FORWARD SIMULATION OF HYPERSPECTRAL REMOTE SENSING IMAGES IN THE FRAME OF THE ENMAP MISSION

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ABSTRACT:

The simulation of remote sensing images is necessary for many tasks, such as the definition of future Earth Observation systems, the optimization of instrument parameters, and the development and validation of data processing algorithms. The presented hyperspectral scene simulator has been developed in the frame of the Environmental Mapping and Analysis Program (EnMAP) mission. It consists of four processing modules producing EnMAP-like reflectance, radiance and digital counts data by means of a sequential processing. As input serve simulated high spectral and spatial resolution reflectance data with realistic surface patterns provided by real remote sensing data. This input reflectance is converted to Top-of-Atmosphere radiance data by an atmospheric radiative transfer model capable of simulating different acquisition scenarios and atmospheric conditions. The sensor geometry is adapted to the EnMAP orbit and operating characteristics. Spatial aberrations such as keystone, telescope distortion and smile and co-registration are all considered in the spatial processing (spatial module). The generated high spectral resolution radiance data are used to generate the final EnMAP images after simulation of the instrumental spectral and radiometric responses.

1. INTRODUCTION

The Environmental Mapping and Analysis Program (EnMAP) (Kaufmann et al., 2008) German hyperspectral mission is intended to provide more and better information about the Earth system than multispectral instruments. EnMAP is designed to sample areas of 30 km x 30 km with a ground sampling distance (GSD) of 30 m, measuring in the 420-2450 nm range by means of two entirely independent prism-based spectrometers covering the visible to near-infrared (VNIR) and the short-wave infrared (SWIR) spectral regions. The mean spectral sampling distance (SSD) and resolution is of 6.5 nm in the VNIR, and of 10 nm in the SWIR. Accurate radiometric and spectral responses are guaranteed by a required signal-to-noise ratio (SNR) about 500:1 in the VNIR and 150:1 in the SWIR for a given mission reference radiance level, radiometric calibration accuracy better than 5% and spectral calibration uncertainty of 0.5 nm in the VNIR and of 1 nm in the SWIR. An across-track pointing capability of up to 30° enables a target revisit time of 4 days. The orbit has a repeat cycle of 23 days, providing global coverage for view zenith angles (VZAs) smaller than 5°. The EnMAP mission entered into the construction phase (phase-C) in November 2008, while the launch is currently scheduled for 2013. A detailed description of the last EnMAP design can be found in Sang et al., 2008.

From the scientific perspective, current EnMAP preparatory activities are focused on the support of mission requirements consolidation and instrument concept development. There is a need for realistic understanding of the effects of different instrument and environmental parameters on scene characteristics (Boerner et al., 2001; Kerekes et al., 2005, Schlaepfer et al, 2007, Verhoef and Bach, 2003). For those reasons, we have designed and implemented a scene simulator for optical remote sensing data, with especial emphasis on EnMAP data simulation (Guanter et al., 2009). The present approach intends to address the entire simulation process carefully, from spatially- and spectrally-oversampled reflectance and atmospheric data to the final DN data convolved to the instrument's spatial and spectral responses. Especial attention has been put on the challenging task of the accurate simulation of non-uniformities in the spatial domain, such as keystone and spectrometer co-registration, as it was requested by the EnMAP double-slit concept during the instrument design phase. Moreover, in order to make the simulated images to be a useful reference data set for pre-processing and scientific algorithms development, a considerable effort has been put on the recreation of a range of environmental conditions. Different natural environments, including vegetation, bare soil, mineral-rich areas and water bodies, have been generated following realistic spatial distribution patterns. Cloud covers, cloud shadows and multitemporal acquisitions are also generated.

2. ENMAP SCENE SIMULATOR

The forward scene simulator is implemented in a modular and flexible way and can be applied to different optical sensors (Figure 1). However, some of the processing steps are optimized for the EnMAP configuration.

