Modeling multi-spectral imagery data with NIRATAM v3.1 and NPLUME v1.6

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ABSTRACT

Spectral imagery data (2.0 to 5.4 μm) was collected of plumes of ships by the NATO Special Working Group 4 ([1]). It provides the means to study the signature of a target spectrally, spatially, and temporally. This experimental data has been used to validate the infrared signature of the plume of a ship as computed by NATO's flow-field program NPLUME v1.6 and the NATO Infra-Red Air Target Model NIRATAM v3.1.

Two spatial positions in the spectral imagery data cube were selected. One which represents the background spectrum, and one which represents the spectrum of the plume of the ship. Theoretical spectra were computed by means of NPLUME v1.6 and NIRATAM v3.1. A computed background spectrum was fitted to the experimental background spectrum using a user-defined atmosphere in accordance with the meteorological conditions during the trial. A computed plume spectrum was fitted to the observed plume spectrum in order to determine the chemical composition of the exhaust gas. Since NIRATAM only takes into account plume radiation from CO, CO_2, H_2O, and soot, the analysis is necessarily limited to these species. Using the derived fitting parameters from the experimental data we make predictions about the infrared signature of the plume in two wavelength bands (mid-wave infrared and the long-wave infrared). The average transmission through the plume in the mid-wave infrared (3.0 to 5.0 μm) ranges from 65 % close to the exit plane, to 100 % where the plume dissolves in the ambient atmosphere. For the long-wave infrared (8.0 to 10.0 μm) the range in transmission is 90 % to 100 %. The active species in the mid-wave infrared and the long-wave infrared are the same for the plume as for the intervening atmosphere. The main difference is that the absorption features are deeper and wider for the plume.

Based on this work we arrive at the conclusion that spectral imagery data of the plume of a ship can be adequately modeled using NIRATAM v3.1 in conjunction with NPLUME v1.6. Alternatively, the experimental data validates NIRATAM v3.1 and NPLUME v1.6. Some modifications to the NIRATAM source code have been proposed as a result of this study. A new release of NIRATAM and NPLUME which incorporates some of these changes is expected shortly (NIRATAM v3.2).

Keywords: spectral imagery, NIRATAM v3.1, NPLUME v1.6, ships, chemical composition of plume

1. INTRODUCTION

With the advancement of spectral imagery new applications for this technique are explored. One of these is target classification. In order to separate the signature of a target from that of its surrounding background, detailed information on the target, the intervening atmosphere, and the surrounding background are required. Here we follow the approach to model spectral imagery data with NIRATAM and NPLUME in order to extract this information.

Spectral imagery records a two dimensional image of a scene in a larger number of adjacent wavelength bands. While a traditional color camera has three colors (red, green, and blue), a spectral imager records several hundred bands. The strength of this technique is that the recorded data contains spatial, spectral, and if time series are available, temporal information on the target and its surrounding background.

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The plume of a ship can be studied in a number of manners. Here we concentrate on passive detection by means of the infrared radiation emitted. The simplest approach would be to measure the radiant intensity in one band (e.g. the 3 to 5 μm atmospheric window). This assumes that the plume is spatially homogenous in temperature, pressure, and chemical composition. A more advanced approach is to spatially resolve the plume using a focal plane array (FPA). This allows the plume to be inhomogeneous: e.g. high density blobs moving away from the exit plane as the gas expands, cools, and mixes with the ambient atmosphere (due to turbulence). Although this latter approach allows spectral variability, the spectra are not recorded. Instead the integrated band intensity is recorded. A more advanced approach is to record the spectral information within the effective wavelength band for a spatial resolved image. The latter approach is taken using the technique of spectral imagery.

We have studied the feasibility to use spectral imagery data to determine the concentrations of the chemical constituents of the plume of a ship, and to predict the spectral characteristics of the plume (transmission and emission) in two wavelength bands in the infrared (mid-wave and long-wave infrared). In order to obtain the chemical concentrations, the NATO Infra Red Air Target Model (NIRATAM v3.1) in conjunction with NATO's flow-field program NPLUME v1.6 have been used. At the same time, the experimental data allows validation of NIRATAM v3.1 and NPLUME v1.6.

With the advancement of more sensitive detectors, instruments can be developed which can obtain spectral imagery data of a target continuously at sufficient high spatial, spectral, and temporal resolution. The computations (of one data cube) as performed for this study take about two minutes on a Pentium 233 MHz processor. With the increase of available computing power these computations could be performed in real-time. If such a time comes, the technique to model spectral imagery data will allow automatic classification of targets in the field.

2. EXPERIMENTAL DATA

2.1 NATO TRIAL DATA

As part of a continuing series of NATO Naval Electronic Warfare (EW) trials, the Special Working Group four (SWG4) has conducted a trial. Spectral imagery data was collected of plumes of ships and infrared decoys. For this study we have made use of the spectral imagery data of the plume of one of the ships ([1]).

