

Infinite impulse response filters for direct analysis of interferogram data from airborne passive Fourier transform infrared spectrometry

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Abstract

Infinite impulse response (IIR) filters and support vector machines (SVMs) are applied to interferogram data to implement the automated detection of heated ethanol plumes by airborne passive Fourier transform infrared (FT-IR) spectrometry. To simulate monitoring of industrial emissions, the spectrometer is mounted in a downward-looking mode on a fixed-wing aircraft and used to detect plumes released from a portable emission stack. Both IIR and finite impulse response (FIR) filters having similar frequency responses are designed and applied to the interferogram data to extract the information associated with the ethanol C–O stretching band at 1066 cm^{-1} . This study investigates the effects of distortions in the interferogram introduced by the nonlinear phase responses of the IIR filters on the ability of the SVMs to recognize ethanol. In addition, three ways to apply the filters to the interferogram are explored. These studies reveal that the phase distortion introduced by the IIR filters causes no measurable degradation in classifier performance. This allows the intrinsically lower filter order of the IIR filters to be used to reduce the length of the interferogram segment required to implement the filtering. With an independent prediction set of interferograms collected during overflights of the stack, the best SVMs miss detecting ethanol in less than 4% of the cases while achieving false detection (false positive) rates of less than 0.5%. This level of performance is accomplished with an interferogram segment of only 24 points, including those points required to implement the filtering. The ability to detect analyte vapor plumes with such a short interferogram segment is particularly advantageous in the airborne measurement because of the potential to increase the interferogram acquisition rate, thereby improving the ability to resolve ground-based targets.

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1. Introduction

Passive Fourier transform infrared (FT-IR) spectrometry provides a rugged and portable method for identifying volatile organic compounds (VOCs) released at a remote location. Important applications of this method include monitoring of stack emissions [1], satellite monitoring of the atmosphere [2], and remote characterization of volcanic gasses [3]. One of the technical difficulties common to these applications is the absence of a stable reference background for use in spectral processing. Constantly changing background signals arising from changes in the ambient IR radiance within the field-of-view (FOV) of the spectrometer can obscure relatively small analyte signals, requiring the

use of an effective background suppression method for a successful field measurement.

The issue of background suppression is particularly problematic when the spectrometer is mounted in a downward-looking mode on an aircraft platform. Unlike ground-based measurements in which the principal background contributions are narrow spectral features from atmospheric species such as water vapor and carbon dioxide, the aircraft-based experiment features widely varying IR radiances caused by a limitless variety of terrain features and ground structures that may be present within the FOV. Here, the principal background contributions are changes in the broad radiance profile detected by the spectrometer.

Shaffer and Combs have demonstrated that background suppression in passive FT-IR measurements can be performed equivalently with signal processing methods applied either to the single-beam spectral data or to the raw interferogram data collected by the spectrometer [4]. When the

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background signals are spectrally broad, the direct interferogram analysis is particularly useful [5–9]. The interferogram representation corresponding to the broad spectral features of the IR background decays much faster than the corresponding representation of the narrower spectral features of a VOC. This difference in decay rates makes it possible to select an interferogram segment that contains a relatively small background contribution. By restricting the analysis to a short interferogram segment, it may be possible to configure the spectrometer to collect a reduced-length interferogram. For rapid airborne surveying applications investigating ground-based sources of VOCs, this may permit a higher rate of interferogram acquisition and furnish better spatial resolution of ground-based targets.

An interferogram segment selected to minimize the contribution of the broad radiance background will still contain contributions from narrow spectral features at all frequencies, however. To increase selectivity for the analyte, an important processing step is the application of bandpass digital filtering to the interferogram segment to suppress contributions from unwanted frequencies such as those associated with the spectral bands of interferences. Through this combination of segment selection and bandpass filtering, a selective analysis can be implemented directly with a short segment of the interferogram.

