

Linking UAV and Spaceborne Imaging Spectroscopy for Multi-scale Calibration and Validation of a Mediterranean Saline Surface

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Abstract

The increasing availability of spaceborne imaging spectroscopy data requires validation approaches capable of linking measurements acquired at different spatial scales. This study examines the temporary Sal 'e Porcus saline pond in western Sardinia, Italy, as a candidate reference surface for cross-scale spectral comparison. Surface reflectance was characterised using ASD FieldSpec ground spectroscopy, UAV-borne hyperspectral imagery acquired with a Specim AISA Kestrel 10 sensor, and temporally proximate PRISMA and EnMAP observations. UAV surface reflectance was derived by empirical-line calibration using field-measured radiometric targets. The four spectra were linearly interpolated onto a common 1 nm wavelength grid over their overlapping interval within 400–1000 nm and compared using correlation, linear regression and residual statistics. At the analysed sampling location, all dataset pairs showed strong spectral co-variation (Pearson's $r = 0.961$ – 0.995). The strongest linear correspondence was obtained between UAV and ASD spectra ($r = 0.995$, slope = 1.001, $R^2 = 0.990$ and residual RMSE = 0.007). Comparisons involving satellite observations retained the broad spectral pattern but showed pair-dependent slopes and larger residual dispersion. Because the acquisitions were non-simultaneous and differed in spatial support and spectral response, these discrepancies cannot be attributed solely to spatial scale or sensor performance. The findings support the potential of UAV imaging spectroscopy as an intermediate observational scale and justify further investigation of Sal 'e Porcus as a candidate CAL/VAL surface.

1. Introduction

The number of operational and planned satellite imaging spectroscopy missions has increased substantially during the last decade, creating new opportunities for the quantitative characterisation of the Earth's surface. Current missions such as the Italian Space Agency's (ASI) PRISMA and the Environmental Mapping and Analysis Program (EnMAP) of the German Aerospace Agency (DLR), together with forthcoming missions such as ESA's Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) and PRISMA Second Generation (PRISMA-SG), require accurate radiometric calibration and independent validation. These procedures are essential for ensuring the reliability and comparability of spectral radiance and derived surface reflectance products across sensors, acquisition conditions, and observation scales.

Imaging spectroscopy calibration and validation (CAL/VAL) commonly rely on well-characterised terrestrial reference surfaces whose reflectance can be independently measured using field instrumentation. Suitable surfaces should ideally exhibit spatial homogeneity, temporal stability, limited vegetation cover, low topographic variability, and reflectance levels that permit reliable comparison with satellite observations. Arid and saline environments may provide favourable conditions for this purpose, although their suitability depends on surface composition, moisture, salt-crust development, and spatial heterogeneity (Melis et al., 2024; Musacchio et al., 2024).

The EnMAP calibration and validation framework combines on-board calibration procedures with vicarious assessment over

selected terrestrial reference sites (Schneider et al., 2012; Carmona et al., 2023). During the first year of operation, EnMAP radiometric performance was evaluated using observations over the RadCalNet sites at Railroad Valley, La Crau, and Gobabeb, together with pseudo-invariant calibration sites used to assess temporal stability (Pato et al., 2023). Subsequent global validation activities extended this assessment across different surface types, atmospheric conditions, and geographic regions during the commissioning phase and the first two years of operational data acquisition (Brell et al., 2026). These activities demonstrate the importance of geographically distributed and independently characterised reference surfaces. In this context, evaluating additional homogeneous surfaces such as Sal 'e Porcus may complement established calibration sites and provide information on EnMAP surface-reflectance performance over bright saline materials.

A fundamental challenge in satellite CAL/VAL is the difference in spatial support between field spectroradiometer measurements and satellite pixels. Field instruments characterise surface areas ranging from centimetres to decimetres, whereas contemporary spaceborne imaging spectrometers typically record reflectance over pixels measuring tens of metres. Direct comparisons between field and satellite spectra may therefore combine sensor-related differences with effects caused by spatial aggregation and sub-pixel surface heterogeneity.

