1. INTRODUCTION

The EarthCARE mission’s main goal is to improve our understanding of the role that aerosols play in cloud and radiation processes. The interactions between aerosols, clouds and radiation and their feedbacks on the Earth’s energy budget are still not well understood. To study these interactions, global observations of the electromagnetic spectrum, provided at several wavelengths and high temporal resolution, are required. Observations from active and passive sensors, such as ground, airborne and spaceborne sensors, provide information that is necessary to get a complete overview of the atmospheric state and better understand the interactions between clouds, aerosols and radiation.

In fact, ground and satellite-based sensors differ in sensitivity, but most of all, in temporal and spatial resolution of the observations. There is not a single sensor or remote sensing technique, capable to fully characterize cloud and aerosol properties. In this context, synergy between ground-based and satellite observations is important. On one hand, the latter complement and extend the ground-based observations by providing increased spatial coverage and multiple observations. On the other hand, the increased sensitivity and resolution of ground-based sensors (i.e. radars and lidars) provides more accurate and additional information, which can be used as benchmark for similar space-based measurements. Hence the synergy of different sensors is needed.

In order to exploit possible sensors synergy techniques involving ground and space-based sensors, there is the need for co-located measurements in time and space. Until now, the availability of datasets generated from different sensors and platforms is limited to expensive in-situ measurement campaigns, with only few satellite overpasses over the remote sensing sites. With the launch of CloudSat-CPR and Calipso-Caliop in NASA’s A-Train constellation the prospects for sensor synergy studies improved largely. However, it remains difficult to find sufficient cases with observations from both space and ground-based sensors. The purpose of this study is to use of the EarthCARE simulator to develop and validate novel retrieval algorithms, and study their sensitivity. These algorithms can then be applied with increased confidence to either in-situ and satellite observations, or observations from the A-Train constellation.

The ECSIM (EarthCare mission end-to-end SIMmulator) will be used to create “realistic” synthetic datasets that correspond to several instruments/platforms observing the same cloud scene. ECSIM has been adapted to simulate ground-based cloud radar and lidar measurements as well as satellite observations from the A-Train sensors. Furthermore, the shortwave radiation module in ECSIM has been modified in order to simulate MODIS and Meteosat/SEVIRI channel bidirectional reflection distribution functions – BRDF. These modifications make ECSIM a simulator capable of fully analyse the same cloud scene with complete co-located and simultaneous datasets, including ground-based radar and lidar observations along with the satellite side including cloud radar, lidar and radiometer/imager retrievals. The simulated BRDFs , for example, may serve as input to passive sensor cloud physical properties retrieval algorithms, such as the KNMI Cloud Physical Properties algorithm (Roebeling et al., 2006).

In this study we present the results from the upgraded ECSIM in order to assess that ECSIM is a feasible and valuable tool to generate controlled, complete and co-located synthetic datasets. The upgraded ECSIM is used to simulate observations of several cloud scenes generated by the ECSIM cloud generator, the Large Eddy Simulations - LES and the Cloud Resolving Models - CRM. These cloud scenes cover different atmospheric scenarios, such as a single layer plane-parallel stratocumulus cloud, a realistic 3D stratocumulus cloud from ASTEX campaign, and a cirrus cloud. Furthermore, for the cirrus cloud the simulated measurements from the ground are compared with the simulated aircraft observations with the radar and lidar sensors in order to show the good agreement between the two observations and to state that ECSIM is capable of simulating ground-based observations. Chapter 2 gives a short description of the ECSIM and explains the modifications made to ECSIM. The three cloud scenes that have been used for the simulations are introduced in Chapter 3. Chapter 4 presents the simulation results with the figures featuring the outputs of the different instruments on the three platforms and the results of the satellite retrievals for the first two stratocumulus scenes. Conclusions and suggestions for future works are given in Chapter 5.

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2. ECSIM

The EarthCARE end-to-end mission simulator, ECSIM, Donovan et al. 2008, is a tool capable of simulating the complete EarthCARE mission. In fact, ECSIM uses a collection of forward and retrieval models, utility programs and plotting tools, to simulate and plot EarthCARE observations. The main purpose of ECSIM is to facilitate the design, the instrument parameter tuning, and the algorithm development of the EarthCARE mission.

ECSIM can simulate all the 4 instruments aboard the EarthCARE satellite, i.e., the 94-GHz cloud profiling radar, the high spectral resolution lidar at 353 nm, the multispectral imager and the broad-band radiometer. Given a static and space-defined cloud scene as input and choosing the instruments to be simulated, ECSIM gives netcdf file outputs for every instrument simulation. The cloud scene that is used as input for the simulations is can be created with the embedded ECSIM cloud generator, or can be converted to ECSIM standard input cloud scene from Cloud Resolving Models or from Large Eddy Simulations.

2.1 ECSIM for ground-based simulations

The original ECSIM configuration, space-based oriented, has been upgraded including new models, in order to simulate also ground-based radar and lidar observations. The new models can simulate ground-based lidar and radar measurements for different configurations. In this work the radar and lidar have standard ground-based configurations. The radar system is a 94 GHz cloud profiling radar with 50 meters vertical resolution, while the lidar emits at 532 nm and collects observations with the same vertical resolution than the radar.

The models for the ground-based instruments included in the ECSIM are the lid_filter, lidar, rad_filter and radar. They have been modified in the code to be able to simulate the upward-looking instruments and to take into considerations the differences in the scattering properties, the surface backscatter and, the resolution and sensors velocity.

The geometry of the cloud scene for the upward-looking configuration positions the satellite at 1 meter above the ground with a speed in the along-direction of 10 m/s, in this way it is as if the cloud moves above the ground-based upward-looking instrument at a 10 m/s speed.

2.2 ECSIM and satellite retrievals

The Shortwave Radiation model in ECSIM can simulate the top of the atmosphere BRDFs operating in two modes using of two radiative transfer models:

a) a 3-D Monte-Carlo solver

b) an Independent Column Approximation mode using the DISORT solver.

In order to simulate the same channels used by MODIS on the TERRA and AQUA satellites, as well as by SEVIRI aboard Meteosat Second Generation, the ECSIM shortwave radiation models in ECSIM have been extended with new correlation-k tables. These include the MODIS 0.645, 0.858, 1.24, 1.64, 2.13, and 3.75 μm channels and the SEVIRI 0.635, 0.81, 1.64, and 3.92 μm channels. The shortwave calculations generate an output file with several parameters for each channel included in the instrument characteristics.

The BRDFs, together with the Sun-satellite zenith and azimuth angles, are used as input into the KNMI - Cloud Physical Properties (CPP) retrieval algorithm (Roebeling et al., 2006). The CPP retrieval algorithm has been developed at the Royal Netherlands Meteorological Institute (KNMI) as part of the EUMETSAT Climate Monitoring – Satellite Application Facility. This algorithm retrieves cloud optical thickness and cloud effective radius in an iterative manner, by comparing satellite observed reflectances at 0.6, 0.8, 1.6, 2.4 and 3.8 μm to radiative transfer model simulated reflectances. When a fixed vertical profile of liquid water content is assumed, the Cloud Liquid Water Path (CLWP) can be computed from the optical depth (τ) and effective radius (\( R_{\text{eff}} \)) using the following formula:

\[
\text{CLWP} = \frac{2}{3} \tau \cdot R_{\text{eff}} \cdot \rho
\]

where \( \rho \) is the density of liquid water. The cloud geometrical thickness and droplet number concentration are retrieved according to the algorithms described in Boers et al., 2006.

In the CPP, the Doubling Adding KNMI (DAK) radiative transfer model (De Haan et al. 1987; Stammes 2001) is used to simulate reflectances for plane-parallel clouds embedded in a midlatitude summer atmosphere. The underlying surface is assumed to be Lambertian, for which the reflectances were obtained from MODIS white-sky albedo data. The vertical distribution of the assumed spherical cloud droplets is parameterized in terms of the effective radius, using a modified gamma distribution with an effective variance of 0.15. The Mie theory is used to calculate the scattering phase functions of these droplets. The cloud reflectances for the Look-Up Tables are simulated at 0.6, 0.8, 1.6, 2.4, 3.8 μm, for optical thicknesses between 0 and 256 and droplet effective radii between 1 and 24 μm.

3. SELECTED CLOUD SCENES

After the modifications made to the ECSIM from the ground-based and satellite sides, the new models have to be tested and checked whether they can be consistent and reliable for future applications.

In order to demonstrate that the modified version of ECSIM is capable to simulate reliable ground-based observations, three clouds scenes have been selected to be used as input for ECSIM. The selected scenes refer to three different cloud
configurations and scenarios, covering different nature-like cloud situations, i.e.: a) a plane-parallel single-layer stratocumulus with one constant effective radius in height; b) a stratocumulus generated by Cloud Resolving Models from the ASTEX cloud campaign, and c) a cirrus cloud generated by Large Eddy Simulations. The three cloud scenes and their properties are described in more details in the following sub-sections.

3.1 Single layer stratocumulus

The first cloud scene is a plane-parallel homogeneous stratocumulus cloud with one cloud effective radius constant in height, which is used to assess the applicability of ECSIM for ground-based simulations and for satellite retrievals.

The left plot in figure 1 shows the characteristics of the first cloud scene. The 2D plot shows that the cloud effective radius constant at 12 μm in the horizontal and vertical extension of a 700 meters deep cloud. The right panel of Figure 1, shows the optical depth of the scene, which is homogenous all over the cloud scene at 23.7. The cloud liquid water path of the cloud scene is about 189 g/m², while the cloud droplet number concentration of about 100 particles/cm³. The horizontal resolution is 500 m, and the vertical resolution 500 m from the ground until an altitude of 1 km, and 100 m from 1 km up to 3 km.

3.2 ASTEX Stratocumulus

The second cloud scene is a realistic 3D stratocumulus cloud, generated from Cloud Resolving Models based on the cloud campaign called the Atlantic Stratocumulus Transition Experiment (ASTEX) that took place in 1992.

This cloud scene has a very high spatial resolution of 50 meters. The cloud effective radii vary between 5 and 7 μm, as seen in the left plot of figure 2, while it extends from an altitude of 600 to 950 m. The right panel on figure 2 shows the horizontal optical depth of the cloud, and it can be seen that it is not an homogeneous cloud field, but there are missing cloud points in the horizontal dimensions. The cloud optical depth varies between 1 to 10, with the majority of values between 5 and 6 (right plot in figure 2).

3.3 Cirrus Cloud

The third cloud scene used for the simulations describes a cirrus cloud, that was generated with an LES model. The left plot in figure 3 shows that the original cloud effective radius is about 60 μm, and that the cloud is confined between 6 and 7.5 km. The right plot in figure 3 shows that the horizontal optical depth of the cirrus cloud is inhomogeneous and varies between 0 to 2. The cirrus cloud has an horizontal and vertical resolution of 100 m.

4. ECSIM SIMULATION OUTPUTS

The new version of ECSIM, including the ground-based feature, has been tested on the three aforementioned cloud scenes. For the two stratocumulus scenes, the simulations include the ground- and space-based radar and lidar, and the passive sensor shortwave radiation. The latter for the KNMI-CPP algorithm retrievals. For the cirrus cloud scene passive sensor shortwave radiation simulations have not been done, instead the cirrus cloud has been observed with simulated airborne cloud radar and lidar measurements. The simulations have been run with the same orbit settings for each space-borne observation as well as for the ground-based ones. The shortwave radiation was simulated with a nadir satellite viewing angle and a sun zenith angle of 45 degrees with swath and resolution of 2 km.

4.1 Single Layer Stratocumulus

In figure 4 the results of the simulations for the first scene are plotted. The top-left plot shows the radar reflectivity for the space-borne cloud profiling radar, while the bottom-left plot shows the ground-based radar simulated reflectivity. Despite the
differences in the spatial resolutions, the two radar reflectivities show good agreement in observing the stratocumulus cloud. In the left plots, the outputs of the lidars are shown and again the observations for the space-borne lidar (top) and the ground-based one (bottom) are consistent with each other. Regarding the single-layer plane-parallel stratocumulus cloud, the four instruments all show a good consistency in describing the same scene.

In table 1, the original cloud properties are compared with the satellite retrieved ones using the KNMI-CPP algorithm. The first column lists the cloud properties, the second column gives the original values of the cloud scene, while the third column gives the retrieved cloud properties using the KNMI-CPP for the two MODIS channels (0.6 and 1.6 μm). As it is seen from the table below, the retrieved values are in good agreement with the original cloud property values.

<table>
<thead>
<tr>
<th>Original Scene</th>
<th>CPP retrieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>COT</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td>23.01</td>
</tr>
<tr>
<td>Reff</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>12.58</td>
</tr>
<tr>
<td>LWP</td>
<td>189.6</td>
</tr>
<tr>
<td></td>
<td>192.99</td>
</tr>
<tr>
<td>h</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>668.57</td>
</tr>
<tr>
<td>N</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>62.85</td>
</tr>
</tbody>
</table>

Table 1: Values for the original scene and for the KNMI-CPP retrieved values using MODIS channels 0.6 and 1.6 microns.

### 4.2 ASTEX Stratocumulus

After the simulations for the single-layer plane-parallel stratocumulus cloud, the “realistic” stratocumulus cloud scene generated from ASTEX campaign observed data have been simulated. Figure 5 shows the instrument simulations for the ground-based radar (bottom-left panel) and lidar (bottom-right panel) and for the space-borne radar (top-left) and lidar (top-right). There is good agreement and consistency between the ground-based and the space-borne simulations, as well as with the original scene. The top-left panel in figure 5 shows that the space-borne radar has a low sensitivity in detecting the warm low-level cloud, because it is affected by the surface return that masks the cloud. However, the ground-based radar can detect the top of the stratocumulus cloud. The space-borne lidar, on the other side, can detect the stratocumulus cloud and it is not influenced by the surface return. The lidar from the ground has got good measurements as well.
4.3 Cirrus Cloud

The last cloud scene used to show how the upgraded ECSIM works refers to a cirrus cloud. The simulation results of the cirrus cloud scene are displayed in figure 7 for space-borne cloud radar (top-left) and lidar (top-right), ground-based radar (mid-left) and lidar (mid-right) and for the airborne cloud radar (bottom-left) and lidar (bottom-right). The six images show that ECSIM is well capable to detect and measure the cirrus cloud in the same way. To confirm that ECSIM is as good simulation tool, it can be seen that the ground return is present only for the space-borne and airborne cloud radar measurements, while there is none, obviously, for the ground-based radar. Moreover, it is also possible to see the differences in resolutions and integration times. The plot for the space-borne lidar shows that it attenuates almost at the top of the cirrus, indicating the possible presence of oriented ice crystals.

Figure 7: Outputs from ECSIM for the third cirrus scene. The left column shows the radar reflectivity plots, while the left column shows the lidar signals. The upper row contains the satellite outputs, the middle row the ground-based output and the lower row shows the aircraft simulations.

5. CONCLUSIONS

The work presented in this study intends to show the applicability of ECSIM for simulating ground-based cloud radar and lidar observations, as well satellite based radar, lidar and shortwave radiation observations. The new upgraded ECSIM version, after running the above-presented simulations, is consistent in the simulations for ground-based observations as it has been shown in the previous output figures.

The behaviours of the instruments with respect to the different clouds is correct and conformed to the theory, for example, the surface return for the space-borne radar masking the ASTEX stratocumulus cloud or the attenuation of the space-borne lidar with respect to the cirrus cloud. It is also important to note that the synergy of ground-based and space-borne radar and lidar will help in the cloud property descriptions and retrievals, especially in identifying cloud boundaries.

Furthermore, adding the correlations-k tables for the MODIS and SEVIRI channels, and making the changes in the ECSIM shortwave radiation module, allow simulating BRDFs from MODIS and SEVIRI. It has been shown that the KNMI-CPP retrieval algorithm can be applied then to the ECSIM simulated BRDFs. The results presented in table 1 and figure 6, demonstrate that the CPP retrievals are consistent, with retrieved cloud properties that correspond well to the original scene properties.

The results presented in this study justify that the upgraded ECSIM is a good tool to create synthetic dataset with co-located observations from different sensors from the ground and the space. These synthetic datasets allow testing and validation of new algorithms, which can be then applied to real data with higher confidence as well as for the development of new synergistic retrievals.

In future work, the upgraded ECSIM will be used for studies regarding the satellite retrievals of cloud droplet number concentration and cloud geometrical thickness for stratocumulus clouds. The main idea is to investigate the relationship between effective radius and optical depth retrievals with respect to droplet concentration number and geometrical thickness. The active sensors will be used to measure the cloud geometrical thickness in order to validate the satellite retrieval as well as to remove one unknown in the model. After the cloud geometrical thickness is validated, the focus can move on to the cloud droplet concentration number for an accurate retrieval and application to Meteosat Second Generation observations.

References:


