NBSOIL
Nature-Based Solutions for Soil Management

Figure 1.

Soil Sensing Handbook – initial version

Deliverable [4.1]

31.05.2024

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[1] **R**=Document, report; **DEM**=Demonstrator, pilot, prototype; **DEC**=website, patent fillings, videos, etc.; **OTHER**=other
[2] **PU**=Public, **CO**=Confidential, only for members of the consortium (including the Commission Services), **CI**=Classified

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List of acronyms

MS - Milestone
WP – Work Package
M – Month
D – Deliverable
EO – expected outcome
IP – Impact Pathway
SSH – Soil Sensing Handbook
NBS – Nature Base Solution
UAV – Unmanned Aerial Vehicle

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1 Executive Summary

The present report, Deliverable 4.1 'Soil Sensing Handbook - initial version', contains the first version of the NBSOIL project Soil Sensing Handbook (SSH). SSH contains the first outlines of the material compiled for Module 3 – 'Digital tools for soil health monitoring' of the advanced modules of the Soil Academy. The first update of the SSH will be published in M36 with D4.2 'Soil Sensing Handbook - intermediate version'. The final version will be published in M48 (D4.3 'Soil Sensing Handbook - final version'). The final version will be transformed into the commercial publication formats of the SSH, both e-book and paper editions, including a short version.

The SSH aims to contribute to the accessibility and understanding of Soil Advisors in the use of digital tools and sensing technology to assess, model and map soil health in agriculture, forestry, urban planning and the restoration of industrial sites and former mining operations, based on the Soil Health Mission indicators and the implementation of the Nature Base Solutions (NBS) strategies.

The SSH is being developed by the NBSOIL project experts on the application of sensing technology and digital tools in different environments (WP4) in co-creation with the Academy (WP3 - task 3.3) and the project consortium experts on soil health indicators and NBS strategies (WP1 and WP2). To this end, monthly discussions are being held within WP4 from M1 to M24, and with the other WPs to adapt the content and form of the SSH to the project objectives as the project progresses.

The present Deliverable 4.1 is structured into: *Section 1 Introduction* contains a presentation of the D4.1 framework within the NBSOIL project and the related tasks; *Section 2 Methodology* contains a presentation of the methodology defined by the WP4 partners for the creation of the SSH in co-creation with WP3; and *Section 3 Soil Sensing Handbook* contains the initial Table of Contents, the learning material and the exercises proposed by the WP4 partners for the Module 3 of the advanced modules of the Academy. In this version, the compiled material proposed by the WP4 partners to be included in the final version of the commercial publication has been included in the annexes.

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2 Introduction

The present report, Deliverable 4.1 “Soil Sensing Handbook – initial version”, contains the first version of the NBSOIL project's Soil Sensing Handbook (SSH).

Role of Soil Sensing Handbook in NBSOIL project. SSH is foreseen in NBSOIL project with the aim to gather useful information for existing and aspiring Soil Advisors on the use of available technologies for land and soil monitoring for soil health assessment. For that, it is designed to assist Soil Advisors in using technology to assess, model and map soil health in agriculture, forestry, urban planning and the restoration of industrial sites and former mining operations, based on the Soil Health Mission indicators and the implementation of Nature Base Solutions (NSB) strategies.

Soil Advisors will educated on how to integrate and mapping multiple data sources to assess and monitor Soil Health in an easy and inclusive way including:

- Copernicus satellite data, more concretely Sentinel 2A and 2B images (Task 4.1 “Remote sensing – Sat. images COPERNICUS”).
- Hyperspectral and multispectral cameras from UAV vehicles (Task 4.2 “UAV images”).
- Data measured in-situ or from closed devices or stations, recommending the sensors and stations most adequate for each context (soil type, climate, challenges, land management objectives) (Task 4.3 “Soil sensors”, Task 4.5 “Citizen science – leveraging smartphone use for soil health monitoring”).
- The sensors and instrumentation normally used in the field to obtain data on different variables, both soil and atmospheric, must be designed to be robust, provide quality data and be affordable.

The SSH is being developed by the experts of the WP4 consortium on digital tools and sensing techniques of the NBSOIL project. The contents of the handbook will be used as the basics for the development of the Module 3 – ‘Digital tools for soil health monitoring’ of the advanced modules of the Academy. The co-creation process is one of the fundamental principles of NBS project; therefore, the development is being carried out in co-creation with the Academy (WP3), the experts of the project consortium on soil health indicators and NBS strategies (WP1 and WP2) and the contribution of external experts (Task 3.3). Their contribution will be included in the updates foreseen during the project, i.e., D4.2 "Soil Screening Manual - Provisional Version" in M36 and D4.3 "Soil Screening Manual - Final Version" in M48.

The SSH directly contributes to the achievement of the main objectives of NBSOIL: development of a blended learning program to train Soil Advisors in soil health from a holistic point of view, aligned with agroecology through Nature Based Solutions (NBS), fully in line with the IUCN Global Standard for NBS (IUCN, 2020). This is contributing to the Impact Pathways (IP) building on previous research results and available Open-Source technology (Impact Pathway 1 (IP1), making soil monitoring and mapping tech user-friendly and inclusive (IP3) and embedding soil care across all land management and land related decision-making processes (IP4).

It is also expected to contribute to the achievement of the following expected outcomes: (EO1) Advisory services are strengthened in their knowledge and skill base to provide impartial advice on soils and their sustainable management based on a thorough understanding of soil functions and ecosystems services supported by soils across land uses and climate zones throughout Europe; (EO2) Testing of new forms of advice and established, making more effective use of digitalization and new models for advisor-former-data interactions, land managers (including owners leasing their land) and other practitioners in rural and urban

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areas (e.g. farmers, foresters, local authorities in change of managing green spaces and natural areas) have increased opportunities for access to tailored practice-oriented knowledge and for exchange of experiences on how to manage land and soils in more sustainable ways; and (EO5) Local/regional authorities are in a position to integrate considerations on soil health (e.g. reuse of soils, reduction of soil sealing, management and increase of green spaces in urban areas) into spatial planning and decision-making.

Challenge on Soil Sensing Handbook (SSH) development. The advanced modules have been conceptualised by the Academy in three levels of increasing knowledge and complexity.

The main challenge identified by the WP4 consortium during the development of the first version of the SSH for Module 3 is to aspire to and promote the use of the technology and sensing techniques to the full range of Soil Advisors covered by the project. Soil Advisors considered in the NBS project ranged from land managers, researchers, soil assessors, community organisers, entrepreneurs, technology developers, local authorities and policy makers in a variety of settings (agriculture, forestry, urban planning and the restoration of industrial sites and former mining operations), with a wide range of backgrounds and levels of experience in relation to the use of technology and sensing techniques. Similarly, the usefulness of sensing techniques may vary depending on the setting and, therefore, the partial interest in the learning programme of the Module 3. For instance, in the agricultural context, a Soil Advisor such as a farmer (interested in crop monitoring), is usually not so much concerned with the detail of the spatial resolution as with the frequency of the information. Or, in the urban or mining context, high spatial resolution imagery is often important. Thus, selecting the key information in a simple but balanced language, without trivialising the concepts or over-technicalising the concepts, is the main challenge in approaching the development of the SSH and adapting it the learning material to each level of the Module 3.

Document structure. The present Deliverable 4.1 is structured into: *Section 1 Introduction* contains the presentation of the D4.1 framework within the NBSOIL project and the related tasks; *Section 2 Methodology* contains the presentation of the methodology defined by the WP4 partners for the creation of the SSH in co-creation with WP3; and *Section 3 Soil Sensing Handbook* contains the initial Table of Contents, the learning material and the exercises proposed by the WP4 partners for the Module 3 of the advanced modules of the Academy. In this version, the compiled material proposed by the WP4 partners to be included in the final version of the commercial publication has been included as Annexes.

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3 Materials and methods

This section contains the presentation of (1) the Module 3 - advanced module conceptualization, (2) the definition of profiles of Soil Advisors to assess on the use of technology and sensing techniques for their settings, and (3) the Soil Sensing Handbook development.

3.1 Module 3 - Advanced module

The Module 3 advanced modules have been conceptualised by the Academy (WP3) in three levels of increasing knowledge and complexity:

- **Module 3 – Level 1**, is the one which require less effort, participants take the essential questions. Duration of the module: approx. 15 hours.
- **Module 3 – Level 2**, requires the completion of another 4-6 specific exercises. Duration of the module: approx. 15 hours.
- **Module 3 – Level 3**, is for participants taking the Module Challenge which involves research directly linked to NBSOIL and the Soil Mission main questions. Duration of the module: approx. 30 hours.

3.2 Profiles of Soil Advisors

Target professional profiles: land managers, researchers, soil assessors, community organisers, entrepreneurs, technology developers, local authorities and policy makers.

Threats and NBS addressed in the different settings: agriculture, forestry, urban planning and the restoration of industrial sites and former mining operations, addressed in the NBSOIL project.

3.3 Soil Sensing Handbook development

The development of the Soil Sensing Handbook (SSH) in a co-creation process has been made following the next steps which are presented in Figure 1:

(1). Definition of the technical profile of the target audience for every level. This step was done through discussions both among WP4 members and with the rest of the NBSOIL project partners in live discussion and in an iterative way.

(2). List of key concepts and challenges for the professional profiles defined above that they need to be aware of when using technology or sensing techniques for each level. This step was done through discussions among WP4 members in live discussions and in an iterative way.

(3). Collection of the learning material according to the technical profiles and key concepts previously identified for each level. This phase was carried out first individually by each partner expert in a sensing technique (satellite data, hyperspectral and multispectral cameras from UAV vehicles, ground sensors and data measured in-situ). Then it was shared with all WP4 partners to be discussed.

(4). Integration of learning material collected to identify commonalities and singularities between devices. Then it was shared with all WP4 partners to be discussed.

(5). Design practical exercises by all WP4 partners.

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(6). Review to harmonise the nomenclature and, subsequently, is integrated into the different formats in which it will be made public.

Figure 1. Main steps for the development of the Soil Sensing Handbook**.**

4 Soil Sensing handbook

4.1 Key concepts and challenges

In this section, a draft of the Table of Contents of the SSH's is proposed as starting point for the preparation of the content of every chapter. The Table of Contents is created based on creating a flexible and inclusive handbook for multidisciplinary Soil Advisors with different backgrounds and levels of experience in the use of technology for Soil Health assessment.

Sensing techniques are integral to precision agriculture, enabling precise monitoring of soil conditions and facilitating targeted interventions to enhance crop yield and resource efficiency. Also, these techniques allow to monitor and control fields in different aspects. This kind of monitoring provides data for immediate responses to changing soil conditions, thereby preventing crop stress, disease, and nutrient deficiencies before they become severe. Also, many properties can be monitored with the use of sensors, such as pH levels, soil moisture and many others. Utilizing sensors can promote sustainable farming practices by potential reduction of the use of water, fertilizers, and pesticides, subsequently protecting the environment with the same or better yield. Moreover, sensors provide quantitative data that supports decision-making processes, shifting from subjective to evidence-based management practices.

Understanding the basic concepts of sensing techniques is crucial. The main techniques in agricultural sensing include proximal sensing, ground sensors, and remote sensing. Proximal sensing involves measurements taken close to the subject, such as soil probes and handheld devices. Ground sensors are stationary and typically installed in fields to continuously monitor specific parameters like soil moisture. Remote sensing involves collecting data from a distance, often using satellites or drones.

Selecting the best type of data and sensors inherently involves defining the specific needs of the agricultural operation, considering environmental factors, ensuring accuracy and reliability, integrating with existing systems, and evaluating cost-effectiveness.

Interpreting sensor data involves education on the sensors specification, accuracy and limitations. Ready-to-use products that offer pre-processed data and actionable insights can simplify data interpretation. Data fusion with other sources, such as weather forecasts and historical data, helps validate and contextualize readings.

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Empowering Soil Advisors with knowledge about sensing techniques and data interpretation is a significant step into better understanding of soil properties of specific area. By understanding the types of sensors, their capabilities, and how to select and use them effectively, advisors can make informed decisions that enhance productivity, sustainability, and profitability in agricultural practices.

Table 2 presents the main proposed question/challenges around which the chapters of the Soil Sensing Handbook have been defined and organised and the level at which they will be addressed in Module 3 of the Advanced Modules. The main points to be addressed to solve the question/challenges with is sensor are also listed.

Table 1. Main questions and chapters for the development of the Soil Sensing Handbook

Question/Challenges	**Level**	**Chapter**	**Concepts**			
			Satellite	**UAV**	**Ground sensors**	**External data bases**
Which devices provide you with the best information for your purpose (indicator, temporal and spatial resolution)? Meaning of sensing, methods and methods comparison.	1	1.Generalities	Sensing principals.			
	1	2.Sources of data (devices selection)	Data provided by satellites & satellites.	Data provided by vehicles, cameras & UAVs.	Data provided by ground sensors & ground sensors.	Data provided by external data bases & data bases. WP1
Once the device is chosen, which sensors are the best for your purpose?	1	3.Sensor's selection	Sensors mounted on the devices and characteristics.			
Help for adequate sensing.	2	4.Data acquisition (planning, and data acquisition).	Data acquisition.	Flight planning and data acquisition.	Sensor installation and data acquisition. Maintenance.	Data access.
Help to obtain quality data.	2,3	5.Data post-acquisition processing	[Under discussion]			
How to interpret data	1,2,3	6. Data analysis	[Under discussion]			
Examples.		7.Examples	Practical exercises.			

4.2 Module 3 – Level1

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4.2.1 Generalities and objectives

The Module 3 – Level 1, is designed with the following objectives:

To make Soil Advisors conscious users of the type of data provided by sensors. Why use sensing techniques?

- Provide basic concepts regarding sensing or external devices for good understanding of sensing capabilities.
- Help users on the selection of the best sensors and services to their purpose. Knowing limits and potential.
- How to interpret data provided by sensors and/or services, based on ready to use products.

Hence, learning material will be taken from Chapter1, Chapter2, and Chapter3 and part of the Chapter7, as described in Table 2.

The learning flow and practical exercises proposed are described following, designed to be completed on

15 hours.

4.2.2 Learning flow

The learning flow is designed to progressively increase in complexity. This progression is intended to drive users from the basics concept of sensing to go into detail in the different sensing technology considered in the NBS project. Next, a description of the steps for the Module 3-Level1 with a short description of the basics behind.

(1). The first contact with the Module 3 should around the concept of “sensing” and the data that users will be provided. For this last, the concept of proxy needs to be clear for students (proxy vs. ground truth).

> *Sensing, in its broadest sense, refers to the technology and methods used to measure and observe physical parameters of the environment. Data acquired from sensing acts as a proxy for the observed feature, which means it represents the actual conditions or attributes of the feature indirectly. This proxy data, even if not always perfectly accurate, provides valuable insights that approach the ground truth—the actual, precise state of the observed feature. Each kind of sensing has it owns accuracy which varies from 80 % (for some kinds of satellite imagery) to 98 % (some kind of soil sensors).*

(2). Then, users might be introduced in the two main “apparatus” involved in this task: the sensor and the device. It might be easy then to introduce the different general techniques: proximal sensing, ground sensors, remote sensing, ... And the general structure of sensors. Practical exercise: Examples of the different features users can be sensed and the products obtained (exercise), i.e. transpiration, biomass or leaf area index (LAI) from canopy of vegetation, Digital Elevation Models (DEM), orthophoto, water, temperature, yield maps, weather stations, humidity soil sensors, …

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> *Different types of sensors, such as soil moisture sensors, pH sensors, temperature sensors, and nutrient sensors, serve various purposes. Also, Proximal Sensing techniques and Remote Sensing techniques using cameras in different electromagnetic spectrum can provide less expensive significant support. These kinds of sensors can be placed either on-board of robots (UGVs), drones (UAVs) or satellites.*

(3). Data from sensing I: resolution (geometric, radiometric, spectral, temporal) and geometric features (sizes, shapes, positions, volumes). Exercise: different resolutions by sensor×device.

> *Sensing data resolution includes several important aspects: geometric resolution, which shows the detail of spatial data by indicating the size of detectable objects; radiometric resolution, which measures the sensor's ability to see slight differences in energy; spectral resolution, which covers the number and width of spectral bands the sensor detects; and temporal resolution, which tells how often data is collected over the same area.*

(4). Data from sensing II: bio-physical features. Maybe introduce here the concept of calibration, why it is required and important.

> *There are several types of data that can be used for monitoring purposes in agriculture. For example, weather data that include information on temperature, humidity, precipitation, and wind speed, resulting in products like weather forecast. DEM provide terrain elevation, slope, and aspect, used for example for erosion analysis or soil type. High-resoluton orthophotomaps aiding in detailed soil zone maps and land use planning. Satellite imagery delivers information on vegetation health, land cover, and surface temperature, essential for land classification maps, zonal analysis and vegetation monitoring. Ground data measure among others soil moisture, soil temperature, and pH levels, producing e.g., soil health assessments and irrigation schedules. Canopy sensors can provide Leaf Area Index (LAI), which are used for crop health monitoring and growth analysis. Lastly, Yield data reflects crop yield and harvest quantity, resulting in yield maps and productivity analysis*

(5). Data acquisition. Concept of processed data (what it means, broadly introduce key steps on data processing) and formats. When selecting a product, need to be able to identify good quality data.

> *Data acquisition involves collecting and storing data from sensors. Processing includes normalizing (standardizing data), and analyzing (extracting insights). Well-processed data is essential for reliable, actionable information. When choosing a sensing product, ensure the data is accurately processed, calibrated, and formatted correctly, leading to better agricultural management and outcomes.*

4.2.3 Practical exercises

The practical exercises proposed for Module 3-Level 1 have been designed for entry-level students with no experience of using GIS data on GIS software, with the aim of introducing them to the interpretation of sensor-

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derived products. It is also intended to stimulate students' interest in the use of sensor-derived products and motivate them to further explore sensor technology at Levels 2 and 3. The exercises have been designed using ready-to-use products accessible from existing platforms, following a 'learning-by-doing' approach. The proposed practical exercises are briefly described below.

Exercise 1-3 (UNITO). A free online platform (Copernicus Data Space Ecosystem; accessible at: https://dataspace.copernicus.eu/) will be suggested to freely manage Sentinel-2 multispectral data and explore images and play with main image proprieties.

1. Comparing main spectral signatures
   In this exercise, students will explore the spectral signatures of 3-4 land cover features in the study area related to the NBS addressed in the NBSOIL project (e.g. forest, urban, water, crop). Students will use the Copernicus Browser 'Spectral explorer tool' by adding pins to locate the NBS in the study area by visualising the Open Street basemap layer. In particular, the exercise can follow these steps:
   a. Selecting a 2023 summer Sentinel-2 L2A image.
   b. Add a pin over an urban area and describe the general shape of the signature.
   c. Add a second pin over a forest area and describe the general shape of the signature.
   d. Add a third pin over a water body and describe the general shape of the signature.
   e. Repeat from (a) to (d) selecting a winter image.
   f. Recap the main differences among the spectra and link them to the observed NBS feature.

2. Comparing spectral signature of soils having different moisture content
   In this exercise, students will focus on soil spectral proprieties related to the NBS addressed in the NBSOIL project. In particular, they will explore spectral signatures (from 3 to 4) of agricultural soils. Students will adopt the "Spectral explorer tool" of Copernicus Browser by adding 3-4 pins over a study area by visualizing S2 true color composite layer. In particular, the exercise can follow such steps:
   a. Selecting a 2023 spring Sentinel-2 L2A image.
   b. Add a pin over a bare soil area and describe the general shape of the signature.
   c. Copy the spectral values from table into Excel (also google sheet)
   d. Add a second pin over a second soil and repeat (b)
   e. Replicate for other point from a to b.
   f. Compare by plotting spectra and describe the general shape of the signatures.
   g. Recap the main differences among the spectra and link them to the surface proprieties.

3. False color photointerpretation
   In this exercise, students will focus on the multispectral image photo interpretation. In particular, they will explore false color composite over an agricultural landscape with one of the NBS addressed in the NBSOIL project. Students will adopt the "False color layers" of Copernicus Browser by selecting different spectral bands combinations. In particular, the exercise can follow such steps:
   a. Select a Sentinel-2 L2A summer image.
   b. Explore the layer titled: "False color (bands 8,4,3)"
   c. Play with "Show effects and advanced options" stretching the image by GAIN and GAMMA to emphasize the contrast among vegetation.
   d. Explore the layer titled: "False color (bands 8,4,3)"
   e. Play with "Show effects and advanced options" stretching the image by GAIN and GAMMA to emphasize the contrast among vegetation.
   f. Explore the layer titled: "SWIR (bands 12, 8A,4)"
   g. Play with "Show effects and advanced options" stretching the image by GAIN and GAMMA to emphasize the contrast among soil having different moistures.

