

# First Two Years of (Multi-Sensor) Airborne Campaigns with the ARES Observatory

Marius Vögtli<sup>1</sup>, Jesse Ray Murray LaHaye<sup>2</sup>, Andreas Hueni<sup>1</sup>

<sup>1</sup>Department of Geography, University of Zurich, Zurich, Switzerland - marius.voegtli@geo.uzh.ch, andreas.hueni@geo.uzh.ch

<sup>2</sup>Earth Sensing and Observation Lab, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland - jesse.lahaye@epfl.ch

**Keywords:** AVIRIS, Airborne, Multi-Sensor, Imaging Spectroscopy, Laser Scanning, Photogrammetry

## Abstract

Since 2024, the ARES (Airborne Research of the Earth System) Observatory at the University of Zurich, Switzerland, has operated the Airborne Visible and Infrared Imaging Spectrometer-4 (AVIRIS-4) instrument, complemented since 2025 by a Riegl VQ-1560 II-S airborne laser scanner with a built-in Phase One iXU-RS 1000 photogrammetric camera. The first two years of ARES were primarily focused on establishing data processing chains, while also encompassing 61 successful airborne missions and the acquisition of 535 datasets. In this article, we highlight key aspects from the first two years of ARES operations. We introduce the three instruments of the ARES multi-sensor platform and the respective processing chains. We provide an overview of the airborne activities in the first two years, show examples of available ARES data, and look ahead to further developments foreseen for the following years.

## 1. Introduction

After several decades of continued technological and analytical progress, imaging spectroscopy from both airborne and spaceborne platforms has matured into a reliable tool for various Earth observation applications, such as vegetation system studies, geological mapping, or atmospheric gas detection (Green et al., 1998; Schaepman et al., 2009; Rast and Painter, 2019).

However, the investigation of some aspects of the Earth system cannot be accomplished with products derived from reflectance or radiance alone. For example, while many physiological plant properties can be estimated using imaging spectroscopy, the estimation of structural properties is limited due to the need for 3D information (Schaepman et al., 2009; Ustin and Middleton, 2021). At the same time, such 3D surface information, ideally highly resolved and simultaneously acquired, is inevitably required, but often not available, for key steps in the processing chain of imaging spectroscopy data, like the surface reflectance retrieval or the orthorectification (Dozier et al., 2022; Carmon et al., 2023). These two challenges highlight the benefit of having an additional source of simultaneous 3D surface data acquired alongside imaging spectroscopy measurements.

Aircraft are ideal platforms for obtaining simultaneous 3D surface data and imaging spectroscopy data, as they provide the capability to carry multiple additional instruments during flight, such as an airborne laser scanner or a high-resolution photogrammetric camera. This has already been successfully demonstrated by various airborne multi-sensor platforms, like the Carnegie/Global Airborne Observatory (Asner et al., 2012), the NEON Airborne Observation Platform (Kampe et al., 2010), or the CzechGlobe Flying Laboratory of Imaging Systems (Hanuš et al., 2023).

Since 2025, the ARES Observatory has complemented these established airborne multi-sensor platforms, operating the Airborne Visible and Infrared Imaging Spectrometer-4 (AVIRIS-4, Hueni et al. (2025)) alongside a Riegl VQ-1560 II-S airborne laser scanner and a Phase One iXU-RS 1000 photogrammetric camera.

AVIRIS-4 is operational since early 2024 and succeeds the University of Zurich's Airborne Prism EXperiment (APEX) imaging spectrometer (Schaepman et al., 2015), which flew between 2009 and 2019. The instrument was designed and constructed by NASA/JPL and was formerly known as the Compact Wide-Swath Imaging Spectrometer-II (CWIS-II, Shaw et al. (2022)). AVIRIS-4 completed the flight certification and a successful first flight mission in February 2024. The data and experience collected during this first flight were used to establish a data processing and archiving workflow (detailed in Subsection 2.3) in anticipation of the first flight season. The completed ground-work allowed for a first, single-sensor AVIRIS-4 flight season to successfully take place between July and October 2024.

An extended flight certification was obtained in spring 2025 to allow the ARES Observatory to operate a complementary Riegl VQ-1560 II-S full-waveform airborne laser scanner including a built-in Phase One iXU-RS 1000 photogrammetric camera concurrently with AVIRIS-4. A first multi-sensor flight campaign took place in southern Italy followed by a second successful flight season through October 2025. At the same time, the ARES partners at the École Polytechnique Fédérale de Lausanne (EPFL) launched the Addlidar portal (Jospin et al., 2025) for the processing and dissemination of ARES laser scanning and photogrammetry data, which is described in more detail in Subsections 2.4 and 2.5.

Both flight seasons were concluded by extensive radiometric and optical calibration campaigns for AVIRIS-4 at the German Aerospace Center's Calibration Home Base (Brachmann et al., 2016). The acquired calibration data are being gradually added to the AVIRIS-4 data processing chain.

## 2. Data and Methods

### 2.1 Instruments

At the time of writing, the ARES Observatory multi-sensor platform features three different instruments: the AVIRIS-4 airborne imaging spectrometer, which is complemented by a Riegl airborne laser scanner with a built-in Phase One photogrammetric

camera, owned by Swiss Flight Services SA (SFS), Switzerland. The three instruments are fitted to the two hatches of a Cessna 208B EX Grand Caravan aircraft (see Figure 1), operated by SFS, with a mission envelope covering flight levels from FL010 to FL200. Over terrain at sea level, these correspond to flight altitudes of approximately 300 m to 6000 m above ground level (AGL); over higher-elevation terrain, the corresponding AGL altitudes are lower. Imaging is performed at flight speeds between 85 and 155 kt (160 km h<sup>-1</sup> to 290 km h<sup>-1</sup>).

**AVIRIS-4** AVIRIS-4 is a NASA/JPL-built airborne imaging spectrometer. The instrument operates on a line-scanning (push-broom) principle with a Dyson-type optical design and a single 328 x 1280 pixel cadmium mercury telluride detector covering the full spectral range (Shaw et al., 2022). AVIRIS-4 measures reflected light between 375 nm to 2504 nm in 287 distributed bands with a spectral sampling of 7.45 nm (Hueni et al., 2025). A high frame rate of up to 213 frames per second and 1241 distributed spatial pixels over a field-of-view (FOV) of 40.2° enable the acquisition of data with an along-track and across-track spatial resolution of up to 0.3 m per pixel (Hueni et al., 2025). A co-mounted iXblue/Exail Atlans A7 inertial navigation system (INS) and a coupled Septentrio global navigation satellite system (GNSS) receiver measure the attitude and position of the instrument at 200 Hz and 5 Hz respectively. Further technical specifications of AVIRIS-4 are summarized in Table 1.