Unmanned aerial vehicle (UAV) imaging spectroscopy provides an intermediate observational scale that can help reduce this spatial gap. UAV hyperspectral sensors produce centimetre-scale surface-reflectance data while covering areas sufficiently large to

characterise variability within individual satellite pixels. When calibrated using field spectroradiometric measurements, UAV imagery can facilitate the transfer of reflectance information from point measurements to the spatial support of satellite observations.

Sal 'e Porcus in western Sardinia has recently been investigated as a potential reference surface for imaging-spectroscopy CAL/VAL. Melis et al. (2024) provided an initial spectral and spatial characterisation of the saline surface, while Musacchio et al. (2024) compared field measurements with PRISMA and EnMAP observations. These investigations indicated the potential of the site but did not explicitly evaluate the role of UAV imaging spectroscopy in bridging the spatial gap between field and satellite observations. The site has also been considered within the COOL project as a potential reference area supporting the development and validation of PRISMA-SG products (Santini et al., 2024).

This study extends the existing framework by incorporating UAV imaging spectroscopy as an intermediate observational scale between ASD field spectroscopy and PRISMA and EnMAP data. The objectives are to:

1. evaluate the spectral consistency of field, UAV, PRISMA and EnMAP reflectance measurements over the Sal 'e Porcus saline surface;
2. characterise pairwise spectral correspondence and wavelength-dependent departures from the fitted linear relationships;
3. assess the ability of UAV imaging spectroscopy to bridge the spatial-scale gap between point-based field spectroscopy and satellite pixels;
4. evaluate the potential and limitations of Sal 'e Porcus as a candidate reference surface for imaging spectroscopy CAL/VAL.

2. Study area

Sal 'e Porcus is a temporary saline pond located on the Sinis Peninsula in western Sardinia, Italy, between the municipalities of San Vero Milis and Riola Sardo (Figure 1). Covering approximately 3.2 km², it is considered the largest temporary pond in Sardinia. The basin has a maximum depth of approximately 1 m and an average depth of about 0.4 m. It has no tributaries or drainage outlets and therefore forms a hydrologically independent basin within the regional system of coastal ponds Melis et al. (2024).

Seasonal water accumulation is controlled mainly by precipitation and evaporation. During the Mediterranean summer, strong evaporation can result in the complete or near-complete drying of the basin, exposing an extensive salt-enriched surface developed over low-permeability, greyish-white clayey sediments. The exposed surface is characterised by limited vegetation, low topographic relief and spatially variable salt-crystallisation. These properties make the site potentially suitable for cross-scale radiometric comparison, although surface moisture, salt-crystallisation composition and local heterogeneity may affect its spectral response. The locations of the field measurements, the UAV survey area and the corresponding PRISMA and EnMAP coverage are shown in Figure 1.

3. Data and methods

3.1 Multi-scale observation design

The study combined field spectroradiometry, UAV-borne imaging spectroscopy, and spaceborne hyperspectral observations to characterise the exposed saline surface across spatial scales ranging from point measurements to 30-m satellite pixels. All observations were acquired during the dry phase of the Sal 'e Porcus pond in July 2023, when the saline crust was extensively exposed and vegetation cover was minimal (Figure 2).

The EnMAP and PRISMA images were acquired on 14 and 15 July 2023, respectively. Field surface spectra were collected using an ASD FieldSpec 3 Pro on 18 July 2023, while the UAV hyperspectral survey was performed on 20 July 2023. Table 1 summarises the principal characteristics of the datasets. Only the common visible and near-infrared wavelength interval between 400 and 1000 nm was used in the cross-platform comparisons. Although the acquisitions were not simultaneous, the short interval between them was selected to minimise temporal differences in surface conditions. No precipitation or other major disturbance of the exposed surface was observed during this period. Records from the nearest meteorological station at San Vero Milis–Putzu Idu (ARPAS, 2024) indicated persistently hot and dry conditions during the acquisition period. Daily maximum air temperature increased from 34.5 °C on 14 July to 40.8 °C on 18 July, while no precipitation was recorded and solar irradiance remained high. These conditions, associated with a persistent North African anticyclonic circulation, reduced the likelihood of rainfall-induced changes in surface moisture between the field, UAV, and satellite acquisitions.

