

Article

UAV-Based Above-Water Spectroradiometry for Detecting Sunscreen UV Filters in Coastal Waters

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Highlights

What are the main findings?

- A UAV-mounted miniaturized spectroradiometric system (*Mar_Spectra*) was developed for the near-real-time detection of sunscreen UV filters in coastal waters, deriving above-water remote sensing reflectance (R_{rs}) in the UV range (300–380 nm) and establishing a strong linear calibration between the spectral index (i_s) and organic UV filter concentrations ($R^2 = 0.964$).
- Environmental factors (turbidity, phytoplankton, and wind) were quantified as key limitations for field detection sensitivity.

What are the implications of the main findings?

- *Mar_Spectra* offers a scalable, cost-effective, and time-efficient alternative to conventional analytical techniques (LC/GC), enabling continuous spatial and temporal mapping of pollutants in high-tourism coastal areas.
- The system supports informed coastal zone management in tourism-intensive regions, contributing to the sustainable protection of marine ecosystems.



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Abstract

Sunscreen-derived ultraviolet (UV) filters are emerging pollutants of increasing concern in coastal ecosystems. This study presents the development, optimization, and field validation of *Mar_Spectra*, a compact spectroradiometric system mounted on an unmanned aerial vehicle (UAV) designed to detect sunscreen UV filters in surface waters. The system integrates an Ocean Optics microspectrometer with a Raspberry Pi microprocessor, a GPS receiver, an altimeter, and an RGB camera for synchronized image acquisition. Spectral measurements were processed to derive remote sensing reflectance (R_{rs}) using a Zenith Lite reference panel. Controlled calibration experiments confirmed the system's sensitivity in the 300–380 nm

range and allowed the definition of a convenient index (i_s) exhibiting a strong linear relationship with total UV-filter concentration ($R^2 = 0.964$). Environmental tests indicated that wind, turbidity, and algal presence reduced detection capacity, while stable solar conditions improved spectral consistency. Despite its sensitivity to environmental variability, the *Mar_Spectra* device demonstrated consistent and reproducible performance under real field conditions, providing a cost-effective and scalable approach for near-real-time monitoring of UV filters and enhancing spatially resolved coastal pollution surveillance

Keywords: organic UV filters; UV spectrometry; remote sensing reflectance; sunscreen pollution; coastal water quality; marine optics

1. Introduction

Coastal areas, representing the dynamic boundary between the atmosphere, hydrosphere, and lithosphere, are exceptionally vulnerable to climate change impacts. Their high productivity and biodiversity, combined with intense human pressure, make them both ecologically and socio-economically critical. Nearly 60% of the world's population is concentrated along coasts [1,2]. In recent decades, rapid population growth and unregulated coastal development have intensified anthropogenic pressures on marine ecosystems [3–6]. Among the most pressing threats are chemical pollutants from land-based activities, including recreational activities [7,8], which contribute to water quality degradation, biodiversity loss, and disruption of ecosystem services [9–11].

Tourism plays a central role in the economic development of many coastal and Mediterranean countries [3,12]. However, its exponential growth, particularly during the summer season, has introduced significant environmental challenges [10,13]. The seasonal influx of beachgoers is strongly correlated with the increased release of emerging contaminants, including UV filters used in personal care products, such as sunscreens [14–16].

UV filters are broadly categorized as organic (chemical, e.g., octocrylene, avobenzone, or ethylhexyl salicylate, among others) or inorganic (physical, e.g., TiO_2 and ZnO) and are designed to protect human skin from solar UV radiation [17,18]. While these compounds are essential for public health [19], their widespread occurrence in waters, sediments, and biota [18,20] has raised concerns due to their persistence, bioaccumulation potential, and toxicological effects on aquatic organisms [9,11,21,22]. Their introduction into coastal ecosystems is typically unintentional, occurring through recreational activities and runoff [7,14,23]. Despite being regulated under EU cosmetic legislation (Regulation EC 1223/2009) [24], environmental monitoring of these compounds remains scarce.

Traditional techniques for the detection and quantification of these contaminants rely on sample collection followed by laboratory analysis, most commonly through liquid chromatography (LC) [25–29]. While accurate [26,27], these approaches are costly and time-consuming [29] and offer limited spatial and temporal resolution [30,31]. Consequently, there is a pressing need for fast, spatially resolved, and cost-effective tools capable of detecting these contaminants in situ and in near real time [32,33].

To address these limitations, recent advances in environmental monitoring have focused on the integration of UAV-based technologies with portable analytical sensors [30,33,34]. UAVs provide rapid, flexible, high-frequency, and cost-effective data collection platforms, enabling near-real-time assessments of water quality parameters across large and inaccessible areas, complementing conventional sampling [35–38].

In this context, this study presents *Mar_Spectra*, a UAV-mounted miniaturized spectro-radiometric system specifically designed for the detection and semi-quantitative assessment

of sunscreen-derived UV filters in coastal waters. The system integrates high-resolution spectral acquisition with real-time environmental monitoring, combining above-water remote sensing reflectance (R_{rs}) measurements with a sunscreen concentration index (i_s) defined in the UV spectral range (300–380 nm). The specific objectives of this work are (i) to characterize the spectral response of commercial sunscreen formulations and establish a validated calibration model against LC measurements; (ii) to evaluate the sensitivity of the system under different optical conditions, including the presence of phytoplankton and suspended sediments; (iii) to optimize the key operational parameters of the UAV-based acquisition protocol, including flight altitude and sensor-to-water distance; and (iv) to validate the system's field performance through deployment campaigns in contrasting coastal environments, demonstrating its capacity to resolve both temporal dynamics and spatial gradients of UV filter dispersion.

2. Materials and Methods

2.1. The *Mar_Spectra* Spectroradiometric System

The *Mar_Spectra* system is a UAV-mounted spectroradiometric platform designed for collecting radiometric measurements of aquatic surfaces. It integrates the compact Ocean Optics ST-UV-25 miniature spectrometer (Ocean Optic, Inc., Orlando, FL, USA) with a Raspberry Pi 3 CM4 NANO-A microcomputer (Raspberry Pi Foundation, Cambridge, UK), a high-precision altimeter (DroneTools, Seville, Spain), an Emlid Reach M2 GPS module (Emlid Tech Kft., Budapest, Hungary), a 2.4 GHz Wi-Fi communication system (Figure 1a,b), and a high-resolution RGB camera.

The Ocean Optics ST-UV-25 miniature spectrometer has dimensions of 42.1 mm × 40.3 mm × 26.6 mm with a total weight of 70.4 g. It operates in the ultraviolet (UV) and visible (VIS) spectral range between approximately 185 nm and 650 nm, with spectral sampling and resolution of 0.3 nm and 2.2 nm, respectively. Digital counts are collected with 14-bit resolution by a charge-coupled device (CCD) detector at 1516 central wavelengths and with an integration time comprised between 3.8 ms and 6 s. The ST-UV-25 is connected to a 2 m Premium UV-VIS optical fiber with a 400 µm core diameter, coupled to a UV-VIS collimating lens providing a field of view (FOV) of approximately 20°.

The Raspberry Pi 3 acts as the control unit, managing data acquisition and real-time wireless communication during flight operations. The system uses a USB Type-C power connector, compatible with external power banks. The internal 3000 mAh lithium-ion battery provides up to 4 h of continuous operation, with the option of extending autonomy via external portable chargers. The complete unit, including sensors and mounting hardware, weighs approximately 450 g (enclosure: 83 mm × 83 mm × 70 mm). Finally, a set of visual status indicators confirms GPS and camera connectivity, ensuring data integrity under variable communication conditions.

Aerial operations employed the DJI Matrice 300 RTK (M300) quadcopter (DJI, Shenzhen, China). At takeoff, the UAV weighs 9 kg and can fly for approximately 35 min with sensors onboard, though flight time is influenced by weather conditions. The M300 was equipped with the DJI Zenmuse Z30 RGB camera (DJI, Shenzhen, China), featuring a 30× optical zoom, capable of capturing synchronized high-resolution images and videos of the water surface. These visual records complement the spectral data by enabling the evaluation of surface conditions, such as wind-induced roughness, wave patterns, algae presence, turbidity, and specular reflections, all of which can influence radiometric measurements. This integrated visual-spectral approach enhances data interpretation and supports the identification of environmental artifacts in the acquired spectra. In addition, a Speeddip (Soarability, Singapore) remote-controlled cable release system was attached to the M300 to enable remote lowering of the *Mar_Spectra* unit once the UAV is positioned over the target.

