appropriate. In order to achieve fiducial reference measurement quality, uncertainties are propagated through each step of the processing chain, taking into account temporal and spectral error-covariance. Examples of measurements from HYPERNETS sites are provided to illustrate the processing.

Differences in angular and spatial characteristics of satellite and *in situ* measurements

In situ measurements are generally acquired and distributed for the specific acquisition viewing and solar geometry, time instant and spatial field of view, and ideally include an estimate of the uncertainty of the *in situ* measurement. When *in situ* measurements are compared with satellite measurements in a matchup validation context, there will be additional uncertainties associated with the different viewing and solar geometry, time instant and spatial field of view. This is addressed in 3 papers from this Research Topic.

The difference in spatial coverage between an *in situ* radiometer footprint (typically 0.1–5 m) and a satellite instantaneous field of view (typically 1–1,000 m) can generate high validation uncertainties for targets with high spatial variability at intermediate length scales. Dogliotti et al. used spatial averaging of higher spatial resolution satellite data to quantify the spatial variability between a small footprint and larger satellite data pixels and estimate the matchup validation uncertainty associated with spatial variability for a range of satellite pixel sizes, from Planet SuperDoves (3 m) to MODIS (1,000 m). A different reference pixel is defined for each satellite pixel size to minimise the difference caused by spatial variability between *in situ* measurement at a HYPERNETS site and satellite measurement and to avoid mixed water/land near the coast.

Jordan et al. analysed high-frequency shipborne autonomous water remote sensing reflectance data using variograms to partition variability into spatial and intrinsic (non-spatial) components and to quantify the validation uncertainty due to spatial discrepancy between *in situ* and satellite measurements. The spatial decorrelation length scale serves as a guideline for selection of spatially independent *in situ* measurements when matching with a satellite image.

As regards angular variability, Schunke et al. studied the relationship between surface Bidirectional reflectance factor (BRF), an intrinsic optical property of the observed target, and the hemispherical conical reflectance factor (HCRF), which can be measured in the field but is affected by factors such as the angular variability of illumination. Simulations were performed on a 3D vegetation scene to analyse the impact of four parameters (atmospheric scattering, measurement device field of view cropping, acquisition duration, non-Lambertian reference panels) for typical Unmanned Airborne Vehicle measurements. It was found that the dominant source of difference between HCRF and BRF is the atmospheric scattering, which can cause a relative root-mean-square difference of more than 10%. Recommendations are provided for field measurements to minimise uncertainty in BRF estimation from HCRF.

Examples of use of *in situ* water and land surface reflectance measurements for satellite calibration and validation

The use of *in situ* measurements for validation of satellite measurements is demonstrated by case studies over water in the following papers:

- Doxaran et al. compared *in situ* measurements from two HYPERNETS sites in French waters, one in a coastal lagoon and one at the mouth of a highly turbid estuary, with high (Sentinel2-MSI and Landsat8/9-OLI) and medium (Sentinel3-OLCI and Aqua-MODIS) spatial resolution satellite data to assess the performance of 8 different atmospheric correction algorithms. The matchup results highlight the failure and limits of several atmospheric correction algorithms in complex/turbid coastal waters. The importance of accurate sun glint corrections in low to moderately-turbid waters is demonstrated while the use of dark targets and spectral fitting to estimate the aerosol contributions is shown to be the most effective approach in turbid waters.
- Gleratti et al. evaluated the performance of the POLYMER atmospheric correction algorithm for the Ocean and Land Colour Instrument (OLCI) onboard Sentinel-3 (S3) for the retrieval of remote sensing reflectance in the transitional waters near Plymouth. The impact of different satellite-*in situ* time windows, spatial averages and quality control flags on matchup statistics were studied.
- Ruddick et al. used *in situ* measurements from two WATERHYPERNET sites with very different turbidity to analyse the performance of different atmospheric correction algorithms for Sentinel-2 data using statistical metrics

calculated on many matchups. A Validation Diagnostic Sheet was automatically generated for each matchup and was subjectively analysed by experts for the outlier cases, approximately the worst 1/3 of matchups. This analysis concluded with hypotheses on the causes of poor performance. For example, a positive bias (mean difference) was found for ACOLITE_DSF processing of Sentinel-2 in clear waters (Acqua Alta) and clues were provided on how to improve the ACOLITE_DSF processing.

