BOA REFLECTANCE BASED DEAD AND DEFECTIVE PIXEL INTERPOLATION IN THE ENMAP GROUND SEGMENT PROCESSING CHAIN

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ABSTRACT

The EnMAP mission, launched in April 2022, is a remote sensing in the optical domain (VNIR / SWIR) with a high spatial (30 m GSD) and spectral (FWHM ~ 6-12 nm) resolution. In general, remote sensing data can suffer from pixel defects caused by various factors like aging, component degradation, vibrations, and transmission failures. These defects result in missing or low-quality data, non-uniformity effects, and out-of-range radiance values. To address this, interpolation techniques are applied during data processing, both at the TOA radiances and intermediate BOA reflectance spectra levels. The interpolation implemented in EnMAP aims to improve the accuracy of derived spectral products by not only correcting defective pixels, but additionally, reconstructing datasets with missing bands, taking advantage of the high spectral/spatial resolution of this data. The algorithm's performance is evaluated by comparing the results with reference values and with more traditional interpolation methods, like for example the one used by the DESIS sensor. The study also explores the algorithm's capabilities in scenarios involving partial loss of radiance data.

Index Terms— EnMAP, DESIS, hyperspectral, remote sensing, dead pixel interpolation

1. INTRODUCTION

The high-resolution imaging spectroscopy remote sensing mission ”Environmental Mapping and Analysis Program” (EnMAP) [1] was successfully launched on April 1st, 2022 and entered operational phase on November 2nd, 2022.

The data acquired by remote sensing platforms might be affected by different types of pixel defects, due to aging, degradation of electronic components, mechanical vibrations and data transmission failures [2]. These can produce from missing to low quality data (i.e. low- and high-gain linearity effects, non-uniformity effects (photo-response non-uniformity (PRNU), dark-signal non-uniformity (DSNU)) as well as low and high radiance values outside of the allowed dynamic range). In addition, sensor noise can reduce the quality of the data in some pixels in strong atmospheric absorption spectral regions. In particular in strong atmospheric absorption regions the narrow spectral bands may suffer from low signal to noise values.

This paper gives a description of the dead and defective pixel correction algorithm as implemented in the EnMAP L1B processor. Results are evaluated intrinsically by generating artificial dead-pixel maps, masking healthy nominal pixels of an acquired EnMAP datatake in order to be able to compare the interpolated results with valid reference values. Further interpolation results are extrinsically and quantitatively compared to the dead-pixel interpolated processor output of the DESIS hyperspectral sensor, for which dead-pixel correction is conducted by common means of interpolating in spectral dimension on top-of-atmosphere (TOA) radiances and only on hardware-based defects (in contrary to the EnMAP dead and defective pixel masks which includes quality flagging). Additionally, the dataset is artificially damaged to simulate partial loss of the radiance data to present the overall performance of the dead-pixel correction reconstruction capabilities within the frame of the file and data deletion conditions.

2. METHODS

While both dead-pixel interpolation algorithms implemented in the DESIS and EnMAP processing chains, rely on common and well-known estimation techniques taking spectral and spatial similarity into account, the main sdifference between them lies in the domain in which the particular interpolations are applied.

One first approach is the linear interpolation in spectral dimension on TOA radiances due to the straight forward and fast application. This method is used i.e. in the ground segment processor of the DLR Earth Sensing Imaging Spectrometer (DESIS) [3]. An interpolation on that data level may lead to large estimation errors due to the variability of the signal, that propagate to derived spectral products i.e. L2A ground reflectance. Therefore, within the EnMAP ground segment processor, an interpolation is applied to defective pixels in spectral dimension on intermediate bottom-of-atmosphere (BOA) reflectance spectra based on the original TOA radiance, obtained by a simplified atmospheric correction as applied by the DLR internal atmospheric correction software PACO [4] (implemented both in the DESIS and EnMAP ground segment processor). This is done to exploit the smoothness of BOA reflectance spectra, which has a positive influence on the overall accuracy of the interpolation process.