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Exercise 4-6 (AgriSat). These exercises are proposed using the GIS tool of the NBSOIL project, developed during the project to support the Soil Advisors in advising the NBSs included in the project. The GIS tool is being developed by adapting the existing AgriSatwebGIS platform developed by AgriSat.

4. Consult values of vegetation indices (NDVI, NNI, biomass) and download data for several crops with different yields.
    a. Consult several dates with images (indicate 3 dates) --> select the date without images (date1: with clear clouds - very intuitive; date2: image with cirrus clouds less intuitive; date3; image free of clouds).
    b. Consult NDVI, NNI and biomass values in pixels of previously defined plots of several crops with well-defined variability --> calculate the area with higher or lower yields based on the vegetation indices.
    c. Download the query in excel format and upload it as a result.

5. Consult data of the ARIES NBSOIL package (same fields as Exercise 1).
    a. Consult spatial resolution --> measure pixel.
    b. Consult source of data --> consult metadata.

6. Connect to WMS to cosult data from external databases, for instance, official layers of Soil type, MDT, orthophotos, ... (same fields as Exercise 1).

Exercise 7-9 (ILOT). A free online platform (Copernicus Data Space Ecosystem; accessible at: https://dataspace.copernicus.eu/) will be suggested to freely manage Sentinel-2 multispectral data and explore images and play with main image properties.

7. Phenomenon and their definitions. In this exercise, students will test their skills in using publicly available sources and knowledge of phenomenon closely related to soil monitoring, such as erosion, landslides or changes in land use. In particular, the exercise can follow such steps:
    a. Use publicly available sources in order to find an appropriate illustration for the described phenomenon.
    b. Look at the list of phenomena with a short definition.
    c. Match 5 images of landslides with the proper definitions.
    d. Repeat these steps for images depicting other phenomena.
8. Types of resolution. In this exercise, students will have the opportunity to use the acquired theoretical knowledge in a practical way, which will enable them to repeat and consolidate material on various types of resolutions. The data provided will come from publicly available sources, e.g., Sentinel-Hub, and definitions will be provided in the form of short 2-3 sentence descriptions. In particular, the exercise can follow such steps:
    a. Look at the list of issues, short definitions and images to be assigned (more than one image for each definition).
    b. Select a definition from the list, e.g. "spatial resolution" and then assign the correct images to it.
    c. Look at several descriptions specifying the key according to which the images should be organized, 3-4 images for each description.
    d. Arrange the images, e.g. according to pixel size - ascending.
9. Equipment and products. Students will acquire knowledge about sensors currently used in soil monitoring and become familiar with the products that can be produced within the use of obtained data. This exercise will help to consolidate knowledge of the equipment and its capabilities. In particular, the exercise can follow such steps:

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   a. Look at the list of sensors with the photo samples and the sample of various types of images to assign.
   b. Look at the short 2-3 sentence definitions of sensors and at the sample of images to assign.
   c. Assign the definition to the correct image e.g., an orthophotomap in real colors to the definition of an RGB camera.

Exercise 10 (ITAP).

10. Using Google Earth for Preliminary Soil Assessment (Level 1). Objective: to learn how to use Google Earth to identify different types of land use and possible areas of interest for monitoring. Detailed Steps:
    a. Installation and configuration
        a. Step 1: Download and install Google Earth Pro.
        b. Step 2: Familiarise yourself with the Google Earth interface by exploring the different tools available.
    b. Local area scanning
        a. Step 3: Select a local area of interest (e.g. a nearby agricultural area).
        b. Step 4: Use the search tool to locate your area of interest.
    c. Land use identification
        a. Step 5: Use Google Earth tools to identify different types of land use (agricultural, forestry, urban, etc.). Use historical images to see changes over time.
        b. Step 6: Activate additional layers such as "Paths", "Borders and Labels" for more information.
    d. Marking of points of interest
        a. Step 7: Mark at least five points of interest using the placemark tool.
        b. Step 8: Add descriptions to each marker, indicating why each point is relevant.
    e. Assessable tasks:
    f. Write a short report (1-2 pages) describing the selected points and justify their importance.
    g. Include screenshots from Google Earth showing the marked points.

4.3 Module 3 – Level 2

4.3.1 Generalities and objectives

The Module 3 – Level 2, is designed with the following objectives:

To make Soil Advisors conscious users of the type of data provided by sensors.

- How to interpret temporal series and deeper knowledge of spatial assessment.

Hence, learning material will be taken from Chapter4, Chapter5, and Chapter6 and part of the Chapter7, as described in Table 2.

The learning flow and practical exercises proposed are designed to be completed within

15 hours.

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4.3.2 Learning flow

The main goal of this Module 3-Level 2 is to provide skills and tools to exploit spectral and geometric content of sensors over a defined time period.

1. Main strategies for data exploitation
   1.1. Change detection: data from sensors (bands, spectral indices or cloud points/DSM) or products acquired at two times (after and before) are compared to derive a map of changes. The analysis is static and is aimed at mapping and quantifying the size of changes of soils/vegetation in a well-defined time range.
   1.2. Multitemporal analysis based on image time series: sequences of data from sensors (bands, spectral indices or cloud points/DSM) are composed and analysed with the aim of dynamically describe the evolution of a certain phenomenon affecting both vegetation and soil. The frequency and duration of acquisitions defines the exploitability of the time series content.
      1.2.1. Short term applications (e.g., agriculture-related ones) rely on yearly sequences of frequent data
      1.2.2. Long term applications (e.g., climate change- or pollutants removal-related ones) can rely on multi-yearly sequence of averagely frequent data

4.3.3 Practical exercises

The proposed exercises will be defined to educate students in preparing image time series:

1. Satellite data (e.g. Sentinel 2
   1.1. Filtering
   1.2. Regularization
   1.3. Smoothing/Modelling
   1.4. Interpretation
      1.4.1. Yearly (Phenological) Metrics
      1.4.2. Trends concerning more years

2. UAV/Aerial data
   2.1. Co-registration (geometric)
   2.2. Radiometric calibration and atmospheric correction (orthomosaic)
   2.3. DSM (Digital Surface Model) and NHM (Normalized Height Model) generation
      2.3.1.1. Point clouds filtering
      2.3.1.2. Point clouds classification
      2.3.1.3. Point clouds regularization/interpolation
   2.4. Time series of multispectral orthomosaics
   2.5. Time series of NHM (crop/vegetation models of crop growing)

4.4 Module 3 – Level 3

4.4.1 Generalities

Module 3 – Level 3, is for participants taking the Module Challenge which involves research directly linked to NBSOIL and the Soil Mission main questions.

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The development of the module will be designed around data integration for modelling.

4.4.2 Learning flow

It will be designed around the final project of the students and thus, in will be created in co-creation with them.

4.4.3 Practical exercises

To be defined with students.

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Annex 1. Learning material

Summary

1. Generalities

   What is remote sensing?
   Which features are we sensing?

   A. Geometric features (sizes, shapes, positions , volumes)

      a. Basics of Digital Photogrammetry
      b. Basics of LiDAR

      Here some application/case studies

   B. Bio-physical features

      a. Basics of Optical RS (ORS)
         Planck, Signal/surface interaction, spectral signature, Reference spectra
      b. Basics of Thermal RS
         Stefan/Boltzmann Law Emissivity of materials
      c. Basics of SAR

      We are mainly focusing on Optical Remote sensing since it is more transferable to low skilled-users.

2. ORS: from Theory to Data
   2.1. Sensors (imaging) are regular samplers of spectral signature
   2.2. General structure of a sensor (pushbroom e frame)
   2.3. Image resolutions (geometric, radiometric, spectral, temporal)

3. Criteria for a conscious data selection
   3.1. Introduction Criteria for remotely sensed imagery acquisition
   3.2. Acquisition resolutions
   3.3. 3D precision
   3.4. Extractable information content

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4. Sensors
    4.1. Imaging Sensors
        4.1.1. Spaceborne sensors
            4.1.1.1. Scientific and Open data
                4.1.1.1.1. Pre-processed data
                    a) Multispectral missions
                    b) Hyperspectral missions
                    c) SAR missions
                4.1.1.1.2. Ready-to-use products
            4.1.1.2. Commercial Data
        4.1.2. Airborne/UAV sensors
            4.1.2.1. Sensor types
                a) RGB sensors
                b) Multispectral
                c) Medium Infrared (MIR)
                d) Thermal (TIR)
                e) LiDAR
            4.1.2.2. Managing Data Acquisition by Drones
                I. Choosing the ideal drone for soil analysis
                II. Preflight checks
                III. Mission planning
                IV. Control points.
                V. Post-flight data processing
    4.2. Ground Sensors

6 Data Analysis and Interpretation
7 Main Applications/ Case Studies
8 REFERENCES

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Generalities

What is remote sensing?

Remote sensing is a technique of obtaining information about land surface features using electromagnetic radiation without direct contact (Shirazy et al., 2021; De Jong et al., 2007). It is a common aspect of daily life; for instance, reading a newspaper or observing passing cars involves remote sensing through the human eye. Our eyes capture reflected solar light, interpreting colors and intensities into valuable insights. However, the human eye is limited to the visible spectrum (400-700 nm). In contrast, remote sensing employs various tools to detect a broader range of wavelengths, including near-infrared, middle-infrared, thermal-infrared, and microwaves (De Jong et al., 2007). The primary goal of remote sensing is to systematically gather extensive information about real-world features in a structured and large-scale manner (Dharaiya, 2022).

Modern soil monitoring leverages advanced remote sensing and optical sensor technologies to analyze soil properties across a broad spectrum of wavelengths. These techniques yield vital data on chemical composition, moisture levels, structure, and other key soil parameters crucial for sustainable management. Optical sensors measure light reflection across various spectral bands, enabling precise mapping of soil characteristics. This technology facilitates the swift detection of soil changes, identification of degraded areas, and optimization of agricultural practices, ultimately enhancing crop efficiency and promoting environmental conservation.

Drones equipped with multispectral cameras are widely used in agriculture to monitor crops, soil, fertilization, and moisture. These cameras capture visible and invisible images of vegetation, providing the quickest method for managing various agricultural aspects. Although RGB sensors (red, green, blue) are the simplest data source captured by drones, multispectral imaging technology offers a more detailed view by recording different wavelengths. This capability is particularly valuable for assessing soil and plant moisture, enabling the creation of detailed land moisture maps and precise identification of areas requiring irrigation. Despite their benefits, the acquisition of such data can still be costly.

Thermal cameras are becoming increasingly prevalent in environmental analysis, particularly in soil studies. Thermal infrared sensors detect radiation emitted by objects, providing a valuable method for examining soil processes. These sensors enable precise temperature measurements and facilitate the study of hydrological dynamics. The utilization of LiDAR (Light Detection and Ranging) in environmental monitoring dates back to the 1960s. Originally employed in aviation for terrain mapping, LiDAR has since been applied to geological, hydrological, and ecological studies. Recent advancements in LiDAR technology have markedly enhanced environmental monitoring and management capabilities, enabling detailed mapping of landforms, land cover, and soil structure. Today, LiDAR is integral to numerous environmental research projects, including the identification and assessment of potential natural hazards.

In summary, remote sensing is a critical technology that has transformed our understanding of the Earth's surface. Its applications in soil monitoring, environmental management, agriculture, urban planning, and disaster management underscore its versatility and importance. As technology advances, the capabilities of remote sensing will continue to expand, providing even greater insights into the complex dynamics of our planet.

Which features are we sensing?

A. Geometric features (sizes, shapes, positions, volumes)

a) Basics of Digital Photogrammetry

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b) Basics of LiDAR

LiDAR or Light Detection and Ranging, is a surveying technique for measuring the distance to an object by illuminating it with laser light and then measuring the reflected light with a sensor. Taking advantage of differences in laser beam return times and wavelengths allows the generation of precise, digital, three-dimensional representations of objects. *In the context of soil monitoring, LiDAR is employed to map various phenomena, including water-induced soil erosion, landslides, flood-prone areas, and topographic terrain features such as soil structure and agricultural land distribution. The versatility in sensor dimensions allows for their deployment on both manned and unmanned aircraft, thereby broadening the scope of their applications (Dong, 2017).* The most common LiDAR data storage formats are LAS (LiDAR Aerial Survey), LAZ (LiDAR Compressed), ASCII (American Standard Code for Information Interchange), PLY (Polygon File Format), XYZ (Cartesian Coordinates) (Vosselman et al., 2010).

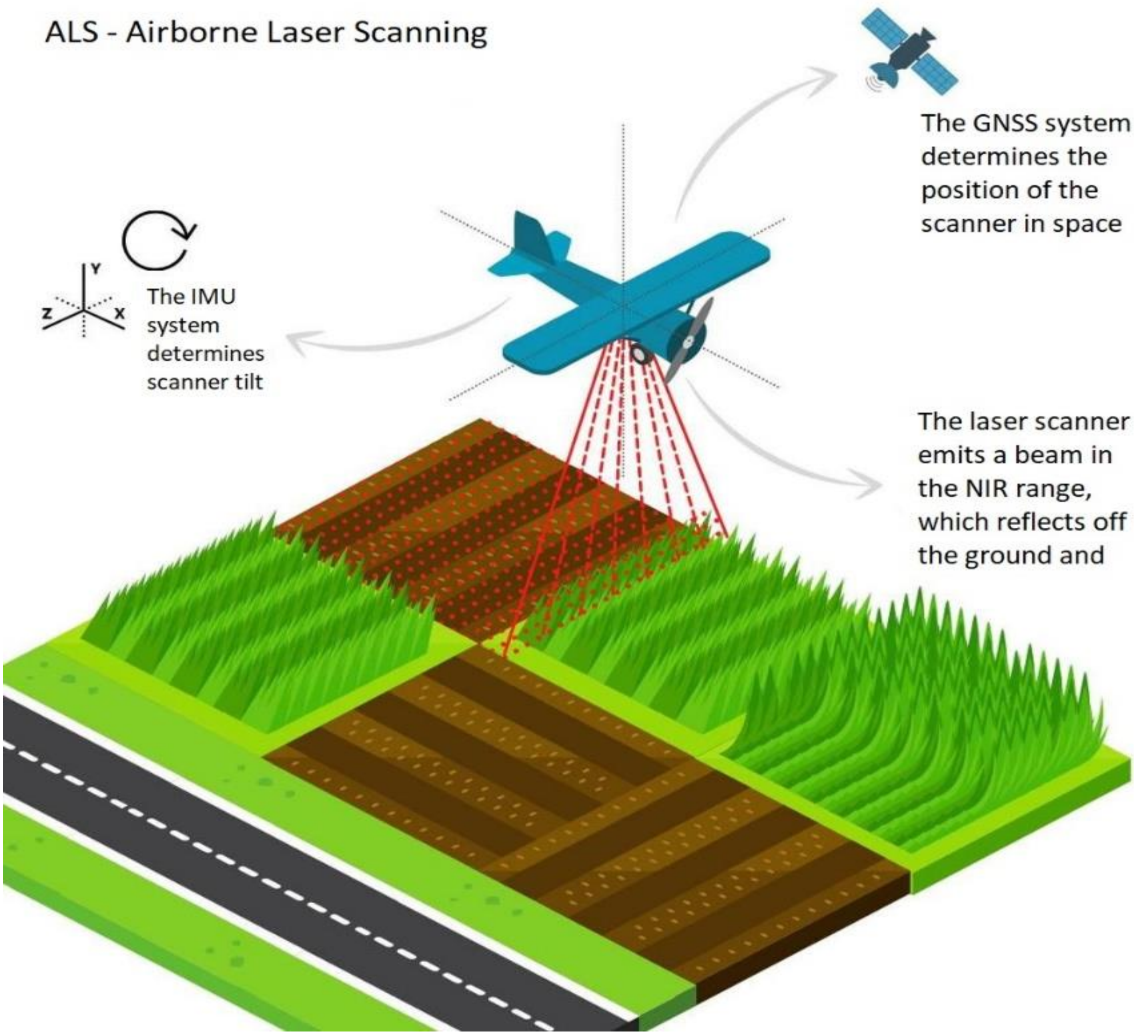

Figure 2 Operation scheme of Airborne Laser Scanning
source: https://agronomist.pl/artykuly/wykorzystanie-lidar-w-rolnictwie

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During the implementation of tasks in the NBSoil project, related to acquiring point clouds for selected areas, the LiDAR RIEGL VUX-1UAV-22 was utilized, which can be mounted on any professional, manned, or unmanned flying platform. This sensor is characterized by its lightweight design and the ability to be mounted in any orientation, which is a significant advantage in cases of limited mass and space on the platform where it is to be installed. Another advantage is its low energy consumption, requiring only a single power source. Furthermore, it ensures fast data acquisition using a narrow infrared laser beam and a rapid scanning mechanism. The scanning mechanism utilizes a swiftly rotating mirror, providing linear, unidirectional, and parallel scan lines, resulting in a regular point pattern[3].

Figure 2 depicts a projection of a multisensor platform generated in one of the graphic programs, comprising, among other elements, the LiDAR - on the right side. Meanwhile, Figure 3 is a photograph presenting the actual appearance of the platform mounted on an Unmanned Aerial Vehicle (UAV).

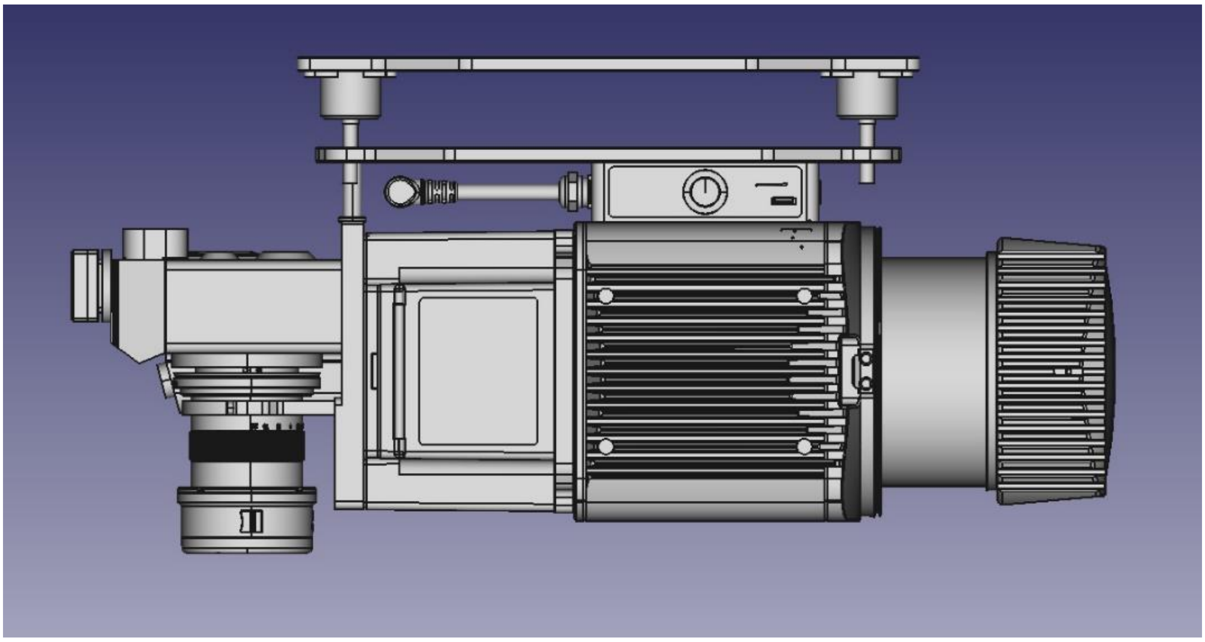

Figure 3 Side view of a rectangular multisensory platform.
source: Łukasiewicz-Institute of Aviation

[3] http://www.riegl.com/products/unmanned-scanning/riegl-vux-1uav22/).

