Review of differential absorption lidar flare emission and performance data

Chief Scientist's Group report

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Professor Doug Wilson
Chief Scientist

Foreword

This report has been produced to inform the Environment Agency about particular past measurements of combustion gases in flare plumes, so it can consider any relevant information when it regulates flare emissions in future. It focuses on measurements made using Differential Absorption LIDAR (DIAL) monitors. These are remote-sensing devices that measure gas concentrations in three dimensions by remotely scanning airborne plumes downwind of emissions sources – like flares.

The study reviews a major archive of DIAL measurements that has been collected by the National Physical Laboratory (NPL) over ~30 years (1983-2015). In general, the measurements cover complex situations with multiple sources e.g. refineries. The measurements include some situations with flares, but they were not especially targeted on flares. The archive had not previously been investigated as a source of data for a general review of flare emissions.

Combustion gases from flares are difficult to measure with conventional in-stack probes because of the flames and high temperatures involved – which can damage probes and pose risks to monitoring personnel. By contrast, remote-sensing instruments like DIAL can quantify the combustion gases more reliably and safely, but may be more expensive.

Measurements of combustion gases from flares are needed to determine how efficiently flares burn hydrocarbons e.g. how efficiently they convert methane to carbon dioxide which is 25 times less polluting as a Greenhouse Gas. But there are relatively few measurements available because of the difficulties with conventional probes and the costs of remote sensing. The NPL archive was therefore a potentially important source of needed extra information on the emissions of flares.

The Environment Agency regulates several industrial sectors that use flares, including refineries, landfills and chemical plants, so extra information on flare performance is useful for regulating these sectors. The Environment Agency is also a lead regulator for the emerging shale-gas industry in England, which may use flares to burn excess methane, so extra information will be useful for this sector too.

The study did not require new measurements, as it used existing results from work that had already been paid for. Also it did not breach confidentiality because the results could be reviewed without disclosing specific locations. So the study was potentially a very cost-effective and practical way of getting extra information on flare performance.

The review confirmed that DIAL is an effective technique for quantifying airborne emissions from flares for key pollutants. The results show that emissions of unburnt hydrocarbons from flares can be elevated, implying that combustion can be inefficient. This means that if flare emissions are estimated by assuming efficient combustion of hydrocarbons, then actual emissions may be underestimated - including methane.

The archive contained a few flare studies that included details of the type of flare and of the flow and composition of the hydrocarbons supplied to it; combustion efficiencies could be evaluated in these cases. However, the archive did not include enough details on flare-types, flows and compositions for efficiencies to be evaluated generally, or for the performances of different flare types to be compared. The study has shown the value of acquiring such information during DIAL measurements, and to help with this it has developed a template for recording these details in future flare studies.

The report describes how DIAL measurements of flare emissions were collated and evaluated, and shows how additional information may be recorded so combustion performance can be determined for more flare types and situations in future. It is not designed to advise on how measurements should be used to reach regulatory decisions, because such advice would be outside the scope of this research. The report is not a statement of the Environment Agency's position, and it does not represent Environment Agency guidance on the matter.

Executive summary

This report presents the results of a study conducted by the National Physical Laboratory (NPL) on behalf of the Environment Agency to review the extensive set of industrial emission measurement campaigns conducted with NPL's differential absorption lidar (DIAL) facilities to identify and assess cases where measurements have been made of flare emissions.

DIAL is an optical technique used for quantifying and spatially mapping emissions of gases, and is particularly suited to the direct measurement of emissions from flares. NPL has over 30 years' experience in operating DIAL systems in industrial emission surveys and the review covered 69 separate DIAL measurement campaigns conducted between 1983 and 2015. This identified 14 measurement campaigns that included measurements of 29 individual flares. In many cases the flare was just measured as one element of the overall site, with no special emphasis on the type of flare or operational status at the time of measurement. However, four campaigns were identified as case studies of more direct relevance to the Environment Agency's objectives and these are discussed in more detail.

While the review and case studies do not provide an exhaustive set of flare performance information and no definitive statements can be made about the appropriateness of particular flare designs to onshore oil and gas operations, a number of key conclusions can be drawn. The range-resolved remote measurements made with the DIAL technique are ideal for providing direct measurements of flare emissions, and this has been demonstrated for a range of gases from different flare types on complex industrial sites. When combined with information about flare flow and composition, various aspects of the operational performance of the flare, such as the combustion efficiency, can be calculated. In addition to providing general information on the performance of a particular flare design and operating condition, the emission measurement results can identify individual flare performance issues which could feed into maintenance and repair programmes.

The flare measurements were usually a small part of a larger measurement campaign and there were often gaps in the supporting metadata that would enable a more detailed technical assessment of the emissions from flares and direct comparison of the different flare performances. A metadata template has been developed as a guide for the additional information that should be gathered in any future measurements carried out with the aim of assessing and comparing flare efficiencies.

If more detailed evidence is required about the levels of emissions from particular flare designs and operating conditions relevant to onshore oil and gas facilities, then this review has demonstrated the capability of the DIAL technique to meet this requirement. Any measurement campaign focused specifically on flare emissions would need to identify the appropriate choice of flare performance parameter and be undertaken in close cooperation with the site operator in order to gather the required metadata information.

Contents

List of tables and figures

1 Introduction and background

This report presents the results of a study conducted by the National Physical Laboratory (NPL) on behalf of the Environment Agency to review the extensive set of industrial emission measurement campaigns conducted with NPL's differential absorption lidar (DIAL) facilities to identify and assess cases where measurements had been made of flare emissions. The background to the Environment Agency's requirement for this work is given below (taken from the task quotation sheet):

- Over the next few decades, the onshore oil and gas (OOG) sector in England is expected to expand as new geological resources are identified (e.g. shale gas, coal bed methane) and new techniques are used to extract them (e.g. hydraulic fracturing or fracking). The Environment Agency is responsible for regulating environmental impacts from the OOG sector, including its impacts on air quality. The Environment Agency is required to consider best available techniques (BAT) for combustion of waste gases at regulated OOG sites; this includes flaring at upcoming sites for hydraulic fracturing of shale gas. There is a need to take air quality impacts in to account when considering BAT.
- Flaring is required as a safety precaution, and also for environmental protection (e.g. so that gas emissions are converted from methane and emitted as carbon dioxide which has lower global warming potential). Open flares have not been deemed BAT due to uncertainties in their methane conversion efficiency. Environment Agency current position is that enclosed flares are BAT, as they allow better control over emissions and offer the best option for minimising air quality impacts. However, there is a shortage of monitoring data to check this position (e.g. by comparing the air pollutant emission performance and destruction efficiency of different flare types). The Environment Agency's BAT position is being challenged by industry, so obtaining data to inform appropriate decisions on flaring of waste gases is now a high priority for the Environment Agency.
- There is very limited data on the air quality performance of flares because their design and high temperatures make them difficult to monitor conventionally (e.g. using in-stack probes). However, they can be monitored using remote-sensing methods, and specifically using DIAL. DIAL is an established method for measuring air quality at OOG sites, and it is likely that DIAL campaign archives contain flare measurements, although these measurements have not yet been collated and used to inform decisions on BAT.

2 Differential absorption lidar measurement of emissions

DIAL is an optical technique used for quantifying and spatially mapping emissions of gases. It is an extension of the lidar (light detection and ranging) method that is the optical equivalent of radar. A technical explanation of the DIAL technique as used by NPL is given in Appendix A, but an outline of the technique follows.

A basic DIAL measurement determines the concentration of a target gas at points along a measurement path. This is achieved by firing two pulses of laser light along the measurement path and measuring the intensity of the light that scatters off particles in the atmosphere and back to the detector from both pulses. The two pulses have different wavelengths. One of these wavelengths, the 'on-resonant wavelength', is absorbed by the target gas, while the other, the 'off-resonant wavelength', is not absorbed by the target gas. This means that at points along the measurement path where the target gas is present the intensity of the on-resonant wavelength will be reduced compared to the off-resonant wavelength. This reduction in intensity can be related to the concentration of the target gas. By considering the time that has elapsed between the transmission of the pulse and the detection of the backscattered light at the detector, the target gas concentration can be determined as a function of range.

A series of DIAL measurements combined with meteorological measurements can be used to determine the flux of a target gas. If a series of DIAL measurements are conducted in a vertical plane (see Figure 2.1), then the combined measurement results give a plane of concentration data. If the wind speed and direction are also known then the flux (or flow rate) of the target gas through the measurement plane can be calculated. For NPL DIAL measurements the wind speed is measured using a meteorological mast with anemometers mounted at different heights. These measurements are used to fit a logarithmic profile of wind speed with height above ground. This means that the wind speed used for flux calculation can be matched to the height of the DIAL measurement.

By orienting the DIAL so that an emission source is upwind of the measurement plane the flux and spatial distribution of the emission from the source can be measured. The ideal configuration for the measurement of any source, including a flare, is for the DIAL system to be located 100 to 200m away from the source with a clear line of sight upwind and downwind of the source. This gives optimum sensitivity for the measurements and enables easy separation of the emissions from the target source from any other emissions.

There are several reasons that the DIAL technique is particularly useful technique for measuring flare emissions:

- DIAL provides a direct measurement of the emissions from a flare with no assumptions about flare combustion efficiency or the operating conditions of the flare. The measurements can therefore be used to test and validate emission estimates.

- DIAL is a remote measurement technique. This is useful as flares are hazardous by their nature, and this technique removes the need to access them directly. This is also useful because flares can be in difficult-to-access locations (e.g. elevated flares). Remote measurements are also non-invasive so an accurate measurement of the emissions from the flare over a wide range of operating conditions can be conducted. Being remote also means it is possible to separate other sources by performing an upwind measurement.
- DIAL measurements are range-resolved and can be used to produce a three-dimensional (3D) map of emissions. This means that the location of emissions and plumes can be mapped and spatially separate sources can be identified and quantified. This can also confirm where any emissions are occurring (e.g. leaks from the pipework and control systems on a flare stack can be discriminated from emissions from the flare tip).
- DIAL is able to measure several different species relevant to flares. DIAL can measure methane, ethane and general hydrocarbons separately, and therefore measure the different levels of unburnt hydrocarbons in a flare's emission. This allows a direct calculation of the efficiency of the flare if the composition and flow rate of the gas is known. Measurements of nitric oxide (NO) and nitrogen dioxide (NO_2) can also be made to give another indication of the flare combustion properties.

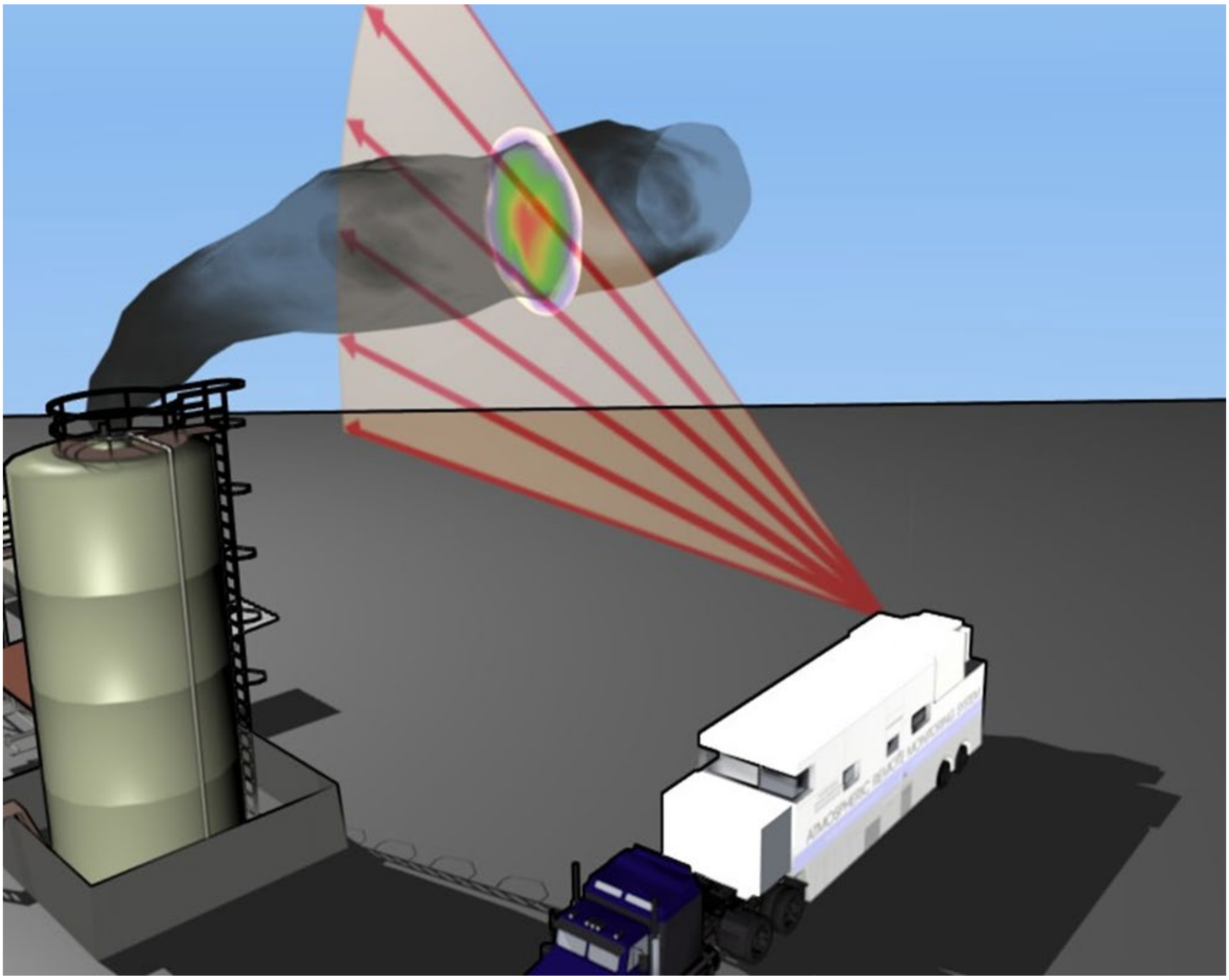


Figure 2.1 Standard DIAL measurement configuration

- The DIAL system is an advanced sensing technique that requires expert operators and is usually deployed for periods of a few days or weeks. It therefore provides a short-term assessment of the emissions at the time of the measurements and is not suited to long-term continuous emission monitoring.
- A typical DIAL measurement scan takes 10 to 15 minutes to complete, so any variations on a shorter timescale will not be captured.
- The size of the DIAL facility (17m long, 2.5m wide, 4m high) can make access to some smaller sites difficult.
- Although emission measurements can be made in most weather conditions, including rain and snow, there are some conditions where they are not possible, in particular very light winds (<0.5m/s) and heavy fog.

