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### Airborne pipeline leak detection: UV or IR?

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#### ABSTRACT

This paper presents a study of different approaches to the measurement of the above ground vapor plume created by the spill caused by a small 0.1 l/min (or less) leak in an underground liquid petroleum pipeline. The scenarios are those for the measurement from an airborne platform. The usual approach is that of IR absorption, but in the case of liquid petroleum products, there are drawbacks that will be discussed, especially when using alkanes to detect a leak. The optical measurements studied include UV enhanced Raman lidar, UV fluorescence lidar and IR absorption path integrated lidars. The breadboards used for testing the different approaches will be described along with the set-ups for leak simulation. Although IR absorption would intuitively be the most sensitive, it is shown that UV-Raman could be an alternative. When using the very broad alkane signature in the IR, the varying ground spectral reflectance are a problem. It is also determined that integrated path measurements are preferred, the UV enhanced Raman measurements showing that the vapor plume stays very close to the ground.

Keywords: Lidar, liquid pipeline, leak detection, airborne, petroleum, crude, absorption, Raman.

#### 1. INTRODUCTION

Detecting small leaks from underground liquid petroleum product pipelines is done or proposed to be done in a number of ways. There are the specialized techniques that require installing a permeable tube or optical fiber along the length of the pipeline, an expensive approach, and mainly installed over environmentally sensitive terrain. There are those that use acoustic detection pigs that travel within a pigeable pipeline. Then there are those that use above ground platforms (especially airborne) that travel along the surface and measure the effects of the leaks. Some of these leak detection systems measure concentration of hydrocarbons in the vapor phase in the air around a leak. This is a successful approach for natural gas pipelines. However, current leak detection systems for liquid petroleum product pipelines are unreliable in the detection of minute leaks (weeper/seepers). Pipeline operators cannot easily and efficiently detect small weeper/seeper leaks over extended lengths of pipeline. Current installed systems cannot detect leaks smaller than approximately 1% of the total flow, which is a significant loss. Weeper/seepers thus go undetected. The best and most feasible external weeper/seeper detection system is a standoff, mobile sensor that regularly surveys the pipeline from the ground or air. The response time is consequently not that for larger leaks, but is significantly cheaper than the aforementioned specialized approaches. Small leaks could indicate the imminence of much larger leaks and their detection should reduce the consequential costs (loss of life, loss of product, prolonged down time, irreversible environmental damage, remediation, legal, manpower, security, etc.). Even though the survey period is long, detecting the leaks at early stages allows for a better management of risks and consequences.

There has been work done on optical remote leak detection, some sponsored by the US  $DOT^{1-5}$ . All of the previous concepts relied on some form of infrared spectroscopy, active (with lasers) or passive<sup>2</sup>, all of them having been originally demonstrated on natural gas pipelines (methane detection). In particular, the classical two wavelength differential absorption lidar in the IR has been demonstrated to be able to detect leaks of liquid petroleum products<sup>4, 5</sup>. But, whatever the approach, a successful optical remote leak detection system (LDS) would need to detect as well as a pig with an acoustic LDS, that is: 0.1 l/min (~1 barrel/day)<sup>6</sup>. Moreover, the false alarm rate must be as low as possible, limiting in numerous circumstances the limit of detection.

This paper presents a summary of the work done through an INO-PHMSA co-funded project on the assessment of technologies for stand-off leak detection for hazardous liquid pipelines<sup>7</sup>. Summary of the optical properties, the feasibility analysis and the concept of operation considered to produce this assessment are presented for the different approaches. Intermediate scale testing results using an underground leak simulator are presented.

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#### 1.1 Concept of operation

The following parameters were used for the feasibility study and were also used as a reference for the realistic definition of the testing phases throughout the project. The leak detection system is mounted on an airborne platform (fixed wing or helicopter), at a flight height of 150 to 300 ft (50 to 100 m). The flight speed would be 80-120 knots (150-220 km/hr) with the platform flying along the pipeline ROW, slightly to the side (~15 ft (5 m) from center) for hundreds of miles (hours of data). The lateral field of view would be the entirety of the ROW (60 to 90 ft or 20 to 30 m). The selected technology should allow for the inspection of pipelines every two weeks (the system should be able to work every day until maintenance). Ideally, the smallest detectable leak would be 0.1 L/min at a spatial resolution of 30 ft (10 m). The airborne platform flies over the right of way (ROW) and the leak detection system illuminates the ROW directly below. The whole width (30 m) of the ROW is scanned or imaged.

