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# An Analysis of FTIR Emission Spectroscopy of Flickering / Pulsing Sources: Application to Rocket Plumes

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## Abstract

The University of Arkansas at Little Rock (UALR) Combustion Research Laboratory focuses on non-invasive spectral techniques applied to flame sources. One of the tools used to monitor these sources is a Fourier Transform Infrared (FTIR) Interferometer. Previous work in this lab has identified various complications in using emission spectroscopy as an analysis tool on non-constant sources. This flicker, or pulsing, has been identified as interference frequencies in sources such as UALR's Hybrid Rocket plume. A mathematical model and simulation of the interaction between the interferometer and these interference frequencies has been developed using the software package MatLab. Using this simulation, predictions can be made concerning the amount of noise introduced into the IR signal due to source intensity fluctuations. A mathematical relationship has been discussed that maps the interference frequencies from the time domain of the interferogram to the frequency domain of the spectrum.

## 1. Introduction and Background:

The University of Arkansas at Little Rock (UALR) Combustion Lab houses a MIDAC M2400-C Fourier Transform Infrared (FTIR) emission spectrometer that offers quick and sensitive measurements of combustion systems. This spectrometer is a rugged, portable instrument with built in analog to digital conversion. It uses an RS-232 interface connected to a 'lunchbox' computer for data acquisition. The 'lunchbox' computer has a 33MHz 486DX processor with proprietary MIDAC interface boards for communication with the spectrometer. Either an MCT or InSb detector can be installed in the instrument. The software used was written in house. It allows remote setting of data acquisition controls and limited data processing once data is acquired. The scanning apparatus in this portable device is a Michelson interferometer, set up to operate in the infrared region of the electromagnetic spectrum. The spectrometer provides a simple, non-invasive platform from which the plume can be analyzed /6/.

When considering FTIR absorption spectroscopy, much care is taken to ensure that the source is a very consistent, constant temperature. This serves to reduce the amount of noise in the signal, yielding a clean, easy to read spectrum. With emission spectroscopy, many times the source cannot be as easily regulated. While a clean, easy to read spectrum is still the goal, it is harder to obtain in emission spectroscopy due to noise introduced to the signal from the source. At UALR, a hybrid rocket plume is one source used for FTIR emission spectroscopy. Plume temperatures have been found to vary between 2500K and 3200K /3, 4/. This is sufficient to excite atomic and molecular emission in the plume.

When obtaining the plume spectrum, an FTIR emission instrument seems at first glance to be a logical choice over the regularly used dispersive instruments. The advantages to FT systems over the dispersive based instrumentation such as a spectrograph or monochromater include the multiplex advantage /5/, greater optical sensitivity in the region of interest, high scan rates, and digital data sets that are easily transformed. However, these systems have previously been identified as less than ideal as plume monitoring devices due to the unstable nature of the source /6/. This paper explains the interaction between the unstable physical phenomena and the FTIR interferometer in use.

## 2. FTIR Problems:

Fourier Transform Spectroscopy appears upon first inspection to be an ideal method for monitoring the exhaust plume from a rocket motor. Much work was done previously to obtain the spectral IR signature of UALR's hybrid motor. This work identified many obstacles in obtaining a valid spectrum with the then currently available equipment. These obstacles included acoustically induced vibrations within the instrument, degradation of signal due to $CO_2$ and water vapor in the atmosphere, and the extremely low emissivities of some of the species sought. These difficulties, while non-trivial, are not insurmountable /7/. The acoustical problems could be diminished by isolating the interferometer from the support structure of the instrument. The weak signal and the presence of noise can be addressed using the right combination of filters and amplifiers.

A more formidable obstacle is related to the flicker of the plume. It has been shown that the plume does exhibit significant optical flicker in the regions around 30Hz and 450Hz and its octaves. There is evidence that suggests that this flicker also exists in the IR region of the spectrum, and this is currently under investigation. It has been suggested that the lower frequencies are attributable to fuel chuffing and the higher due to the acoustic mode of the combustion chamber acting as a ¼ wave tube /8, 9/. This paper focuses on the modeling and simulation of this flicker in an attempt to fully characterize the problem with the goal of eliminating any interference caused by source fluctuations. This would allow for the reintroduction of FTIR emission spectroscopy as a plume analysis tool.

At the heart of the MIDAC M2400-C spectrometer is a Michelson Interferometer. This device exploits the interference of electromagnetic radiation when two sources of radiation are combined. The incident light is split and sent to either a fixed or moveable mirror. The mirror movement causes a change in path length for one of the paths. When the two paths are recombined, they produce interference fringes incident upon the detector. If the source is monochromatic, the intensity, $I$, of the fringe is given by the equation

$$I = \frac{I_0}{2}\left(1+\cos\left(\frac{2\pi(x)}{\lambda}\right)\right) \tag{1}$$

where $I_0$ is the intensity of the incident light, $x$ is the path length difference due to mirror displacement, and $\lambda$ is the wavelength of the monochromatic source. If the light is polychromatic, as is the case with most sources of interest, this intensity becomes a sum of all intensities. This is given by the equation

$$I(x) = \sum_n \frac{I_{\lambda_n}}{2}\left(1+\cos\left(\frac{2\pi(x)}{\lambda_n}\right)\right). \tag{2}$$

This makes it apparent that the intensity of the recombined light (the fringe) is dependent on the individual frequency components of the incident light. If the intensity of the source (plume) fluctuates, this intensity change will be incorrectly mapped as a spectral component by the interferometer. It cannot distinguish between an intensity change due to constructive and destructive interference and an intensity change due to source fluctuations.

