

ON THE USE OF THIN PLASTIC FILMS AS GAS-PHASE ANALOG TARGETS

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ABSTRACT

Acquiring ground-truth data of gaseous effluent releases concomitant with the collection of remotely sensed hyperspectral imagery (HSI) is a difficult task. Precise ground-truth information is required for algorithm development and testing. Imprecise and/or uncertain truth data impede the development and refinement of information-extraction tools and techniques for gaseous effluents remote sensing. Except for a small number of well-instrumented points in space (usually including plume exit apertures), the true three-dimensional physical and chemical structure of gas plumes is generally unknown. Further compounding this uncertainty are the spatial sampling characteristics of the remote sensing system. It is extremely difficult to assign true gas-effluent quantity to the individual plume-containing pixels imaged by HSI sensors. In an attempt to generate well-truthed data, thin plastic films were assessed as gas-phase analog targets. With thin films, material location, abundance, temperature, and subpixel distributions (for mixtures) can be well known, easily measured, and controlled. Large polyethylene (PE) thin-film panels ('plastic plumes') were thus deployed during HSI data collection experiments in 2003 and 2005 at which longwave infrared (LWIR) airborne HSI data were acquired. The polyethylene films yielded spectral signatures similar to those of gases; plastic plumes are viable analogs for gaseous effluents. The theoretical background supporting the use of plastic plumes as gas analogs is discussed as are the results of the analysis of the LWIR HSI airborne and ground-truth data.

Index Terms— hyperspectral imagery, HSI longwave infrared, LWIR, gas, gaseous effluent, plastic plume

1. INTRODUCTION

The detection and identification of gas-phase effluents with longwave infrared (LWIR) hyperspectral imagery (HSI) is readily accomplished with the basic statistical spectral matched filter (and minor variations on that theme) and/or with various orthogonal subspace projection (OSP) algorithms [see, e.g., refs. 1-5 and references cited therein]. Basic spectroscopy and decades-old imaging spectrometry

algorithms combined with trained analysts have rendered the remote detection and identification of gaseous effluents in HSI an essentially solved problem. However, obtaining higher levels of information such as column density (i.e., quantity of gas-phase substance present) and plume temperature from remotely sensed HSI remain challenges. The challenges stem from the difficulty of measuring such parameters of actual gas plumes in the field. Three-dimensional plume size, shape, density, temperature, and location (and all as a function of time) are highly variable and very difficult to determine with certainty. Without knowledge of these quantities, algorithm development and testing against actual plumes in remotely sensed HSI are likewise difficult. In an attempt to generate data for algorithm development and testing, thin plastic films (plastic plumes) of polyethylene (PE) were deployed and tested for their ability to act as gas-phase analog materials. The testing of the plastic plume concept was motivated by the observation that the absorbance spectra of many thin plastic film materials resemble those of gas phase materials. This report presents an exploration of the LWIR HSI data of the PE plastic plume.

2. METHOD

2.1. Overview

The assessment of whether or not the PE plastic plume is a viable gas-phase analog is based primarily on how closely the airborne HSI data are modeled by the basic, commonly used radiative transfer (RT) expression for gases in LWIR remote sensing data. We use the thin plume RT expression in [1]; this expression is given below (*sec. 2.1.4*). Various approaches to extracting temperature and concentration·path-length of the PE plastic plume are explored. We begin with brief descriptions of the LWIR HSI data and the data analysis methods.

2.1.1. SEBASS LWIR HSI Data

SEBASS LWIR HSI data were acquired of the PE plastic plumes. SEBASS is an airborne HSI sensor that collects in the mid- and longwave infrared regions of the spectrum; additional details of the sensor may be found in refs. [6] and [7]. Analyses of the 128-channel LWIR HSI data are

presented here (more precisely, 124 bands after noisy-band removal).

2.1.2. Atmospheric Compensation

Atmospheric correction is required to derive the various terms central to the radiative transfer modeling (and understanding) of gas-phase effluents in HSI data. The In-Scene Atmospheric Correction (ISAC) algorithm [8] as implemented in the ENVI[®] imaging processing software package (<http://ittvis.com/envi/>) was applied to the HSI data.

2.1.3. Absorbance Spectrum of PE

Laboratory measurement of the transmissivity of a witness swatch of the PE thin plastic film was used to derive absorbance (α). Relevant properties of the PE material are given in Appendix I.

