MOOC Document

Beyond the Visible – Introduction to Hyperspectral Remote Sensing

Acknowledgements

Contents

List of Abbreviations

The list includes all terms that are introduced in the MOOC

ACT: Across-track

A/D: analog/digital

AIS: Airborne Imaging Spectrometer

ALT: Along-track

AO: Announcement of Opportunity

API: Application programming interface

ASD: Analytical Spectral Devices

AVIRIS-NG: Airborne Visible Infrared Imaging Spectrometer – Next Generation

BOA: Bottom-of-Atmosphere

BRDF: Bidirectional Reflectance Distribution Function

CHIME: Copernicus Hyperspectral Imaging Mission of the Environment

CP: Commissioning phase

CRAD: Continuum Removed Absorption Depth

DEM: Digital elevation model

DLR: German Aerospace Center

DN: Digital number

EeTeS: EnMAP end-to-end simulator

EnMAP: Environmental Mapping and Analysis Program

EM: Electromagnetic

EMR: Electromagnetic radiation

ISS: International Space Station

JHU: Johns Hopkins University

JPL: Jet Propulsion Laboratory

LAI: Leaf area index

LEO: Low Earth Orbit

LUCAS: Land Use/Cover Area frame statistical Survey

MF: Magnetic field

MIR: Mid infrared

MOOC: Massive open online course

MTV: Modulation transfer function

NASA: National Aeronautics and Space Administration

NIR: Near-infrared

PRISMA: PRecursore IperSpettrale della Missione Applicativa

PSF: Point spread function

RGB: Red Green Blue

RMSE: Root Mean Square Error

RTM: Radiative Transfer Model

SAM: Spectral Angle Mapper

SBG: NASA's Surface Biology and Geology Investigation Mission

SFA: Spectral Feature Analysis

SFF: Spectral Feature Fitting

EM: Endmember

EF: Electrical field

ESA: European Space Agency

FIR: Far infrared

FOV: Field-of-view

FQR: Flight qualification review

FWHM: Full width at half maximum

GFZ: German Research Centre for Geosciences

GIFOV: Ground-projected instantaneous-field-of-view

GSD: Ground sampling distance

GSI: Ground sampling interval

IFOV: Instantaneous-field-of-view

IR: Infrared

SMA: Spectral Mixing Analysis

SNR: Signal-to-noise ratio

SSD: Spatial sampling distance

SVM: Support Vector Machine

SWIR: Short wave infrared

TIR: Thermal infrared

TOA: Top-of-Atmosphere

UV: Ultraviolet

USGS: United States Geological Survey

VIS: Visible (light)

VNIR: Visible near-infrared

List of Figures

1 Welcome

Hi there, welcome to the Massive Open Online Course (MOOC) ‚*Beyond the Visible – Introduction to Hyperspectral Remote Sensing*'!

This course is **structured in six lessons** that usually **contain several topics** and are accompanied as well as completed by a number of **short exercises** and **quizzes**.

The first lesson is accessible to everyone – here, our colleagues will explain the benefits of hyperspectral over other types of remote sensing data, the challenges and opportunities for their respective fields of expertise: soil and geology, agriculture and water. Plus, you can get a first glimpse of EnMAP, the German hyperspectral satellite mission that triggered the creation of this MOOC! This lesson is not compulsory to pass the MOOC but we hope that you find some valuable information relating to your areas of interest in the interviews.

The second lesson is a quiz on the very basics of remote sensing that you need to pass in order to get access to the rest of the course – this is not to discourage you but rather to ensure you have sufficient background knowledge to enjoy this MOOC. Don't worry, you have unlimited attempts to pass …

The third to fifth lesson comprise the actual content and will introduce you to the principles of imaging spectroscopy, provide you with information on sensor technology and data acquisition and present a number of free data resources as well as software. In the last lesson, you'll get the chance to download and/or process hyperspectral imagery yourself.

These „core" thematic lessons (3-5) contain a lot of interactive content and you are requested to **complete a short graded final quiz at the end of each lesson** (10 questions each). In each final lesson-quizzes (3) you **need at least 50 % to pass** to the next lesson. The **course is completed by a final assessment** which includes a total of 15 questions. Here, you need **at least 70 % to pass**. **If you have successfully done this, you will receive your certificate of completion!** You have **unlimited attempts to pass for all quizzes.**

This offline version of the Basic MOOC enables everyone to access the content of such – however, in order to successfully complete the course, one must necessarily pass each of the quizzes, as well as the final exam.

For acquiring the certificate of completion, you need to pass the lesson quizzes, as well as the final assessment online.

We use the sixth lesson to say goodbye – by then, you should have learned …

- what imaging spectroscopy is
- what application fields it is useful for
- what the physical background is
- which sensors are commonly used
- how spectroscopy data are acquired
- where you can get data from
- what software you could use
- and finally first processing steps to analyze them

Advice – how to get through the course smoothly

This course was designed to be taken from a desktop PC or laptop, though most content should work on a tablet or even smart phone as well. For the best learning experience, we recommend to participate using **Google Chrome, Microsoft Edge or Mozilla Firefox on a desktop PC or laptop**. During beta-testing, we observed some issues with Safari – if the content is not displayed properly, try re-loading. If you prefer, you can use the **offline version of the course in PDF format**, which you will find under the resource section on EO-College. To complete the course and get the certificate, however, you still need to answer the quizzes in the online version of the course.

VIDEO: Basic-01: Beyond the Visible – Welcome!

URL of the video: https://youtu.be/qXDVoMy-fgU

Let's move on with the first topic of this 'Welcome!' lesson. Three experts of three different fields of application will give motivating interviews why hyperspectral remote sensing is so exiting and revolutionary.

1.1 Hyperspectral, so what?

… so what is the actual benefit of hyperspectral data? We have asked three colleagues, experts in the fields of imaging spectroscopy of soils & geology, agriculture, and inland & coastal water, what they think about the advantages of hyperspectral imagery and what they think current challenges are for their respective areas of interest. Click on the videos below to see the **interviews**.

And let us and your fellow students know who you are and what question(s) you are interested in in the discussion forum of this topic. There is a separate discussion forum for each topic of this course in the discussion section at EO-College.

Prof. Dr. Sabine Chabrillat (German Research Centre for Geosciences – GFZ in Potsdam, professor for "digital soil mapping" at Leibniz University Hanover, Institute of Soil Sciences) on imaging spectroscopy in the context of **soils and geology**.

Prof. Dr. Astrid Bracher (Alfred-Wegener-Institute for Polar and Marine Research– AWI in Bremerhaven, honorary professor at the University Bremen, Department of Physics and Electrical Engineering) on imaging spectroscopy in the context of **inland and coastal waters applications**.

PD Dr. Tobias B. Hank (Ludwig-Maximilians-Universität München, Department of Geography) on imaging spectroscopy in the context of **agriculture**.

VIDEO: Basic-02: Expert interview: application field "soils and geology"

VIDEO: Basic-03: Expert interview: application field "inland & coastal waters"

VIDEO: Basic-04: Expert interview: application field "agriculture"

URL of the video:
https://www.youtube.com/watch?v=g6zSSjBK1Vk

URL of the video:
https://www.youtube.com/watch?v=LINaeuvmO9E

URL of the video:
https://www.youtube.com/watch?v=DaZF3jRnMfs
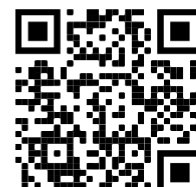
Our experts have selected state-of-the-art literature and own publications for further reading including the ones that were mentioned in the interviews.

Soils and geology:

State-of-the-art publications:

Chabrillat S., Ben-Dor E., Cierniewski J., Gomez C., Schmid T., van Wesemael B. (2019): **Imaging Spectroscopy for Soil Mapping and Monitoring**. Surveys in Geophysics. 40, 361–399. https://doi.org/10.1007/s10712-019-09524-0

Ben-Dor, E., Irons, J. R., & Epema, G. F. (1999): **Soil reflectance**. Remote sensing for the earth sciences: Manual of remote sensing, 3, 111-188.

Demattê, J. A. M., Morgan, C. L. S., Chabrillat, S., Rizzo, R., Franceschini, M. H. D., Vasques, G. M. & Thenkabail, P. S. (2015): **Spectral sensing from ground to space in soil science: State of the art, applications, potential and perspectives.** In Land resources monitoring, modeling, and mapping with remote sensing (pp. 661-732). CRC Press.

Cudahy, T. (2016): **Mineral Mapping for Exploration: An Australian Journey of Evolving Spectral Sensing Technologies and Industry Collaboration**. Geosciences 6, 52. https://doi.org/10.3390/geosciences6040052

Krupnik, D., Khan, S., (2019): **Close-range, ground-based hyperspectral imaging for mining applications at various scales: Review and case studies.** Earth-Science Rev. 198, 102952. https://doi.org/10.1016/j.earscirev.2019.102952

van der Meer, F. 1998): I**maging spectrometry for geological remote sensing**. Geologie en Mijnbouw 77, 137–151. https://doi.org/10.1023/A:1003538401892

Clark, R.N., T.V.V. King, M. Kleijwa, G.A. Swayze & N. Vergo (1990): **High spectral resolution reflectance spectroscopy of minerals.** J. Geophys. Res. 95: 12653-12680

Own publications:

Chabrillat S., Guillaso S., Rabe A., Foerster S., Guanter L. (2016): **From HYSOMA to ENSOMAP— a new open source tool for quantitative soil properties mapping based on hyperspectral imagery from airborne to spaceborne applications.** General Assembly European Geosciences Union, Vienna, Austria, 2016, Geophysical Research Abstracts, Vol 18, EGU2016-14697

Chabrillat S., Eisele A., Guillaso S., Rogaß C., Ben-Dor E., Kaufmann H. (2011): **HYSOMA: an easy-to-use software interface for soil mapping applications of hyperspectral imagery.** In: Proceedings 7th EARSeL SIG imaging spectroscopy workshop, Edinburgh, Scotland

Guanter L., Kaufmann H., Segl K., Foerster S., Rogass C., Chabrillat S., Kuester T., Hollstein A., Rossner G., Chlebek C., Straif C., Fischer S., Schrader S., Storch T., Heiden U., Mueller A., Bachmann M., Mühle H., Müller R., Habermeyer M., Ohndorf A., Hill J., Buddenbaum H., Hostert P., Van der Linden S., Leitão P.J., Rabe A., Doerffer R., Krasemann H., Xi H., Mauser W., Hank T., Locherer M., Rast M., Staenz K., Sang B. (2015): **The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation**. Remote Sens. 2015, 7(7), 8830-8857. https://doi.org/10.3390/rs70708830

Mielke C., Rogaß C., Bösche N., Segl K., Altenberger U. (2016): **EnGeoMAP 2.0—Automated Hyperspectral Mineral Identification for the German EnMAP Space Mission**. Remote Sensing, 8, 2, 127. https://doi.org/10.3390/rs8020127

Steinberg A., Chabrillat S., Stevens A., Segl K., Foerster S. (2016): **Prediction of Common Surface Soil Properties Based on Vis-NIR Airborne and Simulated EnMAP Imaging Spectroscopy Data**: Prediction Accuracy and Influence of Spatial Resolution. – Remote Sensing, 8, 7, 613. https://doi.org/10.3390/rs8070613

Ward K.J., Chabrillat S., Brell M., Castaldi F., Spengler D., Foerster S. (2020): **Mapping Soil Organic Carbon for Airborne and Simulated EnMAP Imagery Using the LUCAS Soil Database and a Local PLSR**. Remote Sensing. 12(20), 3451. https://doi.org/10.3390/rs12203451

Agriculture:

State-of-the-art publications:

Hank T., Berger K., Bach H., Clevers J.G.P.W., Gitelson A., Zarco-Tejada P., Mauser W. (2019): **Spaceborne** Imaging Spectroscopy for Sustainable Agriculture: Contributions and Challenges. Surveys in Geophysics. 40, 515-551. https://doi.org/10.1007/s10712-018-9492-0

Ustin, S.L., & Middleton, E.M. (2021): **Current and near-term advances in Earth observation for ecological applications.** Ecological Processes, 10, 1. https://doi.org/10.1186/s13717-020-00255-4

Verrelst, J., Malenovský, Z., Van der Tol, C., Camps-Valls, G., Gastellu-Etchegorry, J.-P., Lewis, P., North, P., & Moreno, J. (2019): **Quantifying Vegetation Biophysical Variables from Imaging Spectroscopy Data: A Review on Retrieval Methods.** Surveys in Geophysics, 40, 589-629. https://doi.org/10.1007/s10712-018-9478-y

Weiss, M., Jacob, F., & Duveiller, G. (2020): **Remote sensing for agricultural applications: A meta-review.** Remote Sensing of Environment, 236, 111402. https://doi.org/10.1016/j.rse.2019.111402

Own publications:

Berger K., Verrelst J., Féret J.-B., Hank T., Wocher M., Mauser W., Camps-Valls G. (2020): **Retrieval of aboveground crop nitrogen content with a hybrid machine learning method**. International Journal of Applied Earth Observation and Geoinformation. 92, 102174. https://doi.org/10.1016/j.jag.2020.102174

Berger K., Verrelst J., Féret J.-B., Wang Z., Wocher M., Strathmann M., Danner M., Mauser W., Hank T. (2020): **Crop nitrogen monitoring: Recent progress and principal developments in the context of imaging spectroscopy missions**. Remote Sensing of Environment. 242, 111758. https://doi.org/10.1016/j.rse.2020.111758

Berger K., Wang Z., Danner M., Wocher M., Mauser W., Hank T. (2018): **Simulation of Spaceborne Hyperspectral Remote Sensing to Assist Crop Nitrogen Content Monitoring in Agricultural Crops**. In, IEEE International Geoscience and Remote Sensing Symposium (pp. 3801-3804). Valencia, Spain. https://doi.org/10.1109/IGARSS.2018.8518537

1 Welcome

**MOOC – Introduction to
Hyperspectral Remote Sensing**

HYPER
EDU

EnMAP
education
initiative

Danner M., Berger K., Wocher M., Mauser W., Hank T. (2021): **Efficient RTM-based training of machine learning regression algorithms to quantify biophysical & biochemical traits of agricultural crops**. ISPRS Journal of Photogrammetry and Remote Sensing. 173, 278-296. https://doi.org/10.1016/j.isprsjprs.2021.01.017

Danner M., Wocher M., Berger K., Mauser W., Hank T. (2018): D**eveloping a Sandbox Environment for Prosail, Suitable for Education and Research**. In, IEEE International Geoscience and Remote Sensing Symposium (pp. 783-786). Valencia, Spain. https://doi.org/10.1109/IGARSS.2018.8519378

Wocher M., Berger K., Danner M., Mauser W., Hank T. (2020): **RTM-based dynamic absorption integrals for the retrieval of biochemical vegetation traits**. International Journal of Applied Earth Observation and Geoinformation. 93, 102219. https://doi.org/10.1016/j.jag.2020.102219

Wocher M., Berger K., Danner M., Mauser W., Hank T. (2018): **Hyperspectral Retrieval of Canopy Water Content Through Inversion of the Beer-Lambert Law**. In, IEEE International Geoscience and Remote Sensing Symposium (pp. 3805-3808). Valencia, Spain. https://doi.org/10.1109/IGARSS.2018.8518218

Inland and coastal waters:

State-of-the-art publications:

Giardino, C., Brando, V.E., Gege, P. et al. (2019): **Imaging Spectrometry of Inland and Coastal Waters: State of the Art, Achievements and Perspectives**. Surv Geophys 40, 401–429. https://doi.org/10.1007/s10712-018-9476-0

Hestir EL, Brando VE, Bresciani M, Giardino C, Matta E, Villa P, Dekker AG (2015): **Measuring freshwater aquatic ecosystems: the need for a hyperspectral global mapping satellite mission.** Remote Sens Environ 167:181–195. https://doi.org/10.1016/j.rse.2015.05.023

Martin, S. (2014): **An Introduction to Ocean Remote Sensing (2nd ed.).** Cambridge: Cambridge University Press. doi:10.1017/CBO9781139094368

Mobley, C. D. (1994): **Light and water: Radiative transfer in natural waters.** San Diego: Academic Press.

International Ocean Colour Coordinating Group: http://www.ioccg.org/

Own publications:

Alvarado L., Gege P., Losa S.N., Soppa M.A., Dröscher I., Bracher A. (2021): **Phytoplankton functional types retrieval for Lake Constance: evaluation of Desis and OLCI satellite retrievals with field observations**. DESIS Workshop: https://desis2021.welcome-manager.de/archiv/web/userfiles/desis2021/Alvarado_DESISWorkshop_vf.pdf

Bracher A., Soppa M. A., Gege P., Losa S.N., Silva B., Steinmetz F., Dröscher, I. (2021): **Extension of atmospheric correction Polymer to hyperspectral sensors: application to HICO data and first results for DESIS data**. Proceedings of the IGARSS 2021 – 2021 IEEE International Geoscience and Remote Sensing Symposium; article identifier: IG213516

Bracher A., Xi H., Dinter T., Mangin A., Strass V. H., von Appen W.-J., Wiegmann S. (2020): **High resolution water column phytoplankton composition across the Atlantic Ocean from ship-towed vertical undulating radiometry**. Frontiers in Marine Science 7: 235. https://doi.org/10.3389/fmars.2020.00235

Bracher A., Bouman H. A., Bricaud A., Brewin R.W.J., et al. (2017): **Obtaining Phytoplankton Diversity from Ocean Color: A Scientific Roadmap for Future Development.** Frontiers in Marine Science. 4: 00055. https://doi.org/10.3389/fmars.2017.00055

Bracher A., Vountas M., Dinter T., Burrows J.P., Röttgers R., Peeken I. (2009): **Quantitative observation of cyanobacteria and diatoms from space using PhytoDOAS on SCIAMACHY data**. Biogeosciences. 6: 751-764. https://doi.org/10.5194/bg-6-751-2009

Dierssen H., Bracher A., Brando V., Loisel H., Ruddick K. (2020): **Data needs for hyperspectral detection of algal bloom diversity across the globe.** Oceanography 33(1): 74-79. https://doi.org/10.5670/oceanog.2020.111

Hieronymi M. (2019): **Spectral band adaptation of ocean color sensors for applicability of the multi-water biogeo-optical algorithm ONNS.** Opt. Express. 27, A707-A724. https://doi.org/10.1364/OE.27.00A707

Sadeghi A., Dinter T., Vountas M., Taylor B., Altenburg Soppa M., Bracher, A. (2011): **Remote sensing of coccolithophore blooms in selected oceanic regions using the PhytoDOAS method applied to hyper-spectral satellite data**, Biogeosciences Discussion. 8, 11725-11765. https://doi.org/10.5194/bgd-8-11725-2011

Soppa M. A., Silva B., Steinmetz F., Keith D., Scheffler D., Bohn N., Bracher A. (2021): **Assessment of Polymer atmospheric correction algorithm for hyperspectral remote sensing imagery over coastal waters**. Sensors, 21, 4125. https://doi.org/10.3390/s21124125

Soppa M.A., Dinh D.A., Silva B., Steinmetz F., Alvarado L., Bracher A. (2021a): **Intercomparison of DESIS, Sentinel-2 (MSI) and Sentinel-3 (OLCI) data for water colour applications**. DESIS Workshop: https://desis2021.welcome-manager.de/front/content.php?id_article=533

Wolanin A., Soppa M. A., Bracher A. (2016): **Investigation of spectral band requirements for improving retrievals of phytoplankton functional types**. Remote Sensing. 8: 871. https://doi.org/10.3390/rs8100871

1.2 EnMAP – The German Spaceborne Imaging Spectroscopy Mission

"EnMAP" has just been mentioned by our 3 experts. The **Environmental Mapping and Analysis Program** (EnMAP) is a **German hyperspectral satellite mission** that aims at monitoring and characterizing Earth's environment utilizing its regional coverage on a global scale. EnMAP measures and models key dynamic processes of Earth's ecosystems by extracting geochemical, biochemical and biophysical parameters that provide information on the status and evolution of various terrestrial and aquatic ecosystems. It is **funded under the DLR Space Agency with resources from the German Federal Ministry for Economic Affairs and Climate Action** and the mission is **accompanied by an extensive scientific preparation program and educational initiative**. As part of the scientific mission preparation, the EnMAP science team has developed an open source software (EnMAP-Box) and trained a number of experts in the past decade. This MOOC is the next stage in which we want to **share our knowledge with all potential users** of hyperspectral data and **encourage the growth of a global community on imaging spectroscopy**. Get to know EnMAP as well as various other sources of hyperspectral data in the following lessons!

A detailed description of the EnMAP mission, its instrument and orbit characteristics and various application fields can be found on the mission website and in the EnMAP Science Plan as well as Brochure and Flyer that are available for download on the mission website. We will learn more about the EnMAP mission in Lesson 4 and about how to get access to EnMAP data in Lesson 5 later in this course.

VIDEO: Basic-05: Sensor technologies & data acquisition techniques: the EnMAP Mission

URL of the video:
https://www.youtube.com/watch?v=LQZNtLp3RfM
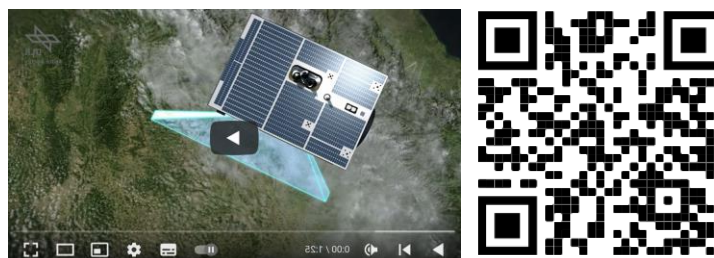
2 Pre-Assessment: Ready for hyperspectral remote sensing?

Are you ready for hyperspectral remote sensing? As mentioned before, in order to really enjoy this course, **you should have some basic understanding of optical remote sensing principles**. If you pass the following quiz, you are very welcome to continue. When you passed the quiz, but still feel as if you need some more repetition of the basics of optical remote sensing, don't worry – the topics of Lesson 3 cover all the basics needed, so please pay particular attention to those! If you don't score the required minimum (7 out of 10 correct answers, 70 %) then we recommend that you **look into the resources listed below**. Anyway, you have **unlimited attempts to pass the quiz**. Here we go and good luck!

Pre-Assessment Quiz

Do the questions look complicated to you? Then try the following resources to prepare yourself for the "Pre-Assessment Quiz" and to be able to explore the hyperspectral remote sensing world afterwards!

Materials:

1. Course 'Land in Focus – Basics of Remote Sensing' by EO-College,

    URL: https://eo-college.org/courses/landinfocus/

2. Webinar 'ARSET – Fundamentals of Remote Sensing' by NASA,

    URL: https://appliedsciences.nasa.gov/join-mission/training/english/arset-fundamentals-remote-sensing

The Pre-Assessment Quiz

A remote sensing system that uses the sun as source of electromagnetic energy is called … (single-choice)

☐   … active

☐   … passive

☐   … neutral

☐   … global

Which parts of the electromagnetic spectrum can we see? (single-choice)

☐   Ultraviolet light

☐   Visible light

☐   Infrared light

☐   Microwaves

An object will appear red to the observer … (single-choice)

☐   … if it absorbs only red wavelengths

☐   … if it transmits only red wavelength

☐   … if it reflects all visible wavelengths equally

☐   … if it mostly reflects red wavelengths

The spectral region where electromagnetic radiation passes through the atmosphere without much attenuation is known as … (single-choice)

☐   … ozone hole

☐   … atmospheric window

☐   … black hole

☐   … skylight

The point just vertically below the observer's position is called … (single-choice)

☐   … zenith

☐   … pole

☐   … nadir

☐   … celestial point

Healthy vegetation strongly reflects light in which parts of the electromagnetic spectrum? (single-choice)

☐   Green and red

☐   Blue and green

☐   Green and near-infrared

☐   Blue and red

Which terms can be assigned to passive RS? (multiple-choice)

☐   Multispectral

☐   LiDAR

☐   Synthetic Aperture Radar (SAR)

☐   Hyperspectral

What are common passive RS satellite missions?

☐   Sentinel-2

☐   Landsat 8

☐   MODIS (Moderate-resolution Imaging Spectroradiometer)

☐   TerraSAR-X

The graphical representation of the spectral response of an object over different wavelengths of the electromagnetic spectrum is termed as … (single-choice)

☐   … line chart

☐   … spectral reflectance curve

☐   … spectral feature

☐   … reflective image

True or false? – "The spatial resolution in remote sensing describes, compared to a photographic image, how much details are visible!"

☐   True

☐   False

3 Principles of imaging spectroscopy

In this lesson, we want to introduce you to the principles of imaging spectroscopy – Charly will give you more details on the specific learning objectives in the video below.

VIDEO: Basic-06: Principles of imaging spectroscopy: Lesson Intro

URL of the video:
https://www.youtube.com/watch?v=_jS7AzpUYZw
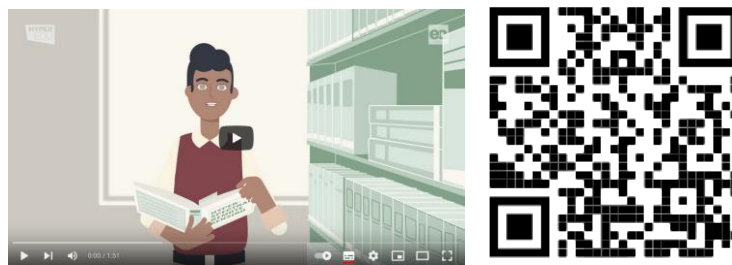
3.1 What is imaging spectroscopy?

