Measurement and Analysis of Benzene and VOC Emissions in the Houston Ship Channel Area and Selected Surrounding Major Stationary Sources Using DIAL (Differential Absorption Light Detection and Ranging) Technology to Support Ambient HAP Concentrations Reductions in the Community (DIAL Project)

Final Report

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Table of Contents

Executive Summary

The Houston Department of Health and Human Services through its Bureau of Pollution Control and Prevention (Houston) conducted a comprehensive survey project regarding emissions from a combined petroleum refinery and chemical plant complex in the Houston Ship Channel area. The complex is a source of emissions of benzene and other volatile organic compounds (VOCs). The project used Differential Absorption Light Detection and Ranging (DIAL), a remote sensing methodology for measuring air pollutants. The survey indicates that measured emissions from process areas and tanks exceed the emission factor estimates for benzene and VOCs. Of the 17 areas where DIAL emissions measurements were conducted, six were compared to VOC emission factor estimates and four were compared to benzene emission factor estimates. In only one process area did emission factors produce a VOC emissions estimate comparable to the DIAL measured results, which was the Catalytic Reformer-3 Unit. Emission factors used to estimate emissions from the Southwest Tanks VOCs produced the most potential underestimated emissions compared to the DIAL measured emissions, off by a factor of 132. The comparison of benzene emission factor estimates to the DIAL measured emissions produced potential underestimated emissions ranging from a factor of 5 at the Aromatics Concentration Unit/Benzene Extraction Unit area, to a factor of 93 for the tanks located south of the ACU/BEU area.

DIAL was shown to be an effective technology for the measurement of mass flux from fugitive, non-point emission sources. DIAL is limited, however, in that it can only measure the mass flux of a single compound or a class of compounds that absorb energy at a defined wavelength during a scan. DIAL cannot directly provide information on the chemical composition of a plume of pollutants, and therefore, additional analysis is necessary to fully characterize the plume's actual composition.

Additional challenges are revealed in this survey. The time period of compositional measurements may prevent characterization of temporal variations of the plume. The compositional measurement techniques are typically limited to fixed locations, usually close to ground level. Moving these analytical platforms above ground level for elevated plumes such as those anticipated for delayed coker emissions, combined with routine changes in wind direction, represents a significant challenge.

The survey also uses two other measurement techniques to explore the efficacy of using them to validate or augment DIAL measurements. The two techniques, open path Fourier transform infrared (FTIR) and a fixed point monitor on a mobile ambient air monitoring laboratory (MAAML), were routinely and simultaneously deployed with DIAL. The pairing of DIAL with these techniques takes advantage of their complementary strengths to allow for improved plume characterization with respect to mass flux and chemical composition. In this survey project, measurements from the FTIR compared better with DIAL emissions than measurements from MAAML. This project identified key factors which should be controlled, if possible, in future investigations to improve the coordinated use of these technologies as well as integration of the collected data. As a result, verification of the data using these techniques in this study is inconclusive in many cases. Most of these factors were anticipated a priori, but remained obstacles. The significance of other factors was not apparent in advance. The main factors to control for improved comparability and usability include: degree of equipment overlap with the DIAL plume, equal MAAML sample collection duration, FTIR detection limits, availability of

scan images, availability of spatially segmented DIAL concentration measurement data, availability of spatially segmented DIAL emissions measurement data, refinement of temporal molecular weight, and ability to sample at plume height. A full discussion is provided in the report.

For surveys focused on a single aromatic compound such as benzene, measurements from Ultraviolet Differential Absorption Spectroscopy (UV DOAS) can be used in a role similar to FTIR. UV DOAS measurements, also deployed during the survey for a limited time, compare well to DIAL measurements.

1. Introduction

The Houston Department of Health and Human Services through its Bureau of Pollution Control and Prevention (Houston) conducted a comprehensive survey project of emissions from a combined petroleum refinery and chemical plant complex in the Houston Ship Channel area. The complex is a source of emissions of benzene and other volatile organic compounds. The project used Differential Absorption Light Detection and Ranging (DIAL), a remote sensing methodology for measuring air pollutants. Feasible emissions reductions strategies were identified with the goal of improving ambient air quality in the community.

The objectives of the project were to:

1) Develop, improve and demonstrate DIAL System emissions measurement methods for estimating the mass flux of benzene and volatile organic compounds (VOC) from individual emissions sources at a Houston area refinery facility with significant benzene emissions.

2) Evaluate and verify the DIAL system benzene and VOC measurements using the City of Houston's Mobile Ambient Air Monitoring Laboratory (MAAML), canister sampling, and other monitoring/open path measurement techniques.

3) Identify unanticipated/underestimated sources of benzene and VOC.

4) Evaluate emission estimation techniques currently utilized to determine VOC and benzene emission rates by comparing DIAL measurements with estimated emissions.

5) Assess the feasibility of emissions reduction strategies based on the measured impact from the most significant individual benzene emissions sources identified at the selected Houston area sites.

6) Assess the cost effectiveness of the DIAL system based on project costs, estimated emissions reduction strategies costs and the estimated cost savings to be realized through preventing the loss of valuable products, intermediates and/or raw materials via the proposed emissions reduction strategies.

2. Methodology

This section details the methods used to measure the emissions during this study. General screening measurements with DIAL, MAAML, and Open-Path Fourier Transform Infrared (FTIR) were conducted initially to ascertain those areas having the most significant emissions. Following screening, the most important areas were re-measured on more than one day, over 6 to 8 hour periods.

2.1 Differential Absorption Light Detection and Ranging (DIAL)

DIAL was located so that measurements occurred along a vertical plane, perpendicular to the predominant wind direction and downwind from any sources of interest. Wind direction and speed attributes for wind field characterization were measured with a mast on the DIAL unit at 12 m above ground level, a portable mast at 2 m above ground level placed in a location downwind from the expected emissions sources, and a mast located outside the site fence line, away from obstructions, at 11 m and 3 m above ground level. A mast on the MAAML at 10 m above ground level was also utilized to collect wind data. Appendix A: NPL DIAL Report, describes how the wind fields were interpreted during the study and how the wind measurements were utilized.

DIAL provided plume locations and estimated concentrations of either alkane VOC or benzene. Where DIAL measured alkane VOC, actually the carbon-hydrogen (C-H) bond associated with alkane hydrocarbons were measured, for hydrocarbon molecules containing three or more carbon atoms. The alkane C-H bond measurements were then used to estimate a mass concentration based on an assumed molecular mass and assumed optical absorption coefficient of the measured species. The molecular mass and optical absorption coefficient for this project were assumed to be that of gasoline, 73.3 and 1.47 (ppm.km)-1 respectively. Therefore, where VOC emissions rates are reported, the mass associated with non-aliphatic hydrocarbon species (such as aromatic and alkene VOC species) are either not included or biased low. Each day of DIAL VOC measurements also included pumped Perkin Elmer Automatic Thermal Desorption (ATD) tubes samples, collected where DIAL and photoionization detector (PID) monitoring indicated the plume was located. The ATD samples were analyzed by gas chromatography (GC) and mass spectrometric (MS) or flame ionization detector (FID) methods. Benzene and VOC emissions rates were estimated by integrating DIAL measured concentrations along the vertical plane with the wind data. DIAL measurements were conducted in accordance with the QAPP as delineated in appendix H.

2.2 City of Houston’s Mobile Ambient Air Monitoring Laboratory (MAAML)

MAAML provided metrological and GC/MS/FID (EPA Method TO-14A/15) measurements of 51 hydrocarbon compounds including alkane VOC and benzene at point locations, 4.27 m above ground level. The MAAML location was at times within 50 meters of the DIAL unit, referred to as the “DIAL dead zone.” The original plan was to place the MAAML in the location where the plume was detected/expected, but site constraints prevented this approach. However, the data gathered by placing of the MAAML outside of the DIAL measurement range did provide some useful information in certain instances. In those instances, MAAML provided data regarding whether or not the DIAL measured plume extended near ground level into the dead zone. MAAML also provided useful data regarding relative concentration levels of hydrocarbons throughout the site, informing where and when those levels were abnormally elevated. MAAML measurements conformed to the QAPP, appendix I.

2.3 Open-Path Fourier Transform Infrared (FTIR)

The FTIR was typically placed outside of the “DIAL dead zone,” at a height of around 2 m above ground level, directly downwind from the selected emissions source (perpendicular to the predominant wind direction). FTIR provided measurements of around 20 compounds including alkane VOC and benzene along a linear path of around 80 m to 150 m. FTIR therefore provided path-length concentrations of compounds in the DIAL measured plume (when the plume was located at or near ground level along the FTIR path). FTIR data can be used to estimate plume composition based on the relative concentrations of the compounds measured by DIAL, as compared to concentration measurements of other compounds <u>not</u> measured by DIAL (when the DIAL measured plume was located at or near ground level and along the FTIR path). The FTIR data could also be used to evaluate whether the molecular weight assumptions utilized for DIAL emissions rates calculations were appropriate and to verify alkane VOC or benzene emissions measured by DIAL when plumes were at or near ground level along the FTIR path.

The DIAL measurements were validated for alkane VOC using an inline gas calibration cell audit, where the calibration cell was filled with a specific concentration of propane, unknown to the DIAL team. The DIAL team then estimated the propane concentration using the DIAL equipment.

Emissions measurements that appeared anomalous were differentiated from routine emissions via interpretation of the DIAL emission results in comparison to process and management details supplied by site representatives. Important process and management details provided by the site representatives that correlated with elevated emissions rates included tank filling, equipment malfunctions and maintenance activities. Both the routine and anomalous emissions provide important information.

2.4 Ultraviolet Differential Absorption Spectroscopy (UV DOAS)

DIAL measurements of benzene were validated using simultaneous UV DOAS measurements. The DIAL – UV DOAS comparison, described in section 5 of the NPL report, was carried out downwind of Tanks T-OL913 and T-OL914, and also the North Wastewater Area. A 51-minute integrated Summa sample (No. 1350) was collected in the plume of T-OL913 and T-OL920 during the comparison and the results indicated that the plume composition was primarily alkanes, alkenes, and toluene. Sorbent tube samples collected by NPL at the wastewater area indicated that the majority of the compounds were alkanes. The DIAL results compared well with the UV DOAS, and spectral or other interferences were not evident. The minor differences in the results could be due to the fact that the DIAL and UV DOAS did not measure exactly the same parcel of air, the DIAL having a vertical scan resolution of 1 meter, and the UV DOAS optical path having a vertical dimension of 0.11 meter. Also, the DIAL scan height was approximately 3 to 4 meters for most of the UV DOAS path, whereas the UV DOAS beam was at a height of 2 m.

3. Results

This section presents an overview of the study results by individual process area: Southwest Tanks, West Tanks, Delayed Coker, Gas Oil Hydrotreater (GOHT), and West Dock Area, Olefins Process Area, Olefins Tanks and Flares Area, Catalytic Reformer-3 (CR-3), East Property Flare, East Tanks, North Wastewater Area, East Wastewater and Flares Area, Tank Farm B, Tanks T-OL913 and T-OL920, North Property Flare, Aromatics Concentration Unit (ACU) and Benzene Extraction Unit (BEU), Tanks South of ACU and BEU, Tanks South of North Wastewater, and Refinery West Tanks. A discussion of the results is presented in the next section.

The overview of the results consists of the summarized DIAL results, as well as the summarized results of the two other measurement techniques routinely employed simultaneously: MAAML and FTIR. Data from an additional two other measurement techniques used less consistently, UV DOAS and SUMMA canisters, are presented in the appendices D and F respectively. The UV DOAS measurements show agreement with DIAL emissions. Also, refer to the appendices for the individual measurements for any specific method.

FTIR data was collected simultaneously with DIAL for three reasons: 1) to provide a percent composition weighted molecular weight for use in comparing emission rate estimates; 2) to validate extreme events detected by DIAL; and 3) to provide chemically speciated plume descriptions.

MAMML data was collected simultaneously with DIAL to validate extreme events detected by DIAL and to provide chemically speciated plume descriptions.

Although the two methods have overlapping objectives, the MAAML and the FTIR have different strengths. The MAAML provides a larger list of speciation constituents at lower detection limits than the FTIR. The major drawbacks of using the MAAML data to compare with DIAL are the differences in measurement method, MAAML is a point monitor, and the difference in sample duration, MAAML reports results in hourly intervals. While the FTIR has a smaller list of speciation constituents and a higher detection limit, it can be more closely aligned with the DIAL path since it measures along a linear path as DIAL does. In addition, the FTIR results are reported in minutes. The collection of both types of data provides insight into their relative merit in assisting and complementing DIAL in characterizing the emissions.

The overview of the results also contains information about where the DIAL plume was located in relation to the MAAML and the FTIR during the scan image of the area that was provided. Based on scans where the image was available, in the majority of instances the plume was low enough that MAAML and the FTIR were sampling air at the same level as DIAL. There are many scans, however, where an image was not provided. Therefore, the MAAML and the FTIR speciation data was not applied: 1) to DIAL scans without an image when DIAL emissions were not correlated with the MAAML and the FTIR data or 2) to DIAL emissions with an image when the emissions were not correlated with the MAAML or the FTIR data.

Within the individual process area section is a table listing a summary of the results followed by a figure of the area where the measurements were taken.

The results table lists the following information:

1) Date of measurements.
2) DIAL location and line of sight (LOS).
3) Time of DIAL measurements.
4) Type of DIAL measurements taken on that day. DIAL measures either benzene or total alkanes detected, which is expressed here more generally as total VOC.
5) Average DIAL measured emission rate for that day (lbs/hr).
6) Time of MAAML measurements.
7) Location of the MAAML vehicle with respect to the plume. The location was based on individual DIAL scan plume images, purported to be representative of the scans along a particular DIAL line of sight (LOS) on that day. This assessment indicated whether the concentrations measured by the MAAML were expected to be related to DIAL data. Unfortunately due to constraints, the MAAML was usually located out of the plume between the plume and the DIAL trailer (out), but in a few DIAL scan plume images it was located in the plume (in). There were many scans where an image was not available. The location noted in the table is based on the times when scan images were available. The plume may have shifted during other scans where images are not available.
8) MAAML concentration correlation with DIAL plume emissions. This column contains the degree of linear correlation of benzene when DIAL was measuring benzene or of the total alkanes when DIAL was measuring total VOCs between the MAAML and DIAL measurements. The total of the alkanes was estimated from the MAAML sum total concentration of: propane, n-pentane and hexane. The MAAML concentration data was reported hourly. In order to relate the MAAML hourly concentrations to the DIAL emission rates, DIAL emissions were averaged over the hour. The statistical correlation was calculated when there were a minimum of four comparable hours. Depending upon the location of the MAAML with respect to the plume, we expected that it would be more likely that MAAML data would be correlated with the DIAL data when the MAAML was in the plume ("in" as described above) than if it was between the trailer and the plume ("out" as described above). In both scenarios, "in" or "out", because we are relating an emission rate measured on a plane to a concentration measured using a fixed point, correlations would only be found if the wind speed remained relatively constant with low variability over the sampling period. While we did not expect to find a correlation between DIAL emissions and MAAML concentration data when the scan showed that the MAAML was "out" of the plume, we assessed the correlation hypothesizing that if we did find correlations, this suggested that the plume shifted from "out" to "in" over time in scans where images were not available or DIAL did not pick up the entire plume. Some datasets included one high value which could be an influential outlier. These outliers are real extreme points because they were picked up by both techniques, however, the correlation coefficient has limited use when it is heavily influenced by one point. When the slope of a linear regression with and without the suspected influential outlier point changed by more than 10%, the point was considered influential. The correlations with and without the point are presented. The estimated correlation is listed in the table.
9) MAAML outliers (the measured VOC concentrations found to be statistical outliers within the MAAML data during the time DIAL was running on the day of measurement) are listed. Outliers were defined as those measurements that appear at magnitudes above

this limit: Outlier limit = upper quartile of measured concentrations + 1.5 x the inter quartile range. When the MAAML benzene or total VOCs were correlated with DIAL emissions, the outliers provided additional information about the constituents in the plume.

10) Time of FTIR measurements.
11) Percent of FTIR measurements aligned with DIAL plume. This column indicates the percentage of the overall FTIR path that aligned with the DIAL plume, based on individual DIAL scan plume images, purported to be representative of the scans along a particular DIAL LOS on that day.
12) FTIR correlation with DIAL plume. The degree of correlation of benzene when DIAL was measuring benzene or total alkanes when DIAL was measuring total VOCs between the FTIR and DIAL measurements. DIAL measurements showed differences in concentration throughout the spatial extent of the measured plumes. These spatial differences coupled with the differing length of the linear path of the two measurements (DIAL had a longer path than FTIR), indicate that the best comparisons between FTIR and DIAL would be between the FTIR and only those DIAL measurements along the FTIR path. Unfortunately, these segmented DIAL measurements were not available. If there was no alignment as described in 11 above, we did not expect correlation, while if there was overlap based on the representative DIAL scan image we did expect correlation. In order to relate the FTIR concentrations to the DIAL emission rates, the FTIR emissions were averaged over the DIAL scan time. If we did find correlation when the FTIR was not aligned with the plume, we hypothesized that the plume shifted for scans where images were not available or DIAL did not pick up the entire plume. As with the MAAML data, some datasets included one high value which could be an influential outlier. When the slope of a linear regression with and without the suspected influential outlier point changed by more than 10%, the point was considered influential. The correlations with and without the point are presented. The estimated correlation, as well as a measure of direction and strength of association, is listed in the table.

The figure in each process area section shows only the DIAL LOS that measured significant plume emission rates. In addition to the DIAL LOS, the figure depicts the location of the MAAML and FTIR, the horizontal location of the plume or plumes based on individual DIAL scan plume images, purported to be representative of the scans along that particular DIAL LOS on that day, as well as the process area structures. There may be additional lines of sight that measured no or insignificant emissions rates but those were not included in the figures. Figures depicting every DIAL LOS can be found in appendix A: NPL DIAL Report.

3.1 Southwest Tanks

Table 3.1 Southwest Tanks

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/13/2010	SDP01/ LOS1, LOS2[†], LOS3[†]	12:26-17:36	VOC	16-19 (possible emission sources: A-333, A-331, A-330, A-329, A-332)	10:00-16:00	In (Scan 12)	r = 0.62, not significant p-value =0.26	Propylene, trichloroethylene, chlorobenzene, 1,1,2,2-tetrachloroethane, 1, 3 butadiene	12:20-16:53	No, 0% (Scan 12)	Not linear
1/15/2010	SPD03/LOS1	11:35-13:21	VOC	11 (possible emission sources: A-325, A-326)	11:00-16:00	Out (Scan 65)	NA, too few data points	Toluene, ethylbenzene, m,p,o xylene, 1,2,4-Trimethylbenzene, 1,3-Dichlorobenzene, 1,2-Dichlorobenzene, 1,2,4-Trichlorobenzene, Hexachloro-1,3-Butadiene	12:30-16:54	No, 0% (Scan 65)	NA, too few data points
1/15/2010	SPD03/LOS2, LOS3	13:42-16:50	VOC	61 (possible emission sources: AP-17, AP-16, with possible contributions from another tanks)	11:00-16:00	Out (Scan 73, Scan 77)	NA, too few data points, plot below is combined data for LOS1, 2 and 3		12:30-16:54	No, 0% (Scan 73, Scan 77)	NA, too few data points
1/19/2010	SPD06/LOS3	12:43-13:17	VOC	43 (possible emission source: AP-17)	9:00-16:00	Out (Scan 157)	NA, too few data points	trichloroethylene, chlorobenzene, 1,1,2,2-tetrachloroethane,	10:44-16:47	No, 0% (Scan 157)	NA, too few data points
2/8/2010	SPD23/LOS1, LOS2[†]	10:55-12:07	Benzene	2-3 (possible emission sources: AP-18, AP-19)	10:00-11:00	In (Scan 545)	NA, too few data points	n-butane, n-pentane	11:09-12:00	Yes, 50% (Scan 545)	NA, too few data points