3 Review of NPL DIAL measurement campaigns

The Emissions and Atmospheric Metrology Group at NPL has over 30 years' experience in operating DIAL systems in emission surveys and has a world-leading level of practical knowledge in the planning, execution and interpretation of DIAL measurement campaigns. The NPL monitoring team has carried out DIAL emission surveys at a wide range of industrial sites (Robinson et al. 2011). A review was carried out of 69 separate DIAL measurement campaigns conducted between 1983 and 2015, which identified the type of site being measured, the particular species being targeted and the different areas of the site – including flares – that were covered during the campaign. The results of this review are summarised in Appendix B (which excludes commercially sensitive information).

3.1 Flare measurements using the NPL DIAL

The 14 measurement campaigns that included flare measurements were then assessed to provide more information about the measurements that had been made and to see what additional information about the flare operation was available. The results of this more detailed assessment are summarised in Appendix C. This assessment was done on an individual flare basis, providing details of the emissions from 29 different flares that have been measured by the NPL DIAL facility. The main purpose of this phase of the review was to identify the number of measurements that had been made, the operational status of the flare at the time of the measurements, and what additional information was available on the flare operation that would enable further calculations, such as flare efficiency, to be made.

In many cases the flare was just measured as one element of the overall site, with no special emphasis on the type of flare or operational status at the time of measurement. However, a number of campaigns were identified which are of more direct relevance to the Environment Agency's objectives, and these are discussed in more detail in the following case studies.

3.2 Flare case study one

During case study one measurements were carried out at two petrochemical facilities: a refinery and a bulk storage facility. The purpose of this campaign was to determine actual emission rates of general hydrocarbons and benzene from difficult-to-measure identified potential sources and compare these to standard emission calculation methodologies. The duration of the total campaign was 26 days.

The intention for the campaign was to measure two flares: an open elevated temporary stack flare and an enclosed ground flare. During measurements of the elevated stack flare, emissions from a second open elevated flare were seen and measured. The elevated flares were measured for 3 days. Measurements of the ground flare took place during one day and one night. The site required the flares to be measured ‘as found’, meaning that no changes took place with the operation of the flare because it was being measured; the flare was measured regardless of the operational status of the flare at the time of measurement. Flow and detailed composition data were not available for these flares.

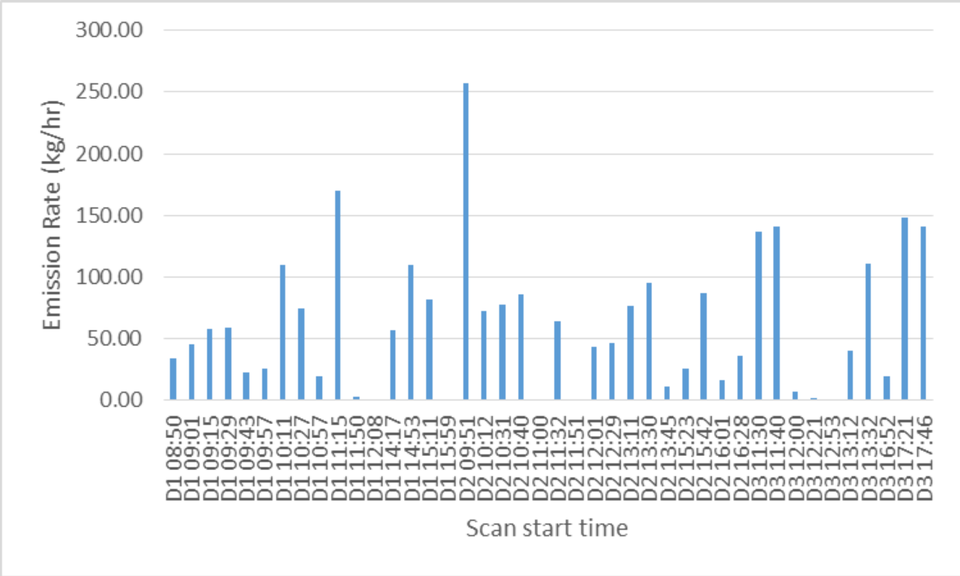
The open elevated flare intended for measurement during this campaign was a temporary steam-assisted stack flare. This flare was burning a by-product hydrogen/general hydrocarbon process stream from a unit undergoing major maintenance work. This flare had a highly visible flame and was measured with the intention of determining general hydrocarbon emission due to incomplete combustion in the flare. This flare was reported to be burning mainly hydrogen and low levels of general hydrocarbon emissions were found.

While the intended flare was being measured high levels of emissions were noticed from a source closer to the DIAL than the intended flare. These emissions were found to be from the elevated open steam-assisted ultra-cracker (ULC) flare. This flare had an almost invisible flame during daylight, but could be seen at night. This flare had been recently built as an emergency or process flare, designed for high flow levels. In normal operation this flare had a low flow rate, which caused inefficient combustion and resulted in high levels of emission. The emission rates from this flare were observed to be variable; this was due to a combination of variability in the emissions and the possibility of movement of the flare’s narrow plume over the period of each DIAL scan. The DIAL measurement plane was up to a maximum distance of 50m downwind of this flare.

General hydrocarbon emission levels from both elevated flares combined are shown in Figure 3.1. Figure 3.2 shows an example 3D plot of the emissions from the ULC flare. For measurements where both flares were upwind of the measurement plane the data were analysed for total emission from both flares as the site required combined emissions, although it would have been possible to spatially separate the emissions if this had been required. Given the observed emission distributions, it is probable that the ULC flare was the source of the majority of the combined emissions.

An enclosed ground flare, called Flare 6, was also measured. The emission levels for this flare are shown in Figure 3.3. As with the ULC flare measurements, the observed emission rates are highly variable, but no information was available on flow rates or flare gas composition. The DIAL measurement plane was 50m downwind of the flare.

To put the flare emission levels in the wider site context, the general hydrocarbon emissions from a number of specific site areas were also measured, including ~17kg/hr from the water treatment area, ~8kg/hr from a coker facility and ~30kg/hr from a crude oil tank farm.



Emission Rate (kg/hr)
300.00
250.00
200.00
150.00
100.00
50.00
0.00
D1 08:50
D1 09:01
D1 09:15
D1 09:29
D1 09:43
D1 09:57
D1 10:11
D1 10:27
D1 10:57
D1 11:15
D1 11:50
D1 12:08
D1 14:17
D1 14:53
D1 15:11
D1 15:59
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D2 12:01
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D2 13:11
D2 13:30
D2 13:45
D2 15:23
D2 15:42
D2 16:01
D2 16:28
D3 11:30
D3 11:40
D3 12:00
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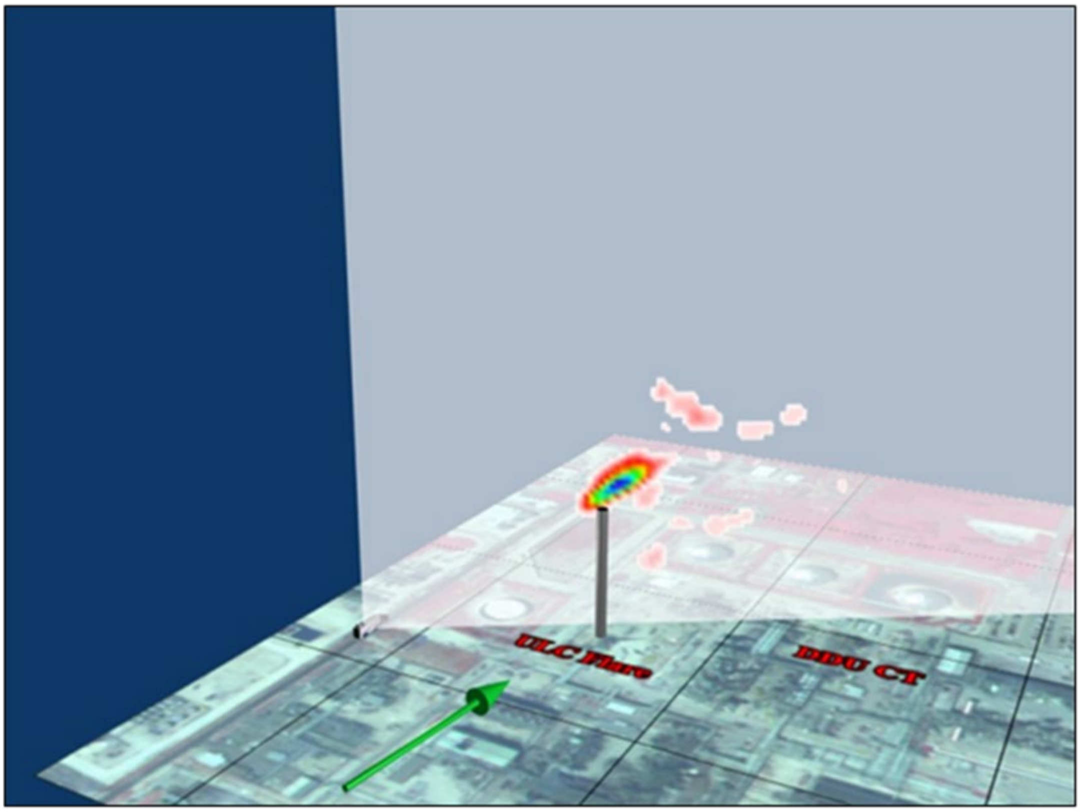
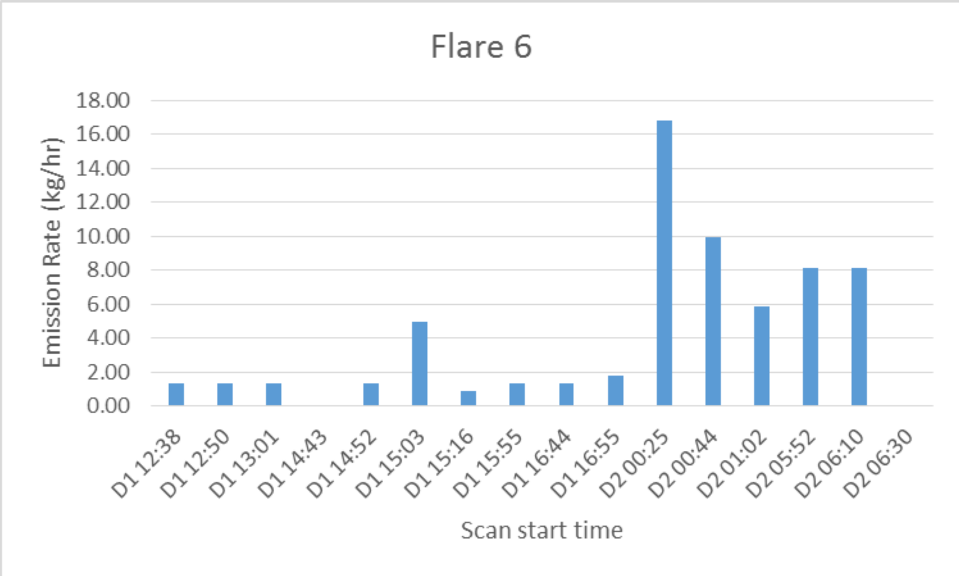
D3 13:12
D3 13:32
D3 16:52
D3 17:21
D3 17:46
Scan start time



ULC Flare
DDU CT



The results from this case study confirm the ability of DIAL to measure flare emissions and also identify and quantify unexpected sources. In this case study, no information about the flow rates or composition of the gas to the flares was available. This means that the flare efficiency could not be calculated and the flare emission levels cannot be compared to others. Also, any variability in the emission level due to changes in the flow rate cannot be identified. These results indicate the need for detailed flow and composition information in a dedicated flare study. The measurements of the ULC flare showed that, at least in this case, operating a steam-assisted flare designed for a high flow rate with a low flow rate caused inefficient combustion and unexpectedly high levels of emissions. This result led to further (non-DIAL) studies which verified this conclusion, and subsequent proposed revision of flare operating rules by the relevant national authority (Texas Commission on Environmental Quality 2010). Therefore this single set of DIAL flare measurements has led to a change in the understanding and accounting of flare efficiency.

