VALIDATION OF SE-WORKBENCH-EO IN THE VISIBLE SPECTRAL BAND

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KEYWORDS: Simulation, ROC, RMSE, Visible domain, Experimentation, Validation, SE-WORKBENCH-EO

ABSTRACT:

In the future, the specification, design, development and validation of new sensors, especially optronic sensors, will increasingly involve simulation. Optronic sensor are used to observe a scene containing a background and objects of interest, and a processing unit. After exploitation of the signals delivered by the sensor, a result is produced which gives, for example, the detection of a certain type of object in the background, the probability of detection, the rate of false alarms …
The simulation of the optronic chain requires in particular to have a set of tools that models the 3D scene as it is "seen" by the sensor. The need for image simulation covering the visible domain (B&W and color) becomes increasingly important in the short or medium term weapons programs using optronic sensors operating in this spectral band.

In order to evaluate the level of realism and physical representativeness of SE-WORKBENCH-EO in the visible spectral band, a methodology of validation was developed. The purpose was to identify improvements to be made to the SE-WORKBENCH-EO tools, specify the evolutions and then implement them in order to validate it in the visible band. In the frame of this methodology of validation, two experimental campaigns were carried out by ONERA/DOTA in order to acquire data with instruments having characteristics compliant with this band. In particular, a hyperspectral camera were used to collect 28 images in the visible spectrum and a spectroradiometer used for the measurement of the spectral reflectance of various materials. This paper focuses on the description, in the first part, of the 2 campaigns of measurements that were performed at DGA trial field at Bourges (France) and Salon de Provence (France): used instruments, collected data (spectral reflectance, hyperspectral images ...). In the second part, the results obtained during the campaign of measurements are compared with the images calculated by the SE-WORKBENCH-EO. These results are analysed using methods such as Rank Order Correlation (ROC), RMS Error. For each case, the analysis is progressive. In the first step, "geotypical" data are used. The analysis of the results obtained by the above mentioned methods gives an initial idea of the physical representativeness. For the next step(s), readjustments are performed: the simulated images are recomputed using "geospecific" data instead of "geotypical" data.

The results obtained showed a good level of physical representativeness and realism of the images generated by the SE-WORKBENCH-EO in the visible spectral band for a first list of physical phenomena such as: diffuse reflection of punctual light sources, diffuse reflection of extended sources ... Nevertheless, additional tests have to be performed to validate the physical representativeness of the SE-WORKBENCH-EO for other physical phenomena (clouds, fog, BRDF ...).

1. SE-WORKBENCH-EO

1.1. Overall presentation of the SE-WORKBENCH

The SE-WORKBENCH is a multi-sensor battlefield modelling WORKBENCH mainly used by:

- Defense agencies as French DGA, German BWB, South Korea MoD, Singapore DSO/DSTA and Swedish FOI
- Research centers as ONERA, IOSB Fraunhofer Institute,
- Industrials in and out of France as MBDA, Dassault, LG, STC.

SE-WORKBENCH-EO is the infrared sensor dedicated part of the SE-WORKBENCH that achieves the synthesis of 3D scene observed by an Electro Optical (EO) sensor, in four steps:

- First, the physical characterization of the 3D scene behavior,
- Then, the scenario edition (definition of the objects of the scenario, of the 3D scene and objects, assignment of trajectories to moving objects, definition of atmospheric and thermal conditions, parameterization of the sensors),
- Then, the computation of the physical radiance signal received by the EO sensor
- At last, the sensor effects modelling.

The SE-WORKBENCH is entirely based on software products developed by OKTAL-SE and realizes the multi-spectral unification of optronics, electromagnetism, laser and GNSS (Global Navigation Satellite System), using a common kernel and physical extensions assignment both aimed at a unique 3D scene and a common technology. The SE-WORKBENCH is a winning initiative for sharing R&D efforts and federating a user group community that intends to exchange experience and knowledge.
The first development was in 1994 and has been strongly boosted by the French SCALP missile program and the qualification of the IR tracking system. At the beginning, the SE-WORKBENCH was focused on the IR domain. In 2001, an electromagnetic version of the workshop was initiated, with the help of ONERA French research center, mainly focused on millimeter waves and wide scenes, typically for SAR applications. A GNSS version for satellite application has started in 2009. The control of the SE-WORBENCH-EO validity domain is based on both a theoretical validation approach (development of physical models, general modelling and simulation knowledge, elementary tests and validity assessment) and a validation process based on comparisons with experiments (SCALP/EG missile [FR], AASM missile [FR] …).

1.2. The SE-WORKBENCH-EO architecture

The SE-WORKBENCH-EO is made of different components, as described hereafter, corresponding to the successive steps of a IR sensor simulation that are the modelling of the synthetic environment, the scenario edition, the rendering without the sensor effects and finally the sensor transfer function simulation. Furthermore, the user can do software integration in order to control the generated scenario execution from a remote or custom application. This can be achieved with the help of the SE-TOOLKIT consisting of a set of dedicated libraries and Application Programming Interfaces (API) to help the complex application design and integration.

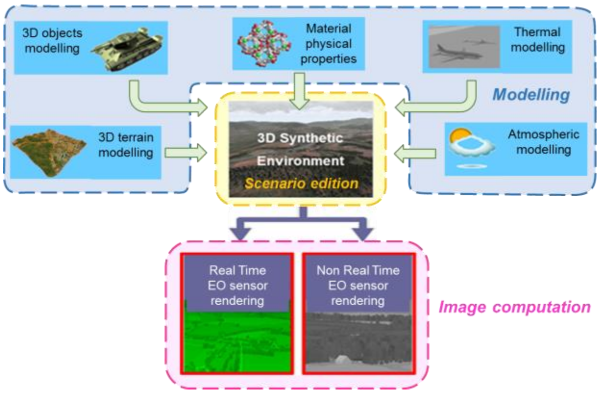

Figure 1. SE-WORKBENCH-EO components

1.3. Visible spectral band simulation with the SE-WORKBENCH-EO

Until now, SE-WORKBENCH-EO has been mainly used to compute images in the infrared bands: ShortWave InfraRed (SWIR), MidWave InfraRed (MWIR) and LongWave InfraRed (LWIR). It has been the subject of numerous presentations and publications to describe features and validation results. SE-WORKBENCH-EO remains compatible for image computation in the visible spectral band. For example: the material database is a multi-domain database and most of the spectral characteristics of the materials spread from 0.3 µm to 14 µm, atmospheric data computation is based on MODTRAN 5 that is fully compliant with the visible spectral band.