- Dogliotti et al. used *in situ* measurements from a HYPERNETS site in the La Plata estuary to evaluate the quality of satellite water reflectance products from multispectral and hyperspectral satellite missions including Landsat 8&9/OLI, Sentinel-2/MSI and Sentinel-3/OLCI, PlanetScope SuperDoves, Aqua/MODIS, SNPP&JPSS1/VIIRS and PRISMA. If sun glint contamination is avoided, the matchups show generally good results for high spatial resolution satellite sensors when using an atmospheric correction approach designed for land targets (e.g., LANDSAT-8 standard product and SEN2COR) and thus avoiding the errors of many atmospheric corrections approaches designed for clearer waters. An example is also provided where *in situ* measurements are used for validation of 8 satellite sensors on a single day, thus demonstrating the multi-mission economy of scale of automated high frequency measurements such as those provided by HYPERNETS.
- Gonzalez Vilas et al. demonstrated use of a Match-up Database (MDB) file structure and tools to facilitate the validation analysis of satellite water products from different sites, satellites and atmospheric correction processors. An MDB file is a NetCDF file containing all the potential match-ups between satellite and *in situ* data on a specific site and within a given time window. These files are generated and manipulated with three modules to implement the validation protocols: extract satellite data, associate each extract with co-located *in situ* radiometry data, and then perform the validation analysis. The approach is demonstrated by a multi-site matchup comparison between satellite data from the Sentinel-2 MSI and Sentinel-3 OLCI sensors, and HYPSTAR® *in situ* data acquired over six water sites from February 2021 to March 2023. Results showed that the performance of the processors depends on the optical regime of the sites. The open-source MDB-based approach is recommended to implement validation protocols and generate automated matchup analyses for different missions, processors and sites.

The use of *in situ* measurements for calibration and validation of satellite measurements over land is demonstrated by case studies in the following papers:

- De Vis et al. demonstrated the feasibility of using surface reflectance data for vicarious calibration of multispectral (Sentinel-2 and Landsat 8/9) and hyperspectral (PRISMA) satellites over two LANDHYPERNET sites: Gobabeb in Namibia and the Princess Elizabeth Base in Antarctica. *In situ* surface reflectance data are spectrally binned and propagated to the top of atmosphere reflectance and compared to the satellite measurements, quantifying mean differences over multiple matchups. The study confirms that data from radiometrically stable HYPERNETS sites with sufficient spatial and angular homogeneity can be used for satellite vicarious calibration purposes.
- Morris et al. compared *in situ* measurements from a forest LANDHYPERNET site with multispectral satellite data from Sentinel-2, Landsat 8 and Landsat 9. No systematic bias was found between the *in situ* and the satellite data, although relative differences varied widely with differences as large as 100% for spectral bands with low reflectance. Hypotheses for the differences included spatial and temporal mismatch between the *in situ* and satellite measurement, or shadowing caused by the flux tower. Recommendations included the incorporation of a Bidirectional Reflectance Distribution Function model into the processing chain for the forest canopy.

Other studies

In addition to the subtopics covered in the preceding sections, this subtopics includes individual papers on specific subtopics with relevance to Optical Radiometry and Satellite validation as follows:

Harmel considered the important issue of modelling the light reflected by the air-water interface for the above water reflectance measurement method, using a newly proposed terminology of surface-to-sky radiance ratio, Rss. Vector radiative transfer computations were performed over the spectral range 350–1,000 nm to provide angular values of Rss for a comprehensive set of aerosol loads and types and water surface roughness expressed in wave slope variances or in equivalent Cox-Munk wind speeds. After separating direct and diffuse light components, it was shown that the spectral shape and amplitude of Rss are very sensitive to aerosol load and type. It was concluded that the viewing geometry should be adapted as function of sun zenith angle and that aerosol measurements should be made concurrently with above water radiometric measurements.