The spectral imagery data has a spatial resolution governed by an 8X8 InSb array. The detection band was 1851 to 5005 cm^{-1} (from 2.0 to 5.4 μm) with a spectral resolution of 4 cm^{-1} apodized cosine. Each spectral imagery data cube corresponds to a four seconds average presentation with a total integration time of one second. This gives a temporal resolution of 4 seconds. Daily measurements of the transmission of the atmosphere were acquired using an 800-degree centigrade blackbody.

Spectral imagery data of the scene was collected as demonstrated in Figure 1. Part of the stack of the ship fills the lower central pixels. The plume fills the central pixels above the stack.

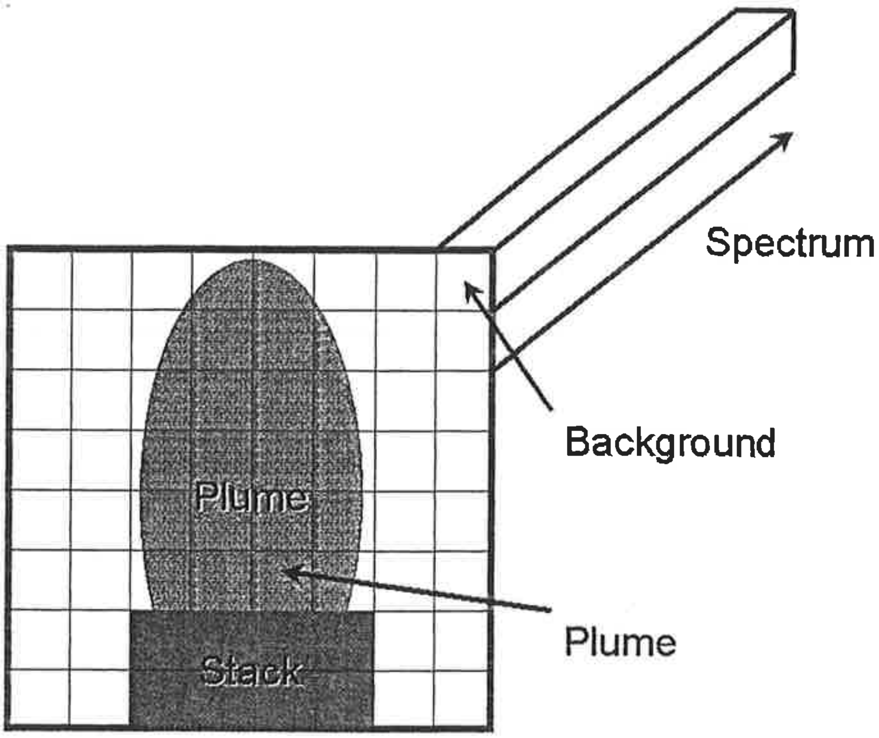

Figure 1: spectral imagery data (8 by 8 pixels) of the stack and the plume of a ship.

From the many spectral imagery data cubes recorded during the trial, we will limit our analysis to one data cube and eliminate the temporal information present in the available experimental data. For the selected cube, the ship moves at full power using the gas turbines and is seen beam-on. Figure 2 is a false color presentation of the spectral imagery data in selected bands (starting in the left upper corner, clock-wise): CO_2 (4.1-4.5 μm), CO (4.5-4.8 μm), CCO/CH (soot, 3.4-4.0 μm), and H_2O (3.4-2.9 μm). The plume is clearly resolved and exhibits structure. The radiant intensity in the selected spectral bands peak at different positions. Such data allow modeling of the plume spatially, spectrally, and since spectral imagery data was collected along a track of the ship, temporally. The latter is outside the scope of this work.