Recently, OKTAL-SE participated, with ONERA DOTA and MBDA France to a project called OREGIS-VC ("Outil REférent de Génération d'Images de Synthèse en Visible Couleur"): reference tool for the computation of synthetic coloured images in the visible spectral band. This project funded by the French Ministry of Economy and Industry started 2 years ago. The purposes of this project are:

- 1) Develop a methodology that allows to assess the level of realism / physical representativeness of SE-WORKBENCH-EO simulated images in the visible domain
- 2) Identify, specify and develop improvements in the SE-WORKBENCH-EO in order to create a validated prototype in the visible domain

This paper focuses on the 1st part of the project: the validation of SE-WORKBENCH-EO in the visible band.

2. Validation process

The validation concerned only the radiometric (luminance level) and spectral aspects.
The validation process for the SE-WORKBENCH-EO in the visible spectral band is a 3 steps process:

- 1st step: comparison between simulated image and image from hyperspectral camera for elementary canonical scenes, in order to validate fundamental radiometric quantities.
- 2nd step: comparison between simulated image and image from hyperspectral camera for canonical scenes with new features (for example, light sources).
- 3rd step: comparison between simulated image and image from hyperspectral camera for complex scenes.

At each step, the complexity increases.

For each step, the methodology for the validation follows the hereunder detailed process:

- 1) Definition of the scene: composition of the scene and condition of environment and illumination.

- 2) Acquisition of the reference spectral image with a luminance calibrated hyperspectral camera and measurement of context data (optical properties of the materials, illumination of the scene, weather data …).
- 3) Modelling of the 3D scene and generation of the simulated image (spectral radiance image).
- 4) Application of the image comparison criterions: for uniform areas of the images, the following computations are performed: spectral comparison, spectral Rank Order Correlation (ROC) and spectral Root Mean Square Error (RMSE) on different zones of interest.
- 5) Analysis of results and adjustment process: The adjustment process consists in replacing the initial values of the modelling data (spectral optical properties of the materials, atmospheric data) from the SE-WORKBENCH-EO internal databases with measured data (spectral reflectance of materials, meteorological data) to improve simulation results.

2.1. Rank Order Correlation (ROC)

Rank Order Correlation is a parameter that is used to evaluate the level of physical representativeness of the simulated image (hierarchy of the radiance levels of the various elements of the scene). The ROC is defined by:

$$ROC = 1 - \frac{6 \cdot \sum_{i=1}^{n} (R_i - R'_i)^2}{n^3 - n} \qquad \text{Eq. 1}$$

With:

- R_i': rank for the scene element i in the simulated image
- R_i: rank for the scene element i in the real reference image
- n: number of control points representative of the different scene elements (material / geometry)

The closer the value is to 1, the better the representativeness.

For the validation of SE-WORKBENCH-EO in the visible spectral band, the ROC is computed at each wavelength.

2.2. Root Mean Square Error (RMSE)

Root Mean Square Error is a parameter that is used to evaluate the bias or gain problems between the simulated image and the measured image. The RMSE is defined by:

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (L_i - L'_i)^2} \qquad \text{Eq. 2}$$

With:

- L_i': average radiance of the scene element i in the simulated image
- L_i: average radiance of the scene element i in the measured image
- n: number of control points representative of the different scene elements (material / geometry).

For the validation of SE-WORKBENCH-EO in the visible spectral band, the RMSE is computed at each wavelength.

The value of the RMSE must be compared, in relative terms, with the radiance value. The smaller the relative value, the better the results.

3. Measurement campaigns

Two measurement campaigns were performed:

- The first one at DGA trial field (Bourges) from Nov, 14 2016 to Nov, 18 2016.
- The second one on the air base 701 (Salon de Provence) from March, 1st 2017 to March, 2nd 2017.

The instruments used for the measurement campaigns are the following:

- A hyperspectral camera NEO Hyspex VNIR-1600 for the acquisition of reference spectral images. This camera has a spectral sampling of 160 spectral sub bands with a resolution of 3.7 nm between 0.414 µm to 0.992 µm.

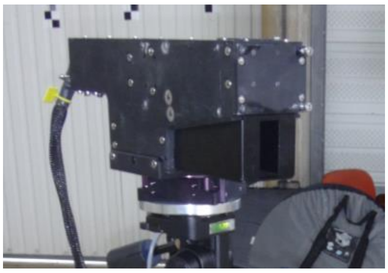

Figure 2. Hyspex camera

- Environmental data measurement instruments composed of: a weather station (that measures atmospheric pressure, air temperature, relative humidity, visibility), a scintillometer for the measurement of atmospheric turbulence (Cn²), a luxmeter for measurement of photometric local irradiance, a fisheye camera for the estimation of cloud cover, an ONERA specific device, called "Chamelon", that allows to automatically measure the spectral radiance of the scene elements in various directions.

Figure 3. Environmental data measurement instruments

- A spectroradiometer ASD FieldSpec 3 for the measurement of spectral reflectance of materials. This device has a spectral resolution of 1 nm between 0.35 µm and 2.5 µm.

Figure 4. ASD Fieldspec 3 spectroradiometer

Altogether, 28 hyperspectral images were taken by the Hyspex camera with the associated weather data, 396 spectral reflectance data files from 107 scene elements were measured by the ASD FieldSpec 3.
Among this amount of data, 4 images were selected that led to 4 scenarios of simulations.

4. Simulation scenarios

Four scenarios of simulation were studied.

Name	Description
 *Figure 5. "canonical scene 0"*	- Indoor scene - One 4 levels of grey target, one 4 colors target, one Macbeth ColorChecker target (all set vertically) - Two solar simulators Steuernagel
 *Figure 6. "canonical scene 2"*	- Outdoor scene with clouds - One 4 levels of grey target, one 4 colors target, one Macbeth ColorChecker target (all set vertically)
 *Figure 7. "canonical scene 3"*	- Outdoor scene with clear sky and Sun - One 4 levels of grey, one 4 colors target, one Macbeth ColorChecker (all set horizontally)
 *Figure 8. "complex scene 1"*	- Outdoor scene with clouds - One 4 levels of grey and one 4 colors target (all set vertically), some trees, 3 office containers, 1 white car, …

4.1. 1st scenario: canonical scene 0

The 1st scenario is an indoor scenario. The targets are set in front of 2 solar simulators. The irradiance of these solar simulators is much larger than the irradiance of the background.