The term spectroscopy refers to physical methods that divide radiation according to certain properties such as wavelength. The resulting intensity distribution is called spectrum. Spectroscopy can be used to study the interaction between electromagnetic energy and matter, specifically looking at what wavelengths of light are reflected or absorbed by an object in order to characterize materials.
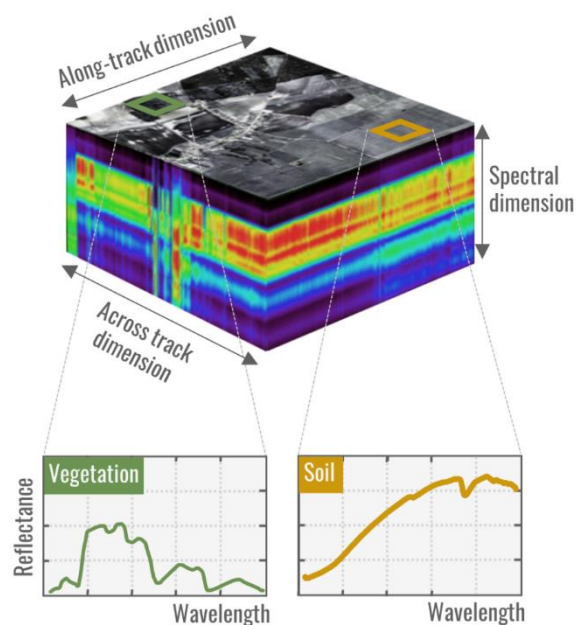
Figure 1 Hyperspectral image cube with two example spectra

Imaging spectroscopy – or hyperspectral remote sensing as it is also frequently called – refers to imaging sensors measuring the spectrum of solar radiation reflected by Earth surface materials in many contiguous wavebands, on the ground as well as air- or spaceborne. You can picture the resulting image – or data cube – like a photograph; however, instead of the usual three RGB channels there are up to hundreds of bands that allow identification and often quantification of materials based on the shape of the spectral curve.

Info box – Did you know?

The term **hyperspectral imaging** is sometimes used interchangeably with imaging spectroscopy. Due to its heavy use in military related applications, the civil world has established a slight preference for using the term imaging spectroscopy.

The term **hyperspectral imaging** derives from the development of NASA's Airborne Imaging Spectrometer (AIS) and AVIRIS in the mid-1980s. Although NASA prefers the earlier term **imaging spectroscopy** over **hyperspectral imaging**, use of the latter term has become more prevalent in scientific and non-scientific language. In a peer reviewed letter, experts recommend using the terms **imaging spectroscopy** or **spectral imaging** and avoiding exaggerated prefixes such as "hyper-," "super-" and "ultra-," to prevent misnomers in discussion.

Source: Wikipedia

3.2 Major milestones

In the following graphic, you can explore the major milestones of imaging spectroscopy. Please note that we focus on non-commercial missions with free data policy in the spaceborne missions' sections.

1660

1660 — 1704

The division of white light into a rainbow of colors

Modern western spectroscopy started back in the 17th century when Sir Isaac Newton demonstrated that white light could be split up into its component colors by a prism. He used the term spectrum for the first time to describe the rainbow of colors that appears when light passes through a prism.

1800 — 1820

The discovery of absorption bands

Later on in the early 18th century, Joseph von Fraunhofer conducted experiments with dispersive spectrometers that enabled precise and quantitative spectroscopic measurements. Fraunhofer and others made systematic observations of the solar spectrum and found narrow dark bands at specific wavelengths. These bands known as Fraunhofer lines are typical spectral absorption lines that are the result of photons being absorbed as light passes from the source to the detector.

1800

1982

The first imaging spectrometers

A few centuries later, the first imaging spectrometers were built to observe the Earth's surface and other objects in our solar system. Significant achievements in imaging spectroscopy are attributed to the first airborne instruments arising in the early 1980s. The Airborne Imaging Spectrometer (AIS) of the Jet Propulsion Laboratory (JPL) with 128 bands in the 900-2100 nm and 1200-2400 nm spectral regions began flight operations in November 1982.

1982

1987

1987

Airborne Visible Infrared Imaging Spectrometer (AVIRIS)

The success of the AIS program soon led to the development of the first full spectrum Airborne Visible Infrared Imaging Spectrometer (AVIRIS) covering the spectral range from 380 to 2510 nm (Goetz et al. 1985, Ustin et al. 2006). The AVIRIS system has been improved continuously and an increasing number of imaging spectrometers has been successfully employed on airborne platforms since, including HyMap, DAIS, APEX, AISA, CASI and others.

2000

The first spaceborne imaging spectrometers

However, it was not until the early 2000nds that the first imaging spectrometers were launched into space with the Hyperion imaging spectrometer aboard NASA's Earth observing mission EO-1 in 2000 and ESA's compact high-resolution imaging spectrometer CHRIS aboard the PROBA satellite in 2001, and HICO aboard the ISS in 2009, all regarded as technology demonstrators

2000

2019

2019

Next-generation spaceborne sensors

Despite their limitations in terms of signal to noise ratio and spectral and spatial coverage, Hyperion and CHRIS successfully demonstrated the great potential of spaceborne hyperspectral systems and provided the basis for algorithms applicable to next-generation spaceborne sensors such as the Italian hyperspectral Precursor of the Application Mission (PRISMA) launched in 2019, DESIS aboard the ISS (2018) and HISUI aboard the ISS (2019).

2022

2022

Launch of the EnMAP mission

Following its launch April 2022, on October 28, 2022, EnMAP successfully completed its Flight Qualification Review (FQR) and thereby, finished the Commissioning Phase (CP). Based on this decision, EnMAP entered routine operations on November 2, 2022.

2027

2027

Future missions

Operational and global: Driven by a strong demand of the scientific community and service developers, further imaging spectroscopy missions are currently in the planning that will deliver data on a regular, operational and global basis such as NASA's Surface Biology and Geology Investigation Mission (SBG) and ESA's Copernicus Hyperspectral Imaging Mission (CHIME).

For more details on the history, milestones and missions please refer to *Schaepman et al. 2009*, *Rast and Painter 2019*, *Taramelli et al. 2020* and other reference publications.

Please complete the quiz below to advance to the next topic.

Quiz: Major milestones

Which of the following sensors are spaceborne instruments? (multiple-choice)

- ☐ AIS
- ☐ PRISMA
- ☐ CHIME
- ☐ EnMAP
- ☐ AVIRIS
- ☐ Hyperion
- ☐ HICO

Which of the following sensors are airborne instruments? (multiple-choice)

- ☐ PRISMA
- ☐ AVIRIS
- ☐ HICO
- ☐ HYPERION
- ☐ AIS
- ☐ CHIME
- ☐ EnMAP

When was the first spaceborne hyperspectral instrument launched? (single-choice)

- ☐ 1982
- ☐ 1995
- ☐ 2000
- ☐ 2022 with the launch of EnMAP as the first hyperspectral sensor in space.

3.3 Electromagnetic radiation (EMR)

The content of this topic is partially based on the Course 'Land in Focus – Basics of Remote Sensing' (highlighted in greyish boxes).

URL: https://eo-college.org/courses/landinfocus/

The fuel of remote sensing

The application of remote sensing sensors and methods relies on the existence of electromagnetic (EM) radiation. Whether it is being measured through the emissions of an object (reflection of sunlight) or whether radiation is actively sent from an instrument, without this source of energy, we cannot analyze a signal. But: What exactly are "waves"? You can think of a wave as a **moving undulation** transporting **energy**.

An example of natural wave development are water waves developing after a stone is thrown into water. Other kind of waves are sound waves developing while speaking or when a police car passes by.

The radiation coming from the Sun is travelling in the form of the so-called **electromagnetic waves**. Here, electrical and magnetic fields are coupled.

A history detour: EM waves

In the 1860's and 1870's, the Scottish scientist **James Clerk Maxwell** developed a scientific **theory** to explain EM waves. He noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves. He summarized this relationship between electricity and magnetism into what are now referred to as "**Maxwell's Equations**".

Heinrich Hertz, a German physicist, applied Maxwell's theories to the **production and reception** of radio waves. The unit of frequency of a radio wave — one cycle per second — is named the **hertz**, in honor of Heinrich Hertz.

His experiment with radio waves solved two problems. Firstly, he demonstrated concretely, what Maxwell had only theorized — that the velocity of radio waves was equal to the **velocity of light**. This proved that radio waves are a form of light. Secondly, Hertz figured how to make the **electric and magnetic fields detach themselves from wires** and go free as Maxwell's waves — electromagnetic waves.

Structural view on an EM wave

As visualized on the right, an EM wave consists of an electrical field (EF, red) and a magnetic field (MF, blue). The EF varies in magnitude in the direction that is perpendicular to that of the travel direction. A corresponding MF is oriented at right angles to the EF. Both fields travel at the speed of light (~300,000 km/s).
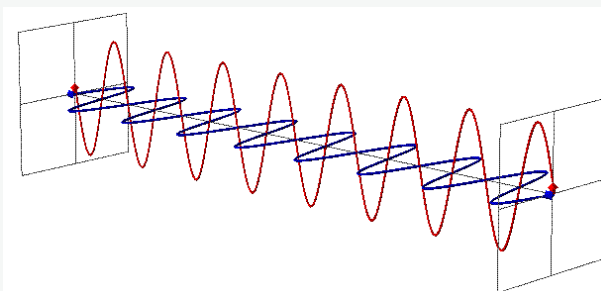

Figure 2 A travelling EM wave with an electric field (red) and a magnetic field (blue) (AWF-Wiki 2013)

How do we describe an EM wave?

The terms light, electromagnetic waves, and radiation all refer to the same physical phenomenon: electromagnetic energy. This energy can be described by frequency (f), wavelength (λ) and the speed of light (c). All three are related mathematically such that if you know one, you can calculate the other two using this equation:

$$c = \lambda f$$

Thus, EM waves can be described through the characteristics of two parameters: **a) wavelength** and **b) frequency**. Both are closely correlated (inversely) and depend on each other.

Wavelength
Electromagnetic waves have crests and troughs similar to those of ocean waves. The distance between crests is referred to as 'wavelength' and is denoted with the symbol λ. The shortest wavelengths are just fractions of the size of an atom, while the longest wavelengths scientists are currently studying can be larger than the diameter of our planet.

Frequency
The number of crests that pass a given point within one second is described as the frequency of the wave. One wave or cycle per second is called a Hertz (Hz), after Heinrich Hertz who established the existence of radio waves. A wave with two cycles that pass a point in one second has a frequency of 2 Hz.

The amplitude is another important variable that characterizes the distance between the peak and trough of a wave. With these three measures (wavelength, amplitude, frequency), you are now able to describe an EM wave.
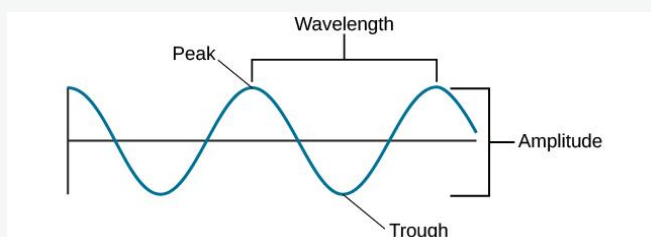

Figure 3 Relation of wavelength and amplitude (Lumen Learning)

💡 Interactive Graphs and Tools

You need to be enrolled and logged in under EO College in order to be forwarded to the interactive Graphs. Figures of those are, however, incorporated in this offline version. For the best learning experience, we recommend to check out the graphs online.

Explore the unique features of an EM wave

This **interactive tool**, available under this LINK, gives you a hands-on experience of the **frequency and the amplitude of a wave**, two very important parameters. Try the sliders below to get a feel of what these parameters actually mean.
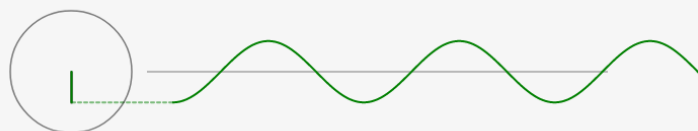
Frequency

Amplitude

Frequency

Amplitude

The spectrum of EM radiation

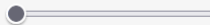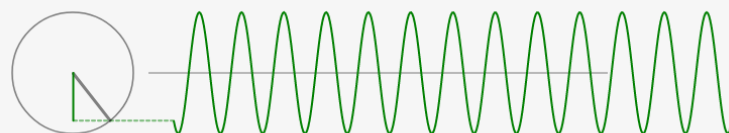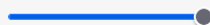Electromagnetic energy **travels in waves** and spans a broad spectrum from very short UV rays to very long microwaves. In remote sensing, it is commonly described by its wavelength, usually indicated in micrometers [μm] or nanometer [nm]. The **human eye** can only detect a small portion of this wavelength spectrum called **visible light (VIS)**. As you can see in the graph below, optical sensors make use of the spectral region between 350 and 2500 nm. The range of light visible to humans (VIS) ranges from 380 to 780 nm and includes the colors violet, blue, green, yellow to orange and red. The visible spectrum is followed by **infrared wavelengths (IR)**, divided into **near infrared (NIR, 700 – 1300 nm*)**, **short wave infrared (SWIR, 1300 – 3000 nm*)**, **mid infrared (MIR)** and **thermal infrared (TIR)** that are followed by long wavelengths such as **microwaves** and **radio waves**.

This definition of wavelength ranges is commonly used in (optical) remote sensing. There are other definitions, e.g. in spectroscopy (from Clark 1999: ultraviolet (UV): 1 to 400 nm, visible: 400 to 700 nm, and near-infrared (NIR): 700 to 3000 nm).
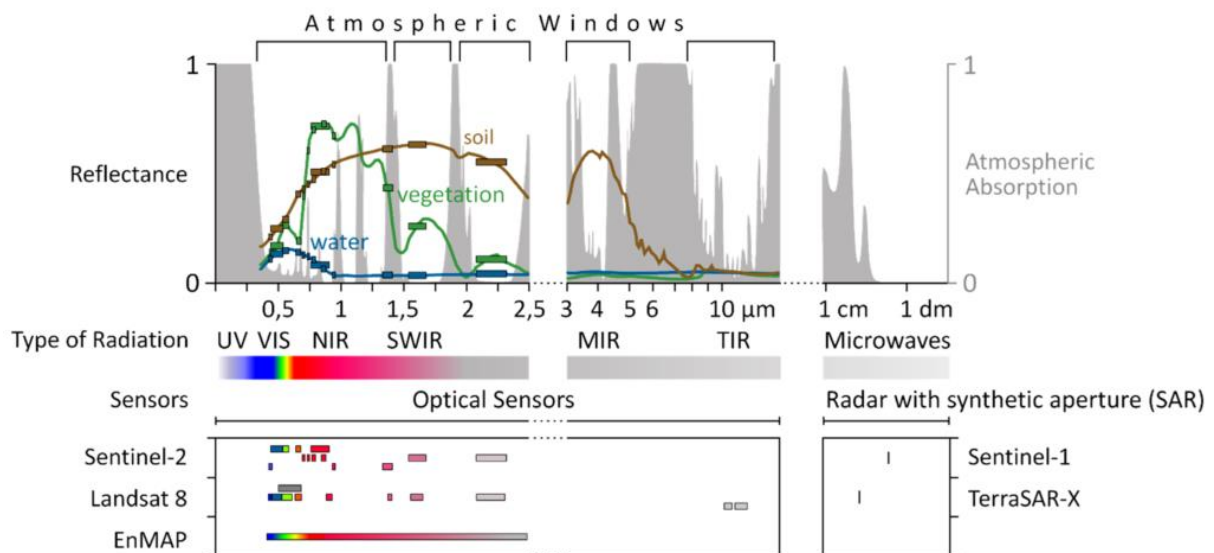

Figure 4 The graph above depicts different ranges of the electromagnetic spectrum (center), reflectance spectra and atmospheric absorption (top) and a selection of sensors sensitive to the displayed types of radiation (bottom)

Radiation is influenced by the atmosphere in many different ways which are wavelength dependent: The sun radiates with highest intensities in the visible spectrum while at the same time the atmospheric transmittance is highest. At longer wavelengths, the transmittance is reduced to narrow ranges. This includes the permeable areas in the thermal infrared through which the Earth emits radiation into space. Also in the microwave range, the atmosphere is almost completely permeable. As the radiation from Sun and Earth is low, this range can be used by active radar systems. Shorter wavelengths such as UV are almost completely absorbed by the atmosphere and therefore negligible for remote sensing, which focuses on the permeable areas (**atmospheric windows**).

Basic laws of radiation

There are four **basic laws of radiation** that you should have heard of when working with optical remote sensing data as they are important to understand how the radiation emanating from an object depends on its temperature and material properties.

Stefan Boltzmann Law

The dependence of emitted radiation on the temperature follows the **Stefan Boltzmann Law**. Basically, every body, whose temperature lies above zero (-273 °C or 0 K) radiates energy in form of electromagnetic radiation. The radiation emitted is proportional to the absolute temperature of the body to the power of four. Ideal emitters (absorbers) are called black bodies.

$$M = \sigma * T^4$$

Where:

- *M = radiation (W/m²)*

- *σ = Stephan-Boltzmann-Constant (5.67051 * 10⁻⁸ W/m²K)*

- *T = absolute temperature (K)*

Wien's Displacement Law

The emission maximum of the temperature radiation is explained by **Wien's displacement Law**, indicating that higher temperatures correspond to a maximum intensity at shorter wavelengths and lower temperatures to a maximum intensity at higher wavelengths. For example, the sun with its high surface temperatures of about 6000 K emits light with a maximum intensity of about 0.5 μm (visible range), while the Earth with an average surface temperature of 300 K emits light predominantly in the mid infrared with a maximum around 10 μm (also called thermal infrared).

$$\lambda_{\text{max}} = \frac{T}{A}$$

Where:

- *λ_{max} = wavelength of max intensity (μm)*
- *A = Wien's displacement constant (2898 μm * K)*
- *T = temperature (K)*
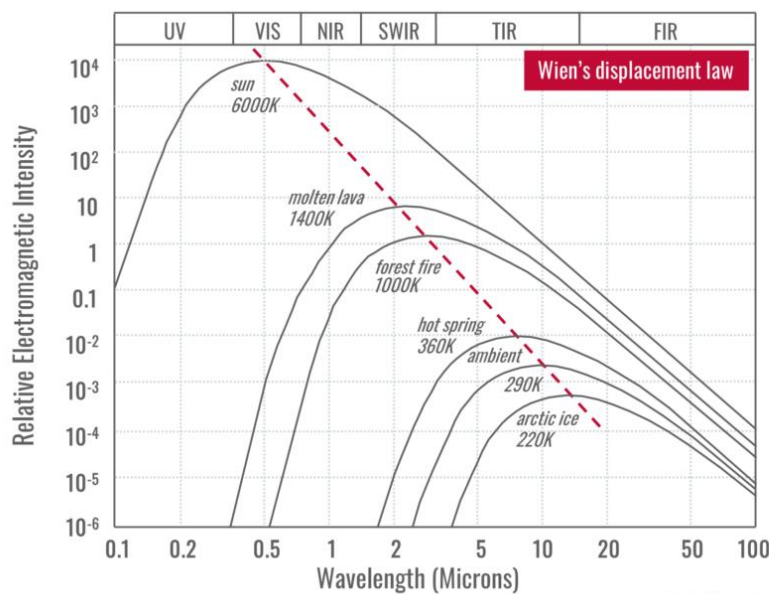
Figure 5 The graph above shows the emission maximum of the temperature radiation

Planck's Law

The typical source of radiation in imaging spectroscopy is the sun. It corresponds to an almost ideal emitter, also called black body. The radiation of the sun depends, as for

any ideal emitter, solely on its temperature (material properties are irrelevant) and can be described with **Planck's Law** of radiation as a function of wavelength.

$$B_{(\lambda,T)} = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Where:

- *B_λ = spectral radiance*
- *k = Boltzmann constant ($1.38064852 * 10^{-23}$ J * K^{-1})*
- *h = Planck constant ($6.626 * 10^{-34}$ J * s)*
- *T = absolute temperature (K)*
- *c = speed of light*

Kirchhoff's Law

Finally, the interdependence of emissivity and absorbency of radiation is given by **Kirchhoff's Law** (establishing the relationship between a black emitter and a real emitter – at equilibrium, the radiation emitted must equal the radiation absorbed).

$$1 - \epsilon = R$$

Where:

- *ε = Emissivity*
- *R = Reflectivity*

Please complete the quiz below to advance to the next topic.

Quiz: Electromagnetic radiation (EMR)

Electromagnetic radiation is described by wavelength and frequency. They are inversely proportional, meaning (single-choice)

☐   … the shorter the wavelength the higher the frequency

☐   … the higher the frequency the longer the wavelength

☐   … they are indicated in the same units

Fill in the blanks (Options: VIS, NIR):

The human eye is sensitive for the wavelength range that we call ☐ . It is located between the UV and the ☐ ranges on the electromagnetic spectrum.

Which of the statements are correct: (multiple-choice)

☐   All objects > 0 K emit radiant energy

☐   Hotter objects radiate more total energy per unit area than colder objects

☐   The hotter the radiant body, the shorter the wavelength of maximum radiation

☐   Perfect absorbers (perfect emitters) are called black bodies

3.4 Interaction of EMR with atmosphere

In this topic, you will learn about the interactions between radiation and the Earth's atmosphere. The layer surrounding our planet has a tremendous effect on the signal that we are measuring. The atmosphere is not a vacuum and, therefore, the radiation gets altered in various ways: Extraterrestrial
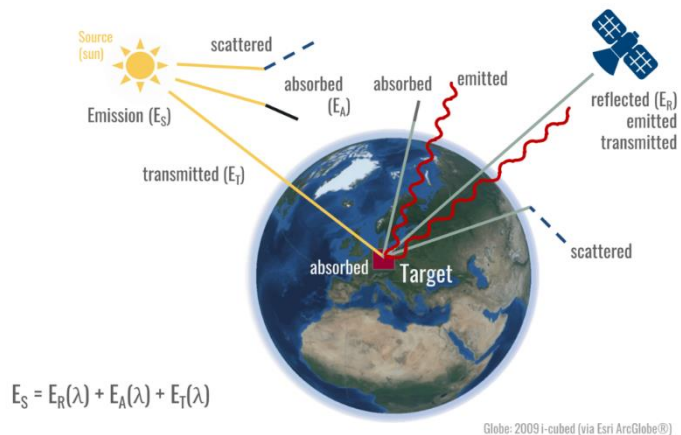
$$E_S = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$$

Figure 6 General interaction of sunlight with the Earth's atmosphere

radiation reaching the Earth first enters the upper layers of the atmosphere, where a part of it is **reflected** back into space. The other part travels through the atmosphere and is subject to further wavelength-dependent processes, for example, radiation is **absorbed** and **scattered** by gaseous and particulate components (a process called extinction). Let's look at the processes in a little more detail …

Absorption

Absorption of electromagnetic radiation **is the way by which the energy of a photon is taken up by matter**. Thus, the electromagnetic energy is transformed to other forms of energy, for example, heat. In certain wavelength ranges, substances in the atmosphere absorb so strongly that very little or no radiation reaches the Earth's surface. These wavelength ranges are called atmospheric **absorption bands** and are mainly caused by water vapor, carbon dioxide and ozone. In remote sensing, we rely on

Figure 7 Atmospheric absorption

(relatively) permeable wavelength regions called **atmospheric windows**. For example, the visible region is relatively transparent to electromagnetic radiation. In contrast to scattering, **absorption is an effective energy loss of the radiation**.
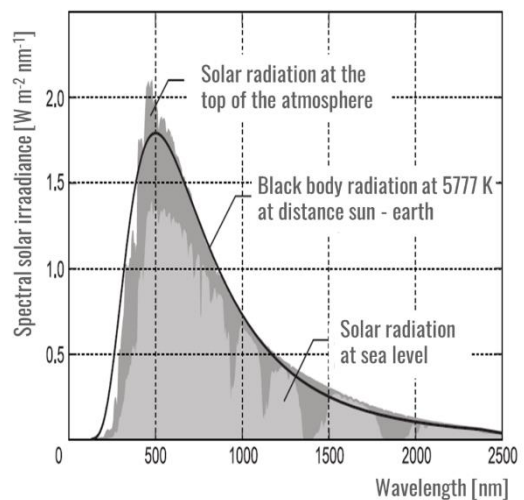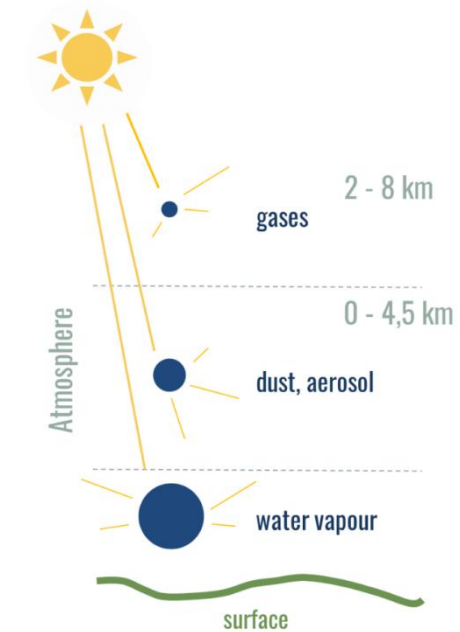
Scattering

Atmospheric scattering describes the scattering of radiation in the atmosphere due to particles. It refers to a change of direction of electromagnetic radiation that is not predictable (unlike reflectance). Scattering **is a function of (1) the wavelength of incoming radiation** and **(2) the size of scattering particles**:

Rayleigh scattering (scattering particle < wavelength) refers to diffuse scattering of electromagnetic waves by tiny particles or molecules (such as nitrogen or oxygen) whose diameter is much smaller than the wavelength. Since the scattering is stronger the shorter the wavelength (the shortest wavelengths are blue), Rayleigh scattering is responsible for the sky appearing blue.