At each sampling location, ten replicate spectra were acquired from approximately 1 m above the surface with the foreoptic directed vertically downwards. A calibrated Spectralon panel was measured at regular intervals to convert the recorded signal to reflectance and account for changes in illumination.

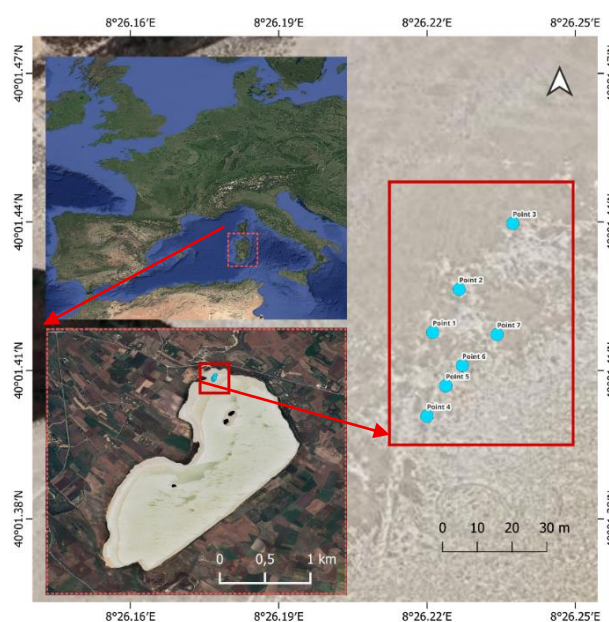


Figure 1. Location of the area and the distribution of the sampled points within the area corresponding to the analyzed pixels belonging to the ASI-PRISMA and DLR-EnMAP.

Observation level	Instrument/sensor/data product	Acquisition date	Spectral range	Spectral sampling/bands	Spatial support
Field	ASD FieldSpec 3 Pro	18 July 2023	350–2500 nm	1–3 nm sampling	point measurement
Airborne	Specim AISA Kestrel 10	20 July 2023, 11:44:56 UTC	400–1000 nm	178 bands (3.5 nm sampling)	~0.10 m GSD
Satellite	EnMAP, ID: ENMAP01-L2A-DT0000026975_20230714T105257Z	14 July 2023, 10:52:57 UTC	~420–2450 nm	224 bands	~30 m
Satellite	PRISMA, ID: PRS_L2D_STD_20230715101537	15 July 2023, 10:15:37 UTC	~400–2500 nm	235 bands	~30 m

Table 1. Overview of the ground, UAV, and satellite datasets used in the study.



Figure 2. Field measurements and UAV hyperspectral data acquisition at Sal 'e Porcus: (A) measurement of a calibrated Spectralon white-reference panel used for the ASD field spectroscopy of the saline surface; (B) RTK GNSS survey of the five radiometric targets used for empirical-line calibration of the UAV imagery; (C) field instrumentation and GNSS base-station setup supporting the UAV survey; and (D) the customised DJI Agras T30 carrying the Specim AISA Kestrel 10 sensor during the VNIR hyperspectral flight.

The ten replicate spectra were subsequently averaged to obtain one representative spectrum per sampling location. Immediately before the UAV flight, the reflectance spectra of five reference targets representing different reflectance levels within the UAV sensor range were measured with the ASD instrument.

