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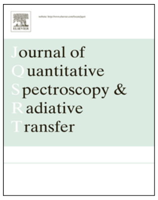

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A fast radiative transfer method for the simulation of visible satellite imagery

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ABSTRACT

A computationally efficient radiative transfer method for the simulation of visible satellite images is presented. The top of atmosphere reflectance is approximated by a function depending on vertically integrated optical depths and effective particle sizes for water and ice clouds, the surface albedo, the sun and satellite zenith angles and the scattering angle. A look-up table (LUT) for this reflectance function is generated by means of the discrete ordinate method (DISORT). For a constant scattering angle the reflectance is a relatively smooth and symmetric function of the two zenith angles, which can be well approximated by the lowest-order terms of a 2D Fourier series. By storing only the lowest Fourier coefficients and adopting a non-equidistant grid for the scattering angle, the LUT is reduced to a size of 21 MB per satellite channel.

The computation of the top of atmosphere reflectance requires only the calculation of the cloud parameters from the model state and the evaluation and interpolation of the reflectance function using the compressed LUT and is thus orders of magnitude faster than DISORT. The accuracy of the method is tested by generating synthetic satellite images for the 0.6 μm and 0.8 μm channels of the SEVIRI instrument for operational COSMO-DE model forecasts from the German Weather Service (DWD) and comparing them to DISORT results. For a test period in June the root mean squared absolute reflectance error is about 10^{-2} and the mean relative reflectance error is less than 2% for both channels. For scattering angles larger than 170° the rapid variation of reflectance with the particle size related to the backscatter glory reduces the accuracy and the errors increase by a factor of 3–4. Speed and accuracy of the new method are sufficient for operational data assimilation and high-resolution model verification applications.

1. Introduction

Imaging satellite instruments provide a wealth of information on the state of the atmosphere. Due to their excellent coverage and high spatial and temporal resolution, satellite observations are well-suited for data assimilation and model verification purposes. Infrared and microwave satellite observations are used increasingly for these applications. Visible satellite channels could provide important, complementary information, in particular about the distribution and properties of clouds. In contrast to infrared observations, visible radiances allow for a clear distinction between low clouds and ground and provide information about particle sizes. Although visible satellite images contain valuable information, they have not been used for operational data assimilation or model verification, because sufficiently fast and accurate forward operators were not available.

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Many fast radiative transfer models for the infrared spectral range have been developed in the last few decades. These models are often based on regression schemes in which the vertical dependency of the variables is approximated by an analytic function. An example is RTTOV [1,2] (Radiative Transfer for TOVS), which was first developed for the simulation of images of the instrument suite TOVS (TIROS Operational Vertical Sounder). Another example is OPTRAN [3] (Optical Path Transmittance), a scheme created for the satellite data assimilation system of the National Centers for Environmental Prediction (NCEP). Its transmission functions of the absorbing gases are calculated at integrated gas quantity levels along the optical path instead of at constant pressure levels. Other schemes use look-up tables to improve performance. An example is OSS [4] (Optimal Spectral Sampling). FIRTM-AD [5] (Fast Infrared Radiative Transfer Model – Adding–Doubling) applies the adding–doubling procedure (reflection and transmission of two sub-layers are combined to calculate reflection and transmission of the combined layer, taking multiple reflections between both into account) and uses look-up tables for the ground reflection, transmissions and emissivity. It is an extension of FIRTM1 [6], FIRTM2 [7] and CHARTS [8] (Code for High resolution Accelerated Radiative Transfer and Scattering). These schemes for the infrared spectral range have been validated against accurate radiation transfer models [2] and are generally sufficiently accurate, i.e. the absolute error is lower than the thermal noise of the instrument which is used for the radiance observation.

In the visible spectral range, scattering and absorption by molecules, water droplets, ice crystals, and aerosol particles play an important role. Multiple scattering makes numerical schemes complex and expensive. The most accurate methods for three-dimensional atmospheres are based on Monte Carlo approaches. However, using 3D Monte Carlo codes like the Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres MYSTIC [9] it may take several CPU days to generate a synthetic satellite image. These approaches are thus far too slow for operational purposes. The computational effort can be reduced significantly by considering only 1D radiative transfer, that is, by assuming that the optical properties of the atmosphere do not vary horizontally. For not too large solar zenith angles, this causes acceptable errors. For instance, for the application to MSG/SEVIRI, [10] found a relative root mean square error (RMSE) of 4–6% of the 1D approximation compared to the full 3D calculation for zenith angles not exceeding 66°.

For an accurate calculation of 1D radiances in cloudy atmospheres, approaches like the discrete ordinate method (DISORT) [11,12] are required. Implementations of DISORT can e.g. be found in the RT software package libRadtran [13]. For a typical calculation with 16 streams, i.e. computational quadrature angles, several CPU hours are required for a scene with $\mathcal{O}(10^5)$ pixels. The 1D spherical harmonics discrete ordinate method SHDOMPPDA [14] is of similar accuracy and requires approximately the same computational effort for the visible spectral range as DISORT. The LIDORT family [15], a widely used group of discrete ordinate multi-layer multiple scattering RT methods that are also able to compute Jacobians, uses some methods to speed up the solution process but still require a computational effort of the same order as DISORT. Wang et al. [16] developed a radiative transfer model for visible and near infrared radiances that is based on the adding–doubling algorithm. The relative error of their method with respect to DISORT with 128 streams is in general lower than 5% and the computational effort is comparable to DISORT with 16 streams. Also the Successive Order of Scattering (SOS) approach is used for the computation of visible radiances. The model 6S [17] is very accurate for cloudless atmospheres. A method derived from SOS, the Successive Order of Interaction model (SOI) [18,19] can also be used for visible radiances. This scheme requires about 13 h to calculate 0.65 μm reflectances for a scene with 1200 × 800 pixels [20] which is comparable to DISORT with 16 streams. Lakhshmanan et al. [20] use a parametric approximation of SOI results based on a neural network to compute synthetic visible satellite images. While their method is very fast (a few seconds for a scene with $\mathcal{O}(10^6)$ pixels) it does not take the variation of the reflectance with sun angle and albedo into account correctly, has a rather large mean absolute reflectance error, and thus does not seem accurate enough for verification or data assimilation purposes. Also the experimental scheme for visible reflectances included in RTTOV 11 shows large errors and is intended more for qualitative than quantitative applications [2]. Jonkheid et al. [21] use a large reflectance LUT for retrieval applications in the visible spectral range. Their method should be orders of magnitude faster than DISORT (no exact values are given in [21]) and they estimate the relative reflectance error to be of order 5%. While this method currently presents probably the best compromise in terms of speed and accuracy, it has some disadvantages related to large size of the LUT. The latter limits both the applicability in an operational data assimilation environment and the speed of the method.

In operational convective scale data assimilation systems with rapid update cycles only a very limited time span, typically on the order of minutes, is available in each assimilation cycle to run forward operators. To avoid huge amounts of data input and output, these operators preferably run online on the same machine as the NWP model, which means additional restrictions concerning memory and CPU use. In order to extract the full information, the uncertainty of the forward operators should ideally be smaller than the error of the simulated instrument. In case of the visible channels of the SEVIRI, the error is a few percent [22]. To our knowledge, the currently available radiative transfer methods for the visible spectral range are thus either too slow or too inaccurate for operational data assimilation and high resolution model verification or (in case of [21]) consume too much memory. In this paper, we present MFASIS (a Method for FAst Satellite Image Simulation), a new technique for the generation of synthetic satellite images in the visible spectral range that is sufficiently fast, sufficiently accurate, and requires only relatively small LUTs. The remainder of this paper is structured as follows: in Section 2 we give a description of the method. The accuracy of our approach is discussed in Section 3 and details on the computational