Airborne Remote Sensing for Environmental and Disaster Management Applications

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Abstract

As a national research institution, the German Aerospace Center (DLR) has the largest fleet of research aircraft in Europe and uses optical imaging systems to provide a valuable research basis for a wide range of applications in the fields of environment and climate, as well as global disaster management. Airborne remote sensing provides an independent database and is essential for developing and validating methods for satellite-based systems. This article gives a brief insight into the current research topics of DLR’s Earth Observation Center (EOC) with a focus on airborne remote sensing with regard to methane source analysis, water remote sensing, forestry, urban energy management and current disaster management missions, and shows how airborne remote sensing can contribute to the understanding and management of climate change.

1. Introduction

Optical remote sensing has become an essential part of research on climate change and it’s effects on the environment (Zhao et al., 2023). While satellite imagery can provide a continuous daily global picture of our planet with a wide range of products, airborne imaging systems can usefully complement this in several key areas because they:

- can be deployed locally and regionally at short notice and with great flexibility,
- enable measurements below the cloud cover,
- achieve higher spatial resolutions,
- enable continuous observation of the same area over several hours,
- often include the option of direct data transmission to the user and
- carry instruments that can be regularly calibrated in the laboratory.

These characteristics make them an ideal tool for collecting observations when satellite observations are not available (e.g. weather or pre-launch), when images need to be available immediately (e.g. in the event of a disaster), or for calibrating and validating satellite measurements. Compared to most of the commercially available drones or ground-based measurements, manned airborne platforms generally offer a larger operational radius and significantly greater ground coverage. They remain an indispensable tool for many applications, including monitoring the effects of climate change.
In the following chapters, we report on some of the earth observation missions in which DLR’s research aircraft have been deployed in order to provide data for a wide range range of scientific research topics. The paper is organized as follows. Section 2 introduces DLR’s research aircraft fleet and the imaging sensors used for further analyses. In section 3, environmental and disaster management applications based on the acquired data are explained. These include analyzing methane emissions, forestry applications, water remote sensing, urban development and disaster management. Section 4 summarizes the missions and their value for current research activities.

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2. Research Aircraft Fleet and Imaging Sensors

2.1 Europe’s Largest Research Aircraft Fleet

The facility for flight experiments of the German Aerospace Center (DLR) operates the largest civilian fleet of research aircraft and helicopters in Europe. The highly modified aircraft stationed at the facility sites in Braunschweig and Oberpfaffenhofen are used as subjects for aeronautical research as well as platforms for different research areas. Depending on the modifications of the aircraft, these can be used for earth observation with optical sensors or radar, atmospheric research, among other fields of study. Both, the research aircraft Cessna 208 Grand Caravan (D-FDLR) (see Figure 1) and Dornier 228 (D-CCFU) stationed in Oberpfaffenhofen are modified with two covered large openings in the bottom of fuselage, which enable the scientific teams to perform flight campaigns with earth observations sensors described below. The helicopters BO 105 (D-HDDP) and Airbus Helicopter EC 135 (D-HFHS) stationed in Braunschweig can be equipped with a sensor pod (see Figure Figure 2) for flight campaigns that make use of the helicopters flight characteristics.

2.2 HySpex Hyperspectral Sensor

DLR has been at the forefront of airborne imaging spectroscopy for more than 30 years. Currently, this tradition is carried forward with a state-of-the-art sensor combination consist-

Figure 1. Fuselage modification of DLR’s research aircraft D-FDLR.

Figure 2. VABENE camera system mounted on DLR’s research helicopter D-HFHS.

ing of two HySpex Norsk Elektro Optikk (2020) spectrometers, a VNIR-3000N and a SWIR-384. Together these instruments cover the visible and near infrared (VNIR) as well as the short-wavelength infrared (SWIR) spectral domains (420 nm – 2500 nm) with a spectral resolution of 3.5 nm to 7 nm and a typical spatial resolution of 0.25 m – 1 m (depending on flight altitude). To guarantee a consistent and traceable data quality that meets the standards of even the most challenging applications, both spectrometers are regularly calibrated at a dedicated facility maintained at EOC, the so-called Calibration Home-Base (Gege et al., 2009).