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

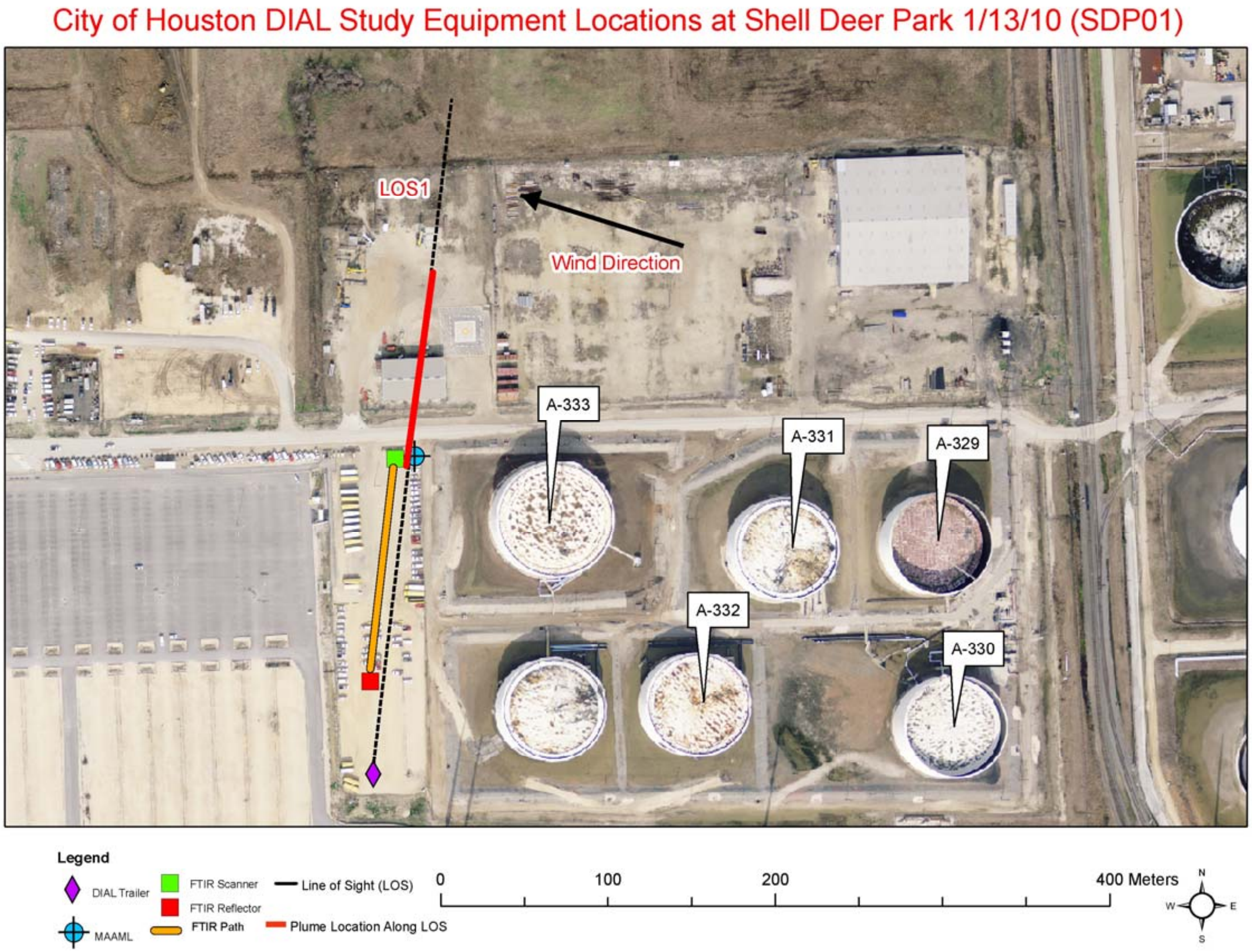


Figure 3.1a Southwest Tanks 1/13/2010

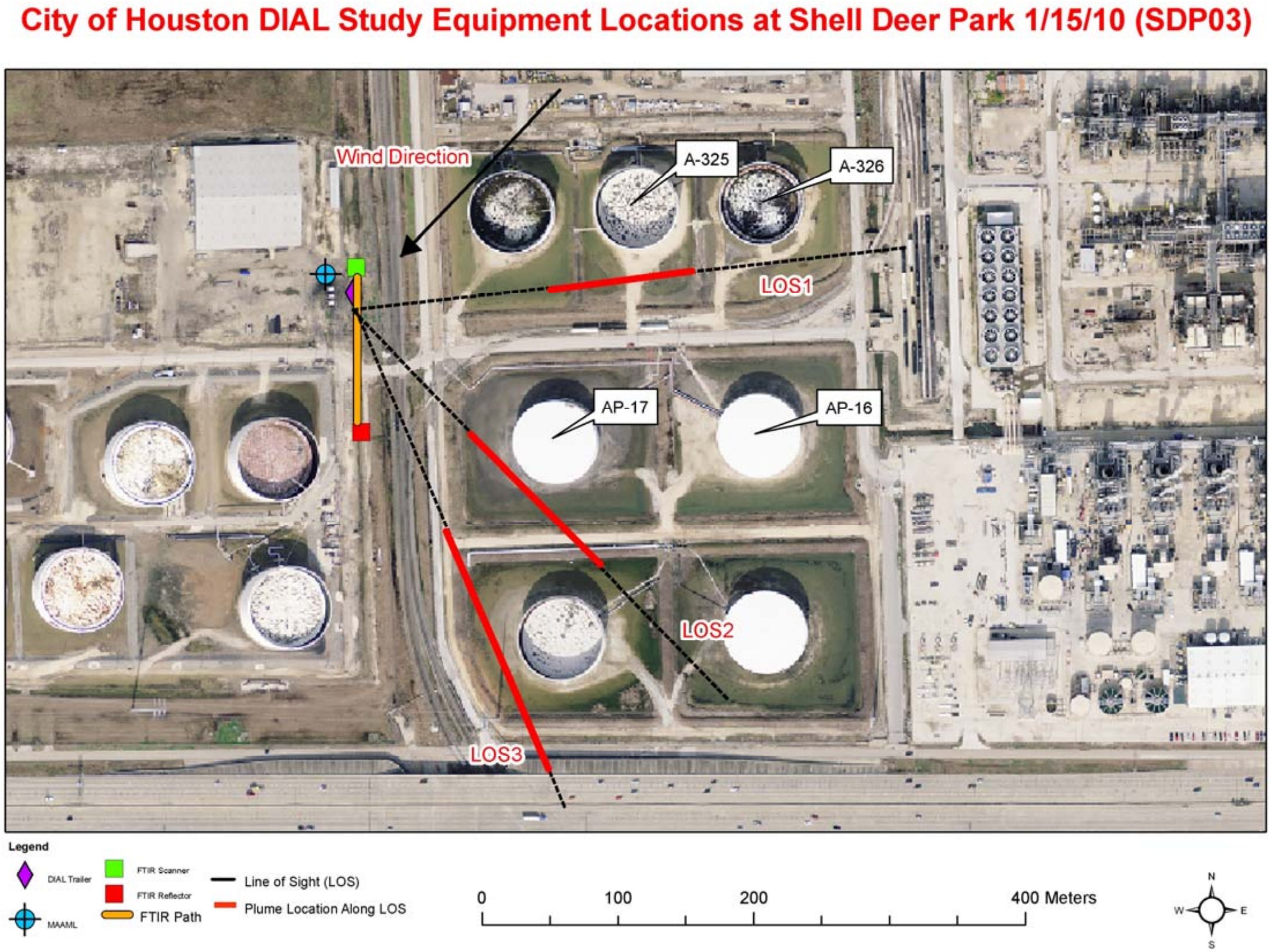


Figure 3.1b Southwest Tanks 1/15/2010

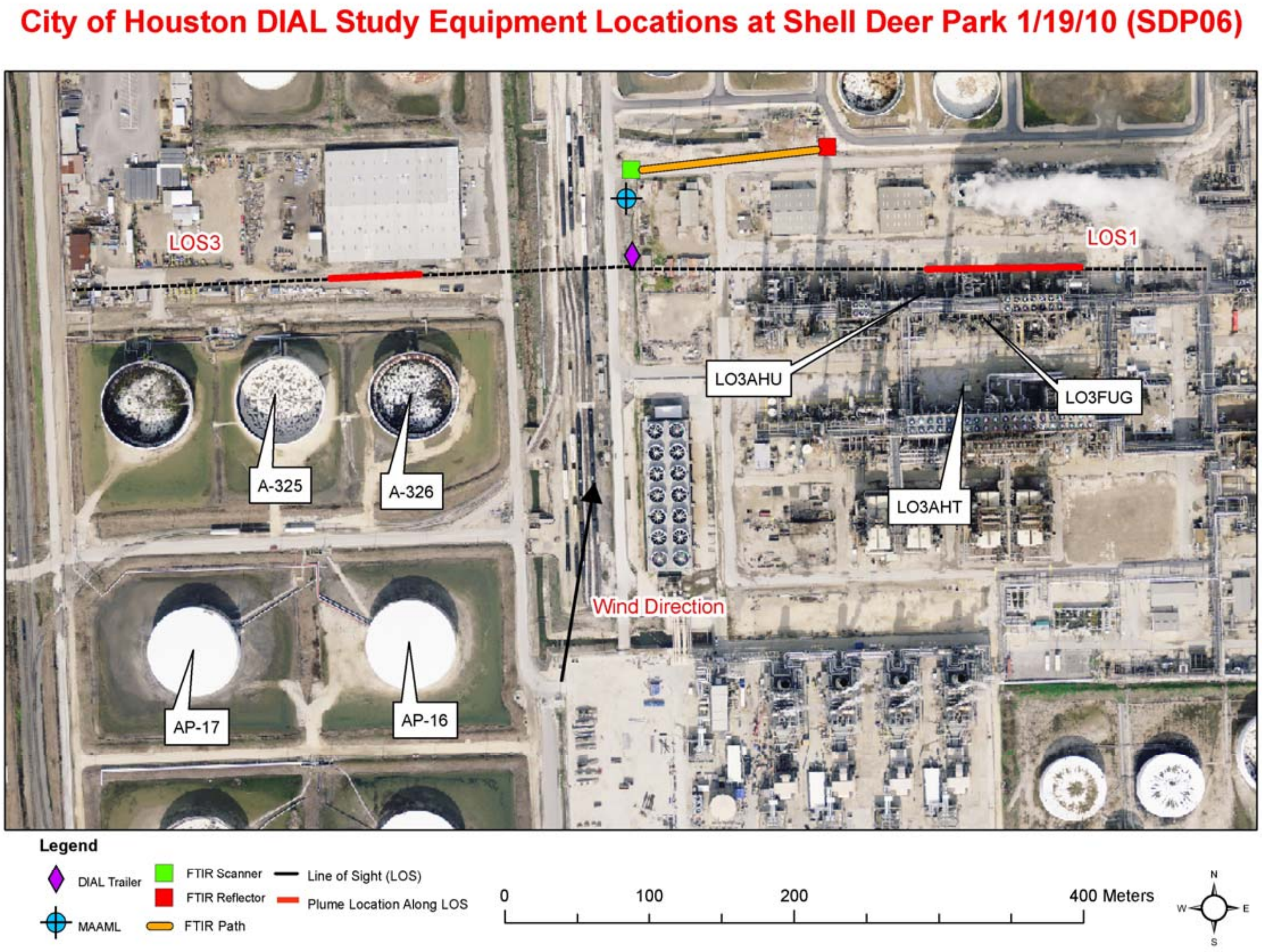


Figure 3.1c Southwest Tanks 1/19/2010

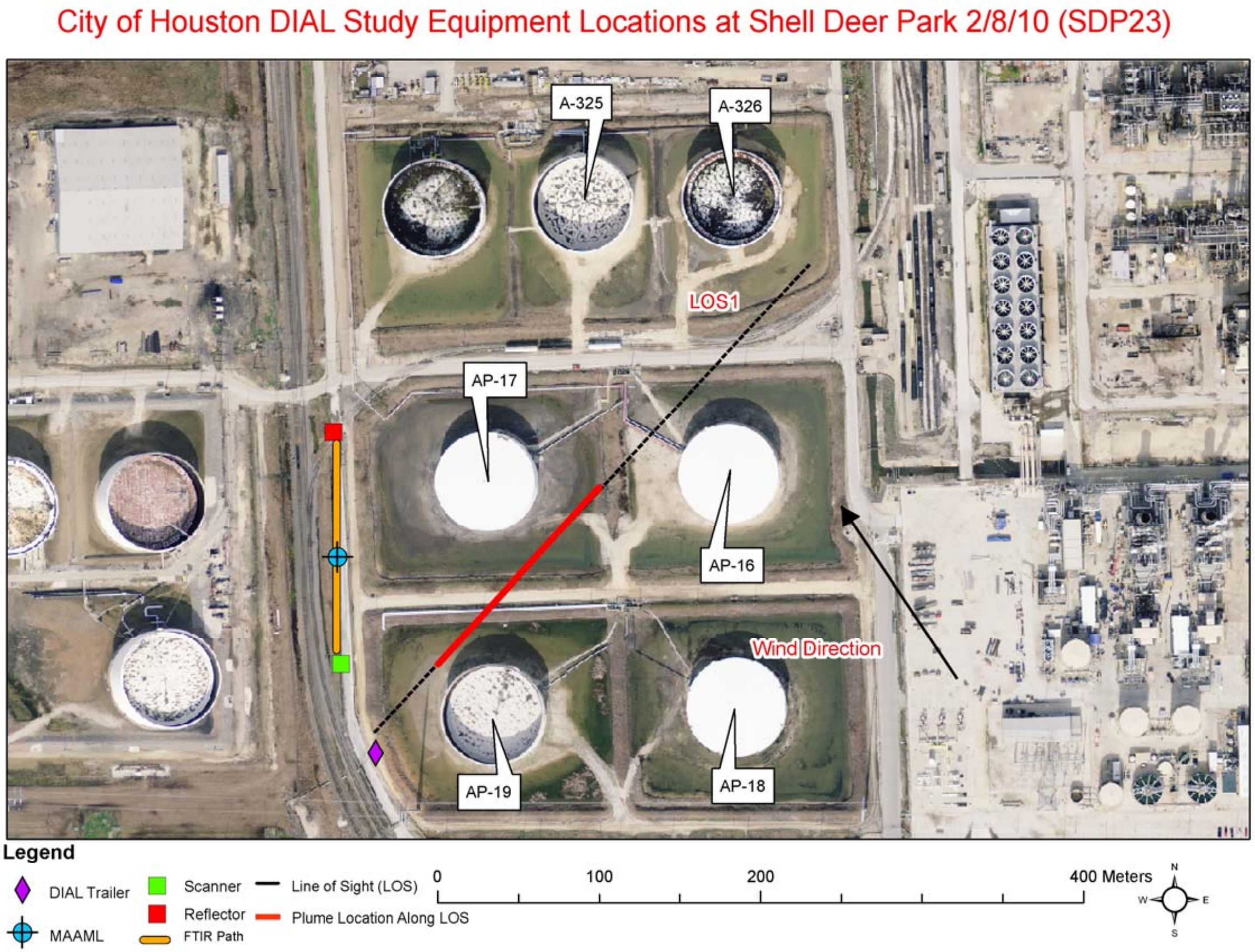


Figure 3.1d Southwest Tanks 2/8/2010

3.2 West Tanks

Table 3.2 West Tanks

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/14/2010	SPD02/LOS1	12:32-14:18, 16:36-17:12	VOC	16 (possible emission sources: A-310, A-319, G-324-R1)	12:00-16:00	Out (Scan 39)	R=-0.53, not significant p-value =0.44	ethylene, propylene, acetylene, vinyl chloride, 1,3-butadiene, methylene chloride, 1-hexene, trichloroethylene, chloroform, 1,2-dichloroethane, chlorobenzene, ethylbenzene, 1,1,2,2-tetrachloroethane, xylene, 1,2,4-trimethylbenzene , 1,2-dichlorobenzene , 1,3-dichlorobenzene , 1,4-dichlorobenzene , hexachloro-1,3-butadiene,	15:28-17:01	No, 0% (Scan 39)	NA, too few data points
1/14/2010	SPD02/LOS2	14:25-15:37, 16:08-16:32	VOC	17 (possible emission sources: AP-1, AP-2, AP-3, AP-4, AP-5, AP-6)	12:00-16:00	Out (Scan 44)	NA, too few data points		15:28-17:01	No, 0% (Scan 44)	NA, too few data points
1/14/2010	SPD02/LOS2	15:56-16:08	VOC	4000 (possible emission source: A-318)	12:00-16:00	Out (Scan 52)	NA, too few data points		15:28-17:01	No, 0% (Scan 52)	FTIR did not pick up the spike found by DIAL
1/16/2010	SPD04/LOS3[†]	12:39-13:48	VOC	0.4 (possible emission source: A-319)	10:00-16:00	Visual Representation of LOS3 not available	NA, too few data points	cumene	15:18-16:13	Visual Representation of LOS3 not available	NA, too few data points

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

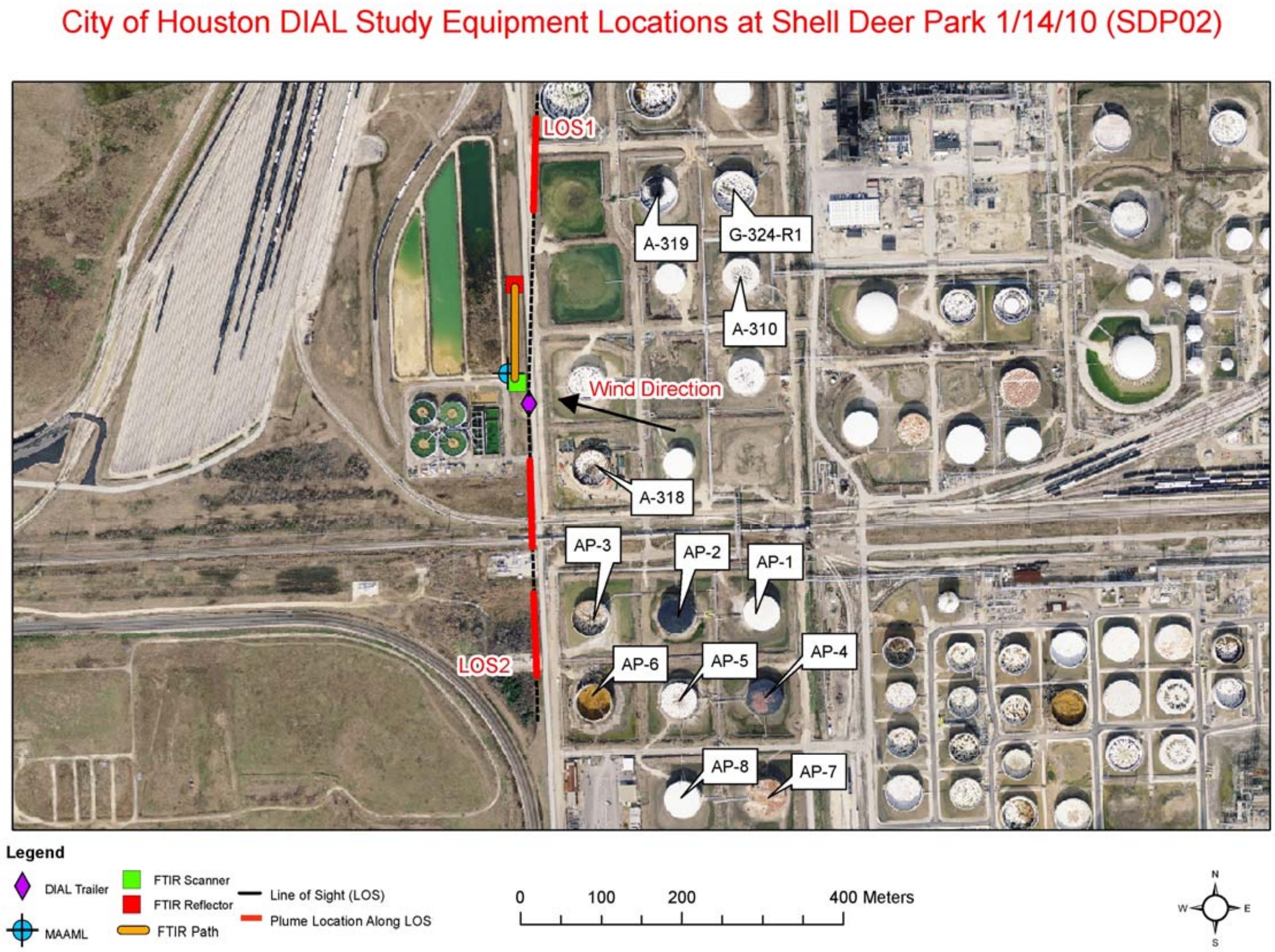


Figure 3.2a West Tanks 1/14/2010

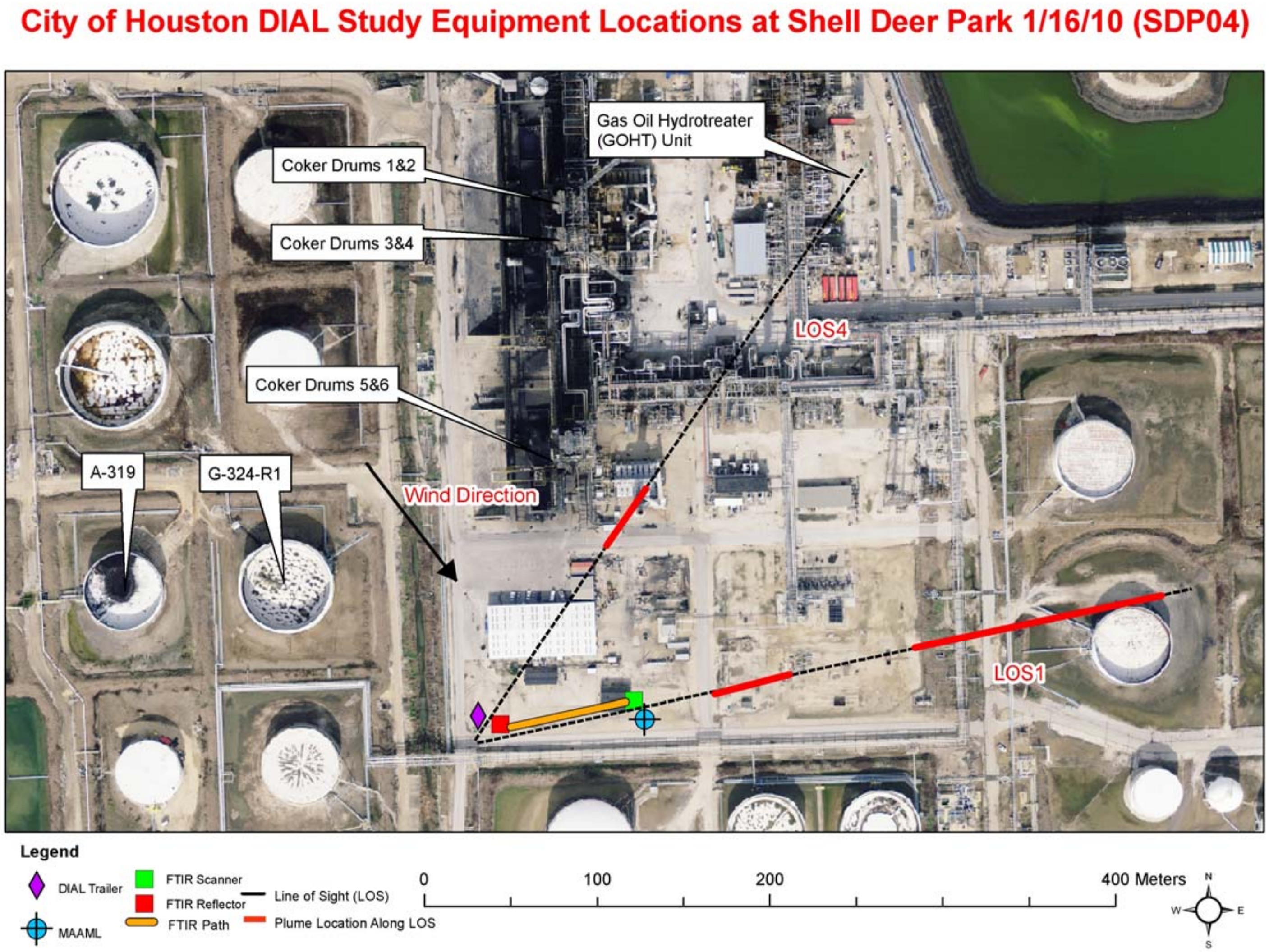


Figure 3.2b West Tanks 1/16/2010

3.3 Coker, GOHT, and West Dock Area

Table 3.3 Coker, GOHT, and West Dock Area

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/16/2010	SPD04/LOS1, LOS2[†], LOS4, LOS5[†]	10:58-12:34, 14:21-17:13	VOC-Coker and flare	2-3 (possible emission source: Coker)	10:00-16:00	Out (Scan 84, Scan 108)	r =-0.95, regression significant p-value=0.01	Trichloro-fluoromethane 1,1,2-Trichloro-trifluoroethane cumene, 1,3-Dichloro-benzene	15:18-16:13	No, 0% (Scan 84, Scan 108)	NA, Too many nondetects in FTIR
1/27/2010	SPD14/ LOS2[†], LOS3[†]	12:53-14:42, 16:53-17:09	VOC-Coker	1-2 (possible emission sources: Coker, GOHT)	10:00-16:00	Visual representation of LOS2 and LOS3 not available	NA, too few data points	Methyl chloride, vinyl chloride, 1,2-Dichloro-ethane, trichloro-ethylene	11:58-16:47	Visual representation of LOS2 and LOS3 not available	NA, Too many nondetects in FTIR
1/27/2010	SPD14/LOS1, LOS4[†]	12:15-12:40, 14:48-15:49	VOC-Dock	9 (possible emission sources: West Dock area and tanks D-363, F-347, F-349)	10:00-16:00	Out (Scan 332)	NA, too few data points		11:58-16:47	No, 0% (Scan 332)	NA, Too many nondetects in FTIR