The fibre-optic foreoptic was held manually at an angle of approximately 45° relative to the target surface and at a constant distance above its central part. A consistent viewing geometry was maintained while avoiding shadows cast by the operator or the instrument and ensuring that the measurement footprint remained entirely within the target. Multiple spectra were acquired for each target and averaged to obtain a representative reflectance spectrum. All ground sampling locations and radiometric targets were surveyed using RTK GNSS. The resulting centimetre-level positions enabled their identification in the georeferenced UAV imagery, while the measured target spectra provided the reference values for empirical-line calibration.

3.2 UAV hyperspectral acquisition

UAV hyperspectral imagery was acquired using an AISA Kestrel 10 push-broom imaging spectrometer manufactured by Specim mounted on a customised DJI Agras T30 multicopter. The sensor recorded data in the 400–1000 nm wavelength range and provided 178 spectral bands in the configuration used during the survey. The flight was conducted at approximately 90 m above ground level with a mean flight speed of approximately 5 m s⁻¹ and a sensor field of view of 40°. These acquisition parameters produced a final ground sampling distance of approximately 0.10 m. Data were collected around local solar noon (Table 1). The flight lines were oriented east-west, with an across-track overlap of approximately 30%. Position and orientation data were recorded using the onboard OXTS xNAV550 GNSS/IMU system. The locations of the radiometric targets, field sampling points, and other reference elements were independently measured using RTK GNSS. These measurements supported the geometric processing of the push-broom imagery and the spatial correspondence between ground observations and image pixels.

3.3 UAV radiometric processing

The raw AISA Kestrel 10 data were subjected to radiometric and geometric preprocessing using CaligeoPRO v2.2.19. Sensor calibration coefficients were applied to convert the recorded digital numbers to at-sensor radiance. Individual flight lines were georectified using the recorded GNSS/IMU trajectory and a lidar-based DSM (0.2 m cell size, see Melis et al., 2024), then mosaicked into a spatially continuous hyperspectral dataset. Surface reflectance was derived using empirical-line calibration implemented in ENVI 5.3. The five field-measured radiometric targets were identified in the georeferenced UAV imagery, and mean image values were extracted from regions of interest located inside each target. For every spectral band, the image values were related to the corresponding ASD-measured target reflectance values using a linear calibration function:

$$\rho_{\lambda} = a_{\lambda}L_{\lambda} + b_{\lambda}, \quad (1)$$

where ρ_{λ} is the estimated surface reflectance at wavelength λ , L_{λ} is the UAV-derived radiance, and a_{λ} and b_{λ} are the band-specific empirical-line coefficients.

The derived functions were subsequently applied to the complete UAV hyperspectral dataset. The calibrated flight lines were mosaicked and resampled to a final spatial resolution of approximately 0.10 m. Spectral quality control included the removal of noisy or invalid bands at the limits of the sensor range.

3.4 PRISMA and EnMAP data

Spaceborne hyperspectral observations were obtained from the Italian ASI PRISMA mission and the German DLR EnMAP mission (Table 1). Both sensors provide VNIR and SWIR hyperspectral measurements at a spatial resolution of approximately 30 m. The analysis used atmospherically corrected surface-reflectance products: the PRISMA Level-2D Standard product and the EnMAP Level-2A product. Only the 400–1000 nm wavelength interval overlapping with the AISA Kestrel 10 data was retained. Bands affected by low signal-to-noise ratios, atmospheric absorption, or product quality flags were excluded. The satellite products were transformed to a common coordinate reference system (EPSG:32632) and spatially aligned with the UAV mosaic. Geolocation was verified against identifiable surface features and RTK GNSS measurements, and residual offsets were corrected using a translational shift.

3.5 Spatial and spectral co-registration

Musacchio et al. (2024) reported broadly similar spectral trends across seven sampling points within the same test area, although absolute reflectance varied among them. Sampling point 2 was selected for the present cross-scale comparison because it was located within the valid overlap of all four datasets and in a comparatively homogeneous part of the exposed saline surface. It was therefore treated as representative of the broad spectral behaviour of the sampled area, but was not intended to characterise its full spatial variability.