Figure 8 Atmospheric scattering

Mie scattering (scattering particle ~ wavelength) is caused by particles in the atmosphere whose diameter is larger than the wavelength of the incident radiation, thus longer wavelengths are affected. Particles causing Mie absorption are called aerosols and include for example: sea salt, dust, biologicals, sulfates, nitrates, etc. resulting from evaporation, industrial pollutions, (forest) fires, and volcanic eruptions.

Non-selective scattering (scattering particle > wavelength) is caused by water vapor or ice particles, that are > 10 times as large as the wavelength of incident radiation and scatters all wavelengths equally well. It occurs closest to the Earth's surface.

Reflectance

Reflectance refers to, surprise, electromagnetic radiation being reflected from a surface, in case of the atmosphere from aerosols or clouds. A large part of incoming radiation in the visible to shortwave infrared range is directly reflected from the latter. This is clearly a disadvantage of optical remote sensing as we **depend on a cloud-free sky**.

Great Britain and Ireland, acquired by MERIS on 7 February 2009. ESA

Figure 9 Atmospheric reflectance – imaging spectroscopy depends on a cloud-free sky!

Radiation transfer (and some terminology)

In optical remote sensing, the **dominant energy source is direct illumination from the Sun (1)** (approximately 90%). In addition, there is **diffuse sky irradiance (2,3)** due to scattering and absorption in the atmosphere. Thereby, the part of the diffuse sky radiation that acts in the direction of the sensor without ever reaching the surface is called **path radiance (2)**. It is determined by the scattering processes within the atmosphere and strongly wavelength-dependent.
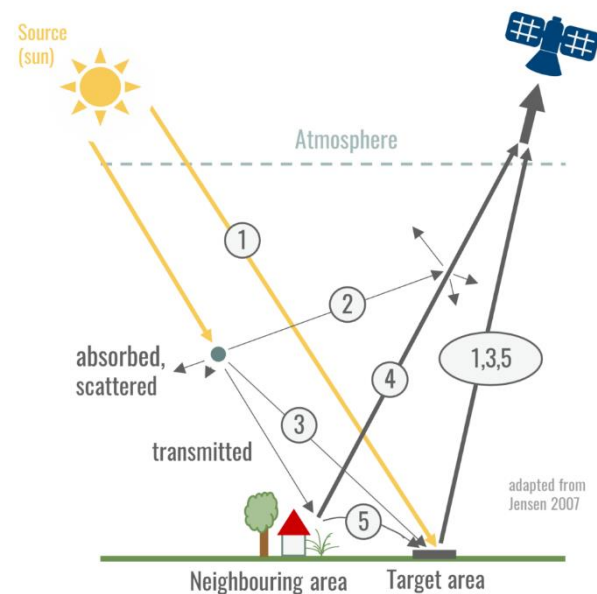
Figure 10 Radiation transfer

On its way to the sensor, all the reflected radiation from the object (1,3,5) has to pass through the atmosphere AGAIN and is thereby attenuated (2,4). So ideally, the signal recorded by the sensor is a true function of the amount of radiance leaving the target within the instantaneous-field-of-view at a specific solid angle. However, in reality, other radiant energy may enter into the sensor's field of view from various other paths and introduce confounding noise (Jensen 2007).

Please complete the quiz below to advance to the next topic.

Quiz: Interaction of EMR with atmosphere

Fill in the blanks (Options: absorbed, reflected):

Electromagnetic radiation reaching the Earth first enters the upper layer of the atmosphere, where a part of it is [   ] back into space. The other part travels through the atmosphere and is [   ] and scattered by gases, molecules, particles, gaseous and/or particulate components.

Scattering is a function of the wavelength of incoming radiation and the size of scattering particles. Sort the type of scattering to the correct particle size (Options: Rayleigh scattering, Mie scattering, Non-selective scattering):

Particles whose diameter is much smaller than the wavelength: Choose an element

Particles whose diameter is larger than the wavelength: Choose an element

Particles whose diameter is > 10 times as large as the wavelength: Choose an element

Which scattering type is responsible for the blue appearance of the sky? (single-choice)

☐   Rayleigh scattering
☐   Mie scattering
☐   Non-selective scattering

3.5 Interaction of EMR with target

On the Earth's surface, the radiation finally interacts with an object. In principle, this interaction is not so different from the atmospheric processes explained above, as the incoming radiation is partly absorbed, reflected, and (in case of non-opaque objects) transmitted. Again, absorption is the uptake of energy by a substance and reflectance means that incoming radiation is reflected without energy being absorbed or emitted. During transmission, the radiation penetrates an object without energy change. The reflected part of the radiation leaves the object as directed spectral radiation, modified by the spectral characteristics (degree of reflection) of the object – this is actually the part that most (imaging) spectroscopy applications are interested in. Besides on its physico-chemical properties, the reflectance of any surface will depend on the **illumination and viewing geometry as well as on surface roughness**, as Charly explains in the following video.

In the course you will see several **videos that we have made interactive for you**. They contain questions that you can try to answer. The answers are not graded, you have countless attempts, you can skip them, and even rewind and fast-forward through the video to find the correct answer. **Give it a try!** They will help you prepare for the graded quizzes and to take away the most important aspects of each topic.

In this document, you will find the questions below the videos. The questions can be answered with the help of the videos. To check the answers, the video must be watched online in the MOOC on https://eo-college.org/courses/beyond-the-visible/.

VIDEO: Basic-07: Principles of imaging spectroscopy: Illumination and surface roughness

URL of the video:
https://www.youtube.com/watch?v=TjeDdcrsas0&t=4s

VIDEO: Principles of imaging spectroscopy: Illumination and surface roughness

The perception of surface roughness is independent of wavelength.

 ☐ True

 ☐ False

Fill in the missing words

"Forward scattering is observed [   ] (with/against) the direction of illumination and backward scattering [   ] (with/against) the direction of illumination. Therefore, the reflection in the backward scattering area is always (weaker/stronger) than in the forward scattering area."

Now you probably know about all processes, aspects and circumstances that can confound your spectral measurements. For most applications, we need to know about these effects in order to correct for them. However, we are usually interested in the physico-chemical characteristics of our target areas. So how do the physico-chemical characteristics of materials influence their reflective properties? Some of these characteristics are so dominant that you can derive them from multispectral data, for example, vegetation "greenness". However, hyperspectral data allows the detection of much more spectral detail and therefore, Charly will try to explain **how physico-chemical properties result in absorption bands that enable material identification and often quantification** in the next video:

VIDEO: Basic-08: Principles of imaging spectroscopy: Electronic processes

URL of the video:
https://www.youtube.com/watch?v=oslWl19VF0E&t=3s
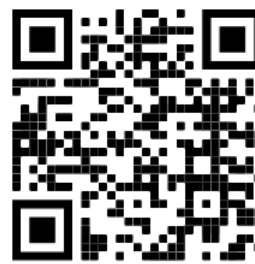
VIDEO: Principles of imaging spectroscopy: Electronic processes

The most important process for optical remote sensing is …

☐   reflectance

☐   transmittance

☐   absorption

Fill in the missing words

Remember? „Electron transfer processes require [_____] (very little/a lot of) energy. The bands caused by them are therefore usually quite [_____] (broad/narrow) and in the short-wave UV range."

„Apart from the geometric conditions of illumination and observation as well as surface roughness, the reflectance properties of an object depend on its … " (multiple-choice)

☐   material properties

☐   chemical properties

☐   physical properties

Please complete the quiz below to advance to the next topic.

Quiz: Interaction of EMR with target

The reflective properties of an object are primarily linked to its surface characteristics. Assign the type of reflection to the correct graph (Options: diffuse / Lambertian, real world case / mix, specular).
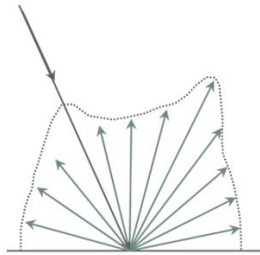
Choose an element
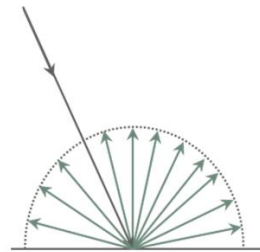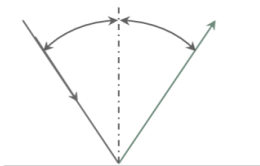
Choose an element

Choose an element

Fill in the blanks (Options: seismic processes, acoustic processes, vibrational processes) The most important process for optical remote sensing is absorption. Radiant energy arriving at an object stimulates electron transfer and Choose an element at the molecular level.

Which geometric factors influence surface reflectance? (multiple-choice)

☐ Color
☐ Viewing angle
☐ Surface roughness
☐ Incidence angle

3.6 Spectral reflectance of selected surface materials

Geology & Minerals

Reflectance spectra of minerals are dominated in the visible near-infrared (VNIR) wavelength range (400 to 1300 nm) by the **presence or absence of transition metal ions** (e.g., Fe, Cr, Co, Ni) resulting in absorption features due to electronic processes. The **presence or absence of water and hydroxyl, carbonate and sulphate**, that are widespread components of the Earth's surface, determine absorption features in the SWIR region (2000 to 2500 nm) due to vibrational processes. In general, absorption band depth is correlated with the (relative) amount of material present.
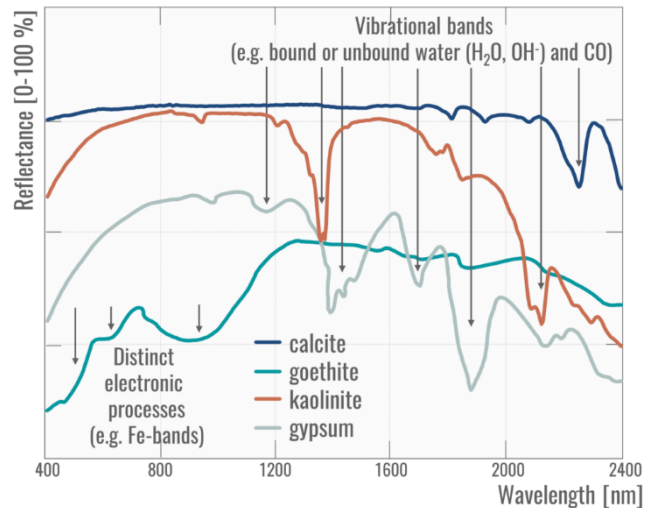
Figure 11 Reflectance spectra of soil and dry vegetation

Always keep in mind that we **only see the surface of materials**! Surface coatings, for example, an iron oxide patina on a mineral or lichens on a rock alter the surface and thus conceal characteristic reflectance features.

Soil

Since the major constituents of soil minerals do not exhibit absorption features in the VNIR and SWIR range (Hunt, 1977), their **spectral reflectance characteristics** are mainly influenced by **organic matter content, clay mineral composition, iron-oxide content, moisture content, salinity, texture and surface roughness**. Typically, soils have broad, shallow absorption features at wavelengths between 400 nm and 2500 nm that are related to iron oxide

Figure 12 Reflectance spectra of soil and dry vegetation

and organic matter. In general, reflectance decreases with increasing organic matter and/or moisture content. Increases in particle size also cause a decrease in overall reflectance. Even small amounts of iron oxides can alter VNIR spectra significantly, causing broad absorption features particularly around 400 nm, 700 nm and 870 nm (Ben-Dor et al. 1999). In contrast, several clay minerals (e.g., montmorillonite, kaolinite, illite, smectite) and carbonates display distinctive narrow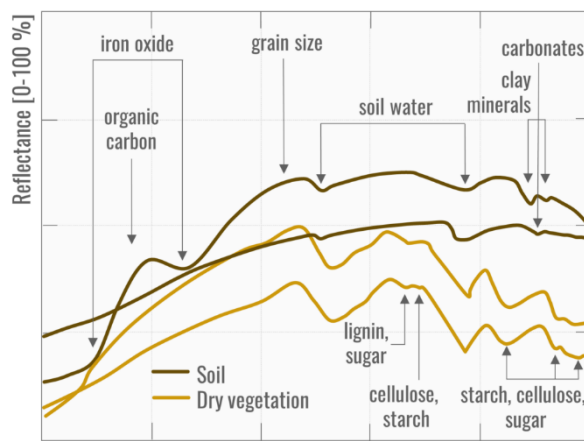-band absorption features in the SWIR range between 2000 nm and 2500 nm (Ustin et al., 2004). By the way, **in order to differentiate between bare soil and dry vegetation, hyperspectral information is crucial** (cellulose absorption).

Green vegetation

Absorption characteristics of vegetation are predominantly very similar, even between plant species, because the molecular mechanisms underlying the absorption are found in various substances of the plants (for example, O-H bond in water, cellulose and starch). Therefore, clear assignments of absorption bands and molecular processes are difficult to make. Except for the leaf pigments (e.g. chlorophyll and carotenoids), many of the biochemical plant substances occur only in low concentrations, so that only minimal absorption bands are measured. In addition, there are **multiple scattering processes at leaf (mesophyll), plant, as well as at canopy level**, which determine the shape of the absorption bands.
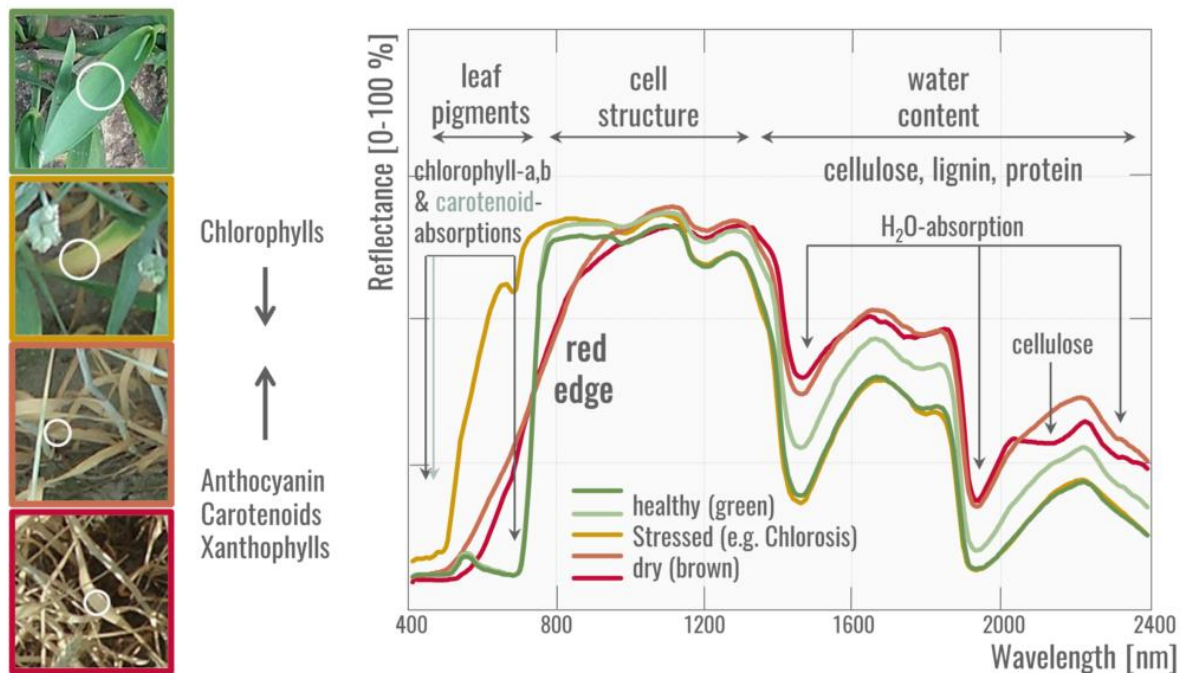

Figure 13 Reflectance spectra of green, stressed and drying vegetation

In general, the **spectral reflectance curve of healthy green vegetation has a minimum in the visible (VIS)** part of the electromagnetic spectrum due to leaf pigments. Chlorophyll pigments selectively absorb blue (400–500 nm) and red (600–700 nm) light for photosynthesis and less green light (500–600 nm), resulting in a "green peak" and the green appearance of healthy vegetation to human eyes. Other pigments like carotenoids and xanthophylls have strong absorptions in the blue wavelengths range (400–500 nm) and are responsible for various leaf colors.

The **spectral reflectance curve increases strongly towards the near-infrared range (NIR)**. In the NIR (700-1300 nm), leaf absorption by pigments and other constituents is small and most energy is transmitted or reflected, depending on leaf structural characteristics, resulting in a high plateau.

The range between red (VIS) light and near infrared is characterized by a steep slope, called "**red edge**" and is used in plant stress detection. The reflectance of stressed vegetation is generally higher in the VIS and lower in the infrared range as compared to healthy vegetation. Besides, there is a flattening and shift to shorter wavelength in the red edge portion of the spectrum. The SWIR region (1300–2500 nm) is dominated by water absorption. An increase in leaf moisture content results in a general decrease of reflectance, especially in the NIR and SWIR, accompanied by an increase (depth, width) of the water absorption features near 1400 and 1900 nm.

Explore the spectra of vegetation

As the slider is moved, the content (values given in parentheses) increases or decreases and the spectrum adjusts accordingly. This figure is based on the IVVRMtool developed for the EnMAP-Box. IVVRM is short for "Interactive Visualization of Vegetation Reflectance Models". In the corresponding tutorial or under this LINK, you can manipulate the parameters by yourself and observe a lot more details in the changes of the spectrum.
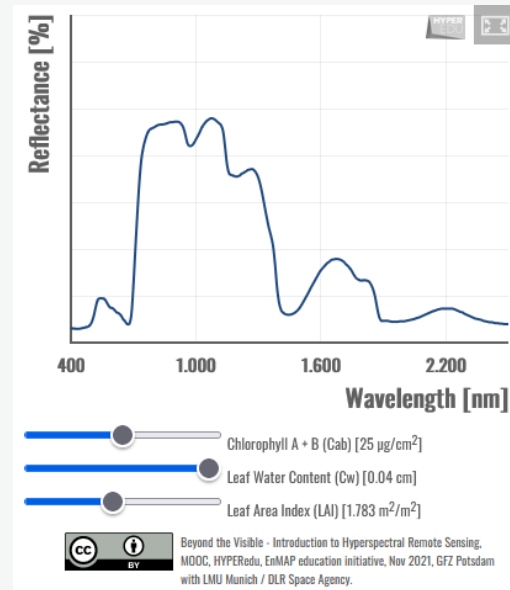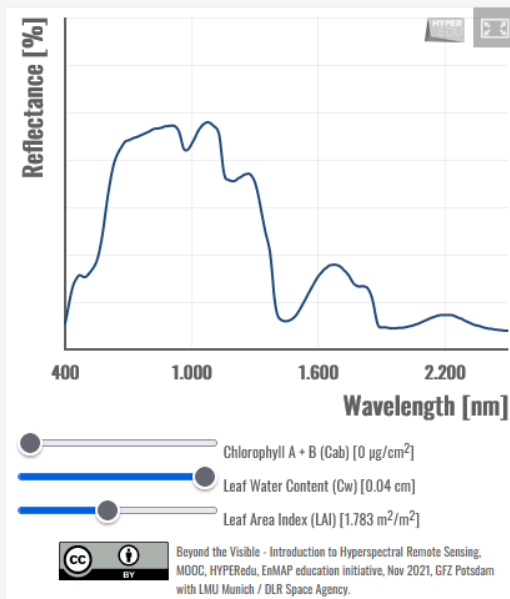
Inland and coastal water

The **reflectance curve of liquid water is characterized by low reflectance** in the visible range and high (almost complete) absorption in the near infrared and beyond. Due to these absorption properties, water bodies and objects containing water can be easily delineated and identified, even by multispectral data. In addition, imaging spectroscopy has been used to measure optical constituents such as pigments (e.g., chlorophyll), a wide range of phytoplanktonic species, dissolved organic matters, and suspended non-algal particles (e.g., minerogenic sediments). Coastal and inland waters are optically more complex as compared to open oceanic waters, which can be characterized mainly by one optical parameter, namely ocean color.
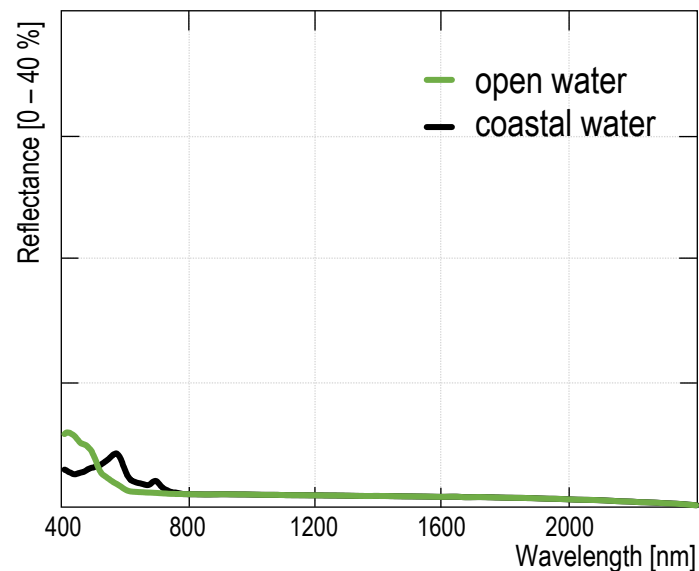
Figure 14a Reflectance spectra of open and coastal water

Please complete the quiz below to advance to the next topic.

Quiz: Spectral reflectance of selected surface materials

The graph shows spectra of three different surface materials – can you identify them?
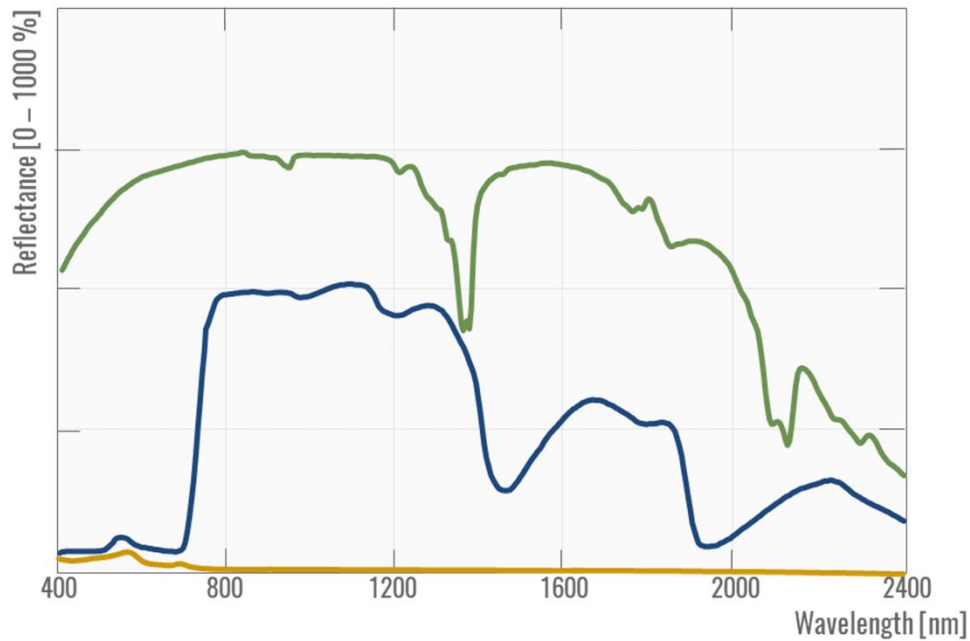
Choose elements (Options: water/open water/inland water/freshwater, Kaolinite/mineral, green vegetation/vegetation/plant/leaf)

Green is …   Choose an element

Blue is …   Choose an element

Yellow is …   Choose an element

Select the two surface materials that are spectrally very similar:
- ☐ Liquid water
- ☐ Green vegetation
- ☐ Dry vegetation
- ☐ Open soil

3.7 Resource section: Lesson 'Principles of imaging spectroscopy'

In this section, we have assembled resources used for the creation of this lesson that we recommend you for further reading as they provide a lot more detail. Please remember that this selection is not a complete overview of all resources – if you think an important resource is missing, let us and your fellow students know (e.g. in the discussion forum). You can find the discussion forum at https://eo-college.org/forums/forum/beyond-the-visible/ under each related topic.

You can find almost all figures of this lecture in the **HYPERedu slide collection**, available on EO-College, where you can additionally leave comments on each of the slide collections.

How to cite: A. Brosinsky, T. Kuester, S. Foerster, H. Kaufmann, K. Segl, L. Guanter (2021). **Principles of imaging spectroscopy – Electromagnetic radiation and its interactions with earth surface materials**, slide collection, HYPERedu, EnMAP education initiative, 1st revision March 2021, originally published October 2019, German Centre for Geosciences GFZ.