Methane, ethane, propane and butanes are gaseous at normal temperature and pressure. The first three are not of great interest for leak monitoring, being a very small proportion of the gaseous plume. Butanes and pentanes are much more interesting. n-pentane was selected for the feasibility study of broadband IR lidar and UV-Raman lidar, being the most abundant molecule going from liquid to the vapor phase (having the highest vapor pressure of the liquid alkanes at normal temperature and pressure). Benzene was selected for the feasibility analysis of the UV fluorescence lidar, being the most abundant molecule in the vapor phase with optical resonances in the UV. Table 1 shows the average composition of Canadian crudes over a 5 year period. Only those components that would be in the gaseous phase in interesting amounts are shown. Benzene and toluene are much less abundant in the vapor plume but are expected to be relatively immune to varying ground spectral reflectance when considering path integrated absorption measurements (but benzene and toluene are not considered here).

Molecular specie	Average (%)	Vapor pressure (torr) @ 25°C
C3-	0.22	gas
Butanes	2.29	gas
Pentanes	3.85	521.6
Hexanes	5.03	151
Heptanes	5.25	46.2
Benzene	0.22	95.8
Toluene	0.57	28.3

Table 1. Average composition (last 5 years) of all crude oil types (light to heavy) logged @ crudemonitor.ca (liquid phase)

#### 2. FEASIBILITY

#### 2.1 Fluorescence

The spectral cross-sections of the different optical scattering processes being considered for the molecules of interest are required for a feasibility analysis. Fluorescence is usually the preferred method for detection. This is because the measured signal is over an essentially zero background (the measurements presented here are in the solar blind region) when excited with a pulsed laser (nanosecond pulsewidth) and when the fluorescence lifetime is short such that fluorescence from the ground can be separated from the fluorescence of the gas plume. The molecule needs to absorb light in order to fluoresce. The curve of Figure 1 shows the UV absorption spectrum of benzene at low pressure (a few torr)<sup>8</sup>. Figure 2 is the fluorescence spectrum of benzene as measured in a gas cell at atmospheric pressure with 6.47 % of benzene when excited at 247.1 nm (first absorption peak in Figure 1). The fluorescence quantum yield (QY) was measured to be  $2 \times 10^{-8}$  (for the light between 265 and 300 nm). QY is the amount of light re-emitted after absorption in the form of fluorescence. This is very low. This is due to a strong quenching at atmospheric pressure in nitrogen. With so little benzene expected in the gas plume in combination with a low QY indicates that fluorescence would not be a good alternative. Fluorescence of alkanes was not considered here since they do not have absorption peaks in the usable UV.



Figure 1. Absorption cross-section of benzene (based on data from ref 8).



Figure 2. Fluorescence spectrum of benzene in the UV.

#### 2.2 Raman

The experimental set-up for testing the Raman approach is the same as for fluorescence except that the excitation wavelength is 355 nm, a wavelength with much more laser power. Raman scattering cross sections are usually much smaller than absorption or fluorescence cross sections or quantum yields. On the other hand, the Raman scattering is on the totality of the hydrocarbon molecules, since what is being detected is C-H bonds. Figure 3 shows the Raman spectrum of pentane (3.8%) in air. Our best estimate of the Raman cross-section is  $1.2 \times 10^{-29}$  cm<sup>2</sup>/mole\*sr for pentane excited at 355 nm. No error analysis has been done on the measurement (the measurement system parameters were analyzed, but many were manufacturer supplied numbers). Results are similar for crude. The Raman of hydrocarbons clearly stands out at this concentration. For much lower concentrations, the Raman from leaked hydrocabons could compete with the Raman from other molecules above ground in vegetation or in the air. The excitation light is pulsed. The pulsewidth needs to be short enough in order to separate the Raman signal from fluorescence originating from the ground. At 355 nm, ambient light could be troublesome. A better wavelength for eliminating ambient light and some of the fluorescence is 266 nm. The Raman cross sections should also be higher at this wavelength. Raman at this wavelength should be more interesting than fluorescence.