The interferometer samples in the spatial domain, sampling in equal intervals of mirror displacement. This is accomplished by using a HeNe laser as a reference source and a quadrature phase detector to determine maxima and minima of the monochromatic source fringes. These maxima are used to trigger data acquisition. These equal sampling intervals are required to satisfy the uniform sampling requirement of the Fast Fourier Transform, which is used to convert the interferogram to a spectrum. Since the mirror velocity of the MIDAC M2400-C is approximately constant over the sampling region, the uniformly spaced samples can be considered uniformly timed samples. This allows the spatial domain to be considered equivalent to the time domain.

## 3. Experimental:

The MIDAC interferometer has a mirror drive controller with selectable scan speeds. This scan speed represents the speed of the movable mirror in the Michelson Interferometer. Previous work has shown that a valid spectrum can be obtained from the hybrid rocket plume if the scan speed is very slow /6/. Due to the detector's integration properties, this causes the plume fluctuations to be smoothed, or averaged, between sample points. This integration is undesirable because it prevents the acquisition of real time data from the plume and can average out very fast events that may be crucial to proper diagnosis of engine health and performance. If the mirror drive is run faster to collect data closer to real time, the plume flicker starts to cause unacceptable interference.

To illustrate the format for the majority of the figures in this paper, refer to Figure 1. This figure shows the spectrum of a Bunsen flame taken with the MIDAC interferometer. Figure 1(a) is the raw interferogram; Figure 1(b) is the spectrum from 2000 to 4000 cm-1; Figure 1(c) is the full-scale spectrum, including regions that lie outside the sensitivity region of the detector in use. Note that no

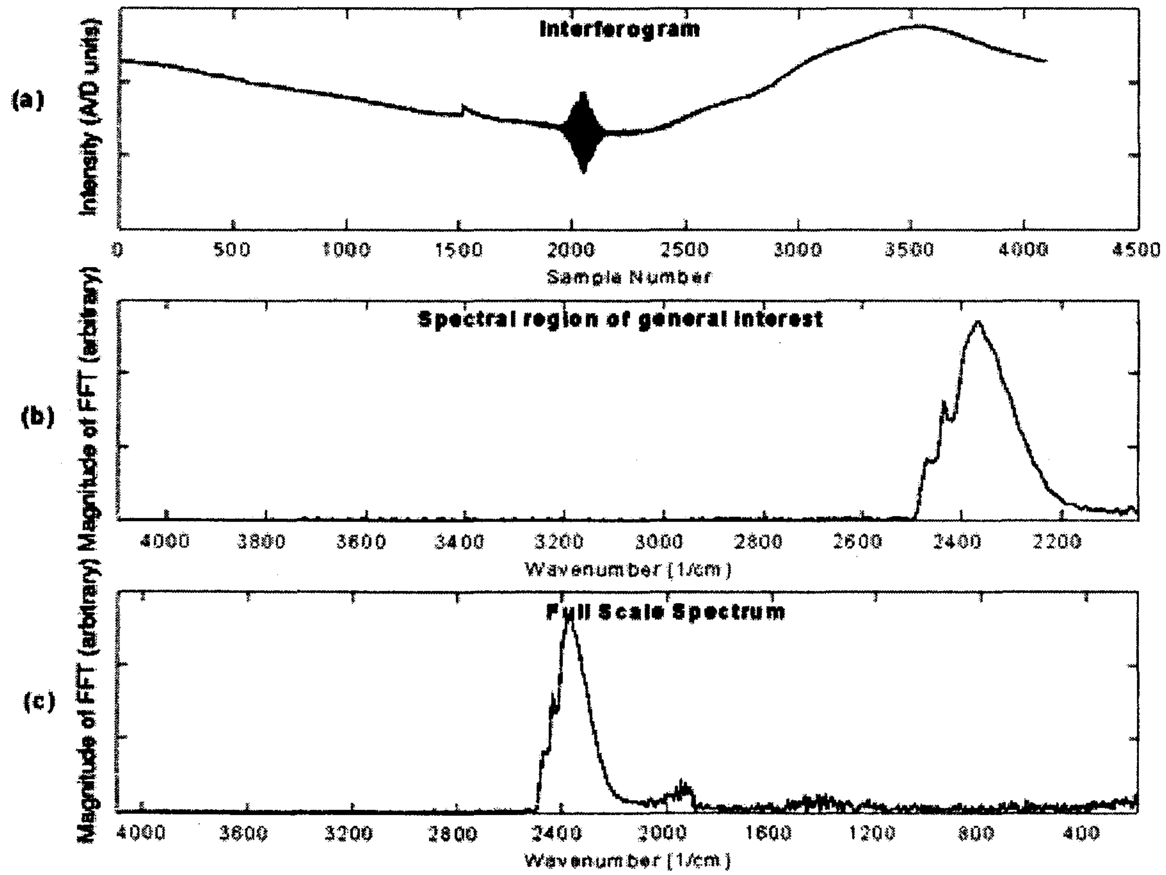

**Fig. 1:** (a) Interferogram of Bunsen flame (b) Spectrum of Bunsen flame showing CO2 peak (c) Full scale spectrum of Bunsen flame, including region outside detectability limit of InSb detector.