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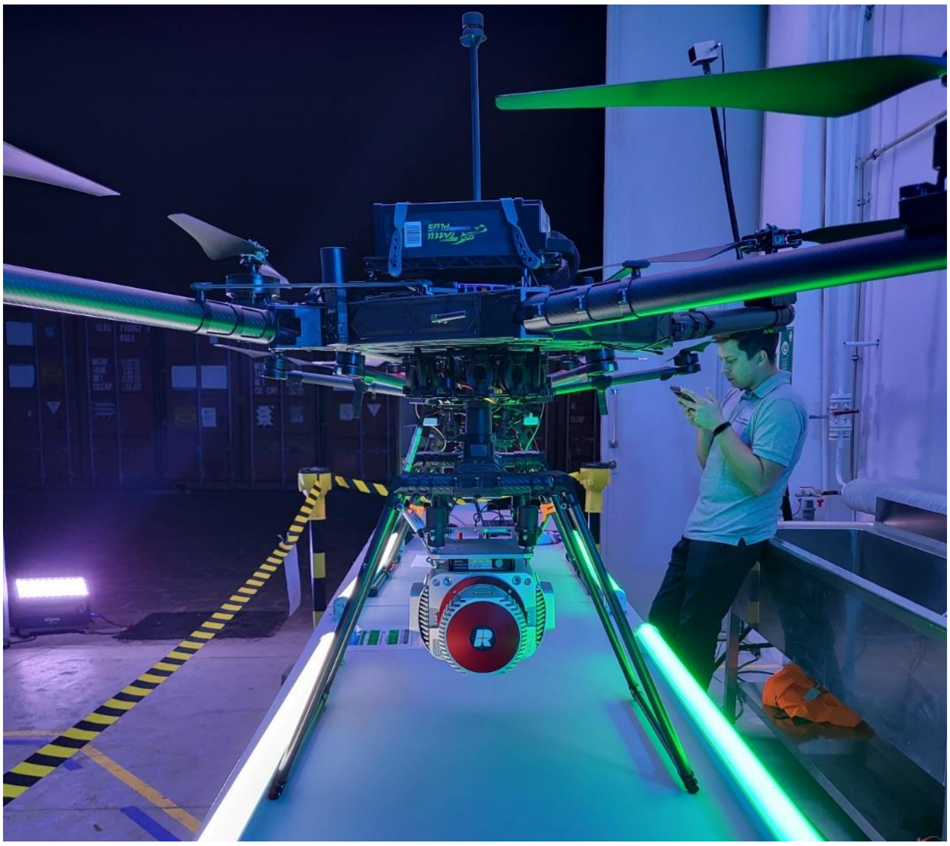

Figure 4 Photograph of a multisensory platform integrated with an UAV.
source: Łukasiewicz-Institute of Aviation

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Table 1 Technical specifications – LiDAR RIEGL VUX-1UAV-22

Main features	Main applications
- 10 mm survey-grade accuracy - scan speed up to 200 scans / second - PRR freely selectable - measurement rate up to 1,200,000 meas./sec (@ 1200 kHz PRR & 360° FOV) - operating flight altitude more than 800 m - field of view up to 360° for practically unrestricted data acquisition - regular point pattern, perfectly parallel scan lines - cutting edge *RIEGL* technology providing - echo signal digitization - online waveform processing - multiple-time-around processing - multiple target capability - up to 15 targets echoes - compact (227x180x125 mm), lightweight (3.5 kg), and rugged - easily mountable to professional UAS / UAV / RPAS - mechanical and electrical interface for IMU mounting - electrical interfaces for GPS data string and Sync Pulse (1PPS) - LAN-TCP/IP interface - internal data storage on Solid State Disc SSD, 1 TByte	- agriculture & forestry - archeology and cultural heritage documentation - corridor Mapping: power line, railway track, and pipeline inspection - topography in Open-Cast Mining - construction-site monitoring - surveying of urban environments - resource management - geological research - disaster management -

source: http://www.riegl.com/products/unmanned-scanning/riegl-vux-1uav22

Challenges related to the use of sensors

The use of LiDAR for comprehensive soil monitoring has numerous advantages, but it also comes with certain challenges that need to be considered when deciding to employ this data acquisition technique.

Among the advantages associated with the use of LiDAR technology, the following can be listed:

- ***High spatial resolution of data** - provides detailed information about the topography and structure of the terrain, enabling precise visualization of soil surface features.*
- ***Rapid data acquisition** - utilizing this technology allows for quick data collection over large areas, enabling efficient monitoring of soil changes across extensive regions.*
- ***High accuracy and precision of measurements** - allows for precise determination of elevation differences and topographic features of the soil, as well as accurate localization of objects relative to their actual positions in the terrain.*
- ***Ability to penetrate vegetation cover** - the capability to penetrate vegetation enables obtaining terrain data even in densely vegetated areas.*

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- ***Applicability in various terrain conditions*** *- data acquired in challenging terrains, including those with diverse topography, exhibit comparable accuracy, which is crucial for their utilization in analyses.*
- ***Independence from lighting conditions*** *- enables operation even in adverse conditions, including after sunset.*

The drawbacks associated with the use of LiDAR include:

- **High cost** - the utilization of this technology is relatively expensive at every stage, from equipment purchase to data processing and analysis, which can be limiting for projects with smaller budgets.
- **Dependence on weather conditions** - data acquisition during rain or in conditions of fog or low clouds is not advisable, as it can adversely affect data accuracy.
- **Difficulty in visualizing certain surfaces** - water, asphalt, tar, snow, or very dark or porous surfaces may absorb or scatter laser beams, which can negatively impact the quality of acquired data.
- **Difficulty in data processing and interpretation** - LiDAR data processing and interpretation often require advanced skills and specialized software, which can be challenging for some users.
- **Very large data volume** - the volume of acquired data, even for small areas, is significant, which can be problematic for mapping larger areas, both in terms of storing raw and processed data and in terms of the time required for processing them.

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C. Bio-physical features

a. Basics of Optical RS (ORS)
Planck, Signal/surface interaction, spectral signature, Reference spectra
b. Basics of Thermal RS
Stefan/Boltzmann Law Emissivity of materials
c. Basics of SAR

We are mainly focusing on Optical Remote sensing since it is more transferable to low skilled users.

1. ORS: from Theory to Data

1.1. Sensors (imaging) are regular samplers of spectral signature
1.2. General structure of a sensor (pushbroom e frame)
1.3. Image resolutions (geometric, radiometric, spectral, temporal)

When determining the quality of remote sensing and photogrammetric sensors, we compare their resolution, among which we distinguish such types as (Orych et al., 2021):

- Spatial resolution - defines the minimum size of distinguishable elements during image interpretation that the sensor is capable of recording.
- Spectral resolution - defines the ranges of electromagnetic radiation that have been recorded by the sensor.
- Radiometric resolution - determines how many shades of grey were used to register the image.
- Temporal resolution - determines at what frequency images of the same area are taken

Spatial resolution

Spatial resolution allows us to determine the quality of the images as well as their interpretative capacity. This means that the size of an element influences its interpretative capacity; the smaller the element is, the more information can be extracted from a given image.

Figure 5. source: https://gisgeography.com/spatial-resolution-vs-spectral-resolution/

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Two measures are used to determine spatial resolution, viz (Orych et al., 2021):

- GRD (Ground Resolved Distance) - field resolvability - is defined as the smallest distinguishable quantity on an image. In principle, with a known flight altitude or distance of the object from the sensor, the relationship between the image of the smallest object defined on the imaging and its length in the field can be defined by the formula:

$$GRD = H \frac{\Delta x_i}{f}$$

- Δxi - linear pixel dimension.
- H - flight height or distance between sensor and object,
- f - focal length of the sensor

For digital sensors, spatial resolution can also be defined as:

- GSD (Ground Sampling Distance) - defined as a measure that describes the distance in the field between the centres of two neighboring pixels. It only provides an approximation of the actual interpretability, in contrast to GRD, which describes the actual resolution considering many additional elements affecting the final image quality.

Spectral resolution

The spectral resolution defines the number of spectral bands and their electromagnetic spectral width that is recorded by the sensor in order to register the differences in spectral reflectance of individual surfaces. The higher it is, the narrower the wavelength range recorded for a channel, which translates directly into a higher number of channels. As the spectral resolution increases, so does the visibility and individual object and the ability to distinguish it in terms of spectral reflectance.

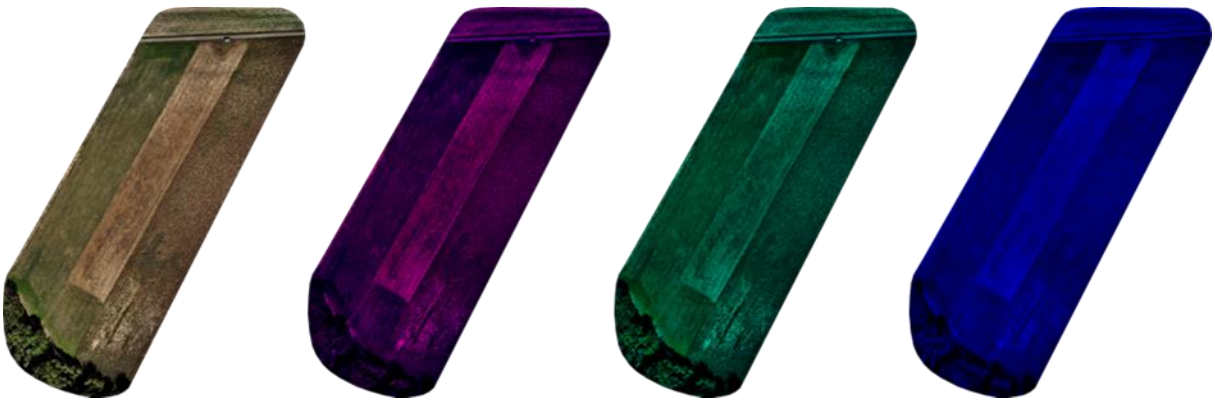

Figure 6. Different spectral bands combinations of the same area, source: ILOT

Satellites, depending on their type, can record radiation in different spectral ranges and present it in different ways. Most passive satellites are called multispectral because they have from several to up to a dozen

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channels. These include the American LANDSAT or the Sentinel-2, supervised by the European Space Agency (ESA)[4].

Table2Types of satellites and their spatial and spectral resolution

Name	Spatial resolution	Spectral resolution	Country
ALOS-2	2.5 m (PAN), 10 m (MS)	4 bands	Japan
Gaofen-1	2 m/px (PAN), 8 m/px (MS)	4 bands	China
Gaofen-2	0.8 m/px (PAN), 3.2 m/px (MS)	4 bands	China
KompSAT	0.4 m (PAN), 1.6 m (MS)	4 bands	Korea
Landsat 8,9	15 m (PAN), 30 m (MS)	9,11 bands	USA
PlanetScope 4 band	3.0 - 5.0 m (MS)	4 bands	USA
Pleiades-1	0.5 m (PAN), 2 m (MS)	4 bands	France
Sentinel-2	10 m (MS), 20 m (MS), 60 m (MS)	13 bands	UE
SkySat	0.8 m (PAN), 1 m (MS)	4 bands	USA
SPOT-7	1.5m (PAN), 6 m (MS)	4 bands	France
TripleSat	0.8 m (PAN), 3.2 m (MS)	4 bands	India
Worldview-1	0.5 m/px (PAN)	1 band	USA
Worldview-2	0.5 m (PAN), 1.84 (MS)	8 bands	USA
Worldview-3	0.3 m (PAN), 1.24 m (MS), 3.7 m (SWIR), 30 m (CAVIS)	29 bands	USA

source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spectral

[4] https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spectral

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Table3Sentinel-2 Bands.

Band	Description	Resolution [m]	Wavelength [nm]
B1	Ultra blue	60	443
B2	Blue	10	490
B3	Green	10	560
B4	Red	10	665
B5	Visible and Near Infrared (VNIR)	20	705
B6	VNIR	20	740
B7	VNIR	20	783
B8	VNIR	20	842
B8a	VNIR	20	865
B9	Short Wave Infrared (SWIR)	60	940
B10	SWIR	60	1375
B11	SWIR	20	1610

source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spectral

Table 4 Landsat 9 Bands.

Band	Description	Resolution [m]	Wavelength [nm]
B1	Coastal Aerosol	30	430-450
B2	Blue	30	450-510
B3	Green	30	530-590
B4	Red	30	640-670
B5	Near-Infrared	30	850-880
B6	SWIR 1	30	1570-1650
B7	SWIR 2	30	2110-2290
B8	Panachromatic (PAN)	15	500-680
B9	Cirrus	30	1360-1380
B10	TIRS 1	100	10600-11190
B11	TRIS 2	100	11500-12510

source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spectral

Radiometric resolution

The radiometric resolution defines the number of grey levels (so-called colour depth), of the recorded electromagnetic spectrum. It specifies how detailed the differences in an image, analysed in terms of its brightness, can be. The measure of this resolution is the number of shades of grey. The number of bits (binary values) defines the maximum number of shades that can be recorded, and so 8-bit images have 256 shades, while 16-bit images have 65,536.

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The higher resolution allows a better and more accurate measurement of small differences in reflectance and emissivity, which directly increases the size of the acquired data. It is worth noting that this does not translate specifically into an increase in quality and the difference in imaging between 6 and 8 bits is only 2-3% (https://www.usgs.gov/faqs/what-radiometric-resolution).

Temporal resolution

The temporal resolution, or revisit time, is defined as the elapsed time between two identical raids over the same point and depends among other things on the altitude and orbit of the satellite as well as the angle of view of the sensor mounted on it (https://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing).

The revisit time for satellites imaging the Earth's surface varies significantly between different systems. For instance, Landsat 9 has a revisit time of 8 days, while Sentinel-2 has a revisit time of 6 days. In contrast, meteorological satellites have a much shorter revisit time; for example, METEOSAT 8 revisits every 15 minutes. Some satellites capture radiation in the visible and infrared ranges, which cannot penetrate cloud cover. Consequently, the temporal resolution of these satellites is affected by the meteorological conditions of our planet, which often include a high percentage of cloud-covered surfaces. During periods of heavy cloud cover, these satellites are unable to accurately capture the area, resulting in images that may not be suitable for further analysis.Images acquired over different time periods, e.g. every month, year or decade, are used to conduct multi-temporal analyses, among which are those concerning (https://seos-project.eu/remotesensing/remotesensing-c03-p05.pl.html):

- Changes in urban areas including urban development.
- Changes in the wider biosystem including, for example, documenting the clearing of equatorial forests, or the effects of floods and earthquakes.

1. The spectrum of visible light in the context of the entire range of electromagnetic radiation.

Table 5 Type and length of electromagnetic waves

Type of waves	Wavelength
Radio waves	above 1 m
Microwaves	from 1 mm to 1 m
Infrared	from 740 nm to 1 mm
Visible light	from 380 nm to 740 nm
Ultraviolet	from 10 nm to 380 nm
X-ray radiation	from 5 pm to 10 nm
Gamma radiation	from 1 pm to 10 pm

source: Łukasiewicz-Institute of Aviation

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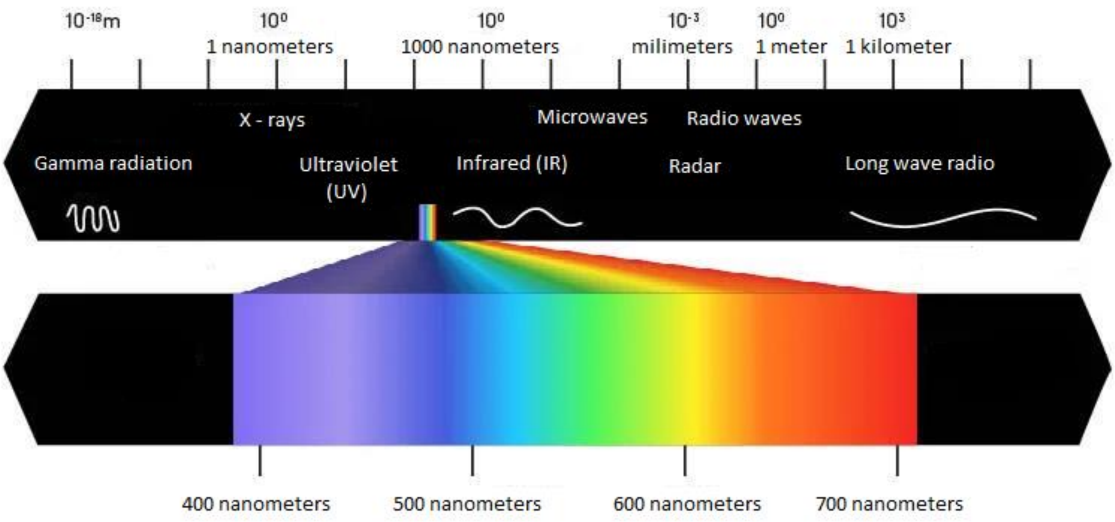

Figure 7The types of electromagnetic waves according to their length and frequency, source: https://www.lenalighting.pl

The figure above shows the types of electromagnetic waves according to their length and frequency, ranked according to the relationship that the longer the wave, the lower its frequency. Waves such as X-rays, gamma rays or ultraviolet are characterized by high frequency, which is associated with high energy. They have a detrimental effect on living organisms and their prolonged exposure can lead to cell damage and even death.

Visible light falls within a very narrow range of wavelengths assumed to be between 380 and 700 nm, with light at the highest wavelength being seen by humans as red, while at the lowest wavelength it is violet. Since the limits of the visible light range are determined by the physiology of the human eye, it has relatively the most precisely defined boundaries.

In this range, the satellite's wavelengths have a sensitivity similar to that of the human eye, which in practice means that they are able to see as much as a human looking at the Earth's surface from a height of 1,000 km, an important observation only possible for objects illuminated by sunlight.

Criteria for a conscious data selection

Promoting the generation and enhancement of both tangible and intangible benefits derived from soil resources necessitates the imperative integration and implementation of Information and Communication Technologies (ICT) as pivotal components of innovation within the global primary production system.

The use of these new technologies by agronomic technicians allows the development of operational tools also suitable for non-specialist use, capable of allowing:

- performing complex analyzes of agro-forestry and territorial data in a guided, simple and economical way;

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- support planning and design decisions of operations according to standardized and reproducible conceptual paths;
- promote integration between technicians, sector operators, policy makers and the social community, while ensuring the transparency of the management operations of agro-forestry assets, on the basis of shared, standardized and highly accessible information platforms (e.g. Web-GIS and App for everyday mobile terminals)

The understanding of territorial resources, encompassing their inventory and spatial distribution, serves as the foundation for informed and optimized policy formulation. Geospatial data, in this context, assume a pivotal role in shaping the cognitive landscape for territorial decision-making processes. Preservation of soil integrity and its judicious utilization represent recurring focal points within environmental planning discourse. In the context of evolving paradigms towards holistic (multifunctional) management approaches, comprehensive territorial knowledge emerges as an indispensable tool for policymakers. The agro-forestry sector, alongside numerous other operational domains directly linked to environmental and territorial dynamics, has witnessed profound transformations with the advent of geomatics technologies. Notably, aerial and satellite remote sensing methodologies facilitate continuous data acquisition, which, upon integration into Geographic Information Systems (GIS), assumes strategic significance in data processing and analysis. This integration is instrumental in delineating future management strategies and formulating intervention plans, including adjustments or business management frameworks.

There can be different scales of work: from the large-area one for monitoring wide areas to the local one, for example, for the management of individual properties (agricultural parcels, single forest or green infrastructure). The purposes are also different: from management applications, which aim to support agronomic and environmental planning, to analytical applications, for example, analysis of primary productivity, assessments of territorial suitability or modeling of phenomena.

Thanks to the introduction of medium-low cost sensors, applications for the survey of vegetated surfaces have been significantly enriched, relying on technologies capable of acquiring spectral and geometric information over large territorial extensions.

Especially in the agro-forestry context, aircraft/drones, equipped with appropriate sensors, can provide information about the investigated surfaces with a high geometric resolution. In this case, the photogrammetric survey of the observed surfaces opens new scenarios largely linked to the possibility of measuring morphometric and structural parameters of vegetation. Furthermore, the current availability of freely available spaceborne multispectral data allows to hypothesize integrated use scenarios in which the spectral and morphometric information determines a more complete knowledge of soil features.

With these premises, aerial and spaceborne remote sensing arrives at a new paradigm in the context of soil management. In fact, the information obtainable is currently among the most accurate in metric terms, capable of acquiring large surfaces in a short time. In particular, this last aspect determines a substantial reduction in survey costs, allowing this technique to be introduced in a sector notoriously poorly supported by financial resources such as the agro-forestry sector.

The identification of the most suitable technical features for the use of remote sensing data useful for spectral and geometric characterization of soils is certainly crucial from soil managers/technicians' perspective. Although many remote sensing sensors and already processed products are available, it is necessary to choose them properly considering the requirements of a given application.

It is important clarify the difference between raw, pre-processed remotely sensed data and ready-to-use products. The former are data, often provided as 2D images, that are measured from a sensor plugged into a vector (e.g., a satellite, airplane, or drone). Raw images are provided as not calibrated data. Therefore, a geometric and radiometric calibration phases are need before a proper analysis and in order to make comparable in space and time different images. Raw images are often the results of airborne acquisition or private companies whose provide high resolution data. Raw data record in the pixel image DNs according to radiometric resolution. In this framework, the acquisition planning and the calibration are demanded to specialized companies or technicians requiring high technical skills.

