Validation of MATISSE background images and cloud simulations: comparing results with MODIS satellite images

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ABSTRACT

In this paper, we present the process of validating the atmospheric modelling software MATISSE (Advanced Modelling of the Earth for the Imaging and the Simulation of the Scenes and their Environment, developed by ONERA) by comparing simulation results of terrestrial and atmospheric background to MODIS satellite images. Analyses have been carried out for wavebands in the visible (VIS) as well as the longwave infrared (LWIR) spectrum.

Keywords: atmospheric simulation model, background simulation, cloud simulation, MATISSE, EO sensors, satellite based missile detection

1. INTRODUCTION

Conducting measurements with a satellite based sensor can become critical in terms of time consumption during the mission planning as well as during the instrumentation phase. Being able to predict the effectiveness of a space based sensor for a certain application, e.g., special earth surface observations, can help reducing the expenses. The simulation software MATISSE (developed by ONERA) is able to reproduce not only spectral characteristics of terrestrial and atmospheric backgrounds, but also sensor based ones. With the help of such a tool, spectral radiance images as seen from a space based field of view can be modelled, thus making a satellite mission dispensable in some cases. Advantages of the simulation process are obvious: a higher variety and flexibility in fields of orbit height, wavelength, cloud formations and geographical as well as seasonal or even diurnal dependencies can be obtained.

To ensure the quality of MATISSE simulations, validations have already been carried out concerning sea radiances [1], terrestrial [2][3] and atmospheric [4] backgrounds in the midwave infrared (MWIR) spectrum. In order to go further in the validation process of MATISSE, these comparisons with MODIS satellite images have been continued for additional wavebands in the VIS and LWIR.

The paper is organized as follows: In section 2, the context data used in connection with the validation process is presented. Then in section 3, the different MATISSE calculation processes that have been applied for terrestrial and atmospheric backgrounds are explained. Section 4 shows the comparison results, and possible sources of error are then discussed successively in section 5. Section 6 gives a short introduction on the application of MATISSE at the Fraunhofer IOSB. In the last section 7 a short outlook on the future work is given.

2. CONTEXT DATA

This chapter gives a brief summary of the applied context data in connection with the validation process. Detailed information has already been published under [3] and [4].
2.1 MODIS satellite images

For the validation of MATISSE surface and cloud computations, two MODIS satellite images were selected: One scene with almost clear sky conditions (March 20th, 2010, at 11:07 UTC) and another one with a variety of cloud types present (August 27th, 2010, at 11:05 UTC). Both images are presented in Figure 1. For more details on the MODIS sensor please refer to [3].

![Selected MODIS images](image1)

Figure 1: Selected MODIS images. The left image is used for the terrestrial background validation, the right one for the cloud comparisons.

For the validation of the terrestrial background computations, 5 distinct (non-cloudy) regions have been chosen - each of them represents one major vegetation type occurring in the scene. Using the example of MODIS band 21 (3.929 – 3.989 µm), the region of interests (ROI) are displayed and color-coded in Figure 2. Each of the ROI comprises 120 x 120 pixels, this roughly corresponds to 120 km x 120 km.

![Analyzed terrestrial background types](image2)

Figure 2: Analyzed terrestrial background types. Excerpt of the MODIS image.

The identification of cloud types on satellite images with only little context information is quite challenging. Although the available context data (as described in 2.2) was studied intensely, the cloud types cannot be determined doubtlessly. A detailed discussion on this issue can be found in section 5. Eventually, five different cloud types have been determined. In Figure 3 their location is indicated by red numbers.
2.2 Meteorological context data

Taking into account the image registration times of the two MODIS images, related context data like radiosounding profiles, sea surface temperature, cloud classification and cloud top altitude information was gathered. With the help of that information, corresponding MATISSE scenarios were assembled. In the following section, a brief summary of the context data is given. For detailed information please see the paper published within the scope of ITBM&S 2013 [4].