Sources and further reading

Topic: What is imaging spectroscopy?
Some discussions of the terms imaging spectroscopy vs. hyperspectral remote sensing:

- https://en.wikipedia.org/wiki/Imaging_spectroscopy

- https://en.wikipedia.org/wiki/Hyperspectral_imaging

- https://avirisng.jpl.nasa.gov/

Topic: Major milestones

- Foerster S., Guanter L., Lopez T., Moreno J., Rast M., Schaepman M.E. (2019): Guest Editorial: **International Space Science Institute (ISSI) Workshop on Space-Borne Imaging Spectroscopy for Exploring the Earth's Ecosystems**. Surveys in Geophysics. 40, 297–301. https://doi.org/10.1007/s10712-019-09516-0

- Goetz A.F.H, Vane G., Solomon J.E., Rock B.N. (1985): **Imaging Spectrometry for Earth Remote Sensing.** Science. 228, 4704. https://doi.org/10.1126/science.228.4704.1147

- MacDonald J., Ustin S.L., Schaepman M.E. (2009): **The contributions of Dr. Alexander F.H. Goetz to imaging spectrometry**. Remote Sensing of Environment. 113, S2–S4. https://doi.org/10.1016/j.rse.2008.10.017

- Rast M., Painter T.H. (2019): **Earth Observation Imaging Spectroscopy for Terrestrial Systems: An Overview of Its History, Techniques, and Applications of Its Missions**. Surveys in Geophysics. 40, 303–331. https://doi.org/10.1007/s10712-019-09517-z

- Schaepman M.E., Ustin S.L., Plaza A.J., Painter T.H., Verrelst J., Liang S. (2009): **Earth system science related imaging spectroscopy—An assessment**. Remote Sensing of Environment. 113, S123–S137. https://doi.org/10.1016/j.rse.2009.03.001

- Taramelli A., Tornato A., Magliozzi M.L., Mariani S., Valentini E., Zavagli M., Costantini M., Nieke J., Adams J., Rast M. (2020)**: An Interaction Methodology to Collect and Assess User-Driven Requirements to Define Potential Opportunities of Future Hyperspectral Imaging Sentinel Mission**. Remote Sensing. 12, 1286. https://doi.org/10.3390/rs12081286

- Ustin S.L, McDonald J., Schaepman M.E. (2006): **A Review of the Contributions of Alexander F.H. Goetz to Imaging Spectroscopy**. IEEE. https://doi.org/10.1109/IGARSS.2006.508

Topics: Electromagnetic radiation (EMR) and its interaction with the atmosphere and targets

- Jensen J.R. (2007): **Remote Sensing Of The Environment: An Earth Resource Perspective**. 2nd Edition, Pearson.

- Lillesand T., Kiefer R.W. & J. Chipman (2008): **Remote Sensing and Image Interpretation**. 6th Edition, Wiley.

- Workman J. Jr & L. Weyer (2007): **Practical Guide to Interpretive Near-Infrared Spectroscopy**. CRC Press.

Topic: Spectral reflectance of surface materials

Geology and Minerals

- Hunt G.R. (1977): **Spectral Signatures of Particulate Minerals in the Visible and near Infrared.** Geophysics. 42 (3), 501–513. https://doi.org/10.1190/1.1440721

- Clark R.N. (1999): Chapter 1: **Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy**. In: Rencz, A.N., Ed., Manual of Remote Sensing, Volume 3, Remote Sensing for the Earth Sciences, John Wiley and Sons, New York, 3-58. Soil:

- van der Meer F.D., van der Werff H.M.A, Van Ruitenbeek F.J.A. et. al (2012): **Multi- and hyperspectral geologic remote sensing: A review.** International Journal of Applied Earth Observation and Geoinformation, 14 (1), 112–128. https://doi.org/10.1016/j.jag.2011.08.002

Soil

- Ben-Dor E., Irons J.A., Epema A. (1999): **Manual of Remote Sensing, chap. Soil Reflectance**, pp. 111–188, NewYork: J. Wiley & Sons, Inc.

- Ben-Dor E., Chabrillat S., Demattê J.A.M., Taylor G.R., Hill J., Whiting M.L., Sommer S. (2009): **Using imaging spectroscopy to study soil properties**. Remote Sens Environ 113: S38–S55. https://doi.org/10.1016/j.rse.2008.09.019

- Chabrillat S., Ben-Dor E., Cierniewski J., Gomez C., Schmid T., van Wesemael B. (2019): **Imaging Spectroscopy for Soil Mapping and Monitoring**. Surveys in Geophysics. 40, 361–399. https://doi.org/10.1007/s10712-019-09524-0

- Rossel R.V., Walvoort D.J.J., McBratney A.B., Janik L.J., Skjemstad J.O. (2006): **Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties**. Geoderma 131(1): 59–75. https://doi.org/10.1016/j.geoderma.2005.03.007

Vegetation

- Huete A.R. (2004): **Remote Sensing for Environmental Monitoring**. In: Artiola, J.F., Pepper, I.L, and M.L. Brussea (Eds), Environmental Monitoring and Characterization, Elsevier Academic Press, 183-206.

- Ustin S., Roberts D., Gamon J., Asner G., Green R. (2004): **Using imaging spectroscopy to study ecosystem processes and properties**, Bioscience, 54 (6), 523–534. https://doi.org/10.1641/0006-3568(2004)054[0523:UISTSE]2.0.CO;2

- Gamon J.A., Somers B., Malenovský Z. et al. (2019) **Assessing Vegetation Function with Imaging Spectroscopy**. Surveys in Geophysics. 40, 489–513. https://doi.org/10.1007/s10712-019-09511-5

Inland and coastal waters

- Giardino C., Brando V. E., Gege P., Pinnel N., Hochberg E., Knaeps E., Reusen I., Doerffer R., Bresciani M., Braga F., Foerster S., Champollion N., Dekker A. (2019): **Imaging Spectrometry of Inland and Coastal Waters: State of the Art, Achievements and Perspectives**. Surveys in Geophysics. 40, 401-429. https://doi.org/10.1007/s10712-018-9476-0

Final Quiz: Lesson 'Principles of imaging spectroscopy'

In this final quiz for the lesson 'Principles of imaging spectroscopy' we have prepared 10 questions for you. **You need 50 % to be correct** to pass to the next lesson. You have **unlimited attempts to pass the quiz**. Good luck!

> In order to receive a certificate, you need to pass the lesson quizzes (3), as well as the final quiz in the online version of this course.

What is the main difference between optical multispectral and hyperspectral data? (multiple-choice)

☐ The illumination source

☐ The wavelength ranges detected

☐ The number of bands acquired

☐ Contiguous vs. discrete bands

Can you assign the major milestones of hyperspectral remote sensing to the corresponding time periods? (Options: First spaceborne imaging spectrometers, First airborne imaging spectrometers, Next-generation spaceborne sensors, Future missions)

Sort elements

Between 1982-1985	Choose an element
Between 2000-2001	Choose an element
Between 2018-2019	Choose an element
Between 2022-2027	Choose an element

In which wavelength ranges do VNIR (visible – near infrared) sensors acquire data? (multiple-choice)

☐ 380 – 1300 nm

☐ 0.38 – 1.3 µm

☐ 380 – 1300 µm

☐ 3.8 – 1.3 nm

In which wavelength ranges do SWIR (short wave infrared) sensors acquire data? (single-choice)

☐ 380 – 1300 nm
☐ 1300 – 3000 nm
☐ 3000 – 5000 nm
☐ 8000 – 12000 nm

Which processes happen when radiation interacts with surface materials? (multiple-choice)
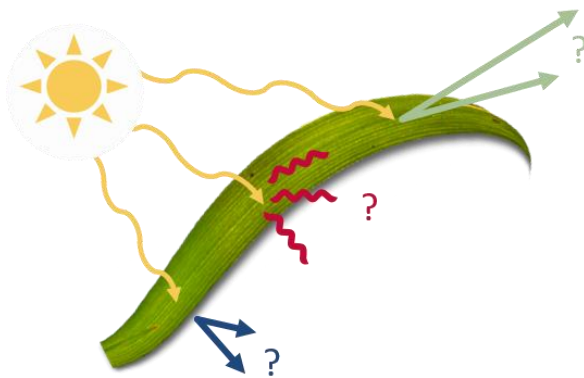
☐ Transmission
☐ Apparition
☐ Reflectance
☐ Absorption

What are atmospheric windows? (single-choice)
☐ Wavelength ranges that are mostly permeable for radiation
☐ Wavelength ranges that are mostly impermeable for radiation
☐ Cloud free target areas
☐ Satellite orbits

Which characteristics of absorption features allow for material identification? (single-choice)
☐ Depth
☐ Gaps
☐ Color
☐ Shape and position

Fill in the blanks (Options: seismic processes, acoustic processes, vibrational processes): The most important process for optical remote sensing is absorption. Radiant energy arriving at an object stimulates electron transfer and _____ at the molecular level.

The spectral reflectance of vegetation is very low in the visible region. Why? (multiple-choice)
- ☐ Due to the cell structure
- ☐ Due to leaf pigments
- ☐ Due to absorption of light for photosynthesis
- ☐ The spectral reflectance of vegetation is actually high in the visible region

Which surface material has usually the lowest reflectance in the SWIR: (single-choice)
- ☐ Clear water
- ☐ Green vegetation
- ☐ Dry vegetation
- ☐ Open soil

4 Principles of sensor technologies and data acquisition techniques

Welcome to our second lesson! Did you ever wonder during the first lesson how such high-dimensional data is acquired and generated? What may sound technical and dull is actually a really fun lesson as we have produced even more interactive content and videos! After introducing some **general concepts of how (imaging) spectrometers acquire data and what the properties of these data** are, you'll get the chance to **explore** a variety of spaceborne as well as airborne (and ground based) instruments **and accompany us as we collect data** in the lab and field. Charly will give you some more details on the learning objectives in the video below.

VIDEO: Basic-09: Sensor technologies & data acquisition techniques: Lesson Intro

URL of the video:
https://www.youtube.com/watch?v=k82wyfOZrA4

Let's move on with the first topic of this lesson.

4.1 Introduction to sensor technologies

Scientific and application requirements together with technical feasibility define sensor design (or in most cases, choice):

- Which surface properties should be detected?
- With what resolution and accuracy should the properties be detected?
- Where should the properties be detected?
- How often should the properties be detected?
- How long should the properties be detected?

These requirements define the spatial, **spectral, radiometric, and temporal resolution** of a sensor. "No property of images is more widely quoted, and simultaneously misused, than *resolution*. It is a term that conveys a strong intuitive meaning, but is difficult to define quantitatively" (Schowengerdt 2007). Thereby, the temporal resolution is mainly related to satellite orbit characteristics while the other resolutions concern the sensor features.
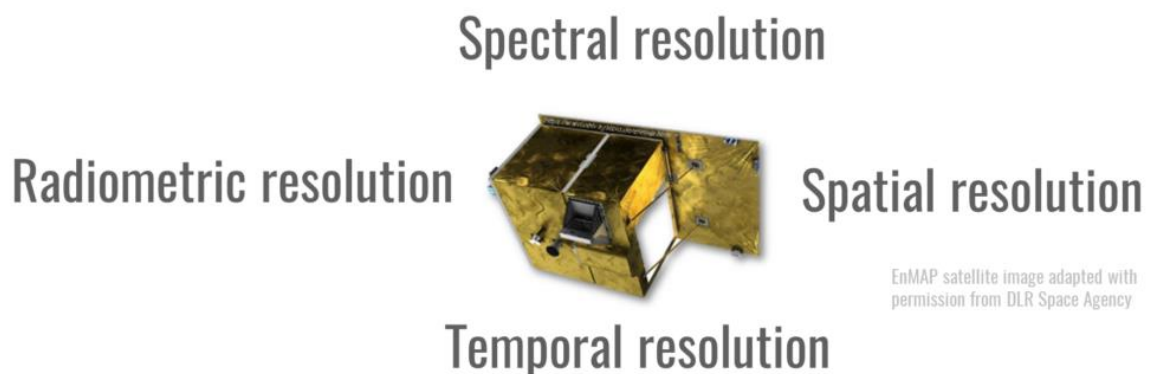
Figure 15 The resolutions of a sensor are defined by scientific requirements and technical feasibility

The following topic will describe the resolution types in more detail. For now, just keep in mind that an imaging spectroscopy data product is determined by the potential application and results from an interaction between:

- used or feasible sensor technology,
- the kind of data acquisition and its parametrization, and
- the generated and resulting data properties

Unfortunately, there are **trade-offs between the resolutions**, meaning that for example, you cannot acquire images of very high spatial AND high spectral resolution without losing radiometric quality as will be shown later.

Figure 16 The final data product – and its resolutions – is determined by the interaction of sensor technology, data acquisition and properties

4.2 Data properties – the 4 resolutions

Spectral resolution

Spectral range is defined by the portion of the **electromagnetic spectrum to which an instrument is sensitive and the position, number and width of its spectral bands**. Imaging spectrometers typically acquire data in hundreds of (contiguous) spectral band within a limited spectral range.
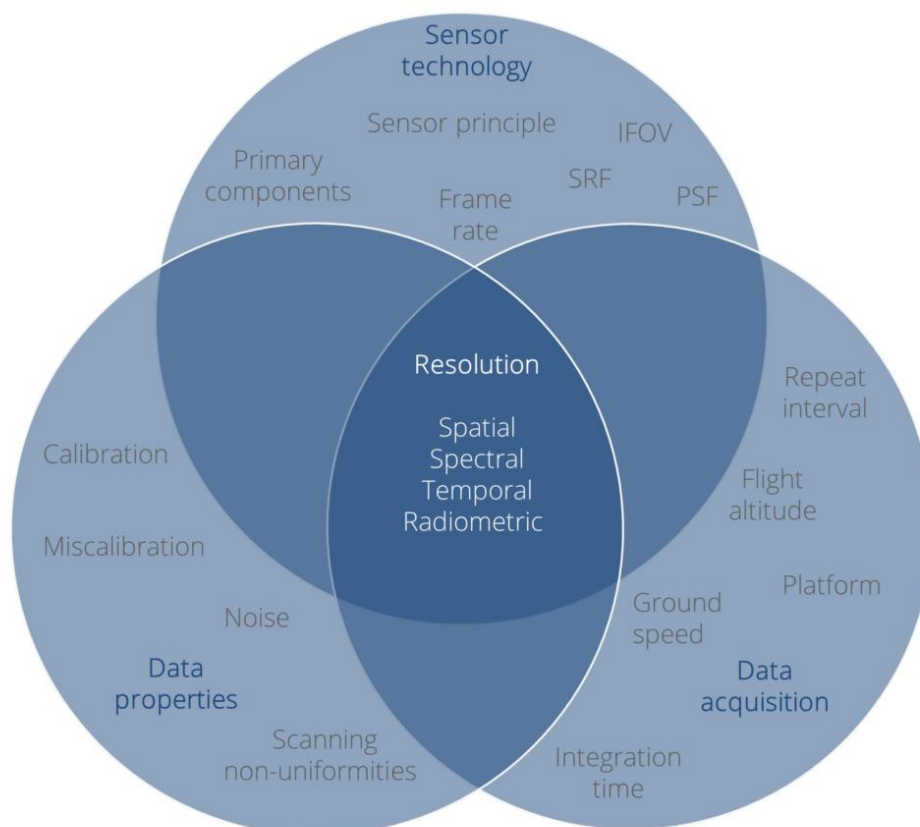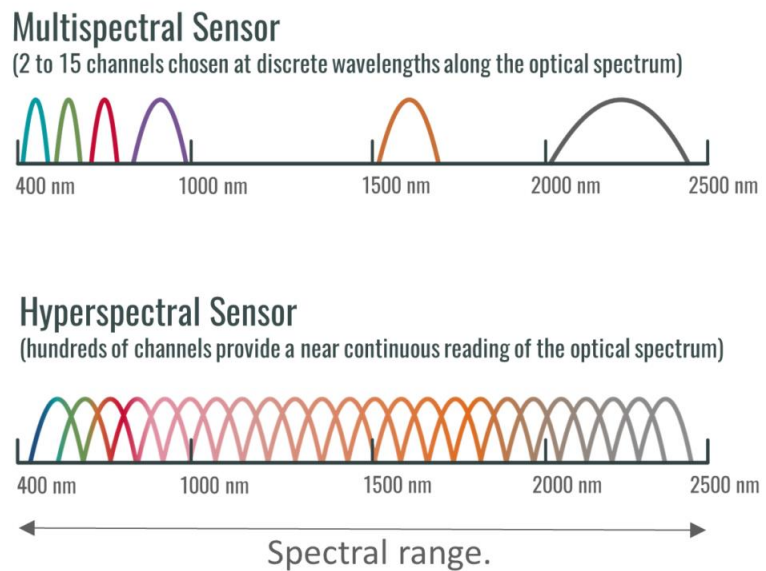
Figure 17 The difference between a multi- and a hyperspectral sensor

"Contiguous spectral coverage between 400 and 2500 nm with a spectral sampling interval at Full Width at Half Maximum (FWHM) of less or equal 10 nm is aspired to by land observing sensors, driven by the need for atmospheric characterization and reflectance retrieval, as well as some geophysical, geo-biophysical, and geochemical retrievals for environmental
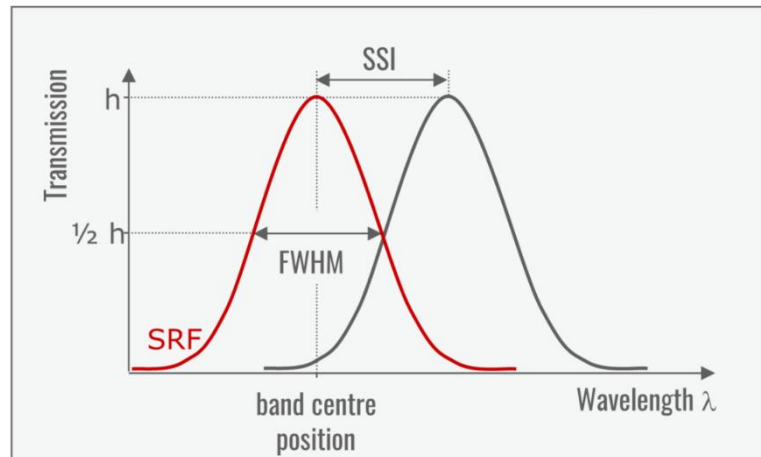
Figure 18 The spectral sampling interval (SSI) describes the spectral distance of the bands, whereas the Full Width at Half Maximum (FWHM) describes the width of the bands as they do not have sharp boundaries (spectral response function (SRF))

measurements and agricultural applications. For ocean-observing sensors often focusing on 'Ocean Color' variables, a spectral sampling around 5 nm is required. For

radiative forcing by impurities in snow, 20 nm is the generally accepted requirement" (Rast and Painter 2019).

Are you familiar with the display of spectral information as spectra? The wavelength is indicated on the x-axis while the intensity of relative reflectance is indicated on the Y-axis. Under this LINK, you can **explore how various common multi- and hyperspectral sensors like EnMAP and Sentinel 2 would capture the same object**:

Interactive Graphs

You need to be enrolled and logged in under EO College in order to be forwarded to the interactive Graphs. Figures of those are, however, incorporated in this offline version. For the best learning experience, we recommend to check out the graphs online.

Interactive graph on different spatial resolutions
Available under this LINK.

Spatial resolution

Spatial resolution is **a measure of the smallest ground feature that can be resolved by a sensor**. As its description is not so straightforward a multitude of metrics exist:

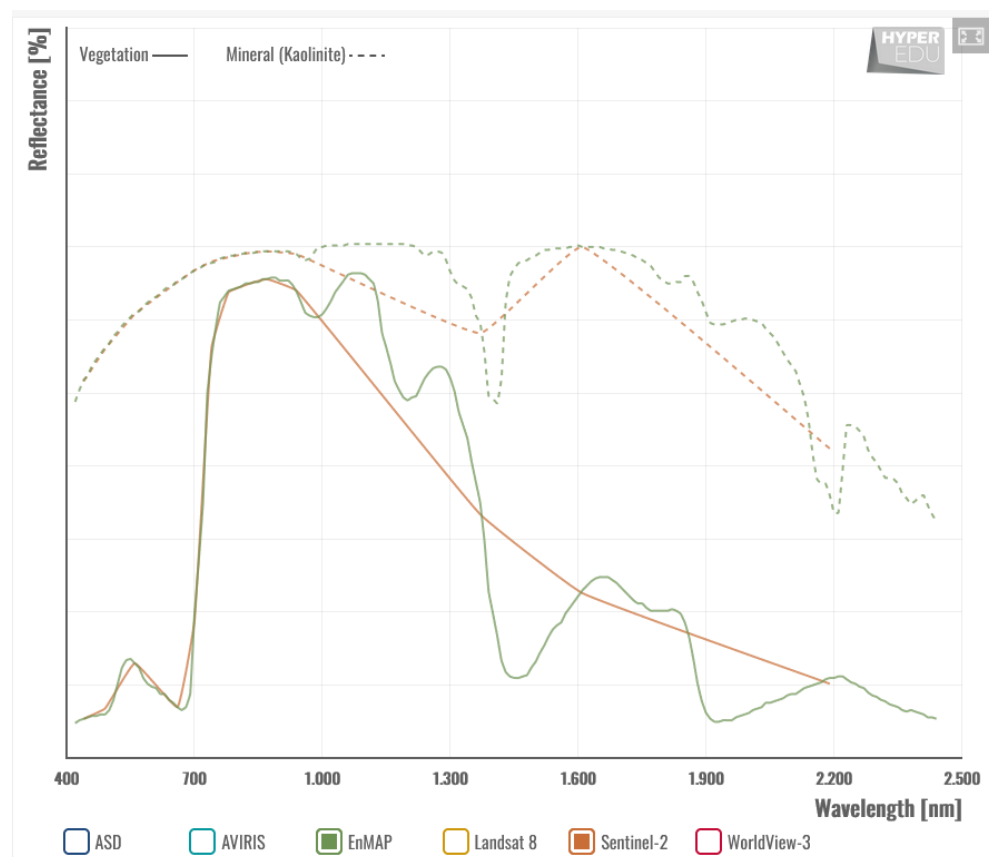- The **instantaneous-field-of-view (IFOV)** is the range of incident angles seen by a single detector element. The **corresponding ground coverage (ground-projected instantaneous-field-of-view GIFOV)**, defined in meters, depends on the satellite elevation and varies with the viewing angle.
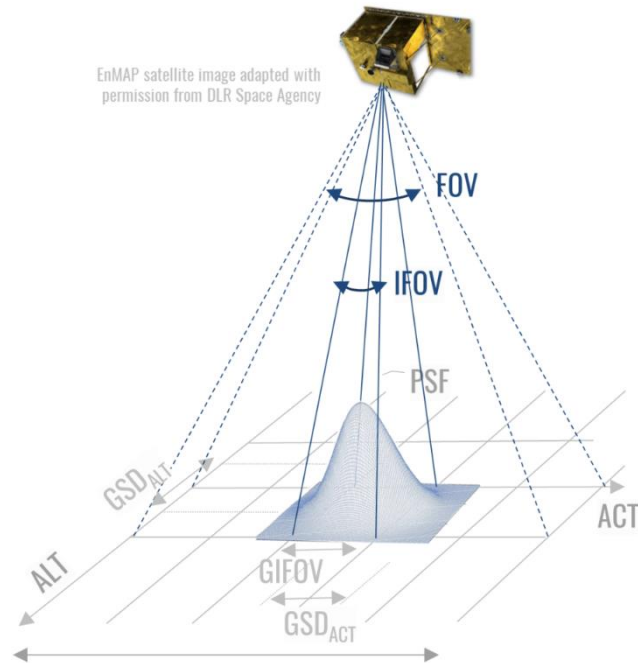
Figure 19 Metrics to describe the spatial resolution

- The **ground sampling distance (GSD)** is the distance between pixel centers on the ground and therefore more or less identical with the GIFOV, though mathematically the GSD is a line segment and the GIFOV is a surface. The GSD is also called spatial sampling distance (SSD) or ground sampling interval (GSI).

- The most accurate way to describe the spatial resolution of an imaging instrument is the modulation transfer function (MTF) that quantifies the amount of contrast transferred from the object to the pixel. It is the Fourier transform of the point spread function (PSF) that best explains the performance of the MTF as a low pass filter.

The **spatial resolution in across-track (ACT) and along-track (ALT) direction** are affected by different factors (e.g. integration time, smearing effects) and are therefore **not necessarily identical**, although this is of course the desired outcome of the instrument design.

Since pixels are usually represented as rectangles in images, a sensor's spatial resolution is often indicated as e.g. 30 m x 30 m (in case of EnMAP). It represents a mean value as it depends on sensor-earth distance, sensor speed and FOV/off-nadir pointing. **Check the interactive graphic** under this LINK to explore the scene in 30 m (e.g. Landsat, EnMAP), 10 m (e.g., Sentinel-2), and 1 m (airborne sensor) resolution*.

Interactive graph on different spatial resolutions
Available under this LINK.

depending on your device, the highest resolution might appear less accurate than 1m x 1 m. You can try to improve the impression by viewing the graph in full screen mode.