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Instead, pre-processed images 2D images where geometric and radiometric calibrations where already performed by international space agencies like NASA or ESA. This kind of remotely sensed images guarantee a more standardized information allowing a spatial and multitemporal images comparison at global scale. Moreover, pre-processed data records reflectance or backscattering values making this kind of data more suitable for a wider not-technical users' community like the one involved in soil management.

Finally, a third type of remotely sensed data are available, i.e. the products. Remote sensing-based products are 2D images providing bio-physical estimates mapped along the footprint of the acquisition. This bio-physical maps are derived by complex algorithms already implemented by products providers. Some examples are spectral indices maps (like NDVI or EVI), leaf-area- index maps and soil moisture maps. A great variety of online services currently exists in order to simplify the access and the download of this type of data.

A review of space/air-borne sensors and products was conducted and summarized here. Particular attention has been paid to the data characteristics like the geometric, spectral, and radiometric resolutions of the products and the possible application in soil monitoring and mapping.

1.4. Criteria for remotely sensed imagery acquisition

The selection of remotely sensed images is primarily determined by the specific applications of the users, who must consider various factors related to both soil/vegetation characteristics and sensor attributes. Regarding soil and vegetation features, constraints are imposed by phenological or agronomic cycles. For instance, soil is exposed and easily detectable only for short periods over agricultural crops, such as during tillage or seeding, whereas natural areas exhibit a leaf-on period where the spectral response is a combination of soil and vegetation. Consequently, it is crucial to acquire data at the optimal moment when the target property contrasts maximally with its surroundings. Additionally, for continuous monitoring of soil or vegetation, missions with high temporal resolution, such as satellite missions, are more suitable than aerial ones. In terms of sensors, technical features impose certain constraints. For aerial surveys, the most relevant issues that users must consider are detailed in the following sections. Establishing a repeatable and standardized method for planning and conducting acquisition missions is essential, particularly if this data is to be integrated with other information sources. Defining the requirements for airborne data in soil applications is necessary for the correct and efficient planning of flights and for the operational applications that will use this data
The main requirements are as follows:

- Acquisition resolutions;
- 3D precision;
- extractable information content.

1.5. Acquisition resolutions

Ordinarily, aerial images are acquired in raster format, i.e, a digital image that expresses a certain geometric resolution. This defines the ground dimension of a pixel (also referred to as Ground Sample Distance, GSD) and can be calculated according to the following formula:

$$GSD = \frac{H}{f} \cdot p$$

- H is the relative flight altitude,
- f the focal length of the camera

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- p is the physical size of the pixel on the sensor (e.g. 3 microns).

While f and p are parameters that depend on the sensor, the flight altitude is an operational parameter that can be influenced in the design of the flight plan.

The optimal dimensions of the GSD for soils survey vary depending on the applications. For example, the photogrammetric survey for the generation of RGB orthophotos and digital models of the heights of agricultural vegetation require GSD of at least 10-20 cm. While the same survey on forest areas requires a GSD of 20-50 cm. Again, the use of thermographic or hyperspectral sensors requires an increase in the size of the GSD to minimize the signal-to-noise ratio of these sensors.

Another characteristic of the images is the spectral resolution. This depends exclusively on the type of sensor and is linked to the regions of the electromagnetic spectrum that each sensor is able to acquire. For example, RGB cameras can only acquire 3 bands (from approximately 400 to 700 nm) and, ordinarily, generate true color images from which it is possible to derive only photogrammetric products such as true color orthophotos and 3D point clouds. Thermographic sensors, on the other hand, acquire only one band in the thermal infrared region (from 7 to 15 μm) where the surfaces show emissive characteristics and are therefore strongly related to their thermal state. High spectral resolutions are instead linked to multi- and hyper-spectral sensors where numerous bands are acquired simultaneously along different regions of the spectrum. The use of these high spectral resolutions in the agro-forestry context allows for greater characterization of the vegetation, allowing its differentiation and recognition.

The temporal resolution of the remotely sensed data is instead linked to the repetition of the surveys. High temporal resolutions are desirable if one wants to monitor the dynamics of the observed surfaces and can be achieved by satellite earth observation missions. Instead, airborne surveys are often characterized by low temporal resolution due to the higher cost of imagery acquisition that depends on weather conditions and surveyors' availability.

1.6. 3D precision

Following the acquisition of a block of aerial images, a subsequent processing of the same is necessary for the extraction of data for agro-forestry and soil mapping. The processing usually occurs with digital photogrammetry techniques. The three-dimensional precision of the returns obtainable from the oriented blocks depends on the characteristics of the sensor (focal and physical pixel), the relative flight altitude and the flight plan, and therefore can be governed by these.

Normally the limiting precision is made up of the vertical component of the measurement (Z). This precision (σ_z) can be estimated in advance once the characteristics of the flight plan according to the formula are known:

$$\sigma_z = \frac{H^2}{fB}\,\sigma_p$$

- H is the relative flight altitude,
- B the baseline,
- f the camera focal length
- σ_p is the measurement uncertainty of the image coordinates (in physical pixel units) which can conservatively be assumed to be equal to half a physical pixel

In particular, the potential planimetric and altimetric accuracies must be estimated before the flight. Such an estimate allows to compare the obtainable accuracies with the metric requirements that a given

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application requires. For example, in the agro-forestry sector, the need for consistency with other maps requires that the precision of the products obtained is equal to or greater than the scale of the maps to be compared. Furthermore, the altimetric precisions must be compatible with the heights of the trees or crops such as to allow a correct morphometric description of the same.

1.7. Extractable information content

The extractable information content depends on the type of sensor used. For example, if you need a morphometric description of surfaces or a true color orthophoto, an RGB sensor is sufficient. While, if one wants to discriminate between different types of surfaces, multi-hyperspectral sensors are necessary for the detection of spectral discriminants. Furthermore, if it is necessary to identify thermal anomalies, energy or evapotranspiration balances, thermographic sensors are required. The common denominator of these information layers is their georeferencing and the maintenance of geometric and radiometric consistencies through photogrammetric processing. If you want to use multispectral or thermographic sensors, their radiometric calibration before their orientation is of fundamental importance.

On the basis of these needs, once the most appropriate sensor has been identified, the flight is planned according to a standard scheme (and formulas) which can be summarized as follows:

- Single frame footprint size (in horizontal HT and vertical VT directions)

  given $\mathbf{s} = \boldsymbol{H/f}$ the average image scale → $\boldsymbol{H_T} = \mathbf{s} \ x \ \boldsymbol{H}$, $\boldsymbol{V_T} = \mathbf{s} \ x \ \boldsymbol{V}$

- Baseline (B) between frames

  if I fly with the longest side of the frame (H) placed parallel to the flight direction

$$B = H_T(1 - O_{Lon})$$

  O_{Lon} is the longitudinal overlap (side) ranging between 0 to 1.
  if I fly with the shortest side of the frame (V) placed parallel to the flight direction

$$B = V_T(1 - O_{Lon})$$

- shutter speed (ts) between two successive frames note the B and aircraft speed (v)

$$t_s = B/v \ [\mathrm{s}]$$

The value obtained must necessarily be higher than the minimum value allowed by the digital camera used (normally declared between 1 and 3 s). If this value is not exceeded, the speed of the aircraft must be reduced.

- Calculation of the flight-line spacing (I)

if I fly with the longest side of the frame (H) placed parallel to the flight direction

$$I = V_T(1 - O_{Lat})$$

O_{Lon} is the latitudinal overlap (forward) ranging between 0 to 1.

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if I fly with the longest side of the frame (H) placed parallel to the direction of flight

$$I = H_T(1 - O_{Lat})$$

Many characteristics of aerial data depend on the survey method, i.e. the flight performed. Correct flight planning allows you to guarantee the precision required for a given application and also mitigate some limitations that a sensor could present, such as: strong focal lengths or too large physical pixels. Flight planning must be conducted considering the topographical conditions of the area to be acquired and the developable GSD. This planning can be supported with special software (e.g. Mission Planner available at https://ardupilot.org/planner/) which, based on the required characteristics (GSD, coverages, etc.) defines the characteristics of the flight lines (altitude, direction, center distance), the acquisition times and the speed of the aircraft/drone.

Sensors

1.8. Imaging Sensors

1.8.1. Spaceborne sensors

1.8.1.1. Scientific and Open data

1.8.1.1.1. Pre-processed data

Satellite images are usually provided as already calibrated data i.e., pixels record reflectance of backscattering values. Moreover, these maps are also geometrically corrected and located making this type of data aligned and comparable to other external geographic layers. Nevertheless, it worth to highlight that this type of data requires a subsequent processing phase (in charge to the user) in order to retrieve bio-physical parameters useful for a real characterization and mapping of soil/vegetation features.

There is an extensive remote sensing literature about the different methods/ techniques developed for this task. Some general overviews of the existing approaches are reported in the following references:

- Mulder, V. L., De Bruin, S., Schaepman, M. E., & Mayr, T. R. (2011). The use of remote sensing in soil and terrain mapping—A review. *Geoderma*, *162*(1-2), 1-19.

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The accuracy of these methods and derived maps are based on the quality of data adopted and processing procedure developed, making slowly the use of this data in the operative sector for a not-scientific community.

A list of the main satellite missions proving multi/hyperspectral, thermal and SAR images is here provided:

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Multispectral missions

Mission	Geometric resolution	Spectral range	Spectral resolution	Radiometric resolution	Temporal resolution	Sensing period	Access
Sentinel-2	10 m- VNIR 20 m - NIR 60 m - UV/NIR/MIR	0.43 -2.2 mm	4 bands – VNIR 6 bands – NIR 3 bands – UV/NIR	12 bits	5 days	2015 -	Free
Landsat-8	30 m- VNIR 15 m - PAN 60 m - UV/NIR/MIR	0.44- 2.29 mm 10.60- 12.51 mm	8 bands– VNIR 1 band – PAN 2 bands – TIR	8 bits	16 days	2013 -	Free
MODIS	250 m - VNIR 500 m - VNIR + MIR 1000 m - VNIR + MIR + TIR	0.4 -14.38 mm	18 bands - VNIR 12 bands - MIR 10 TIR	12 bits	1 day	2000-	Free
Sentinel-3	300 m -VNIR 500 m - VNIR + MIR 1000 m - MIR+ TIR	0.4 - 1.02 mm 10.85 mm 1.37 - 10.85 mm	21 bands - VNIR 5 bands- MIR 3 bands - TIR	12 bits	1 day	2016-	Free
ASTER	15 m - VNIR 30 m - MIR 90 m -TIR	0.52 - 0.86 mm 1.6-2.4 mm 8.12- 11.65 mm	4 bands – VNIR 6 bands – MIR 5 bands – TIR	8 bits	16 days	2000-	Free

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i. Hyperspectral missions

Mission	Geometric resolution	Spectral range	Spectral resolution	Radiometric resolution	Temporal resolution	Sensing period	Access
EnMAP	30 m	0.42 - 2.45 mm	99bands – VNIR 163 bands - MIR	14 bits	4 -27 days	2022 -	Free
PRISMA	30 m	0.4- 2.5 mm 10.60- 12.51 mm	66 bands– VNIR 173 bands – NIR + MIR	12 bits	29 days	2019-	Free

ii. SAR missions

Mission	Geometric resolution	Centre frequency	Polarizations	Radiometric resolution	Temporal resolution	Sensing period	Access
Sentinel-1	1.7 x 4.3 m - SM 2.7 x 22 m - IW	C-band	Dual pol	16 bits	5 days	2015 -	Free
Cosmo SkyMed	1m - Spotlight mode 3 m - Stripmap mode 30 m - ScanSAR mode	X-band	Dual pol	8 bits	16 days	2007 -	Free
TerraSAR-X	0.25 - 1 m Spotlight 3 m - stripmap 18.5 m ScanSAR	X-band	Dual pol	16 bits	11 days	2007-	Free

1.8.1.1.2. Ready-to-use products

A list of the main satellite-based products is here provided:

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Normalized Difference Vegetation Index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
NDVI provide consistent spatial and temporal comparisons of vegetation canopy greenness, a composite property of leaf area, chlorophyll and canopy structure.	Copernicus Global Land Service	2014 -	300 m	10-days composite
	MODIS	2000 -	250 m	16-day composite

Leaf Area index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The LAI is defined as half the total area of green elements of the canopy per unit horizontal ground area. The satellite-derived value corresponds to the total green LAI of all the canopy layers, including the understory which may represent a very significant contribution, particularly for forests. Practically, the LAI quantifies the thickness of the vegetation cover.	Copernicus Global Land Service	2014 -	300 m	1 day
	MODIS	2000 -	500 m	8-day composite

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Vegetation Condition Index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Vegetation Condition Index (VCI) compares the current NDVI to the range of values observed in the same period in previous years. The VCI is expressed in % and gives an idea where the observed value is situated between the extreme values (minimum and maximum) in the previous years. Lower and higher values indicate bad and good vegetation state conditions, respectively.	Copernicus Global Land Service	2013 - 2020	1000 m	10-days composite

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Vegetation Productivity Index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Vegetation Productivity Index (VPI) assesses the overall vegetation condition by referencing the current value of the NDVI with the long-term statistics for the same period. The VPI is a percentile ranking of the current NDVI value against its historical range of variability: values of 0%, 50% and 100% respectively indicate that the current observation corresponds with the historical minimum (worst vegetation state), median (normal) or maximum (best situation) ever observed.	Copernicus Global Land Service	2013 - 2018	1000 m	10-days composite

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Plant Phenology Index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Plant phenology index (PPI) is a physically-based vegetation index for estimating phenology from remotely sensed data. It was developed from radiative transfer theory, and uses the difference vegetation index and a modification of Beer's law to be linear to green leaf area index (LAI) The index has strong correlation with gross primary productivity (GPP), and is shown capable of disentangling remotely sensed plant phenology from snow seasonality. PPI has been reported to be superior to other indices for spring phenology retrieval over the northern latitudes	Copernicus Global Land Service	2017-	10 m	10-days composite

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Vegetation Phenology and Productivity Parameters

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Vegetation Phenology Parameters (VPPs) product bundle are derived from the time series of the PPI index, on a yearly basis, after the end of the growing season. VPP metrics are provided for up to two growing seasons, being e.g. start of the season, end of season, seasonal productivity.	Copernicus Global Land Service	2017-	10 m	Yearly

Dry Matter Productivity

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Dry Matter Productivity (DMP) represents the overall growth rate or dry biomass increase of the vegetation, expressed in kilograms of dry matter per hectare per day (kgDM/ha/day).	Copernicus Global Land Service	2014-	300 m	10-days composite

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Burnt Areas

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Burnt Area products map burn scars, surfaces which have been sufficiently affected by fire to display significant changes in the vegetation cover (destruction of dry material, reduction or loss of green material) and in the ground surface (temporarily darker because of ash). Moreover, they give temporal information on the fire season.	Copernicus Global Land Service	2019-	300 m	1 day or 1 month composite
	MODIS	2000 -	1000 m	1 day or 8 days composite

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Soil Water Index

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Soil Water Index quantifies the moisture condition at various depths in the soil. It is mainly driven by the precipitation via the process of infiltration. Soil moisture is a very heterogeneous variable and varies on small scales with soil properties and drainage patterns. Satellite measurements integrate over relative large-scale areas, with the presence of vegetation adding complexity to the interpretation.	Copernicus Global Land Service	2015-	1000 m	1 day

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Surface Soil Moisture

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Surface Soil Moisture (SSM) is the relative water content of the top few centimeters soil, describing how wet or dry the soil is in its topmost layer, expressed in percent saturation. It is measured by satellite radar sensors and allows insights in local precipitation impacts and soil conditions. SSM is a key driver of water and heat fluxes between the ground and the atmosphere, regulating air temperature and humidity. Moreover, in its role as water supply, it is vital to vegetation health. Vice versa, SSM is very sensitive to external forcing in the form of precipitation, temperature, solar irradiation, humidity, and wind. SSM is thus both an integrator of climatic conditions and a driver of local weather and climate, and plays a major role in global water-, energy- and carbon- cycles.	Copernicus Global Land Service	2014-	1000 m	1 day
	SMOS	2009 -	35000 m	2 to 5 days

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Land Surface Temperature and Emissivity

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Land Surface Temperature (LST) is the radiative skin temperature of the land surface. It is estimated from Top-of-Atmosphere brightness temperatures from the infrared spectral channels	Copernicus Global Land Service	2010-	5000 m	Hourly or 10 days composite
	MODIS	2000 -	1000 m	1 day or 8 days composite

Evapotranspiration

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Evapotranspiration (ET) is the combined term to describe the water loss occurring by the processes of evaporation and transpiration. For vegetated surfaces, its refers to the water consumed by plants over a period of time. Calculation of ET is typically based on the conservation of either energy or mass, or both. Computing ET requires the estimation and combination of two complicated estimations; the stomatal conductance of the vegetation to derive transpiration and evaporation from the ground surface.	MODIS	2000 -	500 m	8-days composite or Yearly

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Snow Cover Extent

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Snow cover is highly sensitive to changes in temperature (freezing/thaw) and precipitation (snowfall, rain, hail) and affects directly the albedo and thus the energy balance of the Earth's surface. It is a relevant input parameter for weather forecasts and climate change observations. Snow stores a significant mass of water and, with its high dynamic, has a strong effect on regional and global energy and water cycles.	MODIS	2000 -	500 m	1 day or 8-days composite or Monthly

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Snow Water Equivalent

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Snow Water Equivalent (SWE) describes the equivalent amount of liquid water stored in the snow pack. It indicates the water column that would theoretically result should the whole snow pack melt instantaneously and is defined as product between the snow layer's depth and density. Information about snow water equivalent is needed in applications such as flood forecasting, controlling the water level of power plant reservoirs, planning for forestry and crop irrigation and as input and control variable for many environment research purposes, including climate change research.	Copernicus Global Land Service	2006-	5000 m	1 day

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Gross Primary Production

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Gross Primary Production product is designed to provide an accurate regular measure of the growth of the terrestrial vegetation. Production is determined by first computing a daily net photosynthesis value which is then composited over an 8-day interval of observations for a year. The product is a cumulative composite of GPP values based on the radiation use efficiency concept that may be used as inputs to data models for calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation.	MODIS	2000 -	1000 m	8-days composite or Yearly

Net Primary Production

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Net Primary Production product is designed to provide an accurate regular measure of the growth of the terrestrial vegetation.	Copernicus Global Land Service	2014-	300 m	10-days composite
	MODIS	2000 -	1000 m	Yearly

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Land Covers

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
Land cover maps represent spatial information on different types (classes) of physical coverage of the Earth's surface, e.g. forests, grasslands, croplands, lakes, wetlands. Dynamic land cover maps include transitions of land cover classes over time and hence captures land cover changes. Land use maps contain spatial information on the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it.	Copernicus Global Land Service	2015-2019	100 m	Yearly
	MODIS	2000 -	500 m	Yearly
	Corine Land Cover	1990, 2000,2006,2012,2018	500 m	1990, 2000,2006,2012,2018

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Fraction of photosynthetically active radiation absorbed by the vegetation

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The proportion of solar energy that is absorbed by living leaves for photosynthesis is measured by the FAPAR. Then, it only refers to the canopy's green and living components. The canopy structure, optical characteristics of the vegetation elements, atmospheric conditions, and angular orientation all affect the FAPAR.	Copernicus Global Land Service	2014 -	300 m	1 day
	MODIS	2000 -	500 m	8-day composite

Fraction of green vegetation cover

Description	Provider	Temporal Coverage	Geometric resolution	Temporal resolution
The Fraction of Vegetation Cover corresponds to the fraction of ground covered by green vegetation. Practically, it quantifies the spatial extent of the vegetation.	Copernicus Global Land Service	2014-	300 m	10-days composite