Figure 3. Raman spectrum of gas cell (10 cm) filled with air and pentane (3.8%) excited at 355 nm.

#### 2.3 IR absorption

Since the absorption is strongest, for the alkanes, in the infrared (IR), this was also studied. Unlike fluorescence or Raman, for which the signal is emitted by the molecules themselves, absorption is an integrated path measurement. It is a change in the return signal from a ground reflection. It is potentially a small variation on a large signal, which is fundamentally harder to mesure than a small signal over a zero background as it is for fluorescence or Raman. The absorption spectra of most alkanes (except methane and ethane) are very similar in the 3.3 to 3.5  $\mu$ m spectral range. This is were absorption is strong. Unlike methane or ethane, it is a very broad, almost featureless absorption band, especially for the heavier alkanes. This limits the selectivity of the approach when looking at the combined absorption of all alkanes in the vapor phase above a pool of crude for example. Figure 4 shows a series of absorbance spectra, for ethane, propane and pentane for 1 ppm-m between 3.325 and 3.395  $\mu$ m. It also has the spectrum of a "typical" crude, scaled to fit with the other spectra. The spectra evolve form a line spectrum to a very broad spectrum with a shift in the main peak towards longer wavelengths. Features become fewer and broader. Butane fits in this progression but is not shown in the graph for clarity. Figure 5 shows the whole band for a sample of crude taken with an FTIR. Note that the x-axis of the spectrum covers almost 300 nm.

The arrows in the graph, close to the peak in absoprtion of crude, show the wavelengths for which there is practically no interference from other molecules in the air (especially water and methane). This is were the slope in the absorption curve is greatest and were a significant, or optimal, differential absorption can be measured on a limited spectral interval. The spectral interval between the wavelength shown by arrows closest to the peak and the furthest one is ~14 nm. If an IR-DiAL system was to be used for detecting a leak using all alkanes, these are the wavelengths that would be used. The laser need not be singlemode, but if a multimode laser is used, the laser linewidth should be substantially lower than 1 nm. A somewhat similar differential can be obtained between 3.414 and 3.430  $\mu$ m, although less in absolute absorption. The higher wavelength range is much less clutered with water and methane absorption features. The spectral window with the less chance of interference is between ~3.47 and ~3.52  $\mu$ m. On this spectral interval, the differential in absorption is also similar to the one close to the peak, but over 40 to 50 nm.

Ideally, one would use most of the alkanes and aromatics for leak detection. But measuring a leak through the integrated path absorption of alkanes in the IR using reflections from the ground implies taking into account ground spectral reflectance (Figure 5, spectra from the ASTER library<sup>9</sup>). In the case of simple molecules and absorption lines a small fraction of a nanometer in width, going from on the peak (a lot of absorption, ON) to besides the peak (no absorption, OFF) does not allow for a significant change in ground reflectance. In the case of the heavier alkanes, going from "ON" to "OFF" represents 50 nm or more. On this same spectral interval, the ground spectral reflectance can change significantly. When selecting wavelengths to monitor for absorption (and thus for leaks), in the outdoors, there needs to

be careful attention not only to the water or methane absorption spectra but also changing soil type, changing vegetation (type, green, dry), changing weather (seasons, rain...) and the like. All will contribute to lower the effective limit of detection for leaks because of potential false alarms. Even on as short a spectral interval as 14 nm, in the spectral ranges considered, a change in reflectance of more than 2 or 3 % (absolute) is possible for a uniform ground and a "transmission" ratio of > 3 (for example a soil rich in carbonates). This makes for a differential "absorbance" measurement (base e) of > 1.1. If the ground was completely uniform, the effect of ground spectral reflectance could be cancelled out. But the ground often changes, for example from dry grass to green grass or from dry soil to wet soil (reflectance curves change substantially when wet), with boundaries eventually resembling those of a leak plume (a puddle of wet ground for example).