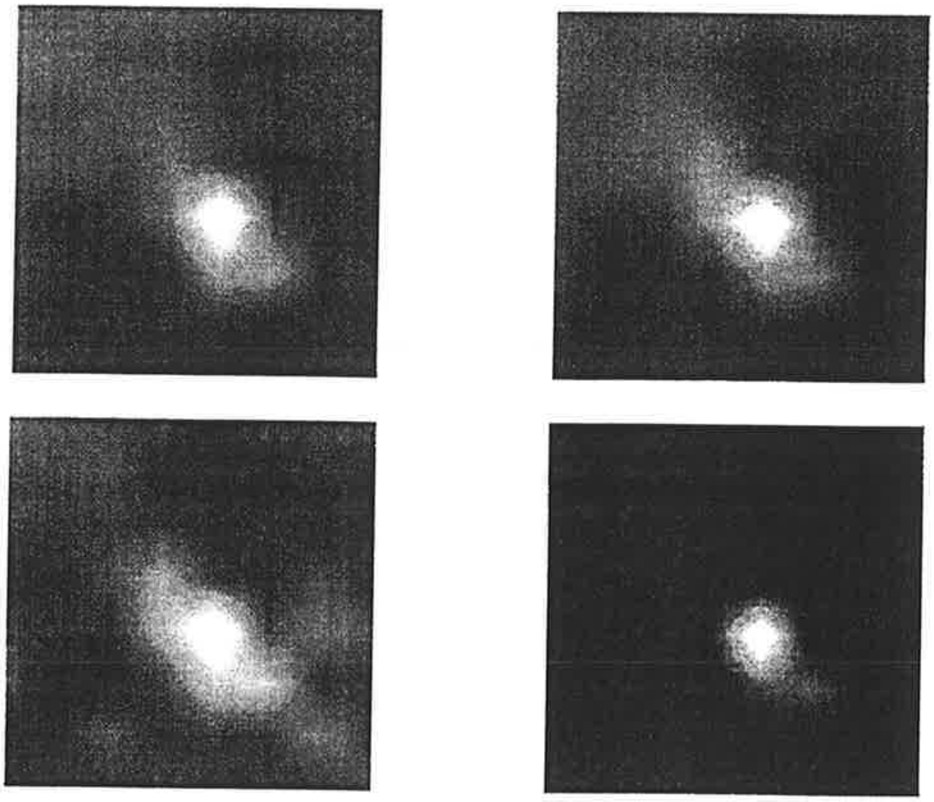

Figure 2: image of the plume of a ship in selected bands (clock-wise starting in the left upper corner: CO_2, CO, soot, and H_2O). The ship moves to the right, and the plume is slightly curved to the rear of the ship (to the left).

3. SOFTWARE TOOLS

To compute the infrared signature of a target and the transmission of the radiation through the earth's atmosphere, there are a number of software tools available. For this study we have made use of NPLUME v1.6, NIRATAM v3.1, and MODTRAN 3.0/LOWTRAN 7.0. These tools have been developed over the years in international collaborations and the models have been validated with experimental data.

3.1 FLOW-FIELD COMPUTED WITH NPLUME V1.6

NPLUME ([2]) is a modification of the US computer program BOAT1 and was designed to predict near field jet entrainment of an air-breathing engine. For this study we make use of NPLUME v1.6 which was released on February 12, 1998, under the auspices of DERA Farnborough ([3]). NPLUME requires information on the physical and chemical conditions at the exit plane and within the engine. Among others temperature, pressure, jet and entrainment velocity, and chemical composition of both the processed gas and the ambient atmosphere. NPLUME is an axi-symmetric plume model and does not take into account wind shear of the plume.

3.2 INFRARED SIGNATURE COMPUTED WITH NIRATAM V3.1

NIRATAM v3.1 (NATO Infra Red Air Target Model) is a computer model which predicts the infrared signature of a target within its natural surrounding by taking into account reflection and thermal radiation from the target and its surrounding background (Figure 3). It s tailored to work from 400 to 5000 cm^{-1} at 5 cm^{-1} spectral resolution (2 to 25 μm with a spectral resolution of 0.0125 μm at 5 μm). Internal treatment of the atmosphere (transmission and emission) is by means of LOWTRAN 5.B routines and is based on a 5 cm^{-1} spectral grid. Plume species included in the computations are CO, CO_2, H_2O, and soot.

NIRATAM requires information about the dimensions, temperature, and emissivity of the hardbody (stack of the ship), flow-field of the plume (made available by NPLUME), and the ambient atmospheric, and meteorological conditions.

The development of NIRATAM has been under the auspices of NATO panel 4 RSG-6, and has now been continued by Panel 4 RSG-18 ([4], [5]). NIRATAM v3.1 was released on 12 February 1998 under auspices of DERA Farnborough ([3]).