1 Date	2 DIAL Location / LOS	3 DIAL hours	4 DIAL	5 Average DIAL emission rate (lbs/hour)	6 MAAML hours	7 Location of MAAML	8 MAAML correlation with DIAL plume	9 MAAML outliers	10 FTIR hours	11 FTIR aligned with DIAL plume	12 FTIR correlation with DIAL plume
2/4/2010	SPD20 /LOS1[†], LOS2	10:17-14:25, 15:01-16:50	VOC	3-4 (possible emission source: Coker)	9:00-16:00	Out (Scan 513)	Not linearly related	1 hexene, methylene chloride, 1,3 butadiene, propylene, ethylene, 1,2 dichloro-ethane, trichloro-ethylene, chloro-benzene, cumene	10:45-16:47	Yes, 100% (Scan 513)	Not statistically linearly correlated, but they do have the same pattern
2/11/2010	SPD27/LOS1, LOS2, LOS3[†]	11:22-16:47	Benzene	5-27 (possible emission source: Coker)	10:00-16:00	Out (Scan 620, Scan 633)	r = -0.49, but regression not statistically significant p-value = 0.32	1 hexene, methylene chloride, 1,3 butadiene, propylene, 1,2 dichloro-ethane, trichloro-ethylene, chloro-benzene, chloroform	11:24-13:53	Yes, 5% (Scan 620) No, 0% (Scan 633)	All nondetect in FTIR
2/17/2010	SPD31/ LOS1[†], LOS3	10:06-11:24, 12:19-15:38, 16:14-16:54	Benzene	22-31 (possible emission sources: Coker, GOHT, West Dock area, tanks D-363, F-347, F-349)	09:00-16:00	Out (Scan 745)	r =-0.59 with all of the data, but regression not statistically significant, and one influential outlier p-value = 0.16, r =0.25 when outlier removed and regression not significant p-value = 0.62, when looking only from 12-16 hrs, r =0.74, no influential outlier and regression not significant p-value= 0.15	Trichlorofluoromethane, methylene chloride, cumene	*10:48-16:46	Yes, 100% (Scan 745)	NA, too few data points, FTIR reports a benzene spike at scan 737 which is not reported by DIAL

1 Date	2 DIAL Location / LOS	3 DIAL hours	4 DIAL	5 Average DIAL emission rate (lbs/hour)	6 MAAML hours	7 Location of MAAML	8 MAAML correlation with DIAL plume	9 MAAML outliers	10 FTIR hours	11 FTIR aligned with DIAL plume	12 FTIR correlation with DIAL plume
3/27/2010	SPD37/ LOS1, LOS3	9:58-11:28, 12:16-16:51	VOC	3-4 (possible emission source: Coker)	09:00-16:00	Out (Scan 844, Scan 868)	r =0.56, regression not statistically significant p-value= 0.18	Cumene, 1,3,5 trimethylbenzene and 1,2,4 trimethylbenzene	9:46-16:47	Yes, 10% (Scan 844) No, 0% (Scan 868)	Analyzed segment with fewest nondetects not linearly related but similar

* FTIR by Time averaging method (TAM)

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

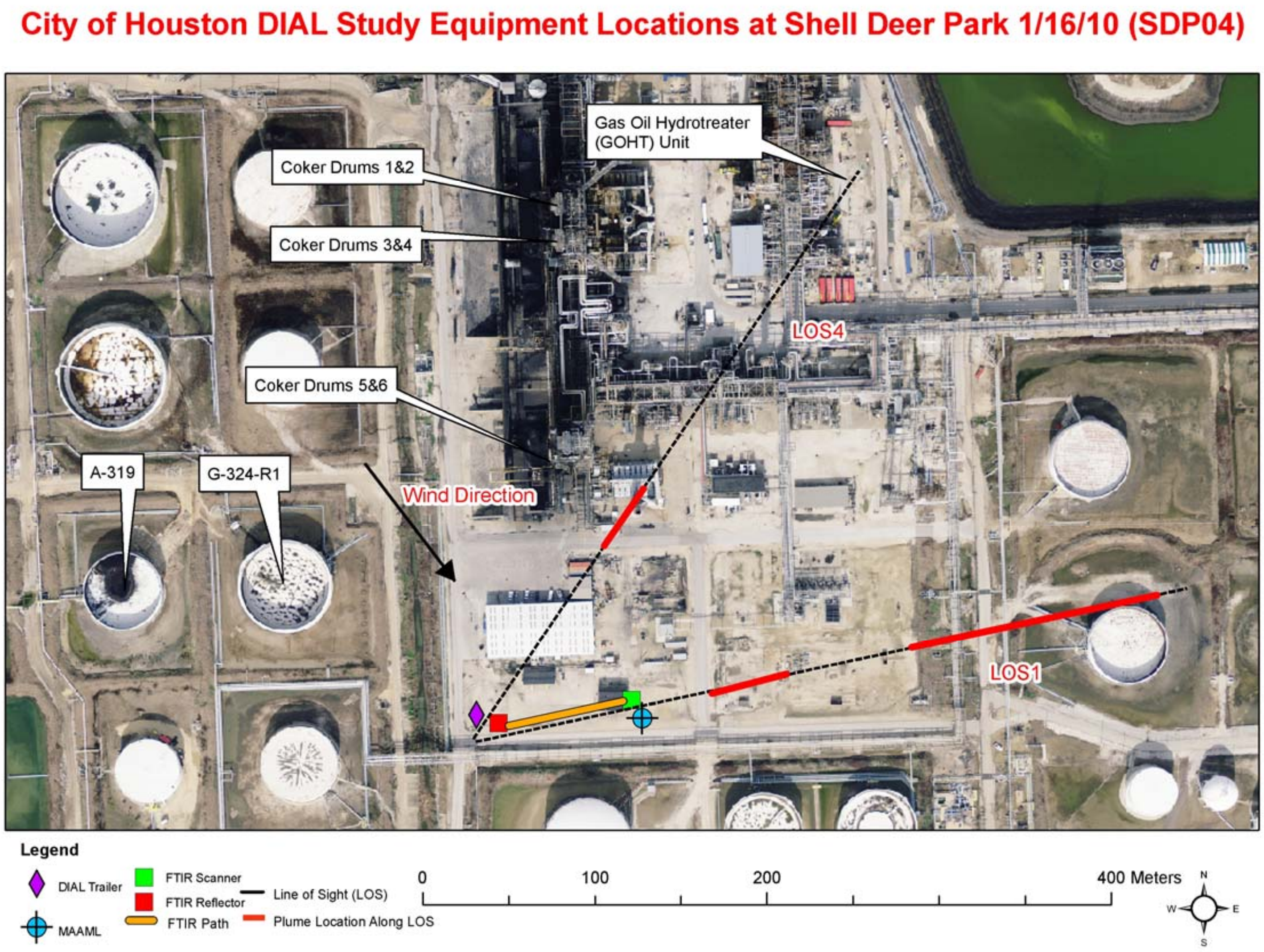
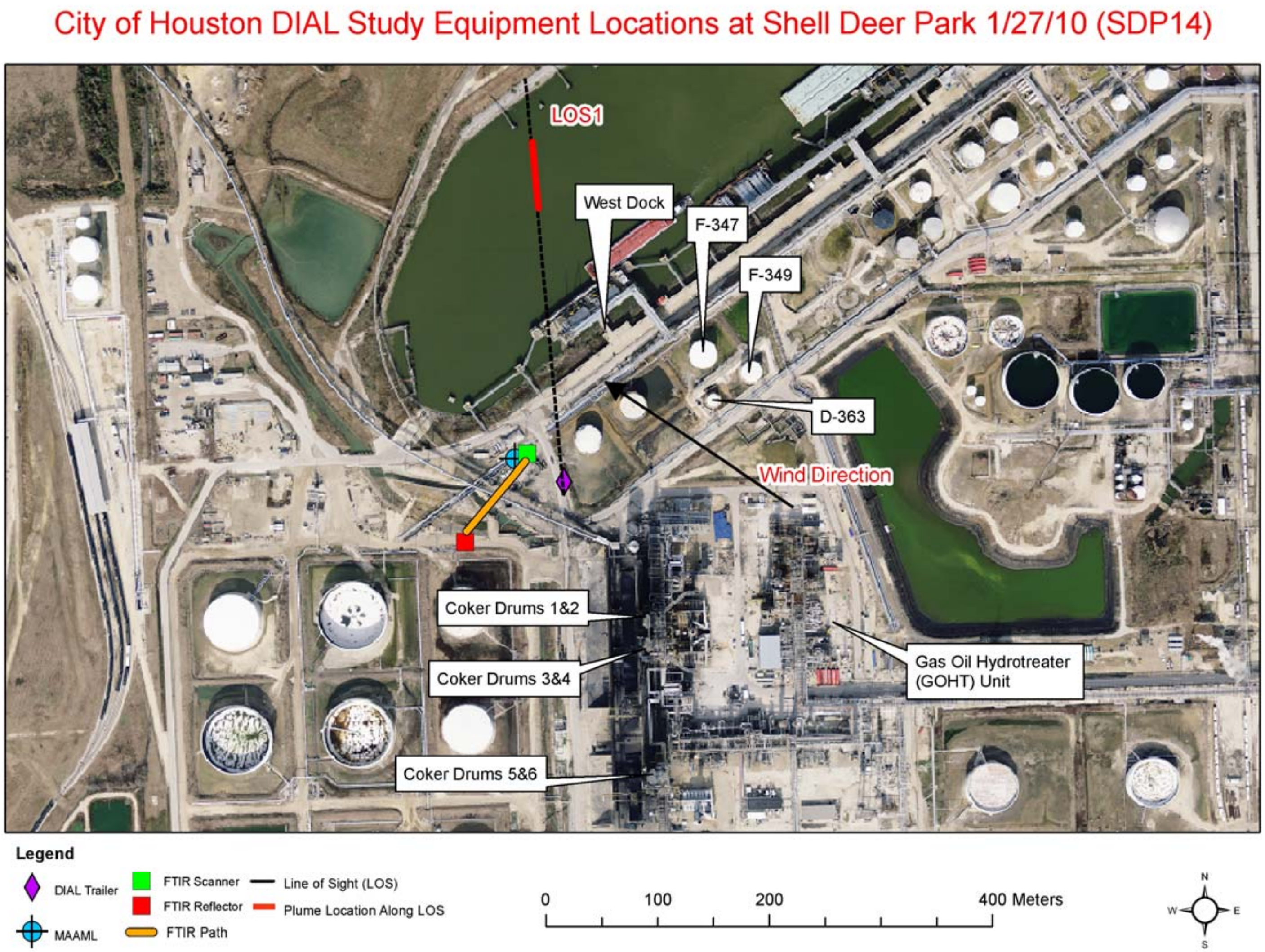


Figure 3.3a Coker, GOHT, and West Dock Area 1/16/2010



City of Houston DIAL Study Equipment Locations at Shell Deer Park 1/27/10 (SDP14)