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1.8.1.2. Commercial Data

i. Multispectral missions

Mission	Geometric resolution	Spectral range	Spectral resolution	Radiometric resolution	Temporal resolution	Sensing period	Access
QUICKBIRD	0.65 m - PAN 2.9m - VNIR	0.45- 0.90 mm	5 bands– VNIR	11 bits	1 to 3.5 days	2001 -	Commercial
GeoEye-1	0.5 m - PAN 1.84 m - VNIR	0.45- 0.92 mm	5 bands – VNIR	11 bits	2 days	2008 -	Commercial
EROS (A, B)	0.38 m - PAN 0.76 m - VNIR	0.45 - 0.90 mm	4 bands – VNIR	12 bits	1 day	2001-	Commercial
WorldView-3	0.3 m - PAN 1.24 m - VNIR 3 m - MIR	0.45- 2.24 mm	8 bands – VNIR 8 bands - MIR	11 bits - VNIR 14 bit - MIR	1 day	2014-	Commercial
ORBVIEW 4	1m - VNIR 4 m - VNIR	0.45 -0.9 mm	5 bands - VNIR	11 bits	< 3 days	2003-	Commercial
Planetscope	3 m - VNIR	0.4 - 0.9 mm	8 bands - VNIR	16 bits	1 day	2016-	Commercial
RAPIDEYE	5 m - VNIR	0.44-0.85 mm	5 bands - VNIR	16 bits	5 days	2012-	Commercial
SKYSAT	0.5 m - VNIR	0.45 - 0.90 mm	5 bands - VNIR	16 bits	6 days	2013-	Commercial
Pléiades	0.5 m - PAN 2 m - VNIR	0.43 - 0.90 mm	6 bands	12 bits	1 day	2011-	Commercial

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ii. SAR missions

Mission	Geometric resolution	Centre frequency	Polarizations	Radiometric resolution	Temporal resolution	Sensing period	Access
ICEYE	0.5 m	X-band	VV	16 bits	1 to 22 days	2018-	Commercial

1.8.2. Airborne/UAV sensors

Aerial sensors List

		**MAPIR - Survey 2**	
Image resolution	16 MPix (4608 x 3450)	Shutter Type	Rolling shutter
Focal length	3.97 mm	Minimum Timelaps	2-3 sec
HFOV	82°	Bands	Red , green, blue, NIR
Sensor filter	Bayer RGB	Radiometric resolution	12, 8 bits
Pixel size	1.34 mm	Output format	Raw, jpg
Weight	64 g	Indicative cost	200-250 € (at 2018)

		**MAPIR - Survey 3**	
Image resolution	12 MPix (4000 x 3000)	Shutter Type	Rolling shutter
Focal length	3.72 or 8.25 mm	Minimum Timelaps	2.7 - 1.5 sec
HFOV	87°or 41°	Bands	Red , cyan, orange, green, blue, red-edge, NIR
Sensor filter	Bayer RGB	Radiometric resolution	12, 8 bits
Pixel size	1.55 mm	Output format	Raw, jpg
Weight	76 g	Indicative cost	350 € (at 2018)

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		**MAPIR - Kernel**	
Image resolution	3.2 MPix (2048 x 1536)	Shutter Type	Rolling shutter
Focal length	9.6 mm	Minimum Timelaps	2-3 sec
HFOV	41°	Bands	Red , cyan, orange, green, blue, red-edge, NIR
Sensor filter	Bayer RGB	Radiometric resolution	12, 16 bits
Pixel size	3.44 mm	Output format	Raw, tiff
Weight	45 g	Indicative cost	1300 €

		**MicaSense - Red-Edge-M**	
Image resolution	1.2 MPix (1280 x 960)	Shutter Type	Global shutter
Focal length	5.4 mm	Minimum Timelaps	1 sec
HFOV	47.2°	Bands	Red , green, blue, red-edge, NIR
Sensor filter	na	Radiometric resolution	12, 16 bits
Pixel size	3.6 mm	Output format	DNG, Raw, jpg
Weight	160 g	Indicative cost	4200 €

		**MicaSense - Red-Edge-MX**	
Image resolution	1.2 MPix (1280 x 960)	Shutter Type	Global shutter
Focal length	5.4 mm	Minimum Timelaps	1 sec
HFOV	47.2°	Bands	Red , green, blue, red-edge, NIR
Sensor filter	na	Radiometric resolution	12 bits
Pixel size	3.6 mm	Output format	Raw
Weight	231 g	Indicative cost	5500 €

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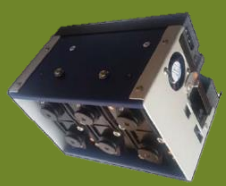
		**MicaSense - Altum**	
Image resolution	3.2 MPix (2064 x 1544)	Shutter Type	Global shutter
Focal length	8 or 1.77 mm	Minimum Timelaps	1 sec
HFOV	48° or 57°	Bands	Red , green, blue, red-edge, NIR
Sensor filter	na	Radiometric resolution	12 bits
Pixel size	3.6 mm	Output format	Raw
Weight	406 g	Indicative cost	12000 €

		**Parrot - Sequoia**	
Image resolution	16 MPix (4608 x 345) - RGB 1.2 (1280 x 960) - VNIR	Shutter Type	Rolling shutter - RGB Global shutter - VNIR
Focal length	4.88 mm - RGB 3.98 mm - VNIR	Minimum Timelaps	1 sec
HFOV	70.6°	Bands	Red, green, blue, red-edge, NIR
Sensor filter	Bayer RGB	Radiometric resolution	12, 8 bits
Pixel size	1.34 mm - RGB 3.75 mm - VNIR	Output format	Raw, jpg
Weight	108 g	Indicative cost	3300 €
		**Tetracam - MACAW**	
Image resolution	1.3 MPix (1280 x 1024)	Shutter Type	Global shutter
Focal length	9.6 mm	Minimum Timelaps	0.5 sec
HFOV	na	Bands	6 bands (450 -1000 nm)
Sensor filter	na	Radiometric resolution	10, 8 bits
Pixel size	4.8 mm	Output format	Tiff
Weight	600 g	Indicative cost	na

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		**Tetracam - Micro MCA**	
Image resolution	1.3 MPix (1280 x 1024)	Shutter Type	Global shutter
Focal length	9.6 mm	Minimum Timelaps	0.5 sec
HFOV	38 °	Bands	6 bands (450 -1000 nm)
Sensor filter	na	Radiometric resolution	10, 8 bits
Pixel size	5.2 mm	Output format	Tiff
Weight	600 g	Indicative cost	na

		**AIRNOV - MultiSpec 4C**	
Image resolution	1.2 MPix (1280 x 960)	Shutter Type	na
Focal length	3.8 mm	Minimum Timelaps	na
HFOV	65°	Bands	Red , green, blue, red-edge, NIR
Sensor filter	na	Radiometric resolution	10 bits
Pixel size	3.75 mm	Output format	Raw, tiff
Weight	160 g	Indicative cost	11500 €

		**SAL Engineering - MAIA S2**	
Image resolution	1.2 MPix (1280 x 960)	Shutter Type	Global shutter
Focal length	7.5 mm	Minimum Timelaps	na
HFOV	35 °	Bands	9 bands (400 -900 nm)
Sensor filter	Bayer RGB	Radiometric resolution	8,10,12 bits
Pixel size	3.75 mm	Output format	Raw
Weight	420 g	Indicative cost	13000 €

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		**Sentera - High-precision NDVI & NDRE Single sensors**	
Image resolution	1.2 MPix (1248 x 950)	Shutter Type	na
Focal length	4.14 mm	Minimum Timelaps	na
HFOV	60 °	Bands	4 bands (400 -850 nm)
Sensor filter	na	Radiometric resolution	na
Pixel size	3.75 mm	Output format	Jpeg, tiff
Weight	30 g	Indicative cost	2000 €

		**Sentera - Double 4 K**	
Image resolution	12.3 MPix (3000x4000)	Shutter Type	na
Focal length	5.39 mm	Minimum Timelaps	na
HFOV	60 °	Bands	4 bands (400 -850 nm)
Sensor filter	na	Radiometric resolution	12, 10 bits
Pixel size	1.55 mm	Output format	Jpeg
Weight	80 g	Indicative cost	2000 €

		**Sentera - Quad Sensor**	
Image resolution	1.2 MPix	Shutter Type	Global shutter
Focal length	5.1 mm	Minimum Timelaps	7 fps
HFOV	50°	Bands	4 bands (400 -850 nm)
Sensor filter	na	Radiometric resolution	na
Pixel size	3.75 mm	Output format	Jpeg, tiff
Weight	170 g	Indicative cost	3800-5000 €

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		**Buzzard - Six bands camera**	
Image resolution	1.3 MPix (1280 x 1024)	Shutter Type	Global shutter
Focal length	11.3 mm	Minimum Timelaps	7 fps
HFOV	32°	Bands	6 bands (400 -850 nm)
Sensor filter	na	Radiometric resolution	8, 10 bits
Pixel size	5 mm	Output format	tiff
Weight	250 g	Indicative cost	6300 €

1.8.2.1. Sensor types

A. RGB sensors

The simplest and most popular way of recording images is to obtain photos in the visible band (RGB - Red, Green, Blue - which is one of the color space models), such data is identical to the image seen by people and at the same time the easiest to analyze using simple methods and by ordinary users. Such sensors are commonly mounted on drones and perform various functions. Their wide availability translates into a large variety of parameters they meet, so there are cheap, small cameras with limited resolution of the recorded image and a built-in lens, costing less than EUR 500, but there are also larger, expensive cameras, with high resolution of the recorded image and interchangeable lenses. The text below will present several examples of popular drones with built-in RGB sensors, with various parameters, and then describe the possibilities of their applications in soil monitoring.

Visible light is electromagnetic radiation in the wavelength range of 400 nanometers (blue) - 750 nanometers (red), which is received and processed by the retina of the human eye. To record images in this radiation band, photosensitive matrices made using CMOS (complementary metal–oxide–semiconductor) or CCD (charge-coupled device) technology are used. The photosensitive matrix consists of a system of photosensitive elements that record an electrical signal depending on the amount of light falling on them. The main difference between CCD and CMOS matrices is the method of converting electrical signals and their further transmission; in the case of a CCD matrix, data from sensors (pixels) are read in entire rows, row by row. In the case of a CMOS matrix, data is read from individual pixels. CCD matrices have greater sensitivity and lower noise of recorded data compared to CMOS matrices, which in turn work faster and do not need so much energy and heat up less.

Table 6 *Wavelength of particular ranges of visible light*

Color	Wave lenght [nm]
Red	635 - 770
Orange	590 - 635
Yellow	565 - 590
Green	520 - 565
Cyan	500 - 520
Blue	450 - 500
Purple	380 - 450

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source: Łukasiewicz-Institute of Aviation

Table 7 Comparison of cameras built into selected commercial drones

Drone	Size	Resolution	Angle of view	Matrix	Aperture	Estimated price
DJI AIR 2S	20MP	5472x3648	88	CMOS 1/2,4"	f/2,8	1 200 €
DJI Avata	48MP	4000x3000	155	CMOS 1/1,7"	f/2,8	700 €
DJI mini 2	12MP	4000x3000	83	CMOS 1/2,3"	f/2,8	350 €
DJI mini 3	12MP	5280x3956	82,1	CMOS 1/1,3"	f/1,7	500 €
DJI Mini 4 Pro	48MP	8064x6048	82,1	CMOS 1/1,3"	f/1,7	1 000 €
DJI mavic 3	20MP	5280x3956	84	CMOS 4/3"	f/2,8 - f/1,1	1 700 €
DJI Phantom 4 Pro	20MP	5472x3648	-	CMOS 1"	-	1 400 €
Ryze Tello edu	5MP	2592x1936	82,6	-	-	180 €
Autel evo max 4T (zoom)	48MP	8000×6000	-	CMOS 1/1/2"	f/2.8-f/4.8	1 700 €
Autel evo max 4T (wide angle)	50MP	3840x2160	85	CMOS 1/1.28"	f/1.9	
Syma X8 PRO	1MP	1280x720	120/90	CMOS	-	100 €
VIAOMI FIMI X8 Mini Pro V2 Standard	12MP	-	81,1	CMOS 1/2,5"	f/2,0	420 €
Autel EVO Lite+	20MP	5472 × 3648	82	CMOS 1"	f/2.8 - f/11	700 €

source: Łukasiewicz-Institute of Aviation

Data obtained from RGB sensors are widely used both as raw data and after processing into photogrammetric and remote sensing products. Based on the data, differences in soil color can be assessed in order to detect differences in the soil type or its granulometry, which can be used to undertake work to change fertilization or change the scope of field work in detected fragments of the field with parameters differing from the entire area.

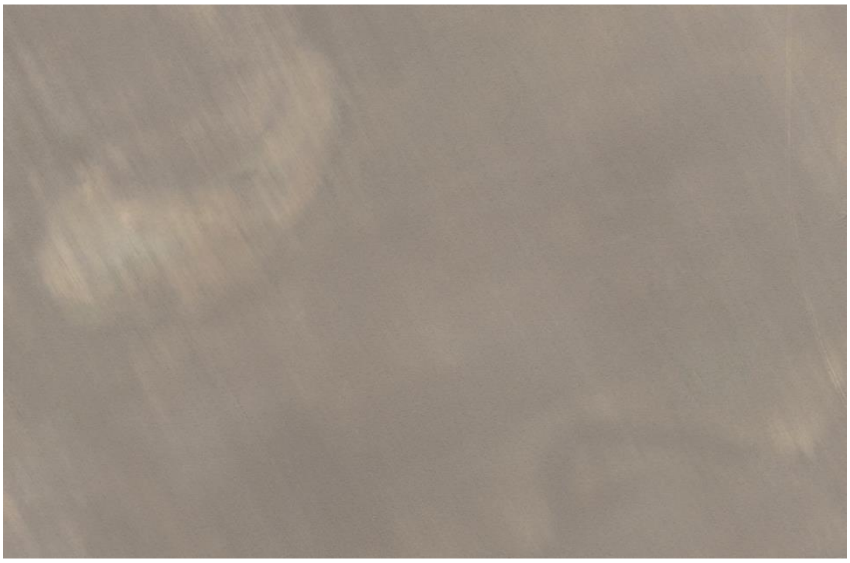

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Figure 8 Example of visibility of soil color change in RGB photos
source: Łukasiewicz-Institute of Aviation

The situation is similar with the analysis of photogrammetric products, e.g. the Digital Terrain Model obtained as a step in generating an orthophotomap from a set of photos. The analysis of this product allows you to determine the topography of the field, determine slopes and associate possible changes in soil class and type with the topography.

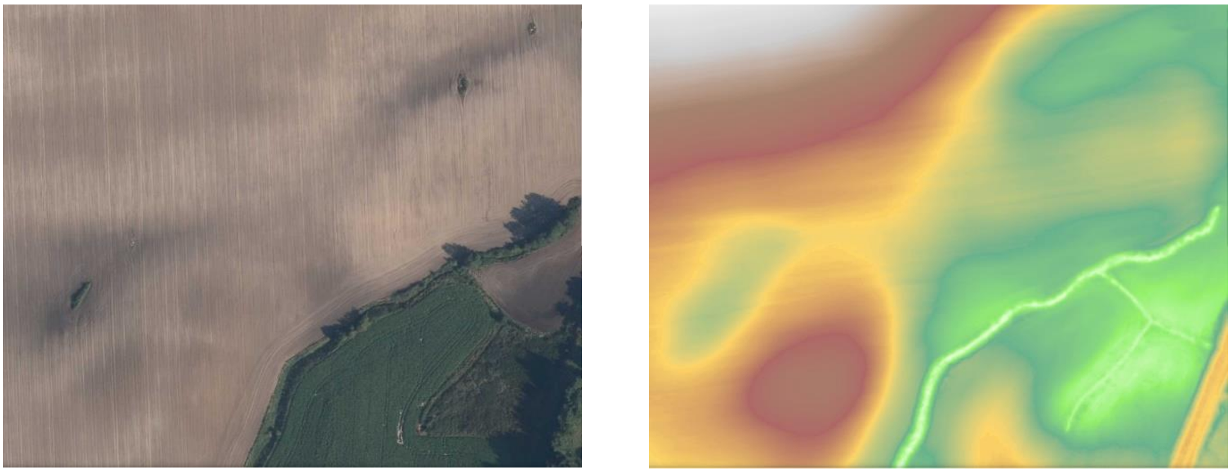

Figure9 Comparison of soil color changes with field topography
source: https://www.geoportal.gov.pl/

RGB photos also allow the classification of soil texture using algorithms based on RGB characteristics (Sun-Ok et al., 2010) and the determination of soil pH using regression of RGB values (Mithun et al., 2023).

The two main problems associated with the analysis of RGB soil photos are:

- a large dependence on the time of day on the appearance of the photo - on clear days, shadows cast by the sun may have a significant impact on the photo, especially in the morning and afternoon.
- the quality of aerial photographs is highly dependent on weather conditions. Ideal weather conditions for aerial photography include:

1. High, even cloud cover: Provides good light dispersion without casting shadows.
2. Clear and sunny: Causes shadows to appear.
3. Partial cloud cover: Results in inconsistent illumination, with some photos having soil illuminated and others shaded, making comparison difficult.
4. Rain: Either prevents flights or complicates them significantly.

It is also important to perform subsequent flights under similar weather conditions to ensure the comparability of the images. Differences in soil moisture in photographs can still yield valuable insights, such as:

- Identifying areas that dry out the fastest.
- Determining where moisture persists the longest.
- This information can help identify regions susceptible to drought or crop rot.

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B. Multispectral

Examples of using multispectral sensor on UAV platforms for soil properties monitoring:

- Wei et al. (2020) employed a 6-band Micro-MCA multispectral sensor mounted on a UAV to estimate **soil salt content (SSC)**. They found that the UAV-borne multispectral remote sensing technique holds significant potential for SSC estimation, with higher reflectance observed in saline soil compared to non-saline soil. Saline soil exhibits absorption peaks at 671 nm and a sensitive band for SSC between 882–997 nm. Among the tested bands, 680 nm, 800 nm, and 900 nm were identified as containing the most salinity-related information. Their findings highlighted the Random Forest (RF) model's superior performance in bare land inversion.
- Yu et al., (2022) utilized the Parrot Sequoia agriculture multispectral camera, as part of the UAV image acquisition system to investigate sensitive parameters and optimal methods for accurate retrieval and spatial distribution of **soil salinity**. During the UAV image acquisition period, the UAV's flight altitude was set to 50 m, with a spatial resolution of 5 cm. The G, R, and NIR bands were identified as sensitive to soil salinity. The proposed Soil Salinity Retrieval Index (SSRI) based on the Random Forest (RF) method exhibited the highest accuracy in predicting soil salinity.
- Zhao et al. (2022) developed and optimized an inversion monitoring model using UAV multispectral remote sensing to track **Soil Salt Content (SSC)**. They employed a multispectral camera with six CMOS image sensors capturing bands from Blue to NIR. Through analysis of multispectral data from areas with diverse vegetation coverage, they established variety models for soil salt inversion, enabling rapid inversion across cultivated and bare land at a regional scale. Spectral index-based models demonstrated notable accuracy, particularly with the red edge band enhancing accuracy in vegetated saline-alkali land. This study provides crucial technical support for swiftly monitoring, inverting, and controlling soil salinization in irrigation areas.
- Gilliot et al. (2016), focusing on environmental issues, a method for predicting **Soil Organic Carbon** (SOC) content in the bare, cultivated topsoil layer based on multispectral images from UAVs was proposed. The study was conducted on a 13-hectare agricultural plot in the western region of Paris. Samples were collected from 23 ground control points, and various measurements, including spectroradiometry, soil roughness, and moisture content, were taken. The model was enhanced by considering moisture and roughness, improving the prediction accuracy of SOC content by 18% in cultivated soil enriched with recycled organic waste.
- Goffart et al. (2022) highlighted the complexity of soil parameters in agriculture, such as **SOC, N, P, exchangeable cations, pH, and soil texture**, influenced by various biological, physical, and historical factors. Crop mapping, facilitated by UAVs equipped with multispectral cameras, aids in understanding crop growth diversity and its correlation with soil properties. Their study demonstrated the effectiveness of the CI-forest (conditional inference forest algorithm) technique in quantifying the impact of soil property spatial variability on crop growth.
- Zhu et al. (2023) investigated **soil moisture** mapping in the root zone of kiwi trees across three crucial fruit growth stages using multispectral UAV images and machine learning (ML) algorithms in China. They utilized a ten-channel Red-Edge MX Dual camera to capture kiwi multispectral (MS) images. The study compared the accuracy of three ML algorithms using the VIP (variable importance) method to select seven sensitive input vegetation indices. Results showed that the VIP method effectively reduced vegetation indices while maintaining model accuracy. Shallow root-zone models exhibited higher accuracy than deep root-zone models, and RF (random Forest) algorithm accuracy varied with growth stages. This research highlights the potential of ML methods for precise irrigation management using UAVs.