Table 1. Technical specifications of the AVIRIS-4 airborne imaging spectrometer based on Hueni et al. (2025).

| Parameter                   | AVIRIS-4          |
|-----------------------------|-------------------|
| <i>Nominal Performance</i>  |                   |
| Signal-to-noise ratio       | > 2000            |
| Frown                       | < 0.03 px         |
| Smile                       | < 0.02 px         |
| Frames per second           | 213               |
| <i>Spectral</i>             |                   |
| Spectral pixels             | 328               |
| Distributed spectral pixels | 287               |
| Sampling range              | 375 nm to 2504 nm |
| Spectral resolution         | 7.45 nm           |
| <i>Spatial</i>              |                   |
| Spatial pixels              | 1280              |
| Distributed spatial pixels  | 1241              |
| Field of view               | 40.2°             |
| Ground sample distance      | ≥ 0.3 m           |

**Riegl VQ-1560 II-S** The Riegl VQ-1560 II-S is a full-waveform airborne laser scanner with two channels with a pulse repetition rate (PRR) of up to 2 x 2000 kHz and a measurement rate of up to 2 x 1.33 MHz at a wavelength of 1064 nm (RIEGL, 2020). Depending on configured PRR, flight speed, and flight altitude, 3D point clouds with a point density of up to 40+ points m<sup>-2</sup> can be acquired. The laser scanner features a built-in Trimble/Applanix POS AV 610 GNSS/INS solution with measurement rates at 200 Hz and 5 Hz, respectively.

**Phase One iXU-RS 1000** The Riegl airborne laser scanner houses a built-in Phase One iXU-RS 1000 photogrammetric camera with a 100 MP RGB sensor (Phase One, 2016). In the configuration flown with ARES, the camera has a 50 mm, f/4.0 lens. From a flight altitude of 1000 m AGL, RGB images with a spatial resolution of 4.6 cm can be acquired and, together with the 3D point clouds from the airborne laser scanner, serve to produce true orthophotos or colorized 3D point clouds.

Table 2. Technical specifications of the Riegl VQ-1560 II-S airborne laser scanner based on RIEGL (2020).

| Parameter             | Riegl VQ-1560 II-S     |
|-----------------------|------------------------|
| Wavelength            | 1064 nm                |
| Pulse repetition rate | Up to 2x 2000 kHz      |
| Measurement rate      | Up to 2x 1.33 MHz      |
| Effective FOV         | 58°                    |
| Beam divergence       | 0.17 mrad to 0.23 mrad |

Table 3. Technical specifications of the Phase One iXU-RS 1000 photogrammetric camera based on Phase One (2016).

| Parameter              | Phase One iXU-RS 1000    |
|------------------------|--------------------------|
| Image size             | 11608 x 8708 px (100 MP) |
| Bands                  | 3 (R, G, B)              |
| Focal length           | 50 mm                    |
| Focal ratio            | f/4.0                    |
| Shutter speed          | ≥ 1/2500                 |
| FOV                    | 56.2° x 43.7°            |
| Ground sample distance | ≥ 0.05 m                 |

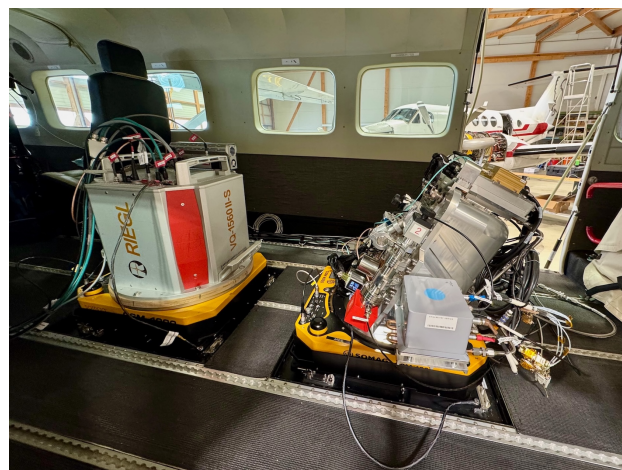


Figure 1. Riegl VQ-1560 II-S with built-in Phase One iXU-RS 1000 (left) and AVIRIS-4 (right) in the aircraft.

## 2.2 System Geometry Calibration

The reliable application of fused AVIRIS-4 and ALS data depends heavily on how well the two data types are co-registered. Misalignment in the georeferenced data, even by a few pixels, leads to cross-corruption of the data, where a spectral signature is incorrectly attributed to the wrong 3D coordinates of a physical structure as represented by the ALS point cloud. Moreover, when using an ALS-derived DEM for the orthorectification of AVIRIS-4 data, imprecise co-registration can corrupt topographic corrections and down-stream radiometric correction processes.

Reliable integration of AVIRIS-4 and ALS requires, among other aspects, the precise calibration of the system geometry as installed in the aircraft. The primary components of the system geometry consist of:

- **Lever Arm:** the 3D offset vector between the GNSS antenna and the center of the INS of each sensor as well as the relative spatial offset between each sensor's INS.
- **Boresight:** the angular offset between each sensor's focal center and their respective INS centers.

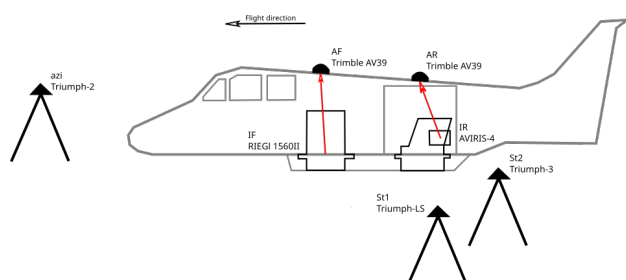


Figure 2. Geodetic lever arm measurement network schematic.

The impacts of the system lever arm and boresight calibration on the georeferencing and spatial alignment errors of the AVIRIS-4 and ALS data are correlated and therefore estimating them jointly in an optimization framework is not reliable (Vallet and Skaloud, 2004). The details of the lever arm and boresight calibration approaches are therefore introduced separately in the following paragraphs.