Figure 4. Absorbance spectra of selected alkanes and a sample of crude oil.



Figure 5. FTIR spectrum of a live oil crude sample (left) and spectral reflectance of selected grounds (right).

There is a small amount of lighter alkanes in crudes; especially propane. The total amount varies greatly among all crude types. Methane is not of interest because it is naturally present in a fairly large amount in the atmosphere. As for propane, a careful look at the absorption spectrum shows that there is no distinctive feature that is not interefered with by water

vapor or methane and it blends in with the other alkanes. This leaves ethane. But again, the strong absorption lines of ethane are interefered with by water vapor and methane. There is essentially two exceptions; the lines at  $3.333 \ \mu m$  and  $3.337 \ \mu m$ . Using ethane as the leak indicator greatly restricts the number of liquid petroleum products that can be detected. Having a wavelength agile system would allow for adapting to various liquid petroleum products. The petroleum products with heavier alkanes and aromatics being those for which the limit of detection for a low false alarm rate would be the worse.

#### 3. EXPERIMENTAL SET-UP

#### 3.1 Leak simulation

In order to simulate field measurements, an intermediate scale set-up was built. The set-up simulated a leak under 1.2 m of dry sand. Vapor monitoring in the ground as well as in the air column above the sand surface up to a height of 5 m was performed. At the same time, measurements of volatile organic compounds using Raman lidar and IR absorption lidar was performed. The leak simulator was a rectangular watertight steel tank. The dimensions are approximately 1.3 m x  $1.8 \text{ m} \times 2.6 \text{ m}$  for an area of  $4.8 \text{ m}^2$  and a volume of  $6.616 \text{ m}^3$ . A liquid petroleum product injection and extraction system was installed inside the container before it was filled with sand. The system was designed to simulate a continuous leak at the bottom of the container. The injection and extraction system is illustrated in Figure 6 and was made of two horizontal wells located at the bottom of the container, on opposite sides and two vertical pipes connected to the middle of each horizontal well and rising along the container wall to a height of 1.5 m (59 in). Finally, approximately 8 metric tons of Temisca grade #18 silica sand (Opta Minerals) were used to fill the container employing a layer-by-layer compaction procedure. The result was a homogenously compacted soil which is representative of a realistic ground. To allow control of the vapor plume above the simulated underground leak while allowing evaporation of the volatile fraction of the petroleum product, a 5 m high polyethylene tent was installed over the container. The upper part was fixed to an air extraction unit. Hydrocarbon vapor progression in the sand and in the air over the simulated leak was monitored using hollow sampling wells (in the ground) and sampling ports (in the air). Each port was sampled and analyzed using both a flame ionization detector and a photoionization detector (FID/PID) from the same Thermo/Foxboro TVA 1000B Vapor Analyzer. INO understands that limiting the vapor migration horizontally concentrates the vapor. In a real world scenario, the heavier than air vapors would spread laterally along the ground and there would be a lateral concentration gradient. In addition, there would be dispersion by wind and possibly enhanced mixing with air. Some grounds would be heated by sunlight that would generate vertical convection currents and enhanced evaporation. Others much less. It would be close to impossible to simulate all possible real world scenarios.

Three petroleum products were used: diesel fuel, pentane and unleaded regular gasoline. These compounds were either injected in the tank through the injection port or simply placed in open pans over the soil to allow rapid evaporation in air. During the injection phase of the experiment, the injection flow rate was on average 0.30 kg/min or 0.36 L/min. During the recirculation phase, the flow rate was set at 0.1 kg/min (0.12 L/min) for both injection and extraction pumps. There was a continuous build-up and migration of the liquid petroleum and of the vapor in the sand. Vapor monitoring results presented in the following sections are reported with respect to the start time of injection on day 1, in the cumulative column (hr), as presented in Table 2. The liquid petroleum product was allowed to migrate in the sand as was the vapor plume above the leak simulator container and measurements with the PID/FID and air samples were taken allowing for post-experiment analysis.