Figure 3.3b Coker, GOHT, and West Dock Area 1/27/2010

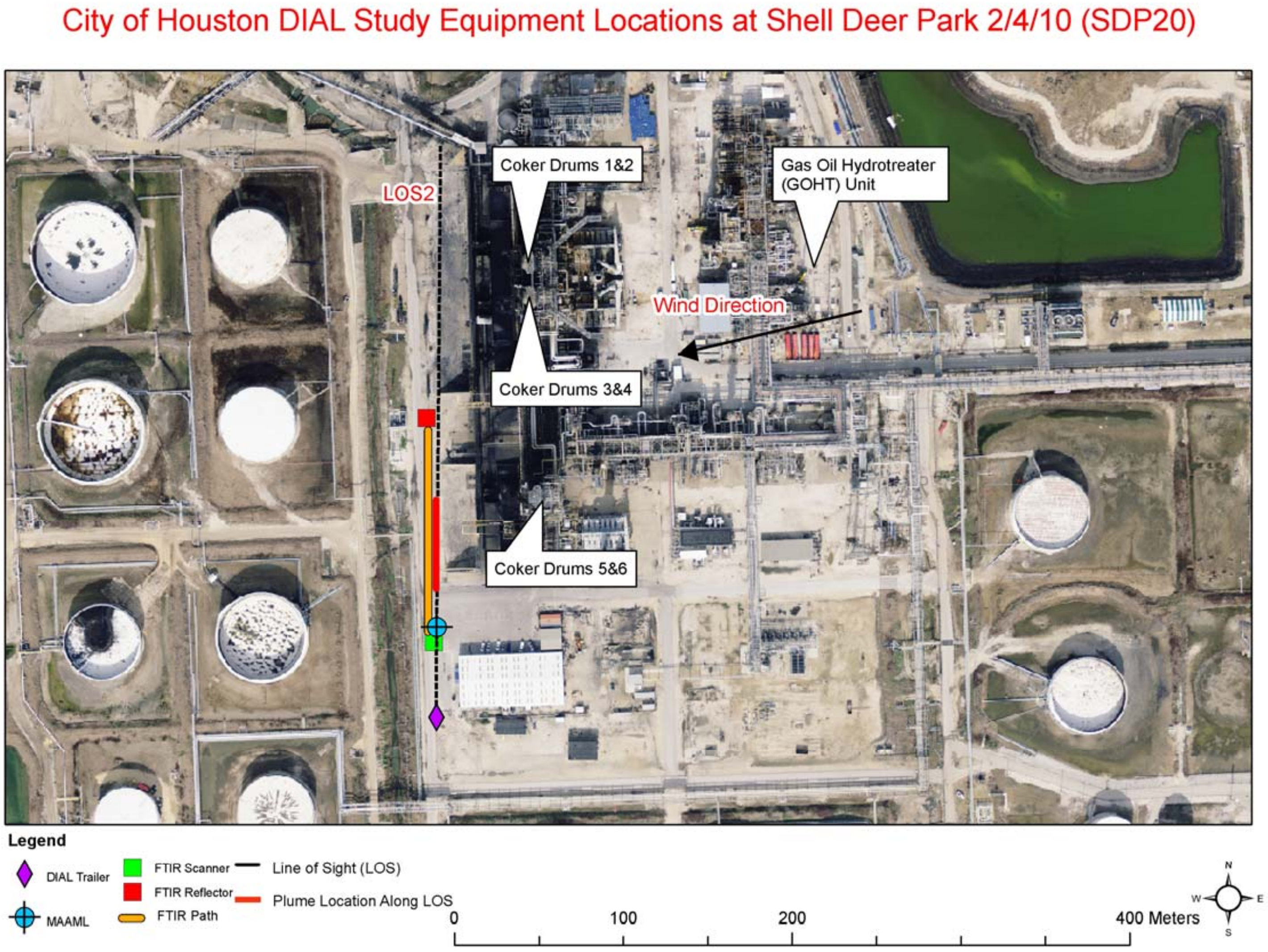


Figure 3.3c Coker, GOHT, and West Dock Area 2/4/2010

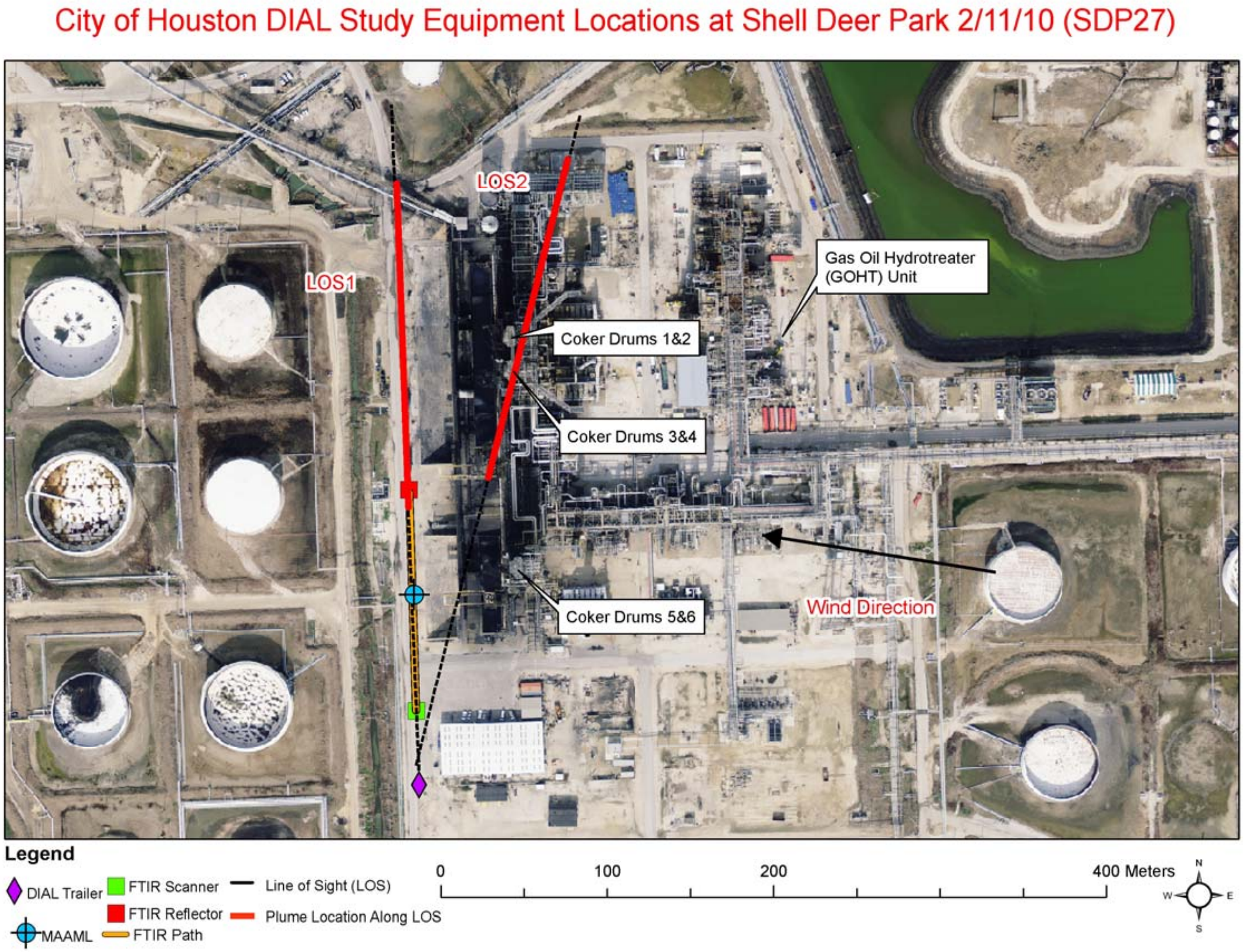


Figure 3.3d Coker, GOHT, and West Dock Area 2/11/2010

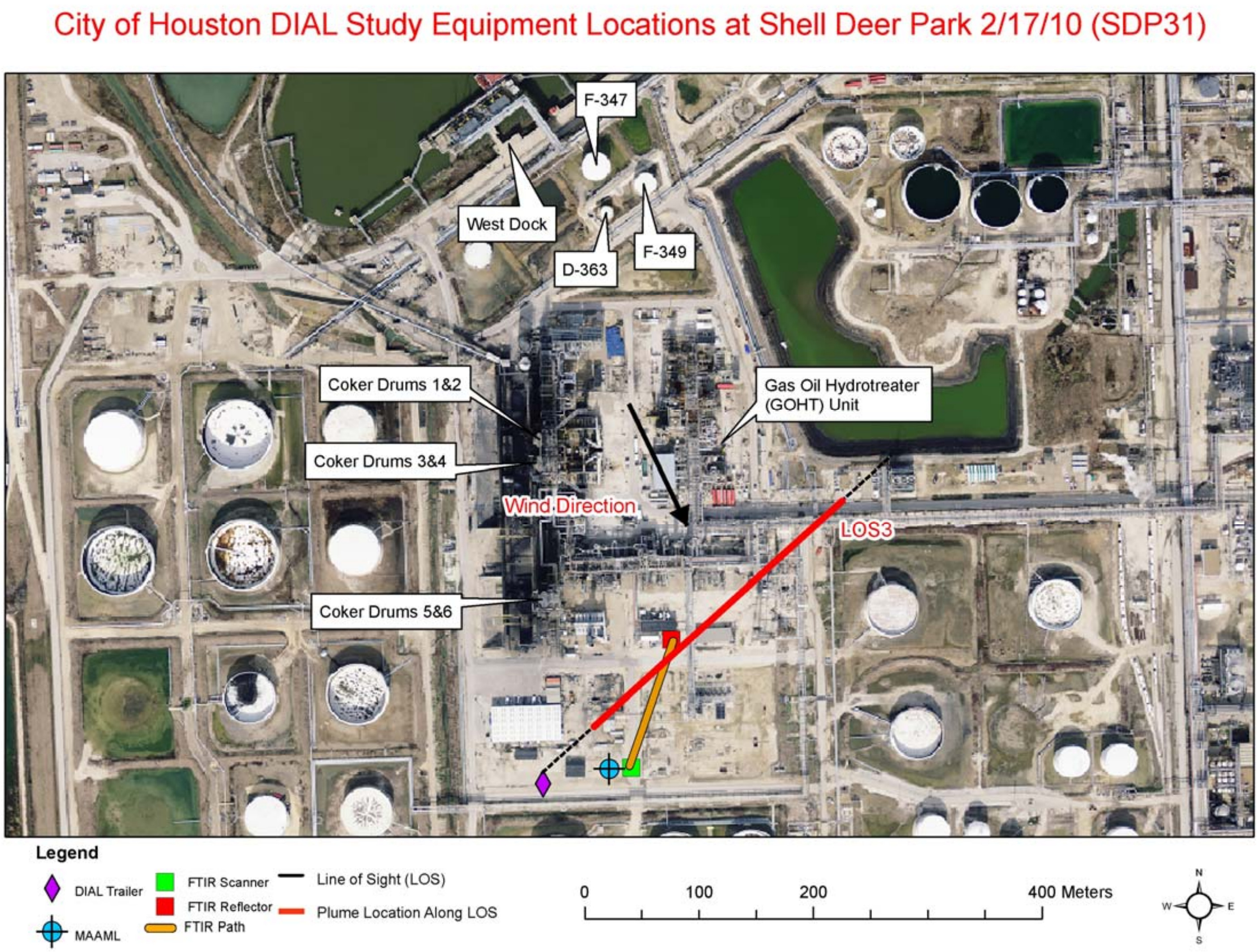


Figure 3.3e Coker, GOHT, and West Dock Area 2/17/2010

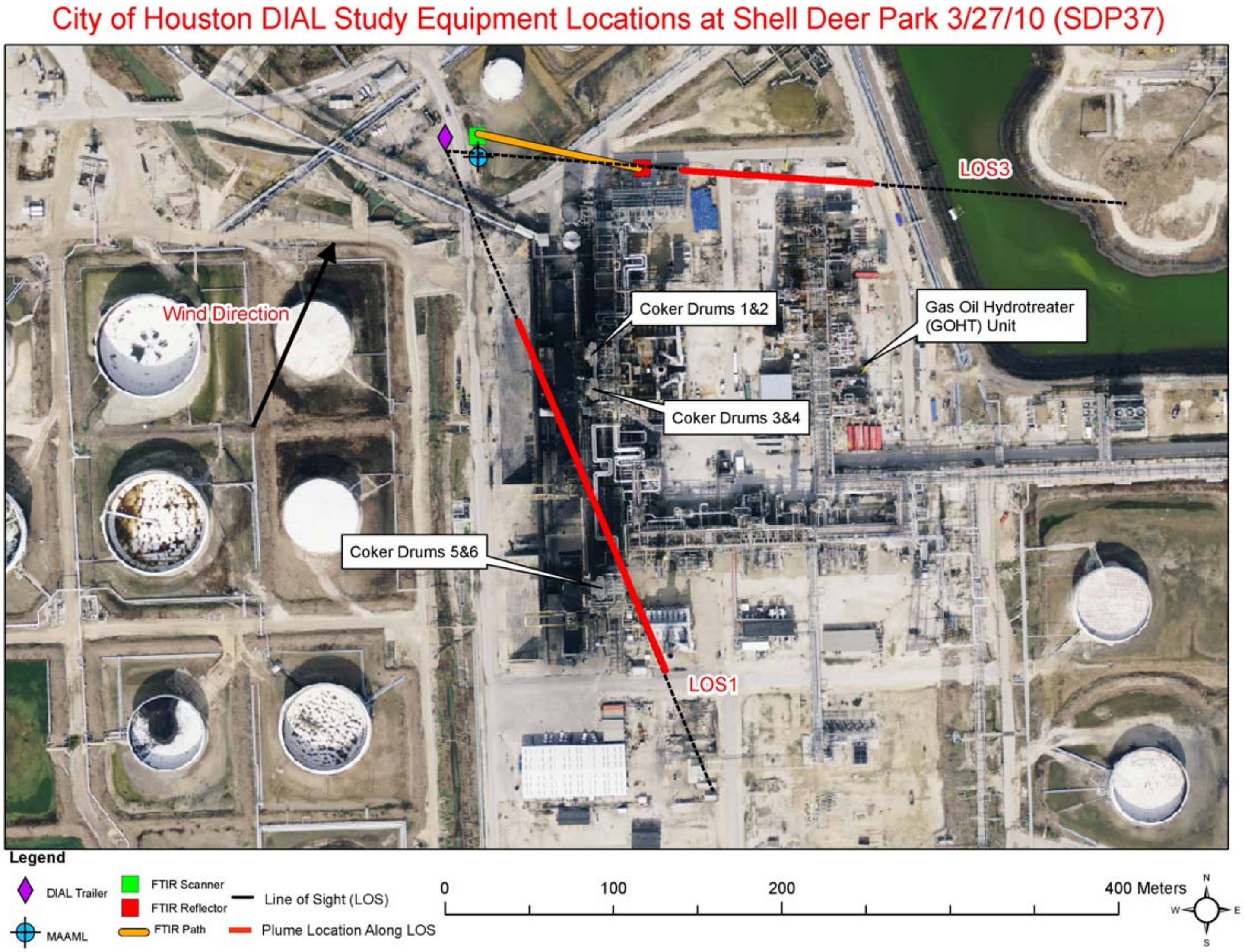


Figure 3.3f Coker, GOHT, and West Dock Area 3/27/2010

3.4 Olefins Process Area

Table 3.4 Olefins Process Area

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/18/2010	SPD05/LOS1, LOS2†, LOS3†	10:46-15:19	VOC	4-5 (possible emission sources: Analyzer House U Vent (LO3AHU), Analyzer House T Vent (LO3AHT), LO3 Unit (LO3FUG))	10:00-16:00	Out (Scan 115)	With all of the data not linearly related. r=0.092 not statistically significant p-value=0.88, removing data with windshift, relationship is log linear, r=.80 for hours 12 on but not statistically significant p-value=0.19	Ethane, ethylene, propylene, 1,3 butadiene	10:46-16:48	No, 0% (Scan 115)	Not linearly related, however, FTIR and Wind Direction are highly correlated at r=0.76
1/19/2010	SPD06/LOS1	10:27-11:51, 13:18-14:18	VOC	4 (possible emission sources: Analyzer House U Vent (LO3AHU), Analyzer House T Vent (LO3AHT), LO3 Unit (LO3FUG))	9:00-16:00	Out (Scan 145)	NA, too few data points	trichloroethylene, tetrachloroethylene, chlorobenzene, 1,1,2,2-tetrachloroethane	10:44-16:47	No, 0% (Scan 145)	Not linearly related

†This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

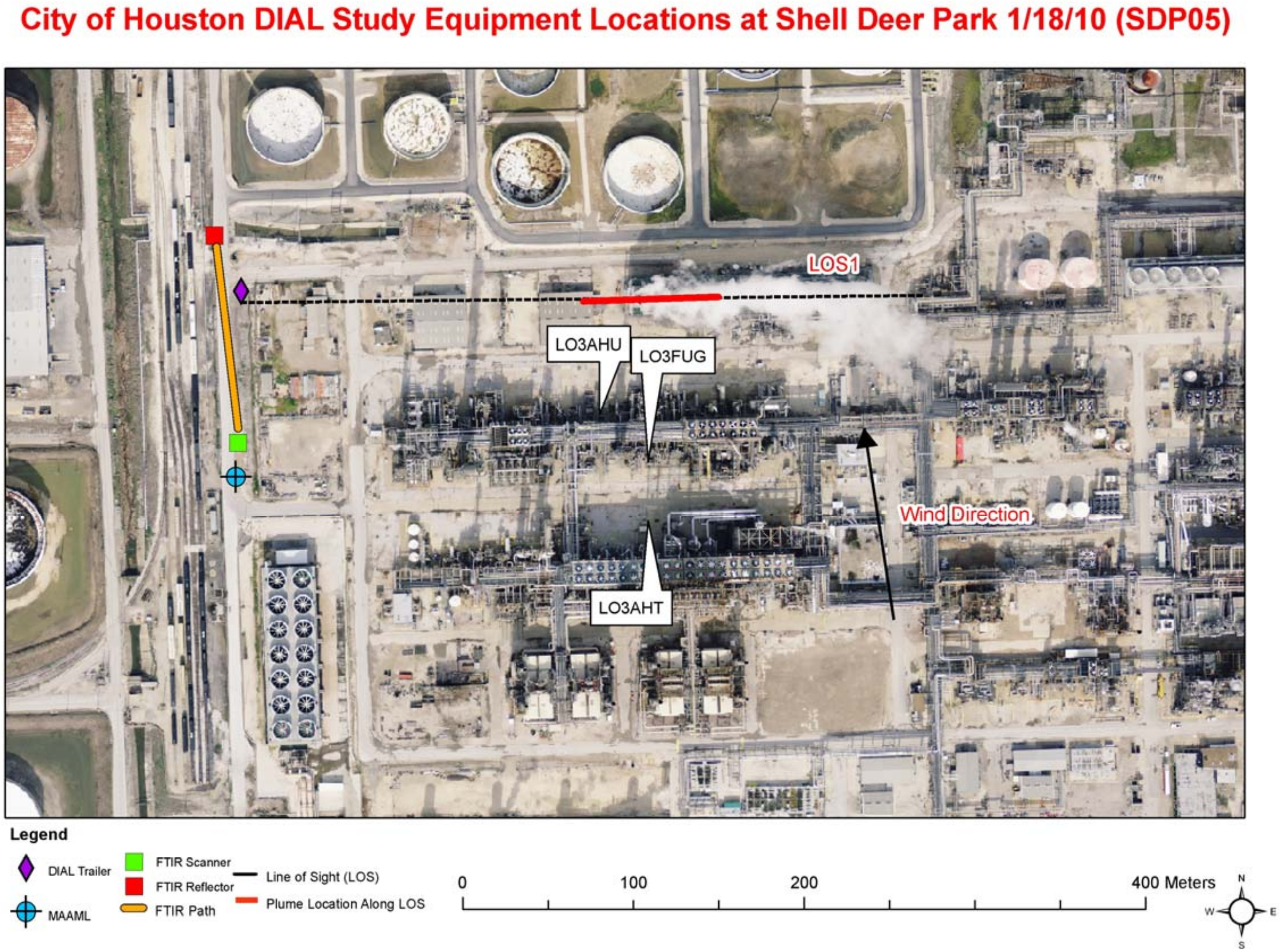
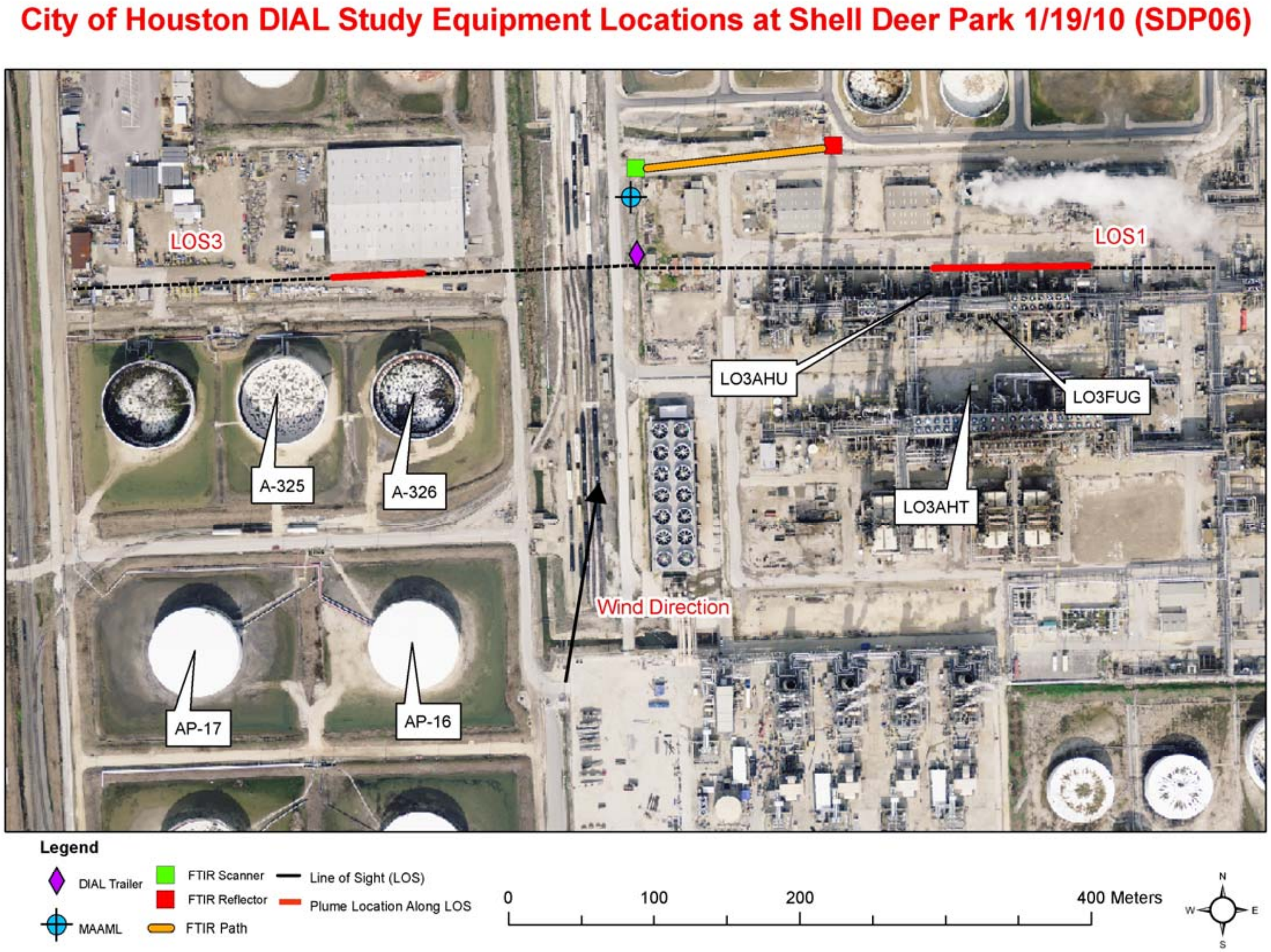


Figure 3.4a Olefins Process Area 1/18/2010



City of Houston DIAL Study Equipment Locations at Shell Deer Park 1/19/10 (SDP06)

Figure 3.4b Olefins Process Area 1/19/2010

3.5 Olefins Tanks and Flares Area

Table 3.5 Olefins Tanks and Flares Area

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/20/2010	SPD08/ LOS1	11:57-13:06, 14:06-14:42	VOC	5 (possible emission sources: tanks R-311, R-312, G-332, G-361, ground flare OP3GRFLA, elevated flares OP3ELFLA, OP2ELFLA)	10:00-16:00	Out (Scan 176)	NA, too few data points	Chloro-benzene, hexachloro 1,3 butadiene, 1,1,1 trichloro-ethane, trichloro-ethylene,	11:24-16:32	No, 0% (Scan 176)	Too many nondetects to assess
1/20/2010	SPD08/ LOS3[†], LOS4	15:00-16:19	VOC	2-3 (possible emission sources: tanks G-332, G-361, ground flare OP3GRFLA, elevated flares OP3ELFLA, OP2ELFLA)	10:00-16:00	Out (Scan 193)	NA, too few data points	none	11:24-16:32	No, 0% (Scan 193)	Too many nondetects to assess
1/29/2010	SPD16/ LOS1[†], LOS2[†], LOS3[†]	14:01-16:56	VOC	0 (target emission sources: ground flare OP3GRFLA, elevated flares OP3ELFLA, OP2ELFLA)	9:00-16:00	Visual representation of LOS1, LOS2, and LOS3 not available	NA, too few data points	none	10:47-16:48	Visual representation of LOS1, LOS2, and LOS3 not available	Too many nondetects to assess