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- Raihan (2018) emphasized the significant influence of spatial scale on **soil moisture** estimation accuracy and the potential of unmanned remote sensing for water management in specific areas, providing high spatial accuracy soil moisture information. Raihan assessed the effectiveness of utilizing multispectral imagery from an Unmanned Aerial System (UAS), satellite images, and thermal data for estimating surface soil moisture (gravimetric water content, GWC). A RedEdge sensor onboard the UAS captured multispectral images with five bands covering various wavelengths. Two indices, the soil moisture index (SMI) and the temperature vegetation dryness index (TVDI), were employed to estimate GWC. The accuracy assessment for soil moisture estimation was conducted at five spatial scales for two surface scenarios. Semi variogram analysis revealed that the strongest correlation between measured GWC and UAS-derived indices occurred at a 1 m spatial scale. UAS images enabled better differentiation between plant canopy and soil surface, further enhancing estimation accuracy.
- Angelopoulou et al. (2019) evaluated the predictive capacity of multispectral images (400-810 nm) obtained from a Parrot Sequoia multispectral camera in estimating soil properties, particularly **organic matter content (SOM)**, in a 6-hectare experimental field in Greece. They conducted comparative analyses with laboratory spectral measurements in the VNIR-SWIR range (400-2500 nm) and chemically characterized soil samples to calibrate prediction models. Utilizing support vector machine for regression (SVR) algorithm, calibrated with imagery data values, laboratory spectral signatures, and spectral indices. Despite differences in spectral information, both methods showed adequate performance in SOM estimation, with similar spatial distribution trends. The study emphasizes the importance of precise data acquisition procedures, radiometric calibration, and corrective tasks for accurate soil property estimation under real field conditions.
- Araya et al. (2020) demonstrated the accurate interpretation of surface **soil moisture** through multispectral UAS remote sensing coupled with machine learning methods. Flights were conducted in clear weather conditions using a fixed-wing unmanned aircraft equipped with a Parrot Sequoia Sensor and a sunshine sensor for radiometric normalization. Machine learning models were developed utilizing terrain attributes and local climatic covariates, achieving precise estimation of surface soil moisture (0–4 cm). Key variables for prediction included precipitation, red spectral range reflectance, potential evapotranspiration, and topographic position indices. The study underscores the feasibility of accurate soil moisture estimation, even in challenging terrain conditions, through UAS remote sensing and machine learning techniques.

Table 8 Example Multispectral sensors

Sensor	Bands/Sensitivity in nm, (Bandwidth in nm)	UAVs platform	Soil application	Literature
Micro-MCA multispectral sensor (Tetracam Corporation, Chatsworth, CA, USA)	B1 - 490, B2 - 550, B3 - 680, B4 - 720, B5 - 800, B6 - 900 (10-25)	DJI Matrice 600 six-rotor UAV (Shenzhen Dajiang Innovation Technology Co., Ltd., Shenzhen, China)	Soil salt content	Wei et al. (2020)
Parrot Sequoia multispectral camera (Parrot SA, Paris, France)	G-550 (40), R- 660 (40), RE -735 (10), NIR - 790 (40)	DJI Matrice 600 Pro (Shenzhen Dajiang Innovation Technology Co.,	Soil salt content	Yu et al., 2022

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		Ltd., Shenzhen, China)		
CMOS image sensors	B - 450 (16), G -560 (16), R - 650 (16), RE -730 (16), NIR - 840 (26)	DJI P4 (DJI-Innovations, Shenzhen, China)	Soil salt content	Zhao et al. (2022)
Airinov MultiSPEC 4C camera (Sensefly ; Airinov)	G-550, R-660, RE-735, NIR-790	UAV platform used was a fixed wing provided by Airinov®	Soil organic carbon	Gilliot et al., (2016)
RedEdge-M™ sensor from MicaSense® (Washington, DC, USA)	B-475 (20), G -560 (20), R-668 (10), RE-717 (10), NIR-840 (40)	DJI Phantom3, DJI-Innovations, Shenzhen, China	Soil organic carbon, nitrogen, phosphorous, exchangeable cations, pH, soil texture	Goffart et al. (2022)
Red-Edge MX Dual camera (MicaSense, Seattle, WA, USA)	B1-444 (28), B2-475 (32), B3-531 (14), B4-560 (27), B5-650 (16), B6-668 (14), B7-705 (10), B8-717 (12), B9-740 (18), b10-842(57)	DJI Matrice 600 Pro (Shenzhen Dajiang Innovation Technology Co., Ltd., Shenzhen, China)	Soil Moisture	Zhu et al., (2023)
MicaSense RedEdge (MicaSense, Seattle, WA, USA)	475 (20), 560 (20), 668 (10), 717 (10), 840 (40)	DJI Matrice 600 Pro (Shenzhen Dajiang Innovation Technology Co., Ltd., Shenzhen, China)	Soil Moisture	Raihan (2018)
Parrot Sequoia multispectral camera (Parrot SA, Paris, France)	G-550 (40), R – 660 (40), RE-735 (10), NIR – 790 (40)	eBee platform	organic matter content - SOM	Angelopoulou et al. (2019)
Parrot Sequoia multispectral camera (Parrot SA, Paris, France)	G-550 (40), R – 660 (40), RE-735 (10), NIR – 790 (40)	Fixed-wing unmanned aircraft (Finwing Sabre, Finwing Technology)	Soil Moisture	Araya et al. (2020)

source: Łukasiewicz-Institute of Aviation

C. Medium Infrared (MIR)

Medium infrared (MIR) or Short-Wave Infrared (SWIR) is a spectral range of wavelength typically between 1.0 and 2.5 µm (1000 – 2500 nm). The band is useful for various applications due to its unique properties. For instance, SWIR light can penetrate through smoke, haze, and some materials, making it valuable for imaging and observational purposes under conditions that would obscure vision in the visible spectrum. It's used in a variety of fields such as remote sensing, night vision, and industrial inspection.

In remote sensing, SWIR sensors can detect moisture content in soil and vegetation, differentiate between types of minerals and rocks, and monitor plant health.

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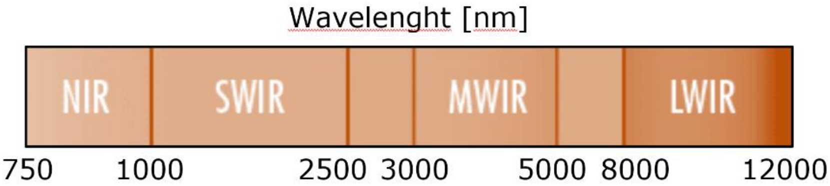

Figure10 Classification of infrared band
source: Łukasiewicz-Institute of Aviation

The application of SWIR cameras mounted on UAVs has demonstrated potential in agriculture and environmental monitoring. Some applications improved due to the use of SWIR cameras are: the accuracy and efficiency of soil moisture estimation, crop traits monitoring, and environmental conservation practices. However, the main disadvantages of these types of sensors is still a high cost of these cameras and complicated exploitation. Some of the examples of cameras for the use with their key features.

Table9. Examples of SWIR cameras for UAVs

Specification	FLIR A6521sc	Raptor Photonics Owl 640	Specim AFX17	Xenics Bobcat-640
Image				
Type	SWIR Camera	SWIR Camera	Hyperspectral SWIR Camera	SWIR Camera
Resolution	640 x 512	640 x 512	640 x 512	640 x 512
Spectral Range	1.0 to 5.0 µm	0.4 to 1.7 µm	900 to 1700 nm	0.9 to 1.7 µm
Frame Rate	Up to 100 Hz (full frame)	Up to 120 Hz (full frame)	Up to 400 fps (reduced spatial resolution)	Up to 100 Hz (full frame)
Cooling	Stirling cooler	Optional: Thermoelectric	Air-cooled (optional liquid cooling)	Thermoelectric
Interface	GigE, Camera Link	GigE, Camera Link	Camera Link	GigE, Camera Link
Weight	~2.3 kg	< 500 g	~ 1.2 kg	< 500 g
Key Features	High sensitivity, large spectral range, interchangeable filters	High sensitivity and resolution in low light	Hyperspectral imaging for detailed analysis	Compact and lightweight design
Applications	Research, Science, Industrial	Military, Surveillance, Scientific Research	Precision Agriculture, Environmental Monitoring	Industrial Inspection, Surveillance
Comments	One spectral range at the moment, no IMU, software included	One spectral range at the moment, no IMU, no	Hyperspectral data, full set with software and IMU	One spectral range at the moment, no

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		software, no lens		IMU, no software
Estimated price	~40 000 EUR	<10 000 EUR	~80 000 EUR	No data

source: Łukasiewicz-Institute of Aviation

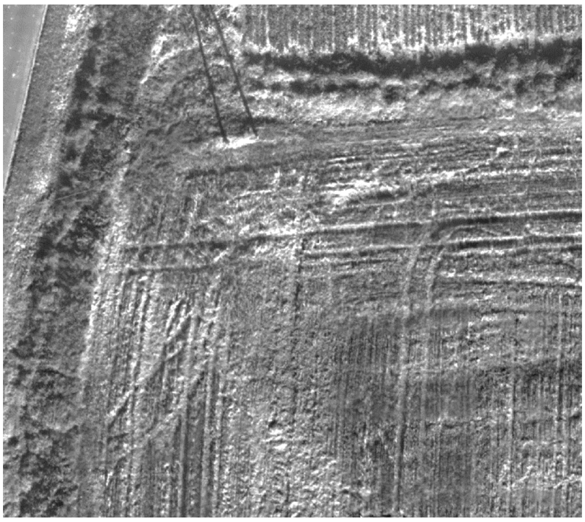

Figure11. Example of image acquired RGB (a) with SWIR (b) camera - FLIR A6521sc
source: Łukasiewicz-Institute of Aviation

Areas of application

- **Disease and Pest Detection**: Certain plant diseases and infestations alter the plant's reflectance in the SWIR range. Most of the research now focus on spectrometry applications including SWIR band. For instance, early detection of Apple Fire Blight is possible with the use of SWIR band (Skoneczny et al. 2020). Early detection of these changes allows for timely intervention, reducing the spread of disease and minimizing crop loss.
- **Crop Type and Maturity Classification**: SWIR imagery can help in identifying different crop types and their maturity stages based on their spectral signatures. This information is valuable for harvest planning and to ensure optimal timing for crop collection. As an example Jenal et al. (2021) investigated a newly developed UAV-mounted VNIR/SWIR imaging system's potential for monitoring winter wheat crop traits.
- **Vegetation Health State**: Plants under stress (due to lack of nutrients, water stress, or disease) exhibit changes in their SWIR spectral reflectance. Early detection helps in mitigating stress factors promptly, ensuring the health and productivity of crops. Some studies applied specific vegetation indices using the system's sensitivity from 600 to 1700 nm, demonstrating its capability in estimating fresh and dry biomass, crop moisture, nitrogen concentration, and uptake with significant accuracy. These findings suggest the imaging system's potential for precision agriculture applications, although further validations are needed (Jenal et al., 2021).
- **Soil Organic Carbon Prediction**: Research on the performance of UAS-compatible multispectral and hyperspectral sensors for soil organic carbon prediction highlights the effectiveness of VNIR and SWIR sensors in estimating soil organic carbon accurately. (Crucil et al., 2019) found that prediction models using narrow bands of multispectral cameras provided similar or better performances than those using continuous spectra from hyperspectral sensors, recommending VIS-NIR instruments for spatially distributed soil data estimation (Crucil et al., 2019).

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- **Moisture Measurement**: SWIR cameras can detect moisture content in soil and plants by sensing water absorption bands in the SWIR spectrum. This is crucial for irrigation planning and drought assessment, helping farmers to optimize water use and reduce waste. A study by Honkavaara et al. (2016) utilized novel visible and near-infrared (VNIR) and SWIR hyperspectral frame cameras for 3-D digital surface modeling and surface moisture estimation of a peat production area.

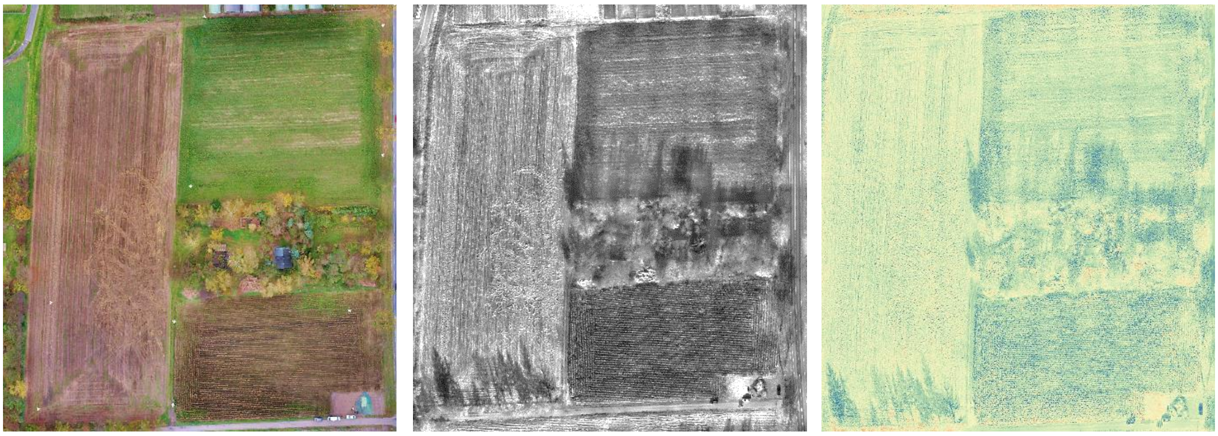

Figure12. Comparison of 3 orthophotomaps of Radonice, Poland, a) RGB b) SWIR c) NDWI (Green-SWIR/Green+SWIR), source: Łukasiewicz-Institute of Aviation

These studies underscore the promising role of SWIR cameras on UAVs in environmental and agricultural monitoring, particularly for soil moisture estimation, crop traits analysis, forage mass monitoring, and soil organic carbon prediction. The integration of SWIR imaging technology with UAVs offers a accurate, and efficient method for soil parameters monitoring, with significant implications for precision agriculture and environmental conservation. All in all, these solutions are still very costly for an individual user, therefore at the first stage this data should be acquired through specialized service providers.

D. Thermal (TIR)

The applications of thermal cameras encompass four main areas: soil type classification, soil temperature measurement, moisture estimation, and microbial activity estimation. Sensors of this category primarily detect radiation emitted by the soil, which falls within the electromagnetic spectrum in the range of 6.0 to 15 µm. According to Wien's law, this corresponds to a temperature range between -80.0 and +209.8 °C, enabling thermal cameras to capture the emissivity of the soil within its typical temperature ranges. The typical sensitivity of such cameras ranges from 0.05 to 0.10 °C, while the spatial resolution is lower compared to RGB or near-infrared cameras and typically ranges up to 2 Mpx. Sensors used on UAV platforms can weigh even less than 20g, making them a complement to optical systems based on RGB cameras, for example. The table below presents some camera models along with their parameters and examples of applications.

Table 10 Example TIR sensor models

Sensor	Matrix and optics	Properties	Sensitivity range (µm)	Soil applications
Zenmuse XT2	Resolution of 640x512, a refresh rate of 30	Gimbal stabilization, compatible with the Matrice 200 series quadcopters and Matrice 600	7,5 – 13,5	Temperature, Moisture

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	Hz. Three lens options: 13mm, 19mm, and 25mm	Pro hexacopters, dimensions: 12.4 × 11.3 × 12.7 cm, mass: 629g		
FLIR VUE Thermal Camera UAS	Resolution of 640x512, a refresh rate of 9 or 30 Hz. 13 or 19mm lens.	Dimensions: 5.72 x 4.45 x 4.45 cm, mass 72g Operating temperature range -20°C to +50°C	7.5 - 13.5	Temperature, Moisture
FLIR E8 TIR	Resolution of 320 x 240 pixels, refresh rate 9Hz,	Dimensions: 24.4 × 9.5 × 14.0 cm. Mass: 575 g. Operating temperature range -20°C to 250°C	7.5 – 13.0 µm	Soil Classification
VarioCAM HD research 900	Resolution of 1024 x 768 pixels, refresh rate 30 Hz (up to 240 Hz in sub-frame mode)	Dimensions: 21,0 x 12.5 x 15.5 cm. Mass: Mass > 1kg. Operating temperature range -40°C to 2000°C	7.5 – 14.0 µm	Microbiology

source: Łukasiewicz-Institute of Aviation

Areas of application

- **Soil classification.** Using i.e. the FLIR E8 thermal imaging camera, soil classification can be indirectly accomplished by monitoring the skin temperature response of soil to changes in moisture, enabling classification based on its hydraulic properties. Those properties should be known before experiment. Thermal analysis with the FLIR E8 camera allows for the observation of soil skin temperature variations, which can be used as a second scenario for soil classification based on its physical structure and type.
- **Soil temperature.** Despite directly recording thermal radiation, precise estimation of soil temperature requires calibration based on mathematical models. Random Forest models are often used for interpreting data in the context of soil temperature estimation. Basurto-Lazada et al. (2020) achieved a temperature estimation precision of 1.77°C using this model while capturing imagery from a 30m altitude.
- **Soil moisture.** In research conducted by Bertalan et al. (2022) concerning methods of estimating soil water content using a thermal camera mounted on a UAV, it was demonstrated that post-processing of data requires the application of machine learning algorithms, with Random Forest being the optimal algorithm. Hsu et al. (2019) utilized thermal images captured at two times of day: during the lowest temperatures (at sunrise) and the highest temperatures (at noon) within one day. Both images were transformed in ArcGIS software into the TDVI index, which after radiometric calibration of the data and consideration of the NDVI index of individual points in the field is negatively correlated with soil moisture (see equations 1-6 in this publication).
- **Microbial activity.** Passive infrared thermography may be used to detect and visualize hotspots and time moments associated with soil microbial activity. I.e. Schwarz et al (2019) aimed to identify optimal soil incubation conditions and data processing to reliably detect microbial activity on the soil surface using IRT and substrate-induced respiration techniques. Surface temperature, determined by IRT, was correlated (r^2 = 0.84) with soil respiration, indicating a clear relationship between thermal response and microbial activity.

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The use of thermal imaging cameras may encounter several technical limitations. Limited spatial resolution requires flying at low altitudes, which can be challenging in some cases. The need to capture data quickly due to changes in sunlight and surface temperature can be a logistical challenge. Additionally, thermal imaging cameras typically lack the ability to directly measure parameters other than temperature, and their effectiveness in other applications, such as estimating soil moisture, relies on algorithmic data processing, which in turn may depend on the algorithm used. Furthermore, the sensitivity of the camera matrix, measured in degrees Celsius, can affect measurement precision. In some cases, measurements are required at specific times of the day (e.g., soil moisture) or after the occurrence of external factors (e.g., classification based on hydraulic properties). Some applications are feasible after monitoring at several or even dozens of time points according to the model of physical, chemical, or biological processes occurring in the soil.

E.LIDAR

Areas of application

- **Erosion** - a process involving the destruction of the top layer of soil by mechanical factors such as wind and water, it may take the form of washing, gouging or blowing away. Soil erosion is closely related to runoff, both processes are characterized by significant temporal and spatial variability (Nachtergaele et al., 2002). The analysis of point clouds developed on the basis of data obtained in an area potentially affected by erosion focuses on searching for, among others, changes in the height of the terrain, places of sediment accumulation or grooves indicating the occurrence of runoff (Vinci et al., 2015)
- **Landslides -** a type of geological formation which is the result of the sudden breaking off of rock material or the gravitational displacement along the surface of a slip of land masses, especially soils, embankments, rocks or weathering (Tofani et al., 2013). The use of LiDAR technology allows data to be acquired to create precise Numerical Terrain Models (NMT) from which it is possible to analyse the changes taking place. This can help identify areas of landslides or those that may be susceptible to them in the future. The materials obtained can also be one of the primary sources for hazard mapping. In the case of this phenomenon, it is crucial to monitor changes over time, i.e. to carry out regular flyovers over the area in question (Anders et al., 2009).
- **Soil structure** – LiDAR data allow analysis of the texture of the terrain, i.e. the distribution of surface features such as roughness, texture or shape. This analysis can provide information on soil texture, including grain composition, degree of compaction or degree of porosity. In addition, LiDAR can be used to identify microtopographic structures such as ditches, depressions or hills, which are associated with soil-forming processes and can affect soil porosity (Filin et al., 2006).
- **Changes in topography and land cover** - due to the high accuracy of LiDAR-acquired data, it is possible to generate high quality NMTs. By comparing them with historical data, it is possible to accurately determine even small differences in elevation; moreover, regular acquisition of data for a selected area makes it possible to track land cover changes over time. This applies not only to areas stripped of vegetation, but also to differences in crop types. Due to such wide-ranging possibilities, LiDAR is used, among other things, to increase the efficiency of forest management in many countries around the world (van der Sande et. al., 2003).

Table 11 contains a comparison of sample sensors from various manufacturers currently available on the market.

Table 11 Examples of LiDAR sensors currently available on the market.