The platforms were installed in a mobile laboratory. The laser beams exiting the lidar platforms were routed towards 12" diameter optical grade mirrors mounted on tripods. The tripod mounted mirrors then routed the laser beams towards a mirror mounted on a gantry crane, immediately above the vapor plume containment tent at 5 m from the surface. This last mirror directed the laser beam towards the leak simulator sand (or soil) surface. The signals generated by scattering, fluorescence or Raman on and above the surface were routed in the opposite direction towards the lidar platforms by the same mirrors. Lidar measurements are time stamped. Similarly, PID/FID measurements reflect compositional values at a specific moment. All measurement parameters are logged along with the raw data for post-processing and analysis. Ambient lighting conditions do not greatly affect the measurements, nor do the wind in these conditions.



Figure 6. Tank layout prior to sand filling (not to scale).

Cumulative	Event description
0.00	Start of diesel injection
4.90	End of diesel injection (100 L injected)
23.50	Start of diesel injection / extraction
25.37	End of diesel injection / extraction (15 L)
25.46	Start of diesel pans experiment (5 pans on sand)
26.03	* Improvement of the sealing at the base of the tent
29.23	End of diesel pans experiment
29.45	Start of pentane pans experiment (5 pans on sand)
30.03	End of pentane pans experiment

#### 3.2 Raman lidar platform

The platform has a modular design. For outdoors use, the optical head includes a large custom collection telescope mounted in a lightweight carbon fiber enclosure, an emission beam expander mounted in front of and on the same optical axis as the receiver telescope and a low power, medium pulse energy 355 nm laser beam (Solar LS Belarus, model LQ215). The short laser pulse minimizes the effect of daylight and allows range resolved measurements. A 365 µm core optical fiber, with one end in the image plane of the receiver telescope, routes the return to an optical filtering unit. Filtering out of the elastic return (the signal at the wavelength of the laser returned by hard surfaces or aerosols) is done inside the telescope, before the input face of the optical fiber (Semrock USA, model LPD01-355RU-25). The Raman signal from nitrogen molecules is kept for calibration and quantification purposes. The filtering unit separates the Raman return of nitrogen from the Raman return of hydrocarbons and partly separates the Raman return form hydrocarbons from other ambient light sources. The thin film based filtering unit is  $\sim 10$  nm in bandwidth for the nitrogen return and  $\sim 10$  nm for the Raman centered at 395 nm. There are two high quantum efficiency photomultiplier tubes, one for the Raman from nitrogen and one for Raman from hydrocarbons (Hamamatsu Japan, model R9880U). The detectors are directly connected to the input of a high bandwidth transient digitizer (TiePie Netherlands, model HS5). It is synchronized with the laser pulse. A block diagram of the system can be found in Figure 7. The UV platform used for the indoors laboratory tests (in gas cells) is slightly different. These tests were for measuring spectra and cross sections of absorption, fluorescence and Raman. The differences with the platform presented in Figure 7 are that a collection fiber

bundle is used instead of the 365 µm core optical fiber and it is connected to a grating spectrograph (Andor UK, model Shamrock 163) equipped with an intensified CCD (Andor iStar 734) capable of a few nanoseconds gating. For the fluorescence measurements, a tunable laser is added to the 355 nm laser. The laser system is then a pulsed 355 nm laser followed by an OPO tunable in the visible spectral range. This light is then doubled in frequency to reach the UV range through a second harmonic generation process (Solar LS Belarus, models LP603 & LG350).



Figure 7. Configuration of the UV-Raman Lidar system as used for the simulated field testing.