The RTK GNSS positions of the field measurements were overlaid on the calibrated UAV mosaic and the PRISMA and EnMAP images. For the comparison reported in this study, spectra were extracted at sampling point 2. A 30×30 m region of interest was defined in the UAV mosaic to approximate the spatial support of a satellite pixel, and all valid UAV pixels within this region were averaged to obtain a mean UAV spectrum for the ROI. The corresponding PRISMA and EnMAP spectra were extracted from the satellite pixels containing the RTK GNSS position. This aggregation partially reduced the difference in spatial support between the approximately 0.10 m UAV observations and the 30 m satellite data.

The ten replicate ASD measurements associated with the sampling location were imported using the `get_spectra()` function from the R package `asreader` (Roudier 2017). Where necessary, individual spectra were linearly interpolated to the wavelength grid of the first ASD measurement using the `approx()` function. The ten aligned spectra were subsequently averaged wavelength by wavelength to obtain one representative ASD spectrum.

The pre-extracted PRISMA, UAV, ASD, and EnMAP spectra were imported from separate CSV files. Records with non-numeric or non-finite wavelength or reflectance values were removed, wavelengths were sorted in ascending order, and duplicate wavelength records were excluded. The common spectral interval was determined from the maximum of the four minimum wavelengths and the minimum of the four maximum wavelengths. A common wavelength grid was then generated at 1 nm intervals, and all four spectra were linearly interpolated to this grid using the R `approx()` function. The resulting harmonised dataset contained 589 common wavelength samples used in the statistical analysis. No convolution with the PRISMA or EnMAP spectral response functions was applied.

3.6 Statistical analysis

Pairwise comparisons were performed among the harmonised PRISMA, UAV, ASD, and EnMAP spectra using the 589 common wavelength samples. For each dataset pair, the first dataset listed was treated as the predictor variable (x_i), and the second dataset as the response variable (y_i). An ordinary least-squares linear regression with an intercept was fitted as

$$y_i = \alpha + \beta x_i + \varepsilon_i \quad (2)$$

where (x_i) and (y_i) are the reflectance values of the compared spectra at the i -th wavelength, λ_i ; α is the regression intercept, β is the regression slope, and ε_i is the residual. A slope close to unity indicates similar reflectance magnitude, whereas high correlation combined with a slope different from unity indicates preservation of spectral shape but a systematic difference in reflectance amplitude. The assignment of the reference and dependent datasets followed the order reported in Table 2.

Deviations from the fitted regression relationships were quantified using the residual root mean square error ($RMSE_{res}$) and residual mean absolute error (MAE_{res}). These statistics describe wavelength-dependent departures (residuals) from the fitted linear relationship and should not be interpreted as direct measures of spectral correspondence:

$$RMSE_{res} = \sqrt{\left(\frac{1}{n} \sum_{i=1}^n (\varepsilon_i)^2\right)} \quad (3)$$

$$MAE_{res} = \frac{1}{n} \sum_{i=1}^n |\varepsilon_i| \quad (4)$$

where n is the number of common wavelength samples (589). All statistical calculations were performed in R v4.4.1.

Because correlation primarily describes spectral co-variation and does not by itself demonstrate agreement in absolute reflectance, the correlation coefficients were interpreted jointly with the regression parameters and residual statistics. Together, these measures characterised the strength of the linear relationships and the wavelength-dependent dispersion around the fitted regression lines. The analysis was descriptive, and significance tests were not applied because the wavelength samples were spectrally autocorrelated and included values interpolated to a common 1 nm grid; therefore, they did not represent independent observations. Accordingly, emphasis was placed on the magnitude of the correlation and regression coefficients and on residual dispersion.

