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Development of generic scene generator for the study of plant covers in passive optical missions.

Desarrollo de un generador de escenas genérico para el estudio de las cubiertas vegetales en misiones ópticas pasivas.

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ABSTRACT

The simulation of synthetic images serves scientists and engineers to study the instrument configuration as well as to develop image processing and retrieval strategies for a sensor in development. Despite synthetic scene simulators have been developed in the past in the frame of satellite missions, their functionality and flexibility to create a user-defined scene is limited by their architecture, design and implementation. This paper introduces the design of a generic scene simulator with the flexibility to generate realistic synthetic scenes by configuration of the surface and atmosphere. Following this generic design, a scene simulator is being developed for the ESA's Earth Explorer 8th candidate mission FLEX in order to reproduce the high spectral resolution signal acquired by its hyperspectral instrument. The proposed design and architecture can be adapted to any other passive optical space and airborne instruments.

Keywords: Scene simulation, radiative transfer models, fluorescence, FLEX, mission simulator.

RESUMEN

La simulación de escenas sintéticas es útil para que científicos e ingenieros estudien la configuración de instrumentos científicos así como desarrollen estrategias de procesado de imagen para un sensor en desarrollo. A pesar de que los simuladores de escenas sintéticas han sido desarrollados en el pasado en el marco de varias misiones espaciales, su funcionalidad y flexibilidad para crear una escena definida por el usuario es limitada dada su arquitectura, diseño e implementación. Este artículo introduce el diseño de un simulador de escenas genérico con la flexibilidad de generar escenas sintéticas realistas mediante la configuración de la superficie y la atmósfera. Siguiendo este diseño genérico, un simulador de escenas está siendo desarrollado para la misión FLEX, candidata para el octavo Earth Explorer del Living Planet Programme de la ESA. El objetivo de este simulador es de reproducir la señal de alta resolución espectral que será adquirida por su instrumento hiperespectral (FLORIS). El diseño propuesto y su arquitectura pueden adaptarse a cualquier otro sensor óptico pasivo en plataformas espaciales y aerotransportadas.

Palabras clave: Simulador de escenas, modelos transferencia radiativa, fluorescencia, FLEX, simulador de misiones

1. INTRODUCTION

The latest technological advances in optical sensors have improved the acquisition of the electromagnetic signal over a much finer Spectral Sampling Interval (SSI) and spectral resolution developing a discipline known as hyperspectral remote sensing. The high spectral resolution of the acquired data by these sensors allows monitoring details on the reflected signal due to variations of the biophysical and atmospheric parameters that were not available with the broader band multispectral sensors. This detailed spectral information, in combination with state-of-the-art algorithms, is improving the image classification results and the retrieval of atmospheric and bio/geophysical parameters. While these sensors have been broadly used in airborne platforms such as the ITRES' CASI or the Specim's AISA family spectrometers, it is not till now that hyperspectral sensors are being developed for spaceborne platforms. DLR's EnMAP mission, ASI's Hyperspectral Precursor and Application Mission (PRISMA), NASA's HyspIRI or ESA's Fluorescence Explorer (FLEX) mission (Drusch *et al.* 2011) are a few examples of the hypserpectral space missions being studied or proposed.

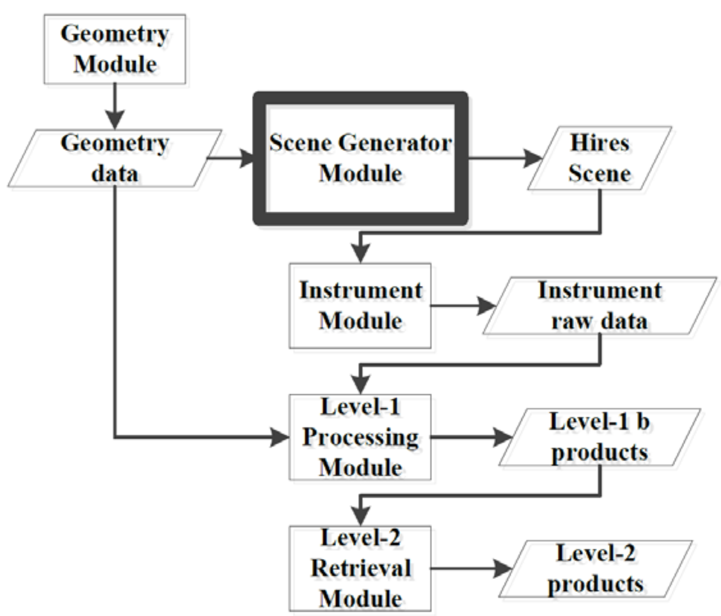

Figure 1. Location of the SGM within a single-instrument/platform mission E2ES**.**