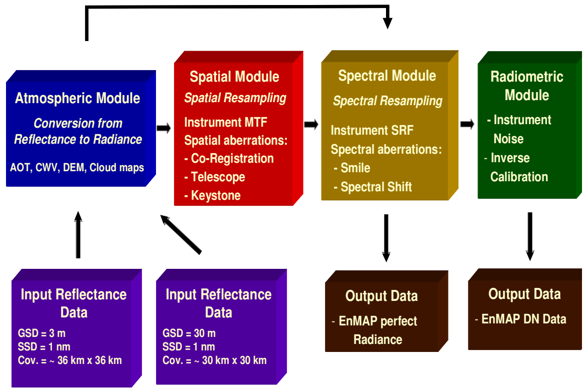

Figure1. Schematic view of the simulation flow in the EnMAP scene simulator

2.1 Input Data

As input serve reflectance data representing the earth surface to be scanned by the sensor and a DEM. The spectral resolution should be $\leq$ 1 nm and the spatial resolution $\leq$ 3 m in order to enable the proper convolution to the instrument spectral response function (SRF) and point spread function. The dimension of the image should be about 36 km x 36 km, instead of the final 30 km x 30 km, to enable the simulation of sensor rotations. As such spectrally and spatially over-sampled data do not exist, they have to be simulated. Realistic images can be achieved e.g. by the combination of spatial patterns from high resolution multispectral data with spectra from field and laboratory measurements using the MESMA spectral unmixing approach (Roberts et al., 1998). As a second option, data with a GSD of 30 m can also be used if no spatial analysis is of interest. Such data can be easily simulated based on Landsat, PROBA/CHRIS and Hyperion data archives.

2.1 Atmospheric Module

The atmospheric module converts surface reflectance to TOA radiance considering the orientation of the sensor towards the sun, pixel-wise horizontal distribution of aerosol optical thickness (AOT) and columnar water vapour (CWV), surface elevation, and cloud covers and shadows. Lambertian reflectance is assumed to be sufficient for the instrument optimization and development of algorithms for single-view data. Atmospheric parameters are calculated on-line during each simulation using the ATLUT program (Guanter et al., 2008) that decouples atmosphere and surface contributions by means of some algebra performed over MODTRAN4 outputs (Berk et al., 2003).

2.2 Spatial Module

The spatial module records the pixel information simulating a flight over the artificial reflectance surface (Figure 2).

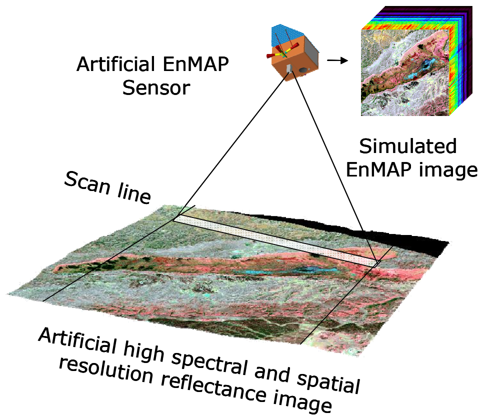

Figure 2. Spatial simulation approach

In the first step the projection of each detector element on the ground has to be calculated for 1 nm bands. The pointing results from the composition of the satellite position and attitude (roll, pitch, yaw) with the attitude (roll and pitch) of each detector element. The latter includes spatial aberrations such as the telescope distortion and smile as well as the keystone (Mouroulis et al., 2000). Keystone is a lateral chromatic aberration intrinsic to pushbroom imaging spectrometers like EnMAP. It is characterized by a shift of each pixel along the spatial direction of the detector array with wavelength. The spatial simulation is performed for each detector separately as EnMAP consists of two completely independent spectrometers. The separation of the field-of-view at the spectrometer entrance is achieved by means of a double slit, recording corresponding pixels with a time delay of 86.7 ms (~ 600m) between VNIR and SWIR detector. Hence, co-registration errors arise with a size of up to 1.5 pixels due to the earth rotation and pointing stability of the platform. Once, the pointing of a detector element is determined the spatial recording of the pixel is performed. This process is characterized by the convolution of the spectral surface information with the point spread function (Schläpfer et al., 2007) along and across track. Their characteristics are defined by the modulation transfer function (MTF) in the Fourier domain incorporating the optical, detector, vibration and motion MTF of the system.

2.3 Spectral Module

The spectral module performs the spectral resampling from the 1 nm resolution to the EnMAP spectral configuration. This involves the simulation of the instrument SRF, the spectral resolution and spectral sampling distance, as well as the spectral non-uniformity, given by smile and spectral shift. Gaussian functions are used to simulate EnMAP SRFs. Smile is an optical aberration typical of pushbroom systems, which causes the spectrometer entrance slit to be projected as a curve on the rectilinear detector array (Mouroulis, 2000). This originates a combination of bending of spectral lines across the spatial axis, known as smile, which leads to the non-linear variation of spectral channel positions along the spatial direction of the detector array. Apart from smile, the mechanical misalignment between the instrument slit and the detector array can also result in a systematic spectral shift which is constant for all the spectral channels and across-track positions in the spectrometer.

2.4 Radiometric Module

The radiometric module adds noise to the spectrally resampled TOA radiance data and performs inverse calibration in order to generate calibration coefficients and the final DN images. Since no detailed model of the instrument electronics is yet available, only multiplicative Gaussian-distributed noise processes are assumed, whose magnitude is given by the SNR requirement in the MRD (about 500:1 in the VNIR, 150:1 in the SWIR). Spatially coherent noise (striping), as well as dead-pixels (those providing a constant read-out) and bad-pixels (those providing a wrong read-out), are simulated according to input values defining the magnitude of striping and the ratio of number of dead/bad pixels to number of normal pixels. Striping and dead and bad-pixels are randomly distributed within the across-track dimension and the complete 2D space, respectively.

3. EXEMPLARY RESULTS

The scene simulator has already been applied to the generation of a number of EnMAP-like images under a range of natural environments, atmospheric and instrumental configurations. A false colour composite of the Makhtesh Ramon geological site in Israel is displayed in Figure 3. The image represents EnMAP DN data showing the miss-registration of the two detectors caused by the time delay, earth rotation, pointing stability and other spatial aberrations. The spatial correction of all these effects within a parametric orthorectification is a challenging task and depends on the accuracy of the sensor and orbit parameters.

The result using perfect parameters is depicted in Figure 4 showing an optimal pixel co-registration. Spatial simulations are very useful to optimize different pre-processing steps such as the best resampling strategy or automatic co-registration.

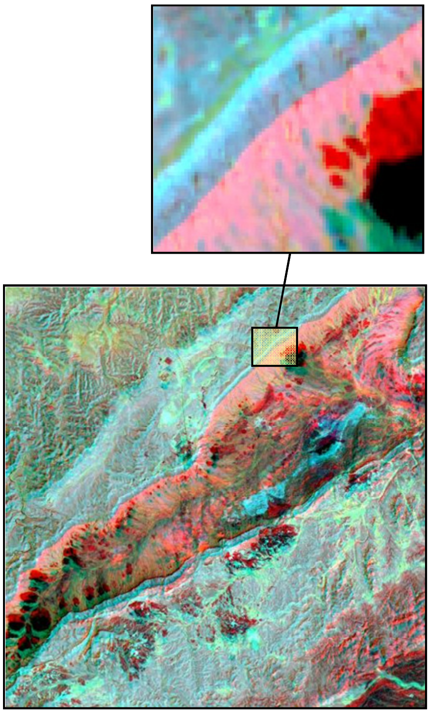

Figure 3. Simulated Makhtesh Ramon – Israel (RGB 2200/800/450 nm

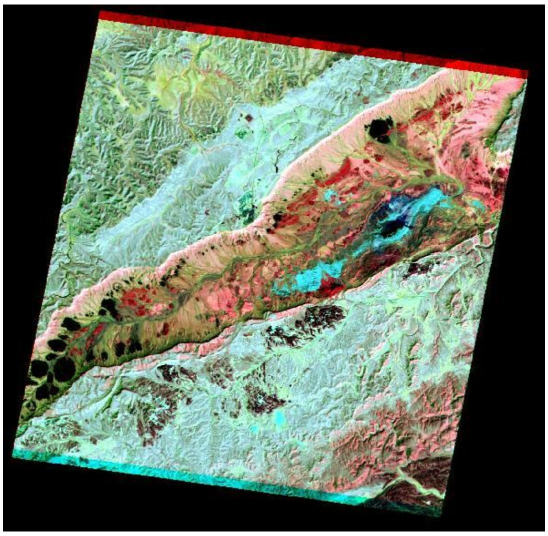

Figure 4. Orthorectified data

Landsat data from two different acquisition dates were used as input in the simulator to create a multitemporal series of the Munich alpine foreland (Figure 3). No spatial simulation has been performed on them (second input option). Different realistic cloud covers were simulated for the two dates within the atmospheric simulation process.

Figure4. Simulated multitemporal munich alpine foreland (Germany): 22.07.2006 (centre) and 10.10.2006 (lower) – RGB 660/530/450 nm

3. CONCLUSIONS

A new tool for the simulation of realistic EnMap data has been presented in this paper. The scene simulator is built according to a modular structure. Four main processing modules are used for the derivation of the final TOA radiance and DN images. The simulator is still a work in progress and improved whenever new details become forthcoming. Some of the modules e.g. the spatial and spectra module reached already a high accuracy. The radiometric module still relies on numbers defined in the MRD but will be improved by a detailed model of the instrument electronics in the near future. The development started during the definition phase of the EnMAP German hyperspectral mission in order to assist the system concept definition. The simulator contributed to the successful optimization of the instrument parameters such as MTF, keystone, spectral smile, spectral sampling distance, spectral width and definition of high and low gain. For the future there exists already a demand for the generation of an EnMAP-like data to serve as a test bench for algorithm development for both the pre-processing and the scientific exploitation of the data.

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