# Plume Sensing Direction Considerations

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## ABSTRACT

Remote sensing using midwave and longwave spectroscopy has been shown to be capable of detecting gaseous effluents from a stack plume release. In general, measurements have been made through the plume cross-section. This paper discusses experiments and measurements conducted to examine the relative merits of viewing the plume's cross-section or viewing the plume along the axis of the plume flow. While viewing along the plume's flow axis increases the path length, additional factors such as wind variance and the effects of optically thick cells may begin to appear.

**Keywords**: Hyperspectral spectroscopy, Infrared spectroscopy, Remote Chemical Detection

## 1. INTRODUCTION

Three approaches are commonly adopted / attempted for viewing gas plumes. The first method is to view the plume from below and use the cold sky as the background. The complement of this technique is to view the plume from above and to use the warm Earth as the background. The third approach is to view the plume horizontally, either from downwind or from upwind. One can make arguments supporting each view as being the "best," but practical limitations imposed by nature often restrict the value of an otherwise promising approach.

The vertical upward view provides the best technique for finding gases that exit a hot stack, if one can view the immediate area around the stack. Within about two stack diameters, gases have cooled to near ambient temperatures and consequently do not provide much contrast against the sky. This technique is useful only if one can be very close to the source of hot gas. If the gas emissions are not hot or if one cannot view the emissions at a distance of less than or equal to one stack diameter from the emission source, this technique is not optimal.

The vertical downward view seeks to find the gas, once cooled, in contrast to the hotter Earth background. Under optimal conditions, temperature differences between the plume and background can reach 25°C. Under such conditions, one can detect much smaller amounts of gas in a plume than one can detect when the temperature differences are less. The Earth's surface temperature and air temperatures will rise and fall during the day; the surface temperature is more responsive to solar input and results in the air temperature lagging behind the surface temperature. Generally, at two points during the day the temperature between the air and the surface will be equal; downward viewing detections at these times become difficult due to the lack of temperature contrast between the plume and the background. Downward viewing geometry is also complicated by variations in the surface geometry and emissivity.

As expected from the Beer-Lambert Law, the absorption/emission from a gas is proportional to the viewed path length through an optically thin gas. This would suggest that horizontal viewing theoretically has a physics-based advantage over vertical viewing, positioning downwind or upwind to view through the length of the plume. Given the angular divergence of an optical sensor's field of view and the angular divergence of a plume with distance from the stack, viewing a plume from upwind toward the release point should produce the best detection results. Complications limiting this viewing geometry include: turbulence in the plume causing it to go optically thick and thus limiting the Beer-Lambert Law gain, plumes wandering in and out of the sensor's view of field due to directional variations in the wind, the stack and other things near the horizon complicating the background, and the fact that at some locations the plume is in emission and at other locations in absorption which tends to cancel the Beer-Lambert gains.



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Given the potential issues with ground-based sensing, the authors measured plumes viewed both vertically and horizontally. These measurements showed a small but definitive gain for the horizontal viewing of hot stack plumes.

## 2. EXPERIMENTAL SETUP

The measurements were made at a small local airport at Waxahachie, Texas, in April 2003. These measurements were part of multiple experiments conducted during this field collection. Some of these measurements have been reported in previous publications[4]. A portable plume generator was used to generate hot plumes containing various gases. The plume generator uses a propane burner to generate a hot plume. The chemicals of interest are metered into a boiler section where they are vaporized and then are mixed into the hot plume. The temperature and liquid flow rates are measured and controlled.

The plume generator was set up so that the outlet stack was in a horizontal position. Gas concentrations were calculated from the metered inlet flow rates. The necessary parameters of the plume generator, such as hot air flow rates, temperatures, and piping diameters were measured. Measurements for a release of methanol are reported. Figure 1 shows a picture of the plume generator and the general experimental setup.