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

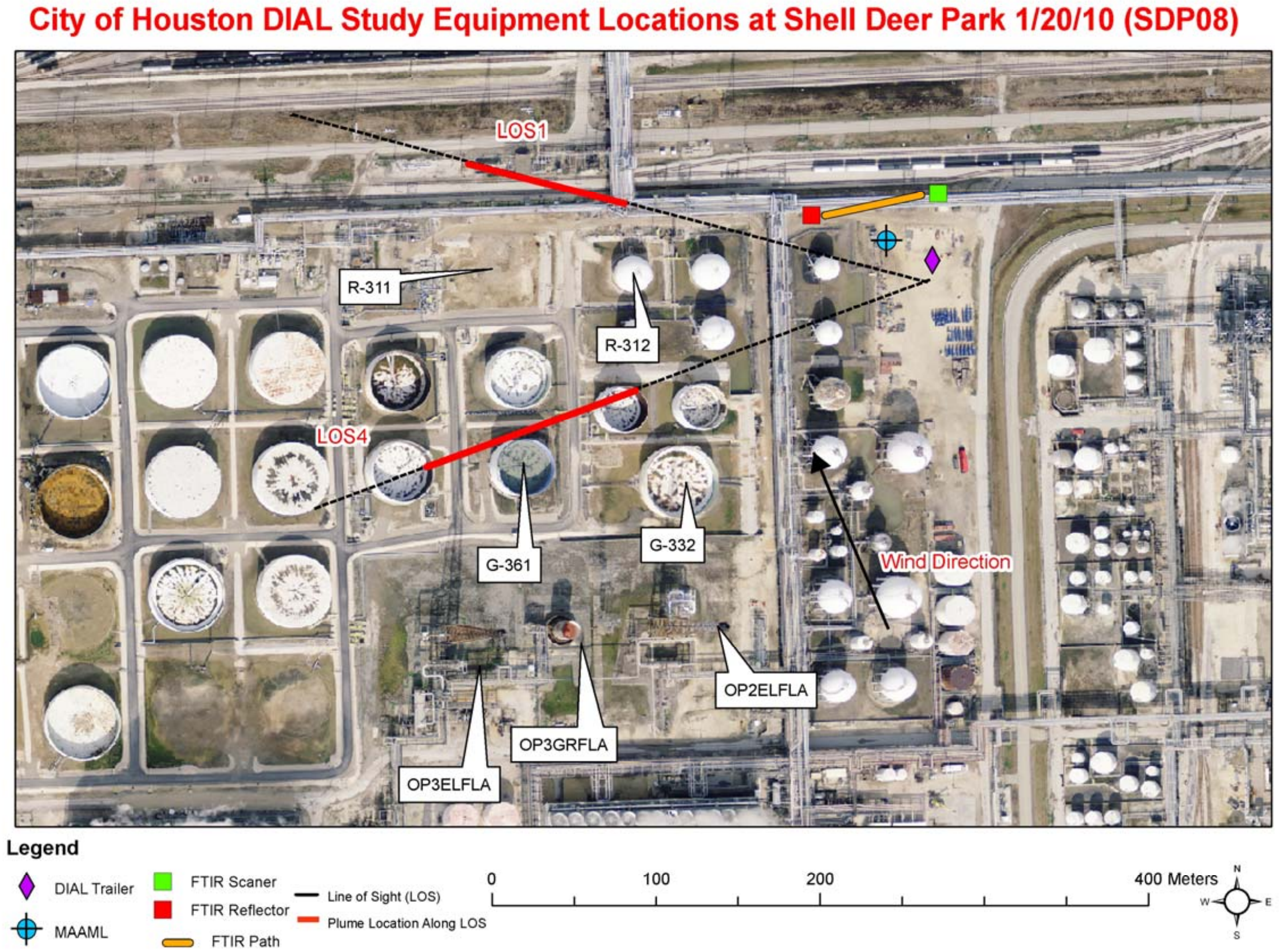


Figure 3.5a Olefins Tanks and Flares Area 1/20/2010

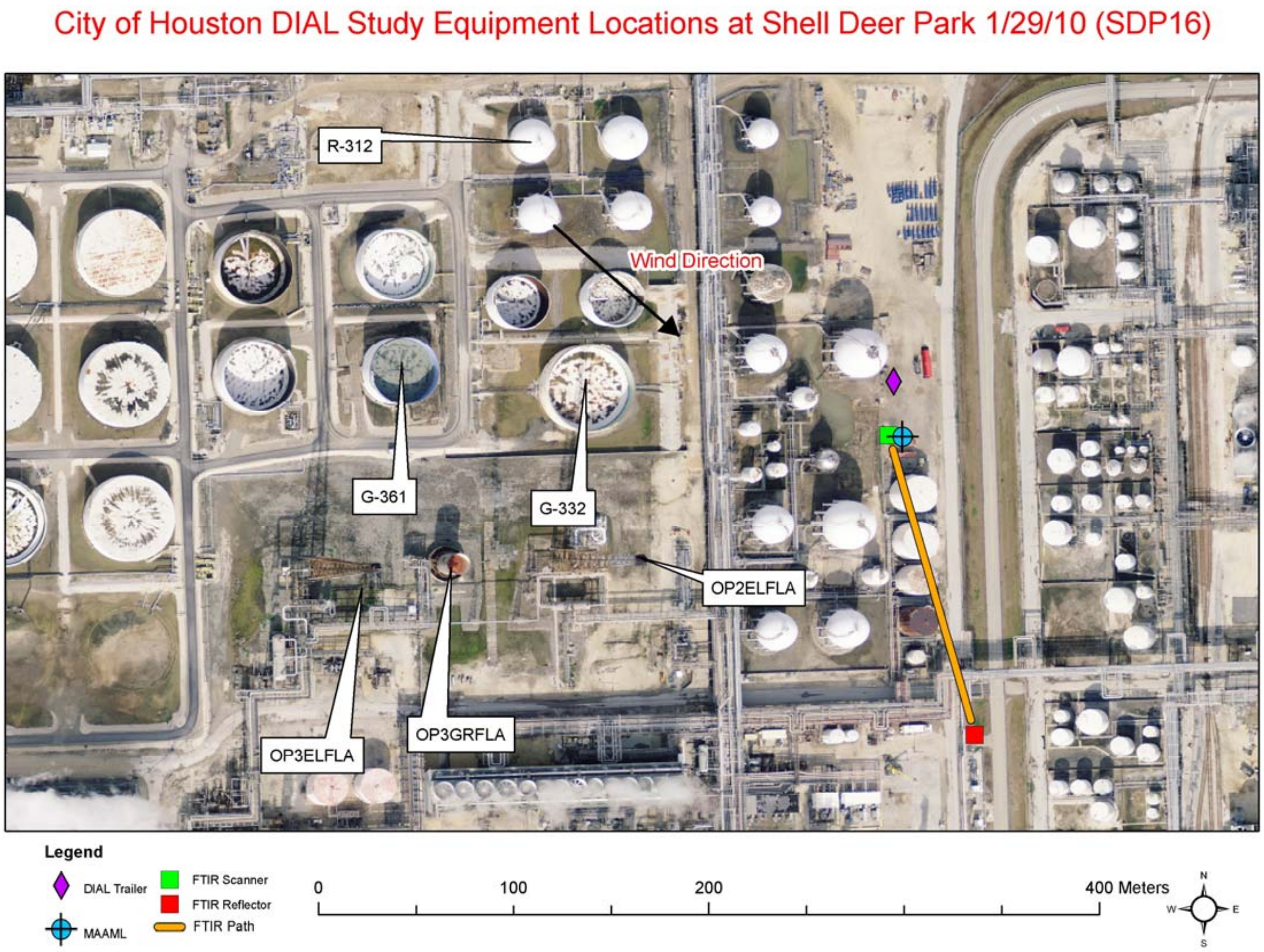


Figure 3.5b Olefins Tanks and Flares Area 1/29/2010

3.6 CR-3

Table 3.6 CR-3

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/21/2010	SPD09/LOS2, LOS3†	13:10-15:23	VOC	8-12	10:00-16:00	Out (Scan 209)	NA, too few data points	1 hexene, tetrachloroethylene, trichloroethylene,	11:08-16:48	No, 0% (Scan 209)	NA, too many nondetects in FTIR
3/25/2010	SPD34/LOS1	10:53-12:56, 14:05-15:00, 15:59-16:54	VOC	30	9:00-16:00	Out (Scan 809)	Not linearly related. r=0.41 not statistically significant p-value=0.59	Ethane, propane, n-pentane, n-butane, chloroform, toluene, tetrachloroethylene, ethylbenzene, m/p-xylene, styrene, cumene, 1,2,4 trimethylbenzene, 1,3 dichlorobenzene, hexachloro 1, 3 butadiene	10:27-16:48	Yes, 90% (Scan 809)	Not statistically linearly related, similar pattern in center of time series

†This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

City of Houston DIAL Study Equipment Locations at Shell Deer Park 1/21/10 (SDP09)

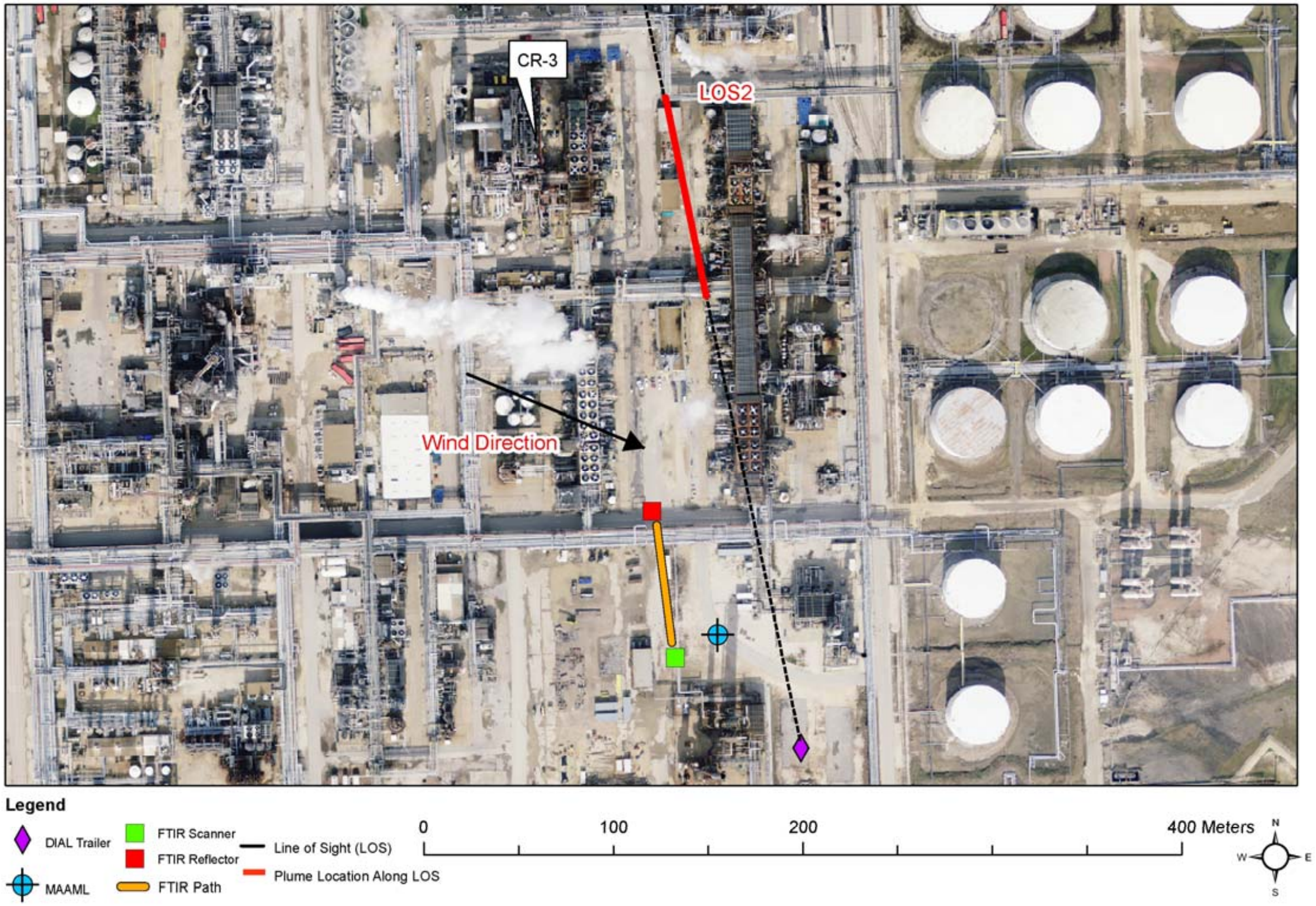


Figure 3.6a CR-3 1/21/2010

City of Houston DIAL Study Equipment Locations at Shell Deer Park 3/25/10 (SDP34)

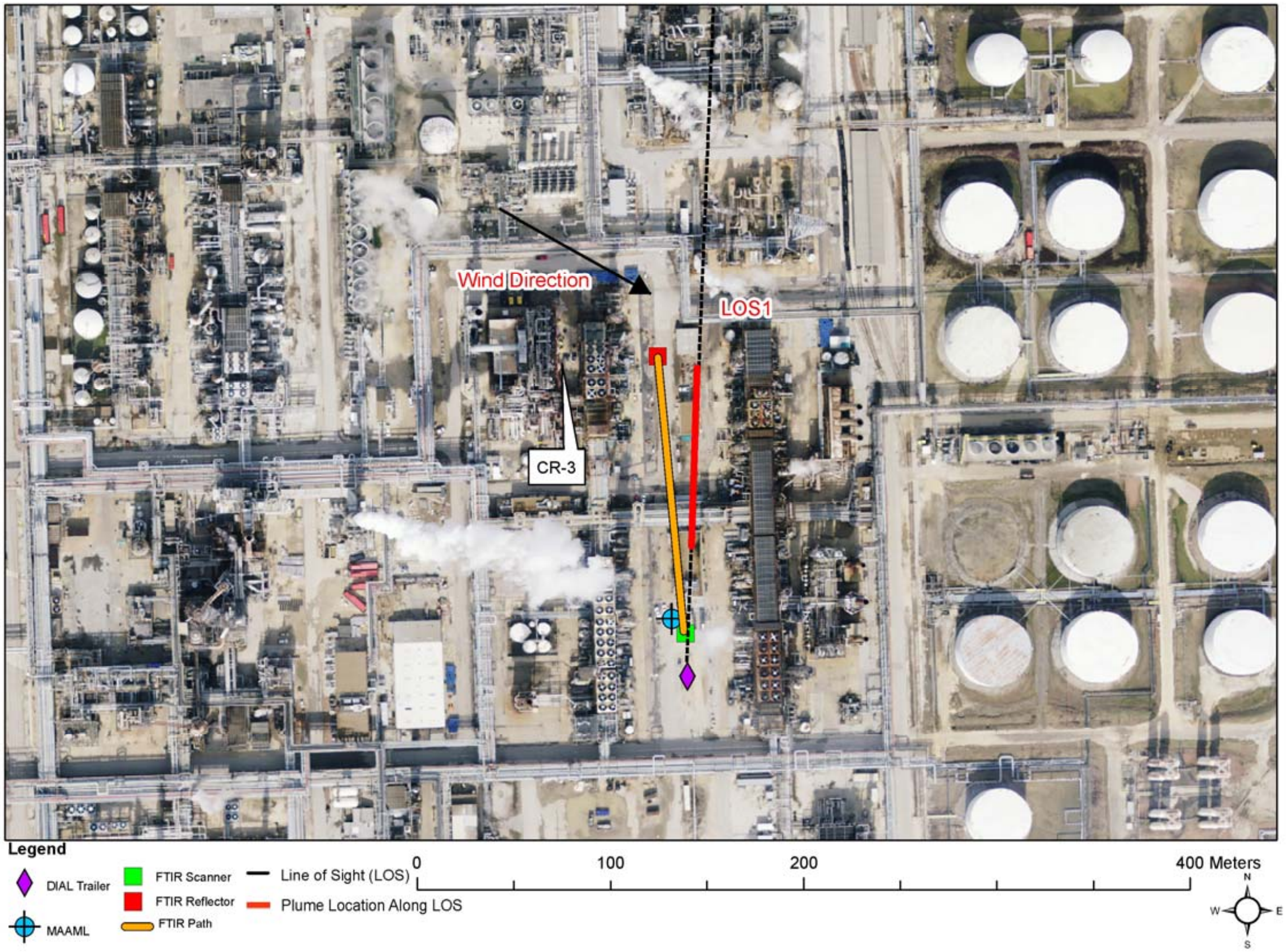


Figure 3.6b CR-3 3/25/2010

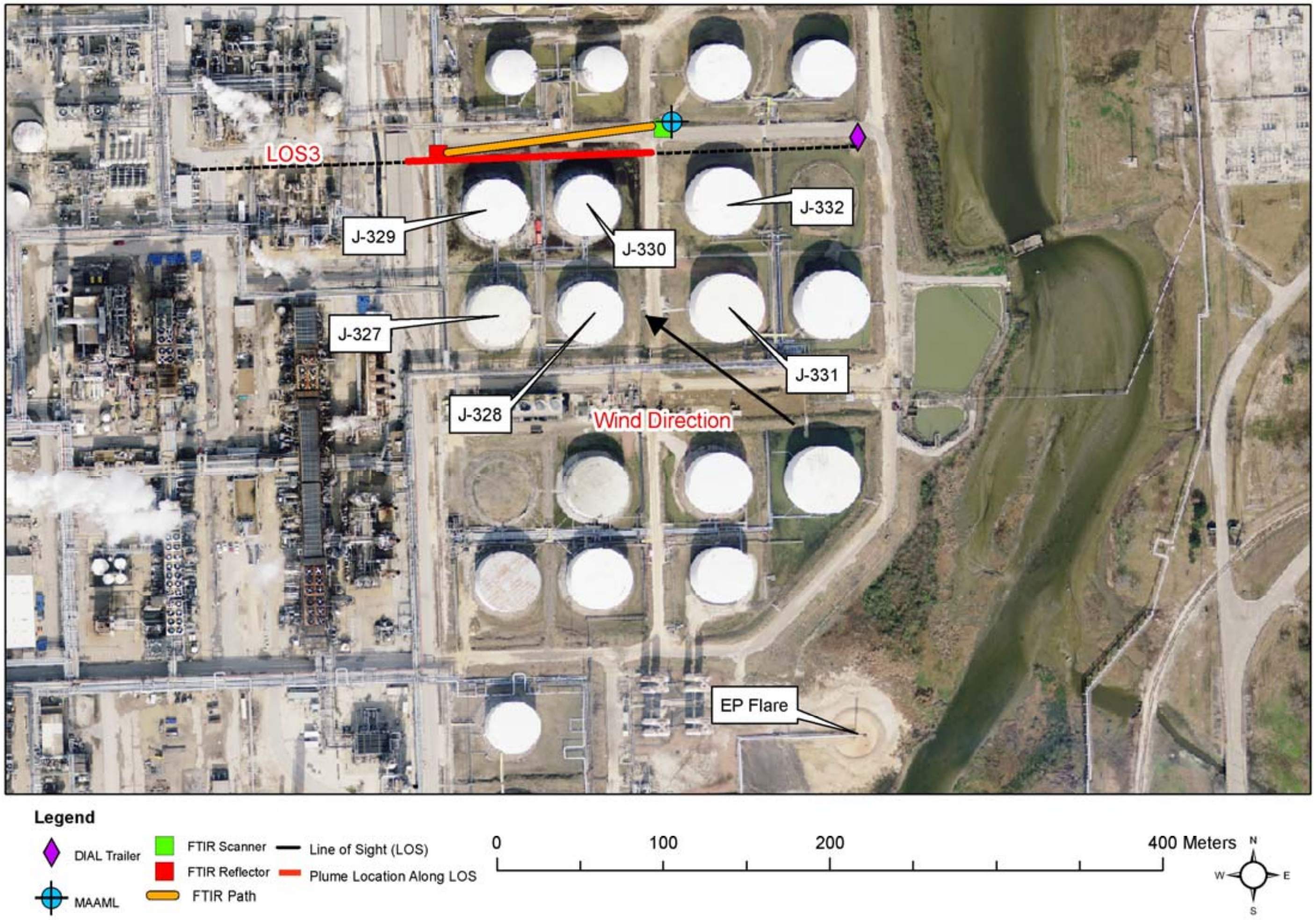
3.7 East Property Flare

Table 3.7 East Property Flare (EP Flare)

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/22/2010	SDP10/LOS1[†]	12:07-12:58, 14:03-14:38	VOC	0	10:00-16:00	Visual representation of LOS1 not available	NA, too few data points	none	*11:22-16:47	Visual representation of LOS1 not available	Not linearly related
2/2/2010	SDP18/ LOS1[†], LOS2[†]	10:54-17:05	VOC	0-1	10:00-16:00	Visual representation of LOS1 and LOS2 not available	Not linearly related. r=-0.59 not statistically significant p-value=0.21	Ethane, propane, 1,3 butadiene, n butane, n pentane, 1 hexene, 1,2 dichloroethane, trichloroethylene, tetrachloroethylene, chlorobenzene, 1,1,2,2-tetrachloroethane	10:56-16:47	Visual representation of LOS1 and LOS2 not available	Not linearly related

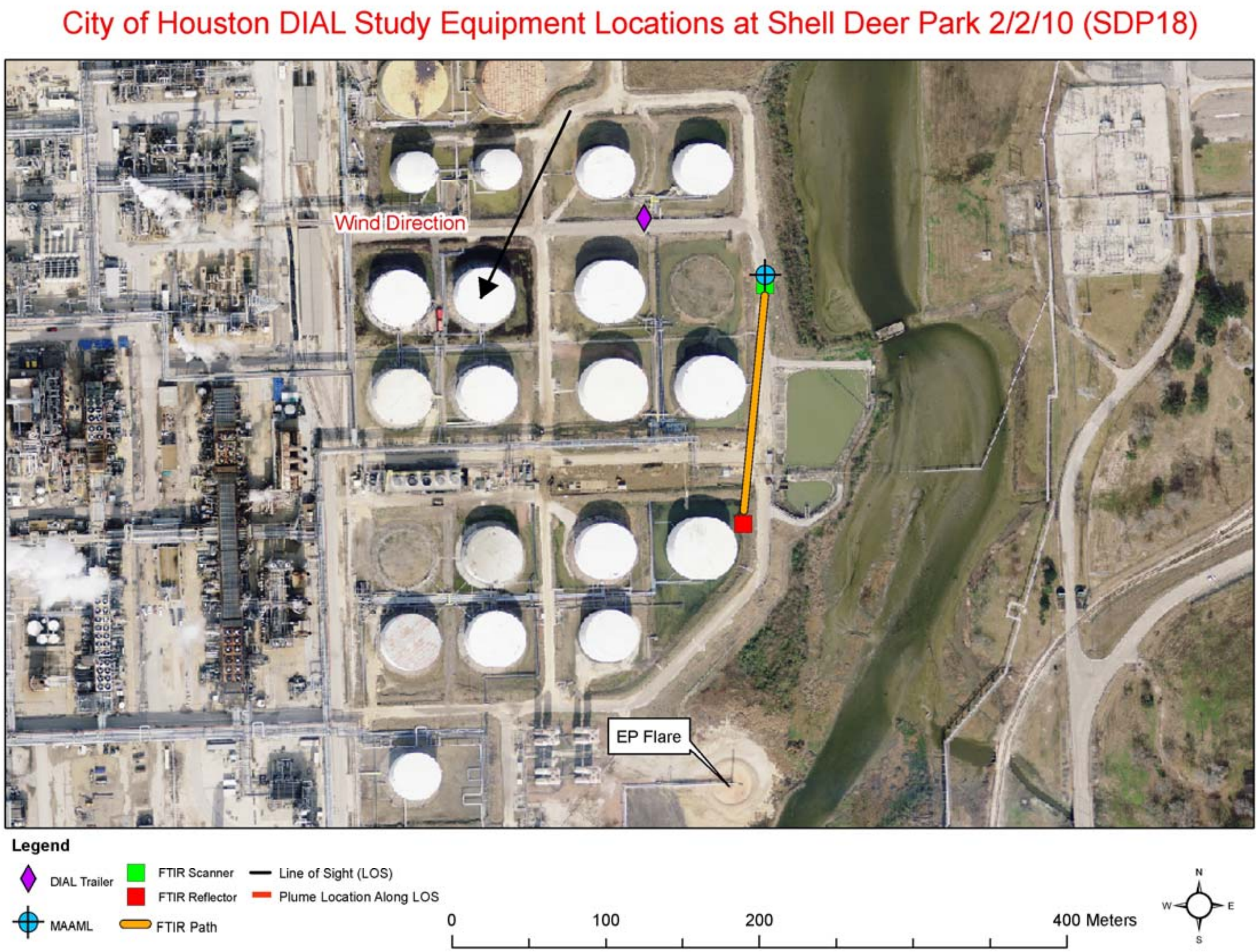
* FTIR by Time averaging method (TAM)

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.