post processing has been applied to the spectra. For instance, no compensation has been made for detector response in different wavelength regions. Also note the lack of a water band that is expected around 3750cm-1. This is due to a fogged KBr beam splitter that corrupts the background scans, negating any water found in the emission scans. As this paper is not concerned with the actual spectra obtained, but rather the ability to obtain the spectra, time was not spent on polishing the spectra for species identification. It is presented in a raw form that still illustrates the difficulties outlined throughout the paper.

Figure 2 shows an interferogram obtained from the rocket plume using the high-speed mirror drive board, which corresponds to a mirror speed of approximately 1.35 cm/sec. Note the high level of noise in the interferogram and the lack of a discernable spectrum. For Figure 2, a plain HTPB fuel grain was fired using gaseous oxygen at a mass flow rate of approximately 0.04lbm/sec. The interferometer was placed approximately 30 feet from and perpendicular to the plume, aligned with a point about three inches from the exit nozzle coincident with the first mach disk /1, 2/.

If the detector in the MIDAC Interferometer is saturated, it will give a signal that upon cursory examination appears similar to the signal given for a non-constant source. In an attempt to confirm that the signal obtained from the rocket motor plume exhibits interference due to intensity fluctuations and not due to detector saturation, the same experiment outlined above was performed on a demonstration rocket motor. This demonstration rocket consists of the same fuel and oxidizer as the labscale motor. The main difference is the lack of an exit nozzle. This keeps the internal pressure very low, as there is no backpressure on the system. This

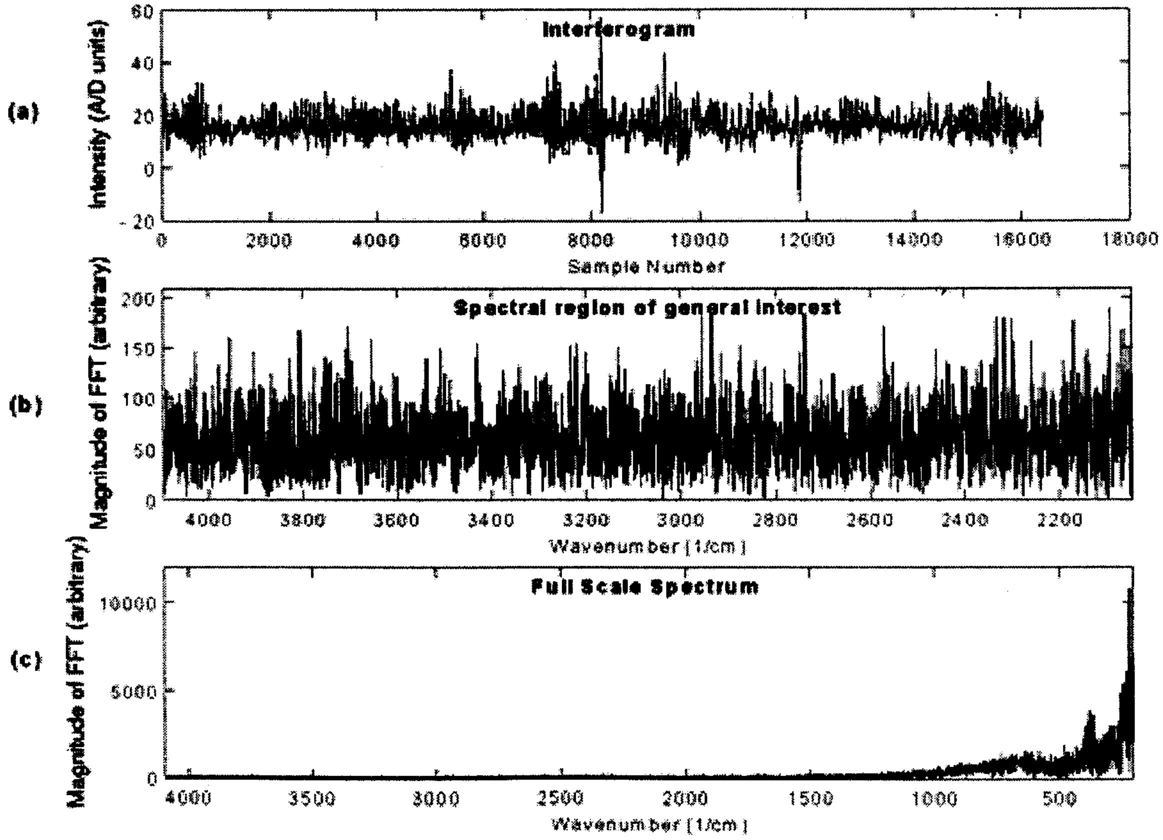

**Fig. 2:** Interferogram (a) and spectrum (b, c) from hybrid rocket plume collected using the high scan speed. Note that no valid spectra is obtained.

plume does exhibit intensity fluctuations of similar frequency but of lower amplitude than those found in the labscale hybrid motor plume. If the interference is from intensity fluctuations and not from detector overloading, the demo unit plume should give an interferogram that is less noisy than the interferogram obtained from the rocket plume. This was found to be the case, as illustrated by Figure 3. This confirms that the interferogram is corrupted by intensity fluctuations within the plume, not from detector saturation.