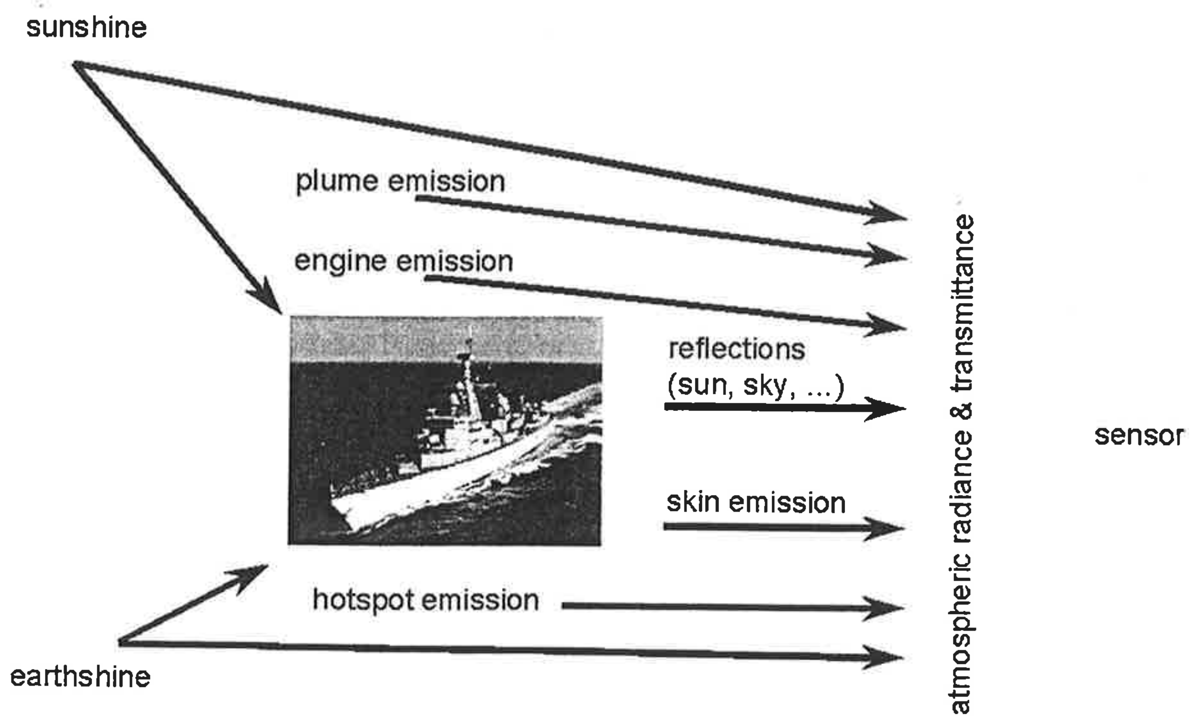

Figure 3: NIRATAM takes into account reflected and thermal radiation from the target and its background.

3.3 ATMOSPHERIC TRANSMISSION COMPUTED WITH MODTRAN 3.0 AND LOWTRAN 7.0

MODTRAN/LOWTRAN ([6]) computes atmospheric transmission, atmospheric background radiance, single-scattered solar and lunar radiance, direct solar and lunar irradiance, and multiple-scattered solar and thermal radiance. The spectral resolution of LOWTRAN 7 is 20 cm^{-1} in average steps of 5 cm^{-1} in the spectral range of 0.2 μm to infinity. The MODTRAN 3.0 resolution is 2.0 cm^{-1} in averaged steps of 1 cm^{-1}. The effect of molecular continuum-type absorption; molecular scattering, aerosol and hydrometeor absorption, and scattering are included. Representative atmospheric aerosol, cloud and rain models are provided within the code with options to replace them with user-modeled or measured values. Spherical refraction and earth curvature (ray bending) are considered in the calculation of the atmospheric slant path and attenuation amounts along the path. LOWTRAN 7.0 takes into account H_2O, O_3, N_2O, CH_4, CO, O_2, CO_2, NO, NO_2, NH_3, and SO_2.

4. ANALYSIS

4.1 VALIDATION OF NIRATAM

The first step is to validate our method. At the time the data was collected, the meteorological conditions were recorded. Based on these conditions we have created a user-defined atmosphere as input for NIRATAM. A fit of the computed background spectrum to the experimental background spectrum is shown in Figure 4. The agreement is quite reasonable and shows that we can model the background satisfactory. At the same time this exercise provides a validation for NIRATAM v3.1.

Based on Figure 4 we reach the following conclusions:

1. The background spectrum follows a blackbody curve corresponding to the air temperature. The correctness of this statement can be demonstrated using the radiative transfer equation ([7]):

   $$I_\sigma = I_\sigma(0)\,\tau_\sigma + (1 - \tau_\sigma)\,B_\sigma(T)$$

   With τ_σ the transmission, and σ the wavenumber.

   For a horizontal path of length infinity, $\tau_\sigma = 0$ for all σ.

   $$I_\sigma = B_\sigma(T)$$

   With T being the air temperature.

   This shows that the observed spectrum is a blackbody at the air temperature;

2. The experimental spectrum shows a broad emission feature between 2.1 and 2.3 μm. This feature is not reproduced by our model computations. This feature is attributed to scattered sunlight. The intensity increases to lower wavelength. However since the efficiency of the array decreases near the edges of our spectra, the net effect is a bump;

3. The experimental spectrum shows a narrow absorption feature centered around 4.3 μm. This feature is not reproduced by our model computations. It is attributed to a difference in CO_2 path length between the two beams of the Fourier interferometer. This leads to a phase error in the spectrum;

4. The experimental spectrum shows a small emission bump near 5.3 μm. This feature is attributed to scattered H_2O emission originating from clouds;

5. The fit between the computed background spectrum and the background spectrum extracted from the experimental spectral imagery data validates our method and the software (NIRATAM v3.1) used for the background spectrum.

