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ABSTRACT:

The SIRIUS rendering engine (Simulateur InteRactif d'Images Ultra Spectrales) developed at ONERA is designed to evaluate the optical signature of satellites by simulating hyperspectral images at high spatial resolution. Among the functionalities of the tool are the possibility to use, modify and visualize the trajectories and the temporal evolution of the attitude of the satellite and the camera in CIC or TLE formats in different reference frames (J2000, geographical coordinates, etc.), the calculation of the depth map (from the observer), the possibility to introduce an active spectral and directional (incoherent) illuminating source, the possibility to define the reflectance for each group of materials and to quickly visualize them on the geometry of the simulated object, the possibility to evaluate the effect of a point spread function to take into account the degradation of the resolution of images by the measuring instrument or by atmospheric turbulence. The tool calculates the visible signature of a satellite and an extension to the infrared (from 0.78 µm to 13 µm) is in progress. The calculation is optimized thanks to the parallelization of the ray tracing on the graphics card. In particular, SIRIUS works on Intel (UHD) and AMD Radeon graphics cards (with GCN memory architecture i.e. compatible with Bit-Code SPIR). Compatibility with Intel cards ensures the possibility of carrying out heavy calculations using a simple laptop equipped with an Intel processor (with an integrated Intel GPU). The radiances simulated with SIRIUS were physically validated through the comparison to radiances analytically calculated for canonical cases, or evaluated with another signature calculation code from ONERA or obtained with satellite measurements carried out by ONERA. The various functionalities of SIRIUS will be presented through a series of test cases.

1. INTRODUCTION

Space domain awareness (SDA) is crucial in many domains due to the variety of services realized through orbiting satellites [1, 2, 3]. The increasing number of unresolved resident space objects is calling for new rapid and effective methods to identify, track and detect changes of these targets. The main concern is especially directed towards objects in geostationary orbit (GEO) where the vulnerability of satellites is particularly evident [2]. Most of the remote sensing data come from radar and optical imaging. The first are mainly used to detect targets in low earth orbit (LEO) while optics allows to access higher orbits. However, ground-based space telescopes can only resolved GEO objects with low spatial resolution making the use of light curves the main source of information.

Remarkably, the optical signature of a satellite is a complex radiometric and spectroscopic (and possibly polarimetric) quantity [4] which is defined as a set of images taken at many wavelengths (and polarization states of the detector) thus allowing the characterization of the shape, the materials and also some geometric variables as the attitude and the solar panels orientation of the satellite. Consequently, the satellite's optical signature can be measured through standard astronomical techniques by ground-based telescopes or by space-based observing satellites. Moreover, modeling the optical signature will improve significantly the possibilities to distinguish satellites from debris and to track their position, activity and changes in time of these objects [2]. At the very end of the retrieval process lies the possibility to follow the activity of orbiting satellites. Nevertheless, all this gain in knowledge can only be possible if the simulations are able to consider the many degrees of freedom required to model this kind of space scenarios such as the moving observer, the target trajectory, the sensor directional pointing, the spectral and temporal point spread function (PSF) of the detector, the complexity of the geometry of the object with the associated materials and the radiative and optical environment of the scene [3].

Finally, the tool we developed is able to provide radiometrically accurate and physically correct hyperspectral images over time of satellites at high spatial and spectral resolution through real-time simulations taking into account the complexity of the space scenarios . This kind of simulations can be used in many ways such as to distinguish an active satellite from a space debris, to evaluate the possibility of limiting the effect of the background on the collected images [5], to identify the materials of the satellite [6], to track the satellite and to identify the category of a satellite based on its spectral signature.

2. THE HYPERSPECTRAL SIMULATION TOOL: SIRIUS

We have developed at ONERA a state-of-the-art hyper-spectral simulation tool called SIRIUS (Simulateur InteRactif d'Images Ultra Spectrales) which is a physically-based ray-tracing rendering engine [7, 8]. The model simulates passive multidimensional optical imaging (from single-band to hyperspectral) into the visible and an extension to the far thermal infrared region of the electromagnetic spectrum is under development. The tool has the capability to simulate images of different satellites with high spatial and spectral resolution required for space-based observations (see Fig.(1)). Low resolution can easily be obtained to model ground-based telescope measurements. As an input, SIRIUS uses 3D satellite models in Wavefront OBJ format (complex geometries as the multi layer insulation (MLI) can also be treated using more precise polygonal modeling). The radiation coming from the Sun, reflected by the Earth and its atmosphere is considered to calculate the specific intensity arriving at each pixel of the detector modeled as a camera with a tunable field of view (FOV). Alternatively, instantaneous field of view (IFOV) can also be given as input. The surface properties assigned to the geometry are those of the corresponding constituent materials i.e. bidirectional reflectance distribution function (BRDF) for accurate radiometric modeling and emissivity/absorption coefficient. Different BRDF models that are common in the literature can be used. In addition we have coded a model for specular reflection with lobes which is very versatile and relies on few parameters as the pure specular component coefficient, the diffusive component (around specular direction) coefficient, the angular spread of the specular lobe, the albedo and the absorption coefficient. It is also possible to import and interpolate laboratory measured data for BRDFs to avoid errors coming from oversimplified BRDF modeling. Accuracy in material BRDF descriptions are necessary to obtain radiometrically accurate modeling of space objects which are made of complex materials not commonly found when modeling standard scenes on Earth. Trajectories of the observer and of the target should be given in CIC or TLE formats even if a fixed configuration can also be used. The attitude of the observed satellite (and of the observer if required) are also taken into account. The radiative contribution of the Earth atmosphere is also calculated with the ONERA radiative transfer code MATISSE [9] which is especially important for ground-based observation to get correct transmissions for every band. In addition, the effect of the PSF of the instrument or atmospheric turbulence (for an observer on the ground or in the atmosphere) on image generation is also treated [10]. It is also possible to specify moving components such as solar panels that track the Sun over time. To image the satellite when it lies in the shadow of the Earth, an incoherent active source can also be simulated with its own spectral interval and angular aperture (this source is available only for space-based observation because the source is placed on the observing satellite or platform). Image resolution up to 5000x5000 pixels and spectral resolution up to 2000 bands can be achieved due to the parallel implementation of the ray-tracing algorithm on the graphics card (GPU). A depth map can also be calculated evaluating the distance of the satellite's parts from the detector in the actual scenario. All the parameters can be initialized with the help of a graphic user interface which also allows for a quick-look visualization of the target satellite as seen by the detector, trajectories visualization and material identification on the geometry of the satellite. The results are exported as a set of TIFF images for every band. Other output formats are PNG and BSQ images. The radiances are integrated on every sub-band (an image integrated on the total detection spectral interval can be obtained by defining a single band).

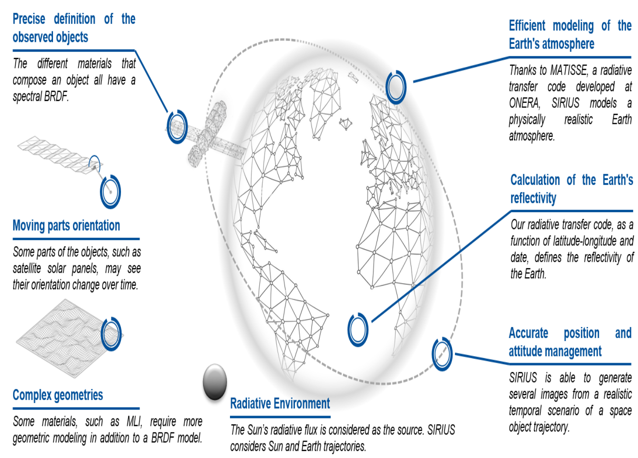

Figure 1. SIRIUS functionalities for the calculation of the optical signature of a satellite.

The simulations can be run at a given time or can also be launched for a time interval taking into account the kinematics and the moving parts. Moreover, the variation over time of the power radiated by the Sun is taken into account depending on the day of the year considered. To conclude, the radiometric values of the specific intensity have been validated against analytical results [11] and with another modeling tool developed at ONERA called CRIRA [12, 13]. Validation through comparisons with measured data is under study for both cases of ground-based observations and space-based observations. The extension of the tool in the thermal infrared is under development requiring the calculation of the surface temperature of the satellite.

3. RESULTS: SATELLITE'S HYPERSPECTRAL SIGNATURE

We present here some results that can be obtained with SIRIUS for the case of the European satellite ENVISAT [14] launched by ESA. The results are in the visible spectrum (380-780 nm) and are simulated for observations done by a hypothetical satellite moving on the same orbit and equipped with a camera with 1000x1000 pixels and a FOV of 0.5°. The average distance between the observer and the target is 5 km. As mentioned before, there are many parameters that need to be chosen in order to correctly initialize the scenario in this kind of space scenarios.