City of Houston DIAL Study Equipment Locations at Shell Deer Park 1/22/10 (SDP10)

Figure 3.7a East Property Flare 1/22/2010



City of Houston DIAL Study Equipment Locations at Shell Deer Park 2/2/10 (SDP18)

Figure 3.7b East Property Flare 2/2/2010

3.8 East Tanks

Table 3.8 East Tanks (J-327, J-328, J-329, J-330, J-331, and J-332)

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/22/2010	SPD10/ LOS3	15:53-17:03	VOC	31	10:00-16:00	Out (Scan 247)	NA, too few data points	none	*11:22-16:47	Yes, 100% (Scan 247)	Not linearly related, similar pattern
1/23/2010	SPD11/ LOS1[†], LOS2	10:57-13:37, 15:50-17:06	VOC	5-19	10:00-16:00	Out (Scan 263)	linearly related r=0.72 not statistically significant p-value=0.16	Ethylene, propylene,n butane, n pentane, 2 methylpentane, hexane, toluene, ethylbenzene, m/p xylene, o xylene, cumene, 1,2 4 trimethylbenzene	10:25-16:47	No, 0% (Scan 263)	Not linearly related
1/28/2010	SPD15/ LOS1[†], LOS2	11:23-14:59, 16:17-16:41	VOC	32-33	10:00-16:00	Out (Scan 365)	With all data points (hour 11 through 14 and hour 16) linearly related inversely with r=-0.11 not statistically significant p-value=0.86, there is a wind shift at hour 11 when removed still no relationship with r=0.31 not statistically significant p- value=0.69	Ethylene, dichlorodifluormethane, acetylene, 1,2 dichlorotetrafluormethane, vinyl chloride, methylene chloride, 1 hexene, trichloroethylene, toluene, tetrachloro-ethylene, chlorobenzene	11:09-16:51	No, 0% (Scan 365)	Linearly related, inverse relationship, r=-0.55, regression is significant p-value =0.02, Dial is positively correlated with wind direction and FTIR is negative correlated with wind direction. Multiple linear regression predicting emission rate from FTIR and wind direction has coefficients not significant

* FTIR by Time averaging method (TAM)

[†] This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

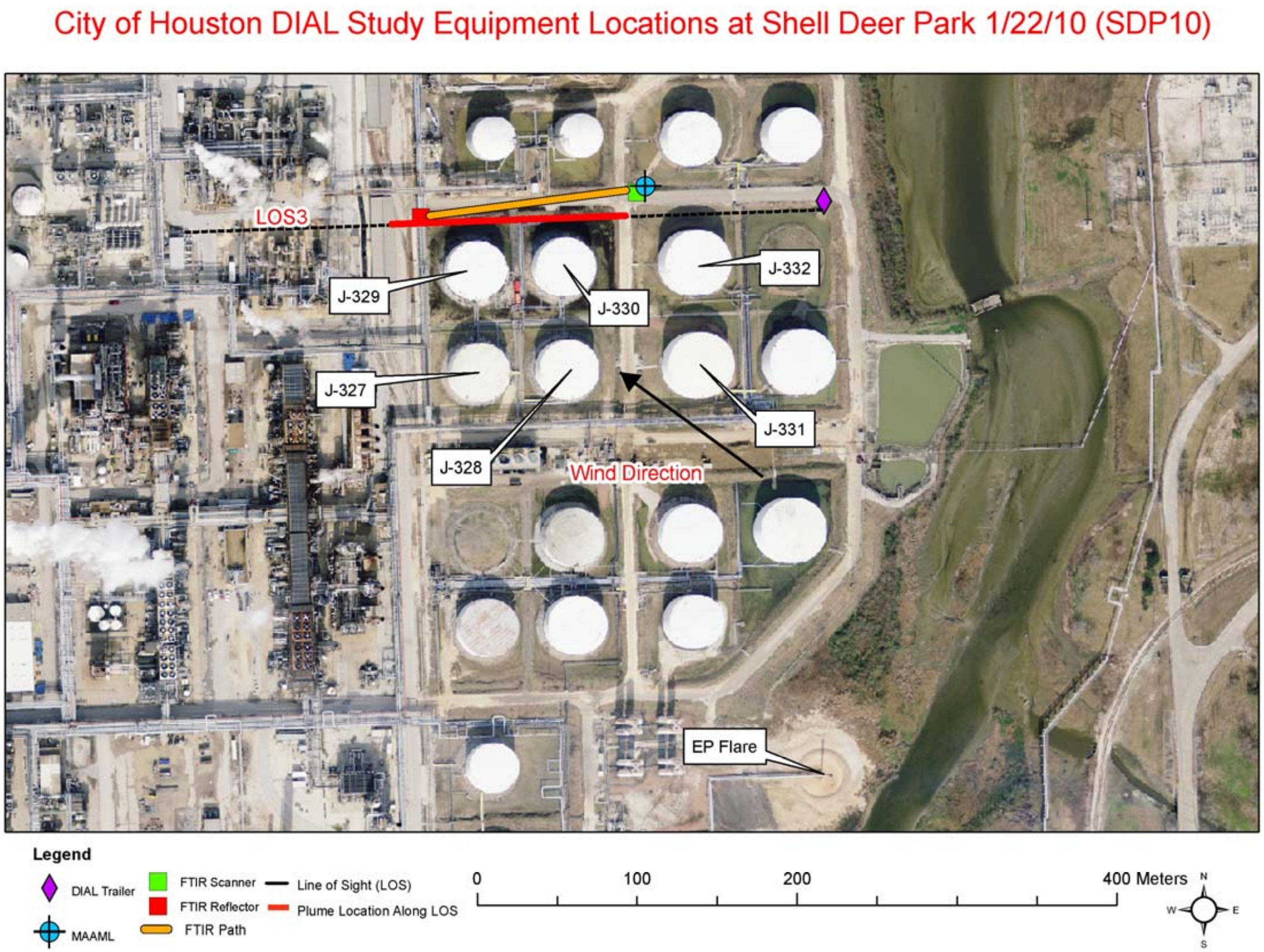


Figure 3.8a East Tanks 1/22/2010

City of Houston DIAL Study Equipment Locations at Shell Deer Park 1/23/10 (SDP11)

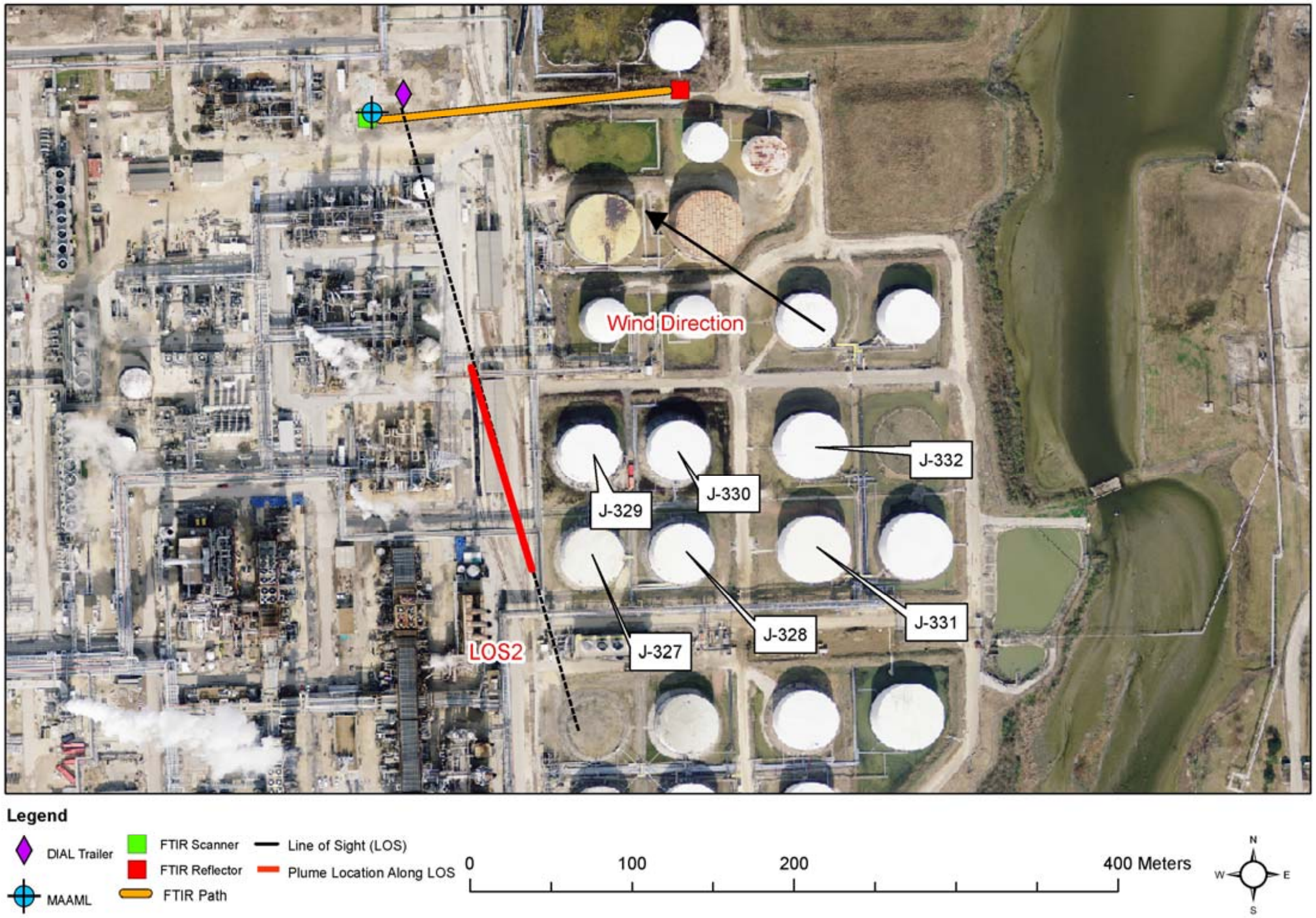


Figure 3.8b East Tanks 1/23/2010

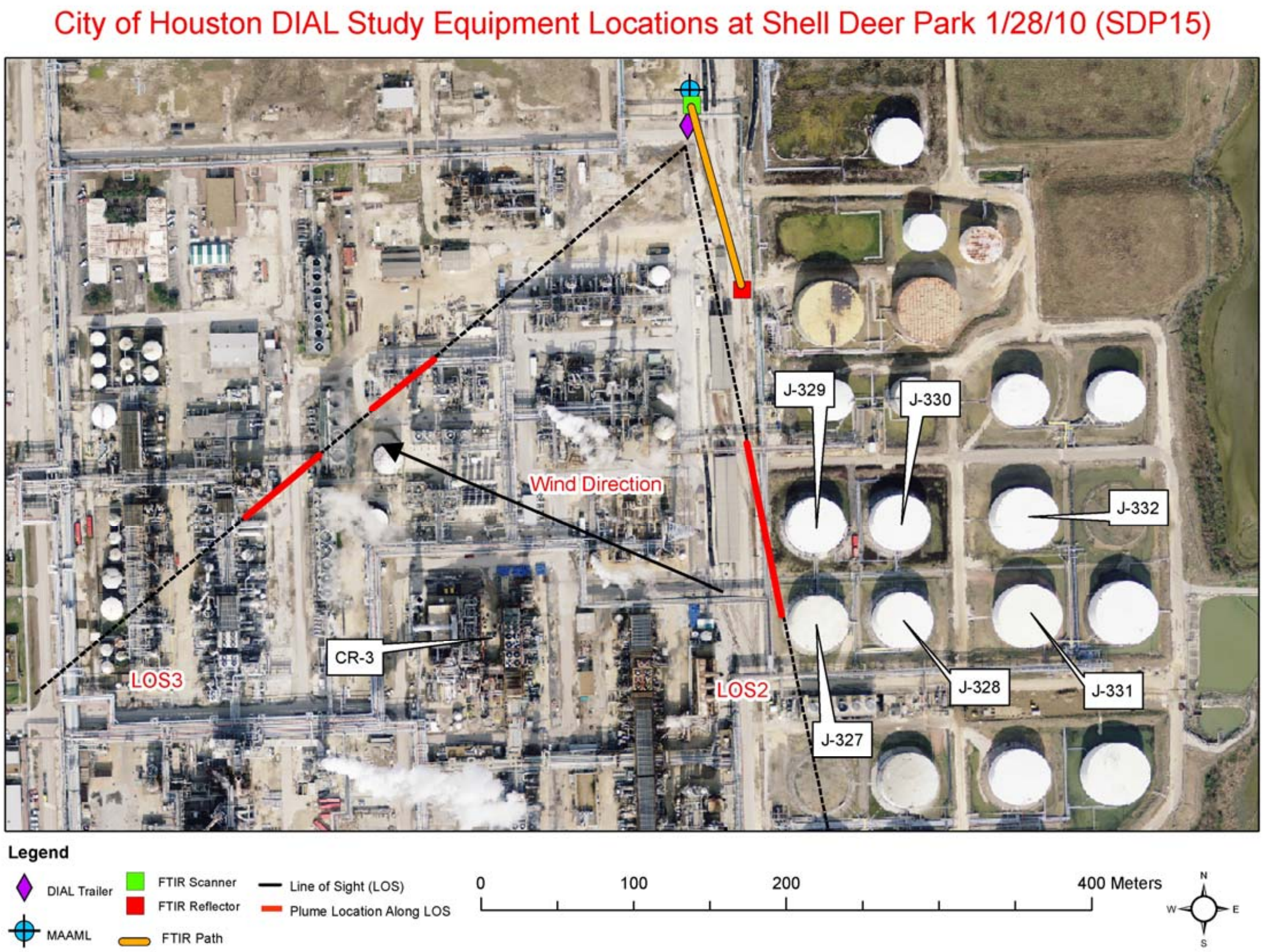


Figure 3.8c East Tanks 1/28/2010

3.9 North Wastewater Area

Table 3.9 North Wastewater Area

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/25/2010	SPD12/LOS1, LOS2[†]	10:42-13:54	VOC	2-22 (possible emission sources: west area of aeration basin SAB (EWT-12) and NAB (EWT-11), and aeration tanks west of aeration basin NDAF (EWT-9), SDAF (EWT-10), X316, FLSHMIX (EWT-7) and FLCCULTR (EWT-8))	10:00-16:00	Out (Scan 280)	NA, too few data points, not linearly related and wind change	Ethane, ethylene, propane, acetylene, vinyl chloride, n butane, methylene chloride, 1,1,2 trichlorotrifluorethane, 1 hexene, trichloroethylene, toluene, tetrachloroethylene, m/p xylene, o xylene, 1,2,4 trimethylbenzene, 1,3 dichlorobenzene, 1,2 dichlorobenzene, hexachloro 1,3 butadiene	10:41-16:47	Yes, 5% (Scan 280)	Linearly related, r=0.95, regression significant p-value<0.001
1/30/2010	SPD12/LOS1, LOS2, LOS5, LOS6[†]	12:26-14:47, 15:48-17:01	VOC	800-1200 (possible emission sources: aeration tanks west of aeration basin NDAF (EWT-9), SDAF (EWT-10), X316, FLSHMIX (EWT-7) and FLCCULTR (EWT-8))	10:00-16:00	Out (Scan 401, Scan 405, Scan 415)	Hour 12-14 (all downwind of wastewater) are correlated, r=0.31, regression is not significant p-value =0.61	1-hexene	11:05-16:50	Yes, 40% (Scan 401) No, 0% (Scan 405) Yes, 10% (Scan 415)	Linearly related, r=0.56, regression significant p-value=<0.04

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/5/2010	SPD21/LOS1, LOS2, SPD22/LOS1	10:50-14:11, 14:47-16:56	VOC	400-600 (possible emission sources: aeration basin SAB (EWT-12) and NAB (EWT-11), and aeration tanks west of aeration basin NDAF (EWT-9), SDAF (EWT-10), X316, FLSHMIX (EWT-7) and FLCCULTR (EWT-8))	10:00-16:00	In (Scan 529, Scan 532) Out (Scan 537)	Not linearly related as a group or by SDP	N-pentane	*14:02-16:48	Yes, 100% (Scan 529, Scan 532) Yes, 30% (Scan 537)	Linearly related, correlated, r=0.66, regression is not significant p-value =0.15
2/9/2010	SPD25/LOS1	10:42-11:59, 13:10-16:57	Benzene	6 (possible emission sources: trickling filter (TKRFIL), NDAF (EWT-9), SDAF (EWT-10), X316, FLSHMIX (EWT-7), FLCCULTR (EWT-8), X-330, X330SM, T-301, and T-302)	9:00-16:00	Out (Scan 571)	Not linearly related, MAAML reported a spike of benzene at hour 15 that DIAL did not report	Ethane, propane, n-butane, 1,1,2 trichlorotrifluoroethane, n pentane, 2 methyl pentane, 1 hexene, hexane, 1,2 dichloroethane, benzene, toluene, chlorobenzene, m/p xylene, o xylene, 1,2,4 trimethylbenzene	*10:46-16:46	No, 0% (Scan 571)	Not linearly related, FTIR reported a spike of benzene at hour 15 that DIAL did not report

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/13/2010	SPD29/LOS3	12:53-14:40, 16:27-16:42	Benzene	4 (possible emission sources: SAB (EWT-12), NAB (EWT-11), EWT-13, EWT-14, trickling filter (TKRFIL), NDAF (EWT-9), SDAF (EWT-10), X316, FLSHMIX (EWT-7), FLCCULTR (EWT-8), X-330, X330SM, T-301, and T-302)	10:00-16:00	Out (Scan 672)	Not linearly related	none	11:22-16:43	No, 0% (Scan 672)	NA,all but one nondetect

* FTIR by Time averaging method (TAM)

