Synergizing airborne Hyperspectral Imaging and ground truth data for environmental monitoring: Insights from the CERAD campaign

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ABSTRACT

This work presents the Cyprus Flight Campaign of ERATOSTHENES Centre of Excellence and DLR (CERAD) that took place in October 2023 within the framework of the EXCELSIOR H2020 Widespread Teaming Phase 2 project titled "ERATOSTHENES: EXcellence Research Centre for Earth SurveiLlance and Space-Based Monitoring of the EnviRonment". The campaign's main goal was to acquire about 100.000 high-resolution stereo 3K images and hyperspectral HySpex images, complemented by ground truth measurements to perform high-resolution hyperspectral analysis and 3D mapping. The campaign aimed at the capacity development of ERATOSTHENES Centre of Excellence staff on processing these imagery, cross-calibration and validation of sensors, and analysis of land, water, and cultural heritage sites with hyperspectral sensors. This campaign captured high-resolution hyperspectral imagery across a wide spectral range (420–2500nm) in several parts of Cyprus (Paphos and Limassol Districts). Parallel to this airborne campaign, the research team of ERATOSTHENES Centre of Excellence conducted a ground-based measurement campaign, which included the collection of spectroradiometric measurements (HR 1024 and GER 1500), water samples for laboratory analysis of water (e.g., dissolved organic matter) and soil (e.g., texture, pH, organic content) samples, GPS tracking, soil moisture and meteorological sensors and on-board UAV multispectral cameras. The collected data will support various applications, such as calibration and validation of satellite products, environmental monitoring, vegetation analysis, and disaster risk assessment. According to the literature, the use of airborne hyperspectral imaging is essential since the airborne remote sensing data acts as a bridge between large-scale satellite and point-scale field observations. Furthermore, hyperspectral imaging is a simultaneous acquisition of spatial images in several spectrally adjacent bands and a highly multidisciplinary and complex field. The present campaign demonstrates the efficiency of airborne hyperspectral imaging in capturing detailed environmental data and highlights the vital role of ground-truth measurements in verifying airborne and enriching environmental data. The combined use of the methods mentioned above paves the way for advanced ecological monitoring thereby contributing to informed decision-making and sustainable development efforts.

Keywords: CERAD, Hyperspectral, HySpex, spectroradiometers, Cyprus, airborne, remote sensing, data acquisition, ground truth

1. INTRODUCTION

This study details the Cyprus Flight Campaign carried out by the ERATOSTHENES Center of Excellence and DLR (CERAD) in October 2023. This campaign was part of the EXCELSIOR H2020 Widespread Teaming Phase 2 project titled "ERATOSTHENES: EXcellence Research Centre for Earth SurveiLlance and Space-Based Monitoring of the EnviRonment". In order to enable high-resolution hyperspectral analysis and 3D mapping, the main objective was to gather about 100,000 high-resolution stereo 3K and hyperspectral HySpex images, reinforced with ground truth measurements.

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The campaign also attempted to improve the capabilities of the ERATOSTHENES Centre of Excellence in the areas of hyperspectral image processing, sensor cross-calibration and validation, and hyperspectral sensor analysis for land, sea, and cultural heritage locations. Across the spectral range of 420–2500 nm, high-resolution hyperspectral images were taken in several parts of Cyprus, including the districts of Paphos and Limassol. The hyperspectral imaging method involves collecting and analyzing data from the entire electromagnetic spectrum. Standard imaging normally uses three color bands (red, green, and blue) [1]. Hyperspectral imaging splits the spectrum into many more bands. These bands frequently cover visible light, infrared, and ultraviolet wavelengths. Hyperspectral imaging aims to identify objects, materials, or processes in a picture by obtaining the spectrum for each pixel. Using a broad range of wavelengths, high-spectral imaging provides the ability to identify and analyze materials and processes that are not visible with traditional imaging techniques [2].