Temporal resolution

Temporal resolution refers to the time interval between two acquisitions of a sensor over the same area. It **depends on satellite orbit altitude and its geometry (repeat cycle)** – optical sensors for environmental observation usually follow sun synchronous near-polar orbits. The larger the inclination angle (98.2° in the example shown here), the lower the maximum observable latitude. The **use of multiple satellites or pointing capabilities** can increase the revisit rate. However, in reality, the actual data yield can vary greatly due to cloud coverage. You might also want to include the lifetime of a mission in the consideration of a sensor's temporal range.
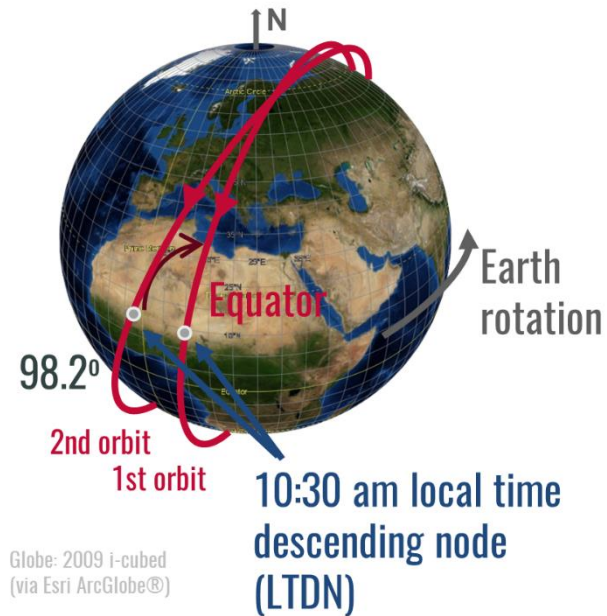
Figure 20 Near-polar, sun-synchronous orbit

Radiometric resolution

And finally, radiometric resolution is defined as the **ability of a sensor to capture differences in radiation**. The finer the radiometric resolution, the better small differences can be discriminated. Eight and twelve bits (256 and 2048 grey values, resp.) are common. Newer sensors like EnMAP

Figure 21 Schematic representation of radiometric resolution

have 14 bits (16384 grey values). However, radiometric resolution is not just about the number of bits, but rather "the smallest difference in signal not masked by noise".

Trade-offs

As mentioned at the beginning of this topic, unfortunately, there are **some common trade-offs between the resolutions**. The amount of photons which could be measured by a sensor over all wavelength is limited by solar illumination and surface reflectance. Fewer photons would result in lower SNR (signal-to-noise-ratio, a measure of radiometric quality) and thus a worse parameter retrieval later. In the relationship of **spatial and spectral**

Figure 22 Common trade-offs between spatial and spectral resolution

resolution, as one increases the other needs to decrease to gain the same amount of photons on the detector. That means you either get an image with high spectral but rather low spatial resolution (1), an image with high spatial but low spectral resolution (2) or something in-between (both medium resolution). Sensor design tries to avoid low SNR (3) and tries to achieve the best trade-off between spectral, spatial resolution and high SNR for a certain application.

In addition to spatial and spectral resolution that are connected via the amount of photons (represented by SNR), there is a certain **trade-off between spatial and temporal resolution:** Smaller pixels result in a smaller swath which generally means lower temporal resolution while higher temporal resolution is usually accompanied by a larger IFOV and thus, larger pixels. This trade-off can be overcome by launching
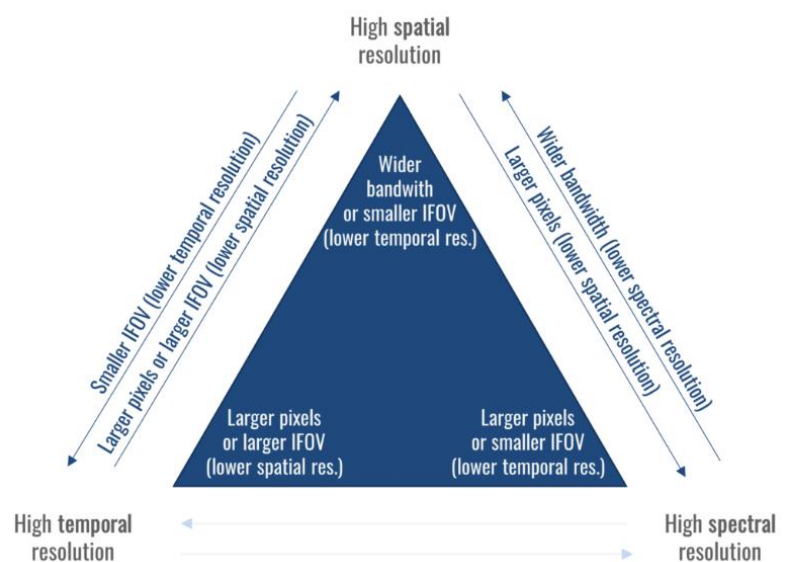
Figure 23 Common trade-offs between spatial, spectral as well as temporal resolution

several identical sensors, as for instance Sentinel-2 A and B. However, spaceborne imaging spectrometers are so complex and the technology still developing so this is not an option – yet.

The **following interactive graphic presents** a selection of past, present and future spaceborne sensors. **Check out their spatial and spectral resolution** as compared to terrestrial and airborne sensors. When moving over the sensors with your mouse, you can find out more detailed information about the respective missions.

Interactive graph – Spaceborne Sensors
Available under this LINK.
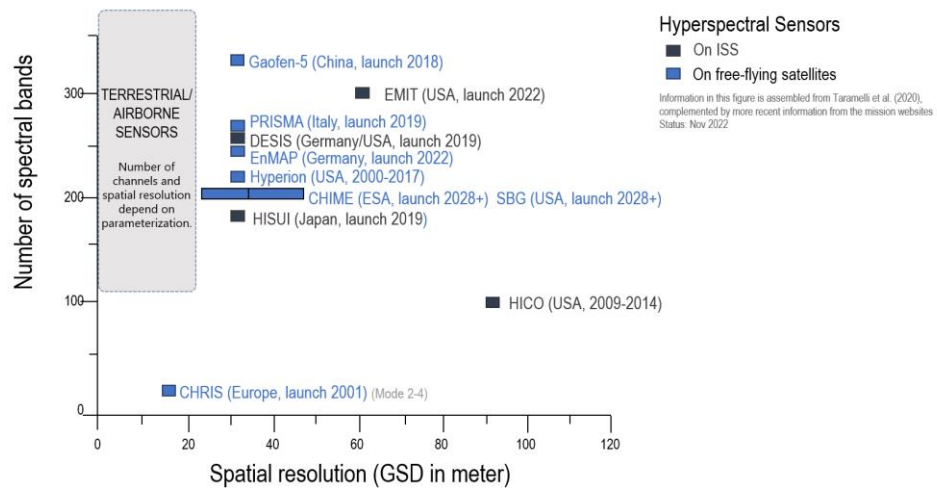
Please complete the quiz below to advance to the next topic.

Quiz: Data properties – the 4 resolutions

We differentiate four types of resolution – can you name them?

1. [   ] resolution

2. [   ] resolution

3. [   ] resolution

4. [   ] resolution

Label the graph of spectral response functions (SRFs) correctly:
(Options: Band center position, Wavelength, FWHM, SSI)
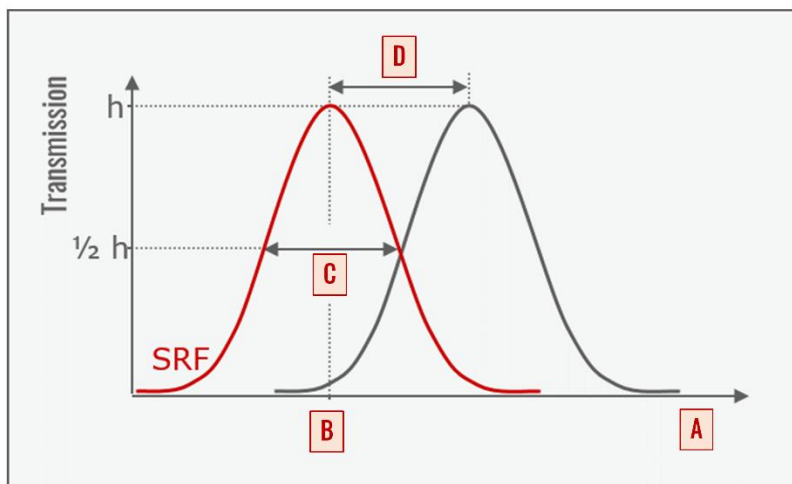
A   Choose an element

B   Choose an element

C   Choose an element

D   Choose an element

Which pixel size belongs with which sensor (drag and drop)?
Sort elements (Options: 5 m, 30 m, 17 m, 90 m)

PRISMA (VNIR/SWIR-hyp)   Choose an element

AVIRIS (airborne)   Choose an element

HICO   Choose an element

CHRIS / PROBA (mode 2-5)   Choose an element

Temporal resolution depends on … (multiple-choice)

☐   satellite orbit characteristics (repeat cycle)
☐   the use of multiple satellites
☐   pointing capabilities
☐   spectral range covered

Unfortunately, there are some common trade-offs between the resolutions. In the relationship of spatial and spectral resolution, as one increases the other needs to decrease … (single-choice)

☐   … to keep data sizes manageable.
☐   … to gain the same amount of photons on the detector.
☐   … to achieve acceptable temporal resolution.
☐   … to allow for rectangular pixels.

4.3 Imaging spectroradiometer – general elements

Now that you have some background on the definitions of **spatial, spectral, radiometric and temporal resolution** of a dataset, we can take a closer look at sensor technology. There are **different scanning systems with resulting differences in data acquisition principles and properties**. Regarding imaging spectroscopy, **pushbroom (or spatial scanning) sensors are most common** in airborne as well as spaceborne systems and therefore, we will focus on this type of system. Charly will explain the general elements of a pushbroom-scanner in the following video before we finally share some experiences in data acquisition at different levels:

VIDEO: Basic-10: Sensor technologies & data acquisition techniques: Imaging Spectrometer

URL of the video:
https://www.youtube.com/watch?v=_-Kedx--a48

VIDEO: Sensor technologies & data acquisition techniques: Imaging Spectrometer

Oops, which part belongs where? Help us re-assemble the sensor!
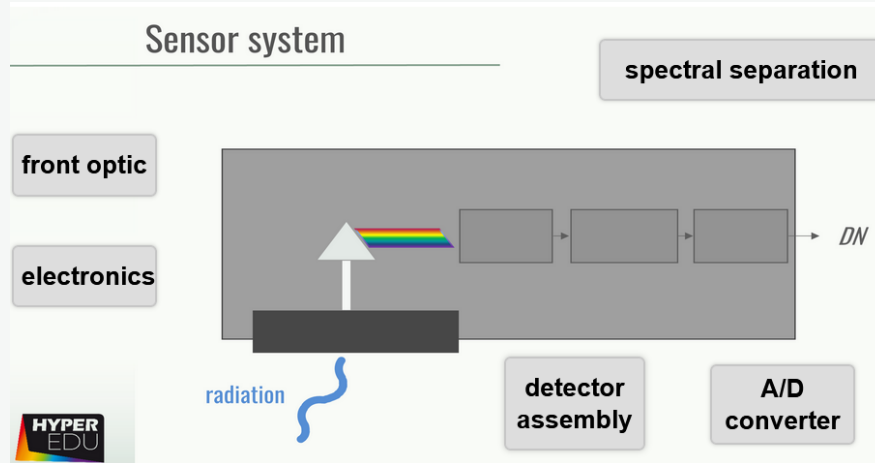
Which system do you think is most common in spaceborne as well as airborne (airplane) systems?

- ☐ Tiled scanning
- ☐ Whiskbroom scanning
- ☐ Spatio-spectral scanning
- ☐ Pushbroom scanning

Please complete the quiz below to advance to the next topic.

Quiz: Imaging spectroradiometer – general elements

In what format is data acquired by the sensor? (single-choice)

☐   Digital numbers

☐   At-surface reflectance

☐   Top-of-atmosphere radiance

☐   Top-of-atmosphere reflectance

4.4 Data acquisition: spaceborne

In the section on major milestones in the previous lesson, you already learned that the first spaceborne hyperspectral missions were launched in the early 2000s. Since then, several imaging spectroscopy sensors have been flown in space and further systems are under development to be launched within the next few years, either onboard of free-flying satellite platforms or onboard of the International Space Station (ISS) that has already become home to several imaging spectrometers such as HICO, DESIS and HISUI. Please note that we focus in this MOOC on non-commercial missions with free data policy.

Interactive graphic – Hyperspectral satellite timeline
Available under this [LINK](#).
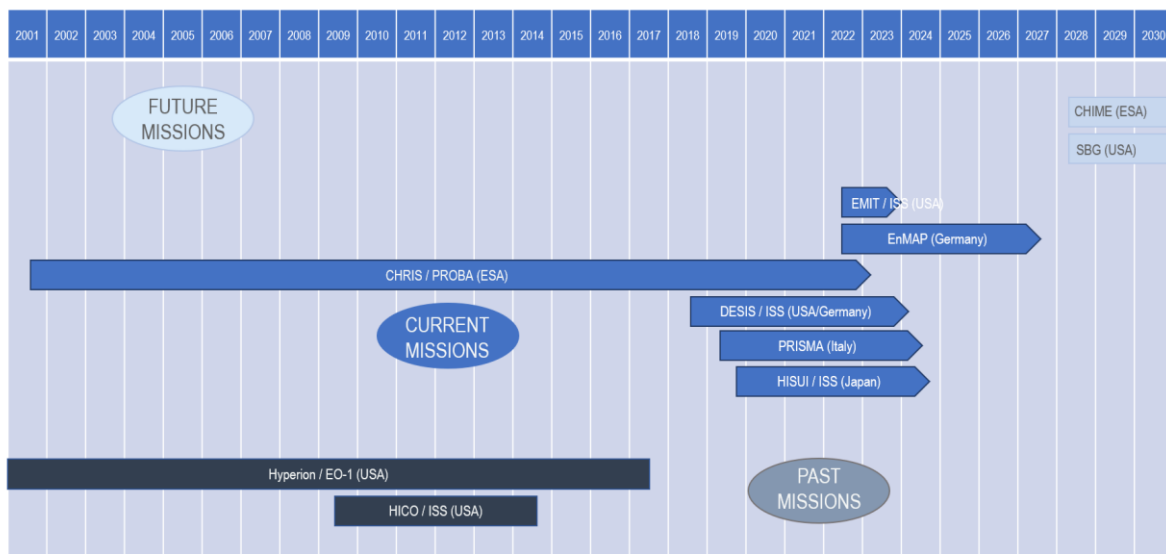
Figure 24a Hyperspectral satellite timeline

The information in this figure is based on the Spaceborne Imaging Spectroscopy Mission Compilation prepared by the EnMAP Ground Segment Team (Status August 2020). It was updated for selected missions to be presented in the revised version of this MOOC in November 2022.

A satellite's orbit describes the path on which a satellite circles around the Earth. Imaging spectrometers on **free-flying satellite platforms** used for environmental monitoring generally follow sun-synchronous near-polar orbits. The orbit inclination ranges typically from 98°-99° for altitudes of 650 – 900 km with always similar position

of the sun (therefore, sun synchronous). Or in other words, it passes the same part of the Earth every day at about the same local time.

The **ISS orbit**, on the contrary, is using a non-sun-synchronous orbit resulting in varying observation and illumination conditions. ISS moves on an orbit with an inclination of 51.6° from west to east and covers areas from 55° N to 52° S. In principle, ISS orbital tracks are repeated every 3 – 5 days.

However, the times of overpasses vary widely resulting in different illumination conditions during the acquisition. Also, the height of the ISS above the Earth varies. It is approximately 400 km, but can typically vary in a range from 370 km to 460 km.

Most man-made objects in space are Low Earth Orbit (LEO), that is Earth-centered with an altitude < 2.000 km or an orbital period < 128 minutes. **Downlink is typically limited** to 10-12 minutes for data transfer (due to visibility of ground stations) using S-band (up to 6 Mbit/s), X-band (up to 150 Mbps or 300 Mbp/s dual polarized) or Ka/Ku-band (~1 Gbp/s). The Tracking and Data Relay Satellite System (TDRSS) is a network of American communication satellites and ground stations used for space communications to increase the time that the spacecrafts are in communication with the ground and, thus, improve data transfer.

EnMAP

You have heard about the EnMAP sensor several times now during this MOOC. Now it is time to take a closer look and introduce the EnMAP orbit and instrument characteristics in a bit more detail. But let's first **watch EnMAP in operation** in the following animation.

VIDEO: Basic-05: Sensor technologies & data acquisition techniques: EnMAP Mission

URL of the video: https://www.youtube.com/watch?v=LQZNtLp3RfM

The sensor covers a **swath width of 30 km with a ground sampling distance of 30 m × 30 m**. The along-track dimension is given by the satellite movement. **Data length up to 5000 km** can be collected per day and downlinked via X-band with 320 Mbits/s in 31 minutes/day. The chosen sun-synchronous orbit combined with a ±**30° off-nadir pointing feature** allows each point on Earth to be revisited within 4 days, viewing nadir within 27 days.

EnMAP is a pushbroom-type imaging spectrometer with a prism-based dual-spectrometer instrument design covering the 420–2450-nm spectral range: a VNIR system (420–1000 nm) and a SWIR system (900–2450 nm). The threshold requirements for the Signal-to-noise ratio (SNR) are

- VNIR >500:1 (@495 nm)

- SWIR > 150:1 (@2200 nm)

and the spectral calibration uncertainty

- VNIR 0.5 nm

- SWIR 1 nm
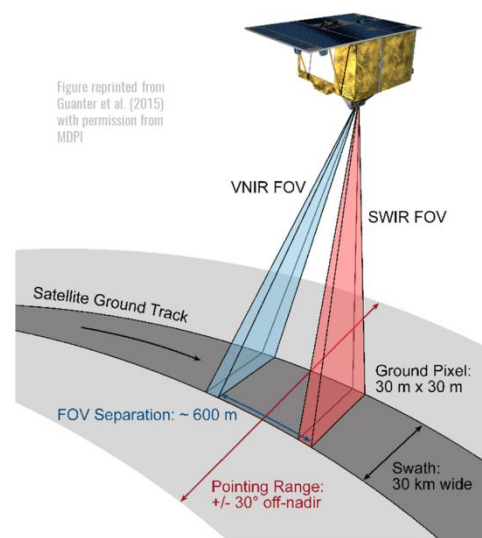
Figure 25b Schematic representation of an EnMAP overpass

The required radiometric calibration accuracy is 5 % and co-registration VNIR-SWIR < 20 % of a pixel.

You might have noticed the different number of bands of the EnMAP sensor mentioned in the video and the mission fact sheet. Indeed, a total of 246 bands are recorded at sensor. However, not all are provided to the users in the final data products, but are used for internal calibration and monitoring processes. **The standard configuration in the L2A product at the start of the nominal phase was 91 (VNIR) and 133 (SWIR) bands, which makes 224 in total.**

Please complete the quiz below to advance to the next topic.

Quiz: Data acquisition: spaceborne

Currently spaceborne imaging spectrometers are deployed on … (multiple-choice)

☐ free-flying satellite platforms following sun-synchronous orbits

☐ the International Space Station (ISS)

☐ none of the above

What is the total observation length per day that EnMAP records data? (single-choice)

☐ 1000 km

☐ 5000 km

☐ 30 km

☐ 500 km

4.5 Data acquisition: airborne

Since the early 1980s, imaging spectrometers have been deployed on aircraft, usually covering the VNIR and often SWIR spectral ranges. They are used in many airborne deployments for research, commercial applications, and for spaceborne imaging spectrometer concept studies. Their **characteristics cannot be easily compared due to their often wide range of parameterization options**.

For airborne sensors, similar parameters as for satellite sensors are required describing the position and attitude of the airplane. **Attitude is expressed by three angles of platform rotation: roll, pitch, and yaw**. However, **variation in attitude, altitude, and ground speed are subject to much larger changes due to wind and turbulence**. Also, a much larger FOV and proximity to the ground amplify off-nadir distortions and angle-dependent illumination effects.

One prominent spectrometer that has been flown for decades on airborne platforms is the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), designed by NASA JPL in California and operated under NASA contract since the mid-1980s. Building upon AVIRIS, the **Airborne Visible Infrared Imaging Spectrometer – Next Generation (AVIRIS NG)** has been developed to eventually replace the AVIRIS instrument with an improved radiometric performance and a higher spectral sampling interval. The **following video takes us on an airplane during the AVIRIS-NG Europe 2021 campaign** that has been conducted as a joint effort of ESA, NASA/JPL and the University of Zurich.

VIDEO: Basic-11: Sensor technologies & data acquisition techniques: AVIRIS-NG

URL of the video:
https://www.youtube.com/watch?v=6kBn7FZNBsE
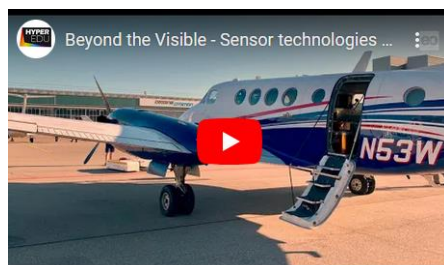
During the **AVIRIS-NG Europe 2021 campaign** more videos have been **produced by the UZH Space Hub of the University of Zurich**. In the following video, Andreas Hüeni talks about this large test flight campaign that took place in summer 2021.

VIDEO: UZH Space Hub: University of Zürich conducts research flights for NASA and ESA projects from Dübendorf, CH

URL of the video:
https://www.youtube.com/watch?v=06ughPtdrHg

Please complete the quiz below to advance to the next topic.

Quiz: Data acquisition: airborne

What is attitude? (single-choice)

☐ The height of sensor operation above sea level

☐ The three angles of sensor platform rotation (roll, pitch, and yaw)

☐ The mood of the sensor operator

☐ The sensor position as captured by GPS coordinates

Variations in attitude, altitude and ground speed are much larger in airborne as compared to spaceborne acquisitions mainly due to … (single-choice)

☐ … differences in irradiance.

☐ … the influence of wind and turbulence.

☐ … untrained airplane pilots.

☐ … differences in airborne / spaceborne sensor design.

4.6 Data acquisition: ground-based

Data acquisition: ground-based (field)

Hyperspectral airborne campaigns are pretty expensive and commonly go along with a simultaneous ground reference data campaign. So usually, when airborne data is collected, there will also be **measurements taken in the field** with a device called spectrometer or spectroradiometer that collects spectral point data. The spectrometer is the base unit of a spectroradiometer, which also includes input optics and calibrations that allow the spectrometer to take calibrated readings. However, in practice many people use the terms spectrometer and spectroradiometer interchangeably. The data collected with such a device can be used as reference for atmospheric correction of the airborne data, however, they are also often acquired independently of airborne imaging campaigns, e.g. to study environmental processes in high temporal resolution and/or to produce spectral libraries. **In the following video, colleagues from the LMU Munich will take you outdoors and show you how they perform regular measurements of agricultural areas**. The instrument they are using is an **ASD Fieldspec 3 spectroradiometer**.

VIDEO: Basic-12: Sensor technologies & data acquisition techniques: ASD Field

URL of the video:
https://www.youtube.com/watch?v=7S1XoN-NifM

Data acquisition: ground-based (lab)

There are dedicated lab spectrometers but actually, you can use some instruments in the field as well as in the lab. You have just seen an ASD Fieldspec in the field – **in the following video, you'll get to see it in a laboratory setup**:

VIDEO: Basic-13: Sensor technologies & data acquisition techniques: ASD Lab

URL of the video:
https://www.youtube.com/watch?v=Ewhk-rZjOTI

But it's not only point spectrometers such as the ASD Fieldspec that are used in the lab – even hyperspectral scanners can be employed in laboratory environments. In a previous video we've shown you the AVIRIS sensor in the air. **In the following video you'll see the HySpex sensor in the laboratory**:

VIDEO: Basic-14: Sensor technologies & data acquisition techniques: HySpex Lab

URL of the video:
https://youtu.be/EaVZ2_McjjY

And if that wasn't enough … In addition to airborne campaigns and laboratory measurements, the **HySpex sensor system can also be used for close-range, ground-based hyperspectral studies**, e.g. for mining applications or in the field of conservation and restoration of cultural property. Unlike the translation stage applied in the lab, in the field setup the sensors are mounted in parallel on a **rotation stage** and both sensor heads rotate the field of view (FOV) line by line with the speed of the rotational movement automatically adjusted to the integration time of the VNIR camera. The resulting 3D image cubes are then radiometrically calibrated, co-registered, resized and stacked to a continuous image cube. The radiance data can be transformed into a reflectance dataset via normalization based on white reference plates previously positioned in the scene. Once pre-processed the hyperspectral data can be used to map e.g. an ore body's surface mineral distribution or serve as a basis for material and damage mapping of cultural heritage.

Figure 26 HySpex Sensors and Cubert Camera mounted on rotation stage to scan a cultural site in close-range (Marienkirche, Frankfurt Oder, Germany)

Please complete the quiz below to advance to the next topic.

Quiz: Data acquisition: ground-based

Why are spectral data acquired on the ground? (multiple-choice)

☐ To provide reference data during flight campaigns

☐ To study processes at high spectral and high temporal resolution

☐ To establish spectral libraries

☐ For educational purposes

4.7 Data product

Data properties

Even if you were maybe completely unaccustomed to hyperspectral data, you are now probably aware of the high complexity of the data beside the resolution issues. Before tackling any data processing, Charly wants to give you an **overview of the properties of imaging spectroscopy data in the following video**:

VIDEO: Basic-15: Sensor technologies & data acquisition techniques: Data product

URL of the video:

https://youtu.be/p4_vWkLtf8w

VIDEO: Sensor technologies & data acquisition techniques: Data product

Gain and offset are constant over time
- ☐ True
- ☐ False

Dead or bad pixels cannot be corrected
- ☐ True
- ☐ False

Fill in the missing word
With increasing spectral resolution, noise introduced by the sensor becomes _____ (less/more) visible.