Radiosounding profiles

Besides standard meteorology profiles (e.g. mid-latitude summer or tropical), MATISSE can also take into account user defined data including the ones calculated out of radiosounding profiles. In the course of the validation process, several radiosounding profiles have been allocated [12] and used in correlation to the geographical area of the occurring cloud types. The profiles are displayed in Figure 4. In case of comparing surface structures, the MATISSE image mode was used and only one profile was included for the simulation of the whole scene (38N 1W, Murcia). More information on the data simulation process can be found in section 0.

Cloud classification and cloud top altitude

Further meteorological products were found at Météo-France including information on cloud classification and cloud top altitude [13]. Although the area covered by the METEOSAT-MSG products matches the one of the MODIS image, the registration time slightly differs by several minutes. Both products are shown in Figure 5 and Figure 6.
very high level, opaque, non cumuliform
high level, opaque, non cumuliform
semitransparent above a cloud
thick semitransparent
moderately thick, semitransparent
thin semitransparent

middle level, non cumuliform
low level, non cumuliform
very low level, non cumuliform
fractional
snow above land
clear land
clear sea

Figure 5: Cloud classification derived from METEOSAT-MSG. Cloud types, March 20th, 2010, 11:00 UTC. Cloudy areas to be analyzed are indicated by orange boxes, see Figure 3.

Figure 6: Cloud top altitude on March 20th, 2010, 11:00 UTC. Cloudy areas to be analyzed are indicated by white boxes, see Figure 3.

Water temperature

The sea surface temperature is deduced from a NOAA18 image, see Figure 7. The temperature scale is averaged over 10 days and the measurement period is slightly posterior to the studied MODIS image’s one, but the thermal inertia of sea water is high and the Mediterranean can be assimilated to a large thermostatic tank. The observed cirrus clouds are assumed to be semi-transparent, so the terrestrial surface can be seen through the clouds and therefore a good knowledge of the surface temperature underneath those clouds is essential. For the remaining cloud types, the sea surface temperature is not of any relevance, as those types are supposed to be opaque.

Figure 7: NOAA image showing the water temperature in the Mediterranean Sea averaged over 10 days (21st – 31st March 2010). The scale reaches from 80 °K (light blue) to 220 °K (dark red).

3. DATA SIMULATION WITH MATISSE

MATISSE is a radiative transfer code which has been developed by ONERA (French Aerospace Lab) for DGA (Délégation Générale de l’Armement, France) applications. At Fraunhofer IOSB, the software has been in use for several
years, e.g. to estimate atmospheric effects on space-based sensor systems. The presented computation results have been carried out using the latest version of the software, MATSSEv2.1.

For both of the analysed background types - terrestrial and atmospheric - different approaches have been pursued and are explained in the subsections 3.1 and 3.2.

3.1 Simulation of the terrestrial background

For the calculation of a synthetic image with the imagery mode of MATISSE-v2.1, the corresponding MODIS image parameters like date, time, sensor position, viewing direction etc. have been used as input. Corresponding to the analysed wavebands in the VIS and LWIR the spectral responsivity of the MODIS sensor in these bands was also included (Figure 8). Furthermore, a meteorological profile was created using the MATISSE “atmospheric profiles creator” and also incorporated into the calculation process. As a basis, the radiosounding data of the station Murcia was selected, as it is located the closest to the mid point of the image (see Figure 4, profile 38N 1W).

The MODIS image consists of 204 stripes, each measuring 1354 x 10 pixels. Within its standard calculation mode, MATISSE-v2.0 generates scenes where the observed position is the centre point of the scene (nadir). For simulating MODIS images, the calculation mode had to be adjusted to fit the format of the satellite image: every single MODIS-stripe (height: 10 pixels) was computed and afterwards assembled as a whole scene. The following Table 1 contrasts simulated and measured image for the analysed wavebands.

<table>
<thead>
<tr>
<th>Band 4 (0.545 – 0.565 µm)</th>
<th>Band 29 (8.4 – 8.7 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>Simulation</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
</tr>
</tbody>
</table>

Table 1: Comparison of measured and simulated spectral radiance image in the analysed wavebands (excerpt).