2.3 3K Camera System

The 3K camera system is an aerial camera system that was built and approved for scientific research in the field of disaster management and traffic monitoring and in particular for developing real-time applications on board DLR’s research aircraft (Rosenbaum et al., 2008). Equipped with three commercially available Canon EOS 1Ds Mark II cameras, an inertial measurement system for high-precision positioning, a computer unit for direct data processing and a data link for direct transmission of images and evaluations, this system has been in successful use for many years.

2.4 VABENE System

Similar to the 3K camera system, the VABENE system was originally developed in the field of traffic research and was already designed for real-time applications using helicopters (Kurz et al., 2014). It has two CANON EOS 1D-X Mk II cameras, which are suitable for large-scale mapping with their field of view of up to 60°. In addition, a professional PhaseOne aerial camera with 150 Mpix ensures detailed images of the highest quality. Three high-performance computers ensure immediate further processing, georeferencing the images in real time and enabling further deep learning-based analyses on board. To save additional time, for example during crisis mapping, the system has an LTE connection that transmits aerial images and derived information to the ground, where the data can be further processed or integrated into geoinformation systems as a web service via an implemented interface.

3. Environmental and Disaster Management Applications

The following describes applications based on the data recorded by the measurement systems described above.

3.1 Methane Emissions

The detection and quantification of methane (CH_4) sources has become a major research topic in the last decade in the context of climate change mitigation, since reducing (anthropogenic) CH_4 emissions could help limit global warming on comparatively short timescales of 10-20 years. The detection of localized sources (e.g. coal mine ventilation shafts or landfills), however, requires remote sensing instruments featuring a fine geometric resolution in combination with an at least decent spectral resolution. State-of-the-art hyperspectral instruments have been demonstrated to meet these criteria and many studies (Thompson et al., 2015, 2016; Thorpe et al., 2013, 2014; Foote et al., 2020) have examined various airborne and spaceborne spectrometers regarding their respective suitability for the detection and quantification of methane emissions, mostly using two SWIR CH_4 absorption bands centered at $1.6\mu m$ and $2.3\mu m$. However, many challenges remain as hyperspectral imagers are not optimal suited for measuring atmospheric composition. Their comparatively low spectral resolution makes it difficult to clearly distinguish CH_4 signals from low frequency variations in surface reflectance. In addition, overlapping absorption bands of other atmospheric gases (mostly water vapour) are difficult to disentangle from CH_4 spectral signatures at the typical spectral resolution available. Given these challenges, it is essential to develop enhanced retrieval techniques in order to achieve more reliable results. Since 2018 DLR collected several HySpex datasets over various CH_4 sources in order to foster this research. Hochstaffl et al. (2023) used these datasets and applied a covariance-weighted Generalized Least Squares (GLS) retrieval. The method utilizes both CH_4 absorption bands (1.6 μm and 2.3 μm) and its setup enables an unconstrained nonlinear least squares fit. By accounting for correlated errors and background variability in the spectrum, the retrieval significantly improves the accuracy of the inferred methane, especially in complex environments, delivering robust methane concentration estimates with minimal bias from surface albedo effects.

Figure 3 shows an example of a methane plume retrieved from HySpex observations using the GLS fit. Combining methane concentration data with wind information allows emission rates to be calculated. Table 1 presents the emission rate estimates based on the cross-sectional flux method (Jacob et al., 2022, Sec. 4.2). Given the wind information from collocated ground measurements on June 7th (Luther et al., 2022, Sec. 4.2) an instantaneous emission rate of approximately 17.8 kt/yr for a mean wind speed of 5 m/s is inferred. This is well within the nominal rate expected for this site, but the analysis shows that

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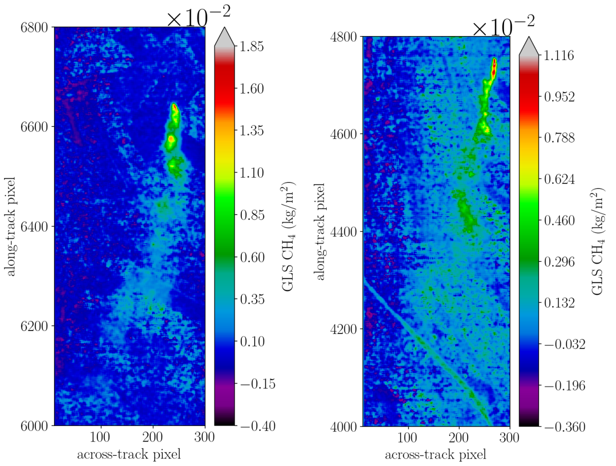