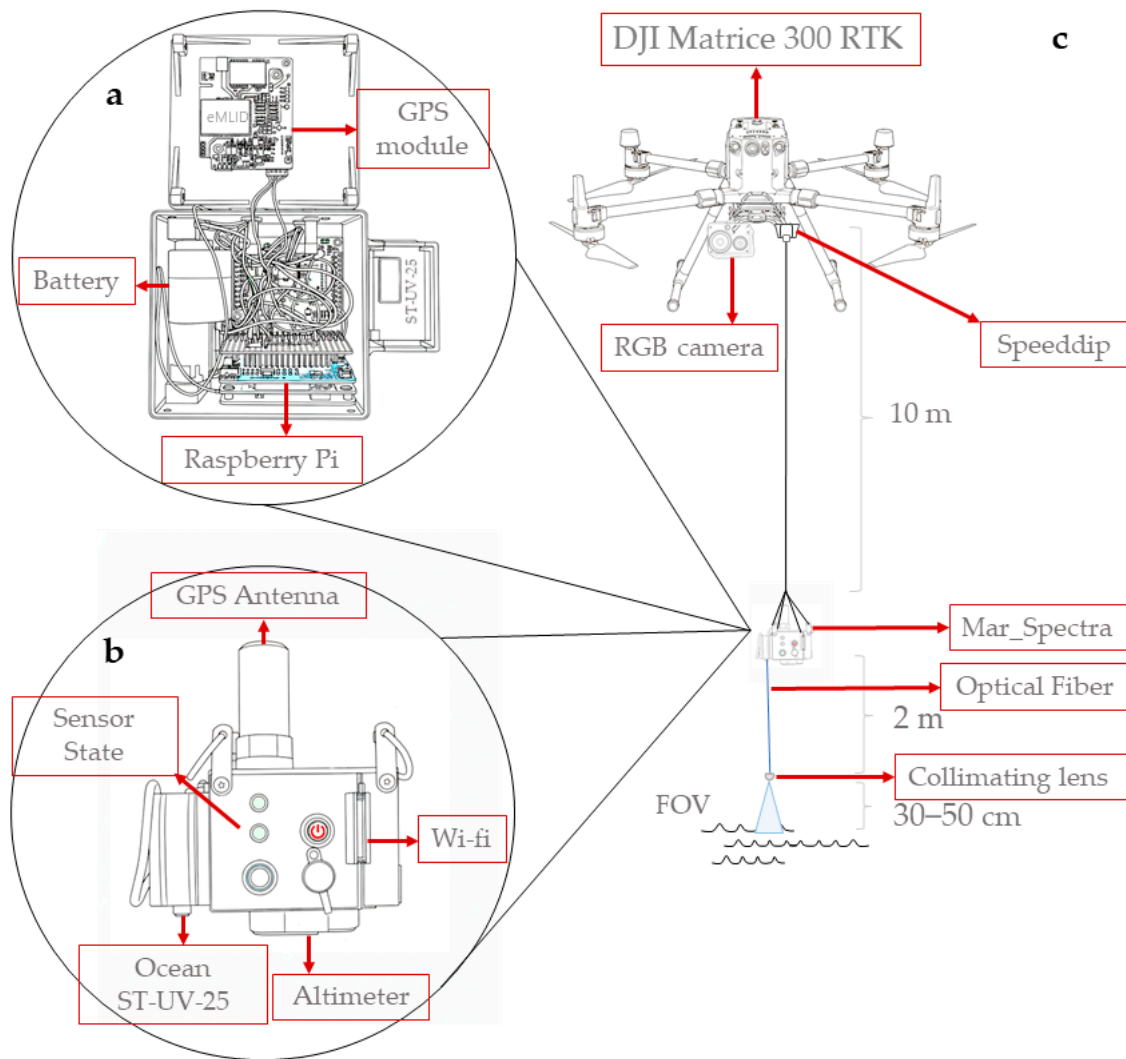


Figure 1. The Mar_Spectra spectroradiometric system. (a) Visual description of the internal components, including Raspberry Pi microcomputer, GPS module, and battery. (b) Visual description of the external components, including the Ocean Optics ST-UV-25 spectrometer, GPS antenna, altimeter, sensor state, and Wi-Fi communication system. (c) Schematic representation of the acquisition setup.

Nominal operations are performed with the UAV at 12 m from the sea surface, corresponding to a distance between the collimating lens and the sea surface of 30–50 cm and a 13–22 cm wide measurement footprint (Figure 1c). This setup minimizes motion interference and decouples sensor height from UAV altitude, allowing improved spatial resolution while, at the same time, reducing perturbations of the sea surface.

A custom graphical user interface (GUI) was developed by DroneTools (DroneTools, Seville, Spain) to adapt the OceanView v.2.0 software for UAV-based operations, enabling full control of integration time, sampling interval, spectral range, scan averaging, and boxcar smoothing. The interface allows real-time monitoring and storage of sensor measurements, GPS position, and altitude directly from the ground station.

2.2. Spectral Data Processing and Theoretical Framework

Radiometric measurements are acquired by the ST-UV-25 in digital counts (DN), each sequence including measurements of the sensor dark signal, as well as of both the surface irradiance (E_s) and the total radiance from the sea surface (L_T). Specifically, measurement sequences comprise:

- (i) The estimation of the dark signal, obtained by performing standard measurements with the sensor fore-optics totally occluded. Two measurements are performed with integration times corresponding to those applied for the collection of the surface irradiance (τ_{Es}) and of the total radiance from the sea surface (τ_{Lt}). These are denoted as $DN_{dark}(\lambda, t_0, \tau_{Es})$ and $DN_{dark}(\lambda, t_0, \tau_{Lt})$, respectively, where λ indicates the central wavelength and t_0 is the start of the measurement sequence.
- (ii) The estimation of the surface irradiance at t_0 , $DN_{Es}(\lambda, t_0, \tau_{Es})$, obtained by pointing the sensor toward the center of a Zenith Lite™ (SphereOptics GmbH, Herrsching, am Ammersee, DE) diffuse reflectance panel. The panel was mounted on a leveled tripod, ensuring 90° observing angle and a distance of 10 cm to reduce edge artefacts and shadowing effects.
- (iii) A series of measurements of the total radiance from the sea surface $DN_{Lt}(\lambda, t, \tau_{Lt})$ obtained by pointing the sensor toward the sea surface with an observing angle of 90° and a distance of 40–50 cm. Parameter t indicates the time of each measurement comprised between t_0 and t_{end} .
- (iv) The estimation of the surface irradiance at t_{end} , $DN_{Es}(\lambda, t_{end}, \tau_{Es})$, as in (ii).
- (v) The estimation of the dark signal at t_{end} , $DN_{dark}(\lambda, t_{end}, \tau_{Es})$ and $DN_{dark}(\lambda, t_{end}, \tau_{Lt})$, as in (i).

Remote sensing reflectance $R_{rs}(\lambda, t)$ are thus computed as

$$R_{rs}(\lambda, t) = \frac{[DN_{Lt}(\lambda, t, \tau_{Lt}) - DN_{dark}(\lambda, t, \tau_{Lt})]/\tau_{Lt}}{\pi \cdot [DN_{Es}(\lambda, t, \tau_{Es}) - DN_{dark}(\lambda, t, \tau_{Es})]/\tau_{Es}} \quad (1)$$

where both dark signal and E_s estimates at times t ($DN_{dark}(\lambda, t, \tau_{Lt})$, $DN_{Es}(\lambda, t, \tau_{Es})$, and $DN_{dark}(\lambda, t, \tau_{Es})$) are obtained by linear interpolation relying on measurements performed at times t_0 and t_{end} , i.e.,

$$DN(\lambda, t) = DN(\lambda, t_0) + \frac{DN(\lambda, t_{end}) - DN(\lambda, t_0)}{t_{end} - t_0} \times (t - t_0) \quad (2)$$

A sunscreen concentration index (i_s) is then computed as detailed in the next section, based on the obtained R_{rs} measurements.

2.3. Experimental Methodology and Validation

This section describes the methodological framework adopted to develop, calibrate, and validate the *Mar_Spectra* UAV-based radiometric system for detecting sunscreen-derived UV filters in coastal waters. The workflow was structured to ensure progression from controlled laboratory experiments to complex coastal deployments. Specifically, the methodology comprised (i) laboratory characterization and calibration curve validation by HPLC, (ii) sensitivity assessment under different optical conditions, (iii) optimization of UAV-based spectral acquisition parameters, and (iv) implementation of a standardized spectral acquisition protocol in coastal environments.

2.3.1. Analytical Characterization and Calibration Procedures for UV Filter Detection

To evaluate the detection capability of the *Mar_Spectra* system for sunscreen-derived pollutants, a series of controlled outdoor experiments was designed to reproduce environmentally realistic exposure conditions. This section includes characterization of individual sunscreen formulations, LC validation, and definition of the sunscreen concentration index (i_s).

Initially, 14 commercial sunscreens (Table 1) were individually characterized to determine their specific spectral responses. Each product differed in sun protection factor (SPF) values, application types (cream, spray, gel, and lotion), and active ingredients (organic and inorganic UV filters were represented, including titanium dioxide (TiO₂) and zinc

oxide (ZnO)). Each formulation was tested by diluting 0.25 g in 50 mL of natural seawater, homogenizing at 200 rpm for 30 min, and spreading over the water surface. Spectral measurements were acquired using a transparent container filled with 2 L of natural seawater, positioned on a leveled surface under direct sunlight. The spectrometer was mounted 30 cm above the water surface in a nadir-facing orientation (Figure S1), allowing the identification of formulation-specific reflectance signatures.

Table 1. Characteristics of commercial sunscreen products: sun protection factor (SPF); “ocean-friendly” label included on packaging; texture indicated by the manufacturer; and identified chemical UV filters.

Sunscreen	SPF	Ocean-Friendly	Texture	UV Filters ¹
1	30	Yes	Sun milk	2, 3, 4, 5, 6, 9
2	30	No	Gel	1, 2, 3, 5, 6, 9
3	50+	Yes	Gel cream	9, 10
4	50+	No	Fluid	2, 3, 4, 5, 6, 9
5	50	Yes	Milk	1, 3, 5, 8, 9
6	50+	No	Spray	2, 3, 5, 6, 7
7	50+	Yes	Spray	2, 3, 4, 5, 6, 7
8	50	Yes	Spray	2, 3, 4, 5, 6
9	30	No	Spray Milk	1, 2, 3, 4, 5, 6, 8
10	50+	No	Sun milk	1, 2, 3, 5
11	30	No	Cream	1, 2, 3, 8
12	30	No	Oil spray	1, 3, 5, 6
13	30	Yes	Milk	2, 3, 5
14	30	Yes	Cream	3, 5, 6

¹ UV filters: 1 Octocrylene; 2 Bis-ethylhexyloxyphenol methoxyphenyl triazine; 3 Butyl methoxydibenzoylmethane; 4 Diethylhexyl butamido triazone; 5 Ethylhexyl salicylate; 6 Ethylhexyl triazone; 7 Drometrizole trisiloxane; 8 Homosalate; 9 Titanium dioxide; 10 Zinc oxide.