**Lever Arm Determination** To estimate the lever arms of the AVIRIS-4/ALS sensors in the mission aircraft, an observation network including geodetic surveying (total station) and GNSS positioning measurements, and CAD-derived target geometry were established (Figure 2). The measured distances, angles, and GNSS coordinates are processed through a Least Squares Adjustment (LSA) framework (Trinet+, Guillaume (2002)) to obtain topo-centric coordinates of all targets in the geodetic network frame. Precise lever arm dimensions are then derived in the body frame of each instrument by common measured points (or by construction from an additional azimuth GNSS station).

**AVIRIS-4/ALS Boresight Calibration** The determination of the orientation of the AVIRIS-4 and ALS data is dynamic and is susceptible to errors propagated from navigation sensors (noise and biases) and imperfect knowledge of system mounting parameters (e.g. boresight) and optical sensor properties (e.g. focal length variation due to changes in temperature and pressure) which result in georeferencing and co-registration errors if left uncompensated. An approach based on the extension of the Dynamic Network (DN) factor-graph based optimization framework (Cucci et al., 2017) and the open web service Online Dynamic Network solver (ODYN, <https://odyn.epfl.ch>) was applied for sensor geometry calibration and noise compensation. DN combines priors on the trajectory with GNSS positions, raw-inertial data, and optical tie point observations to jointly optimize sensor trajectory and other parameters (inertial measurement unit (IMU) or GNSS errors, optical distortion, and mounting parameters such as boresight).

## 2.3 Imaging Spectroscopy Data Processing

The AVIRIS-4 data are processed from *level-0* (digital numbers, DNs) to *level-2geo* (georectified surface reflectance) through several processing steps.

**Step 1: Radiance Calibration** The radiance calibration of the AVIRIS-4 data is based on NASA/JPL's open EMIT radiance code (<https://github.com/emit-sds/emit-sds-11b>). It includes corrections for several optical and electronic effects (scattering, ghost, bad pixels) and the conversion from raw DNs to calibrated at-sensor radiance ( $\text{W m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$ ). A detailed overview of the applied correction steps is provided in Hueni et al. (2025).

**Step 2: Trajectory Processing** The GNSS/INS data acquired by the iXblue/Exail Atlans A7 system are processed using the manufacturer-provided Delph INS software package (Exail, 2026). Besides the trajectory data, the lever arm offsets between GNSS antenna and INS and between INS and AVIRIS-4, as well as optional GNSS base station data are ingested into the processing environment. Then, a smoothed best estimate of trajectory (SBET) at 200 Hz is generated through Kalman filtering and recursive smoothing. Finally, the SBET is matched with GNSS timestamps imprinted in the AVIRIS-4 raw data and interpolated to the 213 frames per second frame rate of AVIRIS-4, to obtain per-frame position and attitude data.

**Step 3: Geometric Processing** The geometric processing of the AVIRIS-4 data is carried out using the ReSe PARGE parametric georeferencing solution (Schläpfer and Richter, 2002). In PARGE, the AVIRIS-4 image data are combined with the SBET, the laboratory-calibrated sensor model, estimated boresight angles, and a high-resolution digital elevation model (DEM), to produce an image geometry map (IGM) with per-pixel X/Y/Z coordinates. Additionally, outputs required for the surface reflectance retrieval are produced, including per-pixel scan angles, topography (slope, aspect, elevation), sky view factor, and illumination conditions (local solar zenith angle). Finally, a mapping array with raw-geometry row/column for every imaged real-world coordinate is calculated, serving for a later georectification of AVIRIS-4 data and derived products.

**Step 4: Surface Reflectance Retrieval** The default AVIRIS-4 surface reflectance retrieval is based on the ReSe ATCOR-A (formerly ATCOR-4) solution (Richter and Schläpfer, 2002), which employs atmospheric look-up tables derived from the MODerate resolution atmospheric TRANsmission (MODTRAN) model (Berk et al., 2006) to characterize the radiative transfer through the atmosphere. Additionally, the PARGE-derived topographic products are used for the characterization of the radiance and irradiance fields. Atmospheric water vapor is estimated using the Atmospheric Precorrected Differential Absorption (APDA) algorithm (Schläpfer et al., 1998) using spectral bands within the 940 nm water vapor absorption feature, while the aerosol optical thickness (AOT) is estimated with the dark dense vegetation (DDV) approach (Kaufman et al., 1997). Finally, the data are corrected for topography-induced illumination effects using the Modified Minnaert topographic correction algorithm (Richter et al., 2009) and delivered as hemispherical-conical reflectance factors (HCRF).

As an optional alternative to the ATCOR-based surface reflectance retrieval, work towards implementing ISOFIT (Thompson et al., 2018) to retrieve AVIRIS-4 surface reflectance data is carried out at the time of writing and will be completed soon.

**Optional Step 5: BRDF Effects Correction** After surface reflectance retrieval, the AVIRIS-4 data can optionally be corrected for reflectance anisotropy effects with the BREFCOR algorithm (Schläpfer et al., 2015) included in the ATCOR-A software or alternatively with the FlexBRDF solution (Queally et al., 2022). Both approaches compute surface-dependent models of the bi-directional reflectance distribution function (BRDF) using Ross volumetric and Li geometric kernels, which are then used to normalize the surface reflectance to spectral albedo or to a standard observation geometry.

## 2.4 ALS Data Processing

Georeferenced ALS point clouds are produced from the raw laser vectors acquired during flight through the following steps:

1. *Trajectory Estimation*: An initial ALS trajectory is produced as described in step 1 of Subsection 2.3.
2. *Trajectory/Boresight Refinement*: The boresight and calibrated lever arm from Subsection 2.2 are used to generate ALS point clouds through direct georeferencing for each flight line using the RiPROCESS software (RIEGL, 2021). Trajectory and boresight refinement is performed with ALS (lidar-to-lidar) tie points and DN adjustment as proposed in Brun et al. (2025), if errors are identified.
3. *Point Classification/Surface Model Estimation*: Refined, georeferenced point clouds are subsequently classified into standard ASPRS classes and used to estimate digital surface and terrain models (DSM/DTM).

