Hyperspectral Cal/Val Resources

by CEOS WGCV, October 2023

Introduction

This "Hyperspectral Cal/Val Resources" document was created following the request made to the CEOS for guidance on Cal/Val hyperspectral reference instrumentation (see actions: WGCV-51-ACT-13[1] and WGCV-51-ACT-14[2]) for: land, coastal and open ocean measurements with the aim of having a coordinated global network that is relevant across missions (e.g.: EnMAP, DESIS, PRISMA, SBG, CHIME, HISUI, EMIT, etc) with hyperspectral sensors on board. In this context can be noted that many multispectral focused resources apply equally to the hyperspectral domain.

By definition, a spaceborne hyperspectral imaging (or imaging spectroscopy) sensor is an advanced spaceborne optical sensor that captures high spectral resolution images of Earth's surface in many contiguous bands across the electromagnetic spectrum, typically between the visible to shortwave infrared wavelength ranges. These satellites provide diagnostic information on materials and substances on the ground based on their spectral signatures, allowing them to gather detailed biophysical information such as plant biochemicals, mineral composition and speciation, gaseous compositions, etc. The data collected by spaceborne hyperspectral imaging sensors are used in a wide range of applications, including environmental monitoring, agriculture, forestry, and non-renewable resources exploration and extraction.

The list of hyperspectral missions is growing rapidly with new missions being launched by countries around the world. The in-orbit missions include e.g.: PRISMA (Italy), DESIS and EnMap (Germany), HISUI (Japan), PACE (NASA), EMIT (JPL) and future missions are SBG (United States), Jilin-1 Hyperspectral Satellite (5m) (China), CHIME (ESA), etc. All types of optical imaging sensors have vague definitions with respect to their number of spectral bands.
In general Cal/Val activities for a Hyperspectral Mission will include the elements (Methods, Protocols and standards; Network and Instruments; Campaign; Intercomparison exercises and Cal/Val Analysis) sketched in the figure below:

[1] WGCV-51-ACT-13 Prepare a dedicated statement/area on hyperspectral/imaging spectroscopy/spectral radiometry for the WGCV Cal/Val Portal as a means for linking and or pointing to information, guidelines, networks, tools, etc. on this topic.

[2] WGCV-51-ACT-14 Cindy Ong and Philippe Goryl to coordinate a response to Ben Poulter (NASA) regarding his question on hyperspectral/imaging spectroscopy/spectral radiometry cal/val reference site instrumentation:
"...the need for guidance for hyperspectral cal/val reference site instrumentation. If CEOS could provide a document that described instrumentation for land, coastal, open ocean, types of instrumentation that would be relevant across missions (EnMAP, DESIS, PRISMA, SBG, CHIME, HISUI, etc) this would be really useful for having a global coordinated network."

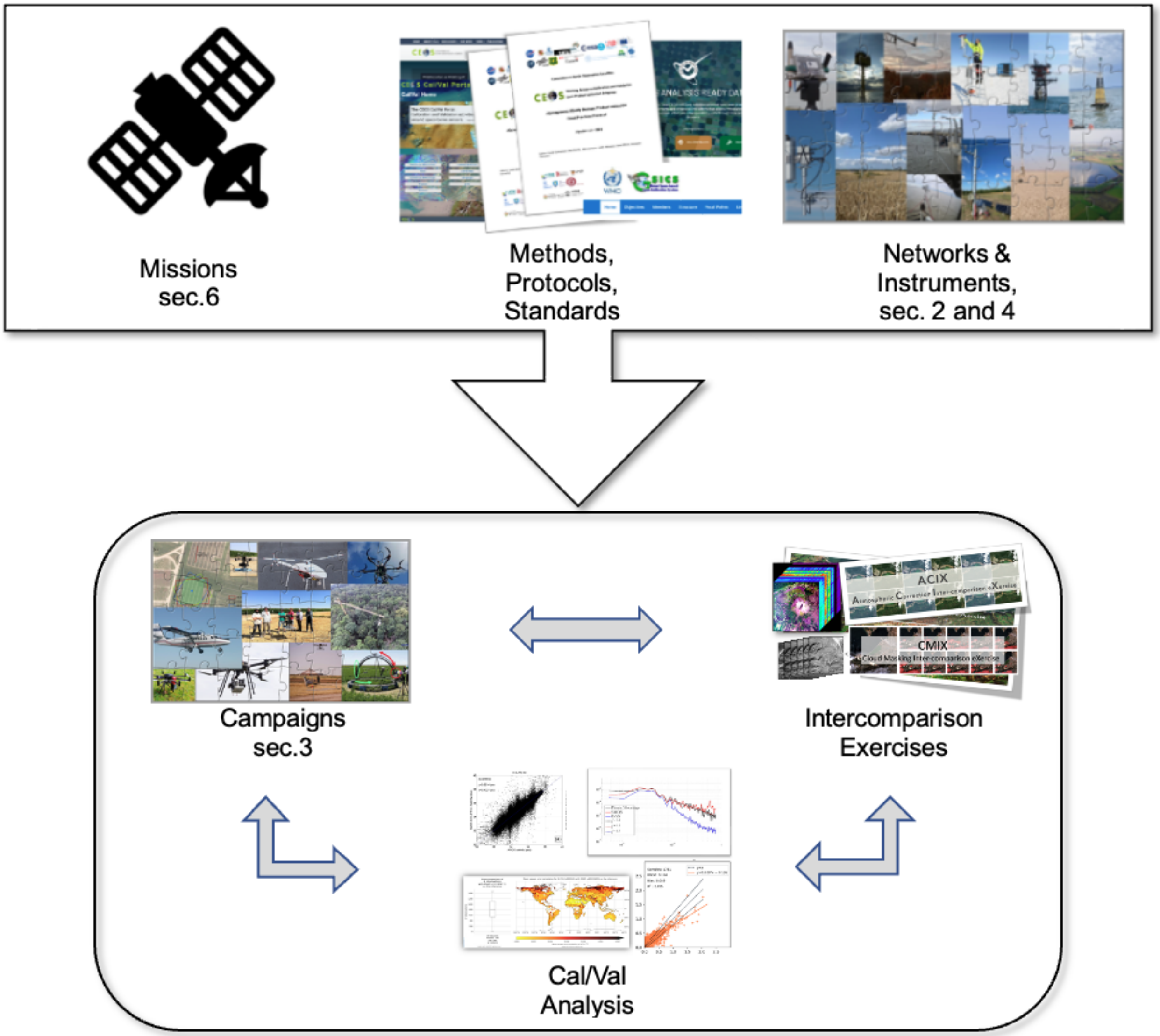

Figure 1: Workflow of typical Cal/Val tasks for a hyperspectral mission

Networks

Among all the Cal/Val activities, the ones based on permanent and automated instruments working in Network are probably the most efficient as it gives a large number of points well characterised against which the satellite measurements can compare.

Among the existing Networks, the following provide useful information for Hyperspectral imaging validation.

HYPERNETS

HYPERNETS[3] is a long-term activity, essential for the validation of not only satellite missions such as Proba-V, Sentinel-2A, 2B, 2C and 2D, Sentinel-3A, 3B, 3C and 3D, Landsat, and 'New Space' missions like the Pleiades and those from Planet, but also for hyperspectral satellites including the future Copernicus mission CHIME. HYPERNETS will provide validation data, including surface reflectance.