3.3 Flare case study two

Measurements for case study two took place at a plant which receives gas from oil fields and treats it according to export specifications. The primary aim of this campaign was to determine the emission rates from three flares on the plant. The emission rates of methane, ethane, general hydrocarbon, NO and NO_2 from the flares was measured. So that oxides of nitrogen (NO_x) measurements can be compared, the NO and NO_2 measurements are combined to give an emission value quoted in grams of NO_x as NO_2. This value is calculated by assuming that any NO measured will oxidise to NO_2 sufficiently far from the source.

The flow rate and composition of the gas to the flare was recorded during these measurements, meaning that the flare combustion efficiency could be calculated using the following formula:

combustion efficiency (%) = [1 – (carbon emitted/carbon in flare gas)] x 100 where carbon refers to the number of carbon atoms in hydrocarbon form.

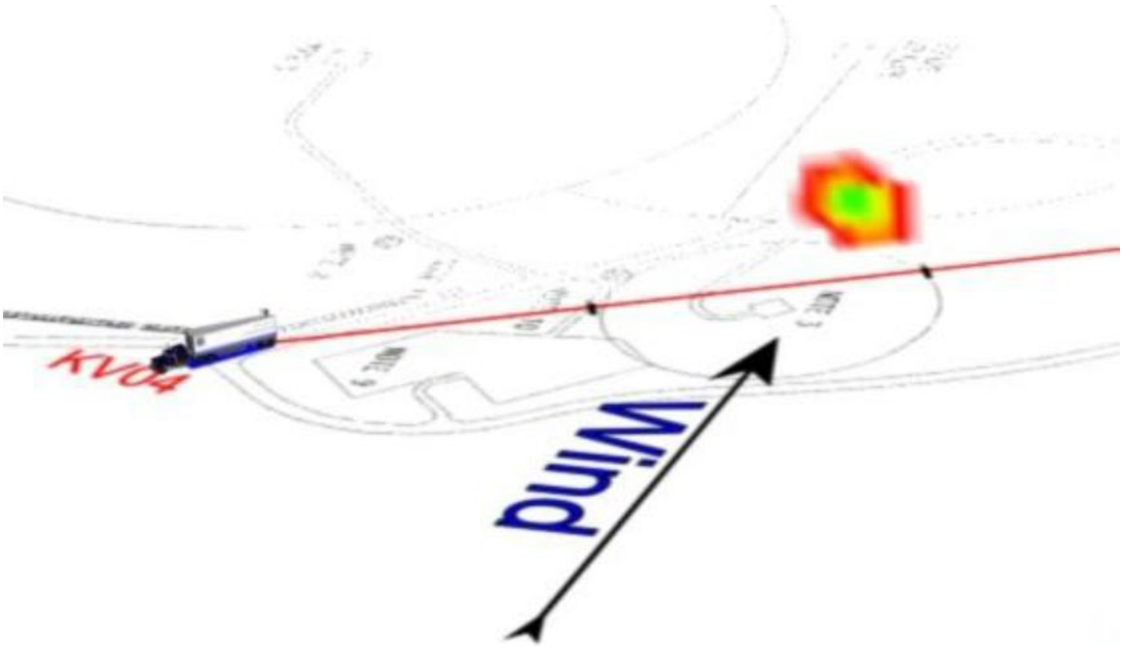
This equation is valid under the following assumptions:

- the gas in the flare plume had the same composition as the supplied gas
- there was not significant production of soot
- there was not significant production of carbon monoxide
- the combustion efficiency was similar during the methane, ethane and general hydrocarbon measurements

The validity of these assumptions is discussed below for each flare measurement.

The low pressure flare is an enclosed ground flare. It is part of the plant system to remove low pressure gas from the process stream under emergency conditions. The flare is continuously purged with nitrogen to prevent oxygen building up in the flare system. This flare burns continuously at low flow. This flare was measured 'as found'. For all species the DIAL measurement plane was 20m downwind of the flare.

The measurements of this flare showed high levels of methane emission compared to the other species, with the flaring efficiency less than 50%. At this level the assumptions in the calculation of flare efficiency are not valid, particularly the final two assumptions. These require a reasonably high level of destruction efficiency. For this reason a value for the flare combustion efficiency was not calculated. No oxides of nitrogen were found above the DIAL detection limit, which is expected with a low combustion efficiency. The main reason for the low combustion efficiency was that the combustible part of the flare gas was about 50% of the volume, and this is further diluted by air drawn around the base of the flare. The emission rates with simultaneous flow rate are given in Table 3.1.



The maintenance flare is an open ground-level flare. This flare is designed to receive gas during routine maintenance on the plant. This flare was measured under normal conditions, where only the pilot burners were lit (‘flare off’), and under an increased flow condition with the main burners lit (‘flare on’). One measurement for each of the species except NO_2 was made in the normal condition state and three or four measurements were made under increased flow conditions for all species. In all cases the maintenance flare was measured with the DIAL measurement plane less than 20m downwind of the flare. Figure 3.4 shows an example 3D plot of the general hydrocarbon emissions from the maintenance flare. The results from the maintenance flare for methane (Figure 3.5), ethane (Figure 3.6), general hydrocarbon (Figure 3.7), NO (Figure 3.8) and NO_2 (Figure 3.9) are shown later in this section. The time the flare was lit is given on each figure, indicating the change from ‘flare off’ to ‘flare on’ conditions. Table 3.2 gives the emission rates and flare flow rates during the ‘flare on’ measurements. Note that Figure 3.8 includes a negative emission value – when emissions levels are less than the DIAL detection limit the measurement noise can lead to some individual scan results being slightly negative. This is normal behaviour for any instrument measuring close to zero.

Table 3.1 Summary of low pressure flare emissions and flaring flow rates

Measured species	Average flux	Standard deviation	Flaring flow rate
	kg/hr	kg/hr	Sm^3/hr
Methane	60.4	4.4	215
Ethane	1.7	0.3	222
General hydrocarbon	3.1	0.6	196

NO	0.0	0.2	229
NO_2	0.1	0.2	229

Table 3.2 Summary of maintenance flare emissions and flow rates

Measured species	Average flux	Standard deviation	Flaring flow rate
	kg/hr	kg/hr	Sm^3/hr
Methane	3.1	0.5	4,150
Ethane	0.9	0.0	3,790
General hydrocarbon	0.1	0.1	5,750
NO	1.1	0.1	3,900
NO_2	0.9	0.2	3,740

This flare showed higher levels of emission during the 'flare off' measurements. This suggests that there was a very low combustion efficiency and the possible presence of a leak. The measurement of NO with the flare off did not find any emission above the DIAL detection limit. The reported average flows during the 'flare off' measurements were 90Sm^3/hr.

By combining the DIAL emission measurements with the gas composition analysed by the site the maintenance flare efficiency was found to be 99.86 ± 0.02% during the 'flare on' measurements, and the destruction efficiencies of methane, ethane and general hydrocarbons for the maintenance flare are given in Table 3.4. The destruction efficiency is defined as the ratio of the amount of the species measured downwind of the flare to the amount of the species present in the flaring gas. The gas composition was not analysed during the general hydrocarbon measurements so the average composition measured during the ethane and methane measurements was used for this calculation.

The assumptions of the combustion efficiency calculation were taken to be valid for measurements of the maintenance flare. The first assumption cannot be proved, but since methane and ethane are the dominant species in the gas flare composition the observed methane and ethane emissions effectively determine the flare combustion efficiency. Even if some of the observed methane and ethane in the flare plume may have been derived from the combustion or breakdown of the general hydrocarbon species, there was so little of these heavier hydrocarbons in the flare gas that it would have had an effect at least an order of magnitude smaller than the uncertainty associated with the DIAL measurements. The second assumption was confirmed visually as no soot or smoke was seen from the flare. Also it is unlikely that a significant proportion of carbon monoxide was generated considering the very good measured hydrocarbon destruction efficiency. The last assumption is also reasonable in light of the excellent and similar destruction efficiency measured for each species showing very good combustion efficiency during each measurement day. Moreover the flaring flow rates during the methane and ethane measurements that effectively determined the flare combustion efficiency were similar.

The NO_x measurements found a NO_x production factor of 0.65g of NO_x as NO_2 per Sm^3 of flare gas.

Finally, the high pressure flare is an elevated open flare designed to receive the full gas pipeline in the event of an emergency. Under normal conditions the flare is operated under a pilot gas or low flow conditions. This flare was measured ‘as found’ – with only pilot gas flow, and under increased flow flaring conditions. Different source gas was used under increased flow conditions than for the pilot gas flow. The composition of the gas to the flare was measured by the site for all measurements of the high pressure flare except for the methane measurements.

The results of the high pressure flare measurements are shown in Figure 3.10, Figure 3.11, Figure 3.12, Figure 3.13 and Figure 3.14 for methane, ethane, general hydrocarbon, NO and NO_2 respectively. Table 3.3 shows the average emission flux for each of the species along with the flow rate during the increased flow measurement. For all species the high pressure flare ‘as found’ measurements were conducted with the DIAL measurement plane up to 20m downwind of the flare. For measurements of the flare under increased flow conditions the distance from the flare to the measurement plane was up to 100m. The difference between the ‘as found’ and actively flaring measurement distances is due to the physical size of the flare – measurements were not conducted through the visible part of the flame.