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Image	Sensor	Purpose	Weight [kg]	Technical Specifications
	**DJI Zenmuse L1**	- geodesy - architecture - mining - archaeology - forestry - engineering and topographic measurements	0,93	wavelength [nm] - **905** frequency [kHz] - **240** measurement speed [point/s] – **240 000** field of view [degrees] - **70** scanning pattern - **non-repetitive and repetitive** maximum laser range [m] - **450** height measurement accuracy [cm] - **5** digitization of the full waveform – **no data** max. number of recorded reflections - **3** example cloud density [points/sq m] - **100 dla 100 m (prędkość 13 m/s)**
	**Geosun GS-100M**	- mapping linear features - mining - forestry - civil engineering - inspection of power lines	0,7	wavelength [nm] - **905** frequency [kHz] – **720** measurement speed [point/s] – **720 000** field of view [degrees] – **70,4** scanning pattern - **linear** maximum laser range [m] - **450** height measurement accuracy [cm] - **2** digitization of the full waveform – **no** max. number of recorded reflections - **3** example cloud density [points/sq m] - **170 dla 100 m**
	**Geosun GS-260X**	- archaeology - environmental research - civil engineering - inspection of power lines	1,3	wavelength [nm] - **905** frequency [kHz] – **1280** measurement speed [point/s] – **1 280 000** field of view [degrees] – **360** scanning pattern - **linear** maximum laser range [m] - **130** height measurement accuracy [cm] - **2** digitization of the full waveform – **no** max. number of recorded reflections - **2**

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				example cloud density [points/sq m] - **64 dla 100 m**
	**GreenValley International LIAIR S220N**	- topographic and geodetic measurement - architecture - inspection	1,7	wavelength [nm] - **905** frequency [kHz] – **700** measurement speed [point/s] – **700 000** field of view [degrees] – **360** scanning pattern - **linear** maximum laser range [m] - **200** height measurement accuracy [cm] - **2** digitization of the full waveform – **no** max. number of recorded reflections - **2** example cloud density [points/sq m] - **600 dla 80 m przy 10 m/s**
	**Leica Geosystems CityMapper-2**	- city mapping	62	wavelength [nm] - **1064** frequency [kHz] – **2000** measurement speed [point/s] – **no data** field of view [degrees] – **20-40** scanning pattern – **no data** maximum laser range [m] - **5500** height measurement accuracy [cm] - **<5** digitization of the full waveform – **yes** max. number of recorded reflections – **no data** example cloud density [points/sq m] – **no data**
	**Riegl Laser Measurement Systems RIEGL VUX-1UAV**	- topographic measurements - mining - agriculture - forestry - archaeology - inspection of power lines, railway tracks, pipelines - monitoring of the construction area - city mapping	3,5	wavelength [nm] - **bliska podczerwień** frequency [kHz] – **550** measurement speed [point/s] – **500 000** field of view [degrees] – **330** scanning pattern – **linear** maximum laser range [m] - **920** height measurement accuracy [cm] – **0,5** digitization of the full waveform – **yes** max. number of recorded reflections – **no data**

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				example cloud density [points/sq m] – **88 dla 100 m (prędkość 10 m/s)**
	**YellowScan Mapper**	- geodesy - architecture - mining - archaeology - forestry - engineering and topographic measurements	1,4	wavelength [nm] - **905** frequency [kHz] – **240** measurement speed [point/s] – **240 000** field of view [degrees] – **81,7** scanning pattern – **non-repetitive** maximum laser range [m] - **115** height measurement accuracy [cm] - **3** digitization of the full waveform – **no data** max. number of recorded reflections – **2** example cloud density [points/sq m] – **400 dla 50 m (prędkość 5 m/s)**
	**YellowScan Vx-20**	- geodesy - architecture - mining - archaeology - forestry - engineering and topographic measurements	3,1	wavelength [nm] - **905** frequency [kHz] – **100-300** measurement speed [point/s] – **100 000/200 000** field of view [degrees] – **360** scanning pattern – **no data** maximum laser range [m] - **250** height measurement accuracy [cm] – **2,5** digitization of the full waveform – **no data** max. number of recorded reflections – **5** example cloud density [points/sq m] – **150 dla 50 m (prędkość 5 m/s)**

source: Łukasiewicz-Institute of Aviation based on „Skanowanie Laserowe", Pakuła Kwiecińska et al., 2022

1.8.2.2. Managing Data Acquisition by Drones

Using unmanned aerial vehicles (UAVs), various areas can be accurately mapped for purposes such as soil erosion management, pest and weed monitoring, vegetation mapping, and irrigation. Drone-generated maps facilitate monitoring the health of plants and animals, enabling the identification of changes or threats before they become unmanageable. UAVs assist in detecting soil and irrigation issues before they critically impact agriculture and wildlife. Although detailed soil analysis still necessitates soil sampling, drones equipped with multispectral and RGB sensors can identify critical hotspots. This allows for the analysis of mineral levels, detection of topsoil degradation, and identification of topographical changes before they cause irreversible

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damage.When it comes to flying a drone, we must be aware that its use is associated with a lot of formalities that must be done before the flight can take place. This includes formal requirements regarding the pilot or operator, as well as technical requirements for the entire system. In this field book, we will focus on acquiring aerial photography using UAVs in European Union. The rules and standards for flying drones in Europe, how they are designed, manufactured and operated are prepared by EASA (European Union Aviation Safety Agency).

Figure 13 Infographics – European rules on drones
source:https://www.easa.europa.eu/en/document-library/general-publications/infographics-drones

The main aspect you need to be aware of to operate your drone safety and in line with the rules:[5]

- You are responsible for every flight – follow the rules and your drone instructions manual
- You must register as a drone operator.
- Complete the online training and tests
- Always keep your drone in sight
- Do not fly above 120 meters
- Keep the right distance from people and property
- Stay away from airfields, airports and aircraft
- Check where you are allowed to fly
- Know how to fly your drone
- Prepare your drone for every flight
- Respect people's privacy

Regulation (EU) 2019/947 and 2019/945 (revision September 2022)[6], which is applicable since 31 December 2020 in all EU Member States, including Norway and Liechtenstein (it is expected that it will soon become applicable in Switzerland and Iceland too), caters for most types of civil drone operations and their levels of risk. It defines three categories of civil drone operations: the 'open', the 'specific' and the 'certified' category. We will focus only on the open category, which is the most suitable for this study.

[5] https://www.easa.europa.eu/en/document-library/general-publications/infographics-drones
[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0947

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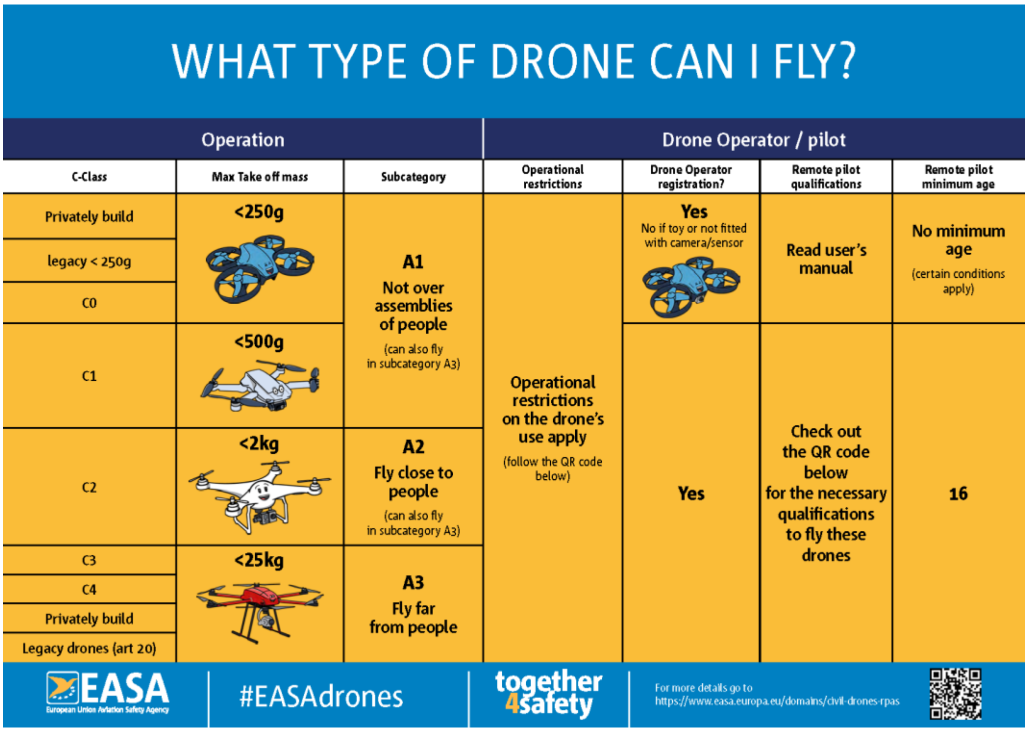

Figure 14 Operations in particular classes of drones
source: https://www.easa.europa.eu/en/document-library/general-publications/infographics-drones

4.1.2.1. Choosing the ideal drone for soil analysis

After defining your task and your needs, comes the question of choosing a drone. Here are the main components to look at when deciding on which one to use.

Ask yourself what your area of mapping is. Longer ***flight times*** let you reach and map the largest or the most remote territories. Moreover, greater endurance allows for maximizing the operational efficiency of every single flight. It keeps the cameras in the air for long periods of time, letting you collect more pictures without returning to base.

Payload capacity is the ability to carry different sensors. Consider how much detail and coverage you need and what sensors would fulfil those needs. Then, look at whether the drone can carry the weight of the camera of your choice and how easily the sensors can be integrated. If you need more cameras, they need to be easy to swap and deploy.

Drone software includes GPS (Global Positioning System) systems, planning, and flight software. Currently, there are GPS systems up to 1 cm commercially available. Planning and flights are becoming increasingly autonomous to bring ease of use to your operations. You need not worry about flight planning, pre-flight checks or navigate it manually if you make sure the software does so autonomously.

Always remember to read User Manual of the UAV before using it.

4.1.2.2. Preflight checks

Before every each flight you must be aware to respect procedures:

- **Inspect your UAV to ensure it's in great overall condition check:**
    - *Secure of payload, verify that gimbal is functionating properly*
    - *Condition of the motors, propellers, verify tight*
    - *Controller – overall condition and battery level*

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    - *UAV battery voltage*
    - *Telemetry link operation*
    - *GNSS satellite reception*
    - *Emergency procedures*
- **Check the Permissions, Permits and Rules of Airspace**
  Every each country has different way to check the Airspace, before the flight pilot should check NOTAM/AUP/UUP - a notification provided by aviation authorities to inform pilots about the operation of aircraft in specific areas or airspace.
- **Assess the weather conditions and any potential obstacles or hazards in the flight area** Cloud cover and weather conditions significantly impact the effectiveness of photogrammetry using Unmanned Aerial Vehicles (UAVs). High cloud cover or adverse weather such as rain, fog, or strong winds can obstruct the aerial imaging process, resulting in lower quality data or even mission cancellation. Therefore, careful monitoring of weather forecasts and selecting suitable flying conditions are crucial to ensure successful UAV photogrammetry operations and obtain accurate and reliable results.
- **Determine if you have enough storage on memory card**
- **Prepare calibration panel for multispectral camera if its required**

4.1.2.3. Mission planning

Depending on the sensor you choose, the design of the flight plan will be different. Most important rules must be followed:

- **Flight altitude** The tighter the accuracy you need, the lower you will need to fly your drone. During the mission altitude should be the same from ground flight level.
- **Flight speed** of the UAV should be calculated according to
    - *Light conditions* on site on flight day. On a bright day, you will want your camera to have less exposure to light and on a dull day, you would want this to be the opposite
    - *Image overlap / Interval.* Every drone mission you fly typically involve taking images at a set interval (every few seconds or every few meters travelled by the drone). This interval is an important consideration in the flight speed as you do not want to fly faster than the camera's capability to take pictures at this interval.
    - *Camera photo Interval.* Every camera has an inherent photo capture interval (The time is takes for the camera to write the image to the SD card). During this photo capture interval, the camera is unavailable and is unable to take further images. Again, if the drone is flying too fast, it would mean that the camera is unable to keep up with the photos and some images will be lost during flight, which is a complete no-no if your goal is high quality data
- **Flight path planning.** Proper UAV mission planning is key to achieving best results in mapping. To prepare ortophotomap or to scan the whole area of interested we need to fly drone along the designed path. The drone captures images at set intervals as it flies back and forth in straight lines over the area. The distance between those lines depends on the sensor that we are going to use, and it's called image *sidelap*. Specifically, it represents the percentage of overlap between images taken by the drone along its flight path, but in the direction perpendicular to the flight direction. Sidelap is important in drone mapping and photogrammetry because it ensures that there is sufficient overlap between images, allowing for accurate stitching and reconstruction of the entire area being surveyedFor images it should be no less the 70-80%, for Lidar 30-40%.

Forward Overlap - This type of overlap refers to the percentage of overlap between consecutive images along the flight path of the drone. For the best result this parameter should be not less than 80%.

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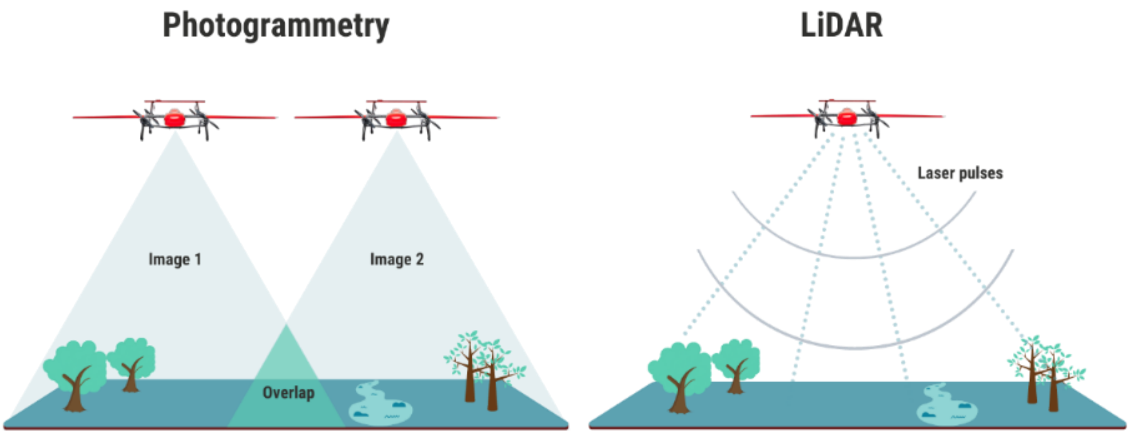

Figure 15 Differences between photogrammetry and LiDAR
source: https://www.rvslandsurveyors.com/lidar-or-photogrammetry

- **Ground Sampling Distance (GSD),** is a parameter that is closely connected with flight altitude, sensor size, image size, and the field of view (FOV) of the lens. Calculating GSD is essential to determining the scale of your mapping project and ensuring reliable results. Without it, you run the risk of collecting inaccurate data or having a map that isn't useful. You can use free web calculator for pre-mission drone surveying accuracy check.

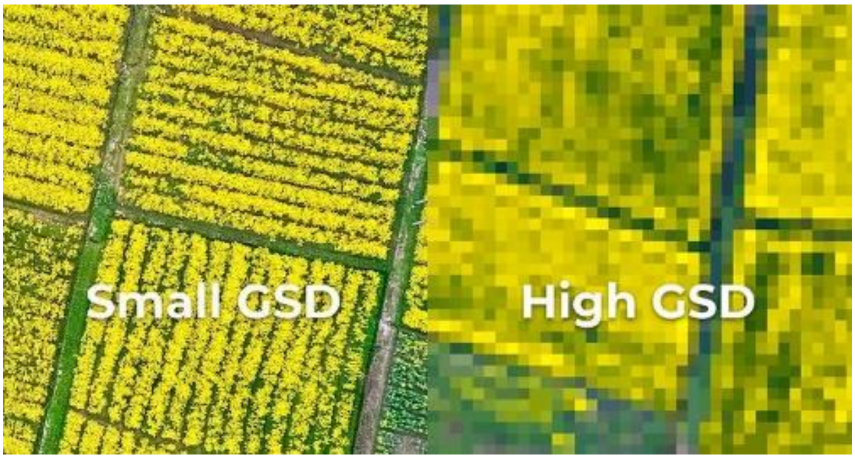

Figure 16Low vs High GSD
source: https://www.hammermissions.com/post/ground-sampling-distance-gsd

- **Images Geotagging –** You will need to align the prepared map to the appropriate coordinate system in order to compare the data from other sources. The best way is to use RTK images tagging (Real Time Kinematic), some UAV manufactures provide such a service. Each photo taken with such a drone has precise coordinates assigned to the image center. Usually we are talking of few centimeters precision. This type of image taking allows us to produce high accuracy products.

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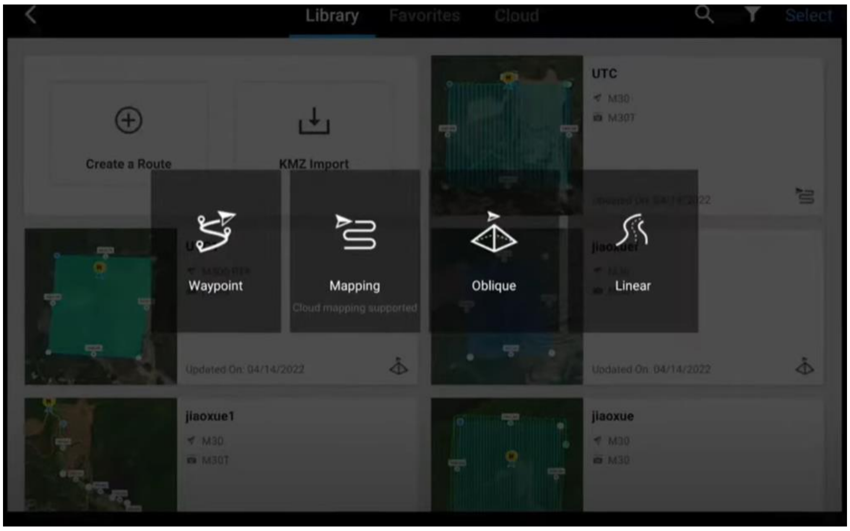
4.1.2.4. Field data collection sample workflow

- Almost every each drone manufacturer delivers with a UAV dedicated software, but not every software provide mission planning, so this should be checked before choose a proper UAV system. In this field book we will focus on one of the most popular drone manufacturer company.

Figure 17 Schema - how works data collection
source: https://www.landpoint.net/services/aerial-data-collection-uav-uas-drones/

- From the main menu choose **Flight Route**
- Click **"Create a Route"** or import prepared KMZ file
- Choose **Route type** (usually Mapping will be the best choice)



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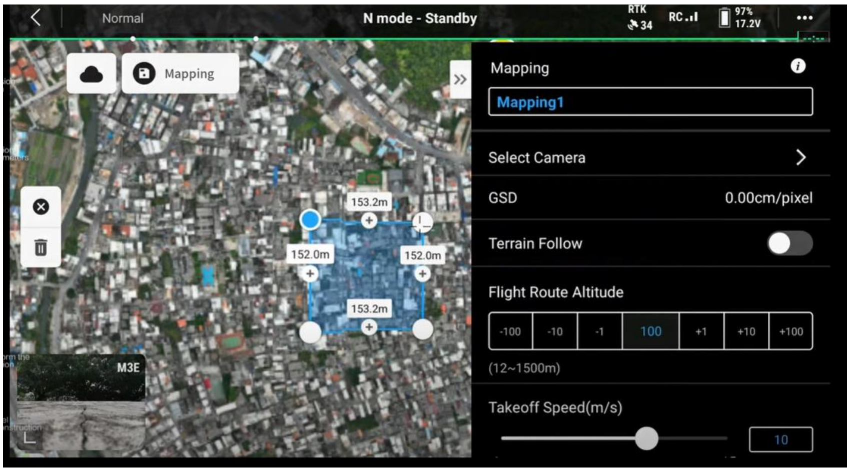
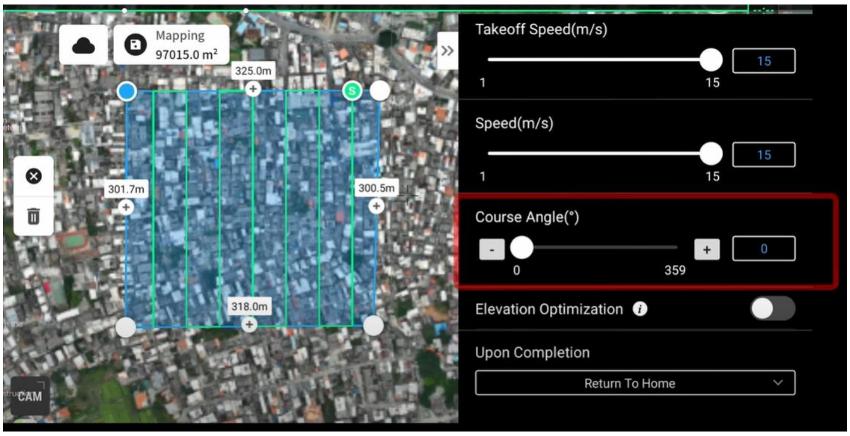
- Tap the screen for target area running



- Select area to map, put the name of the job, Select Camera, and flight route altitude
- Option **terrain follow** allow UAV to follow the terrain data, two options are available Real Time Follow and DSM (Digital Surface Model) Follow.
- Set **Takeoff Speed** – you can set it to the max 15m/s, **speed** when performing the flight route (remember that the flight speed should depend on the flight altitude and the shutter camera speed), **Course Angle** – by default course angle will be calculated for the shortest mission time. You can adjust the angle manually if needed.
  Elevation optimalization – if set on, the aircraft will take an extra group of photos to optimize the elevation data.