3.2 Simulation of the atmospheric background

MATISSE can simulate clouds via two computation modes: the imagery mode and the line-of-sight (LOS) mode. The latter was utilized for comparing cloud simulations with MODIS measurements.

Within the LOS mode, clouds are horizontally homogeneous and vertically stratified with a variable concentration. Depth, top and base altitudes can vary. The effective radius Re is constant throughout the cloud. Low cloud types are made of spherical water particles and the highest cloud types contain spherical ice particles or ice crystals in hexagonal structures. Twenty-two clouds can be modelled using MATISSE, their characteristics are listed in Table 2, see also [5][6].
The phase function of the clouds can be represented by an analytical Henyey-Greenstein function. In addition, the function can also be computed by a Mie scattering code for spherical particles (made of water or ice). PHM code (Pristine Hexagonal Microcrystal, [7]) is used to compute the optical properties of hexagonal particles. Radiance can be modelled from 0.4 µm to 20 µm. Spectral resolution is variable and adjusted to the other MATISSE backgrounds, except the faceted clouds. It is possible to superimpose two types of clouds: For instance, a cirrus cloud at high altitude can partially occult directed solar irradiance above a low cloud.

Several computation options are available: with or without multiple scattering (this choice is recommended if the medium is free of aerosols and clouds). Multiple scattering can be computed by the two-stream model [8] which is the simplest mode. The most accurate mode uses the “Discrete Ordinates Methods” (DOM) with azimuthal variation. DOM can also be used without azimuthal variation. The computation accuracy as well as the computing time strongly depends on the chosen method.

The several contributors to the calculated radiance are the following:

- solar radiance, single scattering
- solar radiance, multiple scattering
- thermal path radiance
- surface emission (Planck law) seen throughout clouds that are not optically thick
- ground reflection seen throughout clouds that are not optically thick (the light provided from direct solar irradiance and atmospheric radiance is reflected on the ground following an isotropic law).

MATISSE cloud simulations have been compared to MODTRAN code simulations [9] for most of the cloud types. As ONERA carried out cloud measurements campaigns in order to contribute to the background knowledge and to validate old ONERA cloud codes, MATISSE was also compared to measurement data for low clouds [10][11].

Taking into account the context data presented in section 2, a set of characteristics was assembled for each of the 5 identified cloud patches (Figure 3). With this information, the best fitting MATISSE cloud type was selected and user-defined parameters like base altitude and layer thickness were adjusted. The following Table 3 gives an overview of the
determined characteristics and the related MATISSE cloud type (see Table 2) that yielded the best comparison results. During the ITBM&S 2013 this process was explained in detail and can be found in [4].

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>Cumulus</th>
<th>Stratus</th>
<th>Stratocumulus</th>
<th>Nimbostratus</th>
<th>Cirrus 1, Cirrus 2 (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiosounding</strong></td>
<td><strong>profile</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>([12])</td>
<td>48N 4W, Brest (FR)</td>
<td>43N 4W, Nimes (FR)</td>
<td>43N 8W, La Coruna (ES)</td>
<td>38N 1W, Murcia (ES)</td>
<td>39N 9E, Decimomannu (IT)</td>
</tr>
<tr>
<td><strong>Top altitude</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(approximated from METEOSAT)</td>
<td>1000 m</td>
<td>2000 m</td>
<td>1600 m</td>
<td>11000 m</td>
<td>10500 m, 12000 m</td>
</tr>
<tr>
<td><strong>Cloud classification</strong></td>
<td>non cumuliform, low altitude, fractional type</td>
<td>non cumuliform, low level</td>
<td>non cumuliform, low level and very low lever</td>
<td>low, medium and high clouds, also different layers of which some are semitransparent</td>
<td>fractional coverage, thin and moderately thick transparent</td>
</tr>
<tr>
<td><strong>Water temperature</strong></td>
<td>not relevant</td>
<td>not relevant</td>
<td>not relevant</td>
<td>not relevant</td>
<td>15 °C</td>
</tr>
<tr>
<td>(NOAA-18)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MATISSE cloud type</strong></td>
<td>13, cumulus</td>
<td>9, stratuts</td>
<td>11, stratocumulus</td>
<td>7, nimbostratus in combination with 17, cirrus</td>
<td>14, cirrus, 17, cirrus</td>
</tr>
</tbody>
</table>

Table 3: Cloud characteristics as determined from the context data and related MATISSE cloud type (representing the best computation results).