## 2.5 Photogrammetry Data Processing

The Phase One iXU-RS 1000 photogrammetric camera of the ARES system is integrated in the ALS system and linked to the same INS and GNSS receiver. An orthomosaic of the exposed images acquired concurrently with the ALS and AVIRIS-4 data is constructed using the standard photogrammetric software suite Metashape (Agisoft, 2026) in the following steps:

1. *Trajectory Synchronization*: position and attitude at the exposure time of each image is interpolated from the trajectory.
2. *Image Pose Transformation*: the camera mounting rotation matrix, INS boresight, and lever arm are used to transform the interpolated attitude for each image from the INS body frame to the camera frame.
3. *Keypoint Matching and Filtering*: sparse image correspondences are established using automated descriptor/matching methods (e.g., SIFT, SURF) and filtered using epipolar constraints, reprojection error and geometric conditioning from computed poses.
4. *Bundle Block Adjustment*: non-linear least-squares optimization is performed to refine 3D point coordinates derived from sparse correspondences, camera poses, and lens distortion parameters, using the INS trajectory as constraint.
5. *Surface Reconstruction*: Aligned images from the bundle adjustment step are used to compute a 2.5D rasterized DEM. This is used as quality control of the lidar point cloud DEM products.
6. *Orthorectification and Mosaic Production*: 3D coordinates from the DEM are back-projected into the image space to compute the orthomosaic image. Aligned images are used to colorize and refine the semantic classification results of the ALS point cloud.

The aligned images are subsequently used in conjunction with the georeferenced point cloud to aid in point cloud classification and production of digital surface and terrain models.

## 3. Results and Discussion

### 3.1 ARES Missions and Applications

Between its first flight in February 2024 and the end of the 2025 flight season, the ARES Observatory completed a total of 61 flight missions (2024: 25, 2025: 36, see Figure 3), of which 48 were flown with AVIRIS-4 alone and 13 with the multi-sensor configuration. In the first two years, 535 flight lines (2024: 234, 2025: 301) in 9 different European countries were acquired.

Among the top applications were methane detection flights (19 missions), notably including a mission supporting a controlled methane release experiment (see McManemin et al. (2026); Meier et al. (2026)), and flights for vegetation or biodiversity studies (16 missions). Besides these widespread applications, ARES also completed some less common missions, such as the mapping of archaeological sites in Sicily (Italy) or an experimental mission under an overcast sky with fully diffuse illumination in Switzerland.

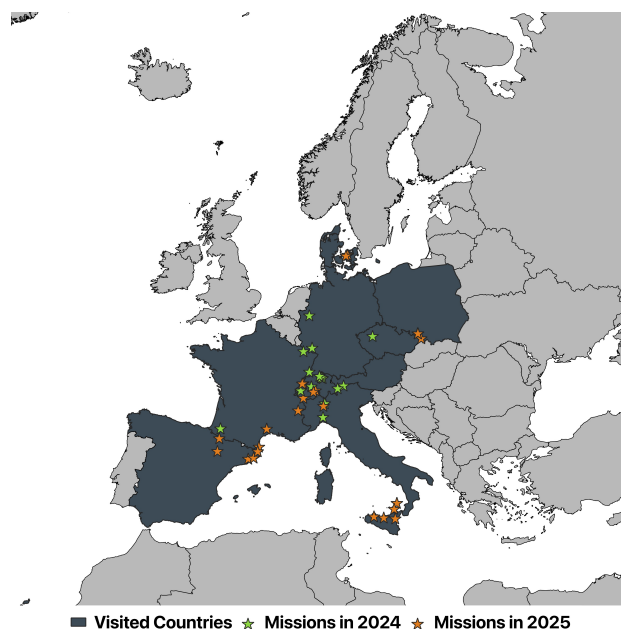


Figure 3. Overview of ARES missions in 2024 and 2025 and visited countries. Map data: Natural Earth, ARES.

### 3.2 ARES Example Data

Various data can be generated from the ARES multi-sensor package. Figure 4 provides an overview of a multi-sensor dataset acquired during a mission in the Lötschental valley (Switzerland) on 11 June 2025 between 12:47 and 12:48 local time (LT) with a solar geometry of 24.7° (zenith) and 157.1° (azimuth) from a flight elevation of 3100 m above an average ground altitude of 1600 m. All data were processed using the processing chains described in Section 2.

The AVIRIS-4 dataset shown in the upper row of Figure 4 has average along-track and across-track resolutions of 0.34 m and 0.83 m, resampled to 1 m. The spectra shown in the figure (mean of 5 x 5 pixel area with envelope of  $\pm$  one standard deviation) were retrieved from orthorectified HCRF data (ATCOR-A without BRDF effects correction) and weakly smoothed using a Savitzky-Golay filter. The Phase One RGB data were processed to a true-orthophoto using the 3D point cloud obtained from the Riegl airborne laser scanning (ALS) data and have a spatial resolution of 0.1 m.

The subset of the classified 3D point cloud shown in the lower row of Figure 4 has a mean point density of roughly 70 points  $m^{-2}$ . Based on this 3D point cloud, digital surface and terrain models with a resolution of 0.1 m were produced.

### 3.3 ARES Multi-Sensor Products

As pointed out in the introductory Section 1, one key advantage of multi-sensor data is the possibility to investigate Earth's