- **Upon Completion -** defines the action, after the mission is completed. Choose *Return To Home*
- **Go to Advanced Settings,** this is one of the most important part of the procedure. In this place we will set up the **Overlap**, it refers to the degree to which successive aerial images overlap each other. A high degree of overlap ensures greater accuracy and quality of data, which is crucial in the process of creating maps and terrain models. The overlapping of images allows for better triangulation of key points and enhances the accuracy of resulting 3D maps. However, increasing the coverage (especially side overlap ratio) reduces the distance between flight lines, thereby increasing the number of flight lines, which significantly extends the flight time. For the best result use recommended settings:
  - **Side Overlap Ratio > 70 %**

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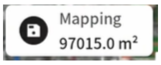
- ○ **Frontal Overlap Ratio > 80 %**

- **Photo Mode –** best result will gave **Distance Interval Shoot**
- After setting all parameters, tap the save icon to save the mission 

- Perform the mission by pressing this button 

- During the mission pay attention to battery life, RTK (Real Time Kinematic) status, Image Exposure and microSD card storage, obstacle avoidance and the mission progress. When mission is finished
- After the mission is finished land the aircraft, check and transfer data to a computer.

4.1.2.5. Control points

Before the flying procedure you can mark and measure several ground control points for data accuracy. Control points in photogrammetry are physical markers or features with precisely known geographic coordinates. These points serve as reference points for accurately aligning and orienting images during the photogrammetric process. They are typically established using highly accurate surveying techniques such as GNSS (Global Navigation Satellite System) or TS (Total Station). They are strategically positioned across the area of interest to ensure proper georeferencing and spatial accuracy in the resulting

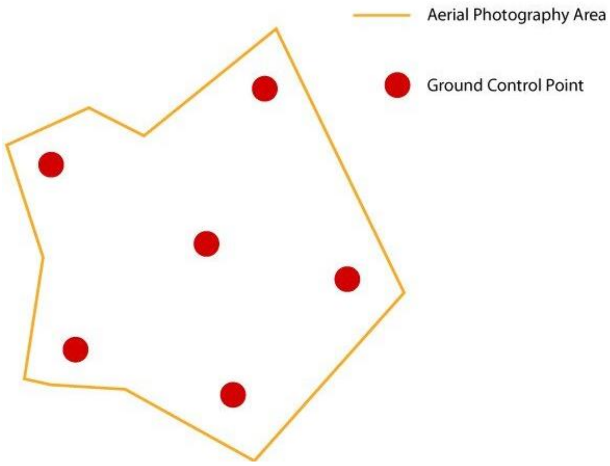


Figure 18 Example of GCP Location
source: Łukasiewicz-Institute of Aviation

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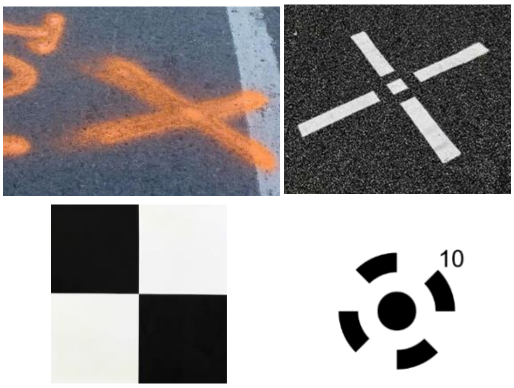

Figure 19 Examples of ground control points
source: Łukasiewicz-Institute of Aviation

The chapter discusses effective methods for acquiring multispectral, RGB, and lidar data using UAV. The author elaborates on the data collection process, highlighting the advantages and challenges of each method. Valuable insights on optimizing drone usage for acquiring diverse spatial data constitute a significant portion of this publication.

The utilization of remote sensing and optical sensors, such as RGB, multispectral, SWIR, thermal, and LiDAR cameras, plays a crucial role in soil monitoring in precision agriculture and environmental protection. They enable remote analysis of soil properties, such as chemical composition, moisture, and structure, facilitating the rapid detection of soil changes and identification of areas requiring attention. Optical sensors also allow monitoring of environmental changes related to agricultural activities, enabling appropriate actions to protect ecosystems and sustainably manage natural resources. RGB images provide a simple and cost-effective way to obtain soil information, while multispectral cameras on UAV platforms allow precise estimation of various soil parameters. SWIR cameras are used to monitor soil moisture, while thermal cameras are utilized for soil type classification, temperature measurement, and moisture estimation. LiDAR, on the other hand, is extremely useful in precise natural resource management and environmental protection, enabling fast data acquisition and mapping of areas from high altitudes. However, it is important to remember that each tool has its advantages and disadvantages, so careful consideration of all aspects is necessary before use to ensure effective task implementation in terms of quality, time, and finances. Data collected using various optical and remote sensing sensors are complex and require proper processing to be useful in analysis and soil condition assessment. Data processing and the use of mathematical models, such as machine learning algorithms or statistical models, enable the interpretation of collected data and forecasting of changes in the soil environment. By selecting appropriate sensors and processing and analyzing remote sensing data, it is possible to remotely determine soil properties, monitor changes in soil quality, and assess the impact of various factors, such as agriculture or urbanization, on the soil environment.

4.2. Ground Sensors

Instrumentation and sensors for the measurement of biophysical variables in soil and atmosphere

The sensors and instrumentation normally used in the field to obtain data on different variables, both soil and atmospheric, must be designed to be robust, provide quality data and be affordable. The objective of using this equipment is none other than to obtain measurements of fluxes (soil and air temperature and humidity, electrical conductivity and soil salts, solar radiation, wind, etc.) that will be used for informed decision making

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in relation to water balances and soil fertility, as well as energy balances (evaporative demand of the atmosphere), among other aspects.

Instrumentation and sensors related to the variables of the troposphere (layers of the atmosphere close to the earth's surface).

In general, a standard weather or agroclimatic station is equipped to measure, record and store the different atmospheric variables that condition life on Earth, such as water relations of plants or other soil organisms, as well as soil evaporation and crop transpiration processes.

Depending on what is to be measured and the purpose of the data, an agroclimatic station may be equipped with a larger or smaller number of sensors. For example, in irrigated crop production areas, one of its main purposes is to obtain the reference evapotranspiration (ETo), or to identify extreme weather events (frosts, hailstorms, etc.) to act in the case of agricultural insurance. The main meteorological variables recorded by the stations are (Table 13):

Table 12Main meteorological variables recorded by the stations.

A) Temperature and relative humidity of the air (sensor is a Vaisala).	
B) Wind speed and direction (cup anemometer and wind vane).	
C) Precipitation (rain gauge).	

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D) Global solar radiation (pyranometer).	
E) General view of an agroclimatic station. Two installation situations (under vegetation cover or bare soil), with the measurement sensors, data acquisition system (datalogger), and data transmission system (via radio, GPRS, WIFI, etc.).	 

These stations should be installed in areas of open and homogeneous countryside, avoiding heat and cold sources, steep areas and possible obstacles/windbreaks (Table 13, section E). In general, these stations are fixed and record data continuously.

More information of sensors (this part is a draft):

cod	Sensor type	Article	URL	Magazine	Location
1	TEROS 11/12	Researchers Zhenhua Wang, Jian Wang, Yingbin Li and Junhua Wang conducted a performance evaluation of the TEROS 11 sensor on different soil types in northwest China.	https://www.sciencedirect.com/journal/agricultural-water-management/issues	Agricultural Water Management	China
2	TEROS 11 MISCELLANEOUS ITEMS	Several articles in which this sensor is used, but it is not the main subject of the test.	https://www.sciencedirect.com/search?qs=TEROS%2011&pub=Agricultural%20Water%20Management&cid=271238	Agricultural Water Management	
3	Miscellaneous including TEROS 10/11/12	Review of research progress on soil moisture sensor technology	https://www.ijabe.org/index.php/ijabe/article/view/6404	IJABE, International Journal of Agriculture and Biological Engineering	Various

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4	Prototype sensors, the best Prototype 1	Development of an Integrated Wireless Sensor Network System for Monitoring Soil Moisture and Nutrients in Precision Agriculture, Sensor's magazine.	https://www.mdpi.com/1424-8220/21/21/7243	Sensor-MDPI	Europe
5	Comparison between various sensors	Review of research progress on soil moisture sensor technology	https://pdfs.semanticscholar.org/4fc7/cb8d262ad0603e53e012e1ff8aef4c2c4775.pdf	International Journal of Agricultural and Biological Engineering	Europe
6	Various	XXXVIII National Irrigation Congress	A-11-2021.pdf (upct.es)	University of Cartagena	Spain
7	Various	Various articles	https://www.mdpi.com/search?q=soil+sensor&journal=sensors	Sensor-MDPI	

Others European project about sensors:

cod	Type of test	Essay	URL	Location
1	It is an EU-funded project that focuses on the development of sustainable soil management practices. The project uses soil sensors to assess soil quality and improve agricultural practices.	SoilCare Project	https://www.soilcare-project.eu/	Europe

Data Analysis and Interpretation

Main Applications/ Case Studies

Instrumentation and sensors related to soil variables.
The commercial instruments and sensors that currently exist for the measurement of soil biophysical variables correspond to:
a) humidity, b) temperature, c) salinity, d) electrical conductivity, and e) fertility.
The objective of these variables is to act on crop management, whether or not to apply irrigation water, sowing/planting time, fertiliser dosage, amendments to correct salinity and electrical conductivity and soil tillage, among other aspects.
a) Soil moisture.
The measurement of soil moisture content is of great relevance for the growth of plants, their physical and chemical properties, and the development of soil micro-organisms. A direct example of the importance of determining soil water content is to know how water moves in the soil profile and how it interacts with the plant, so that it is possible to know when and how much water to apply in an irrigation.

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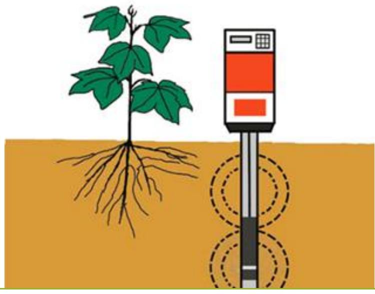
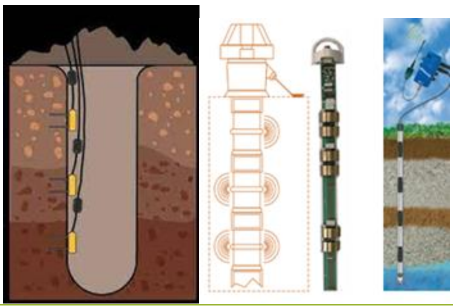
Soil moisture can be measured directly or indirectly. The direct method consists of taking a soil sample (located at a certain depth) and determining its gravimetric moisture content by drying it in an oven at 105 ºC, which can then be transformed into volumetric moisture content by knowing the density of the soil. In the indirect method, it is not the water content in the soil that is measured, but rather a property related to the water in the soil. The main indirect methods are listed in Table 14.

Table 13 Main equipment/sensors for indirect measurement of soil moisture.

A) Neutron probe. This equipment is based on measuring the flux of thermal neutrons through a tube installed in the ground. This flux is proportional to the amount of water (hydrogen atoms interacting with the neutrons) present in the soil.	
B) Time-Domain Reflectometry (TDR). This method measures the dielectric constant of the soil by means of the time taken for an electromagnetic pulse to travel through two steel rods inserted into the soil, which serve as a guide for the probes. Mobile sensor equipped for connection to a data logger; can be installed at different soil depths.	 
C) Capacitance probes (Frequency-Domain Reflectometry; FDR). This method measures the electrical capacitance of the soil by means of a wave previously emitted by the sensor. The capacitance varies as a function of soil moisture.	

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D) Tensiometers. These devices measure the matrix potential of the soil. It consists of a porous ceramic capsule filled with water which is buried in the soil at the measuring depth and connected to a manometer or vacuum gauge (vacuum gauge) through the water-filled tube. The ceramic capsule is permeable to water and solutes, but not to air. They usually measure between 0 and -0.85 bar.	
E) Electrical resistance blocks. This is a block of porous material (gypsum or ceramic) which allows the movement of water between the soil and the block in such a way that the potentials between the two are equalised. In this type of sensor, what is measured is the electrical resistance to the passage of current in it. They measure potentials between 0 and 200 cb; between 0 and 20 cb represent field capacity conditions; between 20-60 cb indicate irrigation conditions; above 80-100 cb the crop shows water deficit conditions.	

Devices A), B) and C) in Table 2 measure volumetric moisture by means of a suitable calibration line. In contrast, instruments D) and E) display data in potential values, requiring soil water retention curves to convert potential to gravimetric moisture.

b) Temperature.

Soil temperature sensors allow the determination of temperature at different soil depths. Their installation is usually fixed with continuous measurements either as a stand-alone sensor or in combination with other sensors (humidity, electrical conductivity, salinity). Its use may be justified to know the appropriate sowing/planting times for crops in cold areas, for example. Their installation procedure is similar to that indicated in Table 2, paragraph C).

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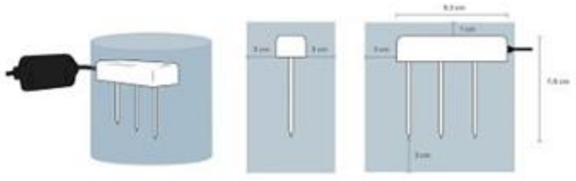
c) Electrical conductivity and salinisation.

Electrical conductivity sensors allow the determination of this parameter at different soil depths in order to monitor salinity and electrical conductivity for decision making in the field of fertilisation management, mainly in fertigation. Their installation procedure is similar to that indicated in Table 2, section C).



d) Soil fertility

This type of soil sensor is suitable for detecting nitrogen, phosphorus and potassium content in soil and determining soil fertility by detecting nitrogen, phosphorus and potassium content in soil, which facilitates systematic evaluation of soil condition. It can be buried in the soil for a long time, resistant to long-term electrolysis, corrosion, vacuum encapsulation, completely waterproof.
The sensor is widely used in the detection of nitrogen, phosphorus and potassium in soil, precision agriculture, forestry, soil research, geological exploration, plant cultivation and other fields.

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Glossary

- Altitude: The height above sea level or the Earth's surface, affecting the orbit and coverage area of satellites and sensors.
- App: Short for "application," a software program designed to perform a specific function or set of functions on a computer or mobile device.
- Angle of View: The angle between the optical axis of a sensor and the line of sight to the target area on the Earth's surface, affecting the spatial coverage and resolution of satellite imagery.
- Bandwidth: It is associated with the spectral bands or channels used by sensors to capture electromagnetic radiation. Remote sensing instruments, such as satellite sensors or airborne sensors, are equipped with detectors that measure electromagnetic radiation across different wavelengths or spectral bands. Each band has a specific bandwidth, which determines the range of wavelengths it can capture. For example, a sensor may have bands for visible light, near-infrared, and thermal infrared, each with its own bandwidth.
- Baseline: The distance between corresponding points on two consecutive waves of a signal used to measure the wavelength or the distance between two images in stereo vision.
- Bits: Binary digits representing the smallest unit of data in a computer, commonly used to quantify the resolution of digital images.
- Calibrated Data: Data that has undergone a process to adjust or standardize its values, ensuring consistency and accuracy in measurements.
- Colour Depth: The number of bits used to represent the color of each pixel in a digital image, determining the range of colors or shades of grey that can be displayed.
- Emissivity: The ability of a surface to emit thermal radiation relative to that of a perfect black body at the same temperature.
- Electromagnetic Radiation: Energy emitted and absorbed by charged particles, propagating through space in the form of waves, including visible light, infrared radiation, and microwaves.
- Forward Overlap: The percentage of overlap between successive images along the flight direction.
- GIS (Geographic Information System): A system designed to collect, store, analyze, manage, and present spatial or geographic data.
- Geomatics: The science and technology of gathering, analyzing, interpreting, distributing, and using geographic information.
- Georeferencing: The process of associating geographic coordinates with spatial data, enabling the data to be positioned accurately in space.
- Geology: Geological applications of remote sensing cover a wide range of activities such as: mapping bedrock, lithology, and structures, as well as exploring and exploiting sand, gravel, minerals, and hydrocarbons.

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- Grey levels: The different levels of brightness or intensity in an image, typically represented as varying shades of grey in black-and-white imagery.
- ICT (Information and Communication Technologies): Technologies that facilitate the transmission, processing, and storage of information.
- LANDSAT: A series of Earth-observing satellites operated by NASA and the US Geological Survey, providing multispectral imagery for various applications, including land cover mapping and environmental monitoring.
- Leaf-area-index (LAI): A measure of the amount of leaf area per unit ground area.
- Longitudinal Overlap: The percentage of overlap between successive images perpendicular to the flight direction.
- Meteorological Satellites: Satellites equipped with instruments for observing weather patterns and atmospheric conditions, providing data for weather forecasting and climate monitoring.
- Microwaves: Electromagnetic waves with wavelengths ranging from one meter to one millimeter, suitable for remote sensing applications such as weather forecasting and soil moisture detection.
- Multi-Temporal Analysis: An analysis technique that involves comparing and analyzing images acquired at different times to detect changes and trends in the Earth's surface over time, useful for monitoring urban development, land use changes, and natural disasters.
- Multispectral: Referring to sensors or satellites that capture electromagnetic radiation across multiple spectral bands, allowing for the analysis of surface properties and environmental conditions.
- NDVI (Normalized Difference Vegetation Index): A numerical index used to assess vegetation health and density based on the difference in reflectance between near-infrared and visible light bands.
- Near Infrared (NIR): Electromagnetic radiation with wavelengths longer than visible light but shorter than mid-infrared radiation, often used in remote sensing for vegetation analysis.
- Orthomosaic: An aerial photograph or satellite image that has been geometrically corrected so that the scale is uniform and can be used for measurements.
- Orthophoto: A geometrically corrected aerial photograph that has been adjusted to remove distortions caused by camera tilt and terrain relief.
- Passive Satellite: A satellite that relies on external sources of radiation (e.g., sunlight) for imaging purposes, as opposed to active satellites that emit their own radiation (e.g., radar).
- Pixel: The smallest element of an image that can be individually processed in a digital display.
- Photogrammetry: The science of making measurements from photographs, especially for recovering the exact positions of surface points.
- Radiometric Resolution: The ability of a sensor to detect and differentiate variations in electromagnetic radiation intensity.

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- Remote Sensing: The process of collecting data about an object or area from a distance, typically via satellites or aircraft, using sensors to gather information about the object's properties without direct physical contact.
- Revisit Time: The elapsed time between successive observations of the same area or point on the Earth's surface by a satellite or sensor.
- Satellite Images: Images recorded by satellites orbiting the Earth, typically used for remote sensing applications to observe and analyze various features and phenomena on the Earth's surface.
- Spectral Bands: Ranges of wavelengths within the electromagnetic spectrum captured by a sensor, used to analyze the spectral reflectance of surfaces and distinguish between different materials or features. They are characterized by a bandwidth.
- Spectral Resolution: The ability of a sensor to distinguish between different wavelengths or colors in the electromagnetic spectrum.
- Soil Moisture: The amount of water present in the soil, usually expressed as a percentage of the soil volume.
- Shutter Speed: The length of time that the camera's shutter is open to expose the camera sensor to light.
- Temporal Resolution: The frequency at which data is collected over time.
- Thermal Infrared: Electromagnetic radiation emitted by objects due to their temperature, commonly used for detecting heat variations and thermal flux.
- Web-GIS: A type of GIS that uses web technologies to provide access to geospatial data and tools over the internet.

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