VIDEO: Sensor technologies & data acquisition techniques: Data product

Did you catch which effect relates to spectral non-uniformities?
- ☐   The so-called „keystone" effect
- ☐   The so-called „smile" effect

The SNR – a measure of radiometric data quality

Remember? The higher the signal-to-noise-ratio the better the data quality. You can explore the effect interactively in the graph below – what happens to the spectrum when you choose a lower SNR?

What do you think, from what SNR could you detect a large feature like the double feature at 2.200 nm
- ☐   For that, you would need a very high SNR of at least 200
- ☐   A low SNR of 25 would make it

Interactive graph – Signal-to-noise-ratio and data quality
Available under this LINK.
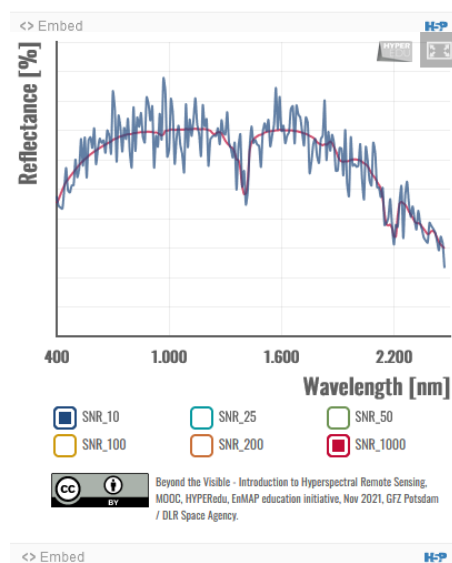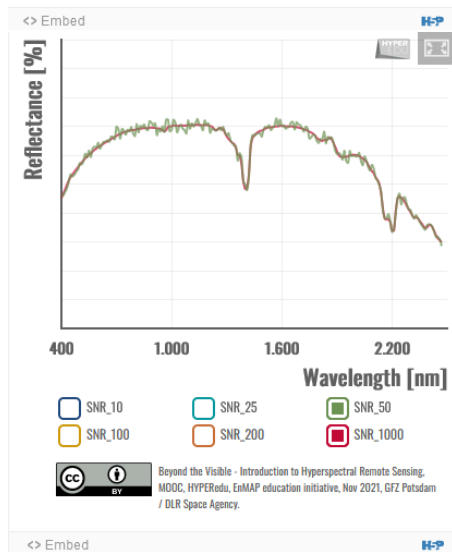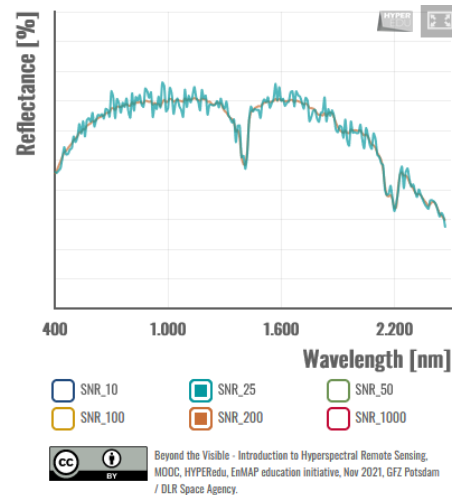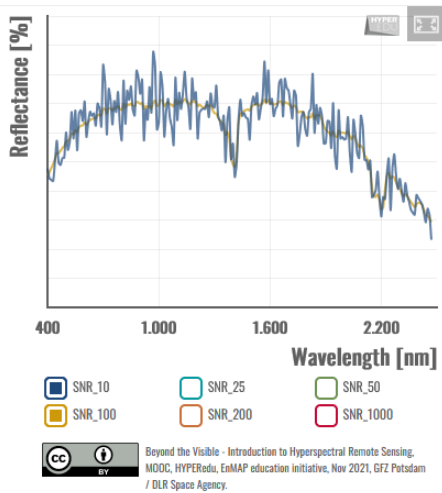
Remember: to view and try the interactive graph, you need to be enrolled to this course and logged in under EO College!

Please complete the quiz below to advance to the next topic.

Quiz: Data product

What is the so-called SNR (signal-to-noise-ratio)? (single-choice)

☐   a measure of radiometric data quality

☐   a measure of spectral data quality

☐   a measure of spatial data quality

☐   a measure of temporal data quality

4.8 Resource section: Lesson 'Principles of sensor technologies and data acquisition techniques'

In this section, we have assembled resources used for the creation of this lesson that we recommend you for further reading as they provide a lot more detail. Please remember that this selection is not a complete overview of all resources – if you think an important resource is missing, let us and your fellow students know (e.g. in the discussion forum). You can find the discussion forum at https://eo-college.org/forums/forum/beyond-the-visible/ under each related topic.

You can find most figures of this lecture in the HYPERedu slide collection, available on EO-College.

How to cite: A. Brosinsky, M. Brell, S. Livens, K. Segl, T. Kuester, H. Kaufmann, L. Guanter, S. Foerster (2021). **Imaging spectroscopy sensor technologies**, slide collection, HYPERedu, EnMAP education initiative, German Centre for Geosciences GFZ.

Available in the EO-College hyperspectral resources section: https://eo-college.org/resource/imaging-spectroscopy-sensor-technologies/

Sources and further reading

Topic: Introduction to sensor technologies and Imaging spectroradiometer – general elements

- Guanter L., Kaufmann H., Segl K., Foerster S., Rogass C., Chabrillat S., Kuester T., Hollstein A., Rossner G., Chlebek C., Straif C., Fischer S., Schrader S., Storch T., Heiden U., Mueller A., Bachmann M., Mühle H., Müller R., Habermeyer M., Ohndorf A., Hill J., Buddenbaum H., Hostert P., Van der Linden S., Leitão P.J., Rabe A., Doerffer R., Krasemann H., Xi H., Mauser W., Hank T., Locherer M., Rast M., Staenz K., Sang B. (2015): **The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation**. Remote Sens. 7(7), 8830-8857. https://doi.org/10.3390/rs70708830

- Jensen J.R. (2007): **Remote Sensing of the Environment: An Earth Resource Perspective**. 2nd Edition, Pearson

- Lillesand T., Kiefer R.W., Chipman J. (2008): **Remote Sensing and Image Interpretation**. 6th Edition, Wiley.

- Livens S. (2018): **Comparing Hyperspectral Imaging Concepts Using Key Properties**. Whispers conference, Amsterdam, The Netherlands.

- Rast M., Painter T.H. (2019): **Earth Observation Imaging Spectroscopy for Terrestrial Systems: An Overview of Its History, Techniques, and Applications of Its Missions**. Surveys in Geophysics. 40, 303–331. https://doi.org/10.1007/s10712-019-09517-z

- Schaepman M.E. (2009): **Imaging spectrometers**. SAGE Handbuch Remote Sensing, 18-166.

Topic: Data acquisition: spaceborne

- Information on the EnMAP sensor can be found on www.enmap.org

- An overview of past, current and future spaceborne imaging spectroscopy mission: https://www.enmap.org/science/community/ (see related documents)

Topic: Data acquisition: airborne

- More information about **AVIRIS-NG**: https://avirisng.jpl.nasa.gov/aviris-ng.html

- More information about **ARES**: https://ares-observatory.ch/

- More information about the **AVIRIS-NG Europe 2021 campaign**: Target list and quicklooks of the 2021 campaign: https://ares-observatory.ch/esa_chime_mission_2021/

- For an overview on some typical airborne hyperspectral imaging systems see table 1 in: Taramelli, A., Tornato, A., Magliozzi, M.L., Mariani, S., Valentini, E., Zavagli, M., Costantini, M., Nieke, J., Adams, J., Rast, M. (2020): **An Interaction Methodology to Collect and Assess User-Driven Requirements to Define Potential Opportunities of Future Hyperspectral Imaging Sentinel Mission**. Remote Sensing, 12, 1286. https://doi.org/10.3390/rs12081286

We have focused on airborne systems using airplanes but hyperspectral sensors are increasingly operated on drones. Some more information can be found in:

- Aasen H., Honkavaara E., Lucieer A., Zarco-Tejada P.J. (2018): **Quantitative Remote Sensing at Ultra-High Resolution with UAV Spectroscopy: A Review of Sensor Technology, Measurement Procedures, and Data Correction Workflows**. Remote Sensing. 10, 1091. https://doi.org/10.3390/rs10071091

- Adão T., Hruška J., Pádua L., Bessa J., Peres E., Morais R., Sousa J.J. (2017): **Hyperspectral Imaging: A Review on UAV-Based Sensors, Data Processing and Applications for Agriculture and Forestry**. Remote Sensing. 9, 1110. https://doi.org/10.3390/rs9111110

- Manfreda S., McCabe M.F., Miller P.E., Lucas R., Pajuelo Madrigal V., Mallinis G., Ben Dor E., Helman D., Estes L., Ciraolo G., Müllerová J., Tauro F., De Lima M.I., De Lima J.L.M.P., Maltese A., Frances F., Caylor K., Kohv M., Perks M., Ruiz-Pérez G., Su Z., Vico G., Toth B. (2018): **On the Use**

of Unmanned Aerial Systems for Environmental Monitoring**. Remote Sensing. 10, 641. https://doi.org/10.3390/rs10040641

- Zhong Y. et al. (2018): **Mini-UAV-Borne Hyperspectral Remote Sensing: From Observation and Processing to Applications**, IEEE Geoscience and Remote Sensing Magazine, vol. 6, no. 4, pp. 46-62. https://doi.org/10.1109/MGRS.2018.2867592

Topic: Data acquisition: ground-based Spectrometers

- Goetz, A. F. H. (1975). **Portable field reflectance spectrometer**. JPL Technical Report (pp. 183 – 188). Pasadena, California Jet Propulsion Laboratory, California Institute of Technology.

- We have used an **ASD FieldSpec HighRes** ®: https://www.malvernpanalytical.com/en/products/product-range/asd-range/fieldspec-range/fieldspec-4-standard-res-spectroradiometer

Field spectroscopy

Our colleagues from LMU Munich as well as others have published great guides on spectral sampling in the field:

- Danner, M.; Locherer, M.; Hank, T.; Richter, K. (2015): **Spectral Sampling with the ASD FieldSpec 4 – Theory, Measurement, Problems, Interpretation**. EnMAP Field Guides Technical Report, GFZ Data Services. http://doi.org/10.2312/enmap.2015.008

- Malthus, TJ, Ong, C, Lau, I, Fearns, P, Byrne G and Thankappan, M., Chisholm,L., Suarez, M., Clarke, K., Scarth, P., Phinn, S. (2018) **A community approach to the standardised validation of surface reflectance data. A technical handbook to support the collection of field reflectance data**. Release version 1.0. CSIRO, Australia. ISBN: 978-1-4863-0991-7

Some considerations on field spectroscopy

- Hueni A., Damm A., Kneubuler M., Schlapfer D., Schaepman M. E. (2017): **Field and Airborne Spectroscopy Cross Validation – Some Considerations**. IEEE Journal of Seleted topics in Applied Earth Observation and Remote Sensing. Vol. 10 No. 3. http://doi.org/10.1109/JSTARS.2016.2593984

- Milton E. (1987): **Principles of field spectroscopy**. International Journal of Remote Sensing. 8:12, 1807-1827. http://dx.doi.org/10.1080/01431168708954818

- Milton E., Fox N., Schaepman M. (2006): **Progress in Field Spectroscopy.** Computer Science, Economics. https://doi.org/10.1109/IGARSS.2006.509

Lab spectroscopy

- Ben-Dor E., Ong C., Lau I.C. (2015): **Reflectance measurements of soils in the laboratory: standards and protocols**. Geoderma. 245–246, 112–124. https://doi.org/10.1016/j.geoderma.2015.01.002 –> *These protocols are currently being further established as ISO as part of the IEEE-SA working group "Standards and protocols for soil spectroscopy" (https://sagroups.ieee.org/4005/)*

- Chabrillat S., Gholizadeh A., Neumann C., Berger D., Milewski R., Ogen Y., Ben-Dor E. (2019): **Preparing a soil spectral library using the Internal Soil Standard (ISS) method: Influence of extreme different humidity laboratory conditions**. Geoderma. 355, 113855. https://doi.org/10.1016/j.geoderma.2019.07.013

- Kopackova-Strnadova V., Ben-Dor E. (2016): **Normalizing reflectance from different spectrometers and protocols with an internal soil standard.** International Journal of Remote Sensing. 37(6), 1276-1290. https://doi.org/10.1080/01431161.2016.1148291

Some references to works performed by our colleagues with the HySpex sensor on the ground

- Atwood E.C., Falcieri F.M., Piehl S., Bochow M., Matthies M., Franke J., Carniel S., Sclavo M., Laforsch C., Siegert F. (2019): **Coastal accumulation of microplastic particles emitted from the Po River, Northern Italy: Comparing remote sensing and hydrodynamic modelling with in situ sample collections**. Marine Pollution Bulletin. Volume 138, Pages 561-574. https://doi.org/10.1016/j.marpolbul.2018.11.045

- Koerting F., Koellner N., Mielke C., Rogass C., Kuras A., Altenberger U., Kaestner F., Hildebrand C. (2021): **Hyperspectral imaging data of the northern mine face and of laboratory samples of the copper-gold-pyrite mine Apliki**, Nicosia District, Republic of Cyprus. GFZ Data Services. https://doi.org/10.5880/GFZ.1.4.2021.001

- Koerting F. (2021): **Hybrid imaging spectroscopy approaches for open pit mining**. Dissertation. University of Potsdam. https://doi.org/10.25932/publishup-49909

Final Quiz: Lesson 'Principles of sensor technologies and data acquisition techniques'

In this final quiz for the lesson 'Principles of sensor technologies and data acquisition techniques' we have prepared 10 questions for you. **You need 50 % to be correct to pass to the next lesson**. You have **unlimited attempts to pass the quiz**. Good luck!

> In order to receive a certificate, you need to pass the lesson quizzes (3) as well as the final quiz in the online version of this course.

Sort the sensors based on their pixel size from 5 m to 90 m (highest spatial resolution on top)

(Options: HICO, AVIRIS (airborne), Sentinel-2 (bands 2-4 and 8), CHRIS/PROBA (mode 2-5), EnMAP)

Choose an element

Choose an element

Choose an element

Choose an element

Choose an element

Sort the sensors by platforms they are/were deployed on
Sort elements (Options: "AVIRIS, AIS, HyMAP, APEX, CASI", "DESIS, HISUI, EMIT", "EnMAP, PRISMA, CHIME, SBG, Hyperion")

Airplane   Choose an element

Satellite   Choose an element

ISS   Choose an element

What pixel size has the hyperspectral EnMAP sensor? (single-choice)

☐ 3 m
☐ 30 m
☐ 300 m
☐ 0.3 m

What is the average altitude of the ISS? (single-choice)

☐ 300 km
☐ 400 km
☐ 1000 km
☐ 1400 km

Name the three angles of platform rotation (attitude) measured during airborne flights

1. ☐

2. ☐

3. ☐

What should you consider when collecting spectral data on the ground (field or lab)? (multiple-choice)

☐ Measure under stable illumination conditions
☐ Avoid bright/colorful/reflecting surfaces nearby
☐ Repeat white reference measurements (and optimization if necessary)
☐ Always keep notes!

Which of the following graphs describes a pushbroom type imaging spectrometer? (single-choice)

adapted from Livens (2018)
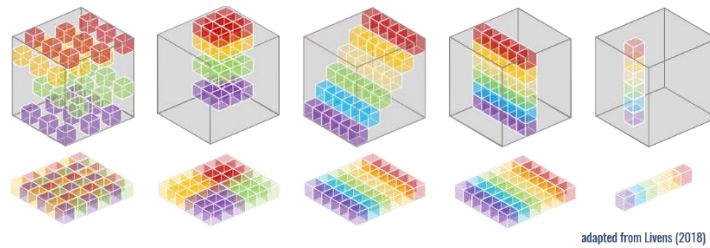
☐ 1
☐ 2
☐ 3
☐ 4
☐ 5

Why are spectral data acquired on the ground? (single-choice)
☐ Because some areas are not accessible by airplane
☐ Because ground-based measurements are independent of atmospheric influence
☐ Because ground-based measurements allow to study processes at high and temporal resolution
☐ Because many scientists get sick in planes and prefer to work on the ground

Unfortunately, there are some common trade-offs between the resolutions. In the relationship of spatial and spectral resolution, as one increases the other needs to decrease … (single-choice)
☐ … to keep data sizes manageable
☐ … to gain the same amount of photons on the detector
☐ … to achieve acceptable temporal resolution
☐ … to allow for rectangular pixels

5 Hands-On training: Data and software

Welcome to our third thematic lesson! As before, Charly will explain the learning objectives of this – final – lesson in the video below.

VIDEO: Basic-16: Hands-on training: Lesson Intro

URL of the video:
https://youtu.be/Mp9p5E4yw4E

Please be aware that the data sources presented in this lesson are not a complete representation of all potential (free) resources but a selection of large and accredited ones and some that we have assembled ourselves.

Please feel free to point out further resources in the discussion forum. You can find the discussion forum at https://eo-college.org/forums/forum/beyond-the-visible/ under each related topic.

Let's move on with the first topic of this lesson.

5.1 From research question to final product

Now, imagine you want to answer your research questions by using imaging spectroscopy data – **what would the general workflow be**? We have prepared a little exercise for you: Can you guess the 6 different steps involved as well as some more concrete sub-steps (Step 2 and Step 4)?

Interactive graph – General Workflow
Available under this LINK.
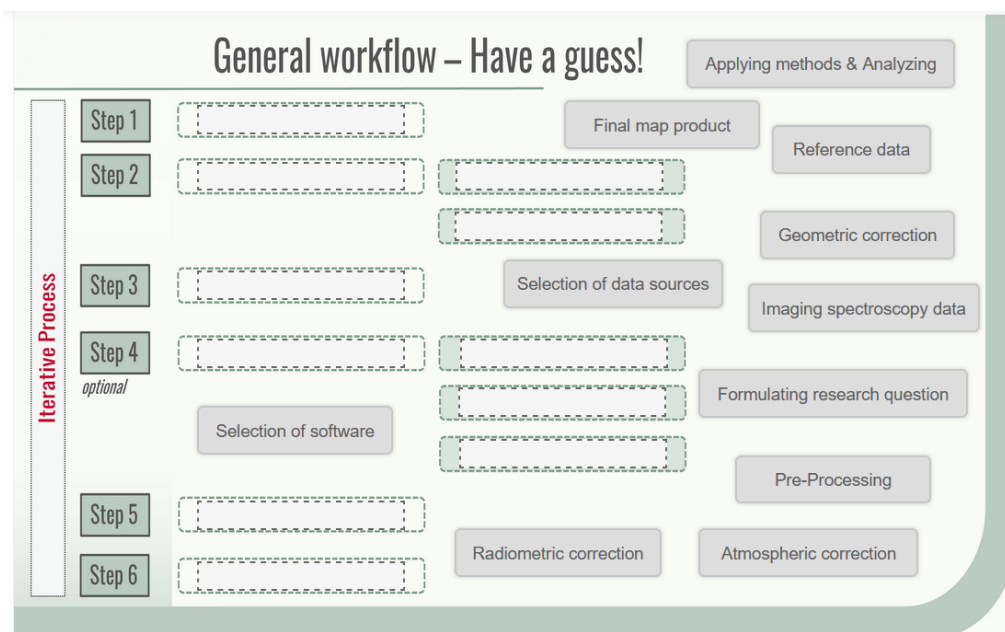
Of course, the workflow shown is very abstract and simplified and you might experience situations where you must iteratively go back and make adjustments. Nevertheless, the exercise shows that the path to a final, qualitative map product based on imaging spectroscopy data involves many steps whose precise definition requires intensive thought and consideration.

While the formulation of the research question is up to you, we will get into more detail of the remaining steps during the following topics of this lesson. Including some very useful tips and initial practical experience. The solution to the general workflow can be found here.

Do you want to **share your pending research question with the MOOC community**? Please **use the discussion forum** of this topic to do so! We are very keen to hear from you!

5.2 Data sources: spaceborne

As you have seen in the previous lesson, there are already a number of Earth observing imaging spectrometers in space today. Often the data is made available free of charge for scientific purposes. In this section we would like **to introduce you to some data sources for imaging spectroscopy spaceborne data**.

PRISMA Data Portal

PRISMA funded by Italian Space Agency (ASI), is an Earth observation satellite with innovative electro-optical instrumentation which combines a hyperspectral sensor with more than 200 bands in the VNIR to SWIR range with a panchromatic camera. The satellite was successfully launched in March 2019. Users can obtain archive data and request new data acquisitions after registering in the **PRISMA data portal**.

With the kind cooperation of ASI, we have produced three screencasts for this MOOC. In the **first video you will get a short overview of the PRISMA mission and learn step by step how to register in the PRISMA data portal**.

<div align="center">

VIDEO: Basic-17: Hands-on training: PRISMA User Registration

URL of the video:
https://www.youtube.com/watch?v=7k5KIlgI7O0&feature=youtu.be

</div>

The **second video demonstrates how to access the PRISMA data catalogue to search for archived data**. You will learn which search parameters are available and how to select, order, and finally download data products. In addition, you will be introduced to EarthBit, a free-and-open-source software, that can be used to visualize the data products.

VIDEO: Basic-18: Hands-on training: PRISMA Image Acquisition

URL of the video:
https://www.youtube.com/watch?v=7EmP0mCYvq8
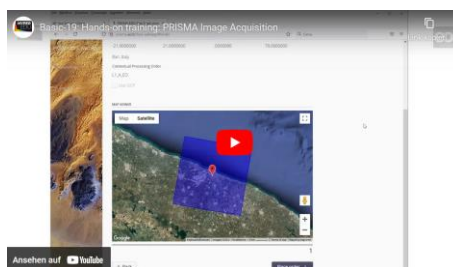
The **third video shows how to request new PRISMA acquisition in the PRISMA data portal** by explaining the parameter settings and data products. Afterwards you will be well prepared to order data for your own study area.

VIDEO: Basic-19: Hands-on training: PRISMA Image Acquisition

URL of the video:
https://youtu.be/GJVJW4K3iJs

EnMAP Data Portal

The Data Access Portal includes two main entry points: the EnMAP Instrument Planning Portal and the EOWEB® GeoPortal. On the EnMAP Instrument Planning Portal users can register, submit proposals, and plan and request future orders. The EOWEB® GeoPortal contains the full EnMAP Data archive.

Users can access EnMAP data using two different options:

- Users can request acquisitions through the EnMAP Instrument Planning Portal. The portal includes the Proposal Portal for proposal submission by all scientific users responding to an Announcement of Opportunity (AO) and the Observation Request Portal providing planning support of observation requests and submission of future orders.
- Users can search, process, and order data from the archive catalog from the German Satellite Data Archive (D-SDA) through the EOWEB® GeoPortal.
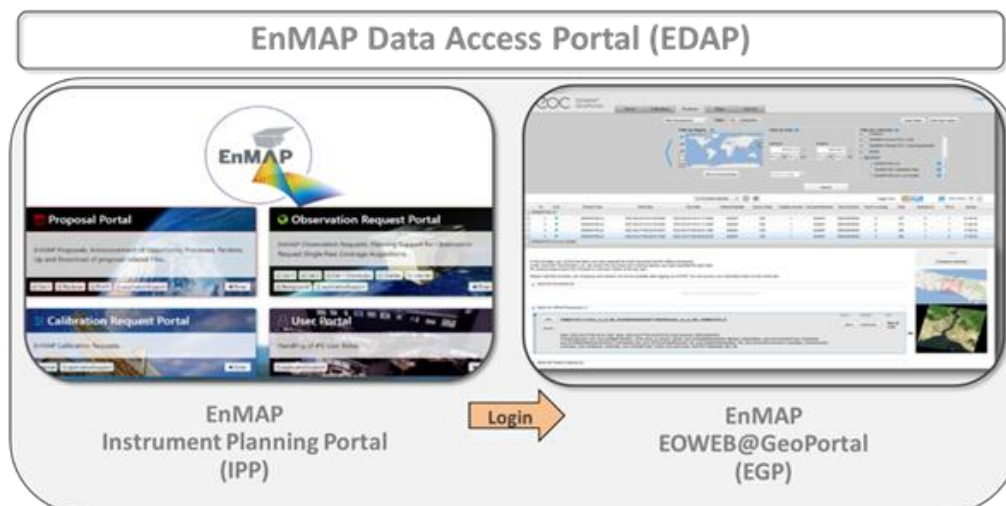
Figure 27 EnMAP Data Access Portal

USGS Earth Explorer Portal

The first imaging spectrometer launched into space in 2000 was the **Hyperion imaging spectrometer**, a technology demonstrator aboard NASA's Earth observing mission EO-1. Despite being planned as a one-year mission, the sensor was in operation until 2017 and data is available via the **USGS Earth Exlorer Portal**.
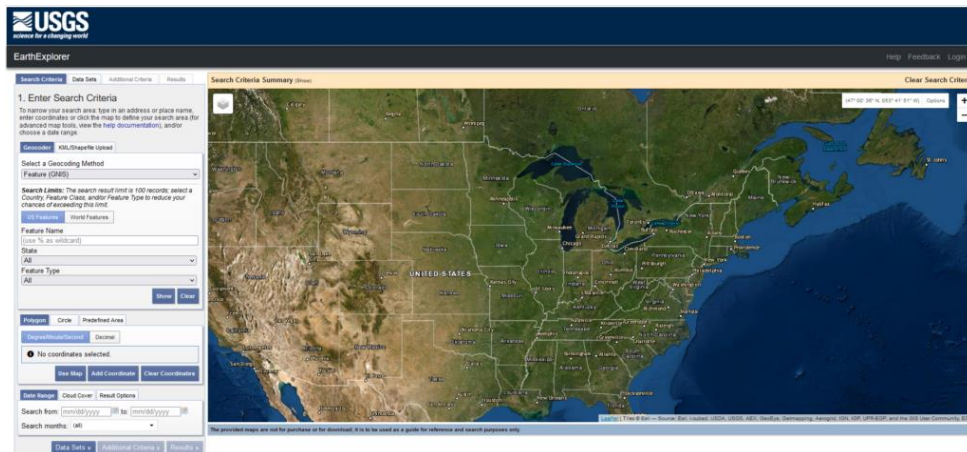
Figure 28 USGS Earth Explorer Portal

This portal provides access to a range of remote sensing data and products in addition to Hyperion and the USGS provides some helpful guidance videos (though not specifically on downloading Hyperion data): An EarthExplorer Introduction discussing the basics of using EarthExplorer or an EarthExplorer Search Criteria discussing the available search options. Have a look on this NASA-ARSET webinar series on imaging spectroscopy, including a Hyperion download tutorial (see resources section of this lesson).

