ATMOSPHERIC CORRECTION OF DESIS AND ENMAP HYPERSPECTRAL DATA: VALIDATION OF L2A PRODUCTS

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ABSTRACT

Since November 2022, the PACO [1] atmospheric correction program has operated routinely as the L2A processor in the ground segment for the hyperspectral missions DESIS [2] and EnMAP [3]. Both missions monitor the Earth's environment similar to other operational hyperspectral missions like PRISMA [4] and EMIT [5]. The Ground Segment L2A processor for the DESIS and EnMAP missions corrects the at-sensor received terrestrial reflection of the incident solar radiation for the effects of atmospheric constituents generating Bottom-Of-Atmosphere (BOA) ground reflectance spectral image cube, along with pixel-classification masks, Aerosol Optical Thickness (AOT) at 550 nm and Water Vapor (WV) maps. In this contribution we summarize the lessons learned on the validation of the atmospheric correction and the related uncertainty of the hyperspectral L2A products, applying the same validation criteria, for both DESIS and EnMAP.

Index Terms**—** Hyperspectral, L2A, atmospheric correction, DESIS, EnMAP, AOT, WV, surface reflectance

1. INTRODUCTION

The "DLR Earth Sensing Imaging Spectrometer" (DESIS) is a VNIR sensor mounted on-board the International Space Station (ISS) and it has been operational since October 2019. DESIS acquires images of the Earth at user request with a swath of about 30 km and 235 bands with a Full Width at Half Maximum (FWHM) of 3.5 nm in the spectral range from 400 to 1000 nm.

The recently launched EnMAP (Environmental Mapping and Analysis Program) is a German hyperspectral satellite mission that monitors and characterizes Earth's environment in the spectral range from 420 to 2450 nm with a FWHM of 6 to 10 nm in the VNIR and 7.5 to 11.5 nm in the SWIR. EnMAP can acquire a total of 5000 km per day with a swath width of 30 km at a spatial resolution of 30 m and with a pointing capability of up to 30 degrees.

The Ground Segment L2A processor for the DESIS and EnMAP missions processes ortho-rectified Top-Of-Atmosphere (TOA) radiance scenes and generates the Bottom-Of-Atmosphere (BOA) ground reflectance spectral image cube, along with pixel-classification masks, Aerosol Optical Thickness (AOT at 550 nm) and Water Vapor (WV) information. The L2A BOA surface reflectance (remote sensing reflectance $\mathrm{R_{rs}} \cdot \pi$) spectral image is the same in DESIS and in EnMAP (so called, in EnMAP, L2A Land_Mode). PACO is also used internally in DLR's EOC for processing multi-spectral data like Sentinel-2 and Landsat-8 and 9. The multi-sensor support of the atmospheric correction software minimizes the differences between the multi-spectral and hyperspectral spectral images. In addition, the EnMAP mission provides water reflectance products over pixels identified as water (so called in EnMAP, L2A Water_Mode or Combined) in units of water leaving reflectance and subsurface irradiance reflectance. These two water products are produced using the MIP (Modular Inversion Program) software [6].

In this paper we will present the joint validation of the L2A products from both hyperspectral missions, comparing the results to atmospheric and ground in-situ measurements as reference, including some validation measurements recommended in the Atmospheric Correction Inter-comparison exercise (ACIX-II) [7]. In particular the ACIX-APU graphs, where U is the Uncertainty in physical units, expressed as $U_{PARAM} < U_{\mathrm{slope}}$ * PARAM + U_{offset}, and used to define EnMAP requirements.

2. VALIDATION OF ATMOSPHERE PARAMETERS: AOT AND WV

For the validation of the estimated atmospheric parameters (AOT and WV), the AERONET [8] (Aerosol Robotic Network) reference data are used.