2.1.4. Thin Plume Radiative Transfer Expression

Eq. (1), derived in [1], is the thin plume approximation of an RT expression commonly utilized for gases in LWIR HSI data. Symbol nomenclature is similar to that used in [1]; a symbol table is provided here in Appendix II. There is a wavelength dependence for each term (except n_c and T_p) but it is not indicated for brevity of notation.

$$N^t = n_c \alpha \tau [B(T_p) - N^g] + N^g \tau + N^a \quad (1)$$

2.1.5. Analysis Methods

Eq. (1) is solved for n_c ; T_p (and thus $B(T_p)$) is varied until n_c equals the true PE plastic plume value. n_c is calculated two ways. First, as a mean of the 124 n_c values obtained for each channel of the LWIR HSI data for a scene-derived, average PE spectrum. Second, n_c is obtained for one channel, only. T_p is varied until n_c equals the true PE plastic plume value based on the band at 11.4366 μm (i.e., eq. (1) is solved for T_p). 11.4366 μm is the center wavelength of a prominent absorbance feature of PE (α spectrum of PE provided below).

The second method (eq. (1) is solved for T_p) is subsequently applied to each band of the mean, scene-derived PE spectrum (n_c set to the truth value) to obtain a plume temperature ‘spectrum.’

Unconstrained linear spectral unmixing is also applied.

3. RESULTS AND ANALYSIS

Figure 1 shows a photograph of a deployment of the PE plastic plume. The sheet has a thickness of 6 mil (0.006 inches) and is the exact same panel deployed during various trials in 2003 and 2005. Analysis of the LWIR HSI data of the PE over the grass background is discussed here; data of the PE over the blue plastic tarpaulin evident in the figure are not reported upon and will not be discussed further. The portion of the PE panel over grass was imaged with nine full

pixels of LWIR HSI data. It is evident in the radiance spectra that the PE material is in absorption; i.e., it is cooler than the underlying background.



Figure 1. Photograph of the PE plastic plume. Half of the panel has an underlying blue tarpaulin. The portion overlying the grass background is analyzed here.

Figure 2 shows the PE absorbance (α) and at-aperture radiance spectra. The radiance spectrum is an average of the several LWIR HSI pixels on the PE plastic plume. The impact of the PE on the radiance spectrum, though evident, is not as pronounced as that of freon (not shown) also released in the vicinity of the PE and captured in the same LWIR HSI data set.

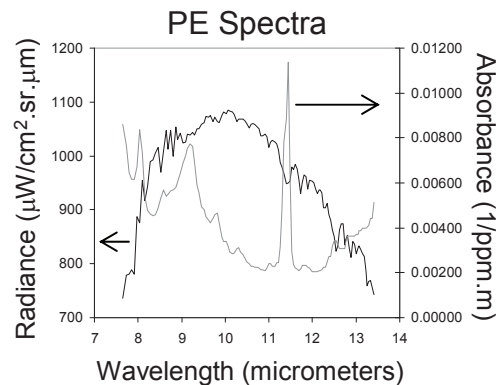


Figure 2. PE absorbance spectrum (gray curve) and average at-aperture radiance spectrum (black curve).

Figure 3 shows an image chip of the LWIR HSI data and a matched-filter output plane for PE (using the α spectrum in Fig. 2). The PE is readily detected and identified with extremely low false-alarm rate (in the much larger data set from which Fig. 3 (right) is spatially subsetted; 1 false alarm pixel in >262,000 pixels). Since the scope of the present report is determining n_c and T_p (based on eq. (1)), detection and identification of PE are not discussed further.



Figure 3. (left) Single-band (9.24 μm) LWIR grayscale image of the PE plastic plume (indicated by arrow). (right) Matched-filter output plane showing the PE panel. The color table has been reversed so that the panel, detected in absorption by the α spectrum in Fig. 2, shows as white.

3.1. n_c and T_p from Equation (1)

3.1.1. n_c from an Average of all Bands

Equation (1) is solved for n_c . N^g in eq. (1) is the ground-leaving radiance (GLR) spectrum of the grass background (immediately adjacent to the PE plastic plume) and is derived from the HSI following application of atmospheric compensation (with ISAC). τ and N^a are also obtained from ISAC; N^t is at-aperture radiance of the PE-containing pixels. N^g is based on a mean spectrum derived from 36 pixels. Indeed, values of all the 'N' terms are based on averages of several pixels. Recall that n_c is known and α is derived from laboratory measurements of PE film transmissivity.