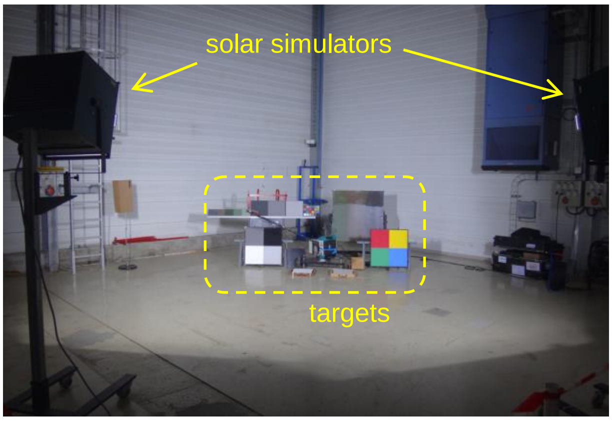

Figure 9. 1st scenario - canonical scene 0

A scenario of simulation is created using a SE-WORKBENCH-EO tool called SE-SCENARIO (cf. Figure 10).

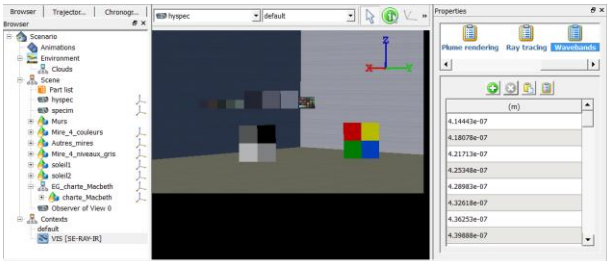

Figure 10. Creation of the scenario of simulation

For the **1st phase** of the evaluation, "geotypical" data are used. Geotypical data represent data that do not necessarily correspond to the features of the element of the 3D scene. For example, the spectral reflectance of the "yellow" part of the 4 colors target comes from a material, called "yellow-painting", from the multi-domain material database of the WORKBENCH-EO. The process that associates physical data to polygons is called "classification". The classification is performed using a tool of SE-WORKBENCH-EO called SE-PHYSICAL-EDITOR. So, in the 1st phase, all the spectral physical data (reflectance) of the materials are those of the multi-domain material database of the SE-WORKBENCH-EO.
There is no atmospheric data. The 3D scene is enlightened by the 2 solar simulators. Spectral intensity values are taken from the documentation of the solar simulators.
SE-RAY-IR, the Non Real Time software of the SE-WORKBENCH-EO is used to compute a spectral image of the 3D scene. The image has a spectral resolution of 5 nm and spreads between 0.38 µm to 0.78 µm. An algorithm of colorimetry is applied on this spectral image. The result is an image that can be displayed on a LCD screen for

example (cf. Figure 11).

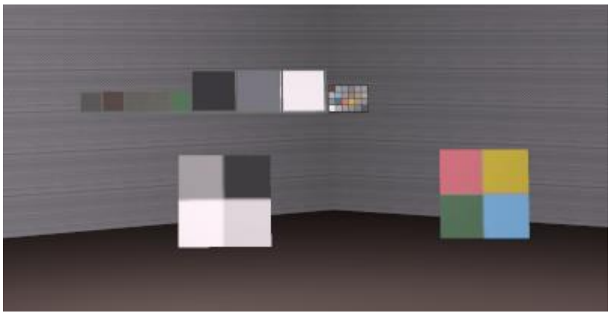

Figure 11. Result of the 1st phase

The evaluation criteria are computed from the simulated spectral image and from the hyperspectral measured image. 8 points of control are chosen in the 4 levels of grey target and the 4 colors target (dashed squares in Figure 12). They are used for ROC, RMSE and spectrum analysis.

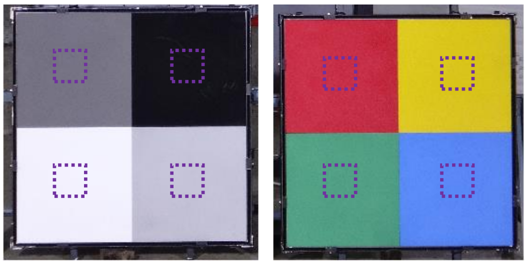

Figure 12. Points of control for ROC, RMSE and spectrum analysis

The analysis of these first results shows that globally the levels of radiance in the simulated image are greater than in the reference image and that there are significant differences in the spectrum (cf. Figure 13). The ROC average value is equal to 0.87 and RMSE average value is equal to 10 mW.m^{-2}.sr^{-1}.nm^{-1}.

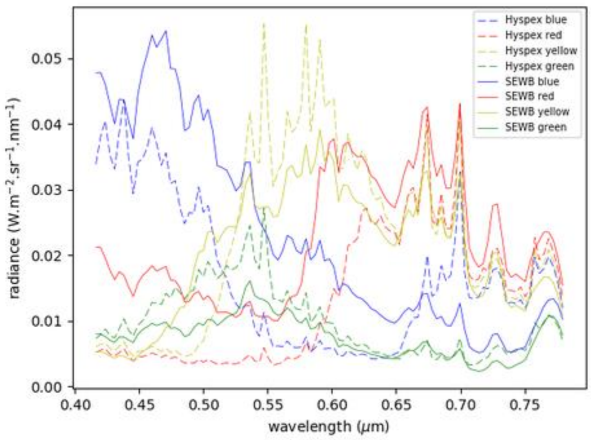

Figure 13. Spectrums for the 4 colors target – 1st phase of canonical scene 0

In the **2nd phase** of the evaluation, an adjustment of the reflectance of the materials is performed. For that, the measurements made by the spectroradiometer are used. Figure 14 shows an example of measured spectral reflectance.

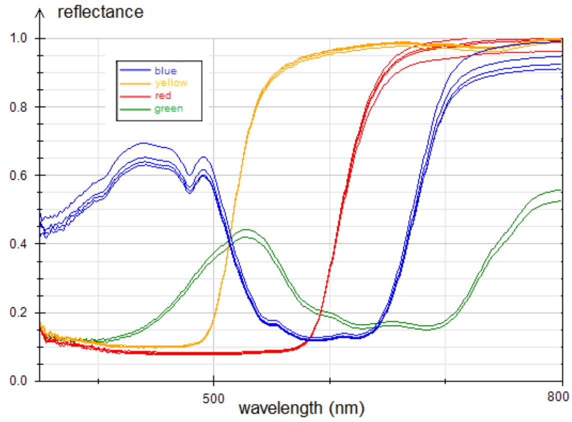

Figure 14. Measured reflectance for the 4 colors target

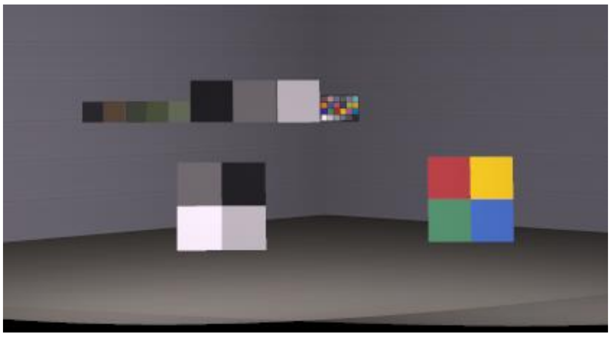

Figure 15. Result of the 2nd phase

The analysis of the image computed using this first adjustment shows that globally the levels of radiance in the simulated image remains greater than in the reference image but the shapes of the spectrums are similar (cf. Figure 16). The ROC average value is equal to 0.99 and RMSE average value remains equal to 10 mW.m^{-2}.sr^{-1}.nm^{-1}.

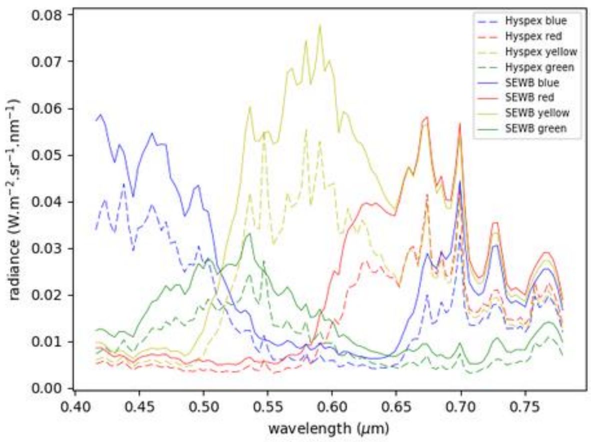

Figure 16. Spectrums for the 4 colors target – 2nd phase of canonical scene 0

In the **3rd phase** of the evaluation, the solar simulator intensity is adjusted. For that, the measurements made by a luxmeter are used (cf. Figure 17).

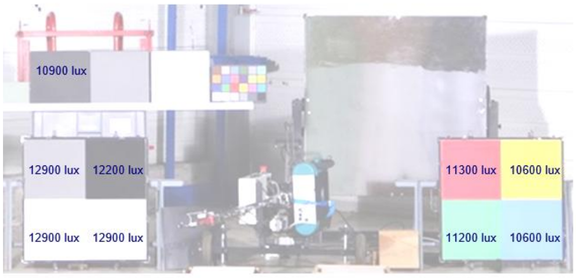

Figure 17. Measurements of photometric irradiance with a luxmeter

The results after this second adjustment are very good (cf. Figure 18). The ROC average value is equal to 0.99 (cf. Figure 19) and RMSE average value is equal to 2.7 $mW.m^{-2}.sr^{-1}.nm^{-1}$ (cf. Figure 20).

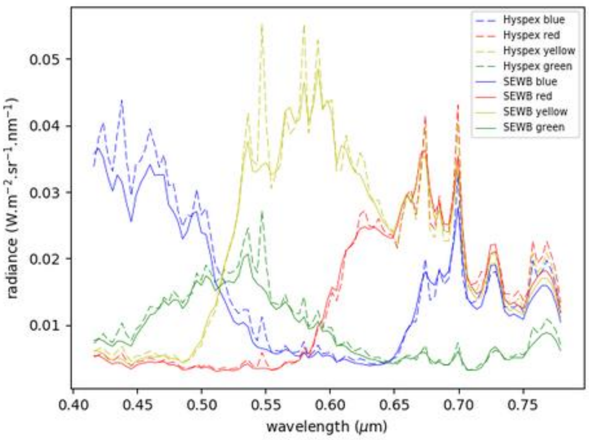

Figure 18. Spectrums for the 4 colors target – 3rd phase of canonical scene 0

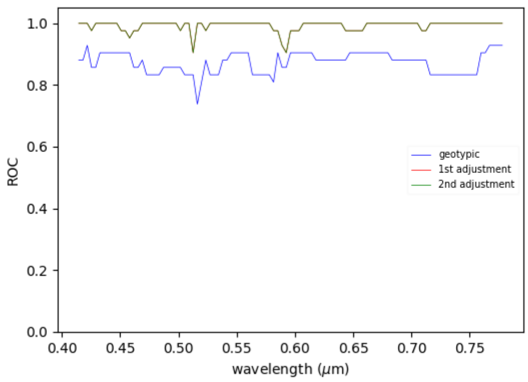

Figure 19. Spectral ROC for canonical scene 0

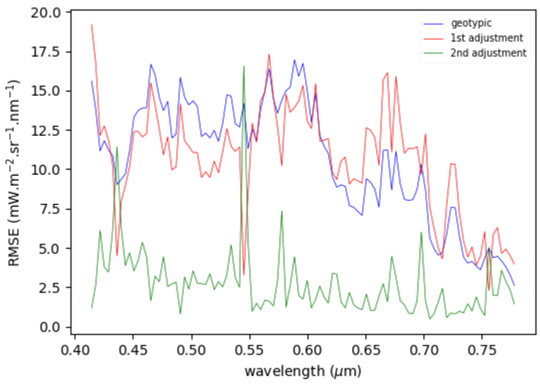

Figure 20. Spectral RMSE for canonical scene 0

With adjustments of the reflectance values and solar simulator intensity, the spectrums of the control points calculated by the SE-WORKBENCH-EO are almost identical to those of the image taken by the Hyspex multispectral camera. These results validate the physical representativeness of the point source reflection model on diffuse materials of the SE-WORKBENCH-EO in the visible color domain.

4.2. 2nd scenario: canonical scene 2

The 2nd scenario is an outdoor scenario with a cloudy sky. The targets are set on a road, in the same relative position as in the previous scenario. The purpose of this scenario is to validate the physical representativeness of the reflection model of extended sources (sky and ground) on diffuse materials.

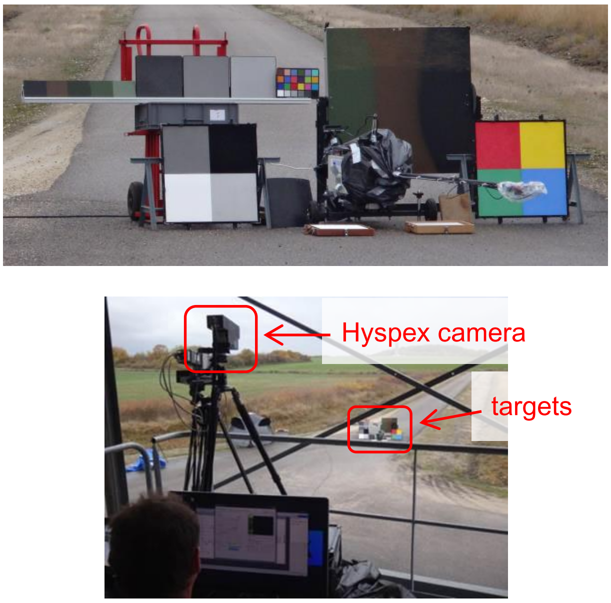

Figure 21. 2nd scenario - canonical scene 2

The same process as for the 1st scenario is used. For the **1st phase**, "geotypical" data are used. Weather data measurements are used to parameterize SE-ATMOSPHERE, which is the SE-WORKBENCH-EO tool dedicated to the computation of atmospheric data.

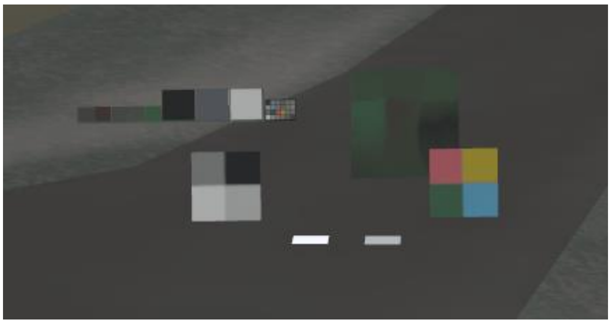

Figure 22. Result of the 1st phase of canonical scene 2

The evaluation criteria are computed with the same points of control as in the 1st scenario (cf. Figure 12) and one more control point on the road.

The analysis of these first results shows that globally the levels of radiance in the simulated image are less than in the reference image and that there are significant differences in the spectrum (cf. Figure 23). The ROC average value is equal to 0.84 and RMSE average value is equal to 1.4 mW.m^{-2}.sr^{-1}.nm^{-1}.

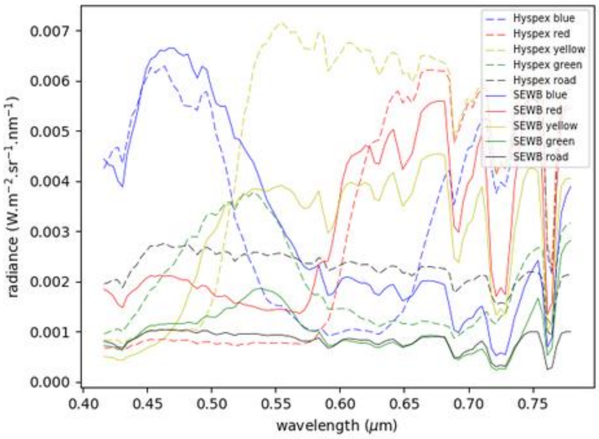

Figure 23. Spectrums for the 4 colors target – 1st phase of canonical scene 2

In the **2nd phase** of the evaluation, an adjustment of the reflectance of the materials is performed. The reflectance measurements made by the spectroradiometer on the targets and on the road are used.

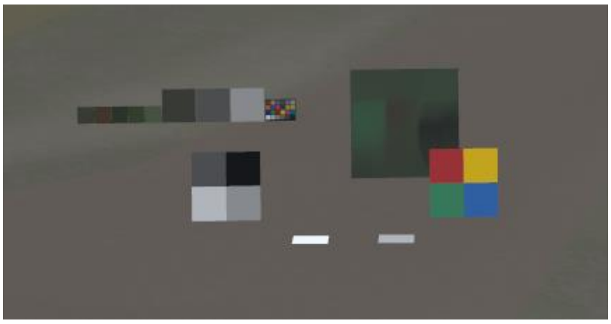

Figure 24. Result of the 2nd phase of canonical scene 2

The results after this adjustment are better than in the 1st phase (cf. Figure 25). The ROC average value is equal to 0.96 and RMSE average value is equal to 0.66 mW.m^{-2}.sr^{-1}.nm^{-1}.

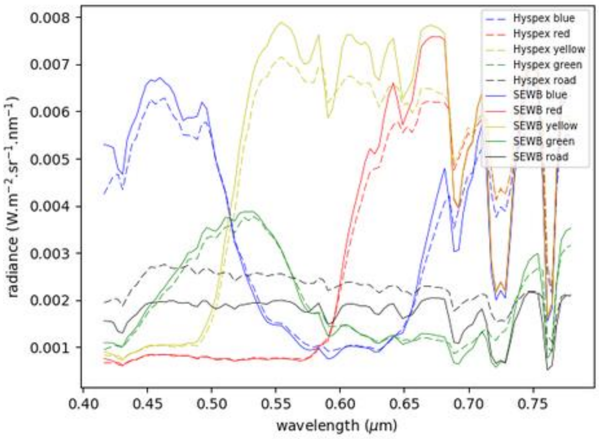

Figure 25. Spectrums for the 4 colors target – 2nd phase of canonical scene 2

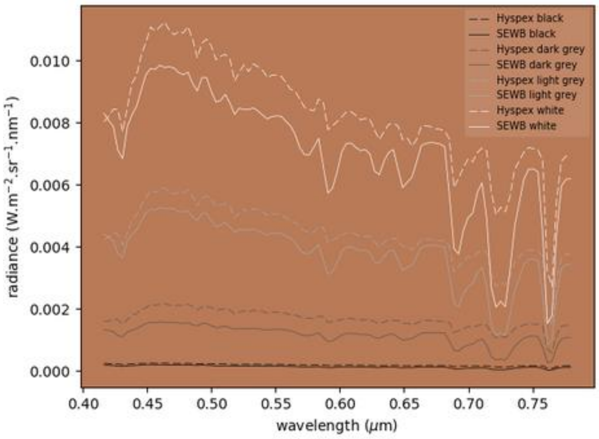

Figure 26. Spectrums for the 4 levels of grey target – 2nd phase of canonical scene 2

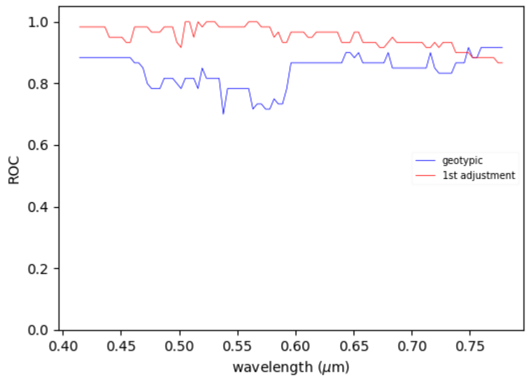

Figure 27. Spectral ROC of canonical scene 2

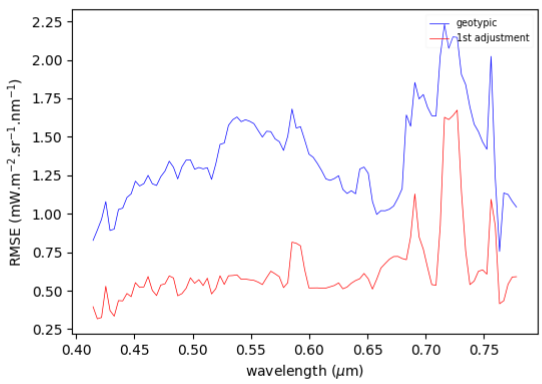

Figure 28. Spectral RMSE of canonical scene 2

The results obtained after the adjustment of the material reflectance are also good. There are some differences on the levels of spectrums, for example between the 4 colors target and the 4 levels of grey target (cf. Figure 25 and Figure 26), which can be explained by their different illuminations (the irradiance on the 4 colors target is not the same as the irradiance on the 4 levels of grey target).

4.3. 3rd scenario: canonical scene 3

The 3rd scenario is an outdoor scenario with fine weather and Sun high in the sky. The targets are set horizontally on an asphalt surface.
The purpose of this scenario is to validate the physical representativeness of the reflection model of extended sources (sky) and punctual source (Sun) on diffuse materials.

Figure 29. 3rd scenario - canonical scene 3

The same process as for the 1st and 2nd scenarios is used. For the **1st phase**, "geotypical" data are used. Weather data measurements are used to parameterize SE-ATMOSPHERE, which is the SE-WORKBENCH-EO tool dedicated to the computation of atmospheric data.

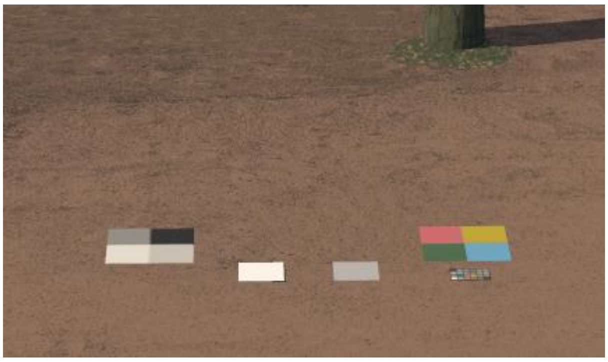

Figure 30. Result of the 1st phase of canonical scene 3

The evaluation criteria are computed with the same points of control as in the 1st scenario (cf. Figure 12) and one more control point on the asphalt.

The analysis of these first results shows that globally the levels of radiance in the simulated image are less than in the reference image and that there are significant differences in the spectrum (cf. Figure 31). The ROC average value is equal to 0.84 and RMSE average value is equal to 40 mW.m^{-2}.sr^{-1}.nm^{-1}.

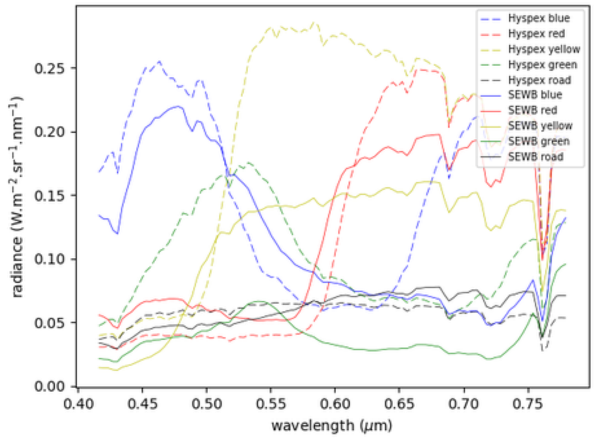

Figure 31. Spectrums for the 4 colors target – 1st phase of canonical scene 3

In the **2nd phase** of the evaluation, an adjustment of the reflectance of the materials is performed. The reflectance measurements made by the spectroradiometer on the targets and on the asphalt (road) are used.

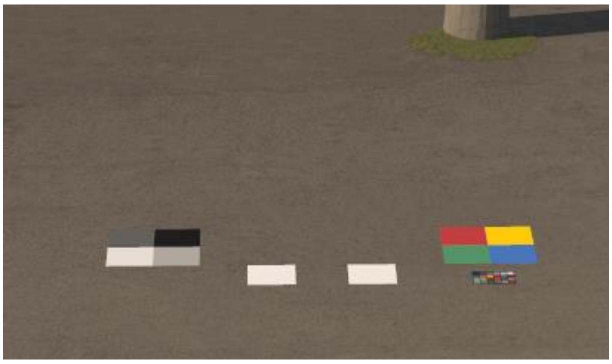

Figure 32. Result of the 2nd phase of canonical scene 3

The results after this adjustment remains good (cf. Figure 33). The ROC average value is equal to 0.93 and RMSE average value is equal to 22.6 mW.m^{-2}.sr^{-1}.nm^{-1}.

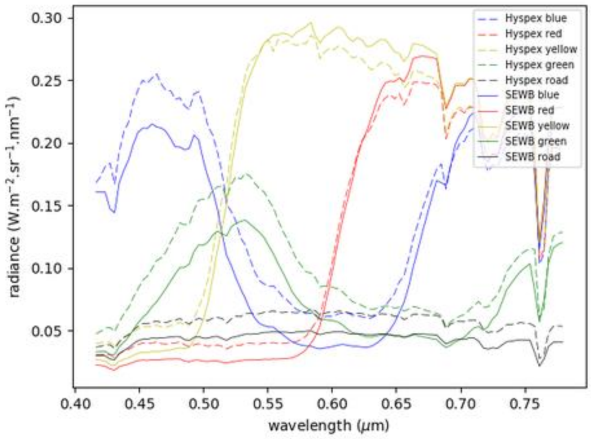

Figure 33. Spectrums for the 4 colors target – 2nd phase of canonical scene 3

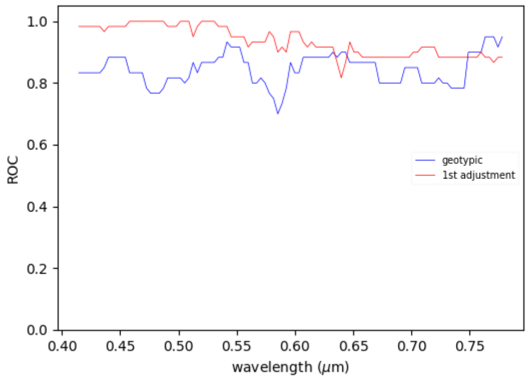

Figure 34. Spectral ROC of canonical scene 3

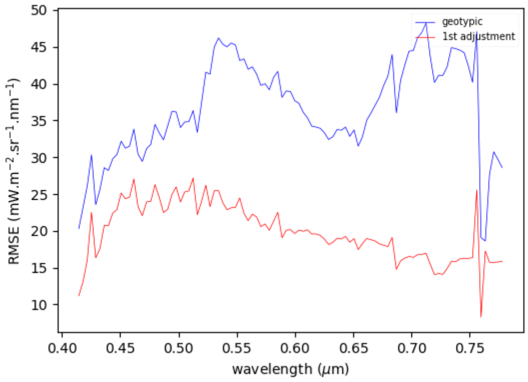

Figure 35. Spectral RMSE of canonical scene 3

4.4. 4th scenario: complex scene 1

The 4th scenario is an outdoor scenario with a cloudy sky. The 3D scene is described by: a set of 3 office containers, 2 concrete tables, 4 wooden tables, the 4 colors target, the 4 levels of grey target, a white car, a field of short grass and in the background, a hedge of shrubs and some trees.

The purpose is to validate the physical representativeness on a more complex scenario.

Figure 36. 4th scenario – complex scene 1

The same process as for the previous scenarios is used. For the **1st phase**, "geotypical" data are used. Weather data measurements are used to parameterize SE-ATMOSPHERE and create an atmospheric file.

Figure 37. Result of the 1st phase of complex scene 1

The evaluation criteria are computed on 13 control points (cf. Figure 38).

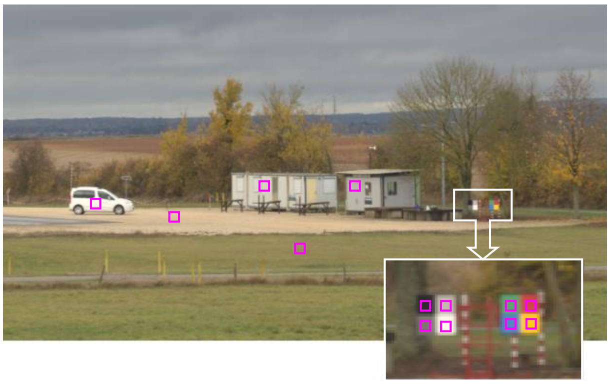

Figure 38. Control points for 4th scenario

The analysis of these first results shows that globally the levels of radiance in the simulated image are much smaller than in the reference image and that there are significant differences in the spectrum (cf. Figure 39). The ROC average value is equal to 0.86 and RMSE average value is equal to 22.8 mW.m^{-2}.sr^{-1}.nm^{-1}.

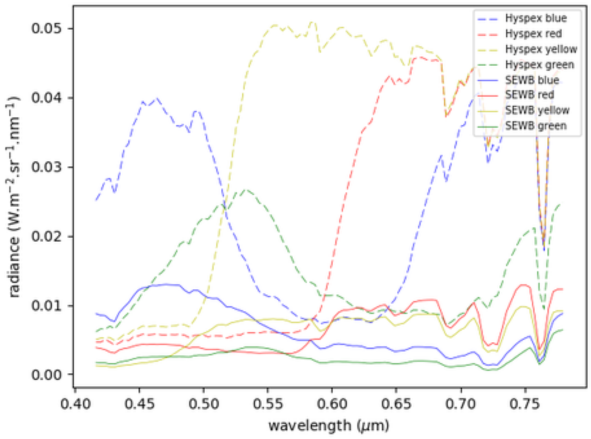

Figure 39. Spectrums for the 4 colors target – 1st phase of complex scene 1

In the **2nd phase** of the evaluation, an adjustment of the reflectance of the materials is performed. The reflectance measurements made by the spectroradiometer on the targets, on the car and on the office containers are used.

Figure 40. Result of the 2nd phase of complex scene 1

The results after this adjustment are better (cf. Figure 40): The ROC average value is equal to 0.93 and the RMSE average value remains at the same value.

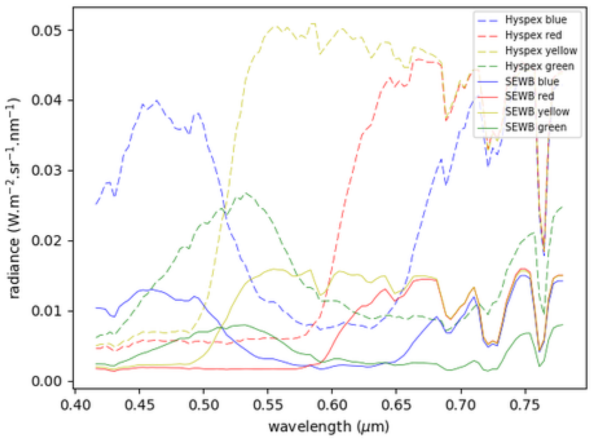

Figure 41. Spectrums for the 4 colors target – 2nd phase of complex scene 1

In the **3rd phase** of the evaluation, the atmospheric data are adjusted. For that, the thickness of the cloud layer in SE-ATMOSPHERE is modified in order to increase the irradiance of the sky.

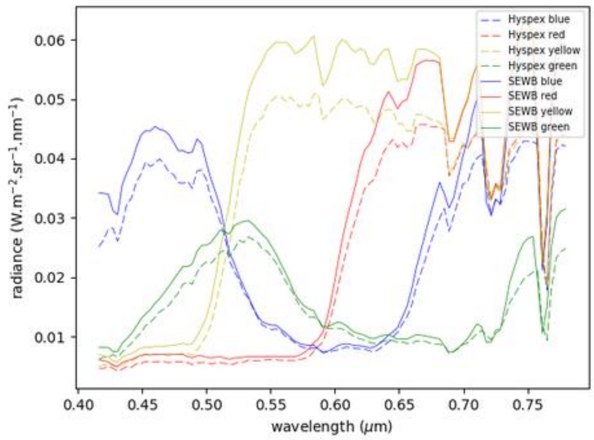

Figure 42. Spectrums for the 4 colors target – 3rd phase of complex scene 1

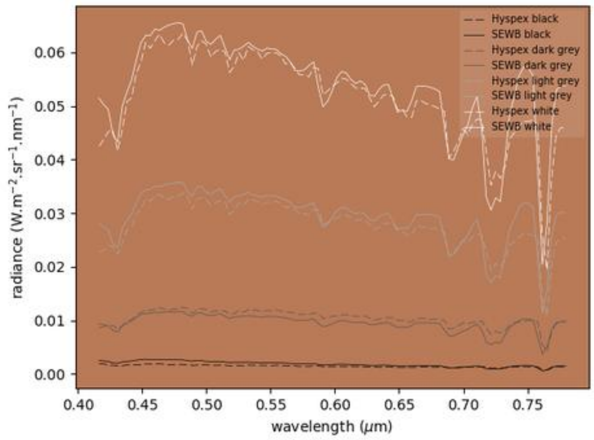

Figure 43. Spectrums for the 4 levels of grey target – 3rd phase of complex scene 1

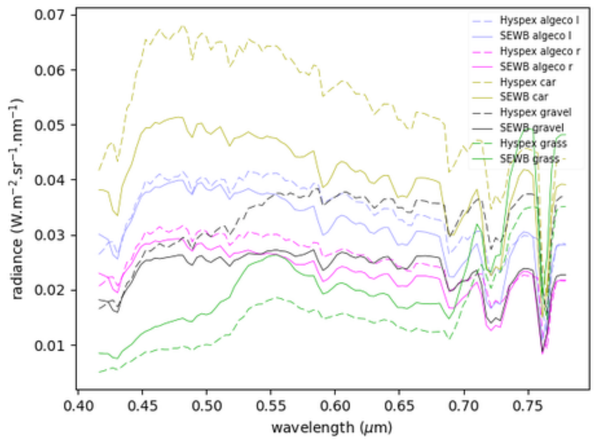

Figure 44. Spectrums for the others control points – 3rd phase of complex scene 1

The results after this second adjustment are better than in the 1st and 2nd phase (cf. Figure 42, Figure 43 et Figure 44). The ROC average value is equal to 0.93 (cf. Figure 45) and RMSE average value is equal to 7.5 mW.m-2.sr-1.nm-1 (cf. Figure 46).

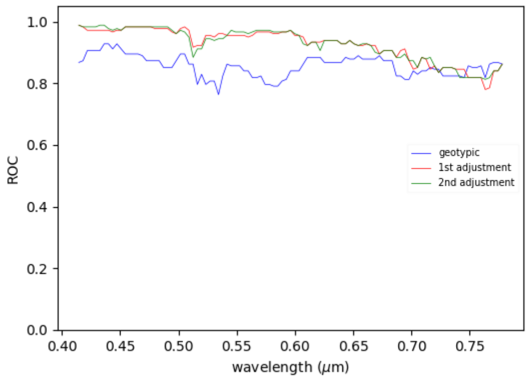

Figure 45. Spectral ROC for complex scene 1

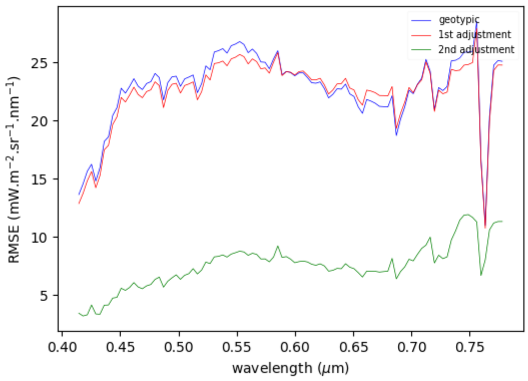

Figure 46. Spectral RMSE for complex scene 1

With an adjustment of the reflectance values and an adjustment of atmospheric data, the results for the 4 colors target and the 4 levels of grey target, the results are very good.
For other areas of the image:

- The results are good on the 2 walls of the office containers.
- For the body of the car, there is a discrepancy which can be explained by the fact that the painting is not a purely diffuse but that it has a specular component which is not taken into account in the modelling.
- For gravels and grass, there is a difference due to the fact that the data used are not geospecific data. Grass and gravel reflectance were not measured during the measurement campaign.

A complementary test was performed on the 3rd phase. SE-WORKBENCH-EO can compute an image with global illumination. The result of this computation is given in Figure 47. This image has to be compared with the one of Figure 40.

Figure 47. With global illumination

5. CONCLUSION AND FUTURE WORK

The results presented in this paper are only one part of a study on the physical representativeness and realism of the images generated by the SE-WORKBENCH-EO in the visible spectral band. The tests performed in the frame of this study focused on a first list of physical phenomena such as: diffuse reflection of punctual light sources, diffuse reflection of extended sources ... For all the scenarios, the results are good. In some cases, the results are as perfect as those of the hyperspectral reference images.

Nevertheless, additional tests need to be carried out to validate the physical representativeness of the SE-WORKBENCH-EO in the visible spectral band for other physical phenomena (clouds, fog, BRDF ...). Preliminary tests were performed concerning the spatial textures. These tests will have to be completed using new metrics such as GLCM (Grey Level Co-occurrence Matrix), spectral SCR (Spectral Signal to Clutter Ratio) …

Moreover, this study has highlighted the evolutions, such as the Wang Tiling method for example, that will be developed in the frame of this project in order to improve the physical representativeness of the SE-WORKBENCH-EO in the visible band.

6. REFERENCES

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