The sensor data are extracted from the AOT and WV maps within a region of interest of 4.5 x 4.5 km around the AERONET station coordinates. The reference data are interpolated to the time of the remote sensing acquisition $\pm$ 30 min. For the AOT in particular, the AERONET data are spectrally interpolated to AOT at 550 nm using the linear relation between the logarithm of the AOT and its wavelength measurements. Only stations with enough vegetated areas are included in the AOT dataset, so that the DDV-algorithm is applied.

Figure 1 shows the scatter plots between AERONET in-situ measurements and the EnMAP estimations of the AOT (at 550 nm) (left) and WV (in cm) (right).

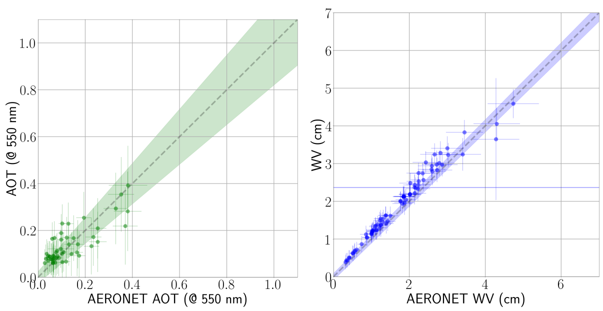

Fig. 1. Scatter of EnMAP AOT [at 550 nm] (left) and WV [in cm] (right) retrieved values versus AERONET reference ones. The green and blue shadowed area corresponds to the EnMAP requirements at 68% c.l. Pearson correlation factor r = 0.822 and 0.987 for AOT and WV, respectively.

	AOT_{550}		WV	
	U_{offset} [a.u.]	U_{slope} [a.u.]	U_{offset} [cm]	U_{slope} [cm^{-1}]
Sentinel-2	0.03	0.29	0.13	0.02
EnMAP	0.04	0.14	0.07	0.10
DESIS	0.15 (@ AOT=0.1)		0.06	0.08

Table 1. Uncertainty slope (U_{slope}) and offset (U_{offset}) of the AOT and WV estimation for VNIR (DESIS) and VSWIR sensors (Sentinel-2 and EnMAP).

There is a clear improvement on the AOT and WV retrieval in hyperspectral sensors, despite the limited number of AERONET overpasses of the hyperspectral missions ($\sim$ 50-100 scenes) compared with Sentinel-2 studies ($>$ 500).

The uncertainty in the WV estimation, relative to the AERONET reference, is below 10% for both hyperspectral missions (Table 1), compared with more than 0.13 cm in the case of Sentinel-2 mission using the PACO software [1].

The AOT estimation has a relative uncertainty in VSWIR sensors of 14% and 29% with respect to the AOT reference values for EnMAP and Sentinel-2 respectively. The absence of SWIR bands in DESIS yields a decrease in the performance of the AOT estimation to an RMSE ~ 0.15 uncertainty compared to the AERONET reference. As an indication, this is nearly double the total RMSE of EnMAP ($\sim$ 0.06) but the dataset distribution is completely different. The AERONET stations for Sentinel-2 are selected randomly among their distribution around the globe. EnMAP and DESIS data sets are dependent on their users orders. However, following the uncertainty propagation from [9], the difference in the AOT contribution to the uncertainty in the BOA measurement (in [%/100]) in DESIS and EnMAP would be ≤ 0.01.

3. L2A SURFACE REFLECTANCE

For the validation of the L2A spectral image of land pixels, the reference data are obtained from RadCalNet (Radiometric Calibration Network) [10].