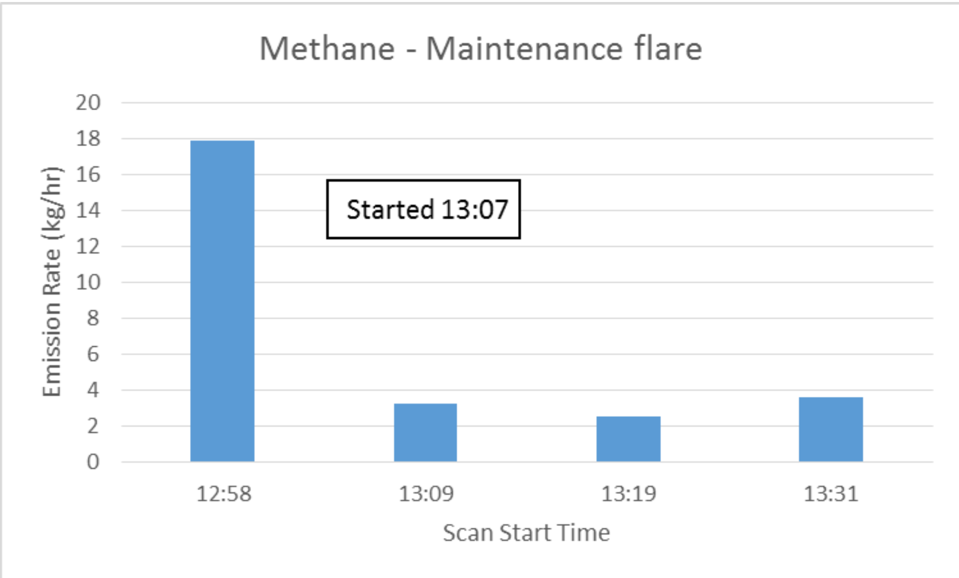


Figure 3.5 Methane emissions from the maintenance flare

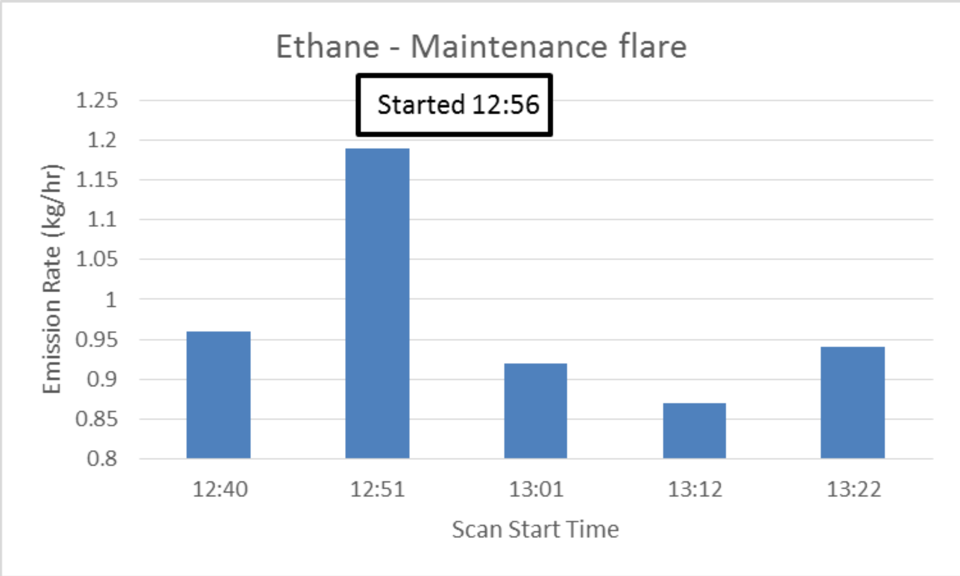


Figure 3.6 Ethane emissions from the maintenance flare

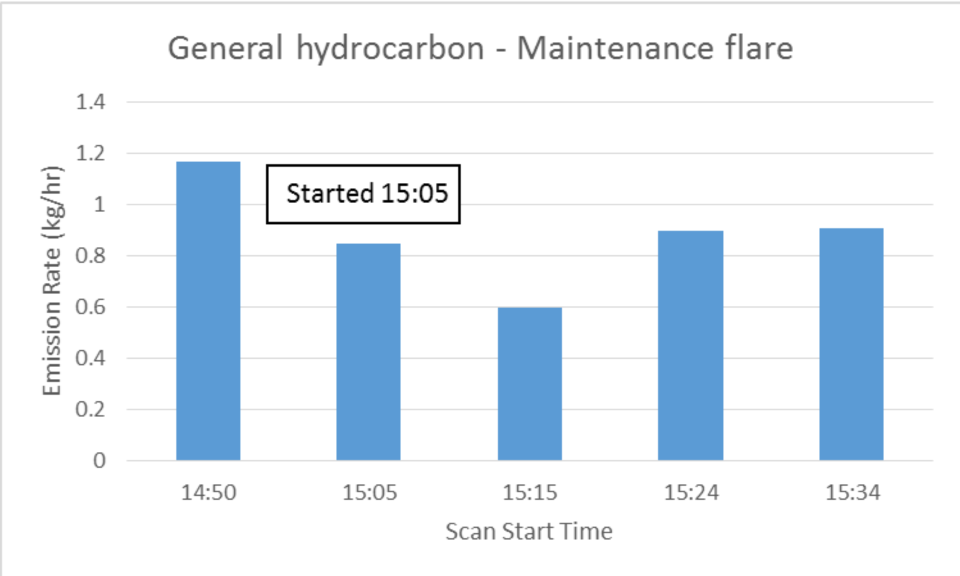


Figure 3.7 General hydrocarbon emissions from the maintenance flare

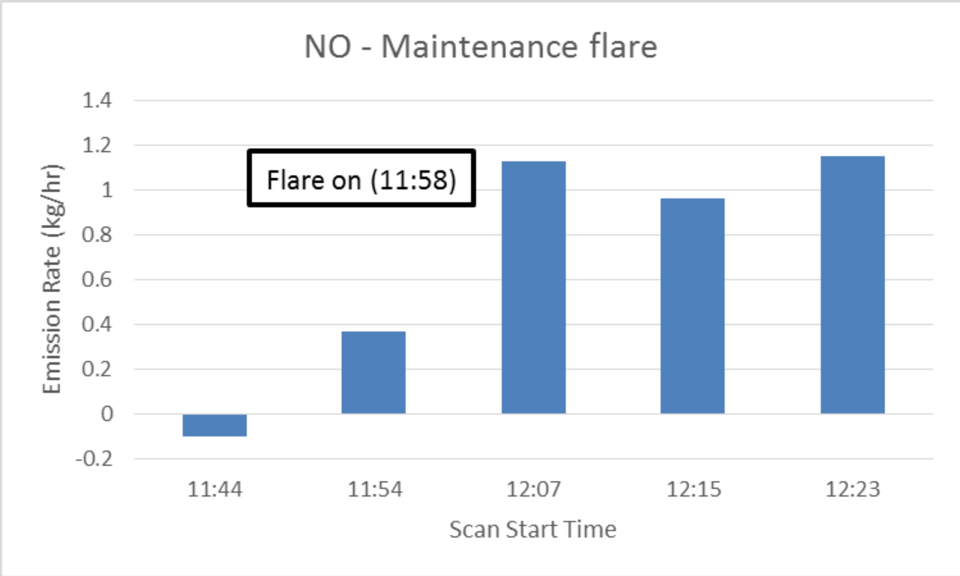


Figure 3.8 NO emissions from the maintenance flare. Note that the negative value reported at 11:44 occurs because of the effect of measurement noise on a very low emission rate

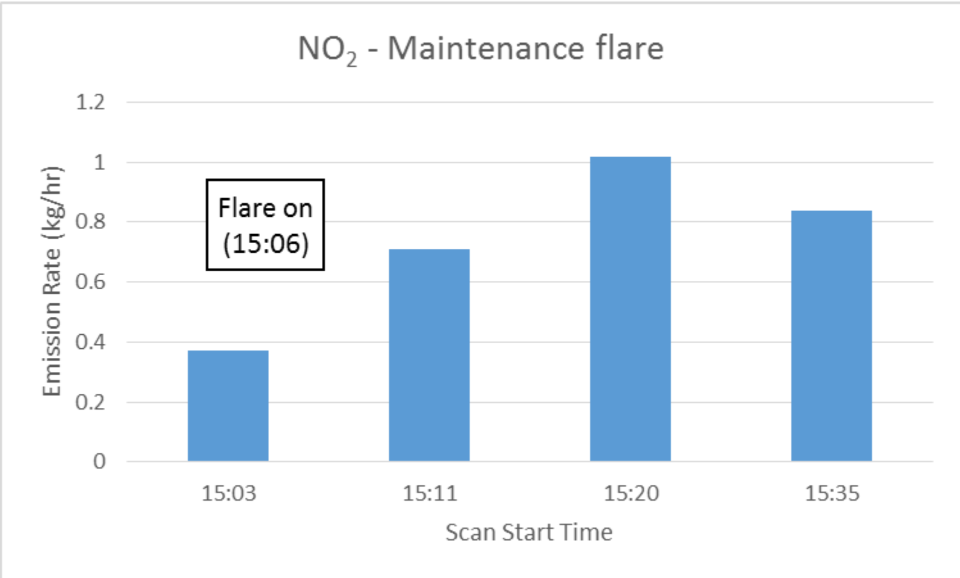


Figure 3.9 NO_2 emissions from the maintenance flare

Table 3.3 Summary of high pressure "flare on" emissions and flow rates

Measured species	Average flux	Standard deviation	Flaring flow rate
	kg/hr	kg/hr	Sm^3/hr
Methane	103.6	35.4	59,740
Ethane	9.5	1.9	52,990
General hydrocarbon	7.3	1.9	110,500
NO	1.2	0.2	9,570
NO_2	1.2	0.2	7,810

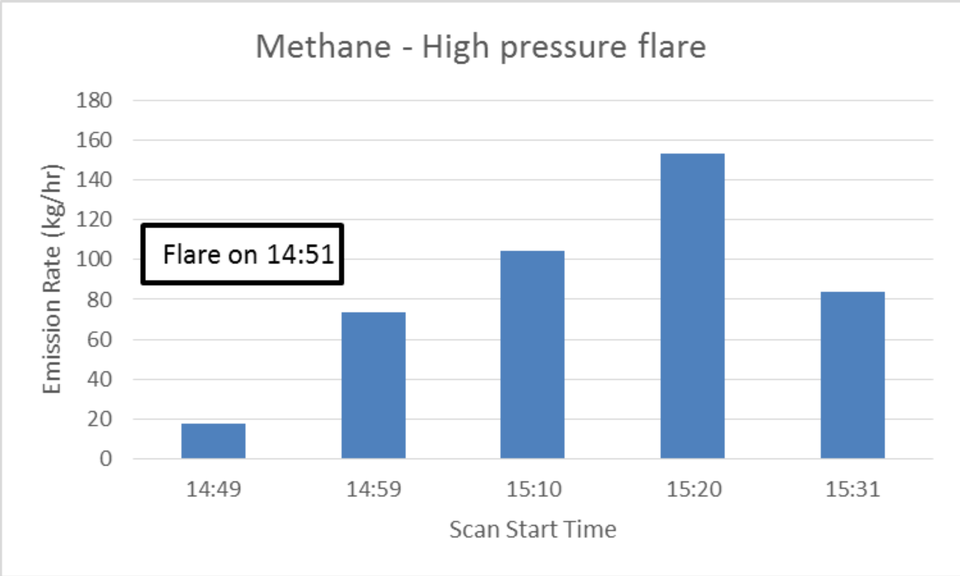


Figure 3.10 Methane emission rates from the high pressure flare

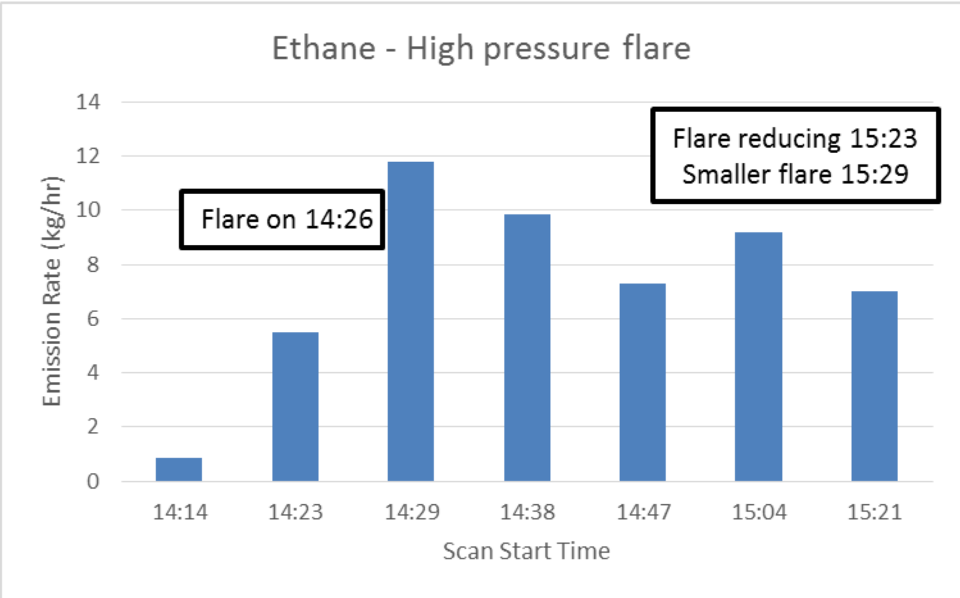


Figure 3.11 Ethane emission rates from the high pressure flare

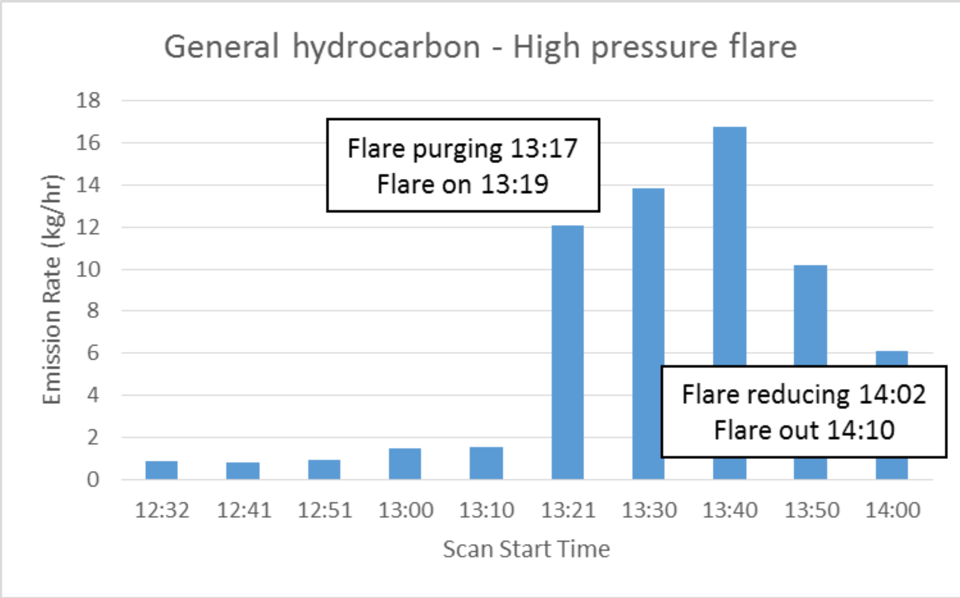


Figure 3.12 General hydrocarbon emission rates from the high pressure flare

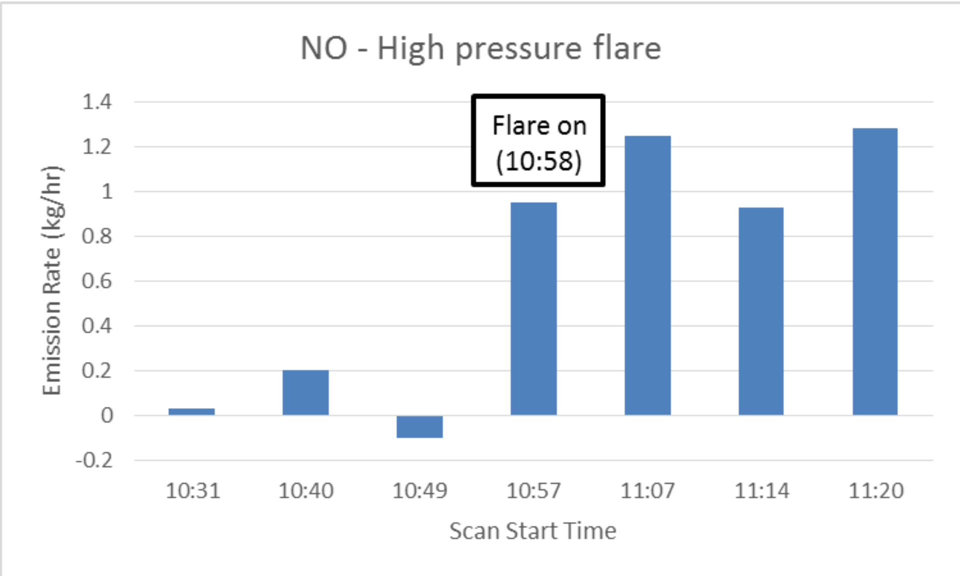


Figure 3.13 NO emission rates from the high pressure flare. Note that the negative value reported at 10:49 occurs because of the effect of measurement noise on a very low emission rate