Figure 3. Methane mass enhancements above the Pniówek V coal mine ventilation shaft in the Upper Silesian Coal Basin in southern Poland on June 7th. The HySpex data was acquired at flight altitudes of 1300 m AGL (left) and 2900 m AGL (right). Enhancements are based on concentrations presented in Hochstaffl et al. (2023).

uncertainties in the prevailing wind dominate the error in the emission estimates. A root mean square error of $\Delta v_\perp = \pm 1.7$ m/s, for example, introduces a significant emission rate error of approximately ± 6 kt/year. In the future, alternative methods for estimating source emissions, particularly those that are less dependent on incomplete wind observations, will be explored (Jongaramrungruang et al., 2022) and work will continue to improve retrieval techniques.

Table 1. Source rate estimates for various wind speeds given the concentrations from Fig. 3. The first column represents the orthogonal wind speed, the second and third columns represent emissions for the 1300 m AGL and 2900 m AGL overpass, respectively. The final column shows the average emission estimate for both scenes, scaled to kilotons per year. Note that the nominal (reported) annual emission for this site is 20.6 kt/yr (personal communication CoMet team).

$v_\perp$ (m/s)	$\mathbf{Q}_{1300}$ (kg/h)	$\mathbf{Q}_{2900}$ (kg/h)	$\mathbf{Q}$ (kt/yr)
3	1250	1235	10.5
4	1660	1650	14.3
5	2082	2060	17.8
6	2500	2470	21.5
7	2920	2880	25.0

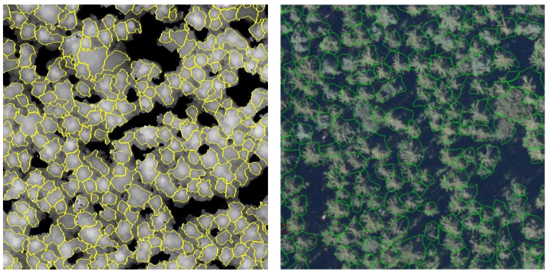
Other ongoing research exploits the comprehensive calibration of the DLR HySpex system to investigate the impact of various sensor characteristics and advanced calibration methods (e.g. Baumgartner and Köhler, 2020) on the retrieved trace gas concentrations per pixel. The ability to acquire coincident high resolution RGB data with the 3K Camera System provides an additional opportunity to characterize the emitting facilities better than with hyperspectral imagery alone. High resolution data can also be used to better estimate the effect of albedo inhomogeneity on the retrieved trace gas concentrations. These measurements provide important insight into the design and calibration of upcoming satellite missions such as CO2Image (Feist et al., 2023).

3.2 Forestry Applications

Increasing temperatures and decreasing precipitation during the growing season are putting a lot of pressure on forests in many places. The trees' natural defenses are weakened, pest infestations increase and additional forest fires endanger entire stands. Until 2020, airborne platforms were the most commonly used source of input for Earth observation (EO)-based forest studies in Germany (Holzwarth et al., 2020). However, in recent years, the number of studies relying on satellite data has significantly surpassed those using aircraft data in the context of EO-based forest monitoring. Despite this shift, airborne data still plays a crucial role, especially for observing forests at the stand and tree level (Holzwarth et al., 2023). This section deals with potential applications of HySpex data as well as data from the 3K camera system.