Numerous studies on environmental monitoring have made substantial use of hyperspectral imaging (HSI) and ground truth data, demonstrating the benefits and adaptability of these methods. Furthermore, HSI is being used more and more in a variety of commercial, industrial, and military applications. In agricultural and environmental studies, HSI has shown to be a useful tool, providing in-depth understanding of plant health and water stress. Colombo et al. remarked that variations in leaf equivalent water thickness (EWT) have an impact on the leaf reflectance in the visible and infrared bands. They emphasized the usefulness of hyperspectral regression indices, which are generated from hyperspectral imaging (HSI), for evaluating water content at the landscape and leaf scales[3]. Using a portable hyperspectral imaging (HSI) device and the photochemical reflectance index, Rascher et al 2007 [4] evaluated water stress in tropical tree leaves and tracked the effects of dehydration over time. According to Rossini et al. 2013 [5]. HSI can accurately map irrigation deficiencies in maize before drought stress affects the canopy structure. This indicates that HSI is useful for identifying drought stress in corn at the farm level. Hyperspectral remote sensing provides effective and reliable insights into water quality indicators, including biological, hydro-physical, and biochemical characteristics, outside of the agricultural domain[6]. This technology makes it easier to quantify the amount of phosphorus, turbidity, chemical oxygen demand, and chlorophyll in water bodies. Many studies focus on the amount of chlorophyll to determine the amount of algae present and assess the cleanliness of the water. Studies have also looked at estuaries, classed different lake properties, researched ammonia changes in wetlands, and analyzed algal blooms. Hyperspectral imaging greatly improves wetland mapping, which improves the quality of the ecosystem [7]. Furthermore, by emphasizing the significance of timely data collecting for monitoring and mapping aquatic vegetation which is essential for ecosystem reconstruction and restoration it has increased our understanding of the properties of vegetation within ecosystems [8].

Through the integration of in-situ measurements with hyperspectral aircraft imaging, one can combine the broad, detailed spectral information obtained from aerial platforms with the precise, localized data collected on the ground. The capabilities of both data collection techniques are combined in this synergistic approach to improve accuracy and offer thorough insights into a variety of disciplines, such as urban management, agriculture, and the environment. Environmental parameters can be precisely and locally measured with ground-truth sensors. The quality and dependability of the remote sensing data are increased when these measurements are combined with hyperspectral data to validate and calibrate it. In many applications, this connection is essential for creating models and analysis. The comprehensive information obtained from hyperspectral imaging and ground sensors can guide focused actions to address environmental problems, ultimately enhancing our comprehension and administration of various regions[9].

Using ground-based sensors and instruments, such as soil moisture probes, water quality sensors, weather stations, and plant health monitors, in-situ measurements entail gathering data directly at the location of interest. Since these measurements capture localized conditions and changes in real-time, their great accuracy and specificity are their main advantages. Hyperspectral airborne imaging, on the other hand, uses cameras that record data in hundreds of small spectral bands to take pictures from aerial platforms such as planes or drones spanning a broad range of wavelengths beyond the visible spectrum. This method's primary benefit is its wide geographic coverage, which makes it possible to identify minute spectrum changes that signify the conditions and qualities of the material[9].

There are various advantages to combining these two data collection techniques. By providing accurate and localized environmental measurements necessary for the calibration and validation of hyperspectral imaging, ground-truth sensors improve data accuracy and dependability by resolving disparities. Integrating in-situ data with accurate hyperspectral information, allows for comprehensive analysis, providing a thorough understanding of geographical variability and the underlying mechanisms. Additionally, the integration helps with model validation and development, making it easier to create reliable models for a range of applications that can monitor changes, anticipate environmental conditions, and support decision-making. This integration has a wide range of uses. It is used in environmental monitoring to evaluate factors including turbidity, chlorophyll content, and contaminant levels to determine the quality of the air and water. By optimizing irrigation, fertilization, and pesticide application based on precise data, precision agriculture is supported by its ability to identify crop health issues such as pests, diseases, and nutritional deficits. Through land use mapping, categorizing urban and green zones, and keeping an eye on infrastructural problems, urban planning gains from this integration. Applications of natural resource management include mining effect monitoring and deposit identification, as well as forestry applications that track biomass, species composition, and forest health [10].

There are several steps in the integration process. At first, data is gathered by in-situ sensors at ground level, then hyperspectral imaging is obtained across the area of interest by flying platforms. The hyperspectral pictures are then subjected to data calibration using in-situ measurements to correct biases and errors. The next step in data fusion is to use statistical and computational methods to merge in-situ and hyperspectral data to create unified datasets that take advantage of both data kinds advantages. Models are developed after a thorough analysis of the gathered data. These actions result in ongoing change monitoring and real-world interventions, where models are updated in response to fresh data[11].