4. VALIDATION OF MATISSE CALCULATIONS

Validations have already been carried out concerning sea radiances [1], terrestrial [2][3] and atmospheric [4] backgrounds in the MWIR spectrum. In order to go further in the validation process of MATISSE, these comparisons with MODIS satellite images have been continued for additional wavebands in the VIS and LWIR and are presented in section 4.1 and section 4.2. The comparisons are concluded and possible sources of error are discussed in section 5.

4.1 Terrestrial background

As presented during the SPIE Remote Sensing Europe 2011 [3], very good comparison results have been received for the MWIR spectrum. The latest analysis have been carried out to investigate the performance of MATISSE code in those parts of the electromagnetic spectrum, were thermal effects are dominating (LWIR) on the one hand, and were reflection is the major contributor on the other hand (VIS). For taking a closer look at the radiance values in in the VIS and LWIR, the same distinct regions have been chosen as in the MWIR, see Figure 2. Each of them represents one major vegetation type occurring in the scene: humid highlands, dry lowlands, sea, and sound (Gibraltar, as mixture of sea and land background).

Table 4 shows the entire results for the latest calculations. The left column depicts the ROIs in detail as well as the land use distribution of MATISSE, the adjacent columns display the comparison of simulated and measured image in each band. All of the ROIs have the same dimensions (120 x 120 pixels). For the analysis of both data sets, histograms were created. The radiance class width was adjusted to be equal and representative for the corresponding pair of ROIs. In addition - and for the purpose of better comparability - the data were normalized to the same maximum (amplitude).

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2 The identified cirrus area was additionally divided into 2 areas: 1) rather thick cloud layer, 2) thin cloud layer.
<table>
<thead>
<tr>
<th>Band 4 (0.545 – 0.565 µm)</th>
<th>Band 29 (8.4 – 8.7 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>LWIR</td>
</tr>
<tr>
<td>Humid highlands</td>
<td></td>
</tr>
<tr>
<td>Dry lowlands</td>
<td></td>
</tr>
<tr>
<td>Sea</td>
<td></td>
</tr>
</tbody>
</table>

**Simulation vs. MODIS**

**Wasser normalisierte Skala**

radiance in W/(m²*sr*µm)
Table 4: Comparison of MODIS and MATISSE images concerning terrestrial background in the VIS and LWIR spectrum. Please note the different scaling of VIS and LWIR results.

For an even better possibility of comparison, the average values for each ROI in the LWIR and VIS are displayed in Figure 9. The best concurrence of simulated and measured data in both bands is reached ROI “sound” representing a mixture of sea and land background. In contrast, the most deviating results are obtained within the ROI “sea” in the visible spectrum, and “highlands” in the MWIR. Possible sources leading to these occurring divergencies are discussed in section 5. Generally, the MATISSE prediction is better in the LWIR, where thermal radiance is the major contributor to the total observed radiance. In contrary, the representation of wavebands, were the reflected fraction is the dominant factor, is less accurate, but still in line with the requirements.

Figure 9: Average values of measured and simulated image by comparison and having taken into account the MODIS calibration error of 2%. Please note the different scaling.

4.2 Atmospheric background

For the validation of the atmospheric background, MATISSE cloud computations have been carried out using the line-of-sight mode. Please note, that neither the particle size, nor the concentration, nor the shape (e.g. cirrus) of the particles were known, so the one best fitting MATISSE cloud model out of 22 possibilities had been chosen using Table 3 as reference guide. The results for the analysed wavebands are shown in Figure 10.
As for the terrestrial background, MATISSE cloud simulations show a better accordance in the LWIR. Here, the average values are diverging only slightly. In the visible band - where the scattering on clouds comes more into effect and therefore the knowledge on the particle shape is an important factor – the results are less accurate. For clouds that are opaque (e.g. cumulus), MATISSE overestimates the radiance values, whereas semi-transparent clouds are underestimated by the simulation. In the LWIR band, the cirrus clouds are overestimated with slightly higher values, whereas opaque clouds are very well represented by the MATISSE computations.

5. DISCUSSION

5.1 Terrestrial background

A detailed discussion on the possible sources of error has already been published in [3] and is still valid, even though other wavebands have been analyzed within the scope of this paper. Diverging simulation results concerning the ROI “sea” in the visible spectrum can be deduced from the fact that Matisse does not take into account all the phenomenon impacting the visible radiance. Especially in the visible spectrum, where reflection is the major contributor to the total observed radiance, simulated results vary from the measured ones. Further sources of error relate to the sea surface temperature, wind speed and direction, and the different distribution of radiance classes due to the MATISSE land cover map.

5.2 Atmospheric background

As the natural variability of clouds is very extensive, the knowledge of context data is essential to perform a substantial validation. The context data have provided information on the temperature profile, cloud type and cloud top altitude.

Knowledge on the thickness of the clouds could only be derived from the radiosounding data; the read-off altitude levels are rather inaccurate. The radiosounding acquirement is often not exactly at the same place and at the same time that the cloud observation took place. Moreover, cloud thickness only impacts on radiance levels for high clouds: In these atmospheric layers relative humidity measurements are difficult because of the reliability of water vapor content.

High altitude winds lead to a fast evolution of not only the cloud form itself, but also the altitude of the cloud edges is influenced heavily. This is another uncertainty factor leading to divergences in resulting radiance values.

Cloud types are classified using different nomenclatures. For example, the METEOSAT nomenclature is not the same as MATISSE’s one. Moreover, the cloud type estimation made by Fraunhofer IOSB is slightly different from the METEOSAT measurements.

However, in spite of scare context information (for example, size and particles shape), a set of possible cloud computations could be defined. Those were quite compatible with the MODIS measurements. Within the so defined envelope, the most suitable result for every analyzed cloud type is very close to the average radiance values in the selected areas on the MODIS image.

This work also demonstrated the need of taking into account clouds in the MATISSE imaging mode. Thus, the insertion of clouds described here does not allow taking into account a realistic cloud structure.
6. APPLICATION OF MATISSE AT FRAUNHOFER IOSB: SPACE BASED MISSILE DETECTION

To detect a BM within a sequence of images, certain image exploitation methods are implemented. For evaluating the effectiveness of such detection- and tracking algorithms, threat scenarios are created simulating the track and signal of a BM within a sensor’s FOV. By using MATISSE, radiance images as observed from a satellite based sensor can be modelled with varying cloud layers and geographic coverage as well as for different wavebands, orbit heights, and sensor specifications (Figure 11). The resulting background images are subsequently overlaid with flight path and height dependent spectral radiance information of a BM (simulation of one image pair see Figure 12).

<table>
<thead>
<tr>
<th>Spectral band A (MWIR)</th>
<th>Spectral band B (MWIR)</th>
<th>loose cloud cover</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 11: MATISSE simulations. The same part of the earth is observed in spectral band A (left), spectral band B (middle), and with loose cumulus cloud cover (right).

<table>
<thead>
<tr>
<th>Satellite on position 1</th>
<th>Satellite on position 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 12: Simulation of a satellite image pair with included BM signal and track. Both sensors observe the same region of interest. The arrows point to the spectral BM signal.

7. FUTURE WORK

Future investigations concerning terrestrial and especially atmospheric backgrounds will comprise a more detailed analysis of the simulation results for further wavebands, where reflectance is the dominant factor. This will include spectral ranges within both, the shortwave IR and the visible spectrum. Thus, the improvement of the MATISSE code can be further advanced.
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REFERENCES