In an attempt to reproduce this interference in the laboratory, an experiment was set up to simulate a non-constant source. The IR source used consists of a Bunsen flame behind a Princeton Applied Research Variable Speed chopper wheel. This wheel has a chopping frequency range of 0 to 2200Hz. The interferometer was placed so that it had to view the source through the chopper wheel. Figure 4 shows this experimental setup. The results of this experiment show that noise is introduced to the interferogram as a frequency component of the source. This noise is mapped from the time domain of the interferogram to the frequency domain of the spectrum. The governing equation for this interference is

$$F_I = \frac{F_C}{2V_M}, \tag{3}$$

where $F_I$ is the interference frequency in cm-1, $F_C$ is the chopping frequency in Hz, and $V_M$ is the moving mirror speed in cm/sec /10/. It is apparent that the noise is manifested as a sharp spike near the right hand edge of the spectrum plot in Figure 5(c). The chopping frequency for this data set was 1200Hz.

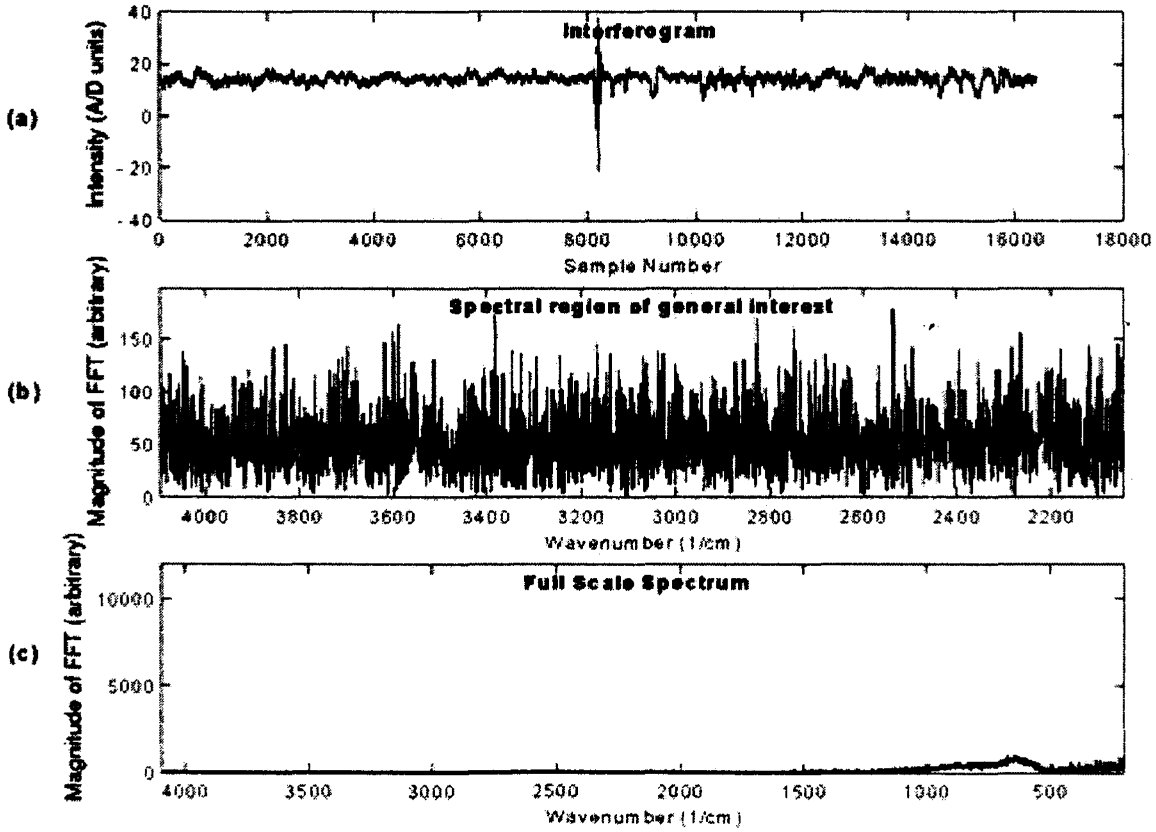

**Fig. 3:** Interferogram (a) and spectrum (b, c) from UALR's Demo Rocket Unit showing less noise than the full pressure motor at low frequencies. Compare the right hand side of Figure 3(c) to the right hand side of Figure 2(c). Note that low frequencies are to the right and high frequencies are to the left on the x-axis.

Note that this was manifested as a sharp spike near 450cm-1. Also note that this falls outside the sensitivity region of the MCT detector.