Developing a space mission requires a close interaction between engineers, scientists and end-users in order to translate the user requirements into mission and instrument technical specifications. Thus, the development of End-to-End Mission Performance Simulators (E2ES) is lately being proposed on several ESA activities (Negueruela *et al.* 2012). An E2ES is a set of algorithms and software tools reproducing the planned mission configuration to assess mission performance; consolidate technical requirements and system implementation; and analyse the suitability of the developed retrieval schemes. E2ES are being designed in a modular fashion to separate between the platform, instrument, scene and image processing issues. Among the different modules composing an E2ES, the Scene Generator Module (SGM) is particularly important as it simulates the synthetic scenes to be acquired by the instrument and later processed up to Level-1b and Level-2 (see Figure 1).

The work presented here describes the design and development of a SGM for hyperspectral passive optical missions in the frame of the ESA's Earth Explorer 8th candidate, the FLEX mission. Section 2 will address the definition and configuration of synthetic scenes, covering both the atmosphere and surface. Section 3 will focus on the coupling between the atmosphere and surface radiative transfer models to simulate the Top-Of-Atmosphere (TOA) radiance signal to be acquired by the instrument. As case of study, the simulation of a synthetic scene for the FLORIS/FLEX sensor will be given in Section 4 showing the potential of the designed and implemented SGM.

2. SCENE GENERATOR MODULE: DEFINITION AND CONFIGURATION

The SGM is in charge of simulating the scene to be observed by an instrument. For passive optical mission, the scene is understood as a Top-Of-Atmosphere (TOA) radiance map given at a spectral/spatial resolution finer than the instrument's response function. The generation of these synthetic scenes includes the distribution of bio/geophysic and atmospheric parameters over the scene map. In addition, the SGM takes also into account the surface topography and the observation/illumination geometry conditions. All these parameters and environmental conditions serve as input for the generation of TOA radiance maps through the use of surface/atmosphere Radiative Transfer Models (RTM) or from external radiometric data (e.g. reflectance, fluorescence and/or TOA radiance spectral databases or external image files).

For simulators developed in past, the scene was defined as seen by the sensor focal plane geometry. The SGM proposed here generates an equispaced grid oriented north-south defined by user-selected location and epoch. This common grid keeps the consistency in the scenes generated for different instrument/platforms flying over it, such the case of FLEX/Sentinel-3 tandem mission, since the distribution of parameters is the same for all sensors.

This section focus on the surface/atmosphere definition and configuration distributing the input parameters for the later execution of a RTM and/or selection of external radiometric data.

2.1 Surface definition and configuration

The surface definition and configuration is related with the distribution of surface-related parameters for each grid point of the scene map. These parameters include classical vegetation leaf/canopy biophysical parameters such as Leaf Area Index (LAI) and Chlorophyll-a (Chl-a) content or proportion of surface types. The distribution of these parameters attends to the surface type (e.g. water, vegetation, urban\lots) of each scene grid point classified through a land-cover map. Thus, the configuration of a scene focuses firstly on the definition of a land-cover map. Different land-cover maps have been implemented in the FLEX SGM: 1) Corine Land Cover (CLC); 2) external; and 3) artificially generated. Each option generates a land-cover map based on patches of different surface types. The global coverage of the CLC automatically associates the location of the scene with given land-cover map.

Each land-cover class is then related to a database defining the spatial and statistical distribution of each parameter needed for the execution of a RTM and/or its surface spectra. The parameter distribution between patches is defined by the central value of the statistical distribution for each patch and limited to min.-max. values. Each individual patch will then follow a geometrical distribution (see Figure 2) with the defined statistical distribution (e.g. gaussian, poisson, exponential…). An example of the information contained in the parameters database is given in Table 1.

Table 1 Example of the content of the parameters database.

Feature	Value
Class name	Vegetation1
Biophysical Parameter	LAI
Range [Min, Max]	[1 - 4]
Statistical distr.	Gaussian
RTM	SCOPE
Intraclass distr.	Concentric
Extraclass distr.	Linear

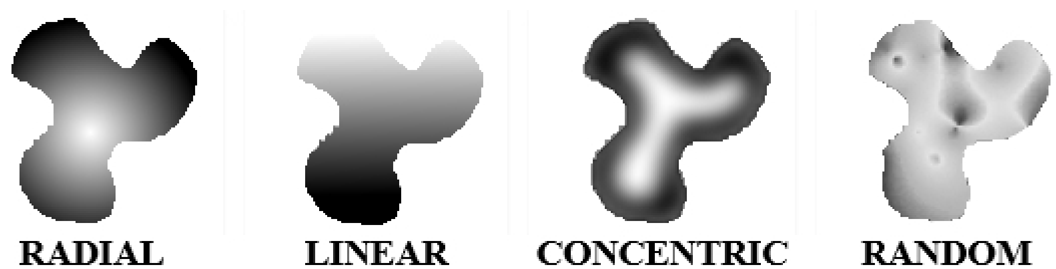

Figure 2 Examples of parameter distribution within a patch.

Alternatively, the database can associate a surface reflectance/fluorescence spectrum included in a spectral database to a given class. Several spectral databases have been integrated in the SGM software that includes spectra for man-made objects, bare soils, snow/ice, water bodies, etc. The user could associate a land-cover class with the spectrum acquired during a field campaign and store its own spectral database.

2.2 Atmosphere definition and configuration

Due to the importance of the absorption and the scattering processes of solar radiation in the atmosphere, the spatial distribution of the absorption species and the aerosols will be a key task in the scene generation. Considering the natural spatial distribution of the oxygen and the carbon dioxide gases, and taking into account the spatial resolution and the area covered by FLEX, around 150km, in this case no modifications of the gas concentration are going to be allowed for O2, O3 and CO2. On the contrary, variations in the concentration of other absorption species such as the water vapour are going to be permitted by the user.

Otherwise, the aerosols spatial distribution is going to be performed modifying, on one hand, the AOT and on the other hand, the aerosol types according to the underlying surface nature.

The atmospheric parameters should also be distributed over each scene grid point of the scene map. Without loss of generality, and considering that MODTRAN5 is the atmospheric RTM used in the SGM, the list of atmospheric parameters is reduced to three main groups: atmospheric model, aerosols and cloud cover.

The **atmosphere** type or model is selected, based on the scene location and epoch, from the standard atmospheres available in MODTRAN5 (i.e. Mid-Latitude Summer/Winter, Tropical and Sub-Artic Summer/Winter). Each atmospheric type is defined by its temperature/pressure and gas-concentration profiles. Only the Content of Water Vapor (CWV) is modified with respect their default values due to their spatial and temporal variability and their impact on the FLEX mission products. The concentration of these gases is taken from the ECMWF's MACC re-analysis total Column Water datasets given the scene location and epoch. Alternatively, the user can select among the different atmosphere types and set the values for the CWV. These values are then distributed over the scene taking into account the surface topography.

The distribution of **aerosols** types (i.e. rural, urban, maritime and desert) over the scene is associated with each surface class. As for the CWV, the amount of aerosol at the scene location and epoch is taken from the MACC re-analysis total Aerosol Optical Depth at 550nm and distributed considering the surface topography. The SGM includes the option of a user-defined aerosol type, distribution and content. Additional aerosol types are defined, as first approximation, by setting their Anstrong exponent and the Henyey-Greenstein phase function isotropy parameter.