The relative uncertainty of the remote sensing irradiance reflectance (U) is below 5% of the RadCalNet data ($\rho_{\text{RCN}} = R_{\text{rs}} \cdot \pi$) for the two sensors and $\rho_{\text{RCN}} > 10\%$ (also $U[\%/100] < 0.05 * \rho_{\text{RCN}}[\%/100] + 0.005$). However, the analysis comparing hyperspectral spectral data to the reference at wavelengths below $\sim$450 nm shows a clear deviation of the U values from a linear power law at shorter wavelengths, even for low sun and viewing angles (SZA$< 30^{\text{o}}$, off-nadir $< 10^{\text{o}}$). Figure 2 illustrates the level of disagreement of the BOA uncertainty with a mere power law for large AOT uncertainties, which for the RadCalNet arid sites could be of $U_{\text{AOT}} \sim 0.2 - 0.3$, adding around $U_\rho \sim 2 - 3\%$ at short wavelengths. This contribution demonstrates the need for a redefinition of the uncertainty requirements specification for L2A products for future hyperspectral missions for different AOT and wavelength ranges, as the EnMAP water spectral validation requirements definition (Table 2).

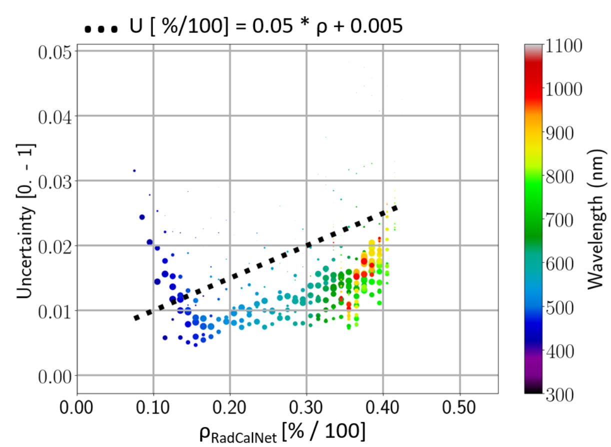

Fig. 2. Uncertainty of the DESIS BOA surface reflectance (color coded by wavelength) compared with RadCalNet Gobabeb in-situ measurements ($\rho_{\text{RadCalNet}}$) in [%/100] units.

Figures 3 and 4 show the level of agreement between multi- (Sentinel-2 and Landsat 9) and hyperspectral sensors (EnMAP) when the AOT at 550 nm estimation is below 0.06 with respect to AERONET (AOT$\sim$ 0.04) and the rest of sensors. The same agreement in the applied AOT ocurred during the EnMAP and DESIS overpass of Gobabeb RadCalNet site (Figure 4) on 02.10.2022. On that day, a high episode of biomass aerosols led to an AOT in-situ measurement of ~ 0.3, which is the default value applied in PACO for this particular arid site. The three hyperspectral measurements (EnMAP, DESIS and RadCalNet) are within 1 σ agreement, except for the first blue bands of DESIS. The same disagreement is visible at TOA level, indicating a calibration discrepancy at these wavelengths.

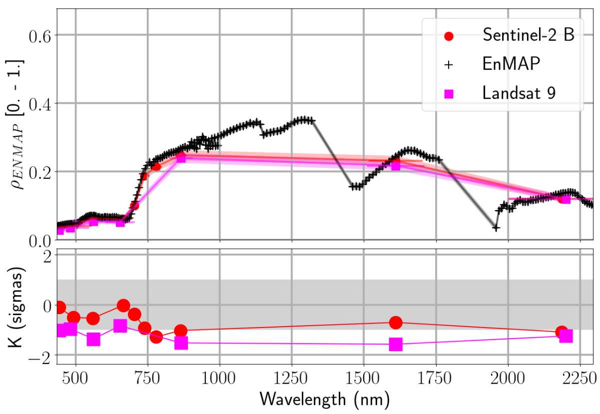

Fig. 3. Top: EnMAP (black cross), Sentinel-2 (red circle) and Landsat-9 (pink square) overpass over Sioux Falls (USA) on 30.08.2022 with an overpass difference of ± 1 hour. Bottom: coverage factor of the spectral difference between EnMAP spectra and the other sensors with respect to the expanded uncertainty of each pair of spectra. The shadow grey area corresponds to $K = \pm 1$ (1σ) [11]