While Griffiths and de Haseth discuss the introduction of noise into the spectrum from a fluctuating source, the discussion is limited to that of slow-scan interferometers. The formula presented above applies to all interferometers; slow and rapid

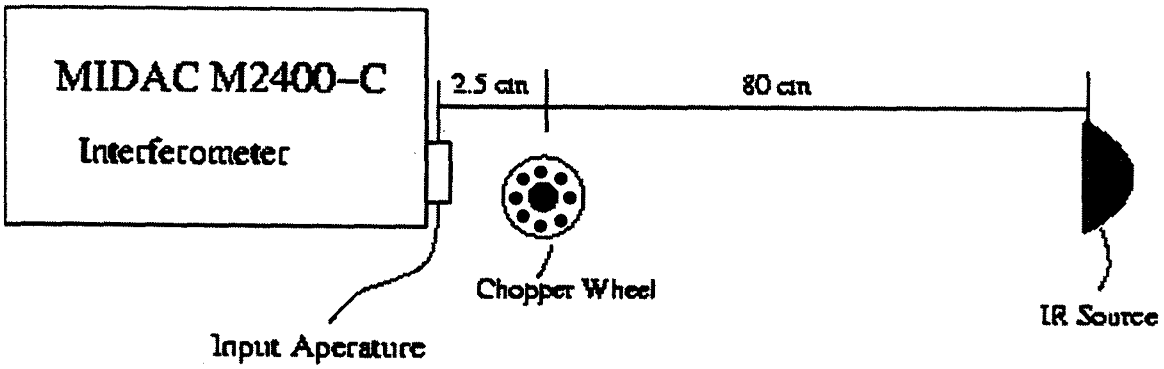

**Fig. 4:** Experimental setup of chopper wheel on Bunsen flame.

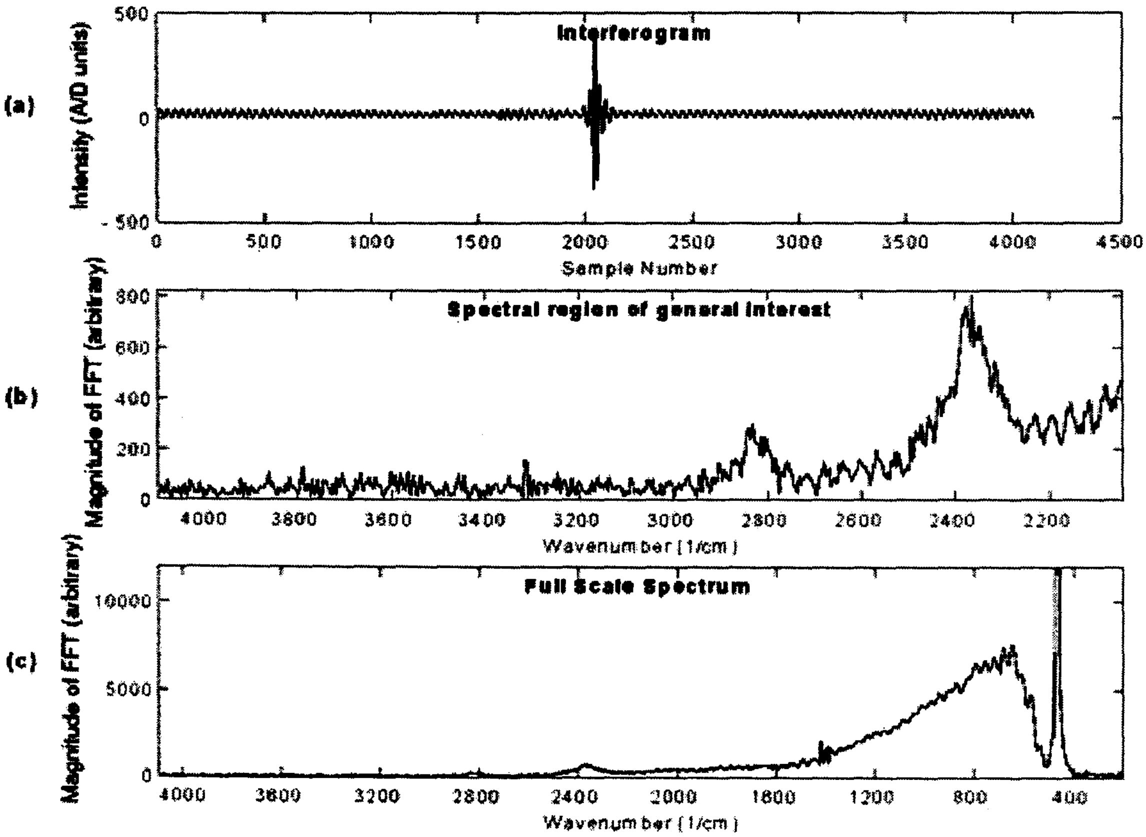

**Fig. 5:** Interferogram (a) and spectrum (b, c) of a chopped Bunsen flame. Note the spike around 450 cm-1 in (c) representing the chopping frequency of 1200Hz. Also note the noise ripple in (a), (b) and (c) due to this single frequency interference.

scan, taking into account the appropriate mirror speed. The solution to the problem of interference presented in Griffiths and de Haseth is to run the mirror at a speed that will move the fluctuations outside the spectral region of interest. For rocket plumes, this would mean scanning at a very slow speed. When this approach is used, an acceptable spectrum can be obtained /6/. However, this approach does not allow for the acquisition of quasi real time data from the plume since the single scan times are several seconds long. In order to gather the interferograms at an acceptable rate, the mirror must have a higher velocity. In practice, this higher velocity maps the fluctuations into the spectral region of interest, resulting in unacceptably noisy IR spectra. Another problem is that the plume intensity fluctuations are broadband and random. This means that the problem of filtering the signal becomes non-trivial.