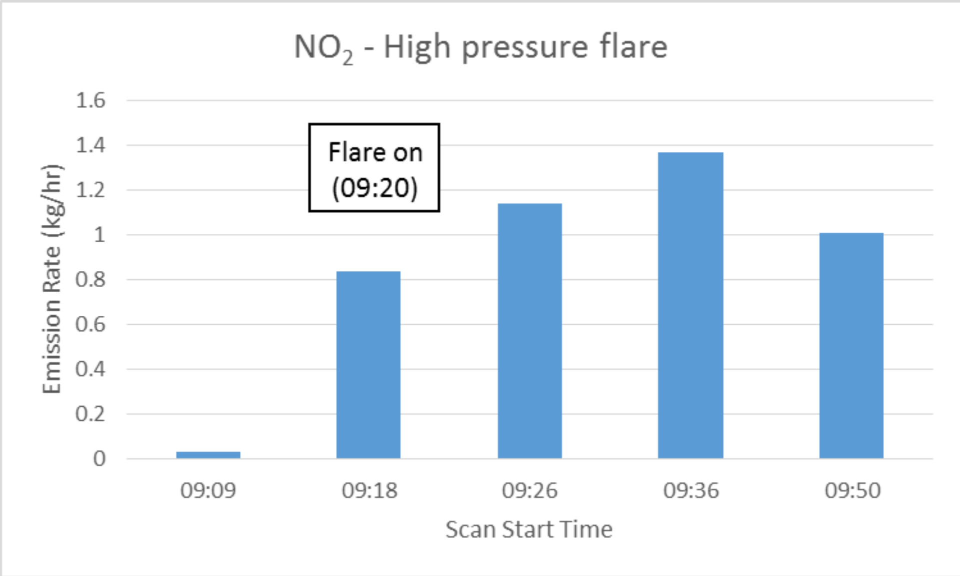


Figure 3.14 NO_2 emission rates from the high pressure flare

Measurements of the flare 'as found' were only taken for ethane and general hydrocarbon. The flare gas at this time contained mainly nitrogen, with reported gas flow rates of 931Sm^3/hr during ethane and 555Sm^3/hr during general hydrocarbon measurements. The measurements showed that under this condition the emission of ethane and general hydrocarbon was approximately 50% of the ethane and general hydrocarbon flare throughput. None of the NO or NO_2 emissions were above the DIAL detection limit during these measurements, as expected for a low combustion efficiency.

Measurements of the high pressure flare under increased flow conditions determined the combustion efficiency to be 99.73 ± 0.08%, the destruction efficiencies of methane, ethane and general hydrocarbons for the maintenance flare are given in Table 3.4. Since the flare gas composition was not available for the methane measurements an average of the gas composition found during the general hydrocarbon and ethane measurements was used for the methane calculation. The gas composition was very similar for these two measurements and was not expected to be different during the methane measurements.

The assumptions of the combustion efficiency calculation were taken to be valid for measurements of the high pressure flare for the same reasons as they were taken to be valid for the maintenance flare.

The NO_x production factor during the increased flow measurements was calculated to be 0.33 ± 0.04g/Sm^3. This value cannot be correlated to the measured combustion efficiency because different gas sources were used and the flow rate was lower for the NO_x measurements, probably resulting in a lower combustion efficiency.

Table 3.4 Summary of flare combustion efficiency overall and for specified species

Flare on	Combustion efficiency (%)	Methane destruction efficiency (%)	Ethane destruction efficiency (%)	General hydrocarbon destruction

				efficiency (%)
High pressure	99.73 ± 0.08	99.74 ± 0.09	99.64 ± 0.07	99.69 ± 0.08
Maintenance	99.86 ± 0.02	99.88 ± 0.02	99.73 ± 0.01	99.65 ± 0.22

The measurements in case study two confirmed the ability of DIAL to measure the emissions of a range of different species from a number of different flare types and operating configurations over a course of a single study. It also showed that combustion efficiencies/emission rates could be calculated for all of these species when the DIAL results are combined with process information on flare gas flow rates and composition. The results showed that flare emissions (and efficiencies) varied significantly with the flare operational configuration and that DIAL could be used to track the temporal variations in the emissions.

3.4 Flare case study three

Case study three took place at a crude oil gathering station. This site receives crude oil from local well sites, stabilises the crude, separates liquid petroleum gas (LPG) and natural gas, and then exports the products via pipelines. This campaign aimed to measure the total fluxes of general hydrocarbons emitted by the site and compare this with the industry's estimation techniques. This information was then intended to improve the country's inventory of general hydrocarbon emissions from identified process units. Measurements at this site took place over 5 days, with the flare measurements taking place during one afternoon.

Three enclosed ground flares were measured during this campaign. Each of these is associated with different process units and they are known as the low temperature, low pressure and high pressure flares. Each flare consists of a set of burners contained within an open-topped box. There is potential for emission of unburned hydrocarbons if the burners are not operating with a high combustion efficiency. These burners are continuously supplied with fuel gas to maintain a pilot light and prevent build-up of explosive mixtures. The metered flare fuel gas rate to each flare was recorded during these measurements, meaning that emission factors could be calculated. However, a detailed composition analysis of the flare gas was not available, meaning that the combustion efficiency used for case study three could not be calculated and a direct comparison of efficiency is not possible. All of these flares were measured with a distance between the flare and the measurement plane of 25m.

The low pressure and high pressure flares were found to be small sources of hydrocarbon emission. Neither of these flares was actively flaring ('on') during the measurement period; however, they were being supplied with a constant flow of fuel gas. The emission rate from each of these flares was found to be approximately 5kg/hr. The high pressure flare was measured once by itself and once with the low pressure flare; this was the only measurement of the low pressure flare. The metered fuel gas to the low pressure and high pressure flares was 6.9 tonnes/day and 7.7 tonnes/day respectively. The emission factor, defined as the ratio between the mass of general hydrocarbon measured and the mass of gas going to the flare, was 1.6% for both of these flares.

The low temperature flare was found to be a significant localised source. This flare was actively flaring during the measurement period (‘flare on’). The average emission from this flare was found to be 100.9 ± 15.8kg/hr. The metered gas flow to this flare was 14.9 tonnes/day, producing an emission factor (defined as above) of 16.2% for the low temperature flare. This shows that under flaring conditions this flare was relatively inefficient. Figure 3.15 shows the emissions measured from the low temperature flare.

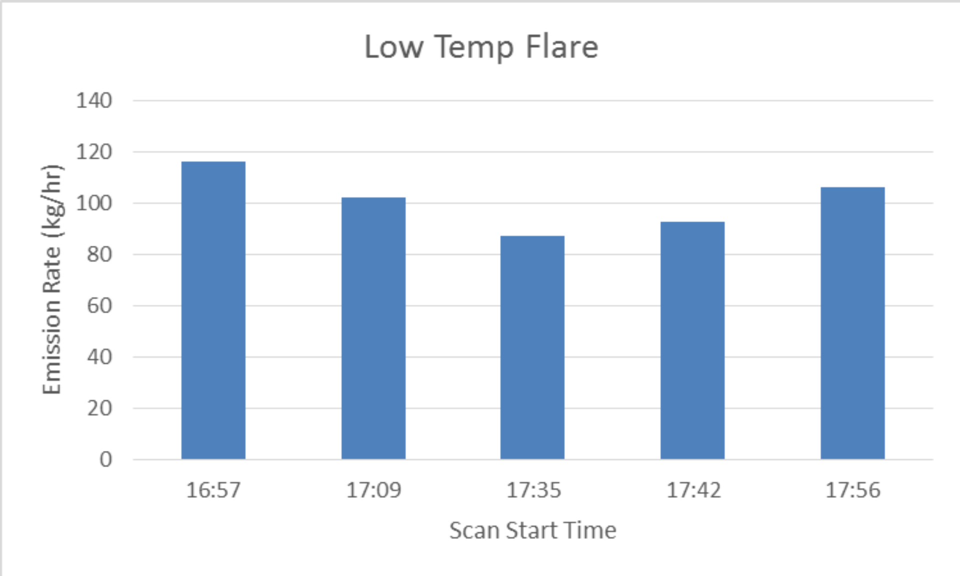


Figure 3.15 General hydrocarbon emission rates from the low temperature flare

The flare emission results compare to a total general hydrocarbon emission of 134kg/hr from the rest of the site, showing that, at the time of measurement, the flare emissions made up ~45% of the total site emissions.

These results again showed the variation in flare efficiencies that can be seen for different flares on the same site. The measurements can therefore be used to identify individual flare performance issues, which could feed into maintenance and repair programmes.

3.5 Flare case study four

Measurements for case study four took place at a conventional onshore oil extraction site. The purpose of this campaign was to produce estimates of the amount and location of fugitive methane emissions across the site. The campaign lasted 4 days and the flare was measured alone for approximately 2 hours.

This site had one enclosed ground flare which was measured ‘as found’. The flare gas flow rate during the DIAL measurements was recorded as 70Sm^3/hr. The average emission from the flare during the measurements was 5.7 ± 0.2kg/hr. The flare was measured with the DIAL measurement plane less than 20m downwind of the flare. The gas composition was not measured during the campaign but the site manager did not expect the composition to have changed since a previous analysis performed 3 years prior to the DIAL measurements. Using these data the methane destruction efficiency, defined as the ratio between the mass of burned methane and the mass of methane in the gas going to the flare, was calculated to be 85%. Since only methane measurements were carried out at this site it is not possible to calculate the full combustion efficiency of this flare. The methane destruction efficiency, however, can be compared to the results from case study two. The total methane emissions from the site (including flare) were measured to be 13.0kg/hr, indicating that the flare contributed ~44% of the overall emissions (at the time of measurement).

Figure 3.16 provides an example 3D plot of the methane emission distribution seen from the enclosed ground flare, while Figure 3.17 shows a time series of the emissions measured downwind of the flare.

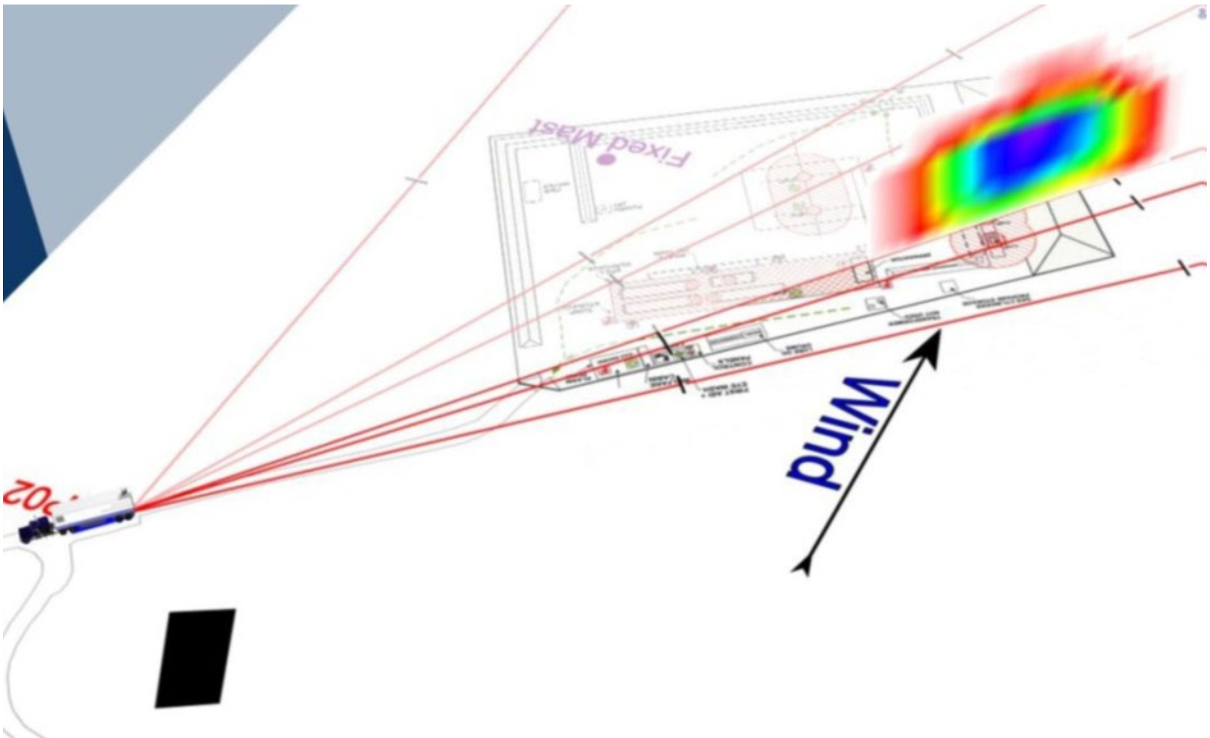


Figure 3.16 Example 3D plot of the methane distribution seen in a vertical scan at case study four, downwind of the enclosed ground flare, showing a localised plume at the position expected for emissions from the ground flare