Combining the advantages of in-situ data and hyperspectral aerial images will allow for the development of more precise, thorough, and useful insights into environmental processes and situations. Effective decision-making and change monitoring are eventually aided by this integration, which also improves data accuracy, permits in-depth investigation of spatial variability and underlying processes, and facilitates the development and validation of strong models for a variety of applications.

2. METHODOLOGY FOR GROUND TRUTH MEASUREMENTS COLLECTION

2.1 Study area

The ERATOSTHENES Centre of Excellence and DLR - CERAD flight campaign covered twelve different survey regions across Cyprus (Figure 1), emphasizing various landscape types and locations of importance. This extensive program sought to gather thorough data in a variety of settings, each of which added distinctively to the overall goals of the research. Two agricultural locations were part of the campaign: Kallepeia and Acheleia**.** These regions were chosen to collect relevant data regarding crop health and agricultural practices, which are essential for comprehending and raising Cyprus's agricultural productivity. The campaign also placed a lot of emphasis on urban regions; surveys were carried out in Limassol and Paphos**.** The purpose of these urban surveys was to offer insightful information about environmental management, urban growth, and planning in heavily populated areas. A number of archeological sites were also the focus of the campaign, including Choirokoitia, Palepafos, and Amathus-Germasogeia. Cyprus has a rich archaeological legacy, and the data gathered will help preserve and research these historically and culturally significant sites. The campaign encompassed communities that had been impacted by fire, with Arakapas serving as a key focal point. The information gathered from this burned area are essential for comprehending how wildfires affect the environment and supporting efforts to manage and mitigate future flames.Data on water resources, essential for Cyprus's sustainable water management, were gathered by studying the dams of Kouris and Germasogeia. Marine and coastal ecosystems were taken into consideration, with Peyia being designated as a maritime site. This region contributed significantly to our understanding and preservation of Cyprus's marine biodiversity by providing important data on marine and coastal ecosystems. The effort also includes woodland areas, with the main forest site being assessed in Peyia, Paphos. The information gathered from this forest region is useful in evaluating the biodiversity, health, and effects of changing environmental conditions on forest ecosystems.

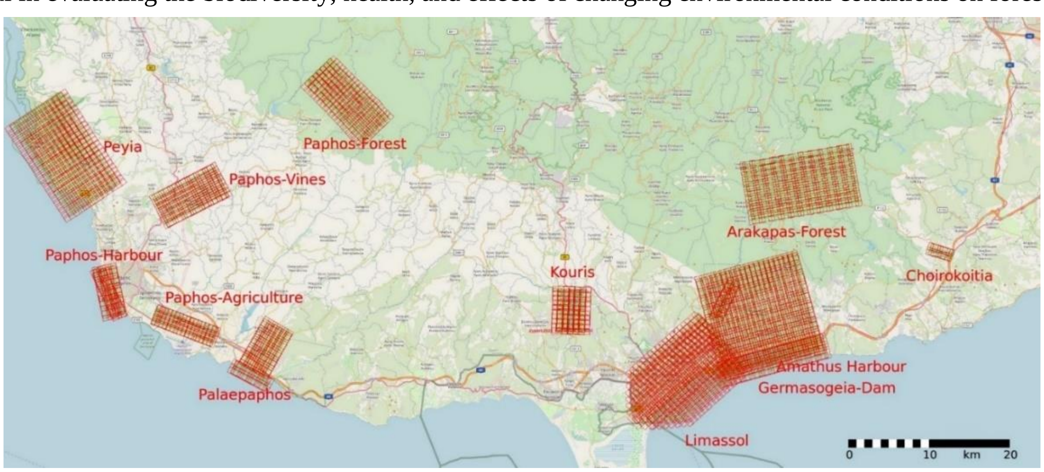

Figure 1.Study areas

In urban areas, measurements were taken using sensors i.e., GPS tracking, and RGB cameras. The combination of hyperspectral imaging with ground truth sensors for temperature, particulate matter, and other environmental parameters in urban areas provides a comprehensive assessment of environmental conditions. It can detect and analyze pollutants, heat islands, vegetation health, and water quality precisely. This data is also valuable for creating spectral signature libraries for various targets like concrete, solar panels, and buildings, which can provide information for energy autonomy and urban planning. Understanding and addressing the complex environmental challenges faced by urban areas, such as those in Limassol, benefits significantly from the in-situ data collected during the flight[12]**.**