3.2.1 HySpex in action for forest ecosystems Airborne hyperspectral data remains one of the preferred data sources for characterizing plant functional traits (Asner et al., 2017). Its high spectral and spatial resolution facilitates the measurement of variables such as chlorophyll and nitrogen concentration, as well as leaf water content (Buddenbaum and Hill, 2020). Additionally, detailed spectral information from hyperspectral sensors is useful for assessing forest health (Lausch et al., 2016) and supports tree species classification through imaging spectroscopy (Fassnacht et al., 2016). The latter two types of airborne hyperspectral data analysis have been studied at DLR using the HySpex system. Data over the Bohemian Forest is regularly collected using DLR's HySpex system as part of the ”Data Pool Initiative for the Bohemian Forest Ecosystem”. This initiative is a collaboration between the Bavarian Forest National Park, Šumava National Park, and various European research organizations and universities. Its primary goals are to provide extensive remote sensing datasets, offer a testing ground for new sensor technologies, serve as a laboratory for Essential Biodiversity Variables (EBV), promote collaborative research, and generate information for national park management (Latifi et al., 2021). HySpex data acquisitions have been conducted since 2013, spanning seven different years until 2024, with varying spatial resolutions and coverage. Several studies on tree species classification using HySpex data have been conducted at DLR as part of the Data Pool Initiative (e.g. Sommer et al. (2015), Fetik (2017), Shi et al. (2018), Shi et al. (2021)). These studies explored various approaches, both methodologically (different classification techniques) and in terms of content (different levels of complexity considering the number of tree species and corresponding features). Additionally, the potential benefits of combining hyperspectral data with and without LiDAR data were analyzed in detail to assess improvements in classification accuracy. The various findings from these studies will be used to further develop large-scale mapping with satellite data (e.g. EnMAP data). Another extensive HySpex campaign was conducted as part of the VitTree project (”VitTree: Automated assessment of forest tree vitality using up-to-date optical satellite data with enhanced spectral and spatial resolution” funded by the Bavarian State Ministry of Food, Agriculture and Forestry) which involved artificially weakening spruce trees by ring barking to simulate a bark beetle infestation. The goal was to monitor the trees' responses to the ring barking through both field observations and various remote sensing techniques. HySpex data acquisitions were carried out at eleven different times during the year of the artificial stress. After analyzing the data, it became evident that changes in the weakened trees were detectable earlier in the HySpex data than in the field observations (see Einzmann et al. (2021), Immitzer et al. (2018)).

3.2.2 3K camera data for individual tree crown segmentation The project ‘Application of remote sensing for the early detection of drought stress at vulnerable forest sites (ForDroughtDet)’ is funded by the German Federal Agency of Agriculture and Food and aims to detect drought stress in an early phase using remote sensing techniques (Tian et al., 2020). Within this project, two flight campaigns were carried out in 2016 and 2018, respectively. The selected three test regions are the Kranzberg forest, as well as one region in Gramschatzer forest and the forest near Traunstein. One of the main aims of the project is to extract individual tree crowns (ITC) to analyse drought stress at tree level. An ITC delineations approach is proposed and tested on the Digital Surface Models (DSMs) generated from 3K aerial imagery. The whole process begins with global thresholding of the DSM, followed by local histogram equalisation (LHE) in areas above the threshold to improve contrast. Gaussian smoothing is then applied to the LHE-DSM to reduce noise(Gonzalez, 2009). After detection the tree locations with the combined use of active contours and Laplacian of Gaussian, a Marker-controlled watershed transform is applied to generate the final ITC boundaries (Kempf et al., 2021). The approach has been applied to the whole forest. One example is shown in Figure 4 (Tian et al., 2020).



(a) (b)

Figure 4. An example of the extracted ITC boundaries from 3K data overlaid on the DSM (a) and original image (b).

3.3 Water Remote Sensing

Another example of the use of airborne sensor technology to prepare and support satellite missions comes from the field of water remote sensing. Prior to the EnMAP satellite mission, HySpex data was used to develop algorithms for the analysis and observation of shallow water areas. In many places, underwater vegetation also suffers from rising (water) temperatures. Seagrass, for example, as an important CO_2 reservoir, is negatively affected by rising sea temperatures and changes in salinity. The potential for determining bathymetry and classifying bottom types was analyzed using field and aerial image data obtained during a campaign in the Baltic Sea in 2016. It was shown that the water depth can be determined from hyperspectral data with an uncertainty of 20 % for substrates with an albedo >5 %, with the visual depth representing the detection limit. Furthermore, it was shown that only two substrate classes can be reliably distinguished in the Baltic Sea. While sand can be identified and its relative proportion per pixel quantified, the other class (predominantly seagrass, mussels) can be recognized and the brightness quantified, but not yet clearly identified. Further research is needed to obtain more precise results in this area. Figure 5 shows an example of benthic classification.

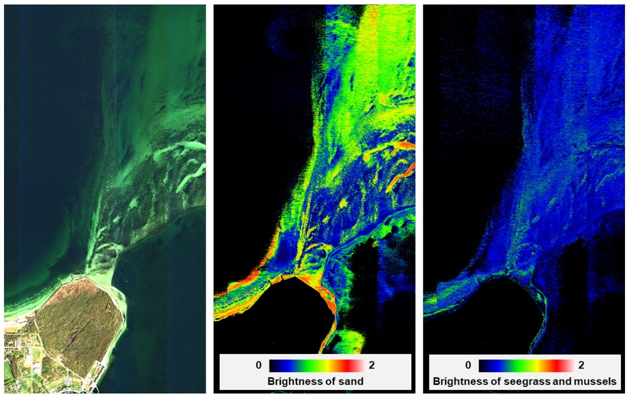


Figure 5. Left: composite of HySpex flight strips at the Baltic Sea near Boltenhagen. Center and right: bottom type classification based on inversion of a physical model.

3.4 Urban Development

Nowadays, urban digital twins are often used to study, simulate and visualize urban and spatial planning issues. These digital twins typically include a highly accurate DSM of the study area, such as those created from 3K data of the cities of Paphos and Limassol during a measurement campaign in Cyprus in 2023 (Mettas et al., 2024). Using a DSMs together with additional information, such as local measurements, the heat distribution of a city can be simulated and the development of heat islands as an observed effect of global warming can be studied. The increased energy demand in this case plays an important role in the urban energy supply. Detailed classifications of the urban area based on airborne remote sensing data also provide comprehensive information on, for example, photovoltaic systems, which in turn influence the local energy supply (Roy et al., 2024).

3.5 Disaster Management Support

Natural disasters such as forest fires, floods and storms cost many lives every year and cause enormous damage. Climate change is also cited as a possible cause in this area. The added value of remote sensing data for disaster management has long been recognized and data and products from remote sensing sensors are now an integral part of operational processes and services such as the cooperation of The International Charter Space and Major Disasters (Disastercharter, 2024) or the Copernicus Emergency Management Service (Directorate Space, Security and Migration, European Commission Joint Research Centre (EC JRC), 2024). These services primarily use satellite data, which can be used to map large areas in short time. The disadvantages, however, are that the images (from optical sensors) are dependent on good weather conditions and provide ground resolutions that may not be suitable for detailed analyses. For this reason, drones are increasingly being used in operational disaster management on site, with which high-resolution data can be recorded and made available directly. Limiting factors here are the range of the drone and its radio link, as well as the strict regulation of the operation of drones in Germany, for example, which makes recording for research purposes and the development of disaster management applications more difficult. Aircraft- or helicopter-based sensors such as the systems already mentioned close the gap between large-scale satellite images and comparatively small-scale drone data. The systems, in particular the VABENE system, can be used flexibly and, thanks to the high-quality inertial measurement unit, the processing unit and the data link on board, provide high-quality aerial images that can be displayed and further analyzed immediately on site.

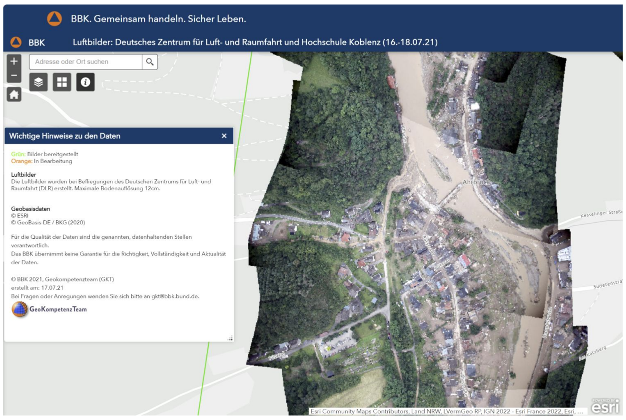


Figure 6. Aerial images of the VABENE system of the flood along the river Ahr in 2021 published via webservice directly after image acquisition (© BBK 2021, Geokompetenzteam GKT).