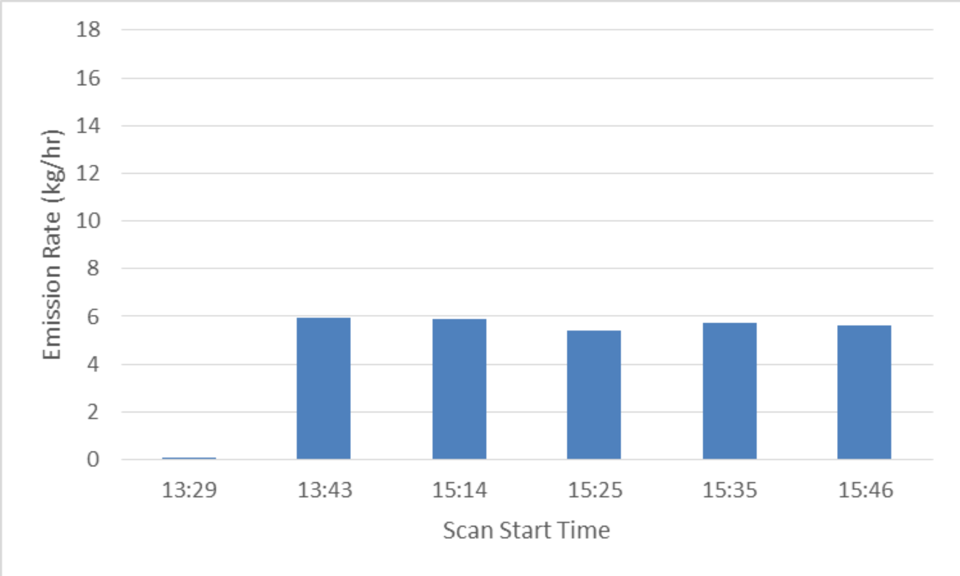


Figure 3.17 Methane emission rate from the enclosed ground flare. Note that the scan at 13:29 was an upwind measurement

This case study is probably closest to the measurement configuration and type of site that would be expected for the OOG activities of particular interest to the Environment Agency, and the flare is of a type that might be used for ongoing (rather than exploratory) onshore operations. The results show that measurable levels of emissions can be produced by flares of this type and that the DIAL technique is capable of mapping and quantifying them. They also show that the emissions from the flare can make up a significant fraction of the overall emissions from this type of site.

4 Conclusions and next steps

The review of 69 NPL DIAL field campaigns over more than 30 years identified measurements of the emissions from 29 different flares. In most cases the flare measurements were just one element of the overall site, with no special emphasis on the type of flare or operational status at the time of measurement. However, four case studies, covering 10 different flares, were identified as having more direct relevance to the Environment Agency’s objectives. The review and case studies do not provide an exhaustive set of flare performance information and no definitive statements can be made about the appropriateness of particular flare designs to OOG operations. However, a number of key conclusions can be drawn from the results of this study, and these are discussed below.

The range-resolved remote measurements made with the DIAL technique are ideal for providing direct measurements of flare emissions, and these can be made with no health and safety risks or impact on site operations. The NPL DIAL facility has demonstrated its capability to measure the emissions from a wide range of different flare types on complex industrial sites, and the emissions from different sources, including unexpected ones, can be mapped and quantified separately. Flare emission measurements have been conducted for a number of different species, including a range of hydrocarbons, sulphur dioxide and NO_x. The results of DIAL flare measurements have already been used by one national regulator to revise guidance on flare operation and update regulatory understanding of flare emission levels.

When combined with information about flare flow and composition, various aspects of the operational performance of the flare, such as the combustion efficiency, can be calculated. The results on flare emissions and combustion efficiency measurements have shown a high degree of variability from flare to flare. Temporal variations in emissions from individual flares are also seen, depending on the operational status of the flare at the time of each measurement. For example, most flares have shown a change in emission levels between ‘flare on’ and ‘flare off’ conditions, but both positive and negative changes in emission levels have been seen for different flares. In addition to providing general information on the performance of a particular flare design and/or operating condition, the emission measurement results can identify individual flare performance issues which could feed into maintenance and repair programmes.

There are several different quantities in use for describing the efficiency of flaring operations and these cannot be directly compared. Given the range of parameters in use, any future work focused on flare efficiencies should agree which of these parameters to use so that a valid comparison of different flares can be made.

It is also clear from the review process that, as the flare measurements were usually a small part of a larger measurement campaign, there were often gaps in the supporting metadata that would enable a more detailed technical assessment of the emissions from flares and direct comparison of the different flare performances. One objective for the review was to produce a metadata template that could be used for future campaigns to maximise the information from flare emission measurements. This template is given in Appendix D, and should be used as a guide for the additional information that should be gathered, where available, in any future DIAL measurements carried out with the aim of assessing and comparing flare efficiencies.

If more detailed evidence is required of the levels of emissions from particular flare designs and operating conditions relevant to OOG facilities, then this review has demonstrated the capability of the DIAL technique to meet this requirement. Any measurement campaign focused specifically on flare emissions would need to be undertaken in close cooperation with the site operator in order to gather the metadata information as set out in Appendix D, and the appropriate choice of flare performance parameters would also need to be made.

Appendix A: Description of the DIAL technique

A.1 Overview of the DIAL technique

The DIAL technique is a laser-based remote monitoring technique which enables range-resolved concentration measurements to be made of a wide range of atmospheric species. This section explains the theory of the DIAL technique and describes the NPL system in detail.

A.2 Description of the theory of DIAL measurements

The atmospheric return signal, P, measured by a DIAL system from range r and at wavelength x is given by the light detection and ranging (lidar) equation, a simplified form of which is given in Equation 1.

$$P_x(r) = E_x \frac{D_x}{r^2} B_x(r) \exp\{-2\int_0^r [A_x(r') + \alpha_x C(r')]dr'\} \quad \text{(Equation 1)}$$

where D_x is a range-independent constant, C(r) is the concentration of an absorber with absorption coefficient α_x and $A_x(r)$ is the absorption coefficient due to all other atmospheric absorption, E_x is the transmitted energy and B_x is the backscatter coefficient for the atmosphere.

The equation has three basic components:

- a backscatter term based on the strength of the signal-scattering medium
- parameters associated with the DIAL system
- a term which is a measure of the amount of absorption of the signal which has occurred due to the presence of the target species

In the DIAL technique, the laser is operated alternately at two adjacent wavelengths. One of these, the ‘on-resonant wavelength’, is chosen to be at a wavelength which is absorbed by the target species. The other, the ‘off-resonant wavelength’, is chosen to be at a wavelength which is not absorbed significantly by the target species, and is not interfered with by other atmospheric constituents.

Pairs of on- and off-resonant signals are then acquired and averaged separately until the required signal to noise ratio is achieved.

The two wavelengths used are close together, hence the atmospheric terms $A_x(r)$ and $B_x(r)$ in the lidar equation can be assumed to be the same for both wavelengths. These terms are then cancelled by taking the ratio of the two returned signals.

The path-integrated concentration (CL) may be derived (Equation 2) by multiplying the logarithm of the ratio of the signals by the ratio of the absorption of the two wavelengths by the target species.

$$CL(r) = \frac{1}{2\Delta\alpha} \frac{1}{N} \sum_{i=1}^{N} \log \frac{S_{ON,i}(r)}{S_{OFF,i}(r)} \quad \text{(Equation 2)}$$

where N is the number of pulse pairs averaged, $\Delta\alpha = \alpha_{OFF} - \alpha_{ON}$ is the differential absorption coefficient and S represents the received power after energy normalisation of the on- and off-resonant signals respectively.

This path-integrated concentration represents the total concentration of the target species in the atmosphere along the measured line of sight out to the range r.

The range-resolved concentration can then be derived by differentiating the path-integrated concentration (Equation 3).

$$C(r) = \frac{dCL(r)}{dr} \quad \text{(Equation 3)}$$

where C(r) is the concentration at range r along the line of sight averaged over the spatial resolution of the DIAL along its line of sight (typically 3.75m).

A.3 Description of the facility operated by NPL

The DIAL system operated by NPL is housed in a mobile laboratory. It can operate in the infrared and ultraviolet spectral regions allowing coverage of a large number of atmospheric species. A scanner system directs the output beam and detection optics, giving almost full coverage in both the horizontal and vertical planes.

The system also contains ancillary equipment for meteorological measurements, including an integral 10m meteorological mast with wind speed, direction, temperature and humidity measurements.

The system is fully self-contained, with power provided by an on-board generator, and has full air conditioning to allow operation in a range of ambient conditions.

The following sections describe the DIAL system in more detail.

Source

The source employs a combination of Nd-YAG and dye lasers together with various non-linear optical stages to generate the tuneable infrared and ultraviolet wavelengths. The source has a pulse repletion rate of 10Hz and an output laser pulse duration of ~10ns. A small fraction of the output beam in each channel is split off by a beam splitter and measured by a pyroelectric detector (PED) to provide a value for the transmitted energy with which to normalise the measured backscatter return.

Detection

The returned atmospheric backscatter signal is collected by the scanning telescope. This directs the collected light into separate paths for the infrared and ultraviolet channels. The returned light passes through band pass filters relevant to each detection channel and is then focused onto the detection elements. Solid-state cryogenically cooled detectors are used in the infrared channel and low-noise photomultipliers in the ultraviolet.

After amplification, the signals from these detectors are digitised using a high speed digitiser. The digitiser is clocked using a clock generator triggered by the same trigger used to fire the lasers. This ensures the range gating is correctly synchronised to the laser pulse transmission. The signals from the PED monitoring the transmitted energy are also digitised and stored.

Data analysis

The data acquired are analysed, using the DIAL techniques described below, to give the range-resolved concentration along each line of sight.

The data analysis process consists of the following steps:

i) Background subtraction

Any Direct Current (DC) background value is subtracted from the signals. This measured background takes account of any DC signal offset which may be present due to electronic offsets and from incident background radiation. The background level is derived from the average value of the far field of the returned lidar signal where no significant level of backscattered light is present.

ii) Normalisation for variation in transmitted energy

The two signal returns are normalised using the monitored values of the transmitted energy for the on- and off-resonant wavelength pulses. The mean transmitted energy is used to normalise the averaged return signal. For this application, this has been shown to be equivalent to normalising individual shots against transmitted energy and then averaging the normalised values.

iii) Calculation of path-integrated concentration

The path-integrated concentration of the target species, out to the range r, is calculated using Equation 2.

The absorption coefficients used in this calculation are derived from high-resolution spectroscopy carried out using reference gas mixtures at NPL.

iv) Derivation of range-resolved concentrations.

The integrated concentration profiles are piecewise differentiated with a selectable range resolution, to give the range-resolved concentration along the line of sight, as in Equation 3.

v) Calculation of emission rates

Range-resolved concentration measurements along different lines of sight are combined to generate a concentration profile. This is carried out using algorithms developed at NPL which reduce artefacts resulting from the difference in data density at different ranges, due to the polar scanning format of the data. The emission rate is then determined using the concentration profile together with meteorological data.

The emitted rate is calculated using the following mathematical steps:

1. The product is formed of the gas concentration measured with the DIAL technique at a given point in space, and the component of the wind velocity perpendicular to the DIAL measurement plane at the same location, taking into account the wind speed profile as a function of elevation.
2. This product is computed at all points within the measured concentration profile, to form a 2D array of data.
3. This array of results is then integrated over the complete concentration profile to produce a value for the total emitted rate.

Considerable care is needed in applying the meteorological data, particularly when the concentration profile measured by the DIAL technique has large spatial variations since, for example, errors in the wind speed in regions where large concentrations are present will significantly affect the accuracy of the results.

A logarithmic wind profile is used to describe the vertical distribution of the wind. Two wind speeds at different heights, usually from the fixed mast sensors, are used to fit this wind profile. The mast-mounted wind speed and direction are measured using wind vanes and cup anemometers, which are calibrated prior to deployment.

The measured meteorological data are processed to provide vector-averaged wind data for the periods of each DIAL scan. The calculated wind field is then combined with the measured gas concentration profile using the procedure described above. For DIAL measurements the ideal wind speed is above 1m/s with a constant direction.

A summary of the ultraviolet and infrared performance capabilities of the NPL DIAL facility are given in Table A.1 and Table A.2. The values given in these tables are based on the actual levels of performance of the system obtained during field measurements, rather than calculations based on theoretical noise performances. For simplicity the numbers are presented as a single concentration sensitivity and maximum range values. However, the detailed performance behaviour of a DIAL system is much more complex and there are a number of key points that should be noted:

- The DIAL measurement is of concentration per unit length rather than just concentration. So the sensitivity applies for a specified pathlength – 50m in this case. Measurements over a shorter path would have a lower sensitivity, and would be more sensitive over a longer path length.
- Since the backscattered lidar signal varies with range, generally following an inverse squared rule (range^{-2}). The sensitivity is also a function of range and the values given in the tables apply at a range of 200m, and these will get poorer at longer ranges.
- The maximum range of the system is generally determined by the energy of the emitted pulse and the sensitivity of the detection system, except in the case of NO where range is limited by oxygen

absorption at the short ultraviolet wavelengths required for this species.