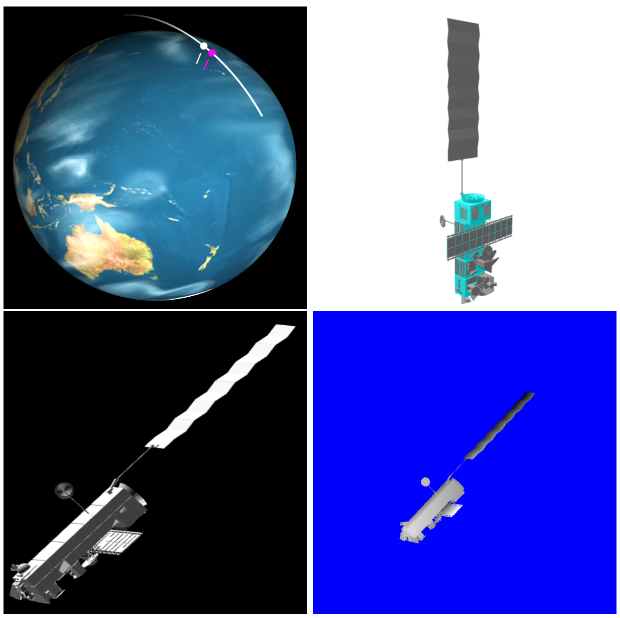

Figure 2. Some examples of the functionalities of the graphical user interface for the scenario definition. Top left: The visualization of the observer and target satellite (their distance is magnified for visualization). Top right: The material visualization on the geometry of the target satellite. Bottom left: The quicklook image of the satellite at a fixed instant (under an isotropic light source). Bottom right: The distance map at a fixed instant showing that the body of the satellite is closer to the observer (brighter means closer).

Due to this complexity it is very useful to have the possibility to rapidly check if all the parameters are correctly defined. Thus, the graphical user interface of SIRIUS can be very useful. The interface allows to visualize the trajectories of the observer and the target satellite around the Earth (the first picture in Fig.(2)). Moreover, it is possible to identify the different materials on the surface of the satellite. Importantly, the user can do a fast check of the detected images on all points of the trajectory by using the quicklook option (based on Blender [15]). It is also possible to activate an homogeneous source in order to visualize the entire target satellites (in case when the natural solar illumination is making hard to see the whole target). In order to understand the orientation of the detected satellite in the measured image, a depth map can also be calculated. This map shows on every pixel the distance of the different parts of the detected satellite from the image plane of the detecting camera.

The main output of the simulation is the calculation of hyper-spectral images. We give in Fig.(3) an example of multi-spectral satellite imaging by calculating four images corresponding to four bands in which the entire visible interval is divided (each with a width of 100 nm). An Earth albedo=0.9 is kept fixed in the 380-480 nm band and zero elsewhere. As expected, only the image in the 380-480 nm band shows the contribution of the light reflected by the Earth while in all other images only a small portion of ENVISAT is visible due to the solar illumination (coming from the bottom-right corner direction; the Sun and Earth positions are calculated with the library Astropy [16].). Interestingly, it is also possible to access pixel-by-pixel the spectra in order to retrieve the materials on the surface of the target satellite. Finally, the whole content of information of the target satellite can be deeply investigated through simulations with SIRIUS.

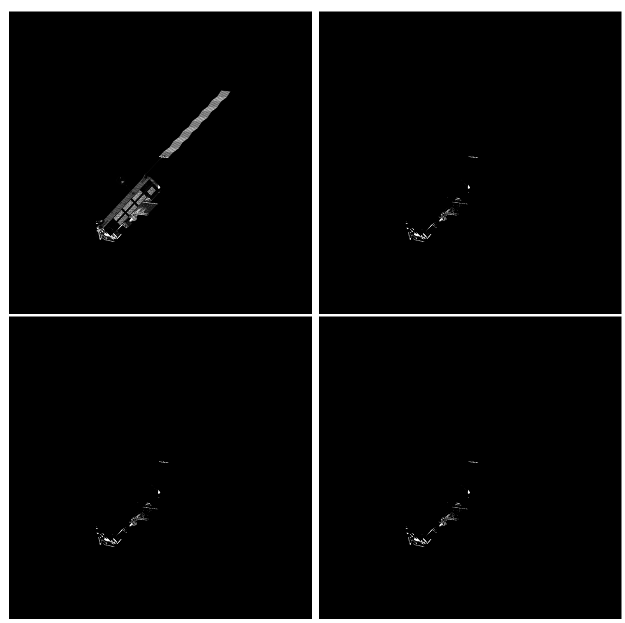

Figure 3. Multi-spectral images of ENVISAT in four different bands. Top left: The 380-480 nm band. Top right: The 480-580 nm band. Bottom left: The 580-680 nm band. Bottom right: The 680-780 nm band. Only in the first band the reflection of the Earth is visible because of chosen fixed blue albedo.

4. CONCLUSIONS

Preliminary results presented in this paper show the potential of using a physics-based simulation tool such as SIRIUS to generate simulated space-based observations that could be used to understand signatures of satellites in the visible spectrum. Nevertheless, there are still many challenges that remain to properly tune these models to correctly reproduce observations. In particular, the lack of spectral information of the BRDFs for the optical characterization of the surface material of the satellite is the main limit of this model.

Finally, access to all the data required to realize remote sensing of a satellite is a challenge in practice. Hence, physics-based simulation can generate data to complete observations. In addition, simulations can be used to plan observation strategies and to figure out the best configuration of the detector parameters.

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