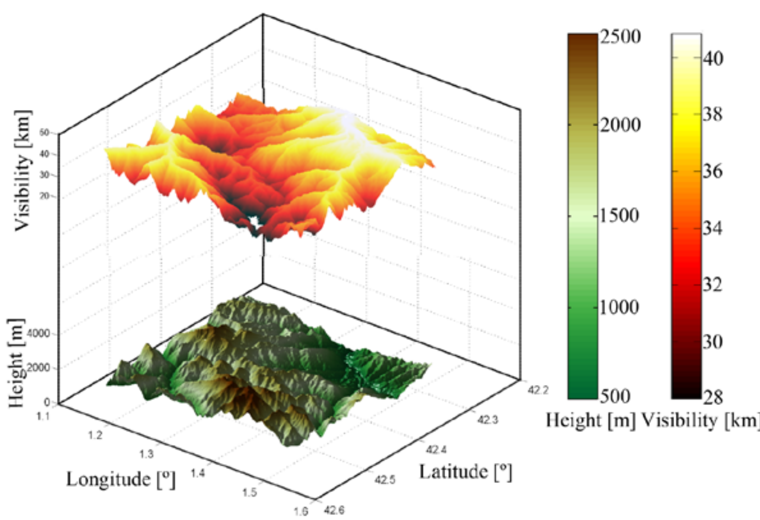

Figure 3. Aerosol content distribution considering the surface topography.

Realistic simulation of 3-dimensional **clouds** at sub-pixel resolution is computationally expensive and out of the scope for FLEX E2ES. The simulation of bright homogeneous clouds is sufficient to study the effects of adjacency and stray-light on the acquired signal and to investigate algorithms for its correction. A spatial cloud pattern database has been created based on the MODIS MOD35 cloud product (see Figure 4). This database contains a set of cloud maps defined by cloud cover percentage, each of them with three cloud types. For a given scene, the user selects the cloud coverage and sets the cloud types among the available options (i.e. cumulus, stratus, stratocumulus and nimbostratus). The cloud optical properties are set to MODTRAN5 default values and their base altitude and thickness are modified according to the scene latitude. In addition, shadows projected by clouds are simulated to modify the solar irradiance at the surface. The wind fields' information from the MACC re-analysis data is included in the SGM to simulate the motion of the cloud pattern between the images acquired by different sensors as in the case of FLEX and Sentinel-3 sensors.

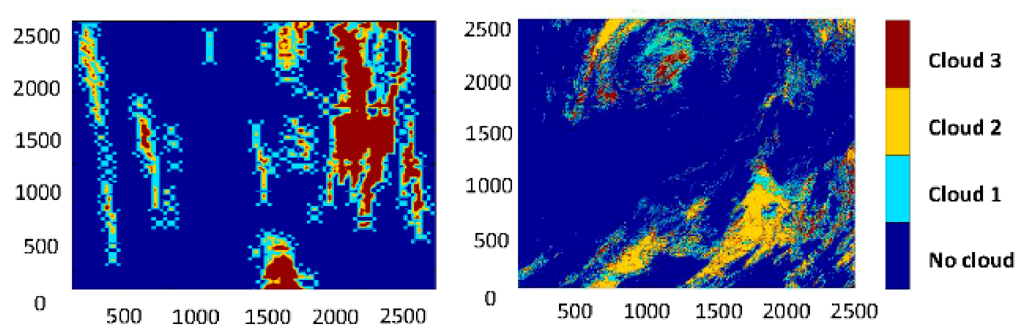

Figure 4 Example of different cloud masks with a cloud cover of 26% with a spatial sub-pixel resolution of 30m (left) and 100 m (right).

3. COUPLING BETWEEN SURFACE AND ATMOSPHERIC RADIATIVE TRANSFER MODELS

The SGM uses the distributed surface and atmospheric parameters (see Section 2) to calculate the synthetic TOA radiance map in the scene. Several options are contemplated for the generation of the TOA radiance maps, from the re-use of actual images acquired by other airborne and spaceborne instruments to the full computation using RTMs. The first option is constrained by the sensor/illumination geometry and the surface/atmosphere parameterization of the external image. Furthermore, these external images are affected by the spatial/spectral characteristics and noises of the sensors acquiring them. For these reasons, the FLEX SGM is based on the use of RTMs as it gives more flexibility for the scene definition for any input sensor geometry and configuration.

The generation of the TOA radiance scene is determined by the surface reflectance and fluorescence emission maps, in addition to the emissivity and temperature in the thermal domain, and the radiance propagation through the atmosphere. The surface reflectance and fluorescence emission is at the same time affected by the incoming radiation from the Sun, thus the same atmosphere configuration is defined for downwards and upwards fluxes. This allows to couple the surface and atmosphere RTMs and keep the consistency between them. The coupling between the RTMs in FLEX SGM follows the 4-streams approach in Verhoef and Bach (2012), taking into account the surface Bi-directional Reflectance Distribution Function (BRDF), separating the light propagation through surface and atmosphere by its direct and diffuse components. The contributions to the TOA radiance come from the atmosphere $\left(L_{p0}\right)$, target $\left(L_{BOA}\tau_{oo}\right)$ and surroundings $\left(L_{adj}\tau_{do}\right)$ (see Figure 5). Considering that the fluorescence emission is a small perturbation on the radiative transfer equation, it can be taken as an additional source of radiation emitted by the surface.