Arena et al. used *in situ* remote sensing reflectance derived from an AERONET-OC site and *in situ* hyperspectral radiometric data to classify optical water types (OWTs) in the turbid waters of the Bahía Blanca Estuary. The OWTs were linked to the concentrations of chlorophyll-*a* and suspended particulate matter and to the absorption coefficients of phytoplankton, non-algal particles, and dissolved organic matter measured on water samples. After a matchup validation analysis to select the best-performing atmospheric correction algorithm for Sentinel-3 OLCI satellite data, the latter was used to describe spatial and temporal variability of the different OWTs in the region.

Tan et al. described a method for constructing hyperspectral downwelling irradiance at 0.5 nm resolution from 315 to 900 nm from multispectral measurements at 4 spectral bands (412, 489, 555, and 705 nm) using a multi-linear regression model. Radiative transfer simulations are made for Sun zenith angles from 0 to 75° and a wide range of atmospheric, surface, and water conditions. The regression model allows estimation of hyperspectral downwelling irradiance with a bias of less than 0.4% in magnitude and an RMS error (RMSE) ranging from 0% to 2.5%, depending on wavelength, for noise-free input data. The impact of noisy input data and of adding extra spectral bands in the ultraviolet, e.g., centred on 325, 340, and 380 nm, is analysed. The results indicate that it is sufficient for many scientific applications, including measurement of hyperspectral reflectance by the HyperNav system (Barnard et al.), to measure downwelling irradiance in a few coarse spectral bands in the ultraviolet to near infrared and reconstruct the hyperspectral signal using the proposed multivariate linear modelling.

Conclusion and perspectives

Spaceborne optical satellites are used routinely for environmental monitoring of water and land surfaces, and spaceborne data is often used to aid management of environmental challenges, such as coastal water quality and the impacts of climate change. The spaceborne data must therefore be of sufficient quality for these purposes and "matchup" validation with simultaneous ground-based measurements is used to determine whether the spaceborne data is sufficiently accurate and to identify any weaknesses that need to be remedied. While fitness for purpose depends on the purpose and the end-user measurand, e.g., aquatic chlorophyll a concentation or a land vegetation index, validation of water and land surface reflectance conveniently indicates overall data quality and poor results for such radiometric validation indicate where data quality needs to be improved, often in the atmospheric correction step of data processing. The works in this Research Topic thus contribute to the understanding and improvement of the quality of spaceborne data used for managing environmental challenges.

While this Research Topic gathers papers describing various aspects of the state-of-the-art of Optical Radiometry and Satellite Validation, it is clear both that some important subtopics have not been covered here and that this field will evolve further in the coming years. The following developments are expected in the future:

- The estimation of measurement uncertainty remains very challenging for these measurements and will undoubtedly improve in the next few years.
- Although within the stated scope for the Research Topic and badly needed for satellite validation, only a few papers address the measurement of land surface reflectance, which is less mature than the measurement of water-leaving radiance reflectance. The lack of such measurements is a clear gap in knowledge.
- The issues of spatial and angular variability of land surface reflectance and how these can be represented when comparing *in situ* and satellite measurements clearly need more attention. This issue has been raised often in recent workshops relating to radiometry and satellite validation and clearly represents a gap in research, only partly addressed here (see above).
- Most of the papers in this Research Topic focus on measurement of only water and land surface reflectance. As automated reflectance data becomes more easily available, it is likely that measurements from additional instruments such as imaging cameras, sun photometers, polarimeters and profiling lidar or other optical measurements of atmospheric properties will be used in synergy with the reflectance measurements to enhance the validation of optical satellites and help identify the cause of atmospheric correction and satellite calibration errors. The potential for synergy with atmospheric data is strong and can be explored with existing data, e.g., from co-located AERONET and HYPERNETS sites.

Author contributions

KR: Writing – original draft, Writing – review and editing. AB: Writing – review and editing. VB: Writing – review and editing. AD: Writing – review and editing. DD: Writing – review and editing. CG: Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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