#### 3.3 IR absorption

The IR absorption platform makes use of a Medium Wavelength Infrared (MWIR) laser source and a large aperture collecting telescope<sup>10, 11</sup> (somewhat similar to the UV platform). The laser beam hits a sandblasted aluminum panel lying on the soil and thus does not penetrate the soil. The light returned from the panel is routed/focused to/onto a MCT detector. The output from the detector is amplified and digitized with a high sampling rate digitizer. A series of pulse returns are measured and stored for post-processing. Telecom grade tunable lasers are used as seeds to the optical parametric generator (OPG). The seed wavelengths are 1533.4 and 1524.6 nm so that the MWIR wavelengths are 3476 and 3522 nm. They are modulated on and off so that each consecutive pump laser pulse sees a different seed wavelength. The laser linewidths are large, between 7 and 10 nm, with large pedestals. This is much larger than the sub-nanometer laser linewidth required for minimum interference from water and methane. But since the atmospheric conditions do not change significantly in the course of the tests, interferences should not skew the results since it is changes in the differential absorption that are monitored. An output pulse energy reference is generated by splitting part of the output beam at the platform and routing it to the same detector as that for the returns. For each pulse, a ratio is made of the return from the panel and the reference pulse. An average is made over a number of pulses. The system works at 5 kHz, and thus is 2.5 kHz per wavelength. An average measurement over 250 ms per wavelength gives a very good signal-tonoise ratio. A single differential absorption measurement could be done within 400 µs or less, the operating frequency being variable up to 100 kHz. The idler pulse energy is  $\sim$ 15 µJ on average.

#### 4. **RESULTS**

#### 4.1 UV enhanced Raman

Figure 8 shows the ratio of the Raman of hydrocarbons to that of nitrogen with respect to distance from the platform. The measurement's spatial resolution is limited by the laser pulse length of 6 to 7 ns which corresponds to approximately 1 m

(back and forth at light speed). The digitizer samples every 5 ns (200 MS/s). Between 32 and 41 m, there clearly is a signal from the hydrocarbons. There is always signal in the nitrogen channel: there is nitrogen everywhere in the atmosphere and at the same concentration, so it is used as a reference. The portion of the signal that is of interest is from 38.6 m to 41 m. This is only 2.4 m. There is a clear rise just above the ground. These curves are for measurements with diesel or pentane pans on the sand inside the tent. The two lower curves are for diesel, the three upper curves for pentane. The pentane level rises with time close to the ground. The pentane level at 1 to 3 m above ground falls with time. The fan at the top of the polyethylene tent was started between the first and second curves, syphoning the vapor at distances above 1 m or so. The important characteristic is that the Raman signal rises when approaching the ground. There is a concentration gradient, with the largest concentration being very close to the ground. Figure 8 (left) shows curves corrected for offsets and other interferences. These are very small signals compared to the reflection from the ground and ground fluorescence. Indeed, there is a very strong return in the Raman hydrocarbons channel coming from the ground at 41 m (not shown in figure). Most likely, this return is a sum of scattering at 355 nm leaking into the detection channel, some Raman signal from nitrogen and hydrocarbons and some fluorescence from the sand that is not completely filtered out.

The differences in amplitude for the points prior to the ground are changes in the signal from the hydrocarbons' channel. These measurements show a good signal-to-noise ratio because they are the averages over multiple Raman returns. Each curve is the average over 963 returns. Each laser pulse is approximately 20 mJ, which translate to  $\sim$ 20 J for the 963 pulses: this is a huge amount of energy. However, averaging over 100 returns would have been sufficient to get a SNR of more than 3. This would then allow for a measurement to be completed in the expected concept of operation determined temporal duration of 300 ms using an adequate laser of >7 watts with a repetition rate not too high (too much ambient light) nor too low (too much pulse energy – bulky laser system). In order to have a good separation between the interfering Raman/fluorescence from the ground and the return from the Raman of hydrocarbons, a much higher spatial resolution is required. Since most of the vapor stays close to the ground, having a 6 to 7 ns laser pulse length limits the separation between the ground effects and the Raman from hydrocarbons in the air. Fluorescence generated by the leading edge of the pulse will swamp the Raman very near the surface. In order to correct for this, a laser pulse length of less than 1 ns would be required, along with detection electronics that can resolve such rapid changes in signal.



Figure 8. Offsets and interferences corrected return curves (left) and integrated Raman signal with respect to time after start of diesel injection (right).