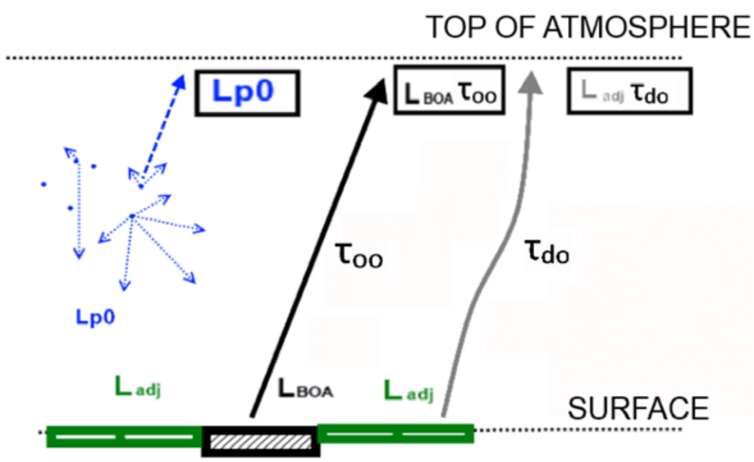

Figure 5 Contributions to the total TOA radiance.

4. IMPLEMENTATION AND TEST CASE

The FLEX SGM software has been implemented in MATLAB®(MathWorks Inc.). The simulation starts by the user-selection of the target location and date/time of the image acquisition. The spatial distribution of input parameters is done as explained in Section 2, using external class-cover maps and Digital Elevation Model. The software integrates the SCOPE model (Van Der Tol *et al.* 2009) for the simulation of vegetation surface reflectance and fluorescence emission and MODTRAN5 for the simulation of the atmospheric radiative transfer with a spectral resolution up to 0.1cm^{-1} (≈ 0.01nm resolution at 800nm). The computational burden of MODTRAN5 (≈ 10min in a standard workstation for the [500 - 800] nm range at 0.1cm^{-1} resolution) limits the possibility of running it for the simulation of every single spectra. This limitation is solved by making use of precomputed Look-Up Table (LUT) covering multiple combination of atmospheric and geometric conditions. The atmospheric LUT is then interpolated for the input atmospheric and geometric parameters on the scene. The execution of SCOPE in a standard workstation takes approximately 2s. for each combination of input parameters, which leads to prohibitive computation times for large scenes if the execution is made pixel-wise. To overcome this problem, SCOPE is run with a subset of the input values generating a temporary LUT of reflectance/fluorescence that is later interpolated for the actual values of each pixel.

Figure 6 shows an example of a generated scene. Its configuration and generation starts from the definition of a land-cover map input by the user and distributes the biophysical parameters (Chlorophyll-a in this example) accordingly to the defined surface database. The CWV is distributed considering the surface topography and similarly occurs for the O_3 and aerosol content maps. With all these input maps, the RTMs are executed generating the TOA radiance map given in RGB composition. The scene includes as well a cloud cover of different cloud types. Figure 7 shows three sample vegetation fluorescence, surface reflectance and TOA radiance spectra from the generated scene in the spectral range and resolution covered by FLORIS.