Measurements at archaeological sites were taken using a spectroradiometer (HR 1024), drones, and RGB cameras. All the data collected is particularly useful in detecting variations of vegetation health or soil characteristics and indicating the presence of buried structures. In-situ measurements provide ground truthing and its combination with hyperspectral data is also effective for detecting archaeological looting and detection of archaeological sites in shallow water [13]**.**

In burned areas, measurements were taken using a spectroradiometer (HR 1024), photo interpretation, and RGB cameras. The combination of hyperspectral imaging with ground truth sensors supports the investigation of fire severity and tree mortality, such as in the Arakapas fire event on July 3, 2021. This technology assists in evaluating the impact of wildfires, guiding recovery and rehabilitation actions, assessing soil changes, monitoring post-fire vegetation regrowth, and detecting invasive species[14]**.**

Measurements at the dams were conducted using a spectroradiometer (GER 1500), RGB cameras, and by collecting water samples. Characterizing the spectral signatures and optical properties of Kouris Dam and Germasogeia, as well as combining hyperspectral imaging with ground-truth sensors, proves useful for detecting pollutants. Changes in water quality and temperature can significantly affect fish populations and other wildlife, making these measurements crucial**.** [15]

Measurements in sea sites were taken using a spectroradiometer (GER 1500) at several depths (0 cm, 50 cm, 100 cm, 150 cm, and 200 cm), RGB cameras, and soil samples. Characterizing the spectral signatures and optical properties in Peyia sea, the combination of hyperspectral imaging with ground truth sensors is useful for detecting variations in water coloration due to dissolved organic matter, chlorophyll concentrations (e.g., phytoplankton levels), and suspended sediments. This technology also monitors overall water quality, identifies areas affected by pollution or algal blooms, and helps in studying coastal erosion.[16]**.**

In forest areas, measurements were taken using Spectro radiometric measurements, GPS measurements, soil samples, drones, and an RGB camera. The combination of hyperspectral imaging with ground truth sensors helps estimate forest biomass by assessing canopy structure and density, and monitoring changes in forest cover and structure over time[17].

2.2 Data Collection

HySpex Hyperspectral Sensor

The HySpex hyperspectral sensor (**Error! Reference source not found.**) was developed by the German Aerospace Center (DLR) Remote Sensing Technology Institute (IMF) in Oberpfaffenhofen. This advanced sensor is an aircraft-borne imaging spectrometer equipped with two push broom line scanning cameras. It boasts a spatial resolution of less than one meter and covers a spectral range from 420 to 2500 nanometers. The HySpex sensor gathers data with exceptionally high spectral resolution, recording 416 channels per pixel. This capability allows it to capture significantly more spectral information compared to standard aerial image data, providing detailed insights across a broad range of wavelengths. The extensive spectral data collected by the HySpex sensor enables in-depth analysis and applications in various fields, enhancing the precision and utility of remote sensing efforts[18] .

Figure 2. HySpex hyperspectral sensor

Ground-based measurement campaign

Parallel to the airborne campaign, the research team of ERATOSTHENES Centre of Excellence conducted a ground-based measurement campaign using the equipment shown in Table 1 During the campaign, two field spectroradiometers (GER 1500 and SVC HR 1024) were used, covering the range from 350 nm to 2500 nm, along with white spectralon panels and fiber optic probes. This equipment is suitable for collecting ground truth spectroradiometric data over different targets including water bodies, soils, vegetation, rocks, asphalt, burned areas, etc. Additionally, water samples were collected for laboratory analysis to determine properties such as dissolved organic matter. Soil samples were also gathered to analyze texture, pH, and organic content. The team employed GPS tracking, soil moisture sensors, and meteorological sensors to collect comprehensive data. Onboard UAV multispectral cameras and ground-based RGB cameras were used to enhance the data collection process. Sensors designed for RGB imaging record visuals by detecting red, green, and blue spectral bands, which are then combined to create full-color imagery of the Earth's surface. These three sensors consist of three detectors, each sensitive to one of the RGB wavelengths. They operate by capturing light reflected off the Earth, using the RGB data to create true color images. The applications of these sensors are numerous and diverse. In agriculture, they are used for monitoring crop health. In forestry, they help assess forest conditions. In urban planning, they contribute to mapping and land use planning. In environmental monitoring, they are useful for observing ecosystems and natural disasters. RGB sensors have many advantages. They produce easily interpretable, true color images, are versatile across many fields, and are capable of high-resolution imagery. However, there are also challenges. Their performance is affected by weather and lighting conditions, and they are limited to the visible spectrum, missing information outside of it. Technological advancements continue to enhance the capabilities and applications of RGB sensors, improving their ability for global monitoring and analysis.

Table 1 Equipment used during the CERAD campaign Soil

Samples	**UAV**	**GPS**	**RGB camera**	**HR 1024**	**GER 1500**	**Water Samples**
						

3. RESULTS AND DISCUSSION

The measurements at the agriculture sites were taken at Acheleia and Kalepeia sites, using a spectroradiometer, soil samples, and RGB cameras. The collection of spectral signatures in combination with hyperspectral imagery is useful for identifying variations in soil properties, moisture levels, and crop health. This technology also aids in weed species detection, yield prediction, and pest management. Additionally, it helps in the optimization of water use by identifying areas of a field that are water-stressed. Figure 3 shows an example from the spectral signatures collected during the campaign. These signatures show distinct patterns across the wavelength range reflecting the unique properties of the measured targets.

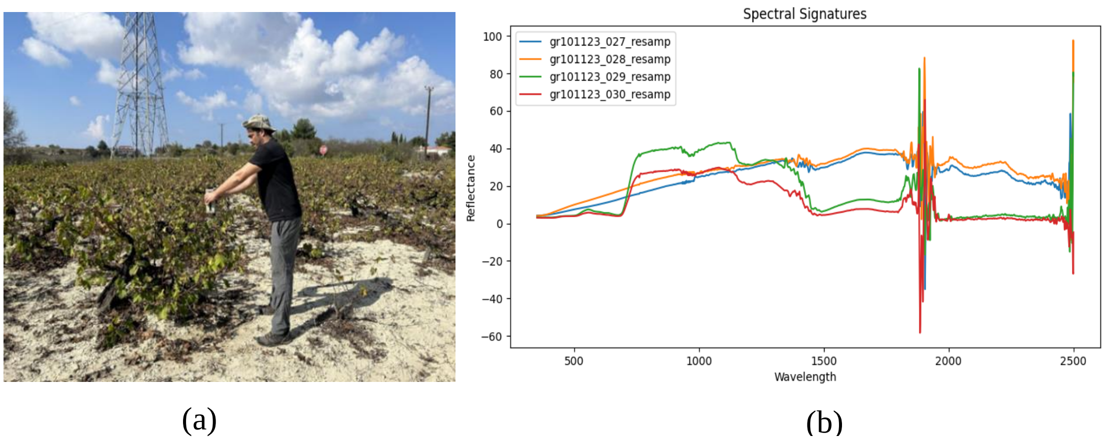

Figure 3. (a) Collection of spectral signatures using HR-1024 spectroradiometer in an agricultural plot during the ground-based measurement campaign, (b) Spectral Signatures Results

Spectral signatures were also collected using the fiber optic probe in the Kourris and Germasogeia dams and the Peyia sea region. In these cases, the spectral signatures were collected in different depths: 0cm (surface), 10cm, 50cm, 100cm, 150cm and 200cm in various positions of the dam and the sea site. We conducted this experience to examine the variations in the spectral signatures because, as described by[19] the mean reflectance values of the Inlet areas are higher than those of the Outlet areas. Apart from that the reflectance variations depended on the different depths as shown in **Error! Reference source not found.**. The figure illustrates the reflectance of water at various depths. The spectral s ignatures demonstrate how reflectance varies with both wavelength and water depth. Shallower depths generally exhibit higher reflectance due to reduced absorption and scattering, while deeper waters show lower reflectance as light penetration decreases. The variation is evident in the percentage reflectance on the dam surface at different depths and this is demonstrates how the depth influences the optical properties of the water as shown in **Error! Reference source not found.** where the reflectance in the visible part of the spectrum decreases with the increasing of the depth.

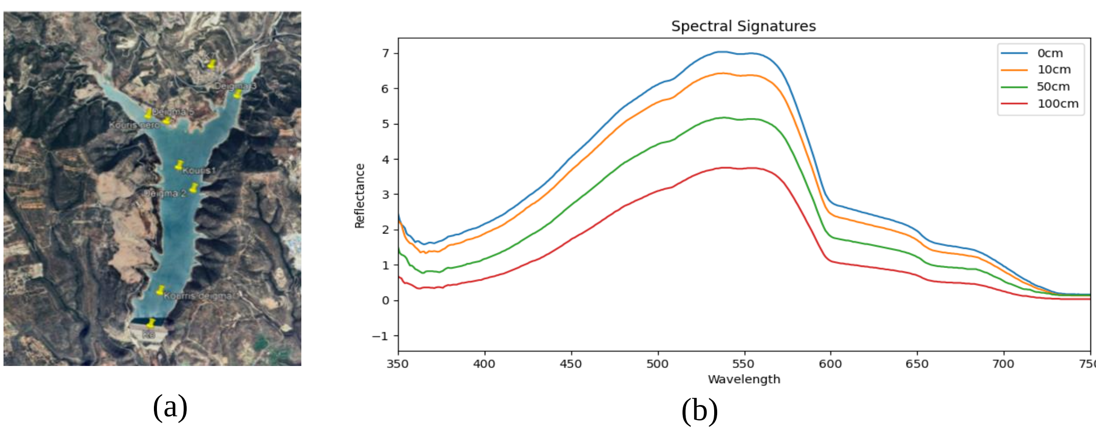

Figure 4 (a) Collection sites in Kourris dam (b) Spectral signatures at various depths

Furthermore, data for the air quality were collected in Limassol's city center as shown in Figure 5. The collected data provide a comprehensive overview of various environmental factors during the route. Table 2 presents the collected values for several parameters, including VOC (ppm), AQS, Temperature (°C), Humidity (%), Pressure (mbar), PM1 (μg/m³), PM2.5 (μg/m³), and PM10 (μg/m³), along with the geographical coordinates (latitude and longitude) of each measurement point. The visual representation in Figure 5 illustrates the air quality along different routes in the city, showing variations in pollution levels: **Green** indicates PM1 (particulate matter with a diameter of 1 micrometer or less) **Yellow** represents PM2.5 (particulate matter with a diameter of 2.5 micrometers or less). **Orange** corresponds to PM10. **Red** signifies NO2 (nitrogen dioxide), a gas primarily emitted from vehicle exhaust and industrial processes. **Light Green** stands for VOC (volatile organic compounds), which include various chemicals emitted from sources like paints, solvents, and fuels.

Table 2. Collected values for several

Date	VOC, ppm	AQS	Temperature, °C	Humidity, %	Pressure, mbar	PM1, ug/m3	PM2.5, ug/m3	PM10, ug/m3	Latitude	Longitude
8/10/2023 0:27	99	88	29	400	100909	80	90	100	347035568	33050566
8/10/2023 0:28	1	88	29	400	100910	80	110	120	347035568	33050566
8/10/2023 0:29	96	87	29	400	100912	90	100	110	347035568	33050566
8/10/2023 0:38	113	87	29	390	100906	90	100	120	347034784	330506669
8/10/2023 0:39	114	90	28	390	100910	70	90	100	347034784	330506669
8/10/2023 0:40	11	88	28	400	100907	80	100	110	347034784	330506669
8/10/2023 8:50	113	87	28	390	100922	90	110	120	3470348	330506518
8/10/2023 8:51	113	87	28	390	100924	90	110	120	3470348	330506518
8/10/2023 8:52	114	87	28	390	100930	90	110	120	3470348	330506518
8/10/2023 9:51	125	87	28	420	100952	90	110	120	347034165	330507027
8/10/2023 9:52	127	87	28	410	100954	90	110	120	347034165	330507027
8/10/2023 9:53	129	88	28	410	100954	80	100	110	347034165	330507027
8/10/2023 10:01	124	87	28	420	100947	90	110	120	347034778	330506653
8/10/2023 10:02	126	87	28	420	100950	90	110	120	347034778	330506653
8/10/2023 10:08	119	88	28	420	100944	80	100	110	347033612	330508195
8/10/2023 10:09	12	88	28	420	100945	80	100	110	347033612	330508195
8/10/2023 10:10	121	88	28	420	100942	80	100	110	347033612	330508195
8/10/2023 10:13	127	88	28	430	100938	80	100	110	347034861	330506592
8/10/2023 10:14	129	88	28	430	100938	80	100	110	347034861	330506592
8/10/2023 10:15	131	90	28	430	100937	70	90	100	347034861	330506592
8/10/2023 11:28	115	85	29	390	100921	100	120	140	347034783	330506564
8/10/2023 11:29	117	85	28	390	100924	100	120	140	347034783	330506564
8/10/2023 11:31	125	85	28	410	100921	100	120	140	347034834	330506528
8/10/2023 13:14	115	85	28	400	100860	100	120	130	34703459	330506188
8/10/2023 13:15	112	85	29	400	100857	100	120	130	34703459	330506188
8/10/2023 13:16	111	85	29	400	100855	100	120	130	34703459	330506188
8/10/2023 13:24	18	85	286	420	100850	100	120	130	347034968	330506674

PM1 PM2.5 PM10 NO2 VOC

Figure 5. Air quality factors along the route

Apart from the above, a 3D model for the city center of Limassol was created using the 3K camera system as shown in Figure 6.

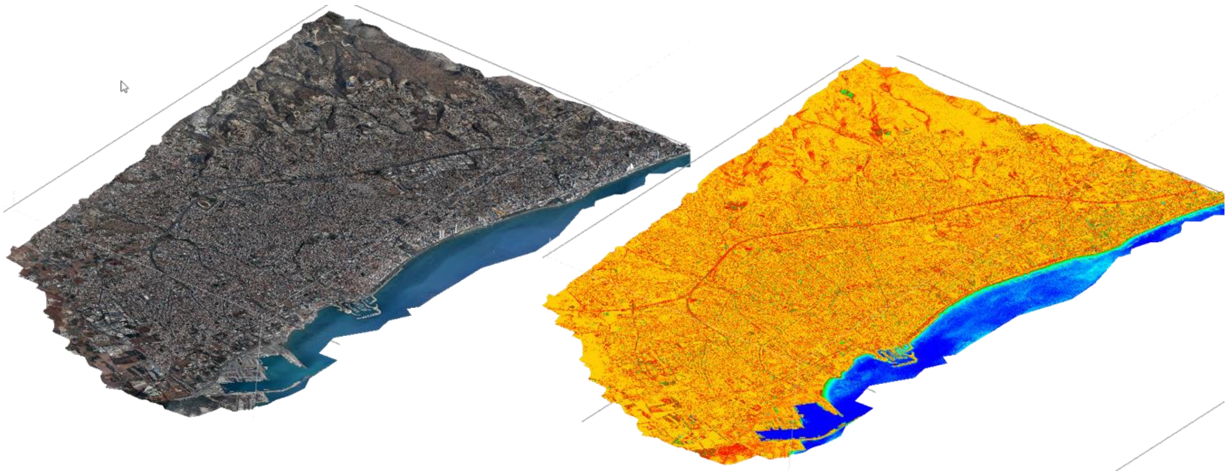

Figure 6. 3D model created from the 3K camera system

Furthermore, the application shown in Figure 7 focuses on archeology. In this case, apart from the spectral signatures, images were also collected using the UAV, and orthophotos were created as shown in Figure 7. ERATOSTHENES Centre of Excellence has an extensive history in the sector of Archeology conducting several studies[20–22] .This campaign helps to enhance the existing information by incorporating the hyperspectral images.

Figure 7. Orthophotos for monitoring the looting in archeological sites

In addition, spectral signatures were also collected in the Arakapas burned area. The spectral signatures were collected to assist in developing a spectral index for fire severity estimation. Prodromou et al., 2023 have implemented the Composite Burn Index based on-site visits and the Differenced Normalized Burn Ratio using Sentinel-2 satellite images for the estimation of fire severity as shown in Figure 8. This campaign aims to enhance these findings by incorporating hyperspectral airborne images and the spectral signatures collected using the HR 1024 spectroradiometer.

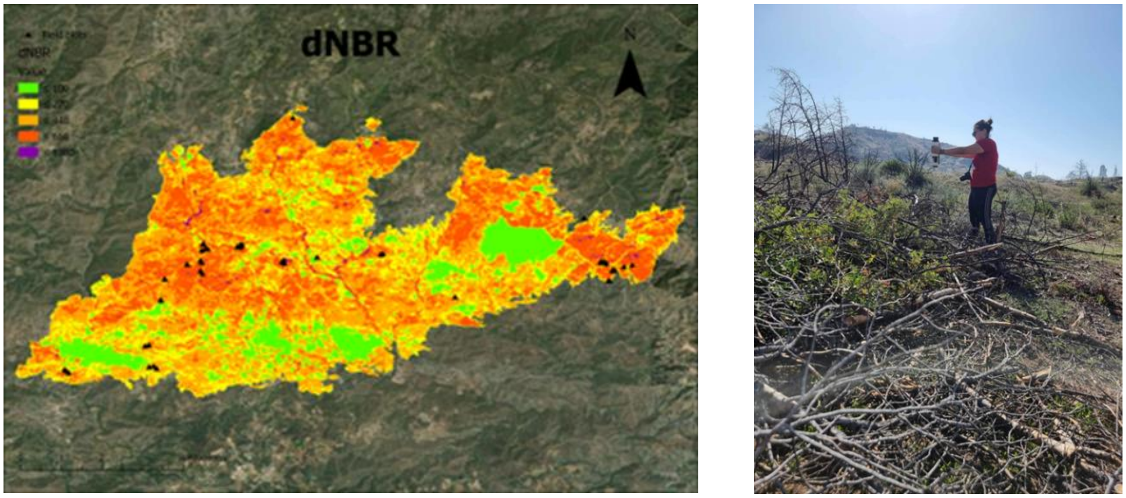

Figure 8. The distribution of the dNBR index for the burnt area near Arakapas village

Additionally, in Paphos Forest, spectral signatures were collected for different forest species. This information is useful in studies for forest species identification like the study conducted by Prodromou et al,2024 [23] for the Forest Habitat Mapping in Natura2000 Regions in Cyprus Using Sentinel-1, Sentinel-2, and Topographical Features. Images were also collected using the UAV in this area for the development of the orthophoto, as shown in Figure 9. Combining hyperspectral imaging with ground-truth data can improve the findings and lead to more detailed mapping.

Figure 9. Orthophoto for the Paphos forest

4. CONCLUSIONS

The Cyprus Flight Campaign, conducted by the ERATOSTHENES Centre of Excellence and DLR (CERAD) as part of the EXCELSIOR H2020 Widespread Teaming Phase 2 project, successfully integrated high-resolution hyperspectral and stereo imaging with ground-truth measurements across Cyprus. This effort aimed to enhance hyperspectral analysis, 3D mapping, and capacity building for ERATOSTHENES Centre of Excellence staff. Key focus areas included agricultural sites, urban environments, archaeological sites, burned areas, dams, sea regions, and forests. The efficiency of airborne hyperspectral imaging in capturing detailed environmental data has been demonstrated. This method highlights the vital role of ground truth measurements in verifying airborne data and enriching the overall environmental dataset. Advanced environmental monitoring is made possible by combining hyperspectral imaging and ground truth measurements, which greatly aids in well-informed decision-making and sustainable development initiatives. The accomplishment of obtaining hyperspectral aerial photos in multiple regions of Cyprus demonstrates the efficacy of employing state-of-the-art technology for environmental evaluation. In order to ensure that the knowledge acquired contributes to ongoing and future actions aimed at protecting and enriching the natural environment, the campaign's outcomes will continue to inform future research endeavors and environmental management plans.

The Cyprus Flight Campaign effectively demonstrated the power of integrating hyperspectral imaging with ground-truth measurements for advanced environmental monitoring and analysis. This approach enhances data accuracy, supports diverse applications, and contributes to sustainable development efforts. The insights gained from this campaign will drive future research and applications, advancing the field of remote sensing and its impact on environmental management and preservation. This study provides a comprehensive description of the field measurements during the CERAD campaign. Our future steps involve detailed analyses of these datasets (both field measurement and the airborne hyperspectral images) for various applications including the calibration and validation of satellite products, environmental monitoring, vegetation analysis, and disaster risk assessment.

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