This is a decisive advantage when it comes to quickly assessing the extent of the damage and coordinating rescue teams and relief supplies. The aerial image systems have already been deployed during several German and European disaster control exercises, such as a firefighting exercise in Spain (Strobl et al., 2016) or the European disaster management exercise IRONORE 2019 (Merkle et al., 2020) and provided up-to-date situation information as well as 3D models derived directly from the data in order to analyze acute slope movements. Aerial images were also recorded during the flood events in Germany 2013, 2021 and 2024 and made available to local authorities and rescue services in the form of maps or as webservices as shown in Figure 6 (Wieland et al., 2022).

During the German national disaster management exercise EUROMED in Hamburg 2024 (BBK, 2024) the VABENE system provided live aerial images of the exercise and the approaching exercise vehicles to the coordination team. The transmission and visualization of the georeferenced aerial images was followed by automated image analysis using modern deep learning methods on site and results were presented within minutes after image acquisition. The analyzed products included masks of road networks and buildings as an indication of the usability of the current infrastructure, as well as for detailed analyses of possible building damage after a disaster (see Figure 7).

However, high-quality and high-resolution aerial images are not only of enormous added value during the response phase after a damage event. Derived 3D models provide information on changes to the terrain, which can indicate slope movements or changes to dykes, for example.

3.6 Calibration and Validation Activities

For spaceborne optical missions, airborne remote sensing plays a significant role during multiple phases of the development. Airborne campaigns are often conducted at the beginning of missions to optimize instrument and processing chain designs and to provide simulated data sets to researchers for application development. In the case of imaging spectrometers, this was -and still is- the case for the German EnMAP mission, and the

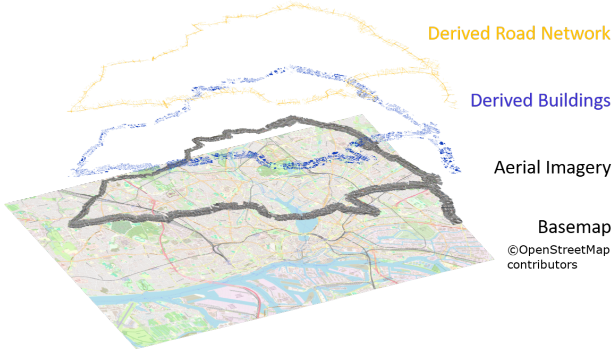


Figure 7. Data provided during the German national exercise EUROMED in Hamburg 2024: Aerial imagery of the VABENE System, buildings (blue) and road network (organge) derived from aerial imagery above a basemap of OpenStreepMap © OpenStreetMap contributors.

ESA FLEX, CHIME and TRUTHS missions (e.g., Taramelli et al. (2020)). Next, after the launch of the spaceborne missions, airborne sensors play a critical role in the calibration and validation (Cal/Val) activities, ensuring the proper functioning and calibration of the spaceborne instrument by vicarious means (see e.g. Storch et al. (2023), Chander et al. (2013), Bachmann et al. (2011)). The advantages of using airborne sensors for this task are manifold: first, the sensors can be characterized before and after the data acquisitions in the lab, ensuring a proper calibration. Secondly, the signal levels detected by airborne sensors are also higher, allowing for a higher signal-to-noise ratio (SNR) and finer spectral resolution. Next, also the spatial resolution is usually finer by a magnitude, allowing for the detailed modeling of the larger footprints of spaceborne instruments. And compared to non-imaging field spectrometers, airborne sensors allow for the characterization of a way larger areas on ground, as highlighted by the spatial details in Fig. 8.

Using these airborne datasets superior in SNR, spectral and spatial resolution, the spatial, spectral and radiometric properties of the spaceborne sensors can be assessed when having underflights over the same areas, and when using radiative transfer codes to simulate or compensate for atmospheric absorption and scattering processes. Examples for such campaigns range from ”extreme” test sites like dry salt lakes with homogeneously and brightly reflecting properties (see Fig. 8 for the CEOS Tuz Gölü 2009 precursor experiment, Bachmann et al. (2011)) to typical environments like the ”Panzerwiese” meadow close to Munich, Germany (Pflug et al. (2023)).