## 4. Model and Simulation:

Examining the formulae presented earlier, it is apparent that any fluctuations in the source intensity ($I_0$) within the time scale of the scan will be interpreted as a frequency component of the source. Based on these formulae, the software package MatLab was used to model and simulate a Michelson Interferometer. This model allows an interferogram to be generated from any spectrum, and a spectrum to be generated from any simulated source. This allows for the introduction of source fluctuations into the interferogram to monitor the effect on the spectrum. Figure 6 shows a valid interferogram and the corresponding spectrum. Note the well-defined central peak and low noise side lobes typical of a clean interferogram (6a). When transformed to the frequency domain, this results in a clean, readable spectrum. Figure 6 should not be

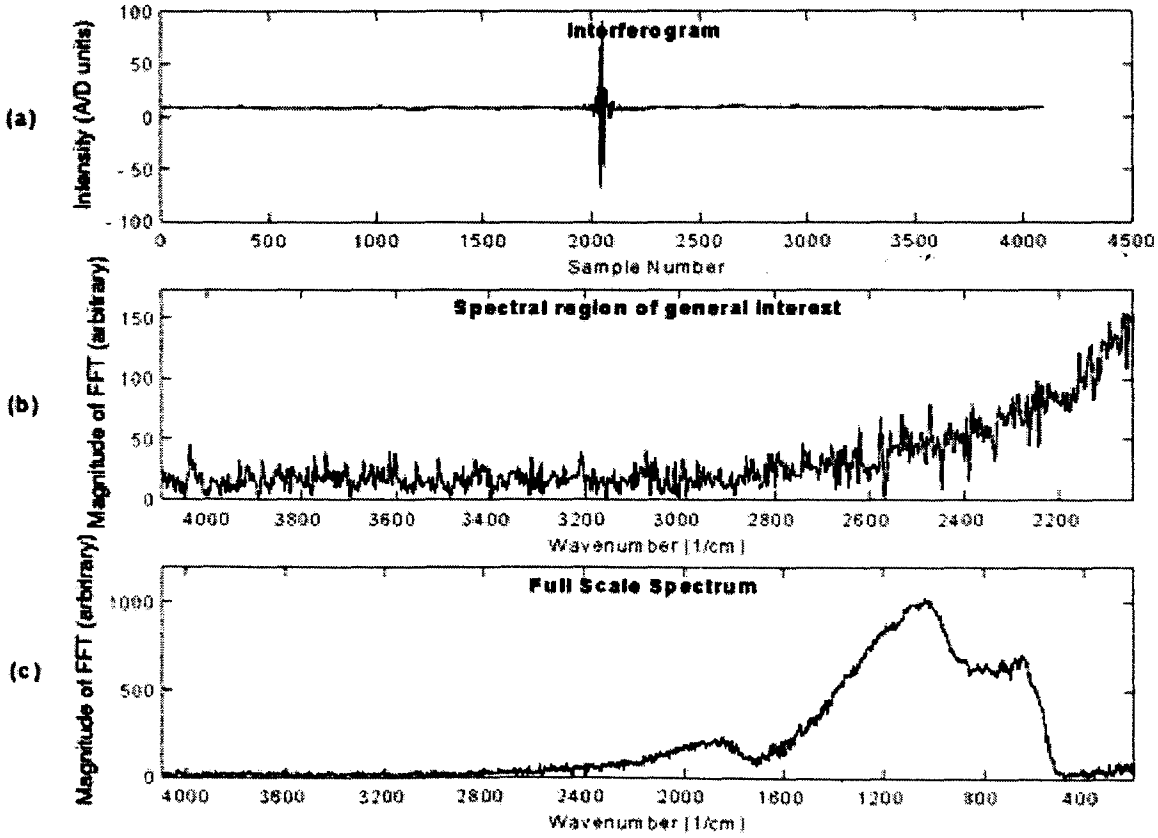

**Fig. 6:** Normal interferogram (a) and corresponding spectrum (b, c). Background scan using the MCT detector.

interpreted in the usual spectral sense. It is a view of the detector response to background radiation without noise compensation. This view is presented in order to illustrate the interference induced by a non-constant source. Figure 7 shows the same interferogram with a single frequency intensity fluctuation introduced by modifying the data file in MatLab. Note the sinusoidal nature of the side lobes. Inspection shows that this single fluctuation frequency is easily identified in the spectrum as a sharp spike. This can be thought of as a monochromatic light source incident upon the detector.

Since the interference in real life is not monochromatic, a random frequency fluctuation was introduced into the simulation. Figure 8 shows the interferogram from Figure 6 with a random frequency fluctuation introduced (varying in both frequency and amplitude). It is apparent that this has the effect of raising the noise floor on the corresponding spectrum. The signal to noise ratio is directly proportional to the percentage of total magnitude fluctuations of the source. If this ratio grows sufficiently, the spectrum will yield no useful data. By visual inspection of Figure 8, it is apparent that a random intensity fluctuation of greater than a few percent of total intensity will render the spectrum too noisy to use.