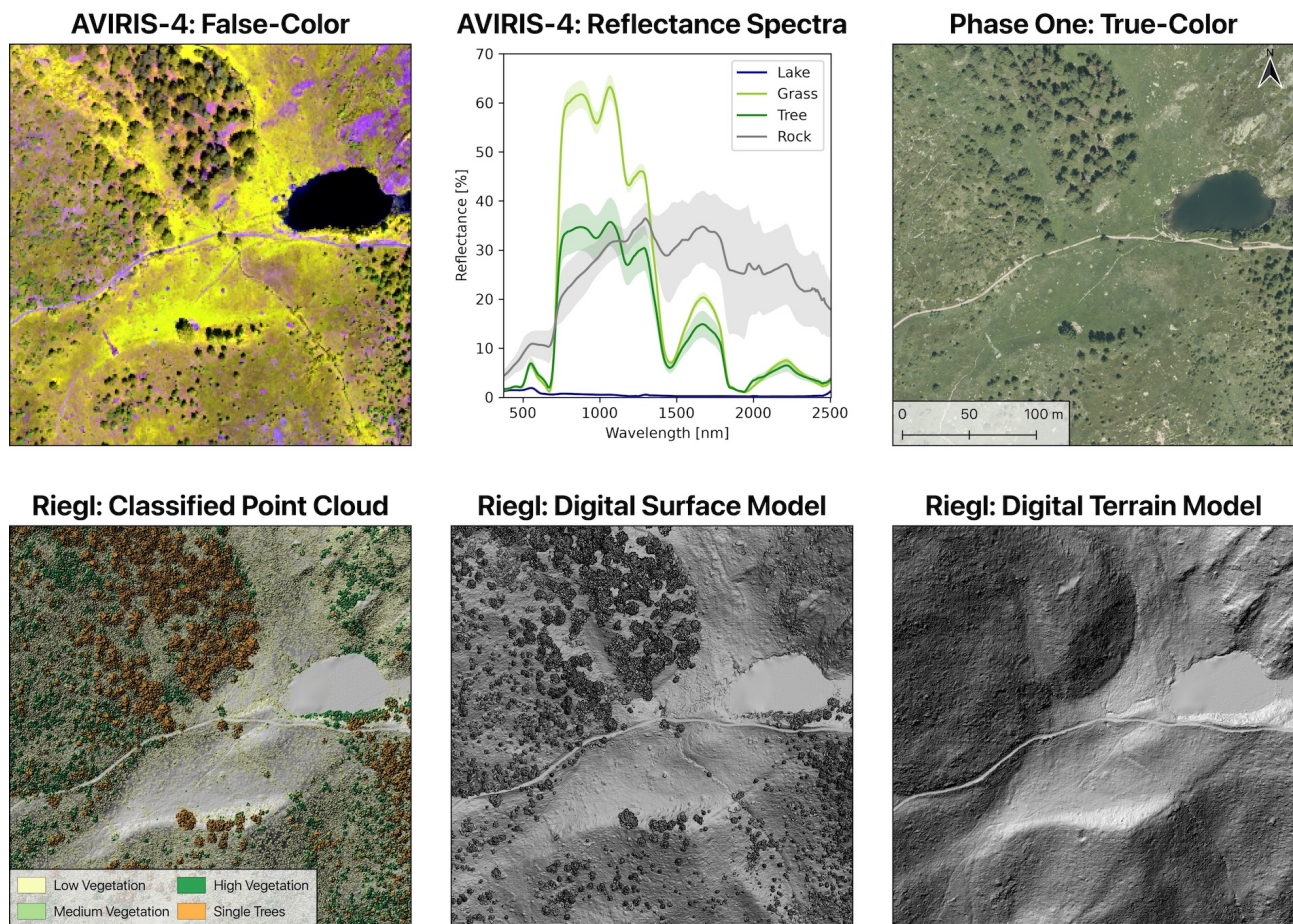


Figure 4. Overview of different products generated from an ARES mission in Lötschental (Switzerland) on 11 June 2025. **Upper row:** AVIRIS-4 false-color composite ( $R = 1200$  nm,  $G = 860$  nm,  $B = 670$  nm) with a spatial resolution of 1 m, exemplary reflectance spectra from the displayed scene, Phase One true-color true-orthophoto with a spatial resolution of 0.1 m. **Lower row:** Riegl classified 3D point cloud, digital surface model, and digital terrain model with a spatial resolution of 0.1 m. The shown ARES data were acquired for the Remote Sensing Spectroscopy (RSS) group at the Department of Geography of the University of Zurich.

spheres in a more complete way than with single-sensor data alone. This is illustrated exemplarily in Figure 5, with AVIRIS-4 AIS and Riegl ALS data.

Using the absorption depth of the 900 nm to 1070 nm water absorption feature, calculated from the AVIRIS-4 AIS data, physiological information about the vegetation, i.e. its water content and thus potential drought stress, can be estimated. The simultaneous availability of a 3D point cloud from the Riegl ALS data enables the calculation of complementary structural vegetation parameters, like the percentage of first returns per 1 m grid cell, which provides information on the uppermost canopy layer density.

The presented dataset also illustrates the potential for soil and water course studies: the right-hand side of the scene shows a rocky stream bed that fans out downstream (top-right). The structure of the bed and the deposits are discernible in the first returns per grid cell. The moisture content of the soil and the surface water are clearly mapped by the 900 nm to 1070 nm absorption depth map with a high spatial variability and yet show a distinct pattern within the fan. These nuances are not visible in the Phase One image, but the higher spatial resolution lends itself to pan-sharpening approaches that would aid small-scale studies.

### 3.4 Enhanced Data Processing

A second advantage of simultaneous AIS and ALS acquisitions is the ready availability of high-resolution surface information for the processing of the imaging spectroscopy data.

Figure 6 shows a subset of AVIRIS-4 data acquired on 09 June 2025 at 11:34 LT in Sicily (Italy) for the Ietas excavation, run by the University of Zurich's chair for Archaeology of the Mediterranean, with a focus on Greek and Roman Antiquity (Mohr and Reinhardt, 2026). The AVIRIS-4 data were acquired from 700 m above ground and have a spatial resolution of 0.4 m. The data passed the processing chain described in Subsection 2.3 from radiance data to orthorectified surface reflectance data once with the publicly available Tintaly DTM (Tarquini et al., 2007, 2023) with a spatial resolution of 10 m and once with the simultaneously acquired ARES DSM with a spatial resolution of 0.2 m. The high-resolution DSM provides several advantages over the coarser-resolution DEM, two of which are examined in more detail below.

The first advantage concerns the orthorectification of the AVIRIS-4 data. The availability of a DSM instead of a DTM allows for a correct localization of vertical structures, like trees or buildings. Additionally, due to its finer spatial resolution and thus more detailed representation of the surface topography,