4. L2A WATER LEAVING REFLECTANCE

The EnMAP normalized water-leaving reflectances are validated using as reference data the AERONET-OC [12] (Ocean Color) among others. Figure 5 shows an example of the EnMAP water leaving product in an overpass of the AERONET-OC station Venise on 16.07.2022, including their comparison with the EnMAP water requirements (Table 2)

Wavelength (nm)	AOT [@550 nm] < 0.4	> 0.4
400 - 450	0.04	0.05
450 - 650	0.02	0.03
650 - 800	0.01	0.02

Table 2. Uncertainty (as upper limit) of the EnMAP water leaving reflectance requirements.

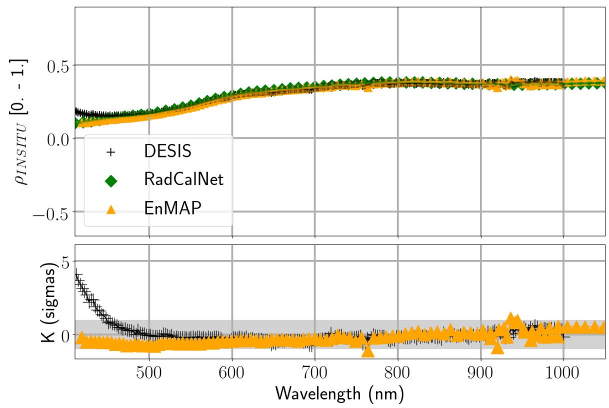

Fig. 4. Top: EnMAP (black crosses), DESIS (yellow triangles) and RadCalNet (green diamonds) overpass over RadCalNet site Gobabeb (Namibia) on 02.10.2022 with an overpass difference of ± 1 hour. Bottom: coverage factor of the spectral difference between EnMAP spectra and the other spectra with respect to the expanded uncertainty of each pair of spectra. The shadow grey area corresponds to $K = \pm 1$

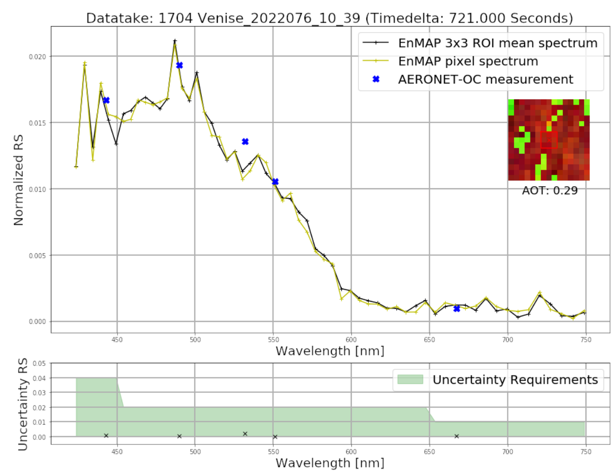

Fig. 5. Top: EnMAP spectra at AOT/Venise AERONET-OC geolocation on 16.07.2022 (yellow dashed) and 3x3 ROI around station (black line) and in-situ measurements (blue cross) with an overpass difference of 12 minutes. Bottom: EnMAP uncertainty water requirements (green ribbon) and uncertainty (RMSE) at in-situ measurement wavelengths (black cross).

5. CONCLUSIONS

Results of atmospheric correction with the PACO software, implemented as L2A processor in DESIS and EnMAP, show a good agreement between multi- and hyperspectral sensors. The measurements at BOA level are within the requirements, except at shorter wavelengths, where the power law as a function of the BOA spectra doesn't take into account other uncertainty sources at specific wavelengths like aerosols.

An expression of the land requirements similar to the EnMAP water requirements would allow atmospheric uncertainties to be included in the BOA requirements and it would also harmonize the L2A missions requirements.

Further CalVal acquisitions under large AOT conditions would provide enough statistics to define them as a function of the AOT ranges.

6. ACKNOWLEDGEMENTS

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