- In all cases the performance parameters are based on those obtained under typical meteorological conditions. For the ultraviolet measurements the meteorological conditions do not have a great effect on the measurements as the backscattered signal level is predominantly determined by molecular (Rayleigh) scattering, and this does not vary greatly. However, in the infrared the dominant scattering mechanism is from particulates (Mie scattering). So the signal level, and therefore the sensitivity, is dependent on the particular loading of the atmosphere, and this can vary dramatically over relatively short timescales.
- The optical configuration of the DIAL system means there is a minimum range between 40 and 100m before measurements can be made.

The NPL DIAL has a theoretical range resolution of 3.75m along the measurement beam, and a vertical and horizontal scan resolution which can be less than 1m at 100m. However, the actual range resolution determined by the signal averaging used will depend on atmospheric conditions and the concentration of the measured pollutant, and may be of the order of 20–30m.

The DIAL is able to make measurements of a wide range of compounds, including benzene and other aromatics, individual hydrocarbons and total general hydrocarbons, see Table A.1 and Table A.2. It consists of the combination of DIAL measurements with air sampling and gas chromatography analysis. The system is able to monitor individual aromatic compounds and general hydrocarbon species, which have absorption features in the infrared and ultraviolet spectral regions covered by the DIAL system. NPL has the spectral expertise, access to spectral libraries and an in-house spectroscopic capability to assess the DIAL sensitivity for additional individual species.

The general hydrocarbon measurement listed in Table A.2 uses an infrared absorption that is similar for all hydrocarbons with three or more carbon atoms, linked to the stretch frequency of the carbon–hydrogen bond. The line strengths for these species are proportional to the number of carbon–hydrogen bonds present and this enables a total mass emission to be determined. As such it provides a measure of the mixture of general hydrocarbons that are present at an oil or petrochemical site. The pair of infrared wavelengths used for this DIAL measurement are selected so that the absorption per unit mass is relatively invariant with respect to the mix of different hydrocarbons that are present. However, the sensitivity of this measurement in terms of parts per billion (ppb) of hydrocarbon depends on the mixture of species present, and the value given in the table reflects the typical mix of hydrocarbons found at oil refineries.

Table A.1 Ultraviolet capability of NPL DIAL facility

Species	**Sensitivity(1)**	**Maximum range(2)**
Nitric oxide	25ppb	500m
Sulphur dioxide	10ppb	3km

Ozone	5ppb	2km
Benzene	10ppb	800m
Toluene	10ppb	800m

Table A.2 Infrared capability of NPL DIAL facility

Species	Sensitivity(1)	Maximum range(2)
Methane	50ppb	1km
Ethane	20ppb	800m
Ethene	10ppb	800m
Ethyne (acetylene)	40ppb	800m
General hydrocarbons	40ppb	800m
Hydrogen chloride	20ppb	1km
Methanol	200ppb	500m
Nitrous oxide	100ppb	800m

(1) The concentration sensitivities apply for measurements of a 50m-wide plume at a range of 200m, under typical meteorological conditions.

(2) The range value represents the typical working maximum range for the NPL DIAL system.

A.4 Relationship between emission rate and concentrations

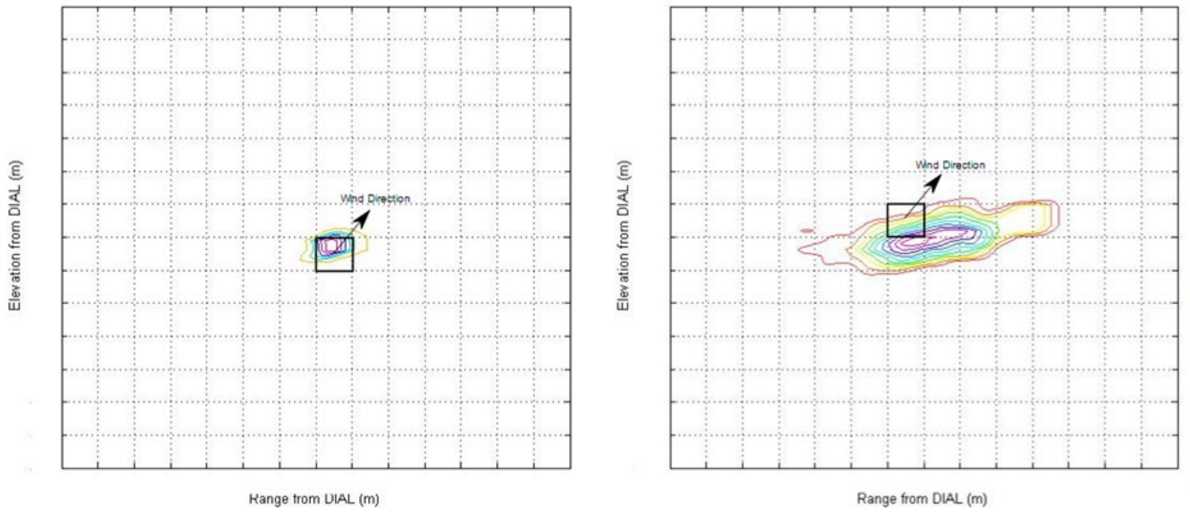


Figure A.1 Illustration of the emission rate calculation approach

Where concentrations are provided as an indication of the levels observed in a measurement scan, the reported concentration in the measurement plane is the maximum concentration seen in a cell in the measurement plane. The resolution of the planes used is equal to the DIAL system resolution and is 3.75m, so each cell is 3.75m square. Figure A.1 shows how plume size affects the emission rate that is calculated. The concentration assigned to each cell is multiplied by the perpendicular wind field determined for that cell, and then the individual cell emission rates are summed to give the total emission rate through the plane. Figure A.1 shows two example plumes (the cell grids are for indication and are not to scale), one which has a small plume, and therefore a small integrated emission rate, and the other which has a larger plume, and therefore represents a larger emissions rate, although the peak concentration in both is similar, and indeed may even be higher in the small plume than the large plume.

Figure A.2 shows a schematic representation of two measurement plane configurations observing the same plume. One has a nearly perpendicular orientation to the plume, and the wind direction is therefore also perpendicular to the measurement plane. The other is at an angle through the plume, and therefore the wind is not perpendicular to the plane of the measurements. If only the concentration profile were observed the right hand measurement configuration would show a larger plume (as it cuts obliquely through the plume). However, when the wind direction is taken into account, the normal component of the wind vector is used, and this therefore reduces the emission rate determined from this scan, resulting in the same emission rate being determined for both measurement orientations.

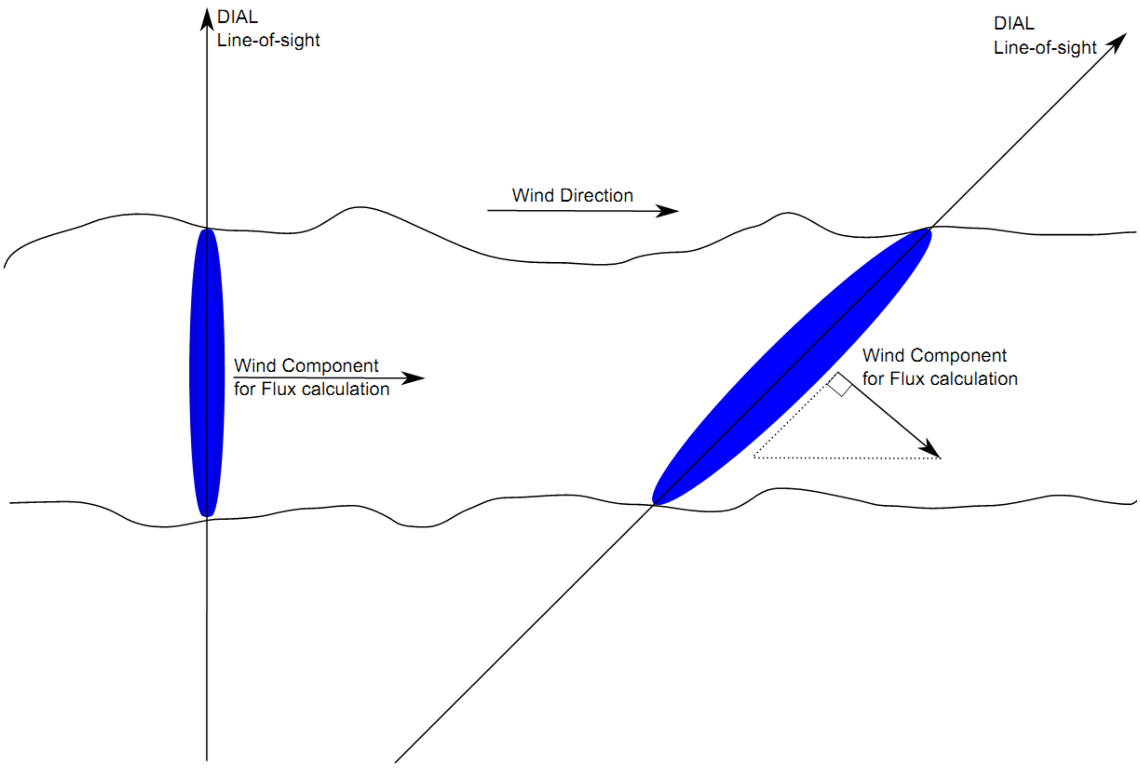


Figure A.2 Schematic showing relationship between emission rate and wind direction

A.5 Calibration and validation

The NPL DIAL system has several in-built calibration techniques and procedures. The most important are the in-line gas calibration cells. The gas cells are filled with known concentrations of the target species, obtained from NPL standard gas mixtures, which are directly traceable to national standards. A fraction of the transmitted beam is split off and directed through a gas cell to a PED, in the same way as with the beam for the transmitted energy monitors. This provides a direct measurement of the differential absorption at the operating wavelengths by the target gas. The transmission through the gas cells is continuously monitored during the operation of the system to detect any possible drift in the laser wavelengths. The calibration cells are also periodically placed in the output beam to show the concentration response of the whole system is as expected.

A number of field comparisons have been undertaken to demonstrate the accuracy of the measurements obtained with DIAL. Examples of these carried out by NPL are summarised below:

- Intercomparisons have been carried out on chemical and petrochemical plants where a large number of different volatile organic species are present. In these intercomparisons, the DIAL beam was directed along the same line of sight as a line of point samplers. The point samplers were operated either by drawing air into internally passivated, evacuated gas cylinders or by pumping air at a known rate, for a specified time, through a series of absorption tubes which efficiently absorb all hydrocarbon species in the range C_2–C_8. The results obtained for the total concentrations of general hydrocarbons measured by the point samplers and those measured by the infrared DIAL technique agreed within ± 15%. The concentrations of atmospheric toluene measured by the ultraviolet DIAL system agreed with those obtained by the point samplers to within ± 20%.
- The ultraviolet DIAL system was used to monitor the emission rates and concentrations of sulphur dioxide produced from combustion and emitted by industrial stacks. These stacks were instrumented with calibrated in-stack sampling instruments. The results of the two sets of measurements agreed to within ± 12%.
- DIAL measurements of controlled releases of methane from a stack agreed with the known emission rates to within ± 15%.

Appendix B: Summary of previous campaigns

The following table lists the DIAL campaigns that were reviewed as part of the study. This identifies the type of site and the species that have been measured. It also shows the different areas of the site that have been covered during the measurements – with the flare measurements highlighted. Commercially sensitive information (such as the site name and the customer for the work) has been removed.