2.1. DESIS dead-pixel interpolation on TOA radiances

The DESIS processor performs an interpolation of flagged abnormal pixels on L1B level before continuing with systematic corrections. This interpolation aims to minimize the impact of the abnormal pixels in the final processing steps of the L1B processor which also perform several interpolation procedures over the image in order to correct systematic effects like rolling shutter, smile, and keystone. The hybrid interpolation method for abnormal pixels selects the optimum value between spectral and spatial cubic spline interpolation. The selection criterion is based on the spectral gradient difference between the interpolated pixels and spatial neighbors.

2.1. EnMAP dead-pixel interpolation on BOA reflectance

In the course of the EnMAP ground segment data processing the abnormal (defective) and dead pixels are detected based on the calibration measurements and on individual datatakes. Dead and defective pixels are then corrected by interpolation during the L1B processing step, implemented as the so called L1B_int subprocessor.

The motivation is to be able to perform any spectral interpolation steps within the processors on BOA reflectance as these reflectance spectra are generally smoother than the expected TOA radiance spectra and therefore are considered to promote better interpolation accuracy. Two different interpolation steps are applied during the EnMAP processing chain after retrieving surface reflectance in L1B_int.

In the case of a smile affected sensor and activated smile correction, an interpolation of the column wise retrieved surface reflectance to the nominal wavelength of each particular band is applied. This is necessary as the surface reflectance in the case of occurring smile up to this point in the chain represent the reflectance related to the shifted wavelengths per column per band.

An interpolation of dead and defective pixels is always conducted. The information on which pixels to interpolate is provided by a binary mask flagging dead pixels and defects generated during L0 processing. By design the interpolation is applied to surface reflectance and in spectral dimension to exploit the high spectral resolution of the EnMAP sensors and as these spectra are considered smoother in comparison to top-of-atmosphere radiances.

After interpolation, the atmospheric correction process is inverted, only in the interpolated values, resulting in original plus interpolated TOA radiance. Further, an extended procedure was implemented for the dead-pixel interpolation algorithm to address the problem of data and file deletion due to transmission errors, where whole and multiple consecutive bands may be missing from the hyperspectral data cube. This spectral and spatial, surface reflectance based and distance weighted interpolation method is able to reconstruct damaged datasets (dependent on the extend of the loss) to a certain degree, thus helping to restore usability.

3. DATA

The data used in the on-hand paper consist of a single EnMAP scene, acquired over the bay of Venice on the 16th July 2022 during the commissioning phase of the EnMAP mission.

As the EnMAP L1B product is used to perform the presented analysis, the VNIR und SWIR hyperspectral cubes are provided in sensor geometry, and are processed separately. The VNIR cube comprises 91 spectral bands from 418.24 nm to 993.08 nm, the SWIR cube consists of 130 spectral bands from 902.26 nm to 2445.53 nm. Both have spatial extends of 1000 pixels in x- and 1024 pixels in y-dimension, with a ground sampling distance (GSD) of 30 meters. With a total number of 2 and 680 dead pixels in the VNIR and SWIR, abnormal pixels make up 0.002% and 0.511% of the whole sensors respectively. This dataset is used for both interpolation approaches.

4. EXPERIMENTS

As the nominal radiance values of the pixels flagged as abnormal in the original scene are unknown, in order to enable the evaluation and comparison of the two interpolation methods nominal pixels were artificially flagged as dead and defective in both hyperspectral cubes and then compared with their original values.

To also test the performance of the algorithms on corrupted and damaged datasets, with partially or fully missing consecutive bands, three different cases, namely normal, corrupted and damaged were produced and processed.

It has to be noted that correction of systematic effects like rolling shutter and keystone was deactivated for the DESIS TOA interpolation algorithm, as they do not occur in the used dataset. This also accounts for smile correction which was deactivated for both, the DESIS and the EnMAP interpolation algorithm used in this work.

5. RESULTS

Figure 1 shows the scatter plots between interpolated and reference dead pixel values for the scenes VNIR and SWIR cube for the *normal* case, where bands are affected by single stripes of dead pixels not showing consecutive missing values over several bands in spectral dimension.

While both algorithms show an overall high correlated between interpolated and target radiance values, the TOA approach shows several systematic outliers (red points outside the 1:1 line in Fig 1), which is connected to the noisiness of certain TOA radiance spectra due to atmospheric absorption and scattering effects as well as extrapolation errors if pixels are missing in the first and last band of the respective cubes spectral range. The BOA approach as implemented in the L1B_int processor can handle these difficult cases better due to the absence of atmospheric effects on BOA reflectance and an applied spatial interpolation in border bands to reduce extrapolation errors (green points in Fig 1). Therefor it provides the overall more accurate and satisfying results already to the L1B and L1C users.