In both cases, the airborne hyperspectral data allows for a detailed assessment of the surface reflectance and spectral variability and thus provides a valuable baseline to check the L2A Bottom-Of-Atmosphere (BOA) reflectance products from spaceborne missions. In the experiment depicted in Fig. 9, the level of agreement between both sensors is within the natural site variability and uncertainties up to ˜1300 nm, with an increasing mismatch towards longer wavelengths. Based on these datasets, now the analysis of influencing factors like view and solar angular dependencies (BRDF), estimation of atmospheric composition (water vapor and aerosols), and checks of the radiometric sensor calibration can be conducted.

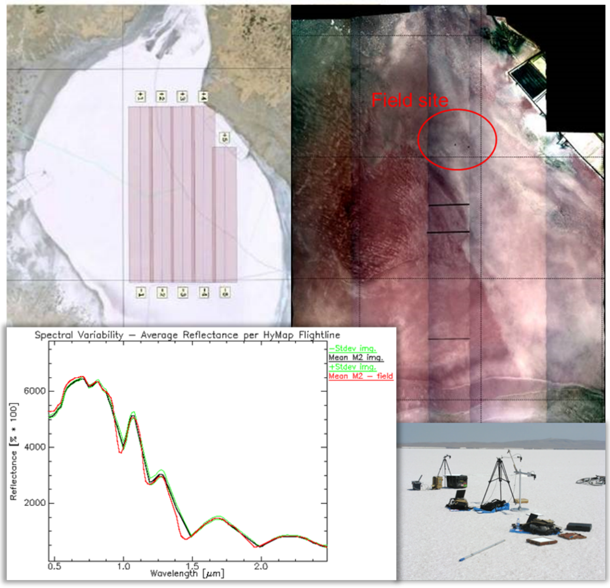


Figure 8. Clockwise from top-left: flight planning for the CEOS Tuz Gölü 2009 Campaign (top-left); airborne HyMap hyperspectral data (true color composite, non-linear image stretch); field spectrometers on site; reflectance spectra from HyMap in comparison with in-situ data.

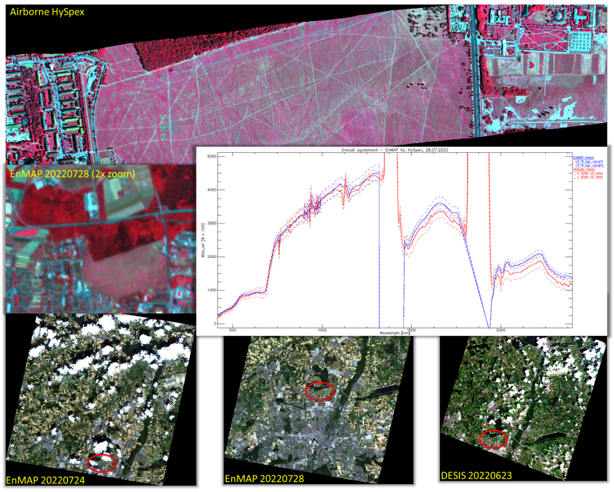


Figure 9. Top: CIR composite of airborne HySpex data over Panzerwiese, Munich; bottom row: true-color composite of corresponding EnMAP and DESIS datasets; center-left: zoom of EnMAP CIR over Panzerwiese; center-right: comparison of EnMAP (blue) and HySpex (red) BOA reflectance

4. Conclusion

This article emphasizes the significance of research based on airborne remote sensing and how it can contribute to understanding and addressing the impacts on climate change and the effects on our environment. Airborne remote sensing is a valuable tool for investigating and monitoring various aspects of climate change, such as the condition of forests, the presence of sea grass, and the evolution of methane sources. It can also provide important information for urban planning, including analyzing heat islands and energy resources to protect residents' health. In the event of natural disasters, airborne situation information can support rescue teams and aid in further analysis. Last but not least, climate-relevant information must be considered globally, for which satellite data is one of the suitable sources of information. And here too, method development and validation are often based on airborne remote sensing. These applications provide a glimpse of the diverse research opportunities currently being pursued using data from the 3K and VABENE camera systems and the HySpex hyperspectral imaging system, and demonstrate that airborne remote sensing can make a valuable contribution to climate research of the future.

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