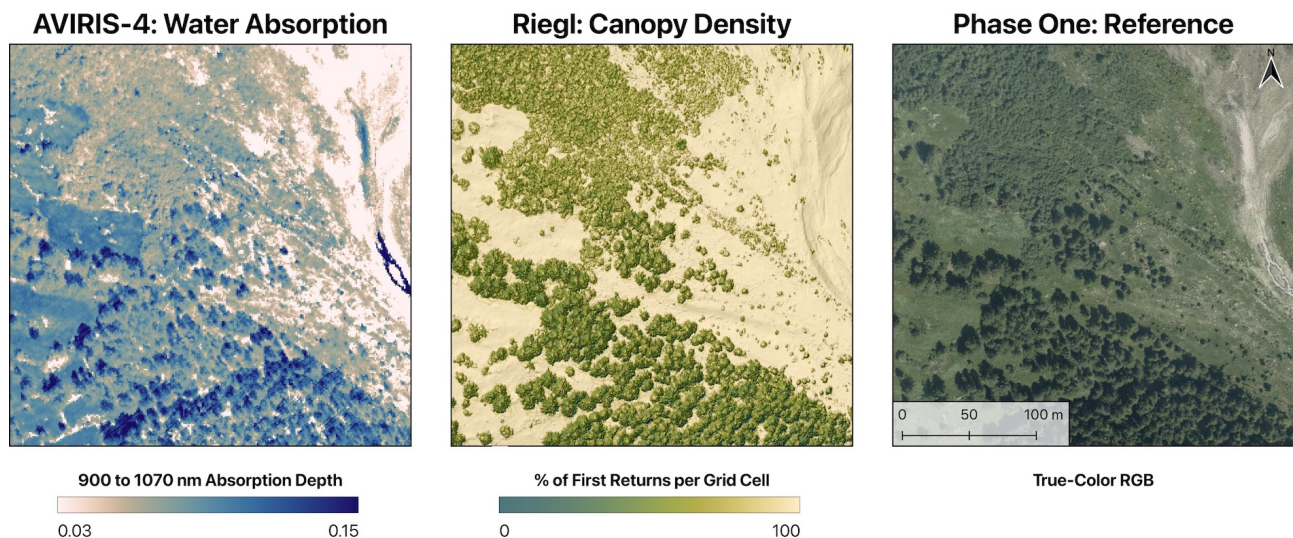


Figure 5. Examples of multi-sensor vegetation products derived from an ARES mission in Lötschental (Switzerland) on 11 June 2025.

**Left:** absorption depth of the vegetation water absorption feature between 900 nm and 1070 nm from AVIRIS-4 airborne imaging spectroscopy data. **Center:** percentage of first returns per grid cell from Riegl airborne laser scanning data. **Right:** high-resolution true-color RGB reference from Phase One data. The shown ARES data were acquired for the Remote Sensing Spectroscopy (RSS) group at the Department of Geography of the University of Zurich.

the high-resolution DSM allows for a much more precise orthorectification of the AVIRIS-4 data. This can be clearly observed in the true-color RGB images in Figure 6, for example when looking at the placement of the tall vertical corn silos in the right part of the image or when comparing the course of the road to the overlaid OpenStreetMap road shape.

In addition to the orthorectification, the surface reflectance retrieval also benefits from high-resolution elevation data, since several steps in the retrieval process require topographic data, like elevation, slope, and aspect, derived from a DEM. One example is the per-pixel illumination condition (calculated as the cosine of the local solar zenith angle,  $\cos(i)$ ), which is used as an input for the topographic correction as a part of the ATCOR-A surface reflectance retrieval. Areas without direct illumination have a  $\cos(i)$  value of 0 and fully illuminated areas have a value of 1. The two images in the lower left of Figure 6 show this illumination condition calculated from the coarser-resolution Tinitally DTM and from the high-resolution ARES DSM. The mean  $\cos(i)$  value in the 100 x 100 px large white rectangle is at 0.671 for the Tinitally DTM and at 0.491 for the ARES DSM, showing that  $\cos(i)$  is overestimated in the coarser data. This has direct consequences on the retrieved reflectance, when a topographic correction, such as the Modified Minnaert method, using the DEM-derived illumination condition, is applied. As a result of the overestimated  $\cos(i)$ , the reflectance is on average underestimated by approximately 2%, as demonstrated by the reflectance spectra on the right side of Figure 6.

#### 4. Conclusion and Outlook

After the first two years of operation, the ARES acquisition and processing infrastructure is fully mission-ready with three instruments, and promising first study results have already been confirmed and published.

In the near future, ARES plans to expand the multi-sensor capabilities by adding additional instruments to its portfolio. A first

experimental flight with AVIRIS-4 and a Telops Hyper-Cam thermal imaging spectroscopy instrument should take place in the second half of 2026. Additionally, efforts aimed at refining calibration and data processing workflows for AVIRIS-4 continue. Finally, public data portals providing access to overviews of all ARES data are planned for release in the near future.

The ARES team welcomes expressions of interest from the spectroscopy community related to airborne acquisitions both in single- as well as multi-sensor configurations.

#### Acknowledgments

We thank our technical and scientific partners at University of Zurich (UZH), École Polytechnique Fédérale de Lausanne (EPFL), Zurich University of Applied Sciences (ZHAW), Swiss Federal Institute of Aquatic Science and Technology (Eawag), Swiss Federal Laboratories for Materials Science and Technology (Empa), Swiss Federal Institute of Technology Zurich (ETHZ), International Centre for Earth Simulation (ICES) Foundation, University of Fribourg (UniFR), and University of Lausanne (UNIL) for the excellent collaboration over the past years and all our customers for the trust in our services.

#### References

- Agisoft, 2026. Agisoft Metashape Professional Edition Version 2.3. User Manual.
- Asner, G. P., Knapp, D. E., Boardman, J., Green, R. O., Kennedy-Bowdoin, T., Eastwood, M., Martin, R. E., Anderson, C., Field, C. B., 2012. Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. *Remote Sensing of Environment*, 124, 454-465. <https://doi.org/10.1016/j.rse.2012.06.012>.