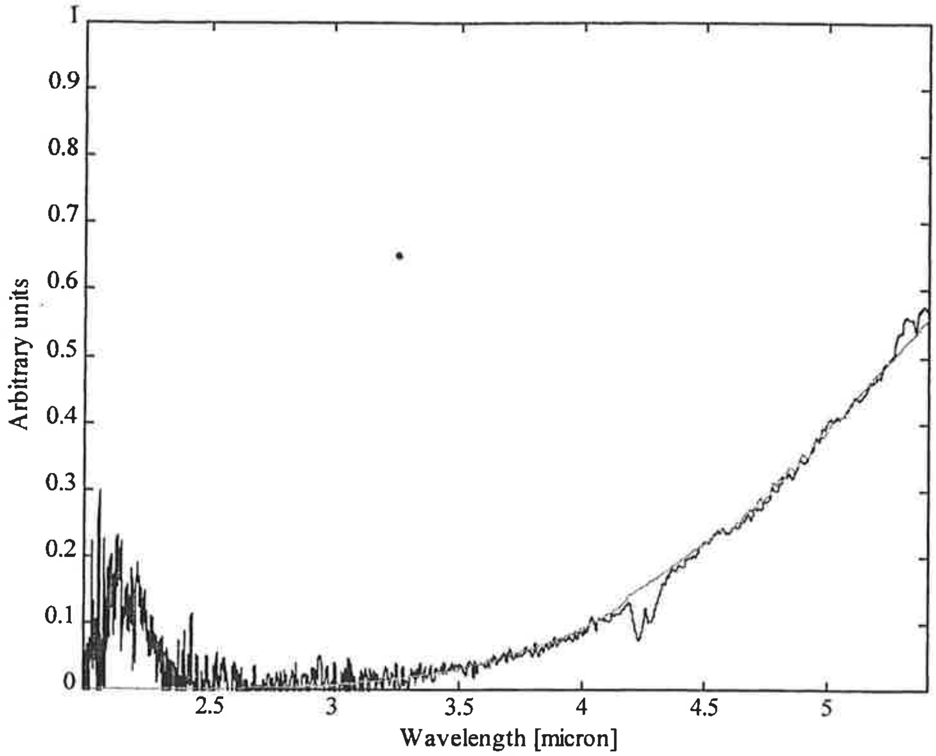

Figure 4: computed versus experimental spectrum of the background (a pixel which is free from radiation from the plume of the ship (see also Figures 1 and 2)). The dark (noisy) line is the experimental spectrum, and the thin line the computed spectrum.

4.2 CHEMICAL COMPOSITION OF THE PLUME OF A SHIP

Our next step is to compute the spectrum of the plume. By taking into account the intervening atmosphere and the background radiation which passes through the plume of the ship. Such an exercise is complicated by the fact that there are several regions within the 2.0 to 5.4 μm window for which the atmospheric transmission is very low. The observed spectrum does not contain information on the plume of the ship, but rather on the intervening atmosphere between the observer and the target.

The signature of the background was removed from the signature of the plume of the ship by subtracting the background spectrum from the target spectrum. The effect of the intervening atmosphere between the target and the observer remains present in the plume spectrum. The resulting emission spectrum of the plume is presented in Figure 5. This spectrum is used for our analysis of the chemical content of the plume of the ship.

NPLUME and NIRATAM were used to compute theoretical spectra of the plume of a ship. Some of the input parameters were known (e.g. temperature, pressure, and velocity of the gas at the exit plane) and were kept fixed during the computations. Since our main goal is to derive the chemical composition of the plume from the experimental spectral imagery data, we varied the mole percentages or concentration of the active species to improve the fit. Therefore only the CO, CO_2, H_2O mole percentages and soot concentration were derived.