Figure 2 shows the same scatter plots for the *corrupted* case where 200 spatial lines of 10 consecutive bands are missing as well as for the *damaged* case which misses 20 whole, consecutive bands, in particular in the spectral border regions.

The correlation between interpolated and target values decreases strongly with the level of data degradation. For these cases the EnMAP dead-pixel interpolation algorithm also clearly outperforms the TOA approach, restoring large amounts of missing consecutive radiance values in the spectral dimension more accurately, which may enable users to use even non-nominally damaged scenes for application, depending on the degree corruption.

Table 1 presents the root mean square (RMSE) error between interpolated and reference for all cubes and cases, showing the better performance of the EnMAP dead-pixel interpolation algorithm. The level of corruption is expressed in % of pixels flagged for interpolation per cube.

Dataset case Lvl of corruption	**TOA Interpolation**	**BOA Interpolation**
normal VNIR 0.12 %	0.177984	0.056853
normal SWIR 0.06%	0.154285	0.011743
corrupted VNIR 3.21%	0.340392	0.135841
corrupted SWIR 2.20%	0.337915	0.086646
damaged VNIR 34.06%	1109.549561	0.402647
damaged SWIR 24.81%	17.470013	0.084542

Table 1. RMSE (in mW cm-1sr-1um-1) of interpolated pixels in final L1B product for TOA (DESIS) and BOA (EnMAP) based dead-pixel interpolation with respect to different levels of data corruption.

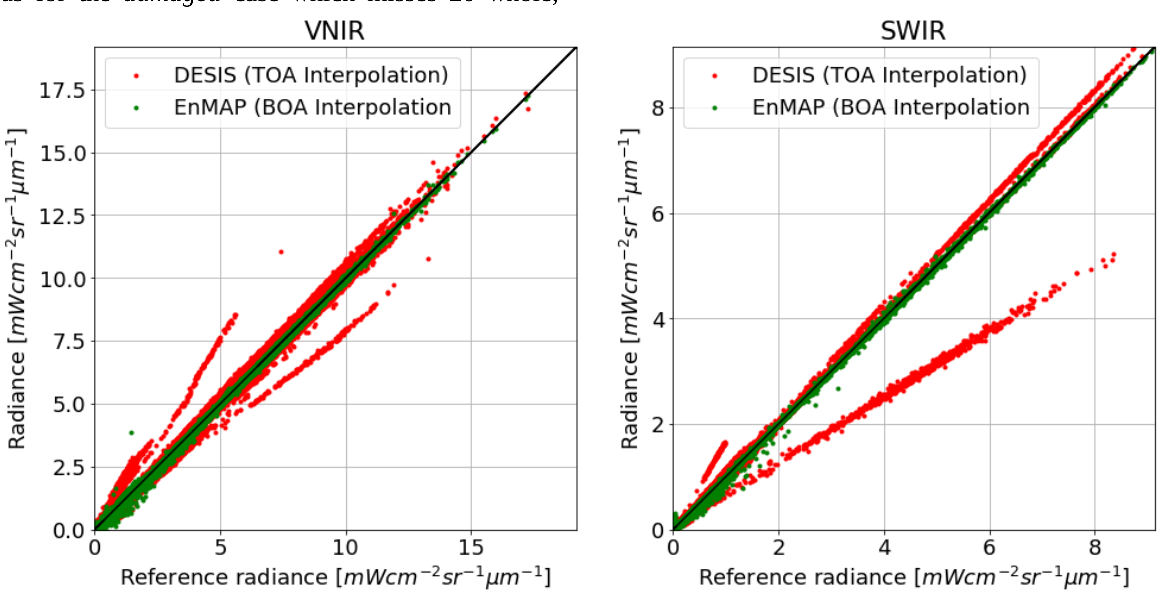

Figure 1. Scatterplot of VNIR (left) and SWIR (right) interpolated dead / abnormal pixels using DESIS (red) and EnMAP (green) interpolation algorithm. The diagonal (black) shows the target line of the reference values.

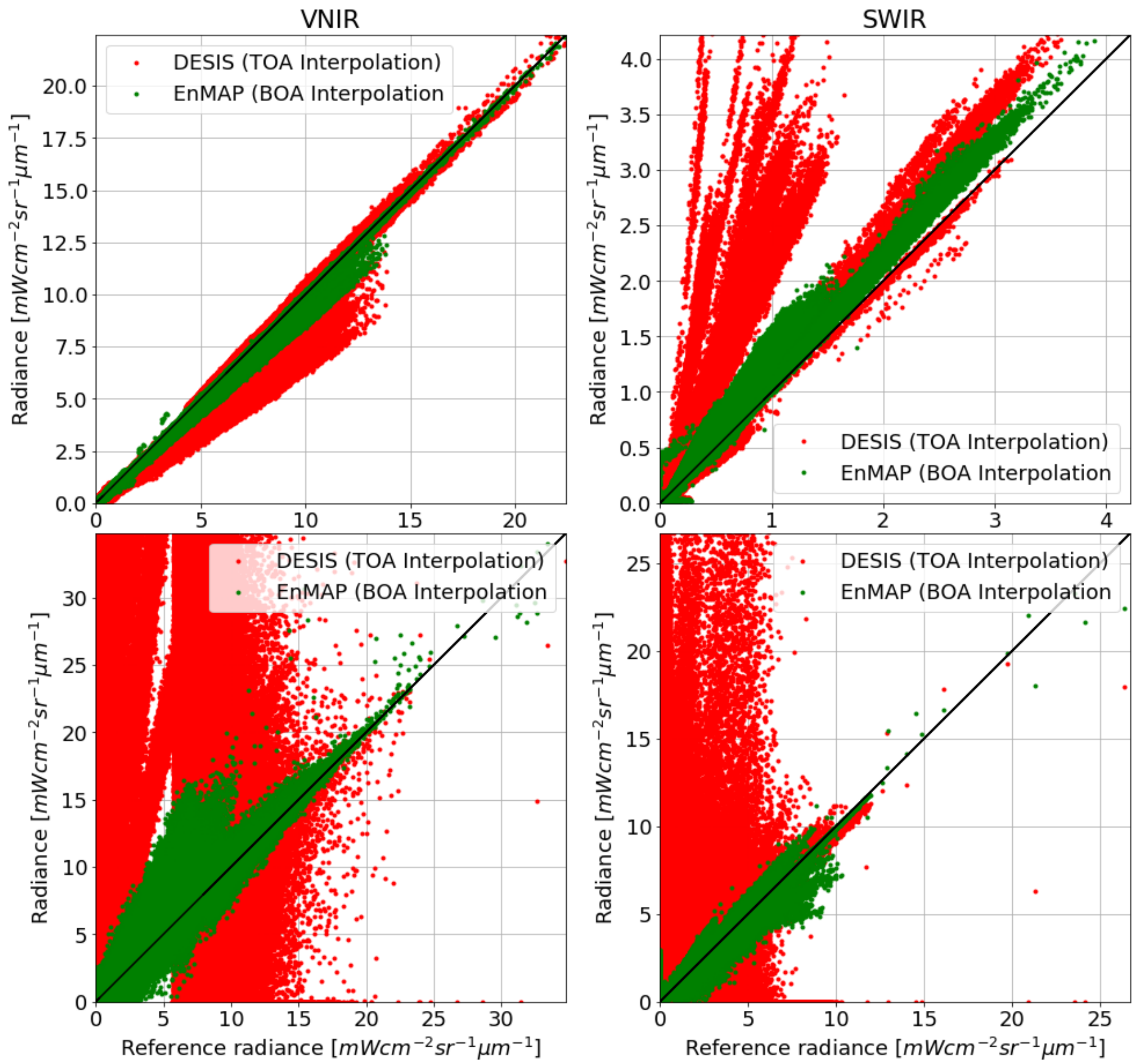

Figure 2. Scatterplot of corrupted (top) and damaged (bottom) cases for VNIR (left) and SWIR (right) interpolated dead / abnormal pixels using DESIS (red) and EnMAP (green) interpolation algorithm. The diagonal (black) shows the target line of the reference values.

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