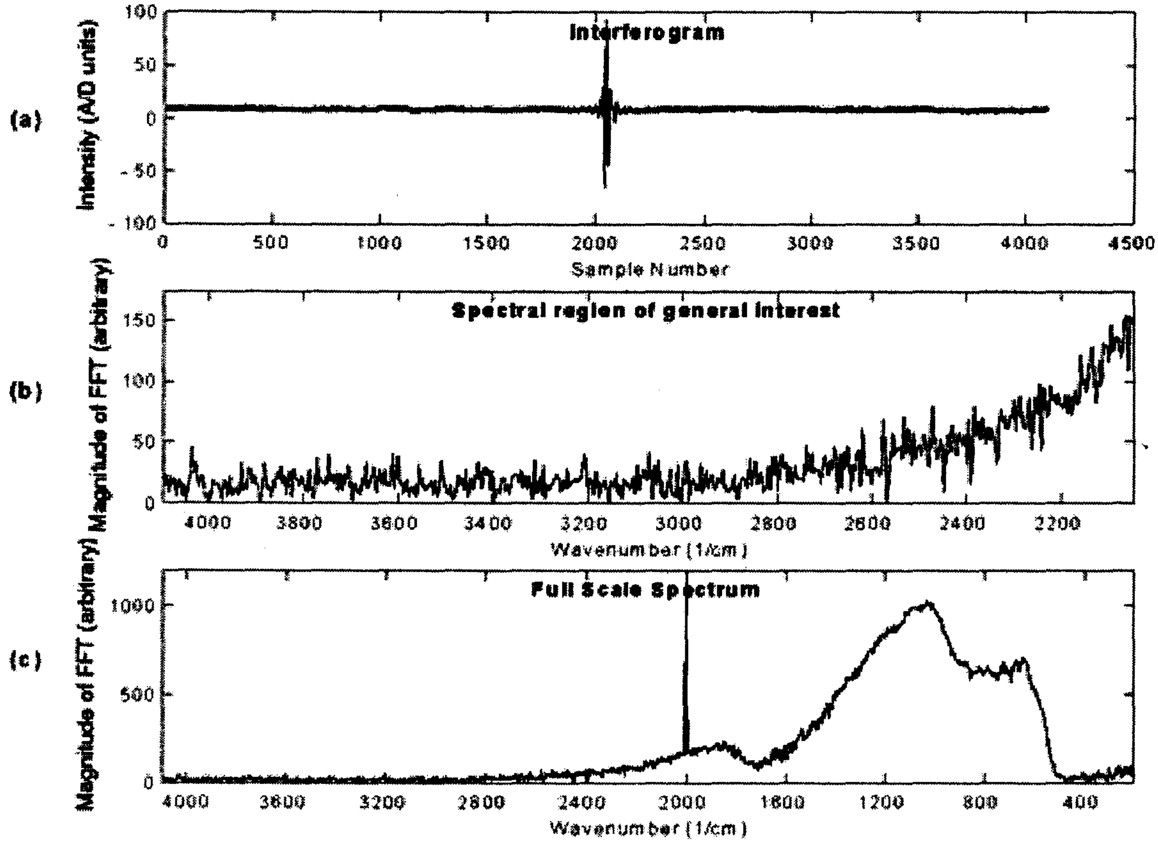

**Fig. 7:** Interferogram (a) with simulated single frequency fluctuation. Note the sharp spike in the corresponding spectrum (b, c) around 2000 cm-1 due to this simulated frequency fluctuation. (Same initial data set as Figure 6.)