† This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

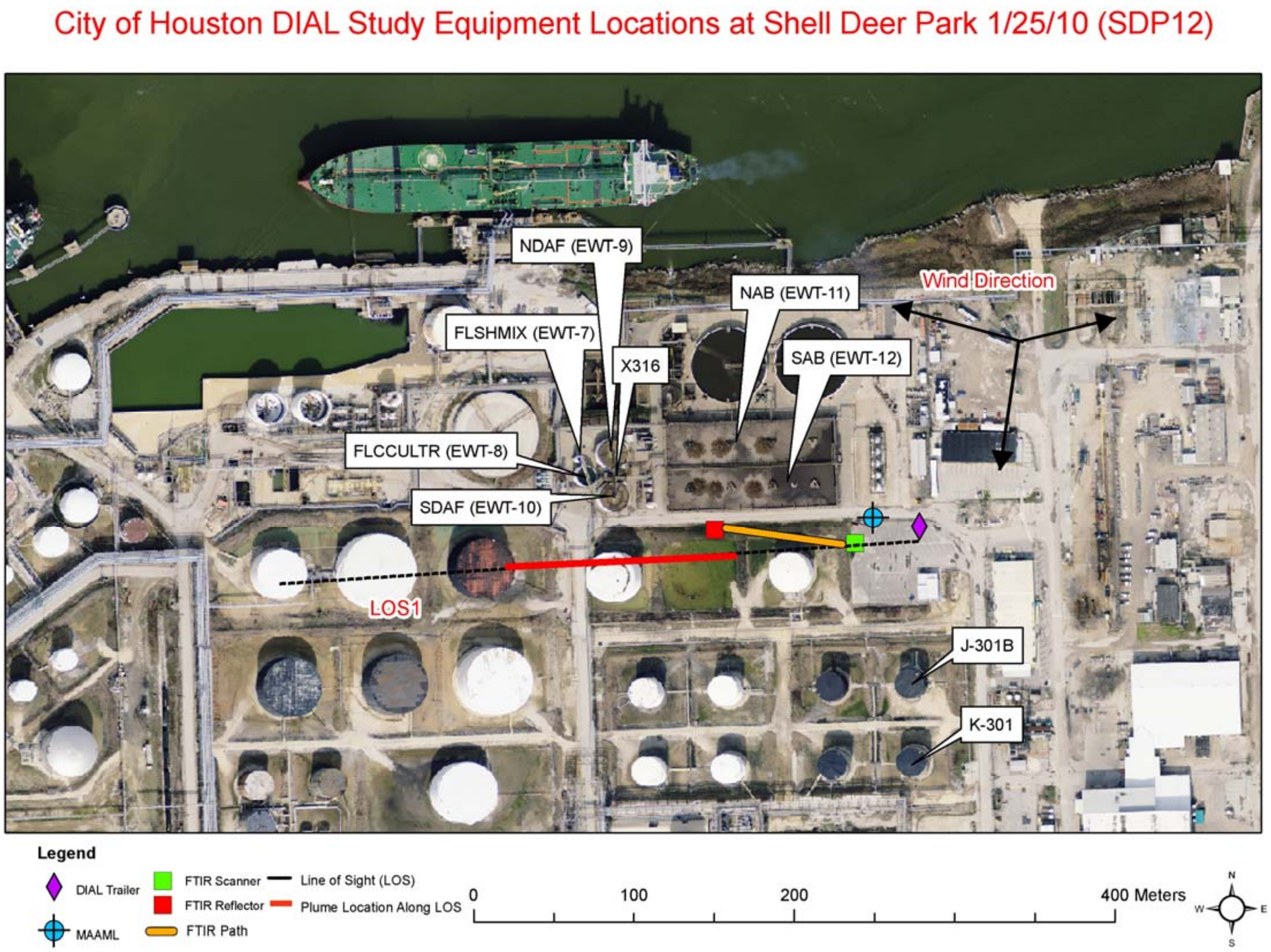


Figure 3.9a North Wastewater Area 1/25/2010

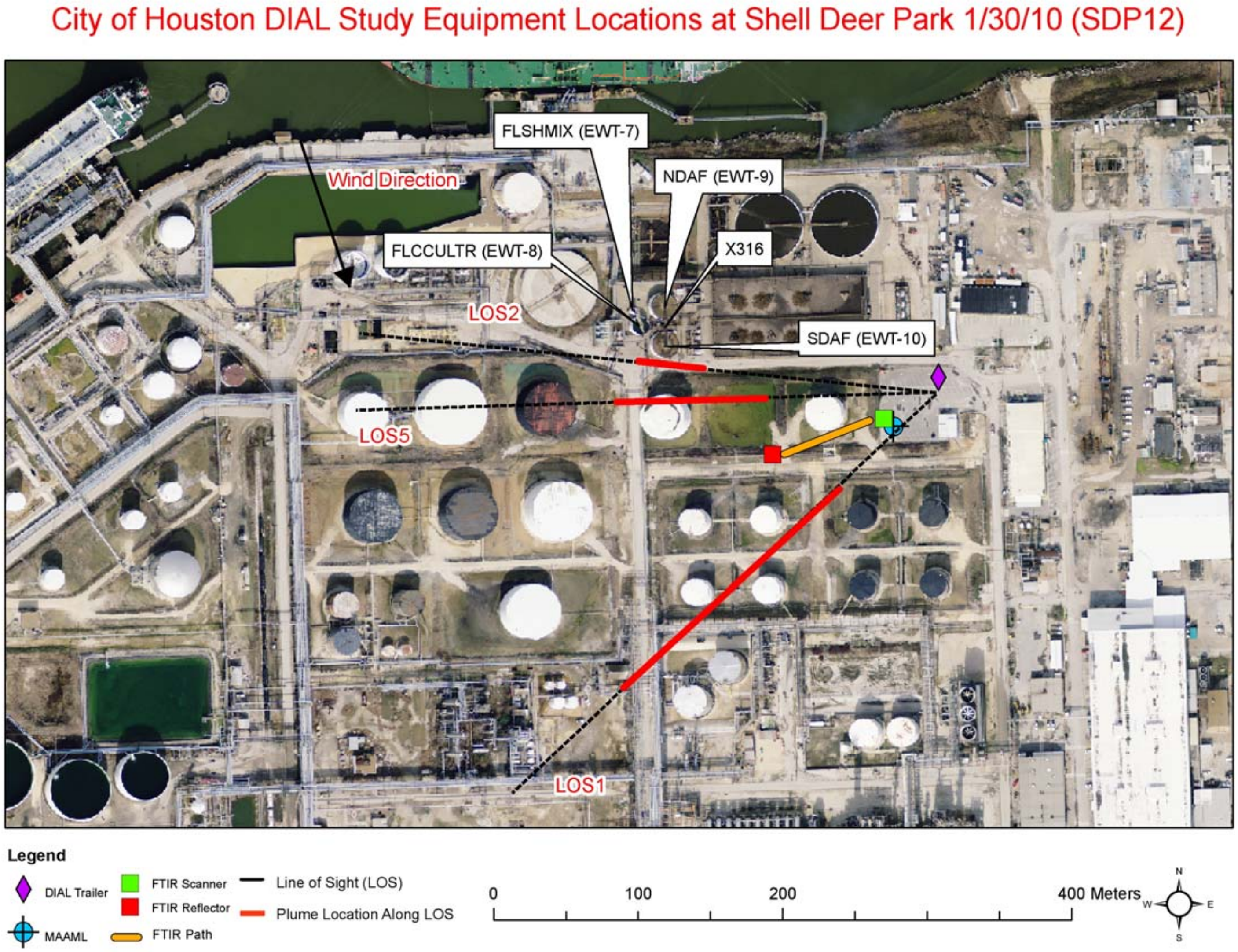


Figure 3.9b North Wastewater Area 1/30/2010

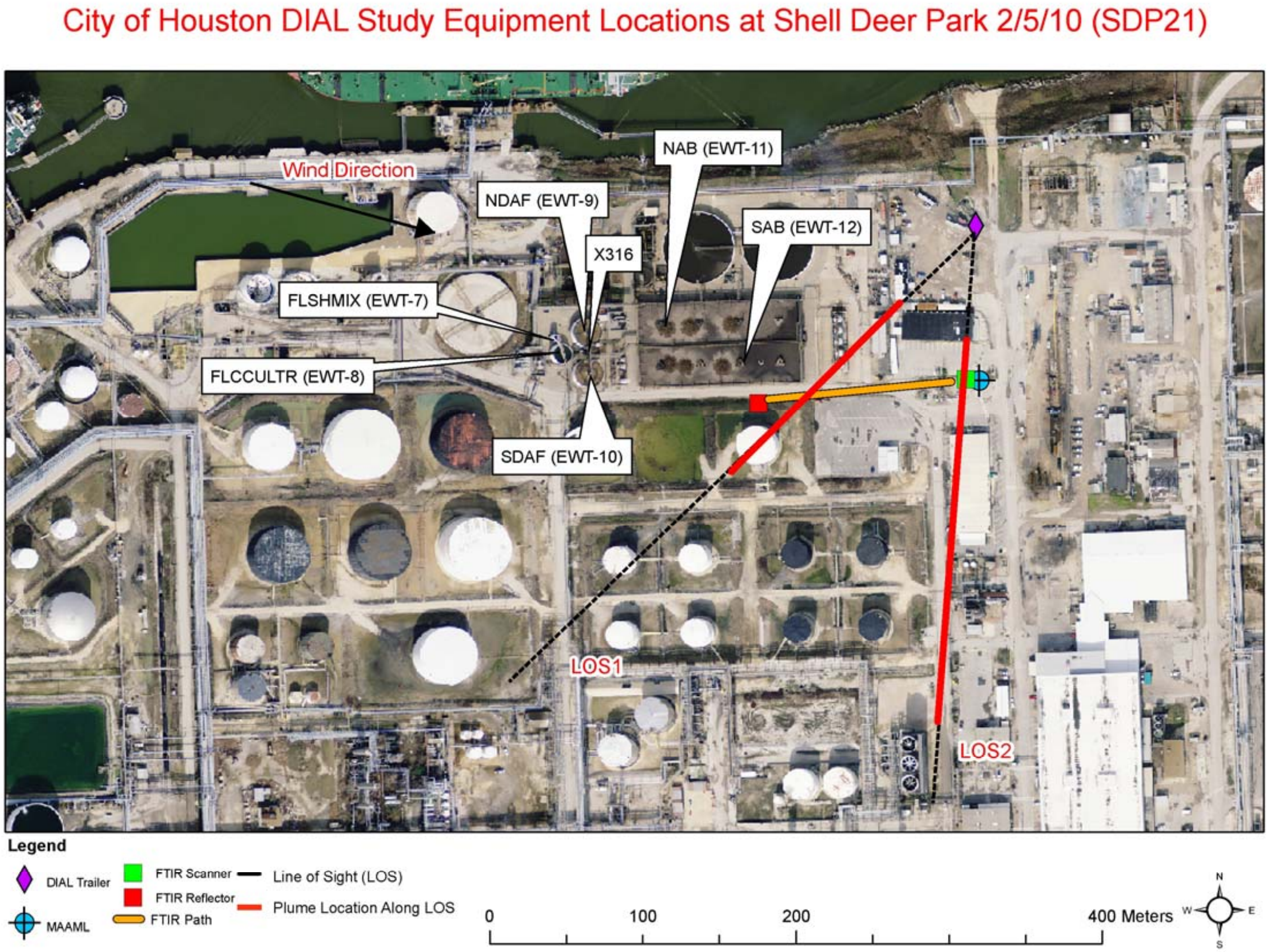


Figure 3.9c North Wastewater Area 2/5/2010

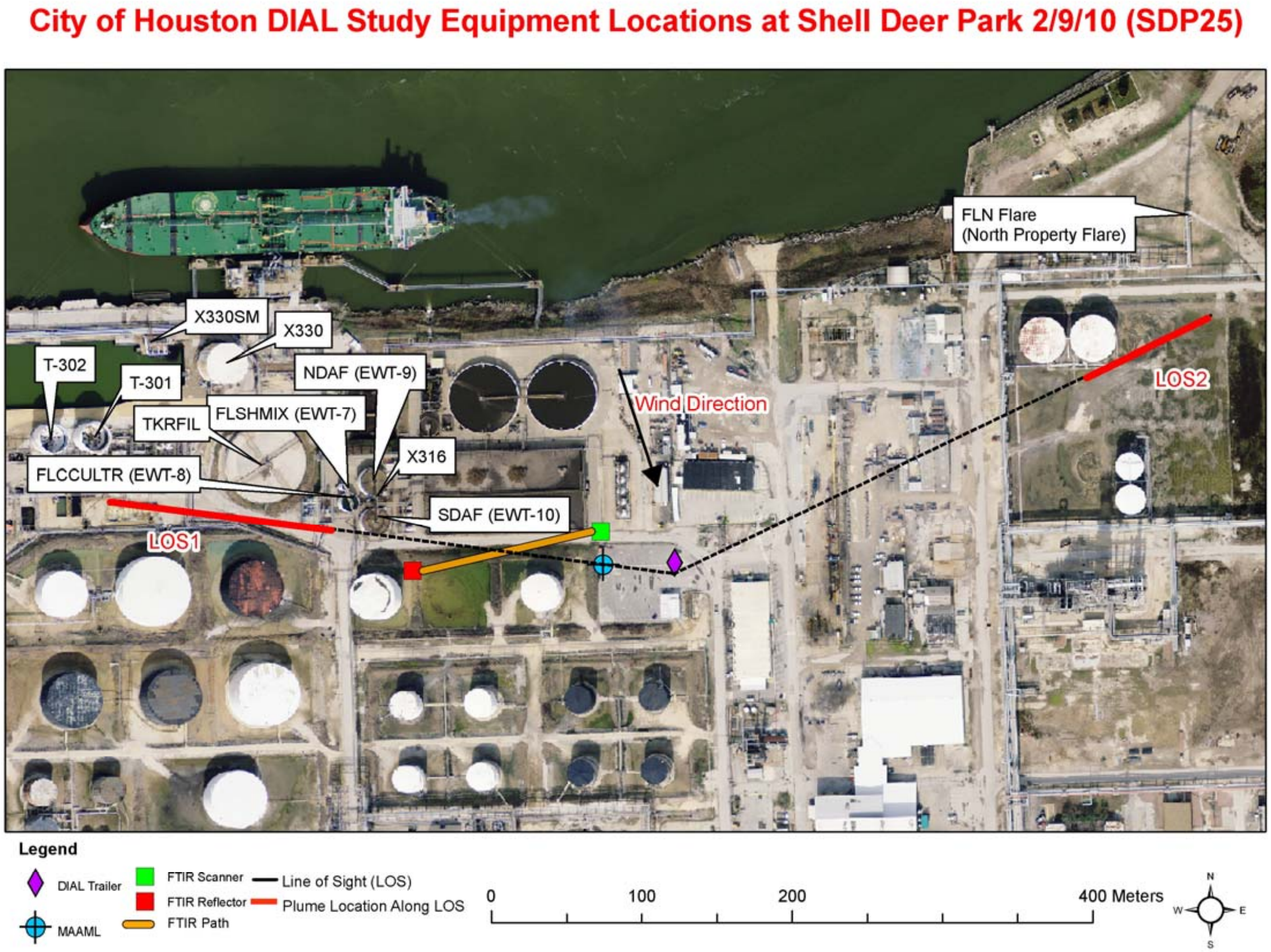
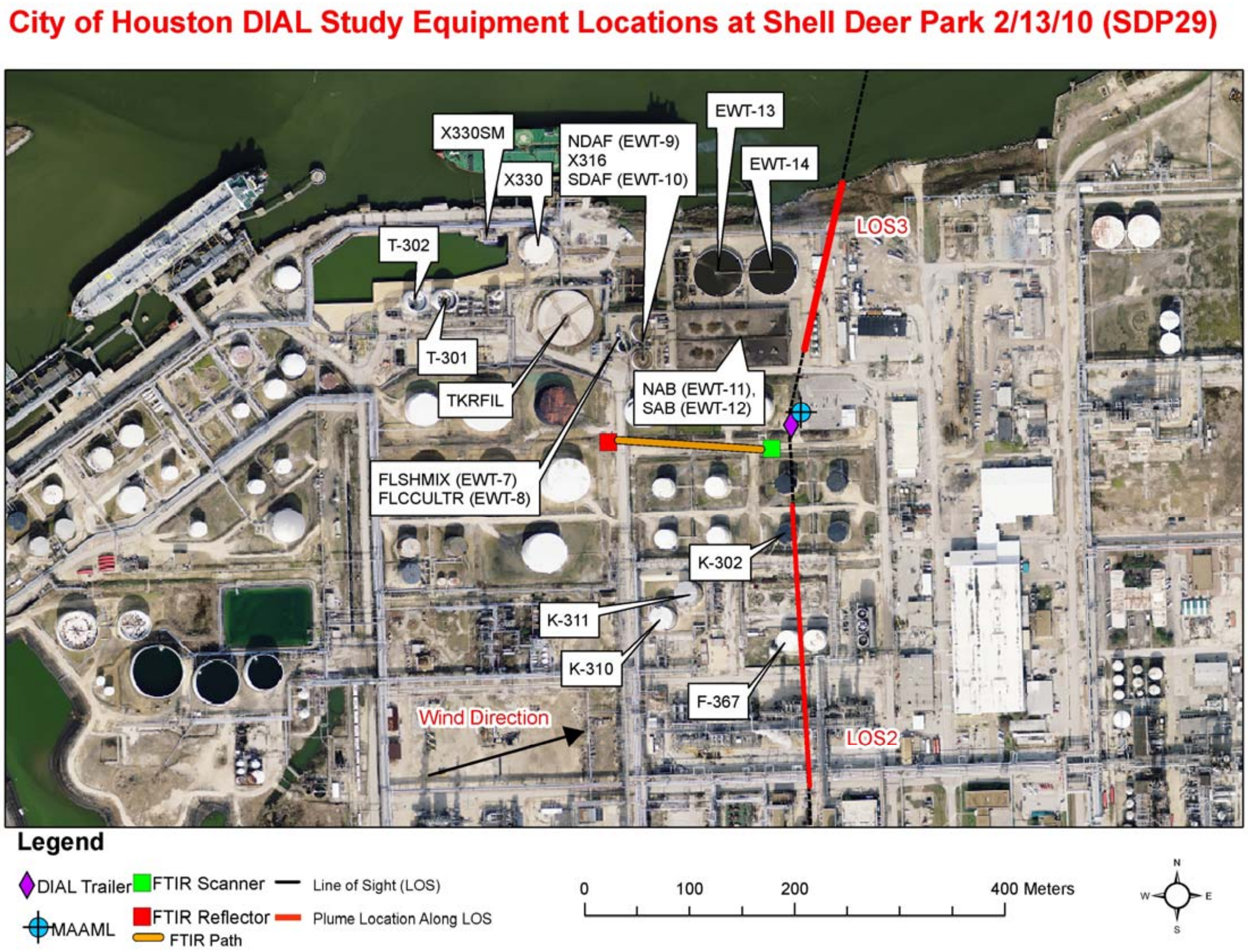


Figure 3.9d North Wastewater Area 2/9/2010



City of Houston DIAL Study Equipment Locations at Shell Deer Park 2/13/10 (SDP29)

Figure 3.9e North Wastewater Area 2/13/2010

3.10 East Wastewater and Flares Area

Table 3.10 East Wastewater and Flares Area

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
1/26/2010	SPD13/ LOS2	14:53-15:21	VOC	1 (possible emission source: A1313 (HIPA Flare))	10:00-16:00	Out (Scan 309)	NA, too few data points	toluene	11:18-16:45	No, 0% (Scan 309)	NA, too few data points
2/1/2010	SPD17/ LOS1, LOS2†, LOS5†	12:16-14:13, 15:46-17:05	VOC	23-27 (possible emission sources: WAERAT, MAERAT, EAERAT, A-13113, A-1304, T-1372, T-1331, T-1332, T-1333, T-1334, T-1310, T-320, NAPI, and SAPI)	10:00-16:00	Out (Scan 422)	NA, too few data points	Ethane, ethylene, propane, propylene, acetylene, vinyl chloride, 1,3 butadiene, tri chlorofluoro-methane, 1 hexene, toluene, 1,2,4 trimethyl-benzene, 1,2 dichloroethane	11:52-16:47	Yes, 10% (Scan 422)	No linear relationship for overall time series, however there is a similar pattern in DIAL and FTIR over time when the wind direction is greater than 100 degrees for time period 12:16-14:13
2/1/2010	SPD17/ LOS3†, LOS4†	14:20-15:10	VOC	0 (possible emission source: A1301 (A&S Flare)	10:00-16:00	Visual representation of LOS3 and LOS4 not available	NA, too few data points	Ethylene, 1,3 butadiene, methylene chloride, chloroform, toluene,	11:52-16:47	Visual representation of LOS3 and LOS4 not available	Few data points, Linearly related, correlated, r=0.56, regression is not significant p-value =0.32