A composite stock solution was then prepared by mixing equal portions of the 14 commercial sunscreens to obtain a representative blend. Using this mixture, spectral measurements were performed after a 15 min stabilization period, including dark signal, surface irradiance, and a series of measurements of total radiance from the water containers exhibiting increasing concentration of sunscreen. Specifically, a baseline spectrum of clean seawater was first recorded, followed by incremental additions of the composite sunscreen solution (9, 18, 27, and 36 mg). For each concentration level, five consecutive measurements were performed, and remote sensing reflectance spectra were calculated as described in Section 2.2.

In addition to radiometric measurements and aiming at validating the relation between i_s and sunscreen concentration, water samples corresponding to each standard solution were collected in amber vials, frozen at $-20\text{ }^{\circ}\text{C}$, and subsequently analyzed by LC with UV detection. To this regard, just before analysis, samples were left to thaw at room temperature, followed by sonication for 15 min to release the UV filters retained in the particulate fraction, and then they were filtered through $0.45\text{ }\mu\text{m}$ nylon membrane filters. Each water sample was adjusted to pH 4 and 5% sodium chloride and then subjected to an extraction method adapted from a previous optimized method based on stir bar sorptive dispersive microextraction (SBSDE) [39]. In summary, 5 mL of each sample was transferred to a 30 mL vial containing a $10\text{ mm} \times 3\text{ mm}$ nickel-coated neodymium stir bar and 25 mg of oleic acid-coated cobalt ferrite (CoFe_2O_4 @oleic acid) magnetic nanoparticles. After 20 min agitation, the stir bar coated with CoFe_2O_4 @oleic acid entrapping the target compounds were removed with plastic thumb forceps, soaked in deionized water, and placed into a vial containing 0.5 mL of ethanol and then agitated for 5 min to desorb the

analytes. The extracts were filtered through 0.45 µm nylon membrane filters, diluted to 1:1 with deionized water, and injected (20 µL) into the LC system under elution gradient conditions by employing ethanol (solvent A) and 1% aqueous formic acid containing 20 mM hydroxypropyl-β-cyclodextrin (solvent B) at 1 mL/min as mobile phase [27]. The separation was performed at 60 °C in a Purospher® STAR RP-18 column (Sigma-Aldrich Corporation, Saint Louis, MO, USA; 125 mm × 4.6 mm i.d., 5 µm) with a detection wavelength of 325 nm. The SBSDE-LC analyses yielded UV filter concentrations consistent with those derived from spectral calibration, thereby confirming the robustness of the optical approach.

Building on previous studies that identified the UV region as the most sensitive to the presence of sunscreen [14,15,17] and adopting a band-ratio approach similar to that used for retrieving chlorophyll-a concentration [40], the sunscreen concentration index (i_s) was defined as the ratio between the maximum of R_{rs}^{-1} in the spectral interval 300–380 nm and its minimum in the interval 400–460 nm:

$$i_s = \frac{\max(R_{rs}(300 : 380)^{-1})}{\min(R_{rs}(400 : 460)^{-1})} \quad (3)$$

It is noted that in optically complex coastal waters, R_{rs} is proportional to the ratio between the backscattering coefficient (b_b) and the sum of absorption and backscattering coefficients ($a + b_b$) [41–43]. Assuming that the sunscreen contribution to the seawater backscattering coefficient is negligible [44] and considering the strong absorbance properties of the sunscreen solutions, the analysis of R_{rs}^{-1} in the UV range is expected to provide useful information on sunscreen concentration. This assumption may not hold for sunscreen formulations containing significant concentrations of strongly scattering inorganic UV filters (e.g., nano-TiO₂ or ZnO) or larger mineral particles, for which changes in both absorption and backscattering could jointly influence the spectral response; in such cases, the interpretation of sunscreen concentration index would require additional investigation.

2.3.2. Sensitivity Assessment Under Different Optical Conditions

To assess potential interferences from natural bio-optical constituents [31,45–47], additional assays were conducted with the green microalga *Tetraselmis chui* Butcher 1959 (PRASINOPHYCEAE), obtained from the Marine Microalgae Culture Collection at the Andalusian Institute of Marine Sciences (CCMM 03/0201, ICMAN-CSIC, Cádiz, Spain). Cultures were grown under standard F/2 conditions and sequentially introduced into seawater previously contaminated with commercial sunscreen at two concentration levels (0.05 g/L and 0.1 g/L). Spectral measurements were acquired after each stepwise addition, corresponding to final algal densities of 5×10^4 , 1×10^5 , and 1.5×10^5 cells/mL (Figure S2), as determined by direct cell counts.

Finally, the effect of water turbidity, expressed in nephelometric turbidity units (NTU), was evaluated under field conditions in the San Pedro river lagoon. After baseline acquisitions in clear water, turbidity was progressively increased by manual sediment resuspension, reaching values from ~5 NTU to >230 NTU. At each level, sunscreen was reapplied, and replicate spectra were recorded. Simultaneous measurements of pH, temperature, salinity, conductivity, and UV irradiance provided environmental context to spectral variability, enabling assessment of their influence on the detection of UV-absorbing compounds.

2.3.3. Optimization of UAV-Based Spectral Acquisition Parameters

The objective of this section is to define the optimal operational parameters for UAV-based spectral data acquisition, focusing on the UAV-related variables, including geometric

configuration, flight altitude, sensor-to-water distance, and the instrumental stability, with particular attention to scan to average.

Evaluation of UAV Geometry and Flight Altitude

Optimization trials were carried out to determine the operational conditions that maximize signal stability and minimize UAV-induced water surface perturbation. All experiments were conducted using the *Mar_Spectra* system integrated into a DJI Matrice 300 RTK platform (Figure 1c). In every case, 2 g of diluted sunscreen was applied directly beneath the sensor to simulate surface contamination, and 11 replicate spectra were acquired under stable irradiance conditions.

Logistically, given that measurements were acquired from the UAV platform, the sensor was positioned in a nadir-oriented geometry (0°) to ensure consistent viewing conditions. To maintain optimal illumination, all experiments were scheduled under solar zenith angles between 30° and 60° , which provide stable downwelling irradiance and reduce bidirectional reflectance effects (Figure S3) [43,48]. Nevertheless, atmospheric and surface conditions also needed to be carefully considered, as variable cloud cover can alter incoming irradiance [48], and wind-driven surface roughness may enhance sunglint and local glitter effects, particularly within the UV region [34,49]. These considerations were integrated into the experimental design to minimize external variability prior to testing UAV altitude effects.

The influence of UAV altitude was first examined by gradually reducing the platform height from 12.4 m to 2.4 m in 2 m intervals, using a remotely operated cable release system (Speeddip). Throughout these tests, the lens-to-water distance (~ 35 cm) remained constant throughout. This design isolated the aerodynamic effects of UAV proximity, such as down-wash and surface perturbations, from geometric variations in sensor positioning (Figure 2).

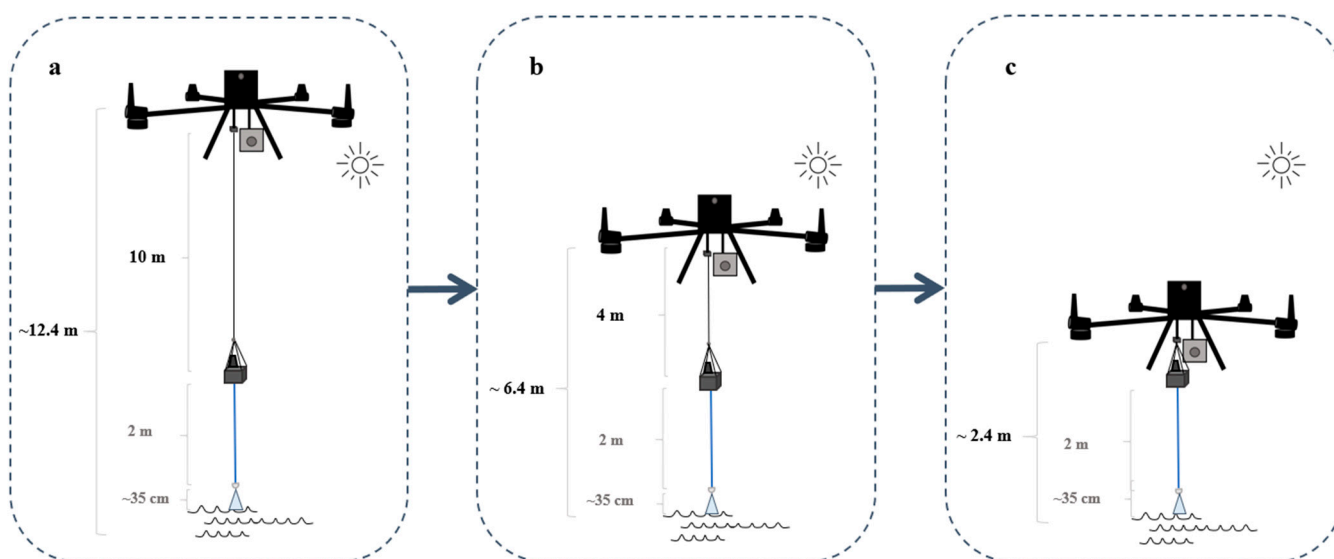


Figure 2. Optimization of UAV flight altitude. Sequential reduction of platform height from approximately 12 m to 2 m (a–c), while maintaining a constant lens-to-water distance of approximately 35 cm and scan averaging of 100. Images illustrate the progressive change in UAV positioning relative to the measurement target.

Subsequently, the effect of lens-to-water distance was tested by adjusting the optical fiber between 15 and 50 cm above the surface while maintaining UAV altitude constant at ~ 12 m (Figure 3). This experiment was designed to find a trade-off between the total flight time and the capability of detecting sunscreen in highly inhomogeneous environments. A closer distance, and consequently a smaller surface footprint, in fact, maximizes the

sensitivity to sunscreen, even in very small patches, and reduces the effect of sunglint. Conversely, larger distances permit covering larger areas more efficiently with the same flight time [36,50].