4. Results

4.1 Spectral characteristics across observation scales

At sampling point 2, the ASD, UAV, PRISMA, and EnMAP spectra exhibited a broadly similar pattern across their common wavelength interval within the 400–1000 nm range (Figure 3). All four spectra showed a general increase in reflectance from the visible towards the near-infrared region. The UAV spectrum followed the ASD field spectrum most closely. Greater differences were visible between the satellite spectra and the ASD and UAV observations, particularly at shorter visible wavelengths and above approximately 900 nm. Several narrow fluctuations occurred near the upper limit of the analysed wavelength range. Thus, the four datasets shared a similar broad spectral pattern but differed in reflectance magnitude at individual wavelengths.

4.2 Pairwise spectral relationships

Pairwise comparisons were performed using 589 wavelength samples interpolated at 1 nm intervals across the common spectral range. All dataset pairs showed strong positive correlations, with Pearson correlation coefficients ranging from 0.961 to 0.995 and coefficients of determination ranging from 0.924 to 0.990 (Table 2).

The strongest linear relationship was observed between the UAV predictor and the ASD response. This comparison produced a Pearson correlation coefficient of 0.995, a regression slope of 1.001, an R^2 of 0.990, a $RMSE_{res}$ of 0.007, and a residual MAE of 0.005. It also had the lowest residual dispersion among the evaluated pairs.

The UAV–EnMAP and ASD–EnMAP comparisons produced correlation coefficients of 0.986 and 0.984, respectively, with

corresponding R^2 values of 0.972 and 0.969. Their regression slopes were 0.824 and 0.817, while their residual RMSE values were 0.009 and 0.010, respectively.

PRISMA showed a higher correlation with ASD ($r = 0.981$, $R^2 = 0.962$) than with the UAV data ($r = 0.970$, $R^2 = 0.942$). The PRISMA–UAV comparison produced the highest $RMSE_{res}$ and MAE_{res} among all six dataset pairs, reaching 0.016 and 0.011, respectively. The lowest correlation was obtained for the PRISMA–EnMAP comparison ($r = 0.961$, $R^2 = 0.924$). This regression also produced the slope furthest from unity ($\beta = 0.714$), a $RMSE_{res}$ of 0.015, and a MAE_{res} of 0.010. The residual statistics varied among dataset pairs and did not follow a strictly monotonic pattern with nominal spatial support.