User needs for radiometric validation data were analysed in the H2020/HYPERNETS project and are summarised by Clémence Goyens, Ruddick, and Kuusk (2018), with a focus on spectral requirements. Briefly, these needs are summarised as:

- Water and land surface reflectance
- Hyperspectral from 380-1020 nm for water and additionally 1000-1700 nm or preferably 1000-2500 nm for land
- Temporal sampling of about 30 minutes, all day during the daytime
- Locations covering as wide a range of surface/atmospheric/sun conditions as possible including for water (oceanic/marine/coastal/inland), from oligotrophic to hypereutrophic, clear to extremely turbid, etc.
- Stated and validated uncertainty
- Directional water-leaving radiance reflectance should be provided for the acquired viewing geometry
- For land, hemispherical-directional surface reflectance should be provided at nadir and a range of zenith/azimuth with priority for azimuth directions perpendicular to line of flight of typical polar-orbiting sensors

Most of these user requirements can be accommodated by the HYPSTAR® and PANTHYR instruments, with the main exception being spectral coverage. PANTHYR is limited to 900 nm near-infrared spectral bands, which is suitable for water, but suboptimal for land while HYPSTAR® is limited to 1700 nm.

Responding to multi-mission radiometric validation needs is the essential aim of HYPERNETS. Providing water and land surface reflectance validation data to ESA, Copernicus Services and other users, across a diverse range of conditions and locations, for all VIS/NIR (400-900 nm) and SWIR1 (1000-1700 nm) spectral bands of all EO satellite missions[4].

[3] https://www.hypernets.eu
[4] https://www.hypernets.eu/from_cms/summary

A pre-operational federated worldwide network is being implemented. This consists of hyperspectral radiometers on pointing systems with automated data acquisition and transmission to the network central processor and automated data processing and public web distribution of surface reflectance and associated uncertainty estimates and quality flags. The proper characterisation of the measurements, following metrology principles[5], allows HYPERNETS to meet the requirements to be considered a Fiducial Reference Measurement (FRM).

RadCalNet

RadCalNet[6] is an initiative of the CEOS Working Group on Calibration and Validation (WGCV). RadCalNet provides satellite operators with SI-traceable Top-of-Atmosphere (TOA) spectrally-resolved reflectances to aid in the post-launch radiometric calibration and validation of optical imaging sensor data, including from hyperspectral sensors.

The network consists of the following instrumented reference test sites[7]:

- University of Arizona's site at Railroad Playa, Nevada, USA,
- AIR's site at Baotou, China,
- the CNES site at La Crau, France,
- the ESA/CNES site in Gobabeb, Namibia,
- the new AIR sandy site at Baotou, China.

These test sites provide nadir-view top-of-atmosphere reflectance, with associated uncertainties, at 30 minute intervals from 9 am to 3 pm local standard time at 10 nm spectral intervals from 400 nm to 2500 nm. This is calculated from ground nadir-view reflectance measurements and atmospheric measurements such as surface pressure, columnar water vapour, columnar ozone, aerosol optical depth and the Angstrom coefficient. Correction to top-of-atmosphere is performed for all sites in the same way, using Modtran.

Each individual site is equipped with automated ground instrumentation in order to provide continuous measurements of both surface reflectance and local environmental/atmospheric conditions needed for the derivation of TOA reflectance values.

TOA reflectances provided from the RadCalNet portal are derived from the individual sites surface and atmosphere measurements using a common method through a central processing system. Each member site takes responsibility for the quality assurance of the surface/atmosphere measurements provided and is subject to peer review and rigorous comparison to ensure site-to-site consistency and SI traceability.

PICs

Pseudo Invariant Calibration Sites (PICS)[8] are terrestrial sites used to monitor long-term in-flight radiometric calibration of Earth Observation optical sensors. Spatial agencies have been using these sites extensively for a considerable amount of time due to their highly uniform spatial characteristics, spectral

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5 https://ieeexplore.ieee.org/document/9553738

6 https://www.radcalnet.org

7 https://doi.org/10.3390/rs11202401

8 https://calvalportal.ceos.org/web/guest/pics_sites

stability, and temporal invariance. A large number of these sites have been identified, with many located in the Sahara desert and the Arabian Peninsula, and are listed in the USGS catalog. Among these sites, six have been endorsed by CEOS as standard reference sites for the calibration of space-based optical imaging sensors after their launch, as announced during the CEOS IVOS-19 meeting in Phoenix, Arizona.

Two projects related to the usage of PICS are PICSCAR and PICSAND. PICSCAR is the study initiated by CNES and Magellium under CEOS to coordinate and prioritize research on PICS. Information on the six endorsed PICS has been collected, and tools to monitor sensor stability using PARASOL BRDF are available. Radiometry monitoring results of Landsat 8/OLI vs S2A/MSI sensors over Libya 4 site are updated every six months and made accessible to users through the PICSCAR website.

PICSAND is an ESA study led by NOVELTIS supported by Office National d'Etudes et de Recherches Aérospatiales (ONERA) and Le Laboratoire des Sciences du Climat et de l'Environnement (LSCE). PICSAND data are made public with the aim to support the reduction of uncertainties in radiometric monitoring methodologies. The study includes revisiting the list of PICS over desert areas, collecting sand samples from an ensemble of identified sites, analysing their physical and optical properties in laboratory, assessing the performance of BRDF models to fit sand spectro-directional measurements, building a sand optical properties database, and determining a climatology of aerosol and atmospheric conditions over the PICS. The PICSAND database is available online through the PICSAND portal, and the final reports of the study can be found on the PICS reports webpage[9].

CEOS-LPV Supersites

The Land Product Validation (LPV) sub-group of the CEOS Working Group on Calibration Validation (WGCV) has identified a new set of sites, named "CEOS-LPV supersites", useful for the validation of satellite-derived land products[10]. This is a selection of sites that satisfy a number of criteria:

- Super characterized (canopy structure and bio-geophysical variables) site following well-established protocols useful for the validation of a number of satellite-derived land products (at least 3) and for 3-D radiative transfer modeling approaches.
- Active, long-term operations, supported by appropriate and sustained funding and infrastructural capacity.
- Supported by airborne LiDAR and hyperspectral acquisitions (desirable).

The CEOS-LPV supersites were primarily selected from well-known and established ground-based networks (e.g., ICOS, NEON, TERN, GBOV). All proposed sites were evaluated for their suitability by ranking them first based on the availability of data (active site) and their spatial representativeness. The sites were additionally classified, based on how many key variables could be validated within a given location, whether structural 3-D information was available for the site and if atmospheric and other ancillary measurements were performed. This process resulted in the selection of 55 globally spread supersites, which were endorsed at CEOS-WGCV level. Some of the examples of networks where these supersites are sources from include the examples below.

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9 https://calvalportal.ceos.org/pics-reports

10 https://lpvs.gsfc.nasa.gov/LPV_Supersites/LPVsites.html

GBOV

GBOV (Ground-Based Observations for Validation)[11], as part of the Copernicus Global Land Service (see below), aims at facilitating the use of observations from operational ground-based monitoring networks and their comparison to Earth observation products through the following objectives:

- Collection of multi-year ground-based observations of high relevance for the understanding of land surface processes from existing global networks. These ground-based observations (Reference Measurements; RMs) are collected over a series of selected sites organised through international research networks.
- Upgrading existing sites with new instrumentation or establishing entirely new monitoring sites to close thematic or geographic gaps. This part of the project will be implemented in the second phase.
- Implementation and maintenance of a database for the distribution of reference measurements (RMs) and the corresponding Land Products (LPs). The focus of GBOV is on providing the information required for in-depth quality assessment of the products offered through the global component of the Copernicus Land Monitoring Service (CLMS), i.e. the Copernicus Global Land Service (CGLS).