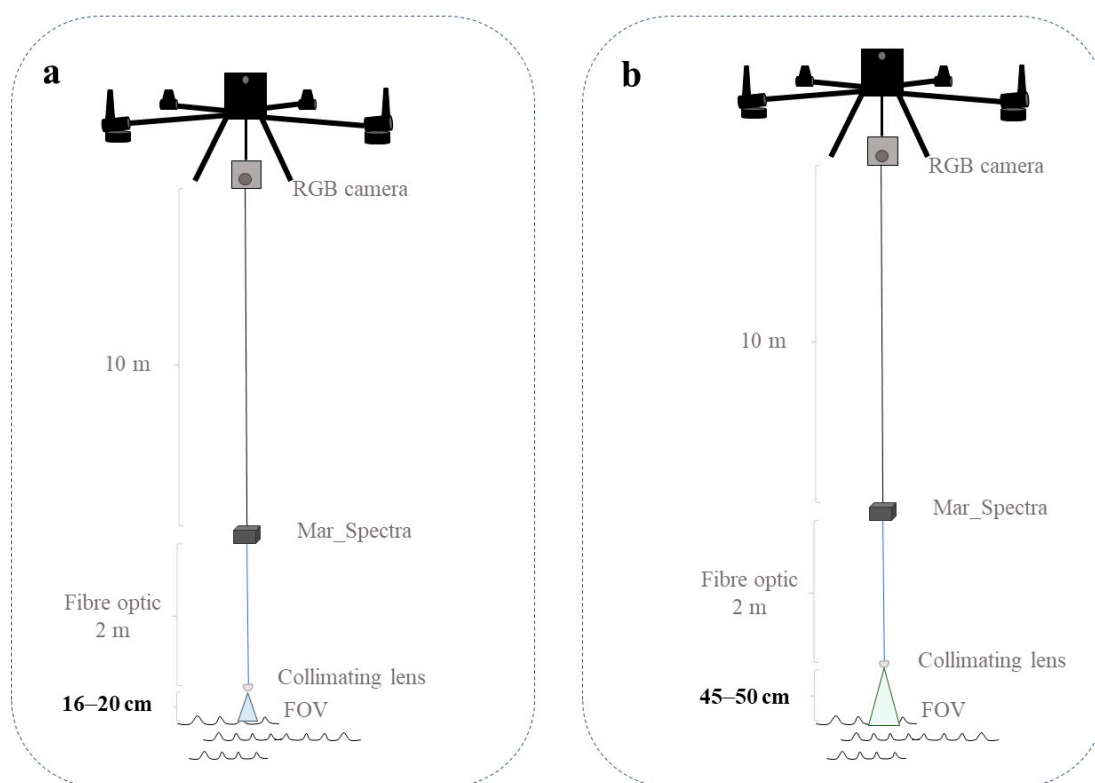


Figure 3. Optimization of lens-to-water distance using the *Mar_Spectra* system. (a) Sensor positioned at 16–20 cm above the water surface, providing a narrow measurement footprint. (b) Sensor positioned at 45–50 cm, increasing the spatial footprint while reducing spectral contrast.

Optimization of Internal Sensor Parameters

Internal acquisition parameters of the *Mar_Spectra* system were optimized to ensure stable and accurate spectral measurements while maintaining efficient acquisition times. This involved testing different configurations of scan averaging and integration time to minimize random noise while avoiding sensor saturation and excessive acquisition durations.

Spectra were recorded varying the averaging settings between 5, 10, 20, and 30 scans, while the integration time was adjusted to reach the maximum signal intensity without saturation. Each configuration was tested independently, with the sunscreen layer reapplied prior to every acquisition to guarantee repeatability and minimize the effect of surface heterogeneity.

The results of these optimization trials were later applied in field experiments at Barceloneta Beach (Barcelona, Spain), using the spectral ratio index (i_s) to assess the configuration that provided the best trade-off between spectral stability and acquisition efficiency.

2.3.4. Spectral Acquisition Protocol in Coastal Environments

The experimental workflow (Figure 4) was designed to ensure the reliability, reproducibility, and scientific validity of radiometric measurements, addressing both environmental and instrumental sources of variability. Each acquisition session began with a 15 min sensor acclimation, followed by sequential procedure described in Section 2.2. Continuous monitoring of ambient UV irradiance with a handheld radiometer was performed to filter out data affected by atmospheric fluctuations. UAV-based acquisitions of the total radiance from the sea surface $DN_{Lt}(\lambda, t, \tau_{Lt})$ and RGB imagery were obtained simultane-

ously. Flights were conducted manually to ensure operational safety in the vicinity of beach users while maintaining the flexibility required to adapt the flight path to changing field conditions. Parallel to UAV acquisitions, for each flight, auxiliary metadata were systematically recorded, including atmospheric and water-surface conditions (cloud cover, wind speed, and surface roughness), flight parameters (altitude, time of day, flight duration, lens-to-water distance, and GPS coordinates), system settings (integration time, number of scans, boxcar, and smoothing), and UAV condition (roll, pitch, and heading). This metadata enabled quality control and facilitated the screening of data affected by unstable irradiance or excessive tilt.

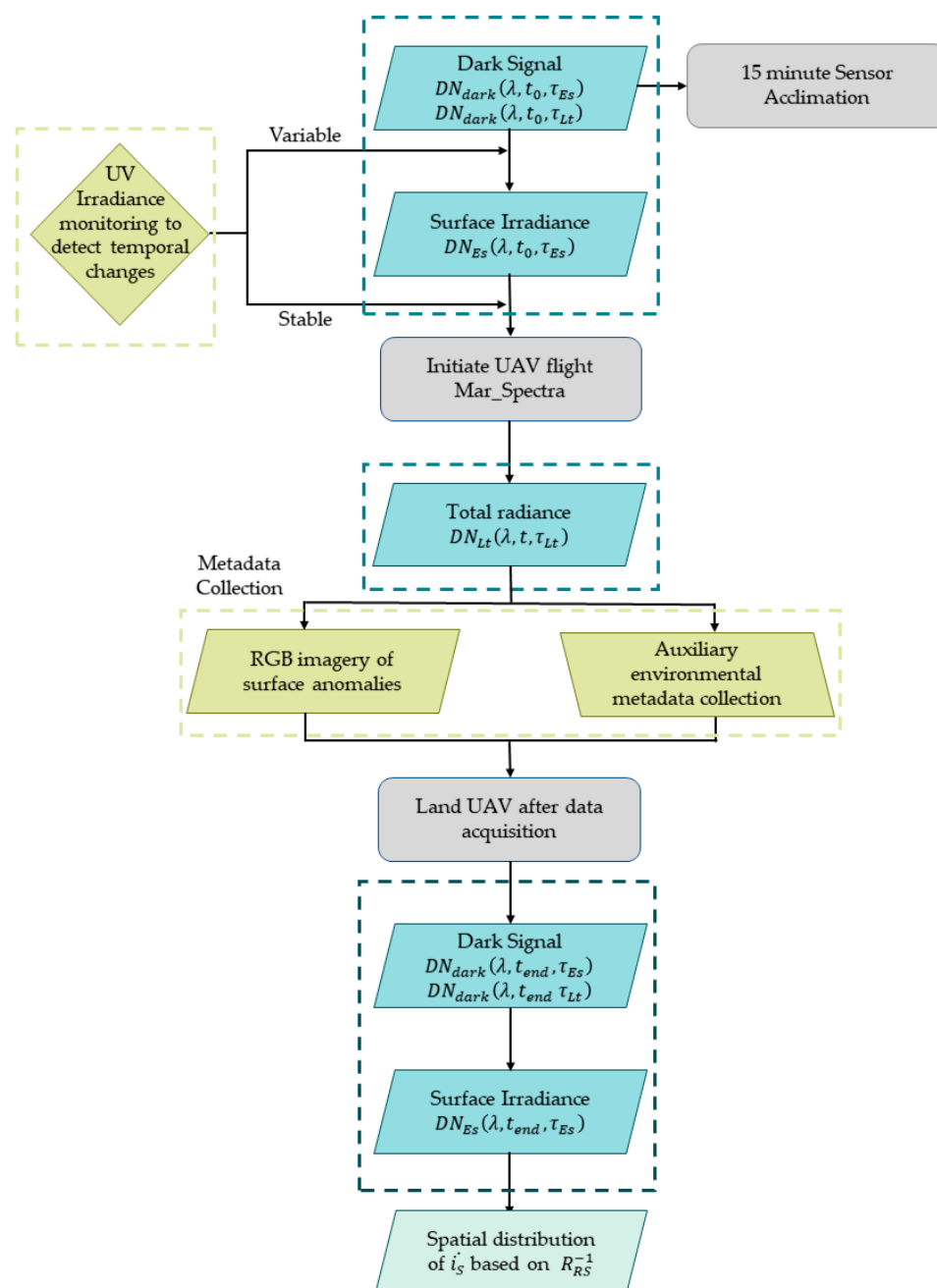


Figure 4. Workflow of the experimental acquisition and processing protocol: yellow-green indicates ancillary environmental data collection; grey denotes operational steps of the measurement protocol; light blue identifies the radiometric measurements required for i_s calculation; and light green-blue represents the final spatial distribution of the calculated i_s index.

The experimental strategy was structured to progressively transition from controlled laboratory assays to increasingly complex field conditions. Building on these results, the acquisition protocol was optimized based on the dark signal drift and surface irradiance alongside a systematic study of the required number of scans and repetition necessary to minimize measurement uncertainty. To evaluate the field performance and environmental adaptability of the *Mar_Spectra* acquisition protocol, three experimental campaigns were conducted under contrasting environmental conditions.

