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Comparison of line-by-line and molecular band IR modeling of high altitude missile plume

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Abstract

This paper deals with the quantitative comparison of modeling IR radiation emitted from the plume of a tactical ballistic missile (TBM) in the boost phase with two different model approaches. IR spectra of the missile plume are calculated both with the high spectral resolution line-by-line radiation model FASCODE 3 (fast atmospheric signature code) using the databases HITEMP or HITRAN and the low spectral resolution IR radiation model NIRATAM (*N*ATO *I*nfra*R*ed *A*ir *TA*rget *M*odel) using molecular band model technique. The influence of the atmosphere on the IR spectra as viewed from a space born sensor is taken into account. The results show, that using an elaborate line-by-line radiation model can improve the accuracy in computation of IR signature compared to the simpler but faster molecular band model technique used in NIRATAM.

Keywords: Infrared modeling; IR signature high altitude missile plume; Line-by-line calculation; FASCODE 3 HITEMP; High spectral resolution; Comparison of model calculations

1. Introduction

Modeling of IR emission from hot combustion gases including radiation transfer through the atmosphere is used for a variety of remote sensing applications ranging from environmental exhaust gas monitoring to detection and tracking of missiles or high temperature events such as volcanic eruptions. For the development of concepts for sensors and satellites it is necessary to know the IR signature of the radiation source. Modeling IR spectra of hot inhomogeneous gases is a challenging task concerning accuracy of theoretical models and necessary computing time.

In this paper we investigate the spectral IR radiance of the exhaust plume of a ballistic missile in the boost phase for different flight altitudes along its trajectory from launch at ground level to burn-out in space. The plume is observed by a space born imaging IR sensor working in several spectral bands in the IR region from 2 to 5 μm.

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The paper compares spectra and in-band radiances of selected lines of sight through the exhaust plume for a variety of conditions calculated with two different radiation models, a fast low spectral resolution molecular band model and an elaborate and more accurate high spectral resolution line-by-line model using two different molecular line databases. The objective of the analysis is to find out spectral regions and conditions, such as gas temperature and pressure, where both models generate similar or different results.

The band model calculations are carried out with the infrared radiation model NIRATAM (*N*ATO *I*nfra*R*ed *A*ir *TA*rget *M*odel) [1]. This model initially developed for aircraft was enhanced jointly by DLR, IABG and BAE Systems for the simulation and analysis of the IR signature of missiles with liquid or solid propulsion systems.

This model uses the molecular band model technique. Band models were introduced more than 30 years ago to calculate IR spectra of the exhaust plume at reasonable computing time and costs with fair accuracy but certain limitations.

The used line-by-line radiation model is FASCODE 3 [2,3] with the high temperature database HITEMP and optional the database HITRAN for ambient atmospheric temperatures.

The spectral resolution used in calculations certainly affects in different ways the accuracy of calculated spectra and in-band radiances especially in the wings of molecular emission bands. The correlation effect of line emission and absorption in the exhaust plume and the atmospheric path to the sensor can cause large deviations in the IR spectra calculated with the different models. The consequences on the calculated in-band radiance for a spectral channel of a simulated IR imaging sensor depend on its spectral position and spectral bandwidth considered. For an application with broad spectral bandwidth of typically 1 μm the deviations of the calculated spectral radiance are compensated frequently by spectral integration and simulate a better consistency for the in-band radiance. If we regard, however, a narrow bandwidth of typically 0.05 μm used for a hyper spectral imaging sensor the discrepancies may no more be tolerable.

This study enables to give recommendations for the optional use of the molecular band model or the more accurate line-by-line model. The study addresses the comparison of band model versus line-by-line calculations of plume radiances, and neither the completeness or accuracies of the used HITEMP molecular database nor the accuracy of the plume signatures illustrated in this paper. Only comparisons with observed data, which are planned in near future, would allow that.

1.1. IR radiation from missiles

In the boost phase missiles are temporally variable and strong IR radiation sources. The three essential sources of radiation are: combustion gases and particles in the exhaust plume, heated parts of the engine and exhaust nozzle, and missile skin surface due to aerodynamic heating, internal heat sources and reflected radiation from ambient sky, ground and sun [4]. In the boost phase the exhaust plume is generally the strongest radiation source. The plume radiation depends on temperature, density, chemical composition and concentration of the combustion gases and the plume size.

The plume emits mainly in the mid IR spectral interval 2–5 μm through spectral selective line radiation of numerous IR active gas species as shown in Fig. 1. The most important IR emission by combustion gases results from the molecular species CO_2, H_2O and CO.

1.2. Band model calculations

Existing computer codes for calculation of the IR radiation of the plume such as NIRATAM, SIRRM, SPIRITS or SIRUS use the molecular band model technique to determine the emission spectra of homogeneous gas layers. Band models are hypothetical models of simplified mathematical structure which were introduced to provide fair representations of the properties of real spectra at reasonable computing time and cost. In general, a band model consists of a set of lines with specified properties regarding the intensities, shape, number and distribution of the lines. Sufficient accuracy can be obtained by using an average absorption coefficient over a specified wave number interval. For convenience, these intervals are expressed as a frequency unit (wave numbers/cm) or just (cm^{-1}). For NIRATAM calculation the intervals chosen are fixed at $\Delta\omega = 5\,cm^{-1}$ resolution.