In order to have a better estimate of the required laser power, a sum over the last 3.4 m of linear space before the ground is done. The result is shown in Figure 8 (right) with respect to time after start of diesel injection at the base of the container. The rise by a factor of ~4 between the diesel pans and the pentane pans is somewhat similar to that using IR absorption (Figure 9) and PID/FID measurements (not shown). The PID/FID results change with gas composition in addition to concentration changes. The more volatile compounds are in higher relative abundance earlier in the sequence. Gas samples were collected and sent to an external laboratory for analysis and this was confirmed, along with the fact that the hydrocarbon gas composition changes with height from the ground. This change in composition, with time and distance from ground, will also affect the optical measurements, but to a much lesser extent.

#### 4.2 IR absorption

Figure 9 shows the differential absorbance measurements (proportional to concentration) done with the leak simulator. This is the natural logarithm of the ratio of the transmission at 3476 nm to that at 3522 nm. The differential is corrected for no alkane in the air. A constant rising slope is seen in the graph after start of injection. Injection was stopped at the end of the first day (4.9 hours after start of injection), and was restarted, along with extraction, for a few hours at the beginning of the next day (1 hour and 52 minutes). A total of 115 liters of diesel was in the leak simulator container. The amount of alkanes rose during the night. The drop before the placement of the diesel pans (indicated by the first vertical dashed line) is probably due to opening of the polyethylene tent, start of vapor control system (fans) or a mix of both. Once the pans are in the tent, the alkane concentration continues to rise, although it is not clear it is solely because of the pans. A continuous slow flow of new liquid would probably be required to simulate an active leak. It is also clear that it takes a long time to establish some sort of equilibrium in the ground and in the air. A clear rise in signal is observed after the filling of the pans with pentane (second vertical dashed line). The absorption cross-sections will vary when going from diesel vapor to pentane vapor, so that comparing the numbers in terms of concentration is slightly misleading. This is especially true in light of the fact that the absorption was very strong with pentane so that returned light levels were very low. In conclusion, differential transmission is easily measured in the IR when the ground reflectance does not change. This would be the best approach, if it were not for the varying ground spectral reflectance in a real life scenario. The pentane pans were removed at the third dashed line.



Figure 9. IR differential absorbance measurements for alkanes in leak simulator

#### 5. CONCLUSION

Test results show that it is not straightforward to correlate a leak size with a hydrocarbon concentration in the air over a leak. Tests show that there is a strong concentration gradient in the air above a leak which indicates that a better overall detection performance should be obtained with a measurement using the air next to the ground. Although the UV-Raman approach showed potential for the selective detection of nearly all hydrocarbons in air with high spatial resolution along the line of sight, hardware limitations prevented the next to the ground volume of air to be analyzed which is a significant drawback for this approach compared to absorption techniques. Enhancements are possible and work should continue along this line. Raman signals can be scaled. The higher the laser power, the stronger the signals. Unfortunately, there are limits to the amount of laser power that can be directed to the ground in a pipeline leak detection scenario.

IR-DiAL showed the best sensitivity for the detection of hydrocarbons (< 1 ppm-m of LOD). The major drawback is that the strength of the return signal depends on the reflectance of the ground and it may be difficult to distinguish between spectral variations of the ground reflectance and the presence of hydrocarbons. Having a high performance data analysis approach is therefore of critical importance for an IR based leak detection system. How exactly the detection of leaks

could be enhanced by the selection of IR wavelengths or the type of signal processing is unclear at this point. Working in the UV would solve some problems, but then only benzene (and maybe toluene) would contribute to the absorption signal, if sufficient amounts of benzene and toluene were in the vapor plume. BTEX is present at a much lesser degree than alkanes in liquid petroleum products and benzene is almost absent in some.

Lidars are well known and routinely used remote measurement approaches. Although it is clearly possible to detect VOCs using UV-Raman or IR absorption, other requirements such as cost, mass, size, power, false alarms and ease of use need to be considered. Absorption techniques are preferred at this point. The right technique might differ from pipeline to pipeline, depending on vapor migration through the ground, soil temperature (in particular frozen ground), soil cover (in particular snow) and the like. None of this is considered in the feasibility presented here. Only iterative field trials will determine the most adequate approach and validate that the technology correctly addresses the problem. Engineering challenges remain to get a mobile platform mountable system.

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