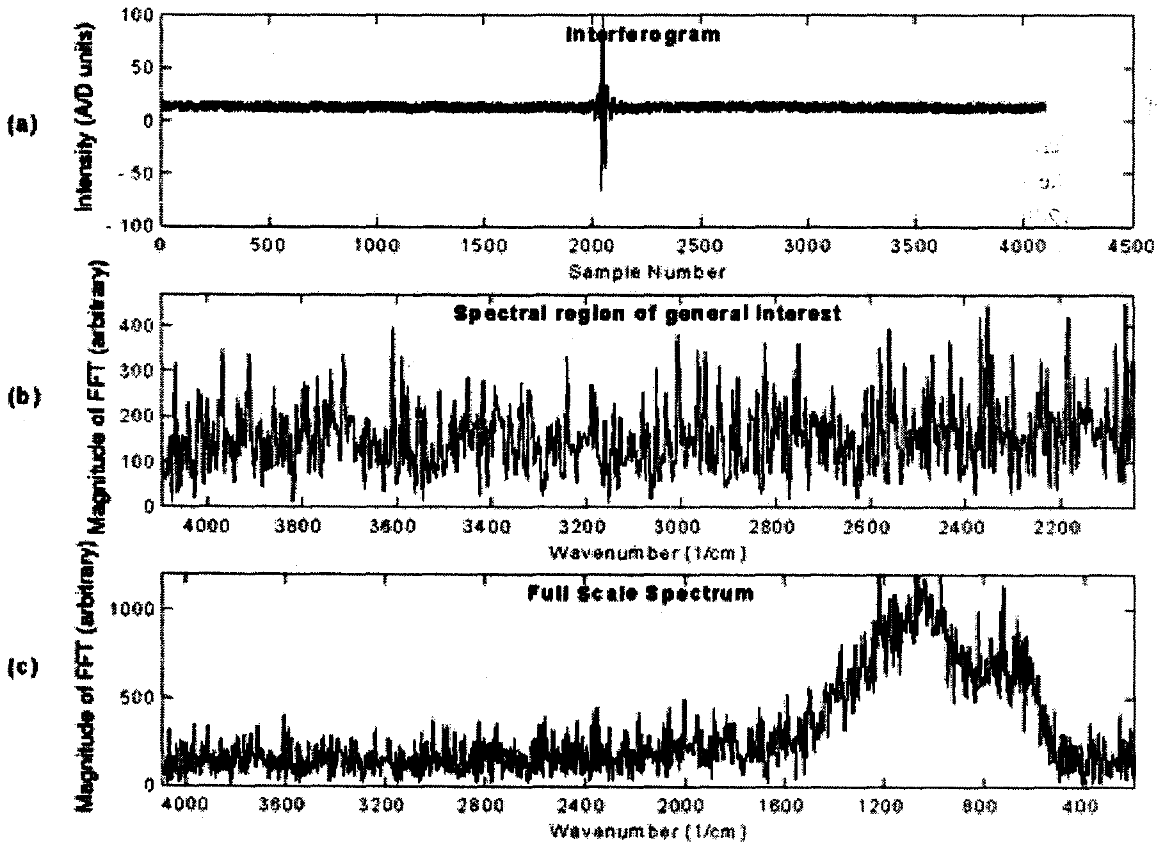

**Fig. 8:** Interferogram (a) with simulated random frequency fluctuation. Note the poor S/N in the spectrum (b, c). (Same initial data set as Figure 6.)

## 5. Results and Discussion:

The technique of FTIR emission spectroscopy would seem at first glance to be an excellent tool for plume monitoring. However, the plume property of pulsing / flicker interferes with the input to the interferometer. The interferometer interprets intensity changes just as it would interference fringes moving across the detector. Although the fringes result from the Michelson's scanning action, the flicker is caused by combustion instability. When many interference frequencies are present, this results in an interferogram yielding no valid spectrum. The advantages of increased computing power and software tools have allowed us to revisit FTIR spectroscopy as a valid tool for making plume spectrum measurements. While the problem has not been eliminated, it has been further characterized.

Using the software package MatLab, a mathematical model and simulation of a Michelson Interferometer has been developed. This model has been used to verify the cause of the interference encountered when trying to monitor a non-constant source with an FTIR emission spectrometer. When applying this model to a hybrid rocket exhaust plume it becomes apparent that the combustion instabilities inherent in the motor cause intensity fluctuations in the time domain that are erroneously mapped to the frequency domain when processed by the spectrometer. This renders the instrument useless for sources with a wide frequency range of fluctuations.

It is interesting to note that while the detector used in an interferometer has a finite sensitivity range, interference due to intensity fluctuations can be mapped outside this range. As an example, examine Figure 5 again. A Mercury Cadmium Telluride (MCT) detector was used to gather this interferogram. This detector has a sensitivity range of 2 – 16 micrometers. This corresponds to 5000 – 625 cm-1. The interference due to a Bunsen flame chopped at 1200Hz is mapped to a wavenumber of approximately 450cm-1. This detector cannot detect spectral components in this region of the spectrum, but the intensity fluctuations due to the chopping of the Bunsen flame are interpreted as interference fringes by the data acquisition board within the instrument. As the chopping frequency (interference frequency) is increased, the spike present in Figure 5 moves left along the x-axis, and vice versa. To interpret Figure 5(c) in the usual spectral sense, the y-axis must be adjusted to allow the sharp spike to extend off the graph. To give an idea of the scale problems present in the figure, note the small bump around 2400 cm-1 representing the CO2 peak present in this region of the spectrum. The y-axis is usually adjusted to allow this peak to reach almost full scale in the y direction. Note the noise level increase in all regions of both the interferogram and spectrum of figure 5. As the number of interference frequencies and / or their amplitude increases, the noise level increases.

## 6. Conclusions:

The MatLab model and simulation have reproduced the results of lab experiments intended to isolate the cause of interference when monitoring a hybrid rocket plume with an FTIR spectrometer. This provides a valuable tool in simulating and understanding the problem of interference caused by intensity fluctuations within the plume. This will aid in correcting the problem caused by this interference and allow the possibility of reintroducing FTIR Emission Spectroscopy as a versatile plume analysis tool. Although the data presented was taken using a hybrid rocket motor, the technique should also be applicable to solid motor systems.

This work has shown that source fluctuations do represent a significant obstacle to using an interferometer with any non-constant source. A single interference frequency increases the noise throughout the entire spectrum. Even if the mapped frequency lies outside the region of spectral interest, the noise floor of the spectrum has been raised. If multiple interference frequencies are present, this noise quickly increases to unacceptable levels.

## Acknowledgements:

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