Extensive research has been performed in our laboratories to design bandpass digital filters for use in direct interferogram analysis [8,10,11]. The digital filters employed previously were based on a time-varying finite impulse response (FIR) filter design. By tailoring the filter design directly to the interferogram, this method requires fewer coefficients than conventional FIR filter designs to obtain bandpass filters with a given frequency response [10,11]. Digital filters with fewer coefficients are advantageous for direct interferogram processing because such filters allow the collection of a shorter interferogram.

To reduce the required length of the interferogram further, the use of infinite impulse response filters is investigated in this study. These filters have been used in several applications in analytical chemistry [12–15]. One of the advantages of IIR filters over FIR filters is that the IIR filter design requires many fewer filter coefficients to achieve a desired frequency response. However, a disadvantage of these filters is their nonlinear phase response which can introduce potentially problematic distortions in the filtered interferogram segment.

To investigate these tradeoffs, both FIR and IIR filters with similar frequency responses are designed and used for direct interferogram analysis. The target application investigated here is the airborne detection of heated plumes of ethanol released from a portable emission stack [6]. This analysis simulates the use of airborne passive FT-IR measurements for monitoring chemical releases from industrial sites. Ethanol is chosen here as representative of VOCs in terms of its spectral features in the midwave IR (MWIR, 8–12 μm) region. To implement an automated detection,

short segments of the filtered interferograms are classified by support vector machines (SVMs). The SVMs are trained with data collected on the ground and subsequently applied to data acquired from the air during overflights of the stack. The optimization of filter design parameters, the starting interferogram point for filtering, and the length of the interferogram segment is also discussed.

2. Experimental

2.1. Instrumentation and data collection

The interferograms employed in this work have been described in a previous study [6]. A brief summary of the experimental procedures is presented here. Interferograms were obtained with a Bomem Model MR254/AB spectrometer (ABB Bomem, Quebec City, Que., Canada) equipped with a Hg:Cd:Te detector operating in the MWIR region. The FOV of the spectrometer was restricted to 0.3° with a Cassegrain telescope. Double-sided interferograms containing 512 points were used in this work. Interferograms were single scans, and the spectral bandwidth was 1975 cm^{-1} . This bandwidth corresponds to sampling every eighth zero-crossing of the HeNe reference laser. Forman phase correction using 64 points on each side of the centerburst and normalization to a vector magnitude of 1.0 were applied prior to further processing. The spectrometer was used to view heated plumes of ethanol, methanol, and mixtures of the two compounds released from a portable emission stack [16]. Interferograms were collected on the ground and also acquired from a fixed-wing aircraft.

For the data collected on the ground, a backdrop of polyvinyl chloride liner material (emissivity ≈ 0.9 , Total Vinyl Products Inc., Ypsilanti, MI) was placed behind the stack to fill the FOV of the spectrometer. This setting simulated the types of backgrounds observed from the air with the entrance aperture of the spectrometer directed at the ground. Over 7 days, the path integrated concentrations of ethanol, methanol, and mixtures of the two were varied between 25 and 300 ppm-m. The stack temperature was also varied from 125 to 200 $^\circ\text{C}$. The FOV of the spectrometer was directed far enough downwind from the stack exit flue such that all the spectral transitions were observed as absorptions. Background interferograms of the liner material were supplemented by collecting the radiance of an extended blackbody source (11–60 $^\circ\text{C}$, Graseby Infrared Inc., Orlando, FL).

Four open-air remote sensing experiments were conducted to obtain the airborne data. The data sets from these experiments will be termed airborne test sets A, B, C, and D. These data sets were acquired from an aircraft flying at altitudes of 600–900 m with a speed of 100–150 knots. The data acquisition rate was approximately 80 interferograms/s. The path integrated concentration of ethanol was varied between 600 and 1500 ppm-m, and the stack temperature was fixed at 200 $^\circ\text{C}$. Consecutive interferograms were

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