Project ID	Type	Sub-type	Country	Year	Species											Areas										
					General VOC	Methane	Ethane	Ethene	Methanol	Hydrogen chloride	Benzene	Nitric oxide	Nitrogen dioxide	Sulphur dioxide	Ozone	Petro-chem						Landfill				
																Tanks	Process	Flares	Loading	Wastewater treatment	Coker	Cells	Active area / tipping	Composting/ ponds	Flares	Gas engines
1	Other	Coke works	US	2010							x						x				x					
2	Oil/Gas	Terminal	US	2007	x											x										
3	Oil/Gas	Refinery	US	2007	x						x			x		x		x		x	x					
4	Oil/Gas	Refinery	US	2010							x					x				x						
5	Oil/Gas	Refinery	US	2010	x						x					x	x	x	x	x	x					
6	Oil/Gas	Processing pl	Norway	2012	x	x					x	x	x				x	x		x						
7	Oil/Gas	Processing pl	Norway	2013	x	x	x					x	x				x	x								
8	Oil/Gas	Terminal	Norway	2012	x	x					x	x	x			x		x	x	x						
9	Oil/Gas	Gas	Norway	2013	x	x	x				x	x	x	x		x	x	x	x							
10	Oil/Gas	Gas	Norway	2013	x	x	x				x					x		x	x	x						
11	Oil/Gas	Refinery	US	2013	x	x	x				x					x					x					
12	Oil/Gas	Refinery	US	2012	x	x					x					x					x					
13	Waste	Landfill	US	2008		x																x	x	x	x	
14	Other	Coke works	Canada	2008	x						x							x	x		x					
15	Waste	Landfill	France	2007		x																x	x	x		x
16	Waste	Landfill	France	2009		x																x				
17	Waste	Landfill	France	2009		x																x	x			x
18	Waste	Landfill	France	2009		x																x	x	x		x
19	Waste	Landfill	France	2009		x																x	x	x		
20	Waste	Landfill	UK	2009		x																x				
21	Waste	Landfill	France	2011		x																x				
22	Waste	Landfill	France	2011		x																x	x	x		x
23	Waste	Landfill	France	2011		x																x	x			
24	Waste	Landfill	France	2013		x																x				
25	Oil/Gas	Terminal	UK	1998	x											x	x	x								
26	Oil/Gas	Gas	UK	1994		x										x										
27	Oil/Gas	Refinery	Sweden	1988	x											x	x			x						
28	Oil/Gas	Terminal	UK	2001		x					x					x	x	x								
29	Oil/Gas	Terminal	UK	1993		x										x	x									
30	Oil/Gas	Other	UK	1995	x						x								x							
31	Oil/Gas	Refinery	Greece	1992	x											x	x		x	x						
32	Oil/Gas	Terminal	Holland	1997	x											x										
33	Oil/Gas	Gas	UK	1994		x										x										
34	Oil/Gas	Terminal	UK	2011		x										x										
35	Other	Cement	UK	1995										x												
36	Other	Cement	UK	1996										x												
37	Other	Chemical	UK	1997	x	x			x	x							x									
38	Oil/Gas	Refinery	UK	1992	x											x		x								
39	Other	Chemical	UK	1994	x	x		x								x	x	x	x							
40	Other	Urban	UK	1983											x											
41	Other	Gas	UK	1992		x																				
42	Oil/Gas	Other	UK	2014		x										x		x								
43	Other	Chemical	Ireland	2010						x							x									
44	Waste	Landfill	Ireland	2010		x																x	x			
45	Oil/Gas	Terminal	UK	2011	x	x										x										
46	Oil/Gas	Terminal	Holland	2011							x					x	x		x	x						
47	Oil/Gas	Terminal	UK	2012		x										x										
48	Waste	Landfill	UK	2013		x																x	x			x
49	Waste	Landfill	France	2013		x																x	x			
50	Waste	Landfill	France	2013		x																x	x			
51	Waste	Water	France	2014		x														x						
52	Oil/Gas	Gas	UK	2014		x																				
53	Oil/Gas	Gas	UK	2014		x																				
54	Waste	Landfill	France	2014		x																x	x			
55	Waste	Landfill	France	2014		x																x	x			
56	Oil/Gas	Other	Denmark	2015	x	x										x										
57	Oil/Gas	Refinery	Norway	2015	x		x				x					x			x	x						
58	Oil/Gas	Refinery	Holland	2011	x															x						
59	Oil/Gas	Refinery	Spain	2011	x															x						
60	Other	Other	UK	2012	x																					
61	Waste	Landfill	UK	2011		x																x	x			x
62	Waste	Landfill	UK	2011		x																x	x			
63	Waste	Landfill	UK	2011		x																x	x			x
64	Waste	Landfill	UK	2011		x																x				
65	Waste	Landfill	UK	2011		x																x				
66	Waste	Landfill	UK	2011		x																x				
67	Waste	Landfill	UK	2011		x																x				
68	Waste	Landfill	UK	2011		x																x				
69	Waste	Landfill	UK	2011		x																x				

Appendix C: Summary of previous flare measurements

The following table gives more details on the DIAL flare measurements, identifying the measurements that have been made on the individually identified flares at each site. The four campaigns that were identified for the case studies have been highlighted.

Project ID	Type	Sub-type	Country	Flare Name	Number of measurements/ on how many days	Species: General VOCs	Methane	Ethane	Benzene	Nitric oxide	Nitrogen dioxide	Sulphur dioxide	Flare efficiency?	Flaring	Pilot only
3	Oil/Gas	Refinery	US	Flare 6	15 downwind (10 day/5 night), 1 upwind (night) over 1 day and 1 night	x							Y		
3	Oil/Gas	Refinery	US	Elevated ULC Flare	34 downwind (13/14/7), 5 upwind (3/2/0), 7 background (2/2/3) over 3 days	x							Y	Flaring for all measurements	
3	Oil/Gas	Refinery	US	Temporary flare stack	37 downwind (13/14/10), 5 upwind (3/2/0), 7 background (2/2/3) over 3 days	x							Y	Flaring for all measurements	
5	Oil/Gas	Refinery	US	Coker flare	11 downwind (day)	x									
5	Oil/Gas	Refinery	US	EP Flare	34 downwind (13/21), 8 upwind (8/0) over 2 days	x									
5	Oil/Gas	Refinery	US	HIPA Flare A1313	2 downwind, 5 upwind over 1 day	x									
5	Oil/Gas	Refinery	US	Olefins OP-2 Flare	8 downwind over 1 day	x									
5	Oil/Gas	Refinery	US	Olefins Ground Flare	2 downwind over 1 day	x									
5	Oil/Gas	Refinery	US	A&S Flare A1301	3 downwind, 2 upwind over 1 day	x									
5	Oil/Gas	Refinery	US	FLN Flare	4 downwind over 1 day				x						
6	Oil/Gas	Processing plant	Norway	Low Pressure Flare	19 downwind (3/4/12) over 3 days	x	x			x	x				
6	Oil/Gas	Processing plant	Norway	Maintenance Flare	10 downwind (4/6), 3 background (3/0) over 2 days		x			x	x				
7	Oil/Gas	Processing plant	Norway	Low pressure flare	16 downwind (4/3/3/6), 6 upwind (3/0/3/0) over 4 days	x	x	x		x	x		Y		
7	Oil/Gas	Processing plant	Norway	High pressure flare	36 downwind (10/7/7/7/5) over 5 days	x	x	x		x	x		Y	23 with flare on (4/5/6/4/4) including 2 with smaller flare (1/0/1/0/0)	12 with flare off (5/2/1/3/1)
7	Oil/Gas	Processing plant	Norway	Maintenance Flare	23 downwind (5/4/5/9), 3 background (0/3/0) over 4 days	x	x	x		x	x		Y	19 (4/3/4/8) with flare on	4 with flare off (1/1/1/1)
8	Oil/Gas	Terminal	Norway	Flare	18 downwind (3/3/3/9), 3 upwind (2/1/0/0) over 4 days	x	x		x	x	x				
9	Oil/Gas	Gas	Norway	HP Flare	21 downwind (4/4/4/6/3), 13 upwind (3/3/1/3/3) over 5 days	x	x	x			x	x			
9	Oil/Gas	Gas	Norway	LP Flare	33 downwind (5/7/3/9/6/3), 18 upwind (3/3/3/3/3/3)over 6 days	x	x	x		x	x	x			
10	Oil/Gas	Gas	Norway	Flare	12 downwind (3/3/3/3) over 4 days	x	x	x	x						
13	Waste	Landfill	US	Landfill gas flare	3 downwind over 1 day		x								
14	Other	Coke works	Canada	Coke oven gas (COG) flare	6 downwind over 1 day	x									
25	Oil/Gas	crude oil gathering station	UK	Low temp flare	5 scans over 1 day	x							Y	all 5 scans while flaring	
25	Oil/Gas	crude oil gathering station	UK	Low pressure flare	1 scans (with HP flare)	x							Y		1 with flare off
25	Oil/Gas	crude oil gathering station	UK	High pressure flare	2 scans over two days (1 with LP flare)	x							Y		both with flare off
28	Oil/Gas	Terminal	UK	Ground flare	3 benzene scans over two days (2/1); 1 methane scan		x		x						
38	Oil/Gas	Refinery	UK	Flare	measured over 7 days	x							Y	one controlled flaring	all except one period
39	Other	Chemical	UK	Flare	1/2 day of measurement	x	x						Y	one 15 min controlled flaring	remaining data
42	Oil/Gas	Onshore oil	UK	Flare	5 scans on 1 day		x						Y	all 5 scans while flaring	
44	Waste	Landfill	Ireland	Flare	3 scans on 1 day		x								

Appendix D: Metadata template for future flare measurement campaigns

Certain information is recorded for all DIAL measurements including:

- species being measured
- time and date of measurement scan
- physical location of DIAL and source
- line of sight of DIAL scan
- wind speed and direction (including vertical wind profile)
- 2D concentration distribution of target species
- emission rate of target species

In addition to this standard information, the following metadata would enable more detailed assessment of flare performance and burning efficiency:

Category	Information	Notes/examples
General site information	Type of site	Info on site operations
	Overall throughput	
	Overall emissions	Include source of information
	Monitoring/reporting requirements	Site-specific requirements. Is site within an Air Quality Management Area?
	Site surroundings	General site topography/geography, and what is in surrounding area (other industry, local population, forest, coast, etc.)
Purpose of measurement	What is the goal of the flare measurements?	E.g. contribution to overall site emissions (as found), flare efficiency (as found), flare efficiency under different conditions (controlled flaring), etc.
Flare design	Flare ID	Unique identifier for flare
	Type of flare	E.g. boxed, shrouded, open, candle, etc.
	Manufacturer	
	Dimensions	Flare stack height and width
	Age/maintenance info	
	Purpose	Continuous process, emergency only, etc.
	Source stream	Where flare gas comes from
	Designed throughput	Maximum flow and operating range

	Location and surroundings	Other structures nearby, including other potential sources of emissions
	Design details	E.g. pilot light, auto-ignition, steam-assist, cold venting
	Monitoring information	Site information on metering, composition, etc. and whether this is continuous or occasional
Flare status (at time of measurement)	Visual status of flare	E.g. visible flare, smoky flare. Either as description or video
	Flare gas flow	Metered flow at time of (each) measurement
	Gas composition	Speciated composition including hydrogen sulphide (H_2S) content. Record whether on-line, sampled or calculated
	Flare state	Active flaring, pilot light, steam-assisted, etc.
	Source of gas	Record where flare gas has come from, whether support fuel gas has been added, and whether gas is from usual operational source or specifically for measurement
	Other flare gas parameters	Pressure, temperature, density, etc.
Meteorological information	Temperature Pressure Humidity Precipitation Isolation Atmospheric stability	In addition to data itself, need to record source, quality and frequency of data

References

ROBINSON, R., GARDINER, T., INNOCENTI, F., WOODS, P. and COLEMAN, M. (2011) Infrared differential absorption lidar (DIAL) measurements of hydrocarbon emissions. *Journal of Environmental Monitoring*, 13, 2213.

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List of abbreviations

2D or 3D – two-dimensional or three-dimensional

BAT – best available techniques

DC – direct current

DIAL – differential absorption lidar

kg/hr – kilograms per hour

lidar – light detection and ranging

Nd-YAG – neodymium-doped yttrium aluminium garnet

NO – nitric oxide

NO_2 – nitrogen dioxide

NO_x – nitrogen oxides ($NO+NO_2$)

NPL – National Physical Laboratory

OOG – onshore oil and gas

PED – pyroelectric detector

Sm^3/hr – standard cubic metres per hour

ULC – ultra-cracker

Glossary

Combustion efficiency – Defined as combustion efficiency (%) = [1 – (carbon emitted/carbon in flare gas)] × 100, where carbon refers to the number of carbon atoms in hydrocarbon form (see section 3.3 for more details).

DIAL detection limit – The smallest amount of a species that the DIAL system can detect (see section 3 for examples and discussion).

Differential absorption lidar – A remote optical sensing technique that enables direct mapping and quantification of emissions of a range of gases.

Elevated flare – A flare with the burner tip raised well (typically >20m) above ground level.

Emission factor – The ratio between the measured mass of gas emitted to mass of gas going to the flare.

Enclosed flare – The flare tip is surrounded by some form of shrouding so the flame is not visible externally.

Flare emissions – Gases released to the air from a flare after combustion has taken place.

Flare off – When the flare is not actively burning the source gas. It should be noted that most flares in this condition are not completely off and will maintain a pilot light fed from a separate support fuel source.

Flare on – When the flare is actively burning gas from a source on the site.

Flux – The mass flow rate (usually in kg/hr) of the target species through the plane measured by the DIAL scan.

General hydrocarbons – In this study this is defined as the total amount of gaseous species made up of molecules containing carbon and hydrogen with at least three carbon atoms.

Ground flare – A flare with the burner tip close to the ground (typically <5m).

Measured as found – In most cases the flare emissions were measured with the flare in whatever condition it was in at the time (i.e. 'as found'). In some other cases the flow of gas to flares was deliberately controlled by plant operators to create a 'flare on' situation.

Measurement campaign – A series of measurements made by DIAL at the same site. This can involve measurements of various emission sources and species around the site.

Methane destruction efficiency – The ratio between the amount of burned methane and amount of methane in the gas to the flare.

NO_x as NO_2 – The mass of NO_x assuming that all of the NO has converted to NO_2.

Off-resonant wavelength – One of the transmitted laser wavelengths, close to the on-resonant wavelength, which is not absorbed by the target species and is used as a reference.

On-resonant wavelength – One of the transmitted laser wavelengths which is absorbed by the target species.

Open flare – The flare tip is exposed and the flame externally visible.

Process flare – A flare connected to the process area on a site.

Range-resolved concentration – The concentration (usually in parts per million by volume) as a function of range from the DIAL facility along a single measurement line.

Steam-assisted flare – A flare design that deliberately introduces steam to reduce the production of smoke in the flame.

Wind field – The distribution of wind speed (as a function of height) and direction through the plane measured by the DIAL scan.

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