Quiz: Data sources: spaceborne

Spaceborne imaging spectroscopy data is currently freely available from the sensor:
(multiple-choice)

☐   PRISMA
☐   EnMAP
☐   Hyperion
☐   SBG

5.3 Data sources: airborne

Another source of imaging spectroscopy data is data from airborne flight campaigns. These are **expensive to acquire** and therefore somewhat **rare**. Often, there are few and, if at all, infrequent revisits of the same area, and additionally the (study) areas are small. However, the data are **increasingly being made available to the user community**. In this chapter we will introduce some data portals for airborne hyperspectral data.

AVIRIS-NG Data Portal

In the previous lesson, we learned about the ESA CHIME & SBG AVIRIS-Next Generation Europe 2021 campaign. As you have learned, AVIRIS-NG is an imaging spectrometer that measures reflected radiance at 5nm intervals in the VNIR-SWIR spectral range from 380-2500nm. The sensor has already been flown in airborne campaigns in many countries and the **AVIRIS-NG Data Portal** provides an **overview of the campaign data and the possibility to download L1 and L2 data products.**
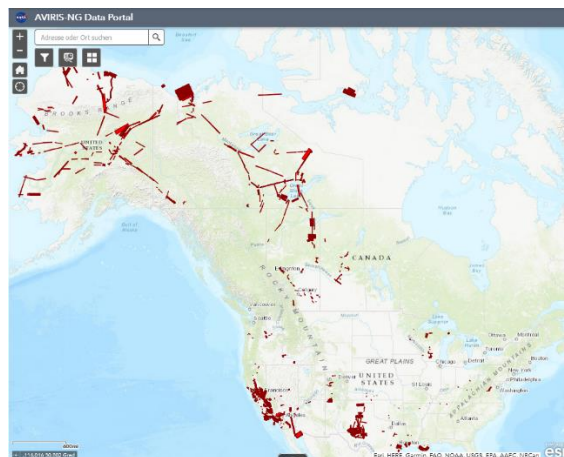

Figure 29 Screenshot of the AVIRIS-NG Data Portal

In addition, the reflectance data of the ESA CHIME & SBG AVIRIS-Next Generation Europe 2021 campaign have been made available for download at the **campaign website of ARES**, the Airborne Research Facility for the Earth System at the University of Zurich.
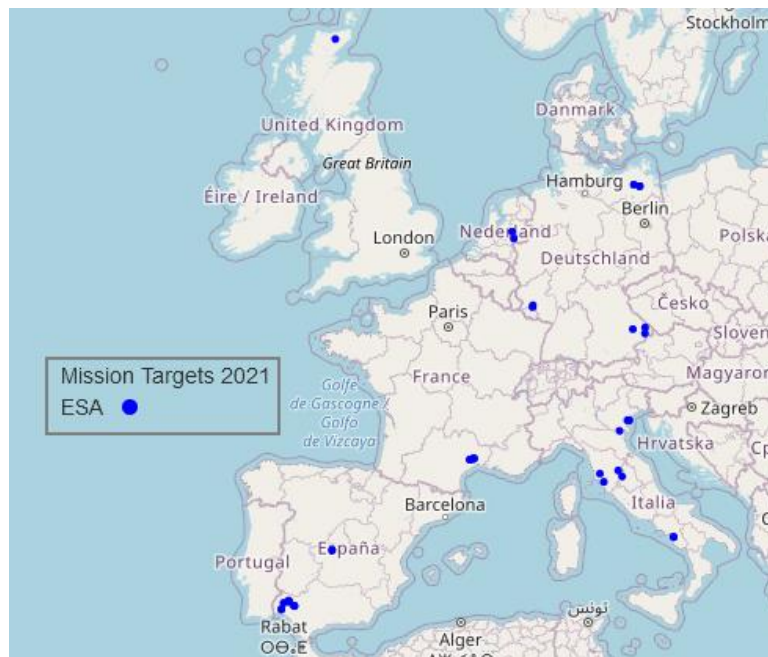
Figure 30 ARES AVIRIS-Next Generation Europe 2021 campaign website

EnMAP Campaign Portal

The **EnMAP Campaign Portal provides access to airborne hyperspectral image data sets along with simulated future EnMAP data** that were generated using the EnMAP end-to-end simulation tool (EeteS). In addition, **associated in-situ data from field and laboratory measurements** are provided. The flight campaigns have been carried out in the framework of the EnMAP preparatory science program to support method and application development in the prelaunch phase of the EnMAP satellite mission. A metadata portal has been set up to provide general information about all the campaigns and direct links to the datasets. The data is made freely available to the scientific community under a Creative Commons License through the GFZ Data Services.

Name	Application	Sensor	Product-Level	Date	DOI
Gerolstein (Germany)	Forest	HySpex	L2	2016-09-08	DOI
Toolik Lake (Alaska, USA)	Vegetation	AISA (Eagle)	L2	2016-08-27	DOI
Demmin (Germany)	Soil	HySpex VNIR-1600 HySpex SWIR320m-e	L2	2015-10-01	DOI
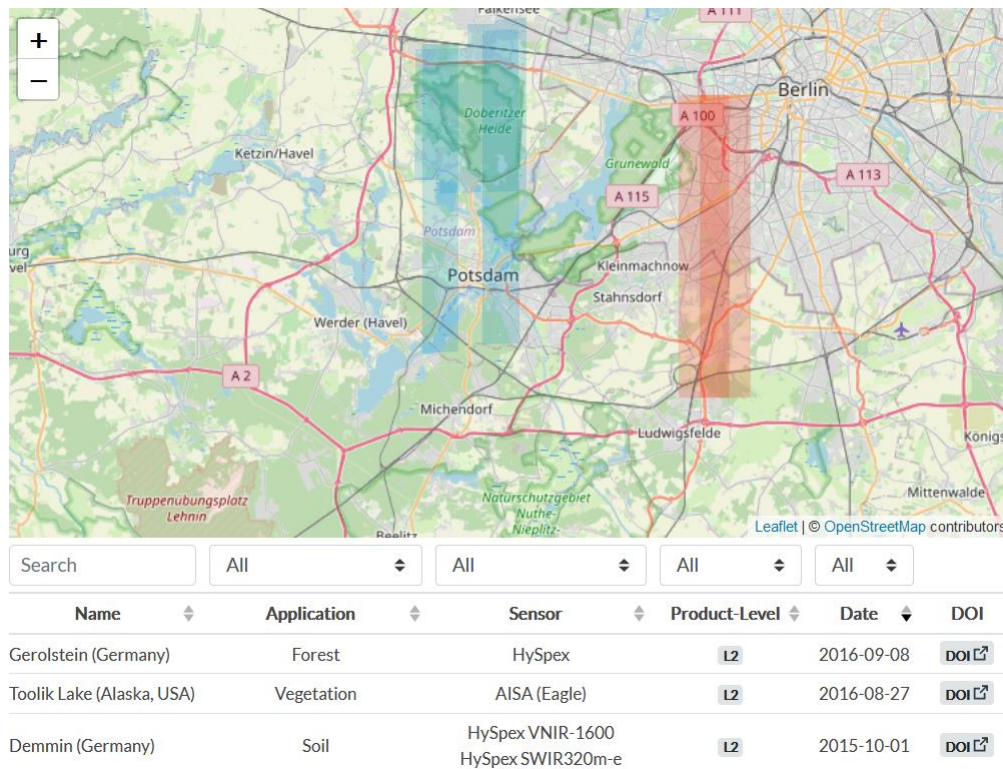
Figure 31 Screenshot of the EnMAP Campaign Portal

Please complete the quiz below to advance to the next topic.

Quiz: Data sources: airborne

Did you check out the portals? Which one offers airborne data AND corresponding ground reference data for direct download? Note: For the others, ground reference data are often available upon request from the contact persons named for the respective campaign. (single-choice)

☐ EnMAP campaign portal
☐ AVIRIS portal
☐ ARES portal

5.4 Data sources: spectral libraries

As presented in the previous lesson, hyperspectral data are not only collected as image cubes but also as **point measurements**, for example **by field- and/or lab spectroscopy**. Sometimes, these measurements are made available to the public in form of spectral libraries that facilitate material identification and mapping in laboratory and field spectroscopy and remote sensing. In the following topic, we will present a **number of freely accessible spectral libraries containing different surface materials**. Reflectance spectral libraries based on imaging spectrometer data and untreated samples are not yet free available in large numbers for the hyperspectral community.

USGS spectral library

A widely known, freely available, accredited library is provided by the USGS. **Reflectance spectra of minerals, mineral mixtures, rock coatings, liquids, frozen volatiles, organic compounds, manmade materials, vegetation and other biological materials** are assembled in the **USGS Spectral Library Version 7**. Detailed sample descriptions are provided with the spectra, including the results of X-ray Diffraction, Electron Probe Micro-Analysis, and other analytical methods. Based on these reference spectra, geological surfaces, for example, can be mapped using image classification. As the spectral data of the library are usually collected by point spectroradiometers, e.g., the Analytical Spectral Devices (ASD) FieldSpec® 3, it is necessary to spectrally adapt them to the characteristics of the sensor with which the image being analyzed was recorded.

ECOSTRESS spectral library

The **ECOSTRESS spectral library** was developed as part of the ASTER and ECOSTRESS projects and released in February 2018 (Version 1.0). It is a **compilation of over 3400 spectra of natural and man-made materials** and includes over 1100 new vegetation and non-photosynthetic vegetation spectra, as well as data from three other spectral libraries: The Johns Hopkins University (JHU), the Jet Propulsion Laboratory (JPL), and the United States Geological Survey (USGS – Reston).

LUCAS SOIL spectral library

The **Land Use/Cover Area frame statistical Survey Soil (LUCAS SOIL)** is an **extensive and regular topsoil survey that is carried out across the European Union** to derive policy-relevant statistics on the effect of land management on soil characteristics (Orgiazzi et al. 2018). **LUCAS SOIL** currently represents the **largest harmonized open-access dataset of topsoil properties** available at continental scale.

In the 2009/2012 and 2015 **LUCAS SOIL** surveys, a range of soil physicochemical properties were measured in a systematic and standardized way, including pH, organic carbon, nutrient concentrations and cation exchange capacity and others based on more than 40.000 collected top-soil samples. In addition to the mentioned physicochemical properties, diffuse **reflectance** spectra of the samples were determined in the spectral range 400 to 2500 nm with a spectral resolution of 2 nm. Details on the methodology of the spectral measurements are described in Nocita et al. (2014) and several studies base on the **LUCAS SOIL spectral library**.

LUCAS SOIL data are available freely upon registration with the **European Soil Data Centre website**.

SPECCHIO spectral information system

SPECCHIO is a **spectral information system designed to hold reference spectra and spectral campaign data obtained by spectroradiometers**. The inclusion of a rich metadata set in the data model ensures the longevity of spectral data and enables the sharing of spectral data between research groups. The information system has been developed at the University of Zurich over nearly 20 years and has been widely used in the community. The latest Version 3 is described in detail in an overview paper by Hueni et al. (2020).

Open Soil Spectral Library

The Soil Spectroscopy for the Global Good (SoilSpec4GG) coordinated Innovation Network announced the release of the **Open Soil Spectral Library (OSSL)** on 5 December 2021 (by the way, that is World Soils Day), which is publicly available here. SoilSpec4GG is a **USDA-funded innovation network that wants** to bring together soil scientists, spectroscopists, informaticians, data scientists and software engineers to overcome some of the current bottlenecks preventing wider and more efficient use of soil spectroscopy.

Again, **please be aware the list of data sources is certainly not complete and only includes freely available data**. Data from further collections, such as the **Brazilian soil spectral library (BSSL)** or the spectral library **SPECTATION - SPECtral database for vegeTATION** might become available to you upon request.

Have you ever downloaded hyperspectral images or used a spectral library? Maybe you are contributing data yourself via a portal not mentioned above? Currently, there is a lot in progress with new portals and/or spectral libraries being developed or access becoming easier.

Please feel free to point out further resources to the community, for example in the discussion forum**.** You can find the discussion forum at https://eo-college.org/forums/forum/beyond-the-visible/ under each related topic.

Please complete the quiz below to advance to the next topic.

Quiz: Data sources: spectral libraries

Now we have a little guess question for you. You can also do some search in the given resources. Here it is: How many base spectra are available for download in the USGS Spectral Library Version 7? (single-choice)

☐   less than 100
☐   100 – 1000
☐   1000 – 2000
☐   more than 2000

The graph shows spectra of three different surface materials – can you identify them?
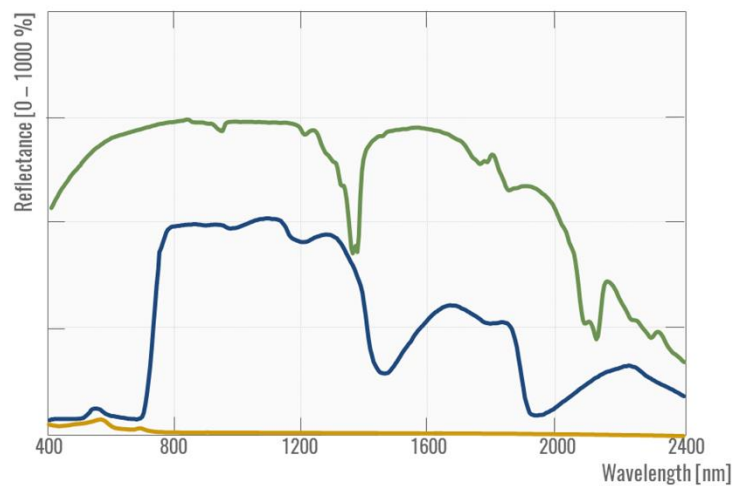
Green is …   Choose an element

Blue is …   Choose an element

Yellow is …   Choose an element

5.5 Data preprocessing

Now that you know where to get data you can start your analyses, right? Well, almost! As we learned at the end of the previous lesson, hyperspectral data are pretty complex and there are a few things to consider. Most data portals presented above provide data in different processing levels including preprocessed ready-to-use Level 2 reflectance data. If preprocessing is not yet done or you are not satisfied with the data quality of the preprocessed data, you may do the correction steps yourself. Charly will explain to you **some aspects to consider on data selection and preprocessing in the next video**:

VIDEO: Basic-20: Hands-on training: Data preprocessing

URL of the video:
https://www.youtube.com/watch?v=drqFyMmyPI0

VIDEO: Hands-on training: Data preprocessing

What does TOA stand for?
- ☐　　Total Absorption
- ☐　　Top of Atmosphere
- ☐　　Total optical Activity

The effect of geometric correction is usually more visible in …
- ☐　　Airborne data
- ☐　　Spaceborne data

If I want to compare data acquired by different sensors but at the same date and location, I do need to apply atmospheric correction!
- ☐　　True
- ☐　　False

Quiz: Data preprocessing

Which preprocessing steps should be applied to hyperspectral data? (multiple-choice)

☐   Radiometric correction
☐   Cosmetic correction
☐   Atmospheric correction
☐   Geometric correction

Geometric correction involves the transformation of irregularly spaced measurements that were acquired in sensor geometry into regularly spaced pixels with a map projection. Which of the two scenes below has been geocorrected: (single-choice)
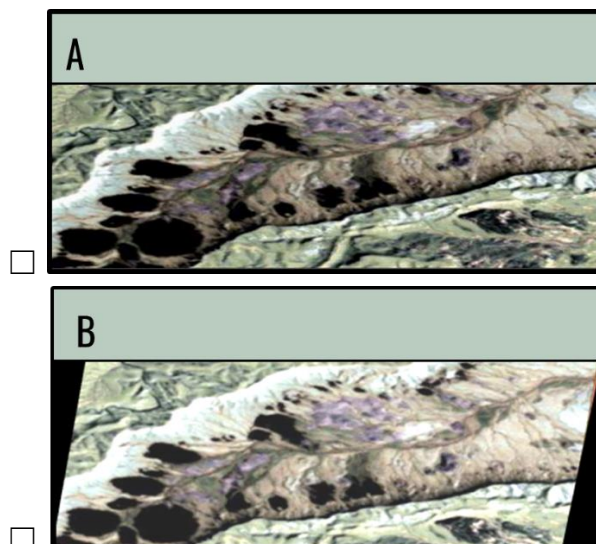
☐

☐

Fill in the blanks, choose from: spectral non-uniformity, spatial non-uniformity, radiometric non-uniformity, temporal non-uniformity, radiometric correction, geometric correction, atmospheric correction

The keystone effect is a ☐ that needs to be considered during ☐ .

What is considered in atmospheric correction? (multiple-choice)
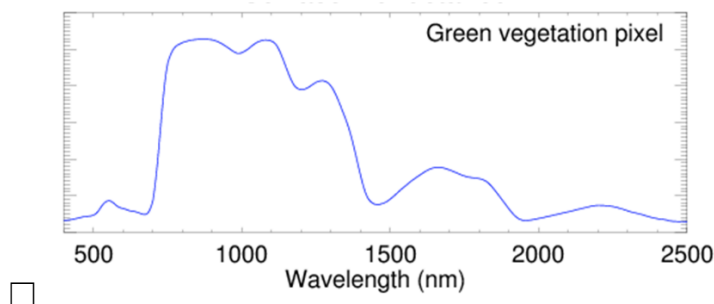
☐   sun position
☐   keystone compensation
☐   atmospheric state
☐   terrain

The two spectra below show a vegetation spectrum before and after atmospheric correct was applied. Click on the one without atmospheric correction? (single-choice)

☐

☐
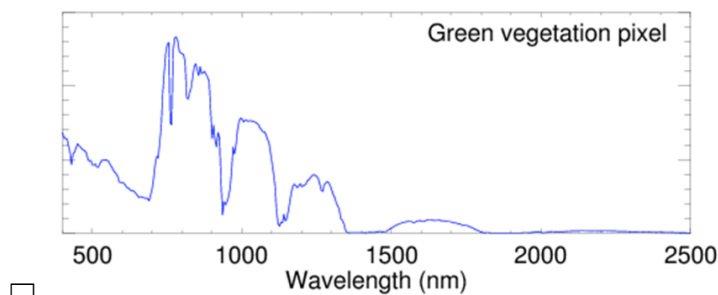
Why is atmospheric correction important? (multiple-choice)
☐   Because it transforms digital numbers to top of atmosphere radiance
☐   Because it transforms surface reflectance to digital numbers
☐   Because it generates surface reflectance that provides a fingerprint of surface materials
☐   Because it generates surface reflectance that is transferable between scenes acquired at different dates or locations

5.6 Methods and software

You are now ready for the actual analysis of your data. There are a **variety of methods for analyzing** the high information content of imaging spectroscopy data. These methods can be structured in different ways. In the following **video**, Charly gives you an **overview of widely used methods** and divides them into those **suitable for classification** and those **suitable for quantification** approaches. He also gives a short overview of software that you can use for the data analysis.

VIDEO: Basic-21: Hands-on training: Methods & software

URL of the video: https://www.youtube.com/watch?v=D-cXsw_A6r0

VIDEO: Hands-on training: Methods & software

Before we have a look at some processing techniques, do you already know what a so-called "endmember" is that is used in some of the techniques? No worries, you will learn more about endmembers in the next slides. A spectral endmember in remote sensing is…

☐ … an unknown target or spectrum
☐ … a target or spectrum of very high purity
☐ … an unknown target or spectrum

VIDEO: Hands-on training: Methods & software

Which target is spectrally more similar to the endmember spectrum based on bands i and j?

☐   A
☐   B
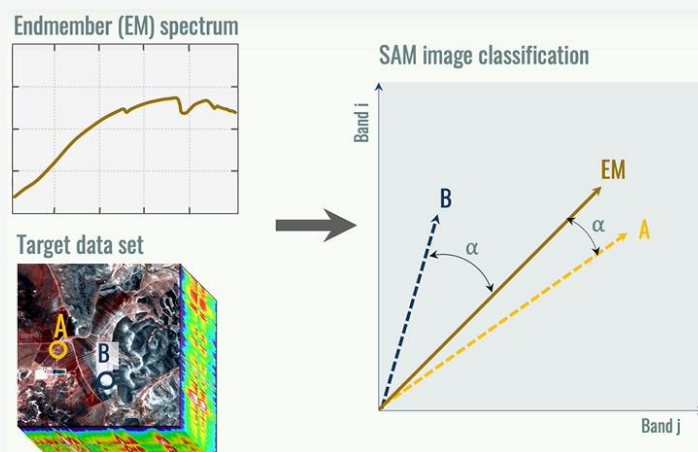
Remember, you've seen this feature before … Do you also remember the corresponding mineral?

☐   Calcite
☐   Gypsum
☐   Kaolinite

VIDEO: Hands-on training: Methods & software

Assign the presented methods to the general groups of
(Options: Spectral Angle Mapper (SAM), Spectral Mixing Analyses (SMA), Spectral Feature Analyses (SFA), Radiative Transfer Modelling (RTM), Spectral Feature Fitting (SFF), Support Vector Machine (SVM) Classification)

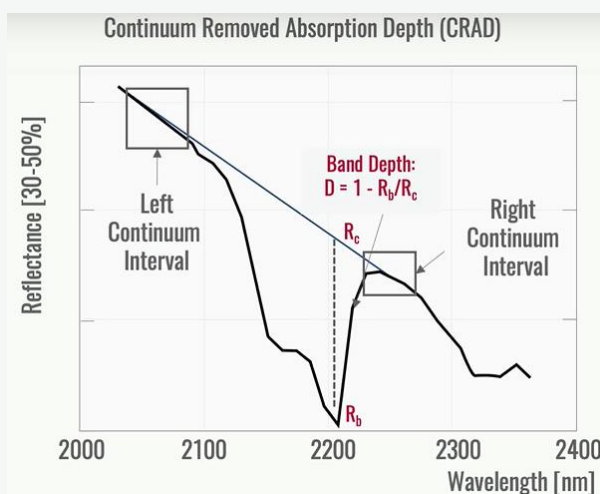| Classification methods	Spectral Mixing Analysis (SMA)
Choose an element	Choose an element
Choose an element	Choose an element
Choose an element	Choose an element

Charly just mentioned a technique called "**continuum removal**" – any idea what that is? Yes? Okay, just go to the next topic. No? Well, the "continuum" is simply a convex hull that can be calculated for (a) the entire spectrum or (b) a specific absorption area (or feature). Removal of the continuum results in a normalization of the spectra and allows for comparison of absorption depths from a common baseline (that equals 1).
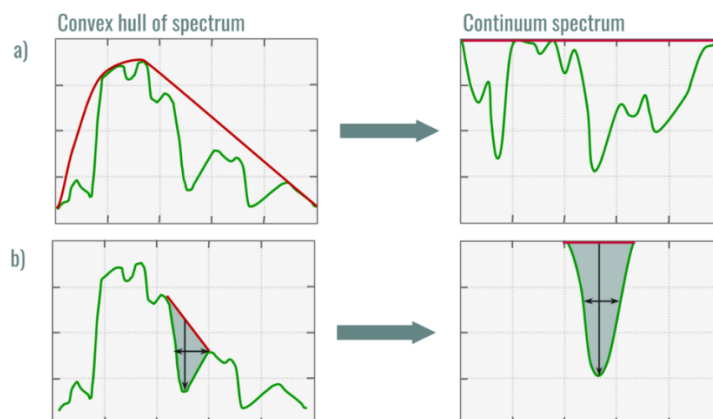
Figure 32 Schematic representation of the continuum removal concept for (a) the entire spectrum and (b) a specific absorption area

Quiz: Methods and software

Assign the presented methods to the general groups of "Classification methods" or "Quantification methods" (Fill in the blank)

Options: classification (3x), quantification (3x)

Spectral Angle Mapper (SAM): Choose an element method

Spectral Feature Fitting (SFF): Choose an element method

Spectral Mixing Analysis (SMA): Choose an element method

Spectral Feature Analysis (SFA): Choose an element method

Support Vector Machine (SVM) classification: Choose an element method

Radiative Transfer Modelling (RTM): Choose an element method

Can you match the correct terms? (Options: inverse mode, forward mode, inversion algorithm, vegetation properties, reflectance data, RTM)

A   Choose an element

B   Choose an element

C   Choose an element

D   Choose an element

E   Choose an element

D   Choose an element

Illustration of the EnMAP satellite with permission from DLR Space Agency
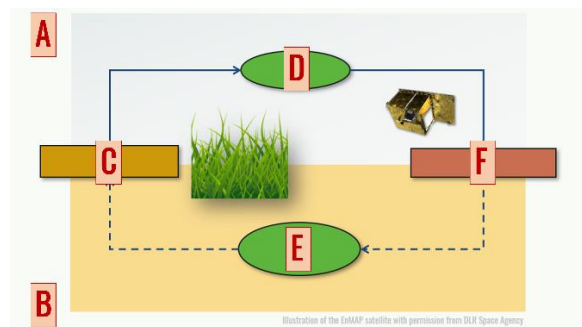
5.7 Introduction to the EnMAP-Box

There are several software options that allow for visualization and analyses of hyperspectral data. One of these options is the **EnMAP-Box**, a **free and open source python plugin for QGIS**, specifically **designed to process and visualize imaging spectroscopy data** such as that from the recent EnMAP mission, but also any other optical remote sensing data. The EnMAP-Box has been developed in the frame of the EnMAP preparatory science program to allow advanced processing of high dimensional spectral remote sensing data and enhanced visualization and exploration of multi-band remote sensing data and spectral libraries in a GIS environment. The plug-in consists of a graphical user interface for data visualization and spectral library management, a set of advanced general and application-oriented algorithms, and a high-level application programming interface (EnMAP API). The EnMAP-Box can be started from QGIS or stand-alone and is registered in the QGIS plug-in repository.