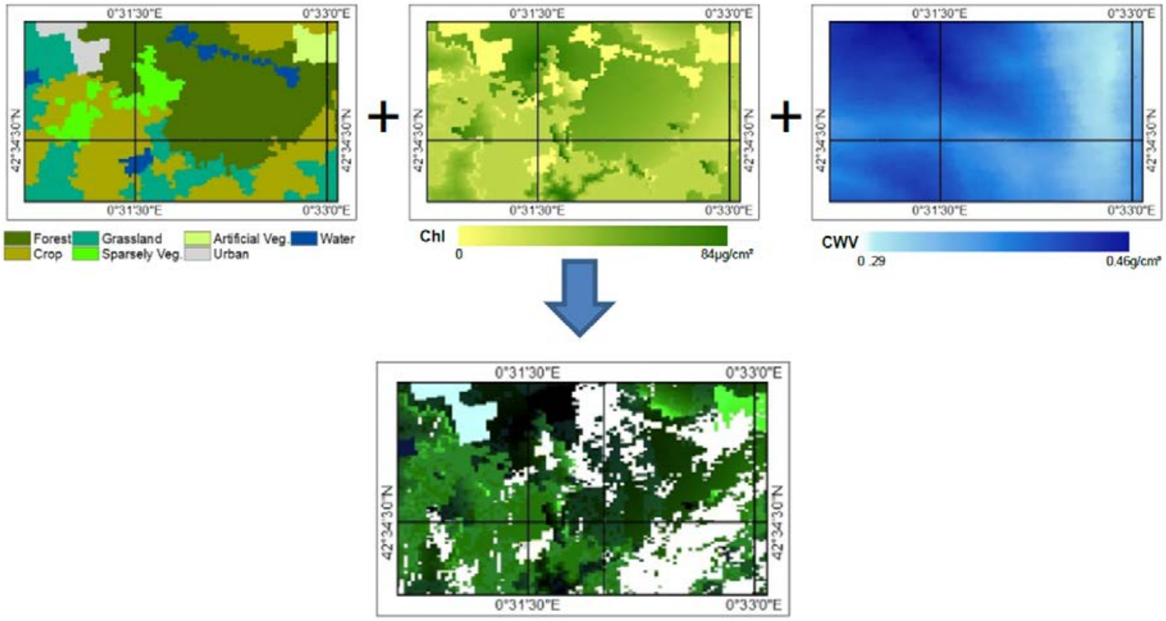

Figure 6 From left to right: land-cover map, Chlorophyll-a distribution, CWV distribution and RGB scene composition.

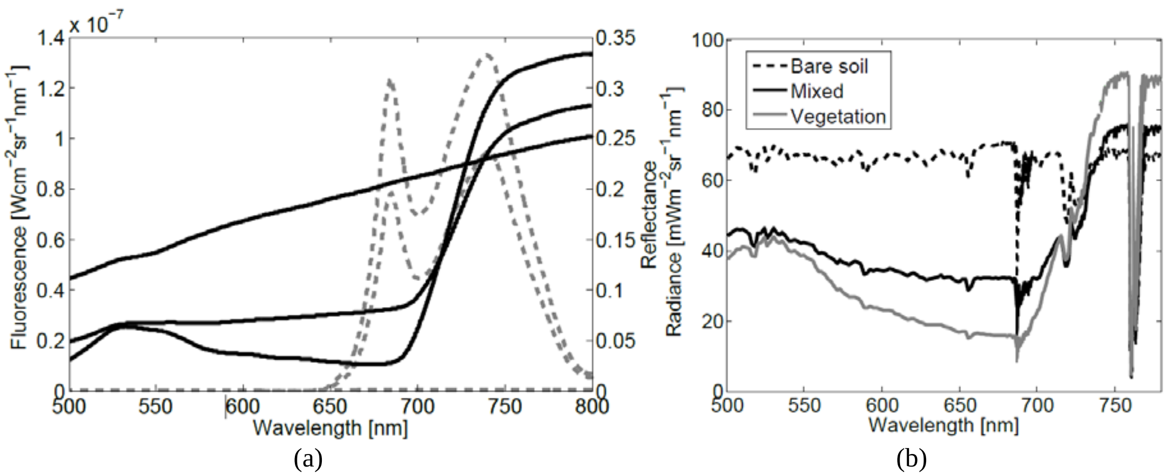

Figure 7 Sample spectra from the generated scene: (a) reflectance/fluorescence and (b) TOA radiance.

5. SUMMARY AND CONCLUSIONS

The development of a Scene Generator Module for passive optical missions has been presented in this paper with emphasis on the generation of hyperspectral synthetic scenes. Though the attention was draw to its particular application to ESA's FLEX/Sentinel-3 tandem mission, the proposed SGM design can be adapted to other satellite missions and instruments covering different spectral regions (e.g. thermal) and spectral/spatial resolutions. The SGM presented in this paper is currently being integrated within FLEX E2ES and it is expected that it will allow the scientific community and engineering teams to optimize and test the image processing algorithms and instrument/mission configuration.

6. REFERENCES

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