† This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

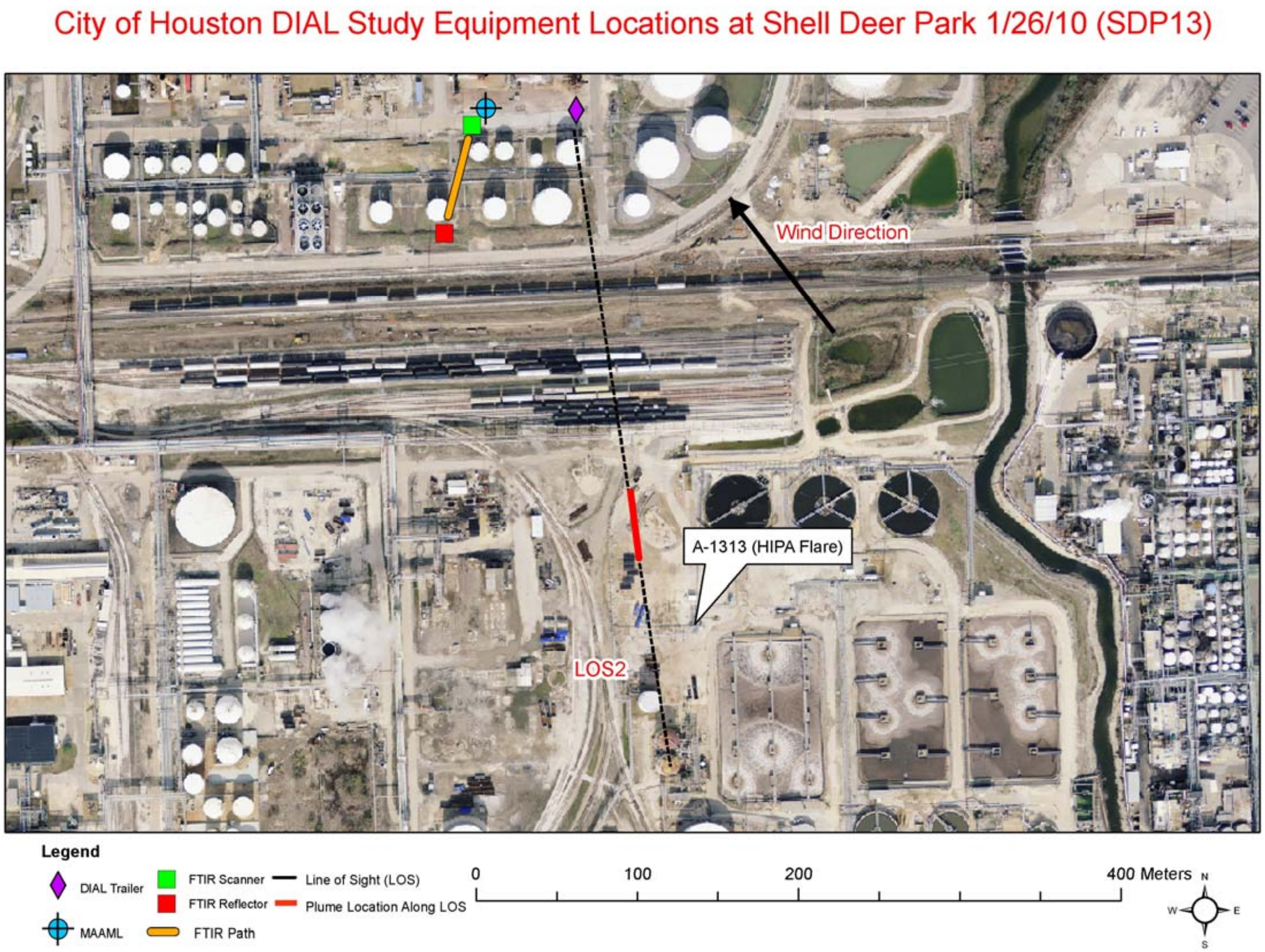


Figure 3.10a East Wastewater and Flares Area 1/26/2010

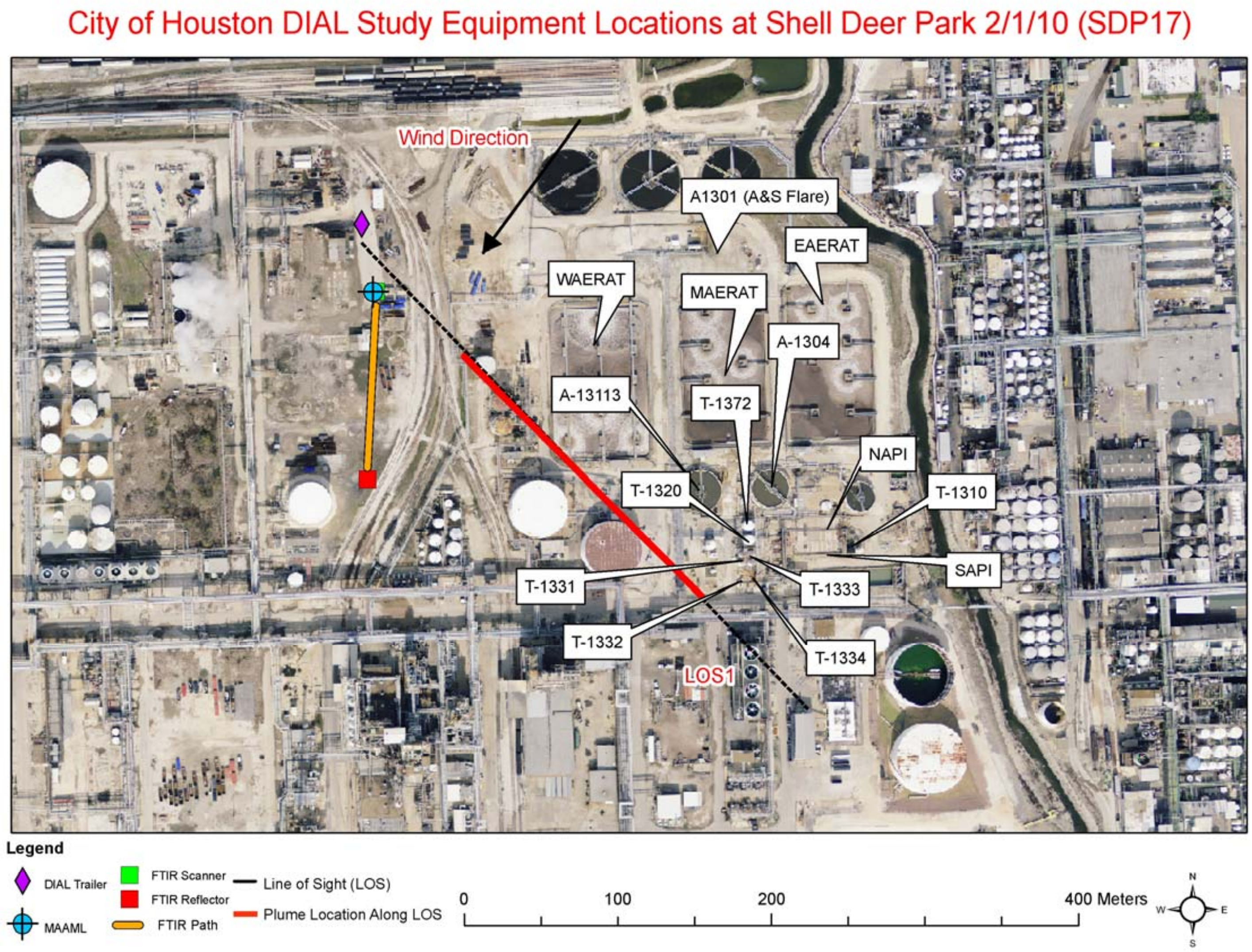


Figure 3.10b East Wastewater and Flares Area 2/1/2010

3.11 Tank Farm B

Table 3.11 Tank Farm B

1 Date	2 DIAL Location / LOS	3 DIAL hours	4 DIAL	5 Average DIAL emission rate (lbs/hour)	6 MAAML hours	7 Location of MAAML	8 MAAML correlation with DIAL plume	9 MAAML outliers	10 FTIR hours	11 FTIR aligned with DIAL plume	12 FTIR correlation with DIAL plume
2/3/2010	SPD19/LOS1	10:30-16:54	VOC	3 (possible emission sources: tanks T3, T4, T216, T89, T181, T185B, T73C, T69C, T3150, T77B, T198, T189, T188, T344, T8B with possible up wind contributions)	9:00-16:00	Out (Scan 487)	Not linearly related	Ethylene, vinyl chloride, 1,3 butadiene, ethyl chloride, methylene chloride, 1,1 dichloroethane, 1 hexene, cis 1,2 dichloroethylene, chloroform, 1,2 dichloroethane, trichloroethylene, 1,1,2 trichloroethane, chlorobenzene	10:22-16:47	Yes, 5% (Scan 487)	Not linearly related, has similar pattern

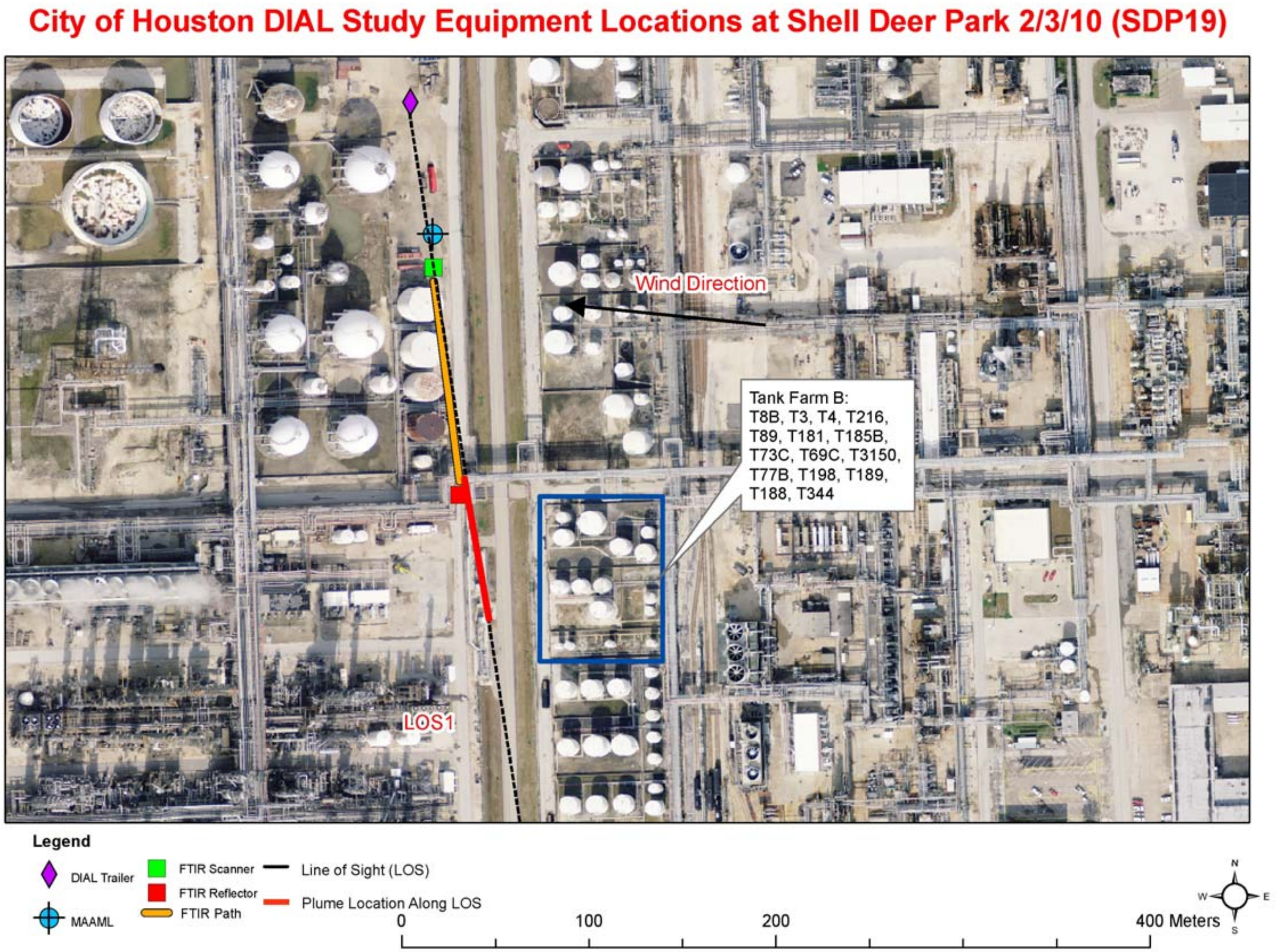


Figure 3.11a Tank Farm B 2/3/2010

3.12 Tanks T-OL913 and T-OL920

Table 3.12 Tanks T-OL913 and T-OL920

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/8/2010	SPD24/LOS1	14:15-17:23	Benzene	6	13:00-16:00	In (Scan 555)	NA, too few data points	1,3 butadiene, n pentane	14:20-16:47	Yes, 80% (Scan 555)	FTIR all nondetect
2/10/2010	SPD26/LOS1	9:55-17:05	Benzene	5	9:00-16:00	Out (Scan 614)	Not linearly related, MAAML detects high benzene in hour 15-16 that isn't well reflected in DIAL	Ethane, ethylene, propylene, acetylene, 1,3 butadiene, trichlorofluormethane, methylene chloride, 1 hexene, hexane, chloroform, 1,2 dichloroethane, benzene, trichlorotheylene	10:45-16:45	Yes, 50% (Scan 614)	FTIR all nondetect except at 12:43 when benzene detected at 64 ppb, nothing in hour 15-16
3/23/2010	SPD33/LOS1	10:18-17:05	Benzene	25	MAAML not deployed	MAAML not deployed	NA	NA	*10:14-16:47	Yes, 100% (Scan 778)	Not linearly related, but similar pattern in time series

* FTIR by Time averaging method (TAM)

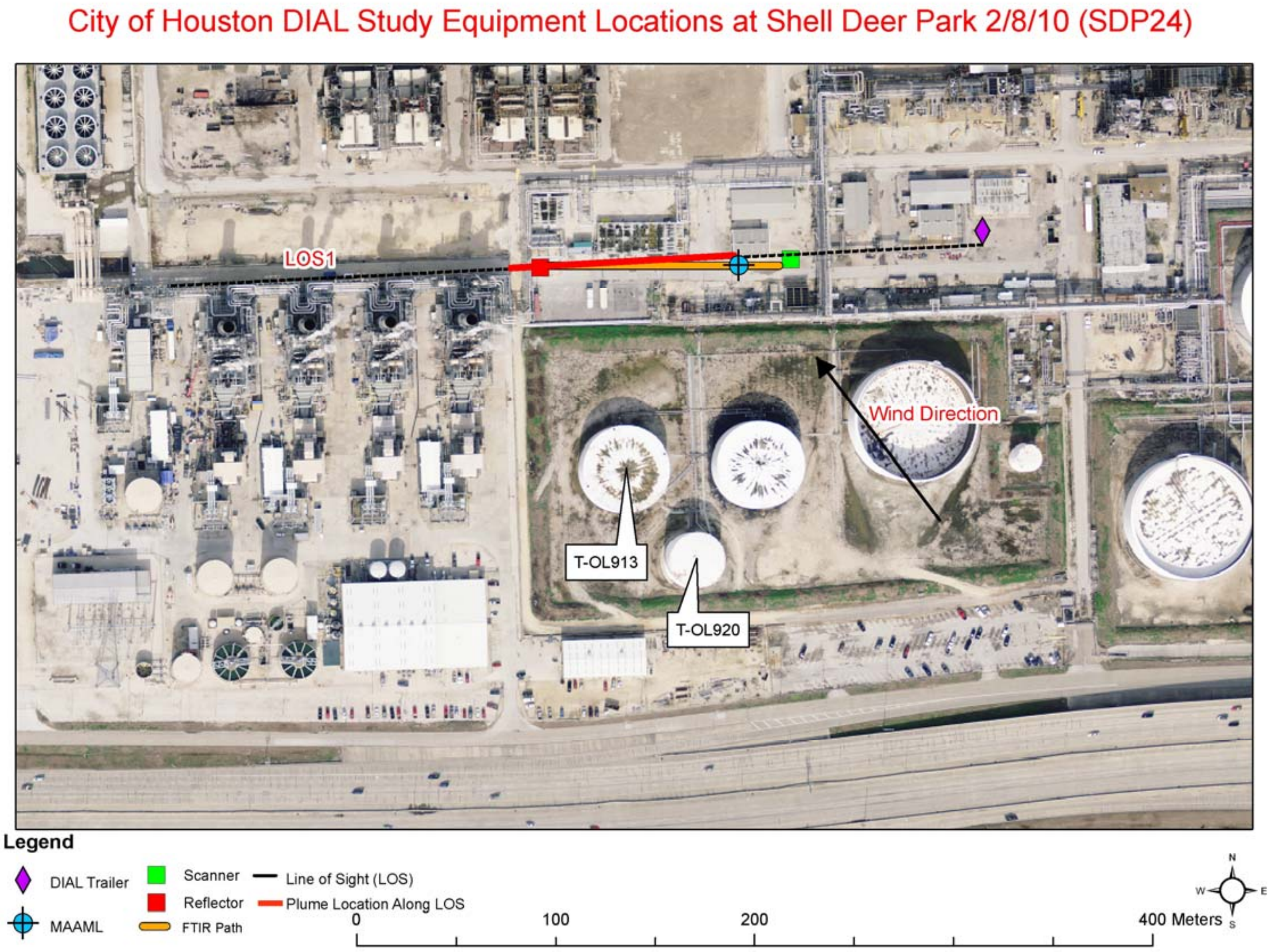


Figure 3.12a Tanks T-OL913 and T-OL920 2/8/2010

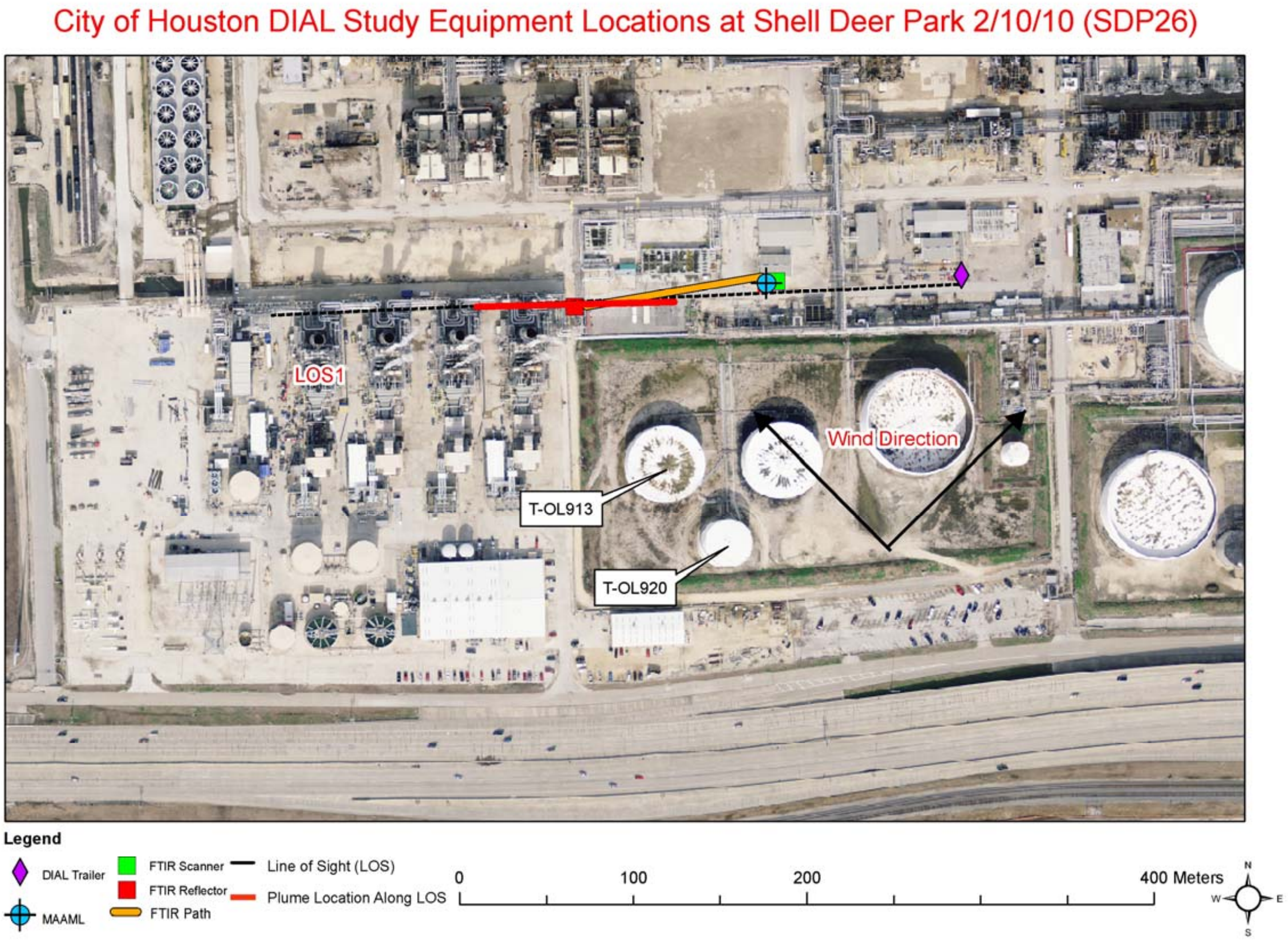


Figure 3.12b Tanks T-OL913 and T-OL920 2/10/2010

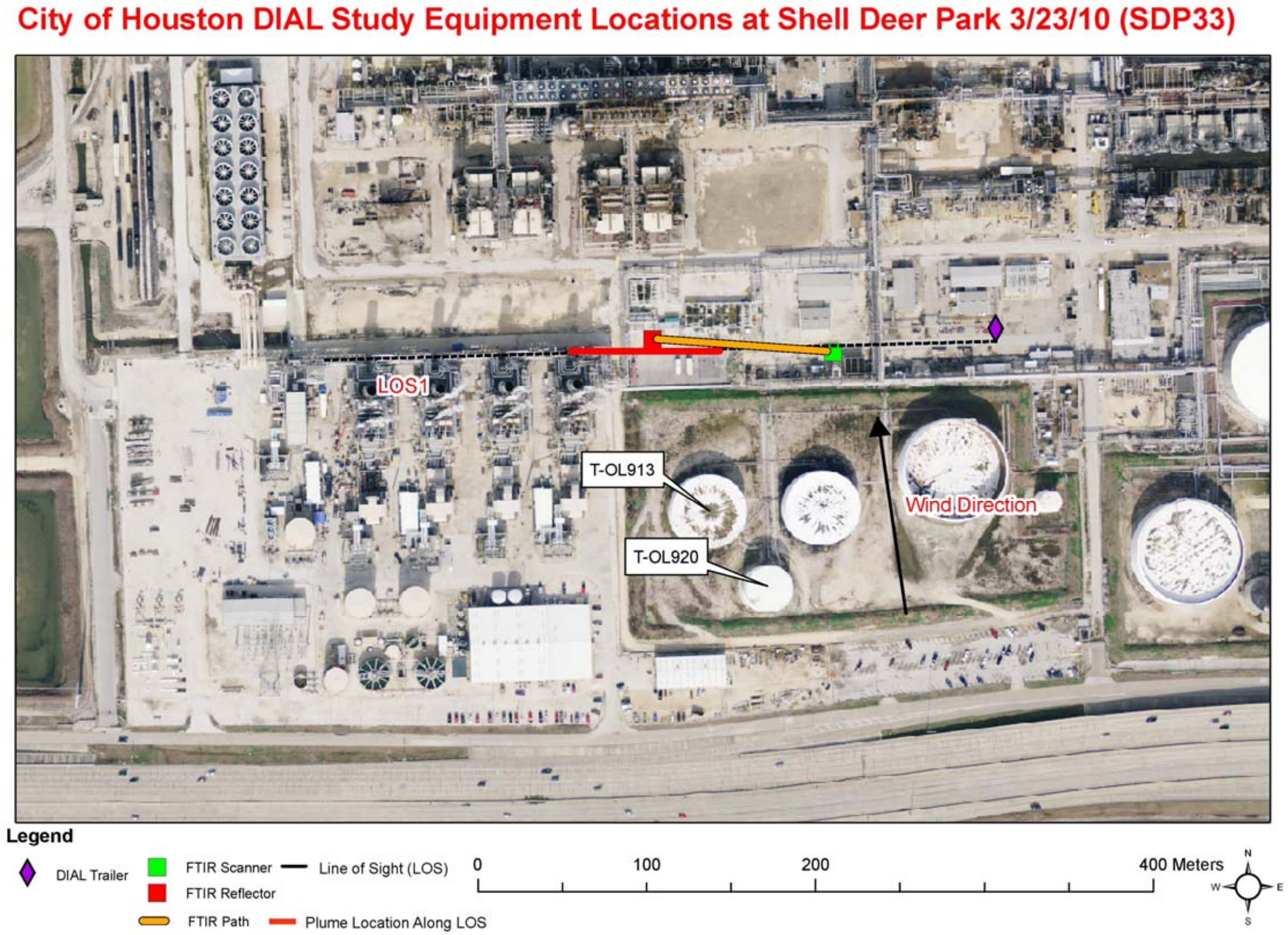