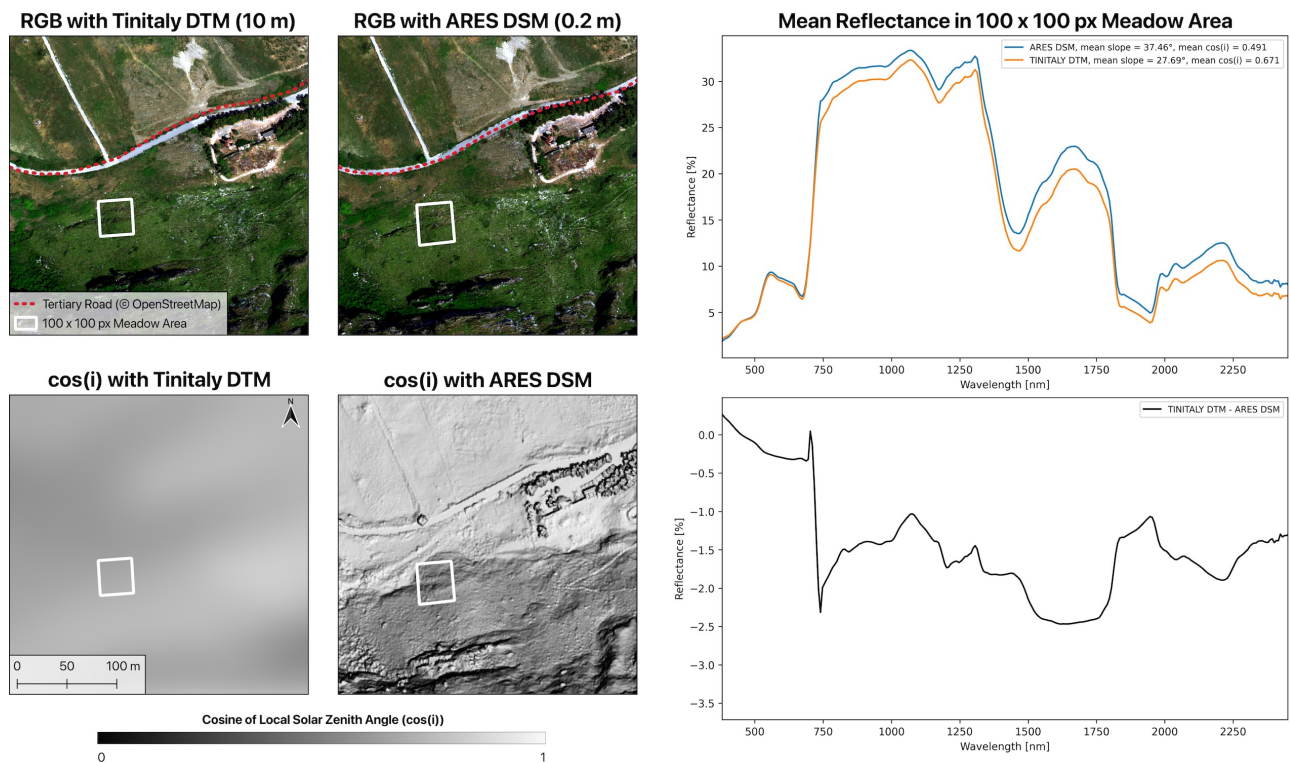


Figure 6. Advantages of a high-resolution digital surface model (DSM) over a coarser-resolution digital terrain model (DTM), like the Tinitaly DTM (Tarquini et al., 2007, 2023), for AVIRIS-4 data processing. The high-resolution DSM allows for a more accurate orthorectification and for the calculation of finer-resolved input data for the reflectance retrieval, like the illumination condition (cosine of the local solar zenith angle). The shown ARES data were acquired for the University of Zurich's chair for Archaeology of the Mediterranean, with a focus on Greek and Roman Antiquity (Mohr and Reinhardt, 2026).

Berk, A., Anderson, G. P., Acharya, P. K., Bernstein, L. S., Muratov, L., Lee, J., Fox, M., Adler-Golden, S. M., Jr., J. H. C., Hoke, M. L., Lockwood, R. B., Gardner, J. A., Cooley, T. W., Borel, C. C., Lewis, P. E., Shettle, E. P., 2006. MODTRAN5: 2006 update. S. S. Shen, P. E. Lewis (eds), *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XII*, 6233, International Society for Optics and Photonics, SPIE, 62331F.

Brachmann, J. F. S., Baumgartner, A., Gege, P., 2016. The Calibration Home Base for Imaging Spectrometers. *Journal of large-scale research facilities JLSRF*, 2(0), 82. <https://doi.org/10.17815/jlsrf-2-137>.

Brun, A., Kolecki, J., Xiao, M., Insolita, L., van der Zwan, E. V., Guerrier, S., Skaloud, J., 2025. Generalization of point-to-point matching for rigorous optimization in kinematic laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 229, 107-121. <https://doi.org/10.1016/j.isprsjprs.2025.08.011>.

Carmon, N., Berk, A., Bohn, N., Brodrick, P. G., Dozier, J., Johnson, M., Miller, C. E., Thompson, D. R., Turmon, M., Bachmann, C. M., Green, R. O., Eckert, R., Liggett, E., Nguyen, H., Ochoa, F., Okin, G. S., Samuels, R., Schimel, D., Song, J. J., Susiluoto, J., 2023. Shape from spectra. *Remote Sensing of Environment*, 288, 113497. <https://doi.org/10.1016/j.rse.2023.113497>.

Cucci, D. A., Rehak, M., Skaloud, J., 2017. Bundle adjustment with raw inertial observations in UAV applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, 130, 1-12. <https://doi.org/10.1016/j.isprsjprs.2017.05.008>.

Dozier, J., Bair, E. H., Baskaran, L., Brodrick, P. G., Carmon, N., Kokaly, R. F., Miller, C. E., Miner, K. R., Painter, T. H., Thompson, D. R., 2022. Error and Uncertainty Degrade Topographic Corrections of Remotely Sensed Data. *Journal of Geophysical Research: Biogeosciences*, 127(11). <https://doi.org/10.1029/2022jg007147>.

Exail, 2026. Delph INS. User Guide Version V1.7.1.

Green, R. O., Eastwood, M. L., Sarture, C. M., Chrien, T. G., Aronsson, M., Chippendale, B. J., Faust, J. A., Pavri, B. E., Chovit, C. J., Solis, M., Olah, M. R., Williams, O., 1998. Imaging Spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). *Remote Sensing of Environment*, 65(3), 227-248. [https://doi.org/10.1016/s0034-4257\(98\)00064-9](https://doi.org/10.1016/s0034-4257(98)00064-9).

Guillaume, S., 2002. Implémentation de la compensation d'observations dans le logiciel trinet. *Travail de diplôme HEIG-VD*.

Hanuš, J., Slezák, L., Fabiánek, T., Fajmon, L., Hanousek, T., Janoutová, R., Kopkáně, D., Novotný, J., Pavelka, K., Píkl, M., Zemek, F., Homolová, L., 2023. Flying Laboratory of Imaging Systems: Fusion of Airborne Hyperspectral and Laser Scanning for Ecosystem Research. *Remote Sensing*, 15(12). <https://doi.org/10.3390/rs15123130>.

Hueni, A., Geier, S., Vögtli, M., LaHaye, J., Rosset, J., Berger, D., Sierro, L. J., Jospin, L. V., Thompson, D. R., Schläpfer, D., Green, R. O., Loeliger, T., Skaloud, J., Schaeppman, M. E., 2025. The AVIRIS-4 Airborne Imaging Spectrometer. *IEEE Geoscience and Remote Sensing Letters*, 22, 1-5. <https://doi.org/10.1109/LGRS.2025.3572349>.