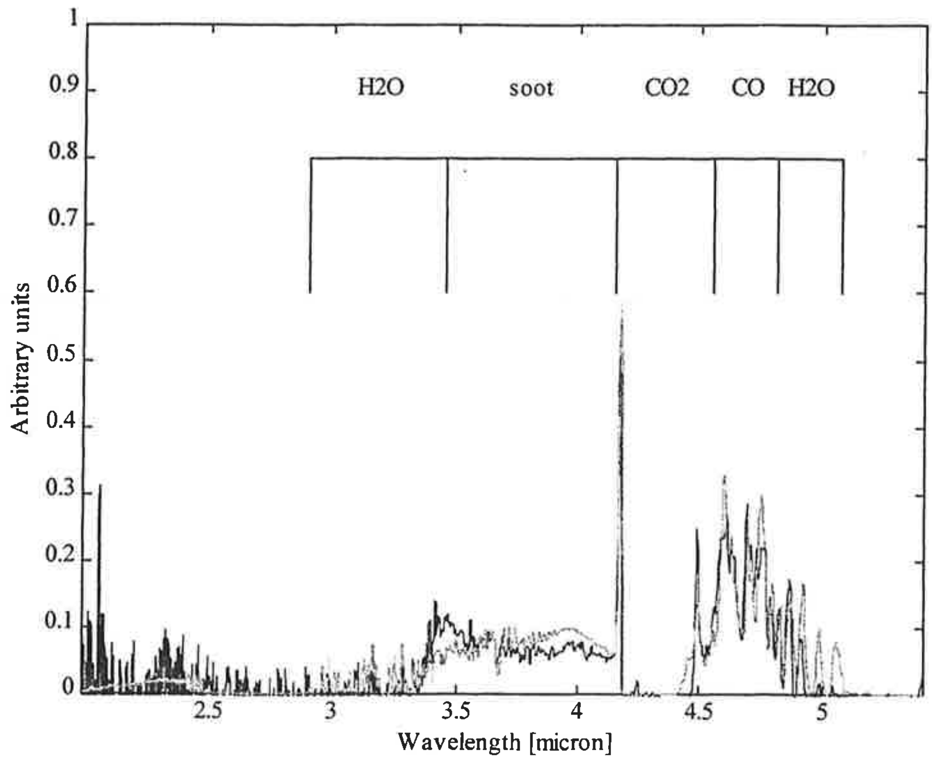

Figure 5: computed spectrum of the plume of a ship fitted to the experimental spectral imagery data. The dark line (the noisy spectrum at 2.25 μm) represents the experimental spectrum and the thin line the computed spectrum. Different regions are marked which are sensitive to particular specie (H_2O, soot, CO_2, and CO).

Based on Figure 5 we reach the following conclusions:

1. The overall appearance of the computed spectrum is most sensitive to the soot concentration. The 3.45 to 4.15 μm plateau proofs to be the best tracer of soot in this part of the spectrum. A fit to this plateau yields a soot concentration of 2.8×10^{-10} g cm^{-3};

2. The spectrum between 4.55 to 4.81 μm is dominated by CO, a fit to this part of the spectrum yields a CO mole percentage of 0.02 %;

3. The intensity of the blue (4.15-4.18 μm) and red (4.45-4.55 μm) spikes of CO_2 have been fitted and yield a CO_2 mole percentage of 2.42 %;

4. Finally, the plateau (which has a signal close to the noise level due to absorption of atmospheric H_2O) between 2.90 and 3.45 μm, and wavelengths longer than 4.81 μm were fitted by changing the H_2O contribution. The best fit was reached for a H_2O mole percentage of 3.00 %;

5. Other species are not constrained by the experimental data and our software tools. We assumed that the N_2 mole percentage in the plume equals that of the ambient gas. The minor species (with an ambient mole percentage of $< 10^{-6}$) were neglected, and the remaining mole percentage is due to O_2. This gives an N_2 and O_2 mole percentage of 78.08 and 16.48 % respectively.

The mole percentages and soot concentration at the exit plane of the stack are summarized in Table 1.

Table 1: sensitivity of spectral bands to the chemical composition of the plume of the ship.

No.	Spectral region (μm)	Fitting parameter	Plume composition	Units
1	2.00-2.19	scattered sunlight		
2	2.19-2.32	atmosphere opaque		
3	2.32-2.46	scattered sunlight		
4	2.46-2.90	atmosphere opaque		
5	2.90-3.45	H_2O	3.00	%
6	3.45-4.15	soot	$2.8\text{x}10^{-10}$	g cm^{-3}
7	4.15-4.18	CO_2 blue spike	2.42	%
8	4.18-4.45	atmosphere opaque		
9	4.45-4.55	CO_2 red spike		
10	4.55-4.81	CO	0.02	%
11	4.81-5.07	H_2O		
12	5.07-5.40	atmosphere opaque		
13		N_2	78.08	%
14		O_2	16.48	%
		total	100.00	%

It is interesting to note that there is no simple relation between the mole percentage (Table 1) and the contrast signature (Table 2) for the detectable species. CO has the largest contribution to the contrast signature, but has the smallest mole percentage. H_2O has the largest mole percentage, but has the smallest contribution to the contrast signature.

Table 2: contribution to the contrast signature (2.0 to 5.4 μm) for detectable species.

Species	Contribution to the contrast signature	Units
CO	53	%
CO_2	26	
Soot	15	
H_2O	6	
Total	100	%

4.3 PREDICTION OF THE TRANSMISSION AND EMISSION OF THE PLUME IN TWO SPECTRAL BANDS

Based on the mole percentages of CO, CO_2, H_2O, and the soot concentration, we computed the transmission through the plume in the mid-wave infrared (MWIR, 3-5 μm), and long-wave infrared (LWIR, 8-10 μm) window (Figure 6). The exit of the stack is at the bottom of the image and the plume is vertically aligned. Wind shear has not been taken into account. The transmission in the MWIR ranges between 65 % close to the stack, to 100 % outside of the plume. In the LWIR the transmission ranges between 90 % and 100 %. The computed and observed emission in the MWIR is shown in Figure 5 for a pixel in the center of the plume of the ship.

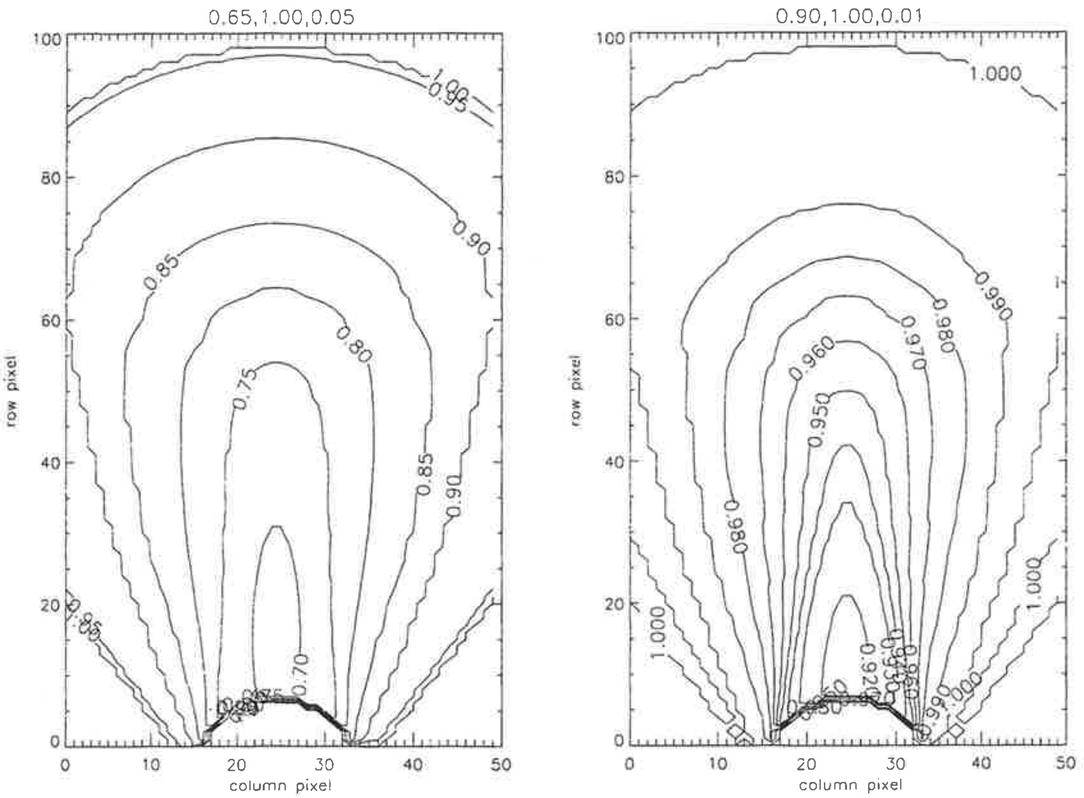

Figure 6: average transmission in the mid-wave infrared (3-5 μm, left panel) and long-wave infrared (8-10 μm, right panel) atmospheric windows through the plume. Both axes give pixel numbers, where each pixel is 22 by 22 centimeters wide. The size of the total frame is therefore to 10.8 meter wide with a height of 21.6 meters.

5. DISCUSSION

NIRATAM in conjunction with NPLUME are suited to analyze spectral imagery data of the plume of a ship. We can accurately predict the signature of the background given the meteorological conditions at the time the data was collected. By varying the mole percentages at the exit plane of the stack, a fit of the computed spectra to the experimental data was made. Mole percentages for CO, CO_2, H_2O, and the soot concentration could be derived. The next step would be to compute theoretical spectra for all available spatial positions of the spectral imagery data. This means an increase of the information by a factor sixteen. Since the mole fractions and soot concentrations should be the same for all these spatial positions (taking into account chemical reactions, and excluding the stack), the temperature and pressure of the plume could possible be derived from the data. Repeating this exercise for different engine conditions could be of interest for algorithm for classification of ships.

The computed transmission through the plume in the mid-wave infrared (MWIR, 3-5 μm atmospheric window), and the long-wave infrared (LWIR, 8-10 μm atmospheric window) have been averaged over the whole band and are displayed in Figure 6. The transmissions are high and the radiation through the plume is not much hindered by the presence of the plume (at most 35 %). A closer look at the spectrum of the plume shows that the active species are the same as those in the intervening atmosphere. The mole percentages of CO, CO_2, H_2O, and the soot concentration have increased, at the expense of O_2. This is the direct result of the combustion process in the ship's engine. The increase of the mole percentages of CO, CO_2, and H_2O, combined with the higher gas temperature, produces a transmission spectrum very similar to the intervening atmosphere, but with deeper (higher mole percentage), and wider (higher temperature) features. The plume transmission overlaid with the atmospheric transmission (Figure 7) shows that the plume only leads to additional absorption in the wings of the features.

Figure 7 presents the transmission spectrum of the plume (at the center of the exit plane) in the MWIR and LWIR bands. Overlaid is the transmission spectrum of the atmosphere for the same path length. In the MWIR the most active species is CO_2 with a strong absorption feature near 4.2 μm. In the LWIR the dominant feature is H_2O. Water vapor has a strong absorption feature which peaks at a wavelength smaller than 8 μm. The red wing of the H_2O feature is present in the 8-10 μm window.

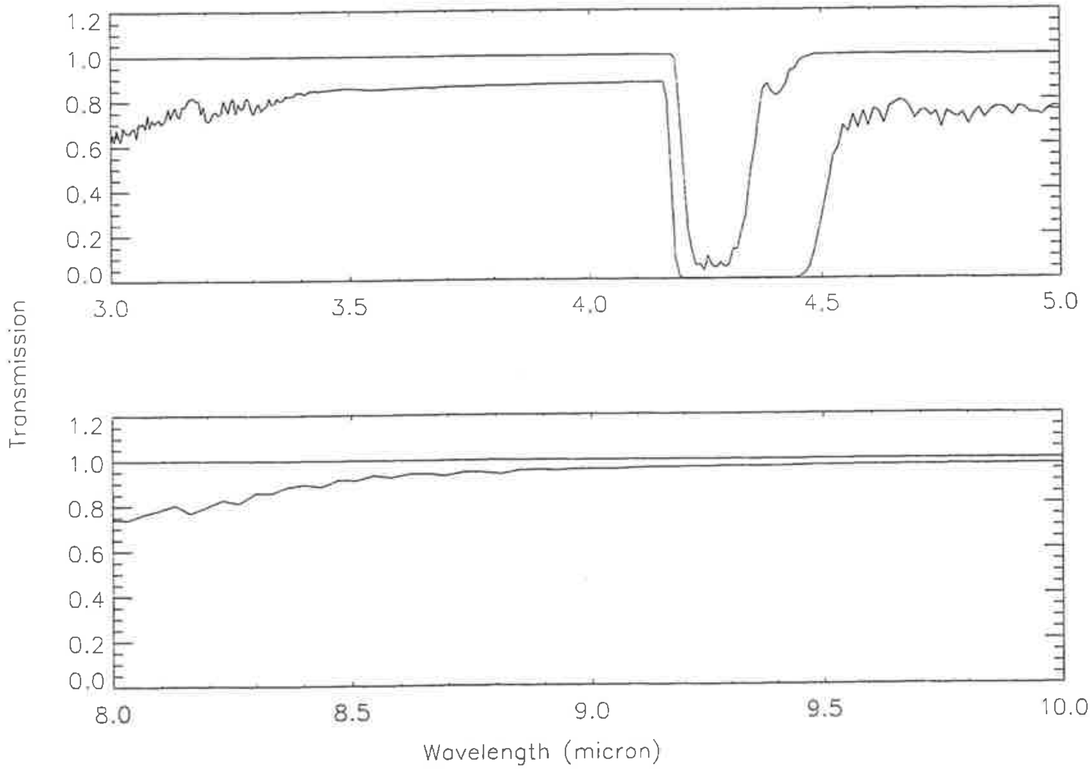

Figure 7: transmission in the mid-wave infrared (upper panel) and long-wave infrared (lower panel) of two selected

line-of-sights. The lower line is the transmission through the plume at the center of the exit plane. The upper lines the transmission through the atmosphere for a path length equal to that of the plume.

6. CONCLUSIONS

Our analysis of the spectral imagery data of the plume of a ship, and the validation and modeling using NPLUME v1.6 and NIRATAM v3.1, have demonstrated that spectral imagery data can be well modeled using these tools. Clearly we have only demonstrated the principle. Full-scale calculations taking into account spectral, spatial, and temporal information present in the spectral imagery data can be made using this approach. Such an extensive study would provide information on the physical (temperature and pressure), and chemical (concentrations of species) conditions in the plume of the ship.

The experimental data has been used to validate NIRATAM v3.1 and NPLUME v1.6. Fits to the observed background and plume spectra are satisfactory. Based on the results of this study we have proposed some modifications to the NIRATAM source code. Some of these modifications will be incorporated in a new release of NIRATAM v3.2. A new release of NIRATAM by MF is expected shortly.

7. ACKNOWLEDGEMENTS

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