T_p is varied until the average n_c value calculated from the values for all bands of the mean PE spectrum (N^t) is equal to the true value of 0.00099 moles/cm². A concentration-path length 'spectrum' is thus generated. The T_p for which the mean n_c equals the true value is 297.5 K. This temperature is equal to the local air temperature at the time of data acquisition as measured by a meteorology station located ~1 km from the plastic plume deployment site.

3.1.2. n_c at 11.4366 Micrometers

The T_p value giving the true n_c value at 11.4366 μm is 306.7 K. This is also the temperature of the adjacent grass background (N^g) if the grass is considered a graybody with an emissivity (ϵ) of 0.98. I.e., the grass-background mean ground-leaving radiance spectrum is fit with a Planck function with $\epsilon = 0.98$ yielding a temperature of ~306.7 K.

Solving eq. (1) for T_p (with the actual value of n_c) yields a plume temperature spectrum with a mean (of 124 values) of 297.4 K.

Figure 4 (top) shows the plume temperature spectrum and the concentration-path-length spectrum (bottom) derived from the calculations described in this and the previous

subsections, respectively. The true n_c value is indicated by the horizontal line in the bottom plot.

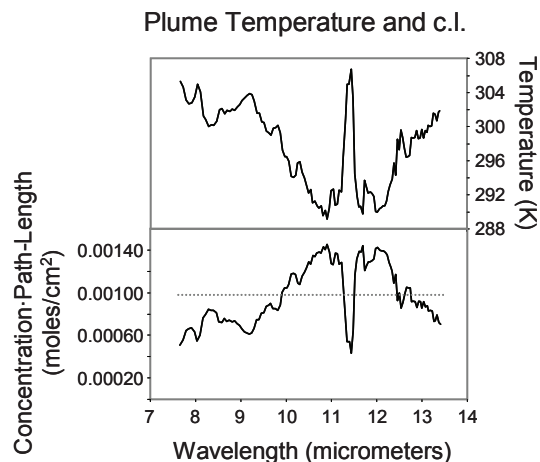


Figure 4. Plume temperature and concentration-path-length (c.l.) spectra. The mean of all values in the upper plot is 297.4 K. The dotted horizontal line in the bottom plot shows the true n_c value of 0.00099 moles/cm². The mean of all c.l. values in the lower plot equals 0.00099 moles/cm².

4. DISCUSSION

The analyses of the LWIR HSI data in the context of eq. (1) yield results consistent with local conditions and the actual n_c value. The use of the α spectrum in Fig. 2 in the basic matched filter (as applied for gas-phase remote sensing) also yields the expected detection and identification of the PE. An unconstrained linear spectral unmixing with two endmembers (average grass background and α of the PE) yields an average grass fraction (of the PE-containing pixels) of 0.94 indicating that the PE plastic plume is transparent (though this analysis is cursory and requires further work). Based on these results and the nature of the at-aperture radiance spectrum of the PE, the PE plastic plume is a viable analog for a gas-phase effluent.

5. SUMMARY AND CONCLUSIONS

The theoretical background supporting the use of plastic plumes as gas analogs is discussed as are the results of the analysis of the LWIR HSI airborne and ground-truth data. The polyethylene plastic plume yields spectral signatures similar to those of gases. Based on the results obtained from analyzing the HSI data in the context of the RT expression given in eq. (1), the PE plastic plume is a viable analog for a gaseous effluent.

6. FUTURE DIRECTIONS

There are several directions for continued work. E.g., analysis of additional LWIR HSI data sets of plastic plume deployments; the analysis of HSI data (mid- and LWIR) of the other plastic materials that have been deployed (e.g., polypropylene); and additional trials of the experiment for which the plastic sheet(s) are cut with holes to have a known fraction of void spaces. This creates a different mixture of plastic plume and background than that afforded by whole pixels of an unbroken film of material. Strips of a second (and even a third) plastic material may be weaved through the cut-out void-spaces to make complicated subpixel mixtures.

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8. REFERENCES

- [1] Hayden, A., Niple, E., and Boyce, B., (1996). Determination of trace-gas amounts in plumes by the use of orthogonal digital filtering of thermal-emission spectra. *Applied Optics*, v. 35, no. 16, pp. 2802-2809.
- [2] Young, S. J., (2002). Detection and Quantification of Gases in Industrial-Stack Plumes Using Thermal-Infrared Hyperspectral Imaging. Aerospace Report ATR-2002(8407)-1, 76 p.
- [3] Griffin, M.K., Kerekes, J.P., Farra, K.E., and Burke, H.K., (2001). Characterization of Gaseous Effluents from Modeling of LWIR Hyperspectral Measurements. In *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery, VII*, edited by Sylvia Shen and Michael R. Descour, Proceedings of the SPIE, v. 4381, doi: 10.1117/12.437026.
- [4] O'Donnell, R. Messinger, D., Salvaggio, C. and Schott, J. Identification and Detection of Gaseous Effluents from Hyperspectral Imagery using Invariant Algorithms, (2004). In *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery X*, Silvia Shen and Paul Lewis, eds., Proceedings of the SPIE, v. 5425, doi: 10.1117/12.542426.
- [5] Funk, C. C., Theiler, J., Roberts, D. A. and Borel, C. C., (2001). Clustering to improve matched filter detection of weak gas plumes in hyperspectral thermal imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 39, pp. 1410-1420.
- [6] Hackwell, J. A., Warren, D. W., Bongiovi, R. P., Hansel, S. J., Hayhurst, T. L., Mabry, D. J., Sivjee, M. G., and Skinner, J. W. (1996). LWIR/MWIR Imaging Hyperspectral Sensor for Airborne and Ground-Based Remote Sensing. *Imaging Spectrometry II*, *Proceedings of the International Soc. for Optical Eng.*, v. 2819, pp. 102-107.
- [7] Kirkland, L. E., K. C. Herr, E. R. Keim, P. M. Adams, J. W. Salisbury, J. A. Hackwell, and A. Treiman, (2002). First Use of an Airborne Thermal Infrared Hyperspectral Scanner for Compositional Mapping. *Remote Sens. Environ.* 80, 447-459. And: http://www.lpi.usra.edu/science/kirkland/Field/home_sebass.htm.
- [8] Young, S.J., Johnson, R.B., and Hackwell, J.A., (2002). An in-scene method for atmospheric compensation of thermal hyperspectral data. *Journal of Geophysical Research*, v. 107, no. D24, 4774, doi:10.1029/2001JD001266, 20 p.

APPENDIX I – Properties of the Polyethylene (PE)

- Formula: CH₂
- Molecular Weight: 14.03 grams/mole
- Density: ~0.91 grams/cm³
- Thickness: 6 mil = 0.006 inches = 0.01524 cm
- Assume a square ‘swatch’ of PE that’s 1 cm on edge; area of swatch: 1.0 cm²
- Total volume (of PE) in a 6 mil x 1 cm x 1 cm cube swatch: 0.01524 cm³
- Grams of PE in a 6 mil x 1 cm x 1 cm cube swatch: 0.0139 grams
- Moles of PE in a 6 mil x 1 cm x 1 cm cube swatch: 9.885 x 10⁻⁴ moles
- Total number of molecules in a 6 mil x 1 cm x 1 cm cube swatch: 5.953 x 10²⁰ molecules
- Concentration of molecules in a 6 mil x 1 cm x 1 cm cube swatch: 3.906 x 10²² molecules/cm³
- Column density (=concentration·path-length) in a 6 mil x 1 cm x 1 cm cube swatch: 5.953 x 10²⁰ molecules/cm²
- Concentration·path-length: 0.9885 x 10⁻⁴ moles/cm²

APPENDIX II – Symbol Table

All terms, except n_c and T_p , have a wavelength dependence that is not indicated for brevity of notation.

- N^t = calibrated, at-aperture radiance data of the PE plastic plume ($\mu\text{W}/\text{cm}^2\cdot\text{sr}\cdot\mu\text{m}$; also known as micro-flicks or μf)
- n_c = concentration·path-length (moles/cm²)
- α = absorbance spectrum of PE (1/ppm·m)
- ppm = parts per million; m = meter
- τ = atmospheric transmissivity (dimensionless)
- $B(T_p)$ = Planck radiance of the plume at temperature T_p
- T_p = plume temperature (K)
- N^g = ground-leaving radiance of the grass background ($\mu\text{W}/\text{cm}^2\cdot\text{sr}\cdot\mu\text{m}$; micro-flicks or μf)
- N^a = atmospheric scattering derived from ISAC ($\mu\text{W}/\text{cm}^2\cdot\text{sr}\cdot\mu\text{m}$; also known as micro-flicks or μf)