- Jospin, L., Lahaye, J., Skaloud, J., 2025. AddLiDAR: An Online Airborne Laser Scanning Processing Portal and Data Repository. Technical report, EPFL.
- Kampe, T. U., Johnson, B. R., Kuester, M. A., Keller, M., 2010. NEON: the first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. *Journal of Applied Remote Sensing*, 4(1), 043510. <https://doi.org/10.1117/1.3361375>.
- Kaufman, Y., Wald, A., Remer, L., Gao, B.-C., Li, R.-R., Flynn, L., 1997. The MODIS 2.1- $\mu\text{m}$  channel-correlation with visible reflectance for use in remote sensing of aerosol. *IEEE Transactions on Geoscience and Remote Sensing*, 35(5), 1286–1298. <https://doi.org/10.1109/36.628795>.
- McManemin, A., Juéry, C., Blandin, V., Baker, M., Bauguitte, S., Brunner, D., Burdeau, P., France, J. L., Fredenslund, A. M., Hueni, A., Kuhlmann, G., Łakomiec, P., Meier, S., Paglini, R., Papaconstantinou, R., Paris, J.-D., Quehe, P.-Y., Röckmann, T., Scheutz, C., Schmidt, M., Vögtli, M., Wietzel, J. B., Brandt, A. R., 2026. From research to reality: Academic methane measurement systems tested at the TADI controlled release facility. *EGUsphere*, 2026, 1–32. <https://doi.org/10.5194/egusphere-2026-1744>.
- Meier, S., Vögtli, M., Hueni, A., McManemin, A., Brandt, A. R., Juéry, C., Blandin, V., Brunner, D., Kuhlmann, G., 2026. Quantifying CH<sub>4</sub> point source emissions with airborne remote sensing: first results from AVIRIS-4. *Atmospheric Measurement Techniques*, 19(1), 333–358. <https://doi.org/10.5194/amt-19-333-2026>.
- Mohr, M., Reinhardt, C., 2026. Forschungen auf dem Monte Iato 2025. *Antike Kunst*, 69, 122–135. <https://doi.org/10.53191/AntK.2026.69.121>.
- Phase One, 2016. Phase One Aerial Cameras – Fully Integrated Aerial Photography Solutions. Data Sheet.
- Queally, N., Ye, Z., Zheng, T., Chlus, A., Schneider, F., Pavlick, R. P., Townsend, P. A., 2022. FlexBRDF: A Flexible BRDF Correction for Grouped Processing of Airborne Imaging Spectroscopy Flightlines. *Journal of Geophysical Research: Biogeosciences*, 127(1). <https://doi.org/10.1029/2021jg006622>.
- 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(3), 303–331. <https://doi.org/10.1007/s10712-019-09517-z>.
- Richter, R., Kellenberger, T., Kaufmann, H., 2009. Comparison of Topographic Correction Methods. *Remote Sensing*, 1(3), 184–196. <https://doi.org/10.3390/rs1030184>.
- Richter, R., Schläpfer, D., 2002. Geo-atmospheric processing of airborne imaging spectrometry data. Part 2: Atmospheric/topographic correction. *International Journal of Remote Sensing*, 23(13), 2631–2649. <https://doi.org/10.1080/01431160110115834>.
- RIEGL, 2020. RIEGL VQ-1560 II-S. Data Sheet.
- RIEGL, 2021. RiPROCESS 1.9. User Manual.
- Schaepman, M. E., Jehle, M., Hueni, A., D’Odorico, P., Damm, A., Weyermann, J., Schneider, F. D., Laurent, V., Popp, C., Seidel, F. C., Lenhard, K., Gege, P., Küchler, C., Brazile, J., Kohler, P., Vos, L. D., Meuleman, K., Meynart, R., Schläpfer, D., Kneubühler, M., Itten, K. I., 2015. Advanced radiometry measurements and Earth science applications with the Airborne Prism Experiment (APEX). *Remote Sensing of Environment*, 158, 207–219. <https://doi.org/10.1016/j.rse.2014.11.014>.
- 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>.
- Schläpfer, D., Borel, C. C., Keller, J., Itten, K. I., 1998. Atmospheric Precorrected Differential Absorption Technique to Retrieve Columnar Water Vapor. *Remote Sensing of Environment*, 65(3), 353–366. [https://doi.org/10.1016/s0034-4257\(98\)00044-3](https://doi.org/10.1016/s0034-4257(98)00044-3).
- Schläpfer, D., Richter, R., 2002. Geo-atmospheric processing of airborne imaging spectrometry data. Part 1: Parametric orthorectification. *International Journal of Remote Sensing*, 23(13), 2609–2630. <https://doi.org/10.1080/01431160110115825>.
- Schläpfer, D., Richter, R., Feingersh, T., 2015. Operational BRDF Effects Correction for Wide-Field-of-View Optical Scanners (BREFCOR). *IEEE Transactions on Geoscience and Remote Sensing*, 53(4), 1855–1864. <https://doi.org/10.1109/tgrs.2014.2349946>.
- Shaw, L. A., Geier, S., McKinley, I. M., Bernas, M. A., Gharakhanian, M., Dergeorkian, A., Eastwood, M. L., Mouroulis, P., Green, R. O., 2022. Design, alignment, and laboratory calibration of the Compact Wide Swath Imaging Spectrometer II (CWIS-II). *Imaging Spectrometry XXV: Applications, Sensors, and Processing*, 12235, 1223502–1223502-10. <https://doi.org/10.1117/12.2634282>.
- Tarquini, S., Isola, I., Favalli, M., Battistini, A., Dotta, G., 2023. TINITALY, a digital elevation model of Italy with a 10 meters cell size (Version 1.1). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/tinitaly/1.1>.
- Tarquini, S., Isola, I., Favalli, M., Mazzarini, F., Bisson, M., Pareschi, M. T., Boschi, E., 2007. TINITALY/01: a new Triangular Irregular Network of Italy. *Annals of Geophysics*, 50(3). <https://doi.org/10.4401/ag-4424>.
- Thompson, D. R., Natraj, V., Green, R. O., Helmlinger, M. C., Gao, B.-C., Eastwood, M. L., 2018. Optimal estimation for imaging spectrometer atmospheric correction. *Remote Sensing of Environment*, 216, 355–373. <https://doi.org/10.1016/j.rse.2018.07.003>.
- Ustin, S. L., Middleton, E. M., 2021. Current and near-term advances in Earth observation for ecological applications. *Ecological Processes*, 10(1), 1. <https://doi.org/10.1186/s13717-020-00255-4>.
- Vallet, J., Skaloud, J., 2004. Development and Experiences with A Fully-Digital Handheld Mapping System Operated from A Helicopter. *ISPRS Congress, Istanbul, Turkey*, 35.