The first campaign took place at the Barceloneta Beach ($41^{\circ}22'59''$ N, $2^{\circ}11'43''$ E), an urban beach located in Barcelona, Spain (Figure 5a), where the system was deployed on a floating platform replicating UAV geometry. This trial focused on optimizing the spectral acquisition procedure and defining scan averaging requirements prior to aerial deployment. Measurements were performed over two consecutive days.



Figure 5. Location of the study sites. (a) Sentinel-2 image from 23 September 2025 (tile T31TDF) of the Barcelona coast, showing the location of Barceloneta Beach, where protocol optimization was performed using a floating platform. (b) Sentinel-2 image from 22 September 2025 (tile 29SQA) over Cádiz Bay (Spain), showing the areas where validation drone surveys were conducted at La Caleta and Camposoto beaches. The photograph of La Caleta Beach was taken during the field operations; the photograph of Camposoto Beach was obtained online from *El Diario de Sevilla*; the photograph of Barceloneta Beach was obtained online from *Barcelife.com* (accessed on 21 July 2026).

Subsequent validation campaigns were performed at La Caleta Beach ($36^{\circ}31'53''$ N, $6^{\circ}18'21''$ W), an urban beach of 450 m in length (Figure 5b), and Camposoto Beach ($36^{\circ}25'51''$ N, $6^{\circ}13'54''$ W), a 6 km long natural beach within the Bahía de Cádiz Natural Park (Figure 5b). Hydrodynamic context (wave height/direction and current speed/direction) for each field campaign was obtained from “Puertos del Estado” SIMAR numerical hindcast data (Table S1). In both cases, the system was mounted on a DJI Matrice 300 RTK UAV with nadir-oriented optics (Figure 1c). Each site was surveyed through longitudinal transects parallel to the coastline, obtaining spectra from ambient water, sunscreen-spiked water (positive controls reference), and unaltered samples. Spatial interpolation of the georeferenced i_s index values obtained along UAV transects were performed using Ocean Data View (ODV) v.5.8.6 [51], with the DIVA gridding algorithm, generating gridded maps of UV filter distribution across each beach site. Automatic cor-

relation length estimation was applied independently for each site domain (Camposoto: $X = 25\%$, $Y = 33\%$; La Caleta: $X = 36\%$, $Y = 32\%$), using a signal-to-noise ratio of 20. Areas of poor interpolation quality were excluded using the built-in “Hide bad estimates” option (quality limit = 3).

These complementary field campaigns provided multi-environment databases enabling assessment of both temporal dynamics (under controlled illumination) and spatial variability (across urban and natural coastal settings), supporting validation of the *Mar_Spectra* protocol.

3. Results

3.1. Sensitivity Assessment in Clear Waters: Analytical Performance and Validation

As detailed in Section 2.2, the inverse of remote sensing reflectance (R_{rs}^{-1}) was employed to detect the UV filter concentration in seawater. Results from the individual characterization are shown in Figure 6.

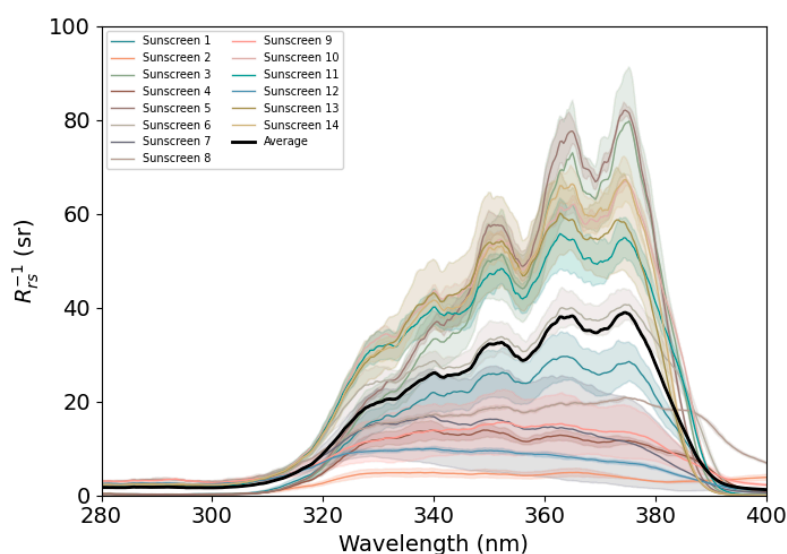


Figure 6. Average values of the inverse of the remote sensing reflectance (R_{rs}^{-1}) obtained for 14 commercial sunscreen formulations (Table 1) measured individually in the 280–420 nm range under direct sunlight (thin lines) and average value of all sunscreens (thick line). For each individual formulation, shaded area indicates the standard deviation of the five replicate measurements; for the thick line, the shaded area represents the standard deviation across the 14 formulations.

The spectral response of the composite sunscreen stock solution was evaluated across increasing concentration levels. A progressive and consistent increase of R_{rs}^{-1} was observed with rising concentration of the sunscreen mixture, with the strongest response occurring in the 320–380 nm range. SBSME-LC validation confirmed the presence of major UV filters in the stock solution, including octocrylene (OC), bis(ethylhexyloxyphenol) methoxyphenyl triazine (BEMT), ethylhexyl salicylate (EHS), and butyl methoxydibenzoylmethane (BMDM), thereby supporting the spectral calibration and ensuring that optical response corresponded to chemically verified contaminants.

The index i_S showed a strong linear correlation with the cumulative UV filter concentration (Figure S4). The regression equation obtained was $i_S = 0.1192 \cdot [\text{UV Filter}] + 1.200$, where [UV Filter] is the summed HPLC concentration of OC, EHS, BEMT, and BMDM ($\mu\text{g} \cdot \text{mL}^{-1}$). The model showed a high coefficient of determination ($R^2 = 0.9643$), with a slope 95% CI of 0.1055–0.1330, intercept 95% CI of 1.151–1.249, RMSE of 0.046 i_S units, and $2.813 \cdot 10^{-16}$ bias, confirming the absence of systematic error over the full calibration range.

(0–5.79 $\mu\text{g}\cdot\text{mL}^{-1}$). The instrument limit of detection (LOD) and limit of quantitation (LOQ) were 1.37 $\mu\text{g}\cdot\text{mL}^{-1}$ and 4.15 $\mu\text{g}\cdot\text{mL}^{-1}$, respectively.

Across all calibration standards, OC was the dominant contributor ($52.4 \pm 1.3\%$ of total quantified UV filter concentration), followed by EHS ($23.0 \pm 1.1\%$), BEMT ($15.7 \pm 2.7\%$), and BMDM ($8.9 \pm 1.3\%$), with proportions remaining consistent across the full concentration range, confirming the stability of the composite mixture.

3.2. Sensitivity Assessment in Optically Complex Waters

In the water column, the detection sensitivity of the *Mar_Spectra* system followed the balance between absorption (a) and backscattering (b_b). *Tetraselmis chui* additions rapidly masked the spectral absorption signature of the sunscreen solutions. For both initial concentrations (0.05 g/L and 0.1 g/L), signal losses approached 80% at 5×10^4 cells mL^{-1} and intensified to 92% at 1.5×10^5 cells mL^{-1} , indicating near-complete suppression of the UV filter imprint at higher biomass levels (Figure 7a). This progressive masking is consistent with increased b_b by phytoplankton cells, reducing the spectral contrast detectable by the *Mar_Spectra* system in biomass-rich waters [41–43,52].

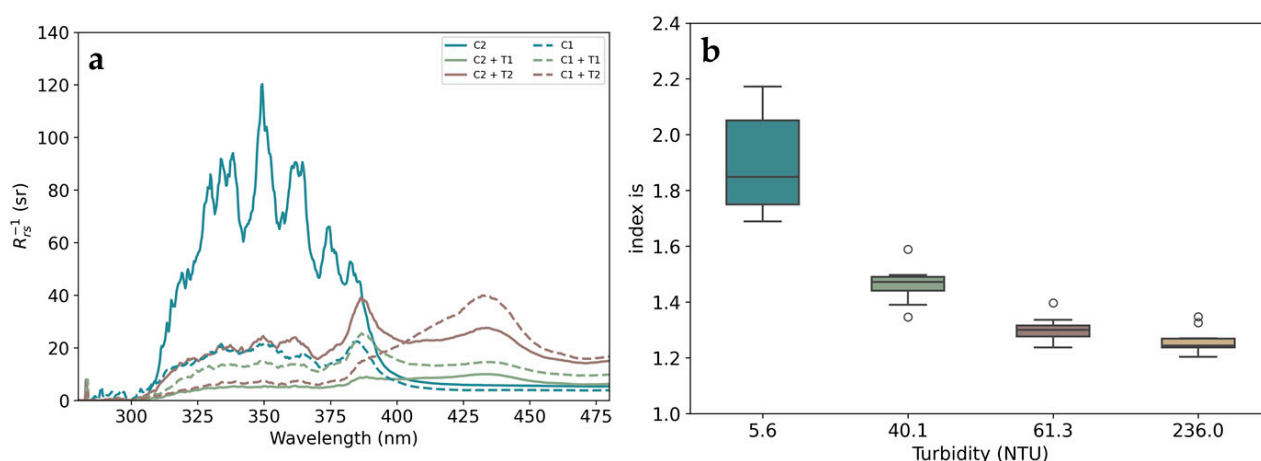


Figure 7. Sensitivity of the *Mar_Spectra* system under optically complex conditions. (a) Attenuation of the R_{rs}^{-1} sunscreen spectral signal in the presence of increasing concentrations of *Tetraselmis chui* for initial sunscreen concentrations of 0.05 g·L^{−1} (C1) and 0.1 g·L^{−1} (C2). Algal densities tested T1 = 5×10^4 cells·mL^{−1}, T2 = 1×10^5 cells·mL^{−1}. (b) Spectral measurements acquired in the turbid waters of the Río San Pedro estuary under progressively increasing turbidity levels (5–236 NTU), illustrating the masking effect of suspended inorganic matter on UV filter detection.