The infrared spectroscopic measurements were made using a Designs & Prototypes (D&P), Inc. MicroFTIR model 101 Fourier Transform spectrometer running at 4 $cm^{-1}$ spectral resolution over the spectral region from 3 to 18 microns. Measurements were made in accordance with the published SITAC protocols for using this sensor[1]. Before each set of runs the D&P interferometer was calibrated using its attached warm and cold blackbody sources. Each set of measurements was followed by a recalibration of the D&P using the same blackbody sources. The reduction of the data to calibrated radiances was performed using the standard methods described in previous publications[2].

For the measurements, the spectrometer was placed at various distances downwind of the plume and at various viewing angles. Measurements were made close to the stack outlet (about 0.3 meters downwind from the outlet), with the spectrometer looking across perpendicular to the plume flow axis and looking toward the sky as a background. The spectrometer was moved downwind farther away from the plume outlet and measurements were made looking across the plume and looking back toward the plume along the axis of the plume flow. In each case, measurements were made against a cold sky background. These measurements ranged from 0.3 meters from the stack outlet to around 30 meters downwind of the plume. Figure 2 shows a schematic illustrating the viewing angles.

In the various measurements, the stack outlet temperature was held constant at around 150-165°C. Concentrations of methanol were varied from the relatively high concentration of about 1400 ppm-m to low concentrations of about 150 ppm-m. In order to measure only the hot plume, measurements were also made in the absence of methanol in the plume.

The plume generator was positioned so that the outlet flow of the plume was aligned with the direction of the prevailing wind as indicated by the wind speed and direction instruments located near the plume generator. During the day, wind speed and direction were variable. When measurements were taken downwind of the plume generator, the spectrometer was positioned and aligned to look as directly upwind as possible.

## 3. RESULTS

A set of measurements was made at various distances downwind from the plume generator, from about 0.5 meter from the stack to about 30 meters from the stack. For these measurements the stack temperature was held constant at about 150°C and methanol release rates were held constant at about 1400 ppm-m. For measurements made close to the stack, about 10 meters or less, the spectrometer was looking up vertically through the plume against the sky background. This is the vertical viewing configuration shown in Figure 1. For the distant cases, the measurements were made vertically up through the plume against the sky and in a horizontal direction back toward the plume generator. This is the horizontal viewing configuration shown in Figure 1. The angle of view was slightly upwards so the background was the sky. A measurement was made that included the stack itself in the spectrometer's field of view. Another measurement was made so that the field of view was just above the plume generator stack. Vertical sky measurements were also made through the plume when no methanol was in the plume. Figure 3 shows a plot of the measured radiance values at 9.43 um, which is the wavelength where emissions for methanol are the highest. Figure 4 shows a plot of the spectra obtained from these measurements[3]. Figure 5 illustrates two selected measurements taken under the same plume conditions, one measurement was made vertically close to the stack while the other measurement was taken far from the stack looking horizontally. The spectral signatures obtained in these cases are nearly identical.

Figure 6 shows the measurements obtained for a set of lower concentration runs. These measurements were made at two distances downwind from the plume generator, 0.33 meter from the stack and 9.1 meters from the stack. For these measurements the stack temperature was held constant at about 165°C and methanol release rates varied from 0 ppm-m to 250 ppm-m. For measurements close to the stack the spectrometer was looking up vertically through the plume against the sky background. For the distant cases, the measurements were made vertically up through the plume against the sky and in a horizontal direction back toward the plume generator. The angle of view was slightly upwards so the background was the sky. The plot shows that the methanol signature obtained at the farther distance is stronger than some of the closer measurements taken with higher plume concentration.

## 4. CONCLUSIONS

The emission/absorption signature from a gas plume is proportional to the viewed path length. However, in actual practice, complications in the viewing geometry potentially limit the gain from increasing the path length. The results from analysis of measurements made show that there was a small but definitive gain when viewing the plume horizontally upwind. There was little difference in the results whether or not the stack itself was part of the background. A sensitivity gain was obtained by viewing the plume horizontally upwind. Figure 7 shows that the spectrum taken when viewing the plume horizontally upwind at a distance of 30 meters from the stack gave the same spectrum as that viewed vertically through the plume at a distance of 3 meters from the stack. This result is significant for understanding how to measure and quantify remote sensing of gaseous emissions from stacks.

## 5. SUMMARY

These measurements show that the detection capability of ground based spectrometers can be increased with changes in the viewing angle. Future measurements will be directed at investigating the differences between viewing horizontally upwind versus horizontally downwind and investigating the extent to which the range of detection can be increased based on the viewing geometry. These results are significant advancements in understanding how to conduct remote sensing measurements and quantification of gaseous emissions from stacks.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Salvaggio, C., *Infrared Field Spectra Collection Protocol*, SITAC report, 8 Nov. 2000.

2. Salvaggio, C. and C. J. Miller, "Methodologies and Protocols for the Collection of Midwave and Longwave Infrared Emissivity Spectra Using a Portable Field Spectrometer," *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultaspectral Imagery VII*, SPIE vol 4381 (2001) pp. 539-548.

3. Hanst, P. L., Library of Gas Spectra, Infrared Analysis Inc., 1998.

4. Mitchell, H. J., G. P. Jellison, D. P. Miller, C. Salvaggio, C. Miller, "The Importance of Background in the Detection and Identification of Gas Plumes Using Emissive Infrared Hyperspectral Sensing," *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery IX*, SPIE vol 5093 (2003) pp. 206-217.

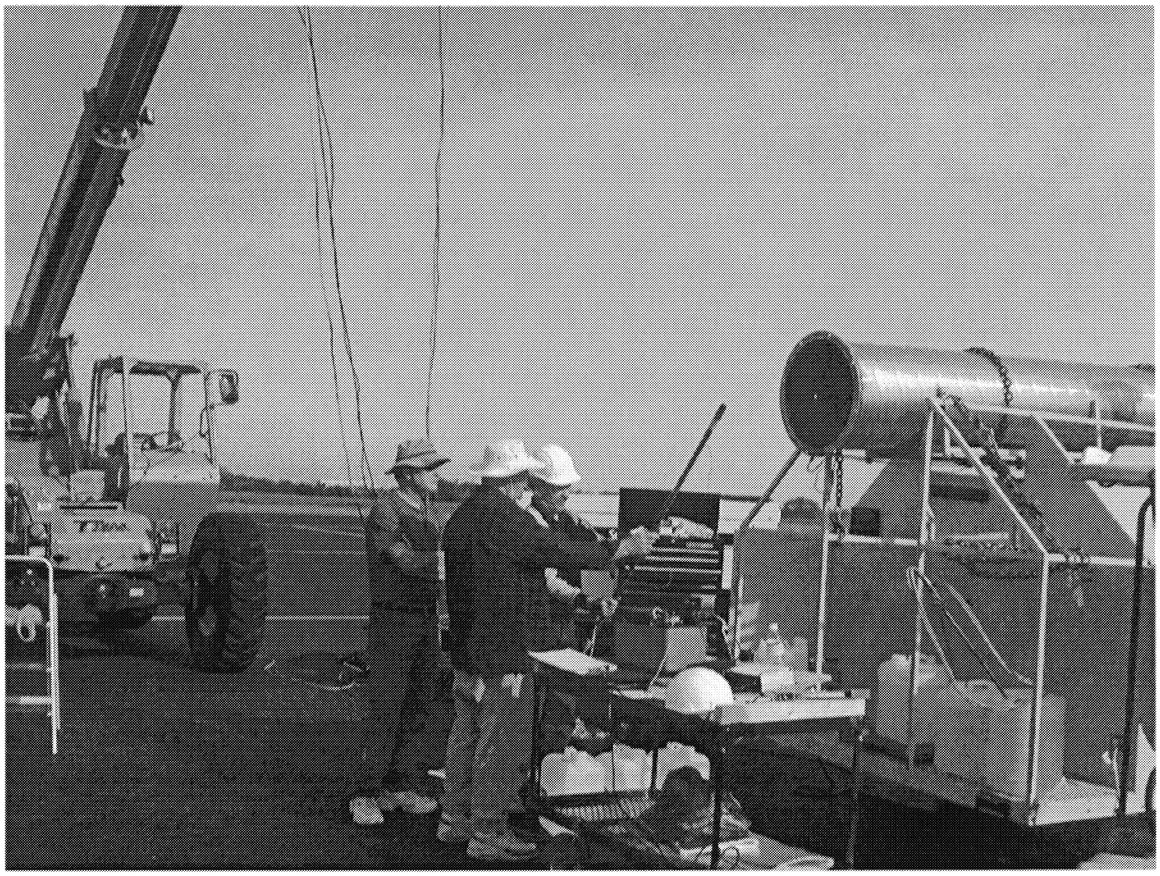

Figure 1. Experimental Setup

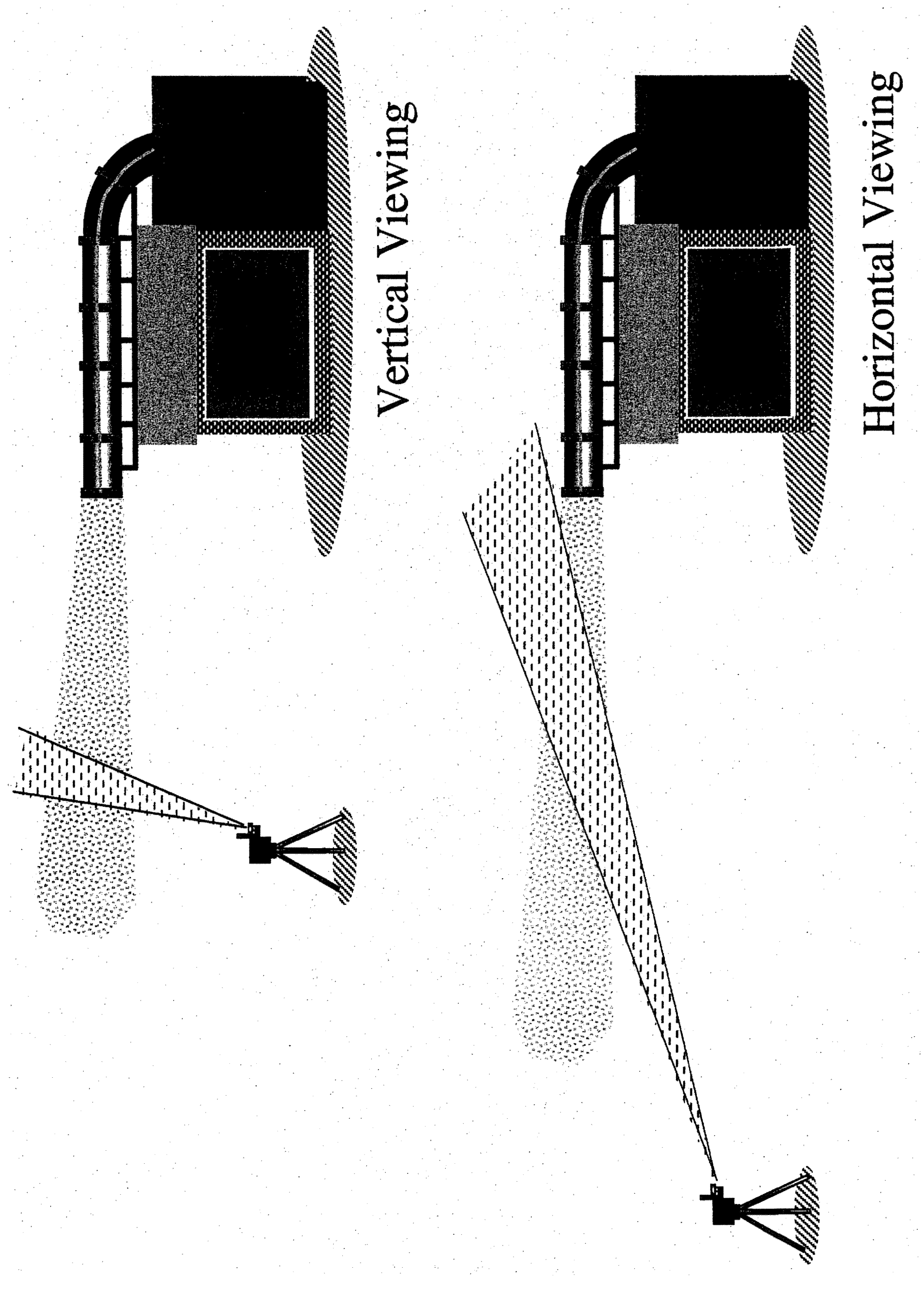


Figure 1. Viewing Directions

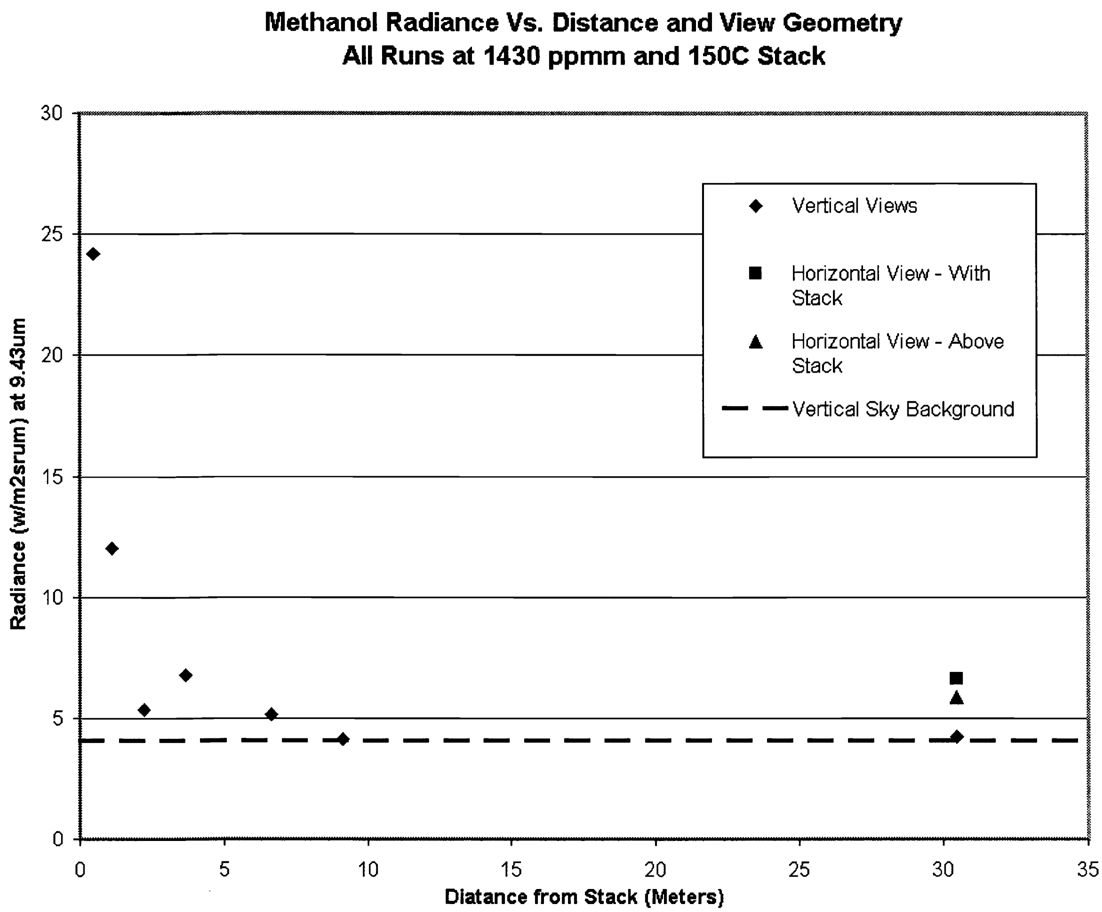


Figure 3. Radiance Vs. Distance and View Geometry

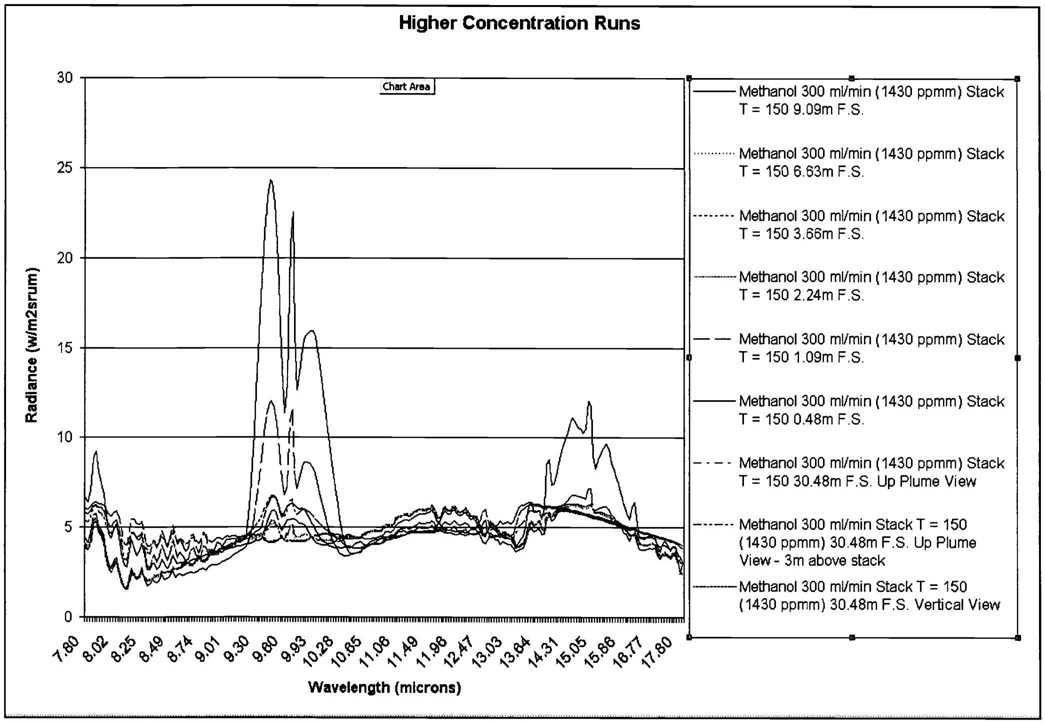


Figure 4. Spectra for Higher Concentration Runs

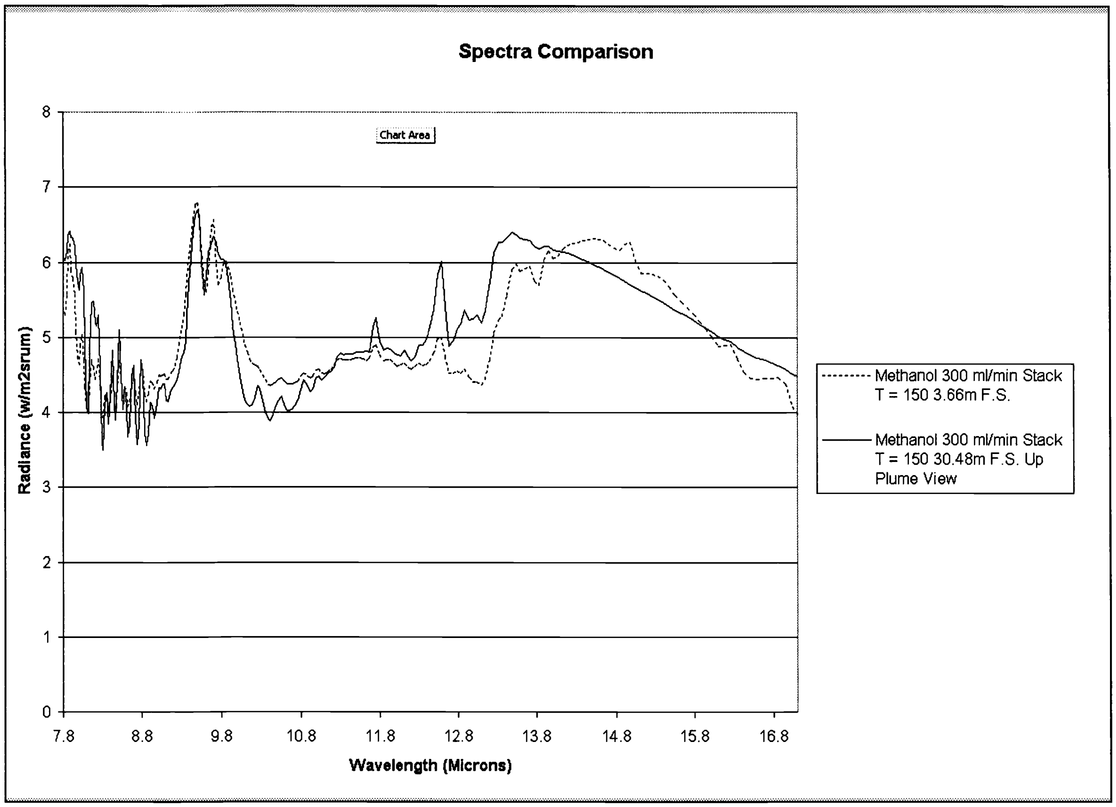


Figure 5. Spectra Comparison

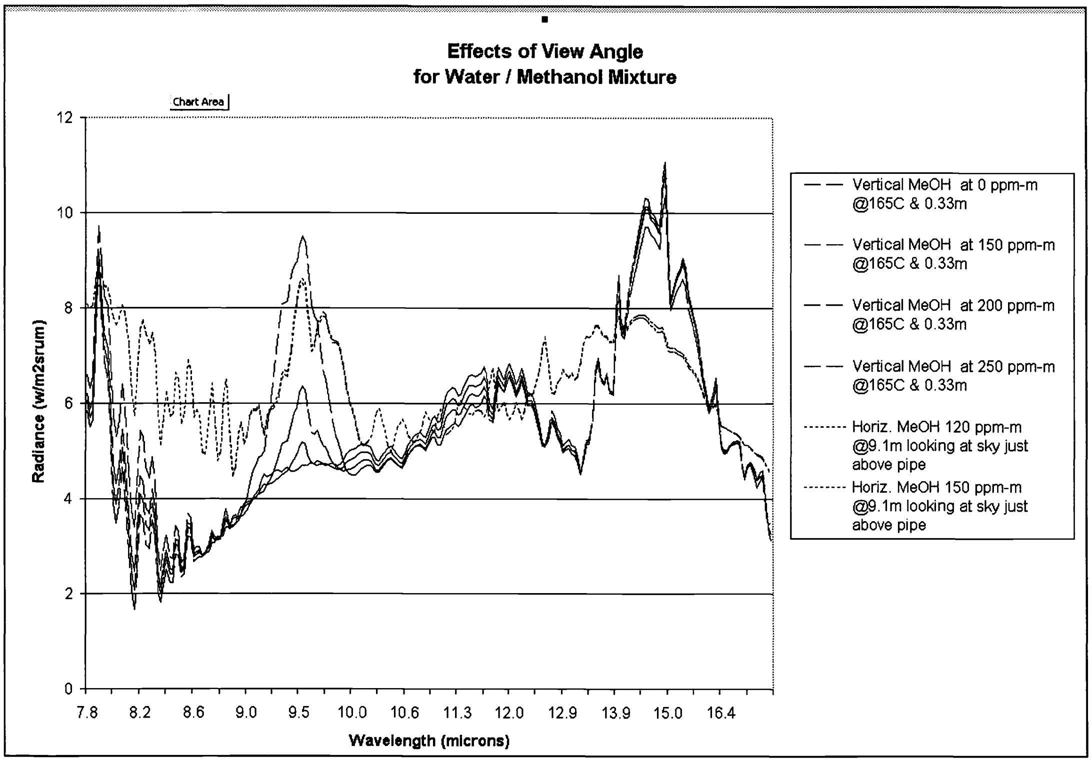


Figure 6. Effects of View Angle