We have produced the **following three screencasts for you to provide a first introduction to working with the EnMAP-Box**. The first screencast explains the **installation of the EnMAP-Box software**, the second the **different visualization tools** and finally the third the different **options for working with spectral libraries**. For detailed and up-to-date information on the EnMAP-Box please visit the **documentation website**, where you can also find a user manual as well as several application tutorials.

Installation of the EnMAP-Box and active participation in any tutorial are not compulsory to pass this MOOC, however, we strongly encourage you to use this opportunity to "get your hands dirty" during some expert-guided hands-on training exercises! Please refer to the installation website for information on the **latest supported QGIS version**.

Installation

VIDEO: Basic-22: Hands-on training: EnMAP-Box Installation

URL of the video:
https://www.youtube.com/watch?v=_SNbLmB8aCQ

Data visualization

VIDEO: Basic-23: Hands-on training: EnMAP-Box Installation

URL of the video:
https://youtu.be/31FQ5zXl2Rw

Working with spectral libraries

VIDEO: Basic-24: Hands-on training: EnMAP-Box Installation

URL of the video:
https://youtu.be/qVoi0CoJheI

5.8 Resource section: Lesson 'Hands-On training: Data and software'

In this section, we have assembled resources used for the creation of this lesson that we recommend you for further reading as they provide a lot more detail. Please remember that this selection is not a complete overview of all resources – if you think an important resource is missing, let us and your fellow students know (e.g. in the discussion forum). You can find the discussion forum at https://eo-college.org/forums/forum/beyond-the-visible/ under each related topic.

You can find many figures of this lecture in the HYPERedu slide collection, available on EO-College.

- K. Berger, C. Atzberger, M. Danner, M. Wocher, T. Kuester, S. Foerster (2020). **Dimensionality reduction of imaging spectroscopy data**, HYPERedu, EnMAP education initiative, March 2020, LMU Munich.

- K. Berger, J. Verrelst, C. Atzberger, M. Weiss, S. Steinhauser, M. Wocher, S. Foerster, T. Kuester (2020). **Retrieval approaches of vegetation traits from imaging spectroscopy data**, HYPERedu, EnMAP education initiative, September 2020, LMU Munich.

Sources and further reading

Topic: Data sources: spaceborne

PRISMA DATA
- http://prisma-i.it

- https://prisma.asi.it

EnMAP Data
- www.enmap.org

- https://eoweb.dlr.de (in the future)

USGS Earth Explorer Portal (Hyperion)

- https://earthexplorer.usgs.gov/

- An EarthExplorer Introduction discussing the basics of using EarthExplorer (by USGS): https://www.youtube.com/watch?v=eAmTxsg6ZYE

- An EarthExplorer Search Criteria discussing the available search options (by USGS): https://www.youtube.com/watch?v=CVsgjp9jRyA

- A tutorial on Hyperion (by NASA ARSET, 29:53 -37:30): https://www.youtube.com/watch?v=x7l6n7njVPo

- A recent webinar series on imaging spectroscopy (by NASA ARSET): https://appliedsciences.nasa.gov/join-mission/training/english/arset-hyperspectral-data-land-and-coastal-systems

Topic: Data sources: airborne

AVIRIS-NG

- Overview of campaign data and download possibility for L1 and L2 data products: https://avirisng.jpl.nasa.gov/dataportal/

- Data of the *ESA CHIME & SBG AVIRIS-Next Generation Europe 2021 campaign* available for download from https://ares-observatory.ch/esa_chime_mission_2021/

EnMAP flight campaign data

- EnMAP data simulated from airborne data (https://www.enmap.org/data_tools/simulated/)

- Overview of campaign data direct links to the dataset landing pages: https://www.enmap.org/data_tools/flights or, alternatively, search and data download via https://dataservices.gfz-potsdam.de/portal/?q=hyperspectral*

Topic: Data sources: spectral libraries

LUCAS

- LUCAS SOIL data available via the European Soil Data Centre website https://esdac.jrc.ec.europa.eu/resource-type/soil-point-data
- Orgiazzi, A.; Ballabio, C.; Panagos, P.; Jones, A.; Fernández-Ugalde, O. (2018): **Lucas soil, the largest expandable soil dataset for Europe: A review**. Eur. J. Soil Sci. 69, 140–153.

Some studies using LUCAS:

- Castaldi F., Chabrillat S., Chartin C., Genot V., Jones A., van Wesemael B. (2018): **Estimation of soil organic carbon in arable soil in Belgium and Luxembourg with the LUCAS topsoil database**. Eur. J. Soil Sci. 2018, 69, 592–603. https://doi.org/10.1111/ejss.12553

- Nocita M., Stevens A., Tóth G., Panagos P., van Wesemael, B., Montanarella L. (2014): **Prediction of soil organic carbon content by diffuse reflectance spectroscopy using a**

local partial least square regression approach. Soil Biology & Biochemistry. 68,337–347. https://doi.org/10.1016/J.SOILBIO.2013.10.022

- Ward K.J., Chabrillat S., Brell M., Castaldi F., Spengler D., Foerster S. (2020): **Mapping Soil Organic Carbon for Airborne and Simulated EnMAP Imagery Using the LUCAS Soil Database and a Local PLSR**. Remote Sensing. 12, 3451. https://doi.org/10.3390/rs12203451

- Ward K.J., Chabrillat S., Neumann C., Foerster S. (2019): **A remote sensing adapted approach for soil organic carbon prediction based on the spectrally clustered LUCAS soil database**. Geoderma. 353, 297–307. https://doi.org/10.1016/j.geoderma.2019.07.010

USGS spectral library

- USGS Spectral Library Version 7 https://crustal.usgs.gov/speclab/QueryAll07a.php

ECOSTRESS spectral library

- https://speclib.jpl.nasa.gov/

- Meerdink S. K., Hook S. J., Roberts D. A., Abbott E. A. (2019): **The ECOSTRESS spectral library version 1.0**. Remote Sensing of Environment. 230(111196), 1–8. https://doi.org/10.1016/j.rse.2019.05.015

SPECCHIO spectral information system

- https://specchio.ch/

- Hueni A., Chisholm L., Ong, C., Malthus T., Wyatt, M., Trim S., A., Schaepman M. E., Thankappan M. (2020): **The SPECCHIO Spectral Information System**. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 13: 5789-5799. https://doi.org/10.1109/JSTARS.2020.3025117

Open Soil Spectral Library

- https://soilspectroscopy.org/

- https://explorer.soilspectroscopy.org/

Brazilian Soil Spectral Library

- https://bibliotecaespectral.wixsite.com/english

SPECTATION

- http://www-app2.gfz-potsdam.de/spectation/?file=main

Topic: Data preprocessing

Pre-processing of airborne data

- Atmospheric / Topographic Correction for Airborne Imagery (ATCOR-4 User Guide, Version 7.4.0, September 2021)

- Muller R., Lehner M., Muller R., Reinartz P., Schroeder M., Vollmer B. (2002): **A program for direct georeferencing of airborne and spaceborne line scanner images.** International

Archives of Photogrammetry Remote Sensing and Spatial Information Sciences. 34, 148–153.

- Richter R., Schläpfer D. (2002): **Geo-atmospheric processing of airborne imaging spectrometry data**. **Part 2: atmospheric/topographic correction**. International Journal of Remote Sensing. 23, 2631–2649. https://doi.org/10.1080/01431160110115834

- Schläpfer D., Richter R. (2002): **Geo-atmospheric processing of airborne imaging spectrometry data. Part 1: Parametric orthorectification**. International Journal of Remote Sensing. 23, 2609–2630. https://doi.org/10.1080/01431160110115825

- Thompson D.R., Guanter L., Berk A., Gao B.-C., Richter R., Schläpfer D., Thome K.J. (2019): **Retrieval of Atmospheric Parameters and Surface Reflectance from Visible and Shortwave Infrared Imaging Spectroscopy Data**. Surveys in Geophysics. 40, 333–360. https://doi.org/10.1007/s10712-018-9488-9

Improved pre-processing by fusing airborne laser scanning and hyperspectral imaging data

- Brell M., Segl K., Guanter L., Bookhagen B. (2019): **3D hyperspectral point cloud generation: Fusing airborne laser scanning and hyperspectral imaging sensors for improved object-based information extraction.** ISPRS Journal of Photogrammetry and Remote Sensing. 149, 200–214. https://doi.org/10.1016/j.isprsjprs.2019.01.022

- Brell M., Segl K., Guanter L., Bookhagen B. (2017): **Hyperspectral and Lidar Intensity Data Fusion: A Framework for the Rigorous Correction of Illumination, Anisotropic Effects, and Cross Calibration**. IEEE Transactions on Geoscience and Remote Sensing. 55, 2799–2810. https://doi.org/10.1109/TGRS.2017.2654516

- Brell M., Rogass C., Segl K., Bookhagen B., Guanter L. (2016): **Improving Sensor Fusion: A Parametric Method for the Geometric Coalignment of Airborne Hyperspectral and Lidar Data**. IEEE Transactions on Geoscience and Remote Sensing. 54, 3460–3474. https://doi.org/10.1109/TGRS.2016.2518930

Topic: Methods and Software

- Lillesand T., Kiefer R.W. & J. Chipman (2008): **Remote Sensing and Image Interpretation**. 6th Edition, Wiley.

- Schowengerdt (2007): **Remote Sensing: Models and Methods for Image Processing**. 3rd Edition, Elsevier

- Verrelst, J., Malenovský, Z., Van der Tol, C. et al. (2019): **Quantifying Vegetation Biophysical Variables from Imaging Spectroscopy Data: A Review on Retrieval Methods**. Surveys in Geophysics. 40, 589–629. https://doi.org/10.1007/s10712-018-9478-y

- Bioucas-Dias, J.M., Plaza, A., Camps-Valls, G., Scheunders, P., Nasrabadi, N., Chanussot, J. (2013): **Hyperspectral remote sensing data analysis and future challenges**. IEEE Geosci. Remote Sens. Mag 1(2), 6–36. https://doi.org/10.1109/MGRS.2013.2244672

- Li, J., Plaza, A. (2016): **Hyperspectral Image Processing. Methods and Approaches**. In: Thenkabail, P.S. (Ed): Remotely Sensed Data Characterization, Classification and Accuracies. Taylor and Francis group. https://www.umbc.edu/rssipl/people/aplaza/Papers/BookChapters/2016.Handbook.Hyperspectral.pdf

- Lv, W., Wang, X. (2020): **Overview of Hyperspectral Image Classification**, Journal of Sensors, vol. 2020, Article ID 4817234. https://doi.org/10.1155/2020/4817234

- Ghamisi, P., Yokoya, N., Li, J., Liao, W., Liu, S., Plaza, J., Rasti, B. and Plaza, A. (2017): **Advances in Hyperspectral Image and Signal Processing: A Comprehensive Overview of the State of the Art**. IEEE Geoscience and Remote Sensing Magazine, vol. 5, no. 4, pp. 37-78, Dec. 2017, https://doi.org/10.1109/MGRS.2017.2762087

Topic: Introduction to the EnMAP-Box

- General information on the EnMAP-Box, a free and open source python plugin for QGIS: https://www.enmap.org/data_tools/enmapbox/

- Download, documentation and tutorials of and with the EnMAP-Box: https://enmap-box.readthedocs.io/

Final Quiz: Lesson 'Hands-On training: Data and software'

In this final quiz for the lesson 'Hands-On training: Data and software' we have prepared 10 questions for you. **You need 50 % to be correct to pass to the next lesson**. You have **unlimited attempts to pass the quiz**. Good luck!

> In order to receive a certificate, you need to pass the lesson quizzes (3) as well as the final quiz in the ONLINE version of this course.

From which sensors you currently can get data? (multiple-choice)

☐ PRISMA

☐ AVIRIS NG

☐ EnMAP

☐ Hyperion

☐ SBG

The EnMAP campaign portal contains datasets from target sites in which of the following countries? Please guess or check the portal. (multiple-choice)

☐ Germany

☐ Spain

☐ USA

☐ Namibia

Which preprocessing steps should be applied to hyperspectral data? (multiple-choice)

☐ Atmospheric correction

☐ Radiometric correction

☐ Cosmetic correction

☐ Geometric correction

Fill in the blank (Options: gain, offset)

Every sensor has its specific gains and offsets applied to the recorded signals. The [____] is determined by measuring the closed shutter and represents the thermally induced dark current. The [____] is determined by measuring the sensor's response to a known radiance target in the laboratory.

What is a radiometric correction and what does it do? (multiple-choice)

☐ It transforms digital numbers to radiance

☐ It transforms digital numbers to reflectance

☐ It involves data resampling using nearest neighbor, bilinear interpolation or cubic convolution methods

☐ It involves a linear transformation in which correction coefficients (gain and offset) are applied to every image pixel

Fill in the blanks, choose from: spectral non-uniformity, spatial non-uniformity, radiometric non-uniformity, temporal non-uniformity, radiometric correction, geometric correction, atmospheric correction

The smile effect is a [_____] that needs to be considered during [_____].

Why can it be useful to apply dimensionality reduction before or as part of actual image analysis? (multiple-choice)

☐ Because it can speed-up processing and reduce computational costs

☐ Because hyperspectral data are often highly redundant and carry highly inter-correlated information

☐ Because redundant data introduce noise and may lead to suboptimal model performances

☐ Because the hundreds of contiguous bands are so confusing

In contrast to classification methods, quantification methods allow … (multiple-choice)

☐ a direct identification of materials

☐ the determination of material abundances in terms of percent fractional cover

☐ the estimation of material contents and properties

☐ assignment of unique classes to each pixel

Let's assume you want to determine the relative abundance of known materials within each image pixel based on the materials' spectral characteristics. Which method would you choose? (single-choice)
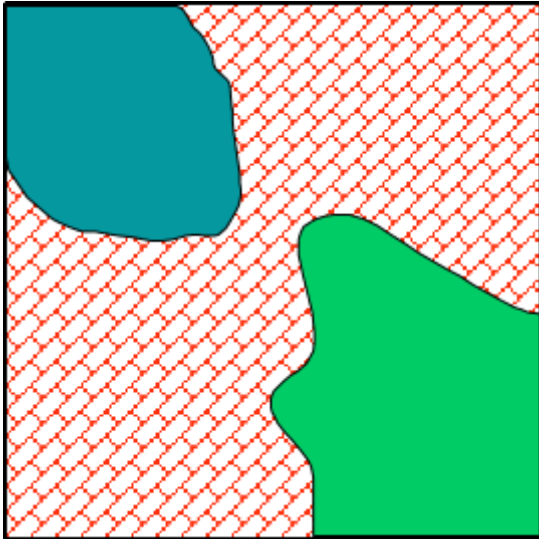
☐   Spectral Mixture Analysis (SMA) or Linear Spectral Unmixing
☐   Spectral Angle Mapper (SAM)
☐   Support Vector Machine (SVM)
☐   Spectral Feature Fitting (SFF)

6 Goodbye!

Well done! You've learned a lot about imaging spectroscopy (or hyperspectral remote sensing) in the past lessons. Let's move on **with the final survey provided in this lesson**! The survey helps us to improve this course and will take you about 2 minutes.

Afterwards it will get serious...we want to test your knowledge with the Final Quiz!

> **Take the Final User Survey ONLNE**

6.1 Final User Survey

Thank you for taking the time to answer our final survey! The feedback provided by earlier participants really helped to provide additional information where requested and to improve the entire course. We are aiming to regularly review your answers and update the course accordingly.

> Please take the Final User Survey ONLINE!

6.2 Final Exam

Here we go, below you find the final quiz. If you've payed close attention in the previous lessons, you should be able to answer them easily. But even if you don't (answer easily), you have unlimited attempts to pass so don't get nervous.

> Please remember: in order to receive a certificate, you need to pass the **lesson quizzes (3)** as well as the **final quiz** in the ONLINE version of this course.

Final Quiz

In this final quiz for the MOOC we have prepared 15 questions for you. Remember, you have **unlimited attempts to pass the quiz**. Once you've completed the quiz with >**70% of correct answers** (online) you'll get your **certificate of completion along with a diploma supplement document** describing the course contents! Fingers crossed!

Oh … and don't forget to say goodbye and check our Making-Of!

Sort the wavelength ranges from short to long wavelengths! (Options: UV, VIS, Microwaves, TIR, SWIR, MIR, NIR)

Short wavelength	Choose an element
	Choose an element
	Choose an element
	Choose an element
	Choose an element
	Choose an element
Long wavelength	Choose an element

Can you identify some advantages of imaging spectroscopy data? (multiple-choice)

☐ The data contains a high level of spectral detail
☐ The data is very cheap to acquire
☐ The data allow for the retrieval of a range of different surface variables
☐ Analysis is much faster and easier compared to other types of remote sensing data

Remember the basic laws of radiation – which of the statements below is correct? (multiple-choice)

☐   All objects > 0 K emit radiant energy

☐   Hotter objects radiate more total energy per unit area than colder objects

☐   The hotter the radiant body, the shorter the wavelength of maximum radiation

☐   Perfect absorbers (perfect emitters) are called black holes

Which surface material has usually the lowest reflectance in the SWIR: (single-choice)

☐   Clear water

☐   Snow

☐   Dry vegetation

☐   Open soil

Which preprocessing steps should not be applied to hyperspectral data? (single-choice)

☐   Cosmetic correction

☐   Geometric correction

☐   Atmospheric correction

☐   Radiometric correction

What is a radiometric correction and what does it do? (multiple-choice)

☐   It transforms digital numbers to radiance

☐   It transforms digital numbers to reflectance

☐   It involves data resampling using nearest neighbor, bilinear interpolation or cubic convolution methods

☐   It involves a linear transformation in which correction coefficients (gain and offset) are applied to every image pixel

Why can it be useful to apply dimensionality reduction before or as part of actual image analysis? (multiple-choice)

☐   Because the human brain has difficulties with more than three dimensions

☐   Because it can speed-up processing and reduce computational costs

☐   Because hyperspectral data are often highly redundant and carry highly inter-correlated information

☐   Because redundant data introduce noise and may lead to suboptimal model performances

You have learned about different data resources in this course. Assign the following resources into the four categories (Fill in the blank)
Options: spaceborne (2x), airborne (2x), spectral library (2x)

EnMAP campaign portal

USGS EarthExplorer
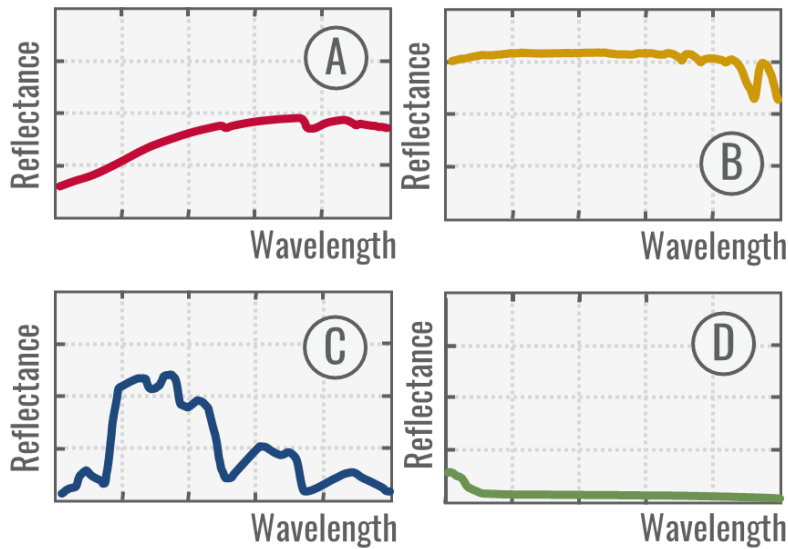
PRISMA data portal

AVIRIS NG

Specchio

ECOSTRESS

Which effect relates to spectral non-uniformities? (single-choice)

☐   The so-called „keystone" effect

☐   The so-called „smile" effect

Assign the correct categories to the following spectra

A   Choose an element

B   Choose an element

C   Choose an element

D   Choose an element

What is a so-called spectral "endmember" in remote sensing? (single-choice)

☐   a target or spectrum with a very low reflectance
☐   the last target or spectrum in a spectral library
☐   a target or spectrum of very high purity
☐   an unknown target or spectrum

What is the correct abbreviation of bi-directional reflectance distribution function? (single-choice)

☐   BRF

☐   BDRF

☐   BRDF

☐   BDRDF

Which factors influence the reflectance of vegetation? (multiple-choice)

☐   Moisture content

☐   Species

☐   Phenology

☐   Health

What is a Lambertian surface? (single-choice)

☐   An ideal specular reflector

☐   An ideal diffuse reflector

☐   A calibration target

☐   A perfect emitter

Which region of occuring absorption features is due to "vibrational processes" and which due to "electronic processes"? (Options: Distinct electronic prosses (e.g. Fe-bands), Vibrational bands (e.g. bound or unbound water (H_2O, $OH-$ and CO))
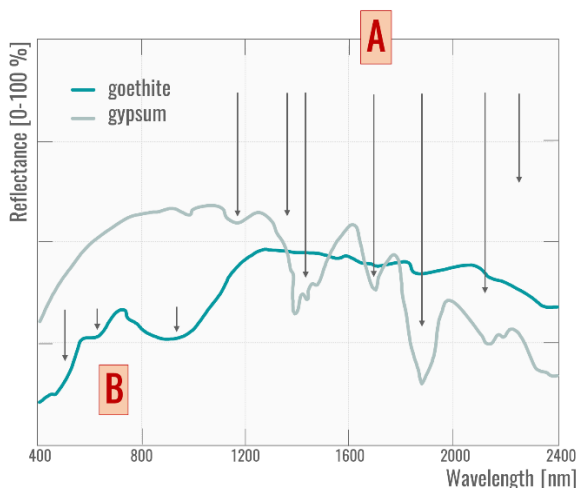

A   Choose an element

B   Choose an element

6.3 Goodbye!

Thank you for completing the entire MOOC on hyperspectral remote sensing! We hope you had as much fun in participating as we did in creating this course (and a comparably steep learning curve) and that you will become an active member of the hyperspectral community! You know, the data is complex and we need a lot of experts…

<div align="center">

VIDEO: Basic-25: Beyond the Visible – Goodbye!

URL of the video: https://www.youtube.com/watch?v=KfWYVZlu6tM

</div>
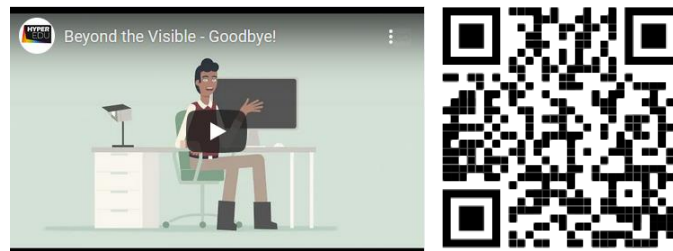
If you still **want to learn more, check out the resource sections of the lessons** where we have tried to link a lot of extra material and further reading. If you **want to practice, install the EnMAP-Box and check out the other tutorials**. Also, stay tuned for our follow-up MOOCs on specific applications.

How many people have been involved? Did you guess?

Oh, by the way, this MOOC was enabled with the know-how, creativity, and hard work of more than – can you guess? – brilliant people. Thanks to all of you!!!

NOW you finally get the chance to officially guess the number of people involved in the creation of this MOOC

- ☐ > 5
- ☐ > 15
- ☐ > 50
- ☐ > 35

6.4 Making of!

Really? The unbelievable number of more than 50 people were involved in the creation of this course (and that does not even include catering, location scouting and make-up)!

THANK YOU ALL for sharing your knowledge, material and precious time!

Watch the Making-of Video!

VIDEO: Basic-26: Beyond the Visible – Introduction to Hyperspectral Remote Sensing – The Making-Of!

URL of the video:
https://youtu.be/xHSsP3eAlUY

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MOOC Document

Beyond the Visible – Introduction to Hyperspectral Remote Sensing

Version: 1.0 (course version 3.0)