A comparable attenuation was observed with suspended inorganic matter. In San Pedro River, R_{rs}^{-1} decreased by approximately 33% as turbidity increased from 5.6 to 236 NTU, coinciding with a marked reduction of UV absorption contrast (Figure 7b). Replicate variance decreased under high-turbid conditions, likely due to damped glitter and micro-oscillations, although this stabilization came at the expense of spectral separability [41–43,52].

Collectively, both biological (phytoplankton) and inorganic (suspended sediment) constituents increased backscattering (b_b) and masked the ΔR_{rs}^{-1} anomalies, reducing the sensitivity of the index i_s in Equation (3). These results define the environmental detection limits of the system in optically complex coastal waters.

3.3. Instrumental and Methodological Optimization

To ensure accuracy and consistency in spectroradiometric measurements, two key methodological aspects were evaluated: (i) UAV-related variables, including flight altitude and sensor-to-water distance, and (ii) internal acquisition parameters, specifically the optimal number of spectral scans per measurement.

3.3.1. Flight and Sensor Optimization

To define an optimal sensor-to-surface distance for *Mar_Spectra*, a series of measurements was performed at distances ranging from 10 to 102 cm. Mean index i_s values decreased systematically as lens height increased, dropping from 1.832 ± 0.095 at 10–20 cm to 1.215 ± 0.065 at 90–100 cm, representing an overall signal reduction of approximately 34% (Figure 8), stabilizing beyond 60 cm. A Mann–Whitney U test confirmed a statistically significant difference between measurements at 20–40 cm ($n = 93$) and 60–70 cm ($n = 6$) ($U = 527$, $p < 0.001$, rank-biserial $r = -0.889$, 95% CI: -0.975 to -0.767 ; Shapiro–Wilk: $W = 0.970$, $p = 0.033$ for the lower-distance group), supporting the existence of a sensitivity threshold at lower distances.

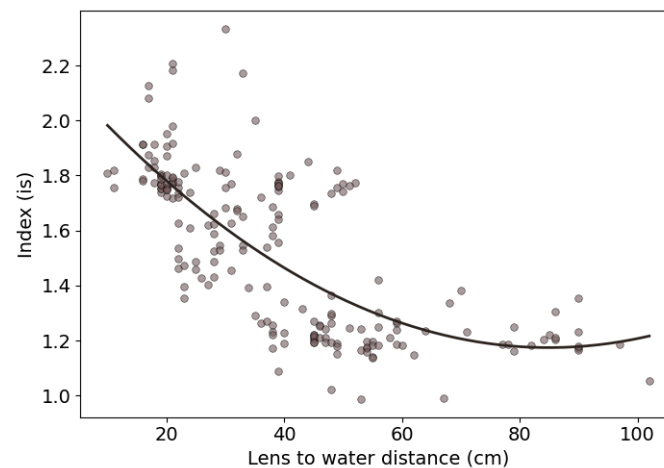


Figure 8. Effect of sensor height on the spectral ratio index (i_s). Each point represents an individual measurement; the solid line shows the fitted power-law attenuation curve ($y = 0.000144x^2 - 0.024459x + 2.212656$), where d is the vertical distance (cm) between the cosine-corrected collimating lens and the water surface.

A complementary series of tests was conducted to evaluate the influence of UAV flight altitude on the integrity of spectral measurements over water, following the procedure described in Figure 2. Results indicated that at lower flight altitudes (2, 4, and 6 m), UAV rotor downwash generates surface perturbations, including micro-wavelets and localized glitter, which artificially elevate R_{rs}^{-1} values in the UV range (320–380 nm). This resulted in higher mean spectral index i_s (up to +86% above the 10 m reference at 4 m) but significantly increased variability (CV = 18–25% at 2–4 m vs. 4.1% at 10 m; SD up to 0.31). In contrast, flights conducted at 8, 10, and 12 m minimized surface disturbances, yielding smooth water conditions and consistent R_{rs}^{-1} spectra suitable for reliable detection (Figure 9). This transition in altitude produced a mean i_s loss of approximately 6% compared to the low-altitude group, but substantially reduced spectral variability, with SD decreasing by approximately 50% and between-replicate variability reaching its minimum at 10 m (SD = 0.057). Comparative imagery (Figure S5) illustrates the clear transition from perturbed surfaces at 6 m to undisturbed conditions at 8 m. Measurements acquired at higher flight altitudes (8–12 m; $n = 12$) showed significantly lower variability than those obtained at lower altitudes (2–4 m; $n = 27$) (Levene’s test: $F = 4.624$, $p = 0.038$), supporting the selection of the 8–10 m operational range. Based on these results, an optimal acquisition altitude of 8–10 m is recommended as the best compromise between surface stability and signal integrity.

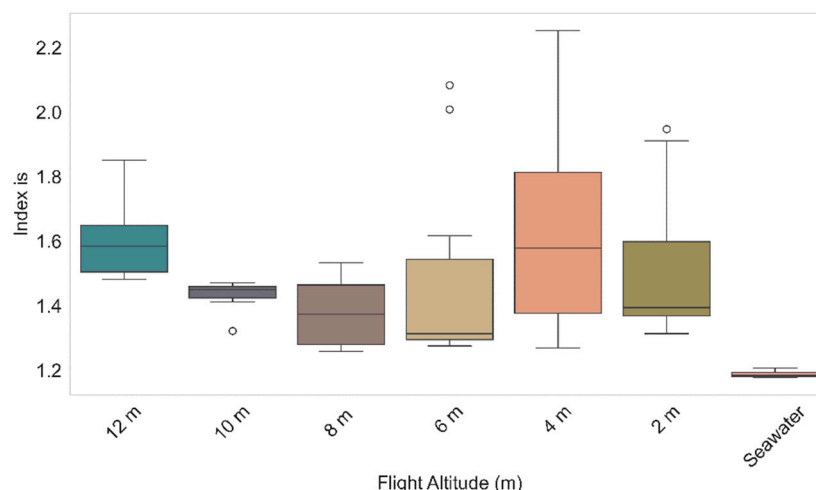


Figure 9. Distribution of the spectral ratio index (i_s) UV filter in seawater across varying UAV flight altitudes (2–12 m). Dots correspond to outliers.

These findings underscore the critical role of flight height in minimizing platform-induced optical artifacts and ensuring data fidelity in UAV-based aquatic remote sensing.

3.3.2. Optimization of Scan Number

A dedicated field experiment at Barceloneta beach was conducted to optimize the number of scans for reliable R_{rs}^{-1} acquisition using the spectral ratio index i_s (Equation (3)). Spectra were acquired with 5, 10, 20, and 30 scans under stable irradiance conditions (Total UV 2.85–3.19 mW/cm²) and a fixed integration time of 200 ms.

The highest coefficient of determination ($R^2 = 0.80$) was initially achieved using the maximum 30 scans configuration. However, variability remained high due to both the inherent heterogeneous dispersion of sunscreen on the water surface and the extended acquisition time. To enhance robustness, a 20% high-pass filter was applied to the data, systematically excluding acquisitions from footprints with insufficient surface coverage. This filtering step resulted in a significant improvement in data quality, yielding a 34% reduction in SD and improving the overall fit to $R^2 = 0.92$ (Figure S6).

3.4. Case Studies: Temporal and Spatial Dynamics in Coastal Water

The Barcelona field campaign enabled the evaluation of *Mar_Spectra* under real coastal conditions, integrating protocol optimization with environmental monitoring. Figure 10 shows the temporal evolution of the i_s index, swimmer count, and wind speed over 2 consecutive days (19–20 June 2025). On the first day (Figure 10a), measurements were conducted during early morning under low wind conditions (mean 3.47 m·s^{−1}) and calm sea surface. During this period, the i_s index increased progressively and proportionally with the number of bathers entering the water (Pearson $r = 0.507$, $p < 0.001$, $n = 176$; mean intra-acquisition SD = 0.158), confirming the system's capacity to detect sunscreen-derived spectral signatures at environmentally relevant concentrations. The close coupling between human activity and spectral response validates the use of i_s as a near-real-time proxy for sunscreen contamination under stable hydrodynamic conditions. On the second day (Figure 10b), wind speed increased substantially during the late morning (mean 6.85 m·s^{−1}, peak gusts 13.0 m·s^{−1}), generating surface turbulence that disrupted the coherence of the sunscreen film and reduced spectral signal stability (mean intra-acquisition SD = 0.307; $1.94\times$ higher than Day 1; Mann–Whitney $p < 0.001$, rank-biserial $r = 0.664$, 95% CI [0.533, 0.794], $n_1 = 176$, $n_2 = 132$). As a consequence, the correlation between i_s and swimmer count weakened progressively ($r = 0.388$, $p < 0.001$, $n = 132$), demonstrating that

wind-driven mixing and surface roughness represent the primary hydrodynamic control on detection reliability in open coastal waters. Across both days, wind speed showed a significant positive relationship with intra-acquisition variability (Spearman $\rho = 0.518$, 95% CI [0.431, 0.595], $p < 0.001$, $n = 308$), reinforcing this interpretation. These observations are consistent with the known behavior of surface-bound contaminant films under increasing turbulence, mirror the spectral instability documented at low-UAV altitudes in Section 3.3.1, and highlight the importance of acquiring spectral data under low-wind, stable irradiance conditions for optimal system performance.

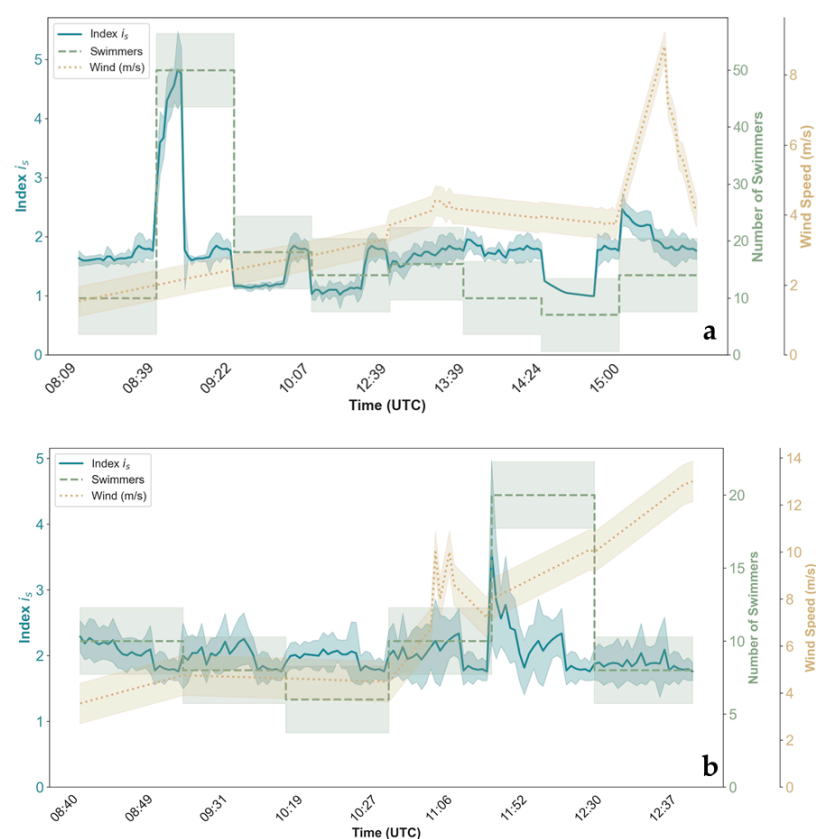


Figure 10. Diurnal variation of i_s index, swimmer count, and wind speed. The plot illustrates the index i_s (Primary Y-axis), determined from collected spectral data, alongside the number of swimmers (Secondary Y-axis), based on field observation logs and the wind speed (Tertiary Y-axis), obtained from Copernicus data. All variables are plotted as a function of time (UTC) (X-axis). (a) Data from 19 June 2025 and (b) data from 20 June 2025 demonstrate their temporal evolution and potential interdependencies throughout the measurement period.

Field campaigns conducted in Cádiz extended this analysis to the spatial dimension, evaluating UV filter distribution across beaches with contrasting hydrodynamic regimes. Transects at La Caleta and Camposoto beaches revealed clear site-dependent variability in i_s values that closely mirrored their differing environmental characteristics. La Caleta, a small, enclosed, and highly urbanized beach, exhibited markedly higher i_s values (Figure 11a), consistent with its limited water renewal capacity and elevated anthropogenic pressure. In contrast, Camposoto, an open, low-urbanization beach with a longer shoreline and greater hydrodynamic flushing, showed substantially lower and more spatially dispersed i_s values (Figure 11b). Interpolated maps from both sites showed a consistent nearshore-to-offshore dilution gradient, reflecting the progressive dispersal of surface-bound UV filters away from the bathing zone.

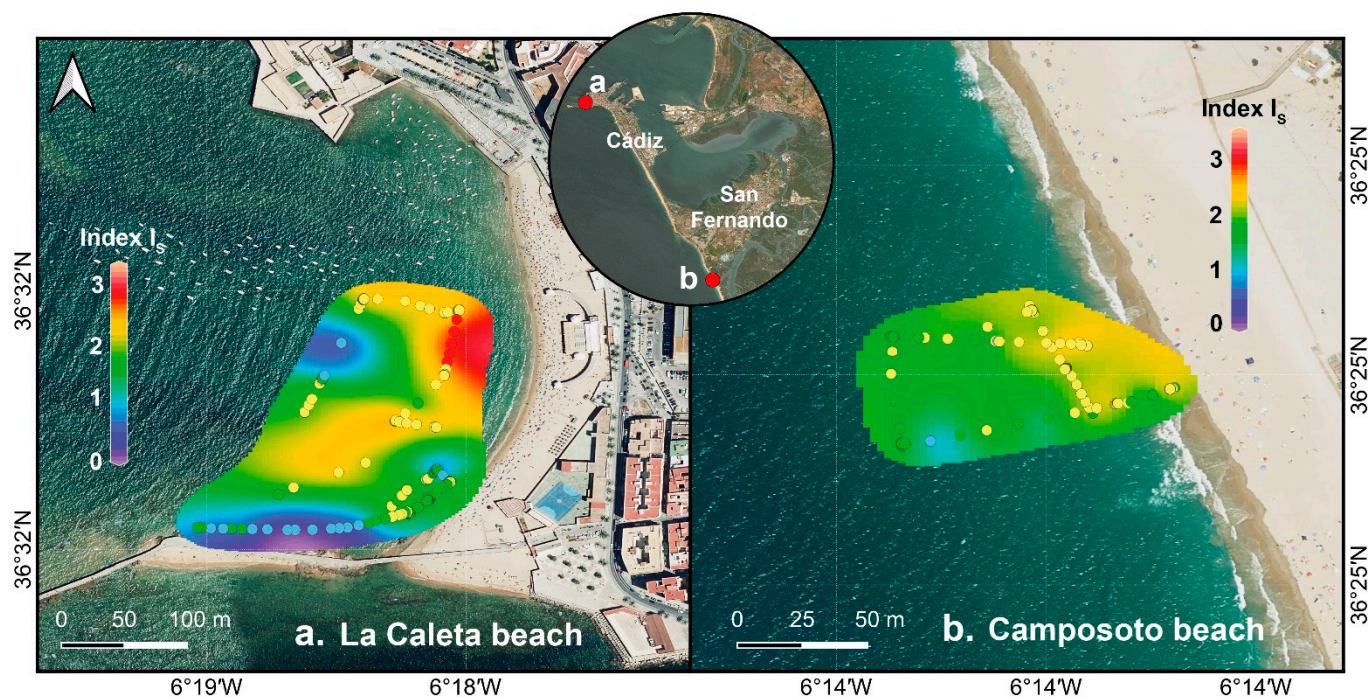


Figure 11. Spatial distribution of surface UV filter concentration in Cádiz. The color gradient of the dots indicates the relative concentration. (a) La Caleta Beach and (b) Camposoto Beach.

Interpolation of transect data further highlighted a consistent spatial gradient along the Cádiz–Camposoto axis. Concentrations were highest in nearshore waters, decreasing progressively with distance from the coastline, a trend reflecting dilution and dispersal processes that reduce the persistence of surface-bound contaminants offshore. Supplementary Figure S7 shows the raw along-track i_s measurements for each transect at Camposoto (Figure S7a) and La Caleta (Figure S7b). These data indicate a high sampling density, with median along-track spacings of 0.14 m ($n = 148$) and 0.20 m ($n = 260$), respectively. The individual observation points are also displayed on the interpolated maps in Figure 11.

4. Discussion

The development of remote sensing tools for the rapid detection of emerging contaminants, such as UV filters, represents a step forward in coastal environmental monitoring. This study established and validated a UAV-based above-water spectroradiometric methodology based on the spectral ratio index i_s , designed to overcome the limitations of conventional in situ sampling in spatially heterogeneous coastal systems.

4.1. Analytical Foundation and Spectral Robustness

The i_s index was developed as a spectral proxy for sunscreen concentration, reducing variability and improving comparability across water types [40,43]. This representation also enhanced calibration transferability (Figure 6), increasing robustness under variable optical conditions [33,48]. The use of a composite sunscreen stock solution further strengthened calibration representativeness by mimicking the chemical complexity of real mixtures rather than relying on single-compound standards.

The 14 commercial sunscreens analysed (Table 1) exhibited distinct UV spectral behaviours. Formulations containing multiple organic UV filters, such as octocrylene, bis-ethylhexyloxyphenol methoxyphenyl triazine, and butyl methoxydibenzoylmethane, produced strong absorption between 300–380 nm, whereas inorganic formulations (TiO_2 and

ZnO) generated weaker responses. Variations in texture, dispersibility, and solubility further modulated spectral intensity, with poorly dispersing sunscreens showing attenuated or heterogeneous reflectance signals [15,28,44]. This was particularly evident for the inorganic-only formulation, which showed a mean R_{rs}^{-1} roughly 85% lower than the organic-containing products. Among the organic-dominated formulations, R_{rs}^{-1} variability averaged 12.3% (CV), reflecting the expected range of spectral behaviour across commercial products of similar composition.

The calibration model derived from controlled laboratory experiments demonstrated a high coefficient of determination ($R^2 = 0.964$), with the spectral index i_s showing strong agreement with UV filter concentrations independently quantified by SBS-DME-LC. This cross-validation against an established analytical reference method confirms the chemical basis of the optical response. It also supports the transferability of the calibration to field conditions, where the same UV-absorbing compounds are expected to dominate the spectral signal in the 300–380 nm range.

4.2. Mitigating Environmental and Surface Interferences

Environmental and optical conditions strongly influenced detection capability. Stable, high irradiance maximized signal-to-noise ratios [48], while low illumination (e.g., cloud cover and low solar angles) weakened UV absorption features. Temperature fluctuations induced 10–20% variation in the dark signal, which was corrected using paired dark acquisitions (Figure 4). Variations in solar irradiance of 5–15% during early morning and sunset required duplicate panel measurements and interpolation to minimize uncertainty. Appropriate integration time settings avoided saturation and improved the clarity of UV-specific features.

A primary limitation for UAV-based detection in natural waters is interference from optically active constituents (OACs). Phytoplankton reduced R_{rs}^{-1} spectral imprint by up to ~80% (Figure 7a), consistent with strong increases in backscattering that suppress absorption-driven variations in reflectance [41–43,52]. Suspended sediments and turbidity induced additional reductions of ~33% (Figure 7b), in agreement with known masking effects in optically complex waters [41–43,52]. These findings confirm that UAV spectro-radiometry performs best in optically clear waters and should be complemented with turbidity and chlorophyll metadata in productive or estuarine systems. Beyond optical interferences, surface hydrodynamics may also affect detectability. As Mar_Spectra relies on above-water reflectance, vertical mixing, wave breaking, and alongshore currents can redistribute UV filters below or away from the surface, leading to potential underestimation of their presence. Accordingly, the system is best regarded as a semi-quantitative screening tool, suited to relative spatial and temporal comparisons of UV filter signal rather than absolute concentration retrieval in optically complex waters.

To counteract noise and footprint heterogeneity, operational optimization was essential:

- (i) Empirical optimization of the measurement protocol: Although averaging 30 scans improved initial stability, results remained sensitive to heterogeneous surface films. A 20% filtering criterion was applied to remove acquisitions with insufficient sunscreen surface coverage, reducing the standard deviation by 34% and improving model fit.
- (ii) Sensor geometry and UAV altitude: A sensor-to-water distance of 30–40 cm provided high spectral contrast while minimizing splash contamination and field-of-view losses [38,48]. At the platform scale, UAV altitude strongly affected data quality. Flights at 2–6 m suffered from rotor-induced turbulence, sun glitter, and surface micro-wavelets, increasing spectral variability (SD up to 0.31) [34,49]. Operating at 8–12 m minimized these artifacts, causing <6% loss in i_s while reducing variability by approximately 50%. Results suggest that an operational height of 10 m provides the

optimal trade-off between signal strength and surface stability. This lower-altitude threshold complements previous UAV-based water reflectance studies, which reported negligible altitude effects only within the 20–100 m range [33], and had not previously been tested for pollutant-specific detection at lower heights. These patterns highlight that illumination, surface roughness, and UAV aerodynamics must be explicitly incorporated into acquisition protocols.

4.3. Field Performance and Spatio-Temporal Dynamics

Field trials demonstrated the operational capability of the UAV–*Mar_Spectra* system for real-world monitoring. In Barcelona (Figure 10), early-morning correlations between index i_s and bathing intensity confirmed the suitability of UAV spectroradiometry as a non-invasive proxy for sunscreen contamination. Under wind-driven turbulence, lateral dispersion of surface plumes reduced correlation strength, highlighting the hydrodynamic control of pollutant patchiness. These findings are consistent with field evidence showing that 25–50% contained in sunscreens applied by beachgoers can be released into seawater during bathing, exceeding 52 kg day^{−1} of sun care products on a single crowded beach receiving around 3000 visitors [18,23,53].

In Cádiz (Figure 11), UAV-based mapping revealed strong spatial gradients across beaches with contrasting hydrodynamics. La Caleta, an enclosed and highly urbanized beach, displayed higher concentrations due to limited flushing and greater anthropogenic pressure, whereas the more open and less urbanized Camposoto Beach exhibited lower values. Interpolated maps showed consistent shoreline-to-offshore dilution patterns. The high median sampling density at both sites, together with the point-data overlay in Figure 11, supports the reliability of the DIVA-interpolated maps; the raw along-track data (Supplementary Figure S7a,b) further allow independent verification of measurement coverage. Together, these field results show that UAV spectroradiometry effectively captures both spatial and temporal variability of UV filter release, offering a scalable, real-time tool for coastal pollution monitoring.

5. Conclusions

This study demonstrated the feasibility of detecting sunscreen residues in seawater through R_{rs}^{-1} measurements using the *Mar_Spectra* system, a compact high-resolution spectroradiometric platform integrated into a UAV. The system enables autonomous and repeatable data collection under real environmental conditions. When deployed at optimal altitude and orientation (nadir) and following a standardized acquisition protocol, *Mar_Spectra* provides robust monitoring of UV-absorbing compounds at the water surface.

Spectral analysis revealed that sunscreen compounds exhibit a distinctive absorption band between 300 and 390 nm. This detection capability was supported by a strong linear correlation ($R^2 = 0.964$) between spectrophotometric data and UV filter concentrations quantified via SBS-DME-LC, ensuring both analytical reliability and methodological reproducibility.

Despite these strengths, several environmental variables were identified as limiting factors in the field application of the technique. The presence of clouds reduces downwelling irradiance, thereby weakening the recorded signal, while wind-induced surface roughness and OACs, such as sea foam, turbidity, and particularly microalgae, can introduce significant noise or signal attenuation, in some cases fully masking the spectral signature of sunscreen compounds. Consequently, the effective sensitivity of the method in real deployments is largely conditioned by interference from OACs, which can reduce the practical limit of detection despite the high intrinsic analytical performance of the technique. In this context, the integration of auxiliary environmental measurements together

with an optimized acquisition protocol proved essential to ensure data quality and to reliably differentiate contaminant plumes from background variability even under optically complex conditions.

Overall, this work provides a solid framework for the real-time monitoring of sunscreen-derived UV filters in coastal environments. The portability, precision, and adaptability of the *Mar_Spectra* system make it a promising tool for environmental surveillance and coastal water quality assessment, especially in high-tourism regions where the impact of personal care products on marine ecosystems remains a growing concern.

Future improvements should include the integration of optical filters to selectively isolate the UV spectral bands and the adoption of a grey diffuse reflectance panel as an alternative reference surface to reduce saturation risk under high solar irradiance and remove the need for manual integration time adjustments. These enhancements will further simplify data acquisition while ensuring high-quality, reproducible measurements, paving the way for the operational deployment of UAV-based high-resolution spectroradiometric monitoring platforms in aquatic environments. Future work should also focus on extending the calibration model to a wider range of optically complex waters, exploring inversion algorithms able to decouple the UV filter signal from chlorophyll and coloured-dissolved organic matter absorption, and integrating *Mar_Spectra* observations with satellite ocean-colour products to upscale the methodology from the local UAV scale to regional coastal monitoring networks.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/drones10080589/s1>, Figure S1: Schematic setup for outdoor near-field spectral measurements. The *Mar_Spectra* spectrometer, connected to a laptop for real-time data acquisition via the custom GUI, is mounted vertically above a transparent container filled with a seawater–sunscreen mixture. The optical fiber is positioned 30 cm above the water surface in nadir orientation; Figure S2: Representative appearance of sunscreen-containing seawater samples after sequential additions of *Tetraselmis chui* cultures to final densities of 5×10^4 and 1×10^5 , illustrating the progressive visual masking effect caused by increasing phytoplankton biomass; Figure S3: Measurement geometry adopted in this study. The spectroradiometer is oriented at nadir (0°) with the solar azimuth positioned at 40° from the vertical plane of the sensor. This configuration minimizes sun glitter and surface-reflected radiance contributions, improving the reliability of UV spectral measurements under field conditions; Figure S4: Linear regression between cumulative UV filter concentration ($\mu\text{g}\cdot\text{mL}^{-1}$) determined by SBS-DME-LC and the corresponding index i_S (Equation (3)); Figure S5: RGB images captured by the onboard UAV camera illustrating the influence of rotor-induced turbulence on water surface conditions. (a) At a total deployment cable length of 8 m (6 m cable + 2 m optical fiber), the water surface remains undisturbed, confirming negligible aerodynamic interference at this height. (b) At a reduced deployment length of 6 m (4 m cable + 2 m fiber), surface distortions caused by rotor downwash are clearly visible, demonstrating the critical importance of maintaining sufficient vertical separation between the UAV platform and the measurement surface; Figure S6: Linear regression between scan number and spectral ratio index i_S after applying a 20% high-pass filter to exclude acquisitions with insufficient surface coverage ($R^2 = 0.92$); Figure S7: Raw along-track spectral ratio index i_S values measured during the UAV surveys at (a) Camposoto and (b) La Caleta beaches. Each coloured line represents an individual flight transect, with points corresponding to consecutive spectral ratio index i_S measurements plotted as a function of distance along the transect. These raw, non-interpolated data illustrate the spatial sampling density used for the DIVA interpolation presented in Figure 11; Table S1: Wave and current conditions during the field campaigns at the three study sites, derived from SIMAR numerical hindcast data (Puertos del Estado, Spain). Values correspond to the sampling periods. For La Caleta, no dominant current direction is reported because of the high directional variability during the survey.

Author Contributions: Conceptualization, A.T.-S., G.N., and M.d.-V.-G.; methodology, M.d.-V.-G., A.T.-S., G.N., G.M., A.C., G.P.-P., J.A.L.-R., and M.T.; software, M.d.-V.-G.; validation, A.C., G.P.-P., G.M., and M.T.; formal analysis, M.d.-V.-G.; investigation, A.T.-S., M.d.-V.-G., G.N., A.R., J.A.L.-R., L.B., and M.T.; resources, A.T.-S., G.N., and M.T.; data curation, M.d.-V.-G., A.C., and G.P.-P.; writing—original draft preparation, M.d.-V.-G.; writing—review and editing, all authors; visualization, M.d.-V.-G., G.N., and A.R.; supervision, A.T.-S., M.T., and G.N.; project administration, A.T.-S. and G.N.; funding acquisition, A.T.-S., G.N., L.B., and J.A.L.-R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FOV	Field of view
GPS	Global positioning system
GUI	Graphical user interface
HPLC	High-performance liquid chromatography
i_s	Sunscreen concentration index
M300	DJI Matrice 300 RTK
NTU	Nephelometric turbidity units
OACs	Optically active constituents
RGB	Red, green, blue
RMSE	Root mean square error
R_{rs}	Remote sensing reflectance
R_{rs}^{-1}	Inverse of remote sensing reflectance
SBSDME	Stir bar sorptive dispersive microextraction
SD	Standard deviation
SPF	Sun protection factor
UAV	Unmanned aerial vehicle
UV	Ultraviolet
VIS	Visible
ZnO	Zinc oxide

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