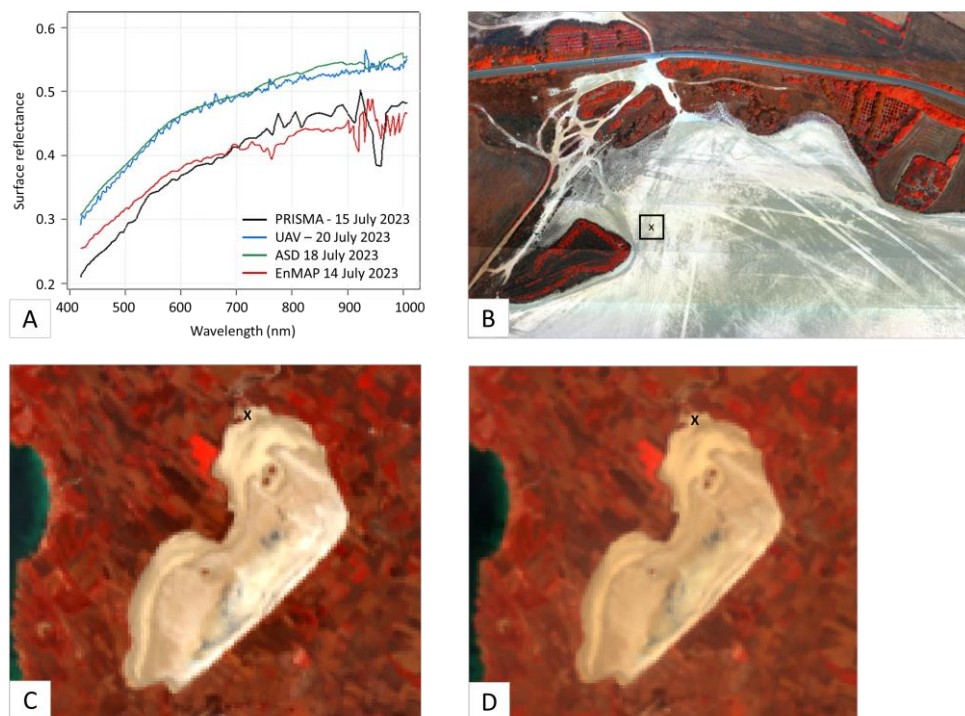


Figure 3. Cross-scale spectral and spatial comparison at sampling point 2: (A) surface-reflectance spectra obtained from EnMAP, PRISMA, ASD FieldSpec and UAV observations; (B) UAV hyperspectral RGB composite, where the black-outlined square indicates the approximate 30×30 m satellite-pixel-scale region of interest centred on ASD sampling point 2; (C) EnMAP Level-2A RGB composite; and (D) PRISMA Level-2D RGB composite. Sampling point 2 is marked by an X in panels (B)–(D). The RGB composites C–D use wavelengths of 796, 550 and 424 nm. The datasets were acquired on 14, 15, 18 and 20 July 2023.

Dataset pair (x vs. y)	n	Pearson r	Regression slope (β)	R^2	$RMSE_{res}$	MAE_{res}	SD_{res}
PRISMA vs. UAV	589	0.970	0.863	0.942	0.016	0.011	0.016
PRISMA vs. ASD	589	0.981	0.877	0.962	0.013	0.008	0.013
PRISMA vs. EnMAP	589	0.961	0.714	0.924	0.015	0.010	0.015
UAV vs. ASD	589	0.995	1.001	0.990	0.007	0.005	0.007
UAV vs. EnMAP	589	0.986	0.824	0.972	0.009	0.006	0.009
ASD vs. EnMAP	589	0.984	0.817	0.969	0.010	0.006	0.010

Table 2. Pairwise linear-regression statistics for the ASD, UAV, PRISMA, and EnMAP spectra at sampling point 2. The first dataset is the predictor x, and the second is the response y. $RMSE_{res}$ and MAE_{res} were calculated from the regression residuals.

5. Discussion

5.1 Spectral correspondence and the role of UAV observations

The high correlations observed among all dataset pairs show that the ASD, UAV, PRISMA, and EnMAP spectra retained the broad wavelength-dependent behaviour of the exposed saline surface. However, correlation primarily measures spectral co-variation and does not demonstrate equality of surface reflectance. Likewise, the residual RMSE and MAE values reported in Table 2 quantify departures from the fitted regression relationships rather than direct differences between the reflectance values of two sensors. The results therefore provide stronger evidence of similarity in broad spectral behaviour than of absolute radiometric agreement.

The UAV–ASD comparison showed the strongest linear correspondence, with $r = 0.995$, a slope of 1.001, and the lowest residual RMSE of 0.007. This close relationship indicates that the empirical-line-calibrated UAV spectrum reproduced the wavelength-dependent variation recorded in the field spectrum at the analysed location. Nevertheless, the UAV calibration was based on reference targets whose reflectance was measured using the same ASD FieldSpec instrument. The comparison therefore assesses the transfer of an ASD-based calibration to the UAV observation of the saline surface and should not be regarded as a completely independent radiometric validation.

The UAV data nevertheless provide an important intermediate observational scale. Field spectroradiometry characterises a relatively small surface footprint, whereas PRISMA and EnMAP measurements integrate reflectance over approximately 30 m pixels. The centimetre-resolution UAV imagery can characterise spatial variability within this intermediate area and can therefore help determine whether a field measurement is representative of the surface observed by a satellite sensor.

5.2 Sources of cross-platform differences

The comparisons involving satellite observations showed greater pair-dependent residual dispersion and regression slopes further from unity. Several factors may have contributed to these differences. EnMAP, PRISMA, ASD, and UAV observations were acquired on 14, 15, 18, and 20 July 2023, respectively. Although no precipitation was recorded during this period, the absence of rainfall does not guarantee unchanged surface moisture or salt-crust properties. Continued evaporation, changes in illumination and viewing geometry, atmospheric-correction differences, geolocation uncertainty, and sub-pixel surface heterogeneity may all have affected the observed reflectance.

The regression results should not be interpreted as a ranking of sensor accuracy. Ordinary least-squares regression assumes that the predictor variable is measured without error, whereas uncertainty is present in all four datasets. In addition, the regression slope depends on which dataset is assigned as the predictor. The non-unity slopes therefore describe pair-specific linear relationships but cannot independently identify whether the differences originate from a particular sensor, acquisition date, atmospheric correction, or observation scale.

5.3 Methodological limitations

Spectral harmonisation represents another limitation. The spectra were linearly interpolated to a common 1 nm grid without convolution using the spectral response functions of PRISMA and EnMAP. Consequently, the 589 interpolated wavelength samples do not represent independent spectral bands or an effective spectral resolution of 1 nm. Differences in sensor bandwidth and band-centre position may have contributed to the narrow discrepancies, particularly near atmospheric absorption regions and above approximately 900 nm. Future analyses should convolve the higher-resolution spectra with the response functions of the compared satellite sensors or resample all datasets to a common effective spectral resolution.

The spatial comparison used an approximate 30×30 m UAV region centred on sampling point 2 to represent satellite-pixel-scale spatial support. However, because the PRISMA and EnMAP pixels containing the RTK GNSS position have different georeferenced footprints, the UAV region did not necessarily coincide exactly with both satellite pixels. A more rigorous comparison would therefore aggregate the UAV observations separately within the footprint of each PRISMA and EnMAP pixel. Although sampling point 2 was located within a comparatively homogeneous part of the exposed saline surface and was considered representative of its broad spectral behaviour, analysis of a single location cannot characterise the full spatial variability of the site. Extending the comparison to the remaining sampling locations would allow spatial homogeneity, within-site variability and the representativeness of individual locations to be quantified.

5.4 Implications for CAL/VAL at Sal 'e Porcus

Despite these limitations, the experiment provides a useful proof of concept for connecting field, UAV, and satellite imaging spectroscopy over an exposed saline surface. The results are consistent with previous investigations that identified Sal 'e Porcus as a potentially useful reference area for imaging-spectroscopy CAL/VAL activities (Melis et al., 2024; Musacchio et al., 2024). However, analysis of a single location and one acquisition period is insufficient to qualify the entire pond as an operational CAL/VAL site. Such qualification would require repeated near-simultaneous observations, analysis of multiple satellite pixels, explicit uncertainty assessment, and evidence of spatial and temporal stability over several dry seasons.

6. Conclusions

This study investigated the use of UAV imaging spectroscopy as an intermediate scale between field spectroradiometry and PRISMA and EnMAP observations over the Sal 'e Porcus saline surface. At the analysed sampling location, all dataset pairs showed strong spectral co-variation, with Pearson correlation coefficients between 0.961 and 0.995. The UAV–ASD comparison produced the strongest linear relationship, a near-unity regression slope and the lowest residual dispersion, indicating an effective transfer of the field-based empirical-line calibration to the UAV surface-reflectance data.

The satellite comparisons preserved the broad spectral behaviour of the surface but showed larger pair-dependent and wavelength-dependent discrepancies. Because the observations were acquired on different dates and differed in spatial support, atmospheric correction, viewing geometry and spectral response,

these discrepancies cannot be attributed to spatial scale or sensor performance alone.

The results support the use of UAV hyperspectral observations for bridging point-based field measurements and satellite pixels. They also confirm that Sal 'e Porcus merits further investigation as a candidate CAL/VAL reference surface. However, the present results do not constitute full qualification of the site. Future work should include simultaneous acquisitions, exact aggregation to individual satellite-pixel footprints, spectral-response-aware harmonisation, analysis of all sampling locations, direct reflectance-difference metrics and repeated campaigns to quantify spatial and temporal stability.

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