The GBOV service primarily serves to ensure the quality control of the core Copernicus land products (top-of-canopy reflectances, surface albedo, fAPAR, LAI, fCover, LST and soil moisture) providing collections of multiple years of ground-based RMs and derived Land Products (LPs). The information offered through GBOV may also be used for a wide range of applications beyond the CGLS. Such external use will be supported by the GBOV data policy granting free and unrestricted access after online registration.

TERN

TERN[12] [10] is Australia's land ecosystem observatory. TERN measures key terrestrial ecosystem attributes over time from continental scale to field sites at hundreds of representative locations and openly provides model-ready data that enables researchers to detect and interpret changes in ecosystems. Among others, TERN is composed of 13 landscapes cal/val sites providing: field survey datasets, airborne datasets, corrected surface reflectance products, and other environmental and landscape research data such as solar radiation, rainfall, and water vapour pressure. The data are procured following the *Effective Field Calibration and Validation Practices*[13] [11] handbook that gives details on how to correct and check remotely sensed data products to ensure they can be used for science and management applications.

NEON

The National Science Foundation's National Ecological Observatory Network (NEON)[14] provides open data from 81 field sites located in different ecosystems across the United States (US). Data collection methods

[11] https://gbov.acri.fr
[12] https://www.tern.org.au/
[13] https://www.tern.org.au/field-survey-apps-and-protocols/
[14] https://www.neonscience.org/

are standardized across the sites and include automated measurements, observational field sampling and airborne remote sensing surveys. The NEON data catalog includes over 175 data products, providing key information about plants, soil, freshwater and the atmosphere. The validation of vegetation variables, i.e., fAPAR, LAI, fCover, within GBOV mostly relies on NEON data.

ICOS

The Integrated Carbon Observation System (ICOS)[15] is a pan-European network aiming at quantifying and understanding the greenhouse gas balance of Europe and neighboring regions. ICOS infrastructure includes more than 100 measurement stations in twelve European countries. These stations measure greenhouse gas concentrations in the atmosphere and fluxes over the terrestrial and marine ecosystems. ICOS measurements include bio-geophysical variables, which are useful for validation of satellite-derived land products, such as fAPAR, LAI, plant traits and surface radiation parameters. All measurements at the Ecosystem stations are strongly standardized, utilizing similar or the same methodologies and equipment. Despite the value of this ecosystem network, ICOS is still not fully exploited for satellite validation. An effort is currently on-going within CEOS-LPV and GBOV to work towards enhanced use of this data within the satellite Cal/Val community.

EUFAR

EUFAR[16] is a Pan-European Portal and Network for Airborne Research Infrastructure dedicated to Environmental Science. EUFAR was born out of the necessity to create a central network for the airborne research community in Europe with the principal aim of supporting scientists by granting them access to research aircraft and instruments otherwise not accessible in their home countries. In this way, scientists all over Europe can have an equal opportunity to carry out various atmospheric and in situ measurements onboard research aircraft. In essence, EUFAR links scientists with operators of research facilities and financially supports this collaboration by providing funding for flight hours as well as for travel and subsistence during campaigns.

Over time EUFAR has grown, introducing new activities and objectives to make itself a unique network and portal of airborne research for the environment and geosciences in Europe. From organising summer schools and expert workshops, and serving as an interactive and dynamic hub of information, to maintaining a central data archive, and developing tools and standards to collect, process and analysis data, EUFAR continues to improve the operational environment for conducting airborne research.

EUFAR seeks to:

- Facilitate and promote transnational access to national research aircraft and instruments
- Reduce redundancy, fill the gaps, and optimise the use and development of airborne facilities to conduct research
- Improve the quality of the service by strengthening expertise through knowledge exchange, development of standards and protocols, the constitution of databases, and joint instrumental research activities

[15] https://www.icos-cp.eu/observations/ecosystem/stations

[16] https://www.eufar.net/

- Promote the use of research facilities, especially for young scientists from countries where such facilities are lacking, by providing education and training opportunities in airborne research
- Support both market pull and technology push driven innovation in airborne research, and develop a culture of cooperation between EUFAR experts and SMEs to transfer airborne research instruments, methodologies and software into new products.

Ocean Sites

The following networks are relevant for marine cal/val activities in the multispectral and hyperspectral domain: Boussole[17]; Moby[18]; AERONET Ocean Color[19]; FRM4SOC Phase 1[20] and FRM4SOC Phase-2[21]

Guidelines and Protocols

CEOS-LPV Protocols

In order to address the issue of disparity in the currently used Cal/Val practices, the CEOS WGCV LPV sub-group is defining standardized approaches for in situ measurements, sampling and upscaling procedures. The definition of CEOS-LPV best practices started in 2014 with the first protocol, and it now includes endorsed protocols for the following variables: LAI, Albedo, Above Ground Woody Biomass, Soil Moisture and Land Surface Temperature[22]. The definition of CEOS-LPV protocols for other land products, in particular land cover, fire/burned areas, vegetation indices is currently on-going and a first version of these documents is expected to be finalized during 2023.

The definition of a Cal/Val protocol is a laborious and collective work, involving contributions from a large team of internationally recognised scientific experts. When a protocol is issued and endorsed at CEOS WGCV level, it has to be promoted and agreed upon by the relevant science community. This is a long process, and the Space Agencies should contribute to broadening consensus. A side effect of this lengthy process is that a protocol may become obsolete, notably in case of latest technological or theoretical advances in the relevant domain. Hence, the protocols should be considered living documents that need to be periodically reviewed and updated in case of major advances in the field.

FRM4Veg Protocols

The Fiducial Reference Measurements for Vegetation (FRM4Veg) project was initiated by ESA in 2018[23] with the objective of establishing the protocols required for traceable in-situ measurements of satellite-derived surface reflectance and vegetation products. In this respect, FRM4Veg contributes to CEOS-LPV endeavor in defining best practices for Cal/Val in the land domain with a reinforced focus on the need of

17 http://www.obs-vlfr.fr/Boussole/html/project/introduction.php
18 https://mlml.sjsu.edu/moby/
19 https://seabass.gsfc.nasa.gov/wiki/AERONET-OC
20 https://frm4soc.org/
21 https://frm4soc2.eumetsat.int/
22 https://lpvs.gsfc.nasa.gov/documents.html
23 https://frm4veg.org/

traceability, ideally to SI units, and a metrologically-sound uncertainty estimate, following the FRM generic principles.

The first phase of FRM4Veg project was concluded at the end of 2019 with the elaboration of initial best practices for in situ measurements and methodologies for validation of satellite-derived SR, fAPAR and Chlorophyll content products. This first phase also included the preparation and execution of two field campaigns over two vegetated sites in Europe in the Wytham Woods forest site (UK) and the Barrax agricultural site (Spain). These sites are compliant to FRM generic principles since they are well characterized and the field measurements within these sites are traceable and follow well-established best practices. A detailed uncertainty budget could therefore be reliably estimated for the validation of satellite-based geophysical products over these sites. An example of such an approach was demonstrated in a recent paper, focusing on the validation of S2 and Proba-V SR products over Barrax cropland site[24]. This paper demonstrated that the adoption of metrological Cal/Val practices for uncertainty characterisation allows for properly evaluating the statistical consistency of satellite and in situ data and to assess the quality of the stated uncertainties.

CEOS WGCV SR Validation Protocol

Details on the Surface Reflectance Validation protocol is available on a technical handbook named "A community approach to the standardised validation of surface reflectance data"[25]. This handbook provides guidelines for systematically collecting field spectroscopic data to validate surface reflectance satellite products on a large regional scale, specifically in Australia but the principles are directly applicable for other areas/regions. The goal is to establish a comprehensive, long-term approach to monitoring and quantifying the accuracy and uncertainties of national as well as continental scale surface reflectance validation data. The document also outlines the process and method of archiving data to ensure its reliable and relevant extraction by future users, promoting the continued effective use of legacy data. Researchers can contribute to a standardized and systematic approach for validating surface reflectance satellite products, building a network of validation reference sites, and creating a valuable and enduring archive of hyperspectral data by using this handbook as a guide.

CEOS endorsed reference solar irradiance spectrum

For many Earth Observation based applications there is a need to utilise a solar irradiance spectrum. This may be as part of a bio-geo-physical 'retrieval' of some form, use of a Radiative transfer code in some way or a conversion in units e.g. radiance to reflectance. In most cases for any self-contained application the most important requirement is, to be consistent in the choice of any exo-atmospheric solar irradiance spectrum and to be clear, in any subsequent documentation describing any result of its use, which spectrum and version was used. In this way, it allows others, in principle to be able to convert and compare similar results which may use different solar Irradiance spectrum. However, following requests from both the user community and satellite operators and developers, CEOS in the early 2000's decided to establish

[24] Origo, N. et al. Fiducial Reference Measurements for validation of Sentinel-2 and Proba-V surface reflectance products. Remote Sens. Environ. 2020, 241, 111690.

[25] https://doi.org/10.25919/5c9d0ba9e9c12

a CEOS endorsed reference solar Irradiance spectrum, based on a community consensus of the 'best' observational spectrum available. In 2003,e this was a composite spectrum, heavily based on a spectrum from the SOLSPEC mission.[26]. In 2022, following results of new satellite missions, particularly the NASA TSIS-1 mission, which provided significantly reduced uncertainty, it was decided to revise the CEOS reference solar irradiance spectrum to that of Coddington et al (2021)[27] (please visit the dedicated page[28] in the CEOS Cal/Val Portal) and later to a version 2 which extends the spectral range to thermal infrared in Coddington et al (2023)[29].

Campaigns and Inter-comparison Exercise

CEOS-LPV DIRECT Database

The DIRECT V2.1 database[30]includes LAI, fAPAR and FCover averaged values over a 3 km x 3 km area, useful for the validation of satellite-derived coarse resolution land products. The ground data was upscaled using high spatial resolution imagery following CEOS WGCV LPV LAI good practices to properly account for the spatial heterogeneity of the site. Ground measurements were resulting from several international field campaigns, including VALERI, BigFoot, SAFARI-2000, CCRS, Boston University and ESA campaigns compiled by S. Garrigues[31], and later ingested in the CEOS WGCV LPV OLIVE tool[32] for accuracy assessment. F. Camacho reviewed DIRECT to remove those sites without understory measurements[33] and expanded the database with more recent ImagineS sites[34]. The DIRECT Version 2.1 is the latest update including 44 new validation cropland sites from China[35] and two sites from the ESA FRM4Veg project[36].

The CEOS WGCV LPV DIRECT V2.1 database constitutes a major effort of the international community to provide ground reference for the validation of LAI and fAPAR ECVs, with a total of 176 sites around the world (7 main biome types) covering the period from 2000 to 2021. The database can be accessed through the CEOS Cal/Val portal at: https://calvalportal.ceos.org/web/guest/lpv-direct-v2.1

[26] https://doi.org/10.1023/A:1024048429145
[27] https://doi.org/10.1029/2020GL091709
[28] https://calvalportal.ceos.org/web/guest/tsis-1-hsrs
[29] https://doi.org/10.1029/2022EA002637
[30] https://calvalportal.ceos.org/documents/10136/844617/CEOS_LPV_OLIVE_DIRECTV2.1.xlsx/75245750-5496-44f1-b723-8544090ea809
[31] Garrigues, S. et al. (2008). Validation and intercomparison of global leaf area index products derived from remote sensing data. J. Geophys. Res. 2008, 113, G02028.
[32]Weiss et al., (2014). On Line Validation Exercise (OLIVE): A Web Based Service for the Validation of Medium Resolution Land Products. Application to FAPAR Products. Remote Sens, 6, 4190-4216
[33] Camacho, F. et al. (2013). GEOV1: LAI, FAPAR essential climate variables and FCOVER global time series capitalizing over existing products. Part 2: Validation and intercomparison with reference products. Remote Sens. Environ, 137, 310–329.
[34] Camacho, F. et al. (2021). Crop specific algorithms trained over ground measurements provide the best performance for GAI and fAPAR estimates from Landsat-8 observations. Remote Sens. Environ, 260, 112453.
[35] Fang, H. et al., (2019). Validation of global moderate resolution leaf area index (LAI) products over croplands in northeastern China. Remote Sens. Environ., 233, 111377.
[36] Brown, L.A. et al (2021). Fiducial Reference Measurements for Vegetation Bio-Geophysical Variables: An End-to-End Uncertainty Evaluation Framework. Remote Sens, 13, 3194.

SRIX4Veg

SRIX4VEG (Surface Reflectance Intercomparison Exercise for Vegetation)37 is contributing towards global community-agreed guidelines for UAV-based surface reflectance product validation.

Hyperspectral information collected from UAVs is expected to become a major source of surface reflectance (SR) validation data in the near future. Unlike traditional SR validation data collection, an existing good practice protocol does not currently exist that considers data collection from UAVs. As such, SRIX4VEG was initiated in the frame of the CEOS Working Group on Calibration and Validation (WGCV) to put forward a good practice protocol that is jointly determined by the participants through a dedicated campaign [38] and a series of *workshops* [39]. The campaign is based on two core experiments where each participant collects data according to their own methods and follows a provisional protocol. In each experiment every participant flies sequentially to every other participant (i.e., a round robin) to ensure that each pair of data is as comparable as possible. The variability of the outputs of each experiment determines the need for a dedicated protocol, while each participant puts forward recommendations on what the final protocol should look like, thereby reaching a community consensus.

ACIX

ACIX[40] is an initiative that brings together the developers of Atmospheric Correction (AC) processors, who are invited to generate Bottom-Of-Atmosphere (BOA) products from Top-Of-Atmosphere (TOA) optical satellite data. It is a collaborative activity of ESA (European Space Agency) and NASA (National Aeronautics and Space Administration) that was initiated in 2016 in the frame of CEOS WGCV. ACIX has been implemented twice on multispectral Copernicus Sentinel-2 and Landsat 8 imagery. More information on the latest analysis and the results can be found on the dedicated web pages for the Land [41] and Aqua[42] focused part of the exercise.

In parallel with ACIXs, a Cloud-Masking Inter-comparison exercise (CMIX) runs over specific areas with reference data available. Similar to ACIXs, the focus of the first CMIX was on open and free imagery acquired by the Copernicus Sentinel-2 (EC/ESA) and Landsat 8 (NASA/USGS) missions. More information on the first CMIX implementation can be found here[43].

Considering the great scientific and users' interest, a third ACIX and second CMIX implementations have been proposed which also includes the hyperspectral data from PRISMA and EnMAP. The data acquired for the exercise encompass a global subset of AERONET and RadCALNET sites, together with Hypersense Campaign match-ups over Europe. Multispectral data of Sentinel-2 and Landsat 8 will still be part of the ACIX-Aqua and CMIX analysis. ACIX-Land will focus only on hyperspectral data, as it was considered unnecessary to repeat the exercise for multispectral data at the moment. The decision is mainly based on

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37 https://frm4veg.org/srix4veg/
38 https://frm4veg.org/srix4veg/campaign-information/
39 https://frm4veg.org/srix4veg/workshop-1/
40 https://calvalportal.ceos.org/projects/acix
41 https://calvalportal.ceos.org/acix-ii-land
42 https://calvalportal.ceos.org/acix-ii-aqua
43 https://calvalportal.ceos.org/cmix

the unavailability of any new reference data to the ones used in the previous exercises. Participation in ACIXs and CMIX is open to all the scientists who:

- are the original developers of the atmospheric correction and/or cloud-masking processor to be inter-compared,
- are authorised by the original developer to run the AC/CM processor on his/her behalf,
- agree on submitting the AC/CM processing results within the required constraints (deadline, format, etc.).

HyperSense Campaign

To best prepare CHIME/SBG[44] for its tasks ahead, and as part of a cooperation between ESA and NASA's Jet Propulsion Laboratory (JPL), the Hypersense campaign, managed by the University of Zurich, made use of the Next Generation Airborne Visible Infrared Imaging Spectrometer, AVIRIS[45], an instrument which resembles the capabilities that CHIME will have once in orbit.

Measurements taken with AVIRIS over more than 20 test sites that represent different types of ecosystems are helping scientists and engineers prepare for and ensure that CHIME will be able to take up the duty of delivering high-quality diagnostic and quantitative data as soon as it is in orbit and operational. Most of these flights coincided with measurements (SR & derived products related vegetation, vegetation, water, minerals, etc) taken on the ground to further help evaluate the data collected by the airborne instrument. The ground SR data acquisition was performed based on CEOS WGCV SR validation protocol.

Instrumentation and Hardware

ASD FieldSpec Range

For over more than 25 years ASD has provided one of the most trusted field-portable UV/Vis/NIR/SWIR spectroradiometers covering the full solar reflected spectrum. The latest version of this spectroradiometer family is the ASD FieldSpec 4[46], designed specifically around the challenges researchers face when collecting spectral measurements in the field. These spectrometers can be used on a variety of key applications including: sensor calibration, spectral remote sensing, ground truthing, etc. A detailed product specification in shown below (excerpt from brochure[47]).

[44] https://ares-observatory.ch/esa_chime_mission_2021
[45] https://aviris.jpl.nasa.gov/
[46] https://www.malvernpanalytical.com/en/products/product-range/asd-range/fieldspec-range
[47] https://www.malvernpanalytical.com/en/assets/PN12276_BR_ASD_Fieldspec%204%20brochure%20EN_tcm50-61709.pdf

Performance Specifications	Standard-Res	Hi-Res	Hi-Res NG
Wavelength range	350 nm – 2500 nm		
Resolution VNIR @ 700 nm	3 nm		
Resolution SWIR @ 1400 & 2100 nm	10 nm	8 nm	6 nm
Spectral Sampling (Bandwidth) VNIR @ 700 nm	1.4 nm		
Spectral Sampling (Bandwidth) SWIR @ 1400 & 2100 nm	1.1 nm		
Scanning time	100 milliseconds		
NEdL (Noise Equivalent Radiance) - VNIR @ 700 nm	1.0×10^{-9} W/cm²/nm/sr		
NEdL - SWIR 1 @ 1400 nm	1.2×10^{-9} W/cm²/nm/sr	1.4×10^{-9} W/cm²/nm/sr	8.0×10^{-9} W/cm²/nm/sr
NEdL - SWIR 2 @ 2100 nm	1.9×10^{-9} W/cm²/nm/sr	2.2×10^{-9} W/cm²/nm/sr	8.0×10^{-9} W/cm²/nm/sr
Wavelength reproducibility	0.1 nm		
Wavelength accuracy	0.5 nm average error of wavelength calibration fit. Wavelength accuracy +/- 1 nm for any one line		
Maximum radiance - VNIR	2x Solar		
Maximum radiance - SWIR	10x Solar		
Data collection speed	2 spectra per second		
Channels	2151		
VNIR (350-1000 nm) detector	512 element NIR-enhanced silicon array		
SWIR 1 (1000-1800 nm) detector	Graded Index InGaAs Photodiode, 2 Stage TE Cooled		
SWIR 2 (1800-2500 nm) detector	Graded Index InGaAs Photodiode, 2 Stage TE Cooled		
Input	1.5 m fiber optic (25° field of view); optional fore optics available		
Weight	5.44 kg (12 lbs.)		
Calibrations	Wavelength, absolute reflectance, radiance*, irradiance*. All calibrations are NIST traceable. (*radiometric calibrations are optional)		
Instrument Controller	Dell Latitude 5490 or other Windows 10 compatible laptop		
Warranty	One-year full warranty including expert customer support		
Storage temperature (°C)	-15 - 45		
Operational temperature range (°C)	0 - 40		

Spectral Evolution

Spectral Evolution[48] designs, manufactures, and services high resolution, high sensitivity, full range UV-VIS-NIR spectrometers and spectroradiometers. These instruments are used around the world for various lab and field assignments. They feature 100% photodiode array construction for low noise and reliable battery operated performance, fast, full spectrum measurements with no moving gratings and integral dark shutter and autoexposure for one-touch scanning.

Field Portable Spectroradiometers for Remote Sensing is one of the products manufactured by Spectral evolution. These are portable devices used for remote sensing. It offers fast and comprehensive measurements across the UV-VIS0NIR spectrum range (350-2500nm) in a single scan. The PSR-1100f model specifically covers the range of 320-1100nm. They are calibrated to NIST-traceable standards, ensuring accurate radiance and irradiance measurements. Typical applications of this device include ground truthing, soil analysis, environmental measurements, remote sensing research, forest canopy studies, and vegetation research.

[48] https://spectralevolution.com/

Some models available in this product line are the SR-6500 and SR-6500A, PSR+, RS-3500, NaturaSpec™, RS-8800, and PSR-1100f.
Compact Spectroradiometers is another device that Spectral Evolution manufactures. These devices have functions such as auto-exposure, autoscaling, and auto dark shutter, and are known to enable fast, accurate, and one-touch scans. Typical applications for these devices include remote sensing, radiometric calibration transfer, solar simulator test and measurement, radiance/irradiance measurement, as well as simultaneous upwelling/downwelling measurement.

SVC

Spectra Vista Corporation (SVC)[49] is a company that specialises in building good quality spectroradiometers. These devices feature array detectors that capture spectral data accurately. The optical design of the devices is optimised to maximise the amount of light collected and sent to the detectors, ensuring accurate and reliable measurements. There are various instrument models offered by SVC such as XHR-1024, HR-1024i, HR-768si, HR-768i, HR-640i. HR-512i. These are high resolution and very high resolution instruments designed for application requiring VNIR ranging from 350nm-1890 nm. More information can be viewed from the company's website.

Hypstar

HYPSTAR® (HYperspectral Pointable System for Terrestrial and Aquatic Radiometry)[50] is an autonomous hyperspectral radiometer system dedicated to surface reflectance validation of all optical Copernicus satellite data products. HYPSTAR takes radiance and irradiance measurements.
A HYPSTAR system comprises of an advanced hyperspectral VNIR spectrometer, an optional SWIR spectrometer, a simple RGB imaging camera alongside hyperspectral measurements, a relative calibration LED source, a pan-tilt mechanism, auxiliary sensors (pressure, humidity, temperature, rain, light, two external cameras), site-dependent accessories (designed mounting frames, carry cases, fixations, designed from commercial off-the-shelf equipment, etc.) and a standardised data stream for easy and systematic exploitation by downstream validation networks WATERHYPERNET[51] and RADCALNET.
Once operated on the fields, a HYPSTAR system is integrated into the WATERHYPERNET or RADCALNET network dedicated to satellite validation, or may be operated independently. The networks automatically acquire measurements from the sites in near real-time, and provide the result data with associated uncertainties evaluated according to ISO/GUM. The uncertainty estimation closely follows the work of the FRM4SOC and FRM4VEG projects, where HYPSTAR scientists are coordinators and partners.
The system is available in two versions: HYPSTAR-SR for deployments on water sites and HYPSTAR-XR for deployments on land sites. They have been rigorously tested in diverse and challenging conditions as regards application (water, land), platform (fixed structure, research crane), environment (cold/ hot, wet/ dry, calm/ windy, biofouling, etc.), and logistics (accessible/ remote, standalone/ heavily instrument site, well-protected/ vulnerable to humans, etc.) during the H2020/HYPERNETS project.

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49 https://spectravista.com/
50 https://hypstar.eu/
51 https://frm4soc.org/

There are twelve HYPSTAR-SR and HYPSTAR-XR prototypes deployed at Acqua Alta Oceanographic Tower (Italy), Río de la Plata (Argentina), and Wytham Woods (The UK), with plans for further testing and deployment in 2023.

For latest updates and news regarding the deployments please follow the Twitter page **@Hypernets_H2020**

The HYPSTAR systems are commercialised by the RSware Limited company based in Tartu, Estonia. For more information, please contact rsware.ou@gmail.com.

PANTHYR

The pan-and-tilt hyperspectral radiometer system, PANTHYR[52] is designed for autonomous measurement of hyperspectral water reflectance to fit the following user requirements:

- Measurement of downwelling irradiance, as well as downward (sky) and upward (water) radiance just above the water surface, at flexible zenith and azimuth (relative to sun), angles for a spectral range covering at least 400–900 nm with full-width half-maximum (FWHM) spectral resolution of 10 nm or better and spectral sampling every 5 nm or better.
- Storage of all measurements and diagnostic logs and regular transmission to a land-based server.
- User interface with flexibility for scientists to easily program pointing and data acquisition scenarios.
- Reliable autonomous operation at remote sites, e.g., offshore platforms, with a typical maintenance frequency of once or twice per year without grid power.
- Resistance to harsh offshore environments, including large temperature ranges (measurement limited to between 2 °V and 40 °C, and survival between −20 °C and 60 °C ambient temperature), rain, salty sea spray, atmospheric deposition, and possible animals (birds, spiders, etc.).
- Modularity to adapt to sites with different possibilities for power (grid/solar/wind), data transmission channels (cabled internet, 3G/4G cellular networks), and mechanical mounting possibilities (rails, masts, etc.), and to cope with future evolution of system components.
- Moderate hardware purchase costs, e.g., typically <10,000 € commercial price excluding taxes for a full system excluding radiometers.
- Pointing accuracy of at least 5° azimuth and 1° zenith.

HySpex VNIR-1800

The HySpex VNIR-1800[53] hyperspectral camera is developed for field, laboratory, and airborne applications. It utilises an actively cooled and stabilised scientific CMOS detector. The dynamic range of 20000 ensures high SNR levels even in darker areas of an image of highly dynamic scenes.

[52] https://www.mdpi.com/2072-4292/11/11/1360
[53] https://www.hyspex.com/hyspex-products/hyspex-classic/hyspex-vnir-1800/

MAIN SPECIFICATIONS	
Spectral range	400 - 1000 nm
Spatial pixels	1800
Spectral channels	186
Spectral sampling	3.26 nm
FOV*	17°
Pixel FOV across/along*	0.16/0.32 mrad
Bit resolution	16 bit
Noise floor	2.4 e-
Dynamic range	20000
Peak SNR (at full resolution)	> 255
Max speed (at full resolution)	260 fps
Power consumption	30 W
Dimensions (l-w-h)	39 - 9.9 - 15 cm
Weight	5.0 kg
Camera Interface	CameraLink

*Can be doubled with FOV expander

HySpex VNIR-3000N

HySpex VNIR-3000N[54] utilises the same spectrograph as the other HySpex VNIR models. It has a pixel size of 3.45 µm, compared to 6.5 µm for VNIR-1800, HySpex VNIR-3000 N has less than 1.6 pixels per FWHM of the PSF spatially and less than 1.8 bands spectrally, ensuring that narrow band features will be resolved equally for all cameras. With 3000 spatial pixels, 300 bands and a noise floor of 2.4e-.

[54] https://www.hyspex.com/hyspex-products/hyspex-classic/hyspex-vnir-3000-n/

MAIN SPECIFICATIONS	
Spectral range	400-1000 nm
Spatial pixels	3000
Spectral channels	300
Spectral sampling	2.0 nm
FOV*	16º
Pixel FOV across/along*	0.096/0.32 mrad
Bit resolution	12 bit
Noise floor	2.37 e-
Dynamic range	11000
Peak SNR (at full resolution)	> 170
Max speed (at full resolution)	117 fps
Power consumption	30 W
Dimensions (l–w–h)	39 – 9.9– 15 cm
Weight	5.0 kg
Camera Interface	USB3

*Can be doubled with FOV expander

HySpex SWIR-384

The HySpex SWIR-384[55] hyperspectral camera is developed for field, laboratory, and airborne applications. The state of the art MCT sensor is cooled down to 150K yielding low background noise, high dynamic range, and high SNR levels.

HySpex SWIR-640

The HySpex SWIR-640[56] hyperspectral camera is developed for field, laboratory, and airborne applications. The state of the art MCT sensor is cooled down to 150K using a sterling cooler, yielding low background noise, high dynamic range, and high SNR levels.

MAIN SPECIFICATIONS	
Spectral range	960-2500 nm
Spatial pixels	640
Spectral channels	360

55 https://www.hyspex.com/hyspex-products/hyspex-classic/hyspex-swir-384/
56 https://www.hyspex.com/hyspex-products/hyspex-classic/hyspex-swir-640/

Spectral sampling	4.38 nm
FOV*	16°
Pixel FOV across/along*	0.44/0.44 mrad
Bit resolution	16 bit
Noise floor	80 e-
Dynamic range	7500
Peak SNR (at full resolution)	> 800
Max speed (at full resolution)	230 fps
Power consumption	10 W
Dimensions (l–w–h)	36 – 11– 15 cm
Weight	4.1 kg
Camera Interface	CameraLink

HySpex Mjolnir VS-62

The HySpex Mjolnir VS-62[57] hyperspectral camera is developed for ground and UAV applications. The VNIR and SWIR optical axis are coaligned in the along track direction, assuring perfect coregistration in the flight direction. The hyperspectral datacube covers the spectral range from 400 - 2500 nm, with 490 bands. Smile and keystone are less than 0.1 pixels for each spectral range. The merged Mjolnir VS-620 data product reports coregistration/keystone values better than 0.2 pixels for the full VNIR-SWIR range.

[57] https://www.hyspex.com/hyspex-products/hyspex-mjolnir/hyspex-mjolnir-vs-620/

MAIN SPECIFICATIONS	V-1240	S-620
Spectral range	400 – 1000 nm	970 – 2500 nm
Combined spectral range	400 – 2500	
Spatial pixels	1240	620
Combined spatial pixels	620	
Spectral channels and sampling	200 bands @ 3.0 nm	300 bands @ 5.1 nm
Combined spectral channels	490	
F-number	F1.8	F1.9
FOV	20°	20°
Combined FOV	20°	
Pixel FOV across/along	0.27/0.54 mrad	0.54/0.54 mrad
Combined Pixel FOV across/along	0.54/0.54 mrad	
Bit resolution (raw data)	12 bit	16 bit
Noise floor	2.3 e-	80 e-
Dynamic range	4400	10000
Peak SNR (at full resolution)	> 180	> 900
Max speed (at full resolution)	285 fps	100 fps
Power consumption*	50 W	
Dimensions (l–w–h)*	374 – 202 – 178 mm	
Weight*	~ 6 kg	

*Includes IMU/GPS and DAU – <6.5 kg including standard battery

Hyper-Cam

The Hyper-Cam[58] cameras from Telops[59] are advanced passive infrared hyperspectral imaging systems that combine high spatial and spectral resolution. It provides real-time radiometrically calibrated data for gas and mineral detection and identification. It is offered in ground-based format and a compact airborne hyperspectral imaging system.

58 https://www.telops.com/products/hyperspectral-cameras/
59 https://www.telops.com

PRODUCT NAME	SPECTRAL RANGE (µM)	SPECTRAL RESOLUTION (CM⁻¹)	SPATIAL RESOLUTION (PIXELS)	FIELD OF VIEW (DEGREES)	TYPICAL NESR (NW/CM² SR CM⁻¹)	RADIOMETRIC ACCURACY (K)
MIDWAVE SERIES						
HYPER-CAM iMW	3 - 5.4	Up to 0.25	320 × 256	6.4 × 5.1	10	< 2.0
HYPER-CAM iMWE	1.5 - 5.4	Up to 0.25	320 × 256	6.4 × 5.1	9.5	< 2.0
HYPER-CAM iMW FAST	3 - 5.4	Up to 0.25	320 × 256	6.4 × 5.1	10	< 2.0
HYPER-CAM iMWE FAST	1.5 - 5.4	Up to 0.25	320 × 256	6.4 × 5.1	9.5	< 2.0
VERY LONG WAVE SERIES						
HYPER-CAM LW	7.7 - 11.8	Up to 0.25	320 × 256	6.4 × 5.1	20	< 1.0
MINI SERIES						
HYPER-CAM AIRBORNE MINI	7.4 - 11.8	Up to 0.5	320 × 256	13.5 × 10.9	< 35	< 5
HYPER-CAM MINI xLW	7.4 - 12.5	Up to 4	320 × 256	14 × 11	< 30	< 3

These specifications are for illustrative purposes only. The exact specifications depend on each configuration and are subject to change.

Headwall Photonics

Headwall Photonic[60] is a company that offers compact and rugged hyperspectral sensors under its HYPERSPEC® family. They provide quality imaging with good signal-to-noise ratio, resolution, and wide field of view. They also provide radiometric calibration services for accurate airborne spectral data collection. There are sensors that operate across the 250 to 2500 nm wavelength range with the MWIR available upon request. They offer UV-VIS 250-500 nm sensors, VNIR 400-1000 nm, Ext-VNIR 600-1700 nm, NIR 900-1700 nm, SWIR 900-2500 nm. Pushbroom scanning, also known as line-scanning, is the technique used by HYPERSPEC® sensors, which are line-scanning hyperspectral cameras. These sensors capture reflected light by using an image slit.

SpecIM

SpecIM[61] offers a range of hyperspectral cameras and imaging systems. These products are designed to capture and analyse detailed spectral information across a wide range of wavelengths, enabling precise and accurate analysis of materials and objects. They offer Visible light (380 - 800 nm), Visible + near infrared light (400 - 1000 nm), Near infrared (900 - 1700 nm), Short-wavelength infrared (1 000 - 2 500 nm), Mid-wavelength infrared (2.7 – 5.3 µm). Details on the types of products can be viewed from the website here.

HyMAP

HyMap[62] is an airborne hyperspectral sensor manufactured and operated by HyVista Corporation. It is mainly used for spectral mapping and offers 128 bands across the reflective solar wavelength region, ranging from 0.45 to 2.5um, with contiguous spectral coverage (except in water vapor bands) and an average bandwidth of 15nm. The sensor operates on a 3 axis gyro-stabilised platform to minimise image distortion caused by aircraft motion and can be easily integrated into aircraft with a standard aerial camera port and transported between survey sites by air freight.

60 https://www.headwallphotonics.com/products/hyperspectral-sensors
61 https://www.specim.com/
62 https://hyvista.com/

It has a high signal-to-noise ratio (>500:1) and enables accurate geocoding of hyperspectral images with precise integration of GPS/IMU. It produces analysis-ready imagery that is of low noise allowing quick post-flight processing direct to "at-sensor" radiance and then to "apparent reflectance". More details can be viewed from the website here.

AVIRIS/AVIRIS Next-gen

Airborne Visible / Infrared Imaging Spectrometer (AVIRIS)[63] is an optical sensor instrument used in Earth remote sensing. It captures calibrated images of upwelling spectral radiance in 224 spectral bands ranging from 400 to 2500 nm. This instrument has been successfully deployed on NASA's ER-2 jet, Twin Otter International's turboprop, Scaled Composites' Proteus, and NASA's WB-57 aircraft platforms.

Airborne Visible / Infrared Imaging Spectrometer Next Generation (AVIRIS -NG)[64] instrument is designed to provide high-quality imaging spectroscopy measurements in the solar reflected spectral range and is intended to replace the AVIRIS instrument that has been in use since 1986. AVIRIS-NG measures wavelengths ranging from 380nm-2510nm with a 5nm sampling interval. It captures spectra as images with 600 cross-track elements and offers spatial sampling ranging from 0.3m to 4.0m from a Twin Otter platform. The sensor demonstrates cross-track spectral uniformity (>95%) and spectral IFOV uniformity (>=95%). The sensor's ability to detect and measure methane point sources is relevant for greenhouse gas research and natural resource exploration. The onboard cloud-screening algorithm is also applicable to space imaging spectrometer missions.

Mission-Specific Resources

EnMAP

The Environmental Mapping and Analysis Program (EnMAP)[65] is a German hyperspectral satellite mission that monitors and characterises Earth's environment on a global scale. EnMAP measures geochemical, biochemical and biophysical variables providing information on the status and evolution of terrestrial and aquatic ecosystems. More information about the main objectives and the status can be found on the mission page which contains information on:

- EnMAP Specifications[66]
- Product Descriptions[67]
- Instructions to obtain EnMAP data through the Instrument Panning Portal[68] and the Catalog
- ATBD documentation for the different products:
    - L1B
    - L1C
    - L2A Land

[63] https://avirisng.jpl.nasa.gov/
[64] https://www.enmap.org/
[65] https://www.enmap.org/
[66] https://www.enmap.org/data/doc/EN-PCV-ICD-2009-2_HSI_Product_Specification_Level1_Level2.pdf
[67] https://www.enmap.org/data/doc/EN-GS-UM-6020_Portals_User_Manual_v1.1.pdf
[68] https://planning.enmap.org/

- L2A Water

More information on the EnMAP mission can be found at https://authors.elsevier.com/sd/article/S0034-4257(23)00183-9

PRISMA

PRISMA[69], owned by the Italian Space Agency, started its journey in space on 22 March 2019, aboard a VEGA carrier. It is an innovative hyperspectral optical sensor, able to provide a unique informative contribution for different applications. Relevant PRISMA assets consist of:

- PRISMA Data Portal[70]
- PRISMA Product Specifications[71]
- ATBDs[72]
- User Manual[73]

DESIS

DLR Earth Sensing Imaging Spectrometer (DESIS)[74] was launched to the International Space Station (ISS) in June 2017. The instrument was developed by DLR and delivered to Teledyne Brown Engineering (TBE) which operates, commands and monitors the instrument. DESIS is realised as a pushbroom imaging spectrometer spectrally sensitive over the visible and near-infrared wavelength range from 400 to 1000 nm. DESIS is a predominantly commercial mission but DLR has the right to task DESIS or request archived data for scientific and humanitarian purposes. Relevant DESIS assets include:

- Instructions to obtain access to DESIS data[75]
- DESIS Product Specifications[76]
- ATBDs[77]

EMIT

EMIT[78] was developed at NASA's Jet Propulsion Laboratory and launched on 14 July 2022. The instrument observes Earth from outside the International Space Station. EMIT data is delivered to NASA Land Processes Distributed Active Archive Center (DAAC) for use by other researchers and the public. EMIT uses an advanced two mirror telescope and high throughput F/1.8 Dyson imaging spectrometer. Relevant online assets are:

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[69] https://www.asi.it/en/earth-science/prisma/
[70] http://prisma.asi.it/missionselect/
[71] http://prisma.asi.it/missionselect/docs/PRISMA%20Product%20Specifications_Is2_3.pdf
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[74] https://www.dlr.de/eoc/desktopdefault.aspx/tabid-13614/
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[77] https://www.dlr.de/eoc/PortalData/60/Resources/dokumente/DESIS/DESIS_Products/PAV-DLR-TN-004.pdf
[78] https://earth.jpl.nasa.gov/emit/

- EMIT Data Product Descriptions[79] and related ATBDs:
    - Level 1b (Radiance at Sensor) ATBD (PDF)
    - Level 2a (Surface Reflectance) ATBD (PDF)
    - Level 2b (Surface Mineralogy) ATBD (PDF)
    - Level 3 (Aggregated Surface Mineralogy) ATBD (PDF)
    - Level 4 (Earth System Model Runs) ATBD (PDF)
- EMIT Open Data Portal [80]
- EMIT data search on NASA Earthdata Portal [81]

HISUI

Hyperspectral Imager Suite (HISUI) was launched to the International Space Station (ISS) in December 2019. It is a hyperspectral earth imaging system developed by the Japanese Ministry of Economy, Trade, and Industry (METI), consisting of a reflective telescope and two spectrometers which cover the visible and near infrared region (VNIR) and the shortwave infrared region (SWIR). Each spectrometer consists of a grating and a two-dimensional detector. Currently, data access is restricted but possible through research proposals [82].

Other useful resources

https://www.grss-ieee.org/technical-committees/geoscience-spaceborne-imaging-spectroscopy/

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Appendix

Acronyms and Abbreviations

Acronyms	Full Versions
ACIX	Atmospheric Correction Inter-comparison eXercise
AERONET	Aerosol Robotic Network
ATBD	Algorithm Theoretical Basis Document
AVIRIS	Airborne Visible / Infrared Imaging Spectrometer
BOA	Bottom-Of-Atmosphere
CEOS	Committee on Earth Observation Satellites
CGLS	Copernicus Global Land Service
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment

CLMS	Copernicus Land Monitoring Service
CMIX	Cloud Masking Inter-comparison eXercise
CMOS	Complementary Metal Oxide Semiconductor
CNES	Centre National D'Etudes Spatiales
DESIS	DLR Earth Sensing Imaging Spectrometer Mission
DLR	German Aerospace Center
EC	European Commission
ECV	Essential Climate Variables
EMIT	Earth Surface Mineral Dust Source Investigation
EnMAP	Environmental Mapping and Analysis Program
ESA	European Space Agency
EUFAR	EUropean Facility for Airborne Research
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
fCOVER	Fraction of Vegetation Cover
FOV	Field of View
FRM	Fiducial Reference Measurements
FRM4Veg	Fiducial Reference Measurements for Vegetation
FRM4VEG	Fiducial Reference Measurements for Vegetation

FRMSOC	Fiducial Reference Measurements for Satellite Ocean Colour
FWHM	Full-Width Half-Maximum
GBOV	Ground-Based Observations for Validation
GPS/IMU	Global Positioning Systems/Inertial Measurement Unit
HISUI	Hyperspectral Imager Suite
HYPSTAR	HYperspectral Pointable System for Terrestrial and Aquatic Radiometry
HYPSTAR-XR	HYperspectral Pointable System for Terrestrial and Aquatic Radiometry eXtended Range
ICOS	Integrated Carbon Observation System
IFOV	Instantaneous field of view
GUM	Guide to the Expression of Uncertainty in Measurement
ISS	International Space Station
IVOS	Infrared and Visible Optical Sensors Subgroup
LAI	Leaf Area Index
LED	Light Emitting Diode
LPs	Land Products
LPV	Land Product Validation
LSCE	Le Laboratoire des Sciences du Climat et de l'Environnement

LST	Land Surface Temperature
METI	Japanese Ministry of Economy, Trade, and Industry
MSI	MultiSpectral Instrument
NASA	National Aeronautics and Space Administration
NASA-JPL	National Aeronautics and Space Administration - Jet Propulsion Laboratory
NEON	National Ecological Observatory Network
NIR	Near Infrared
NIST	National Institute of Standards and Technology
OLI	Operational Land Imager
OLIVE	On Line Validation Exercise
ONERA	Office National d'Etudes et de Recherches Aérospatiales
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PANTHYR	Pan-and-tilt hyperspectral radiometer
PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PICS	Pseudo Invariant Calibration Sites
PRISMA	Hyperspectral Precursor of the Application Mission
PSF	Point Spread Function

RADCALNET	Radiometric Calibration Network
S2A	Sentinel-2A
SBG	Surface Biology and Geology
SI	International System of Units
SNR	Signal-to-noise ratio
SR	Surface Reflectance
SRIX4Veg	Surface Reflectance Intercomparison Exercise for Vegetation
SVC	Spectra Vista Corporation
SWIR	Shortwave Infrared Region
TBE	Teledyne Brown Engineering
TERN	Terrestrial Ecosystem Research Network
TOA	TOP of Atmosphere
UAV	Unmanned Aerial Vehicles
UK	United Kingdom
USGS	United States Geological Survey
VIS	Visible Spectrum
VNIR	Visible and Near Infrared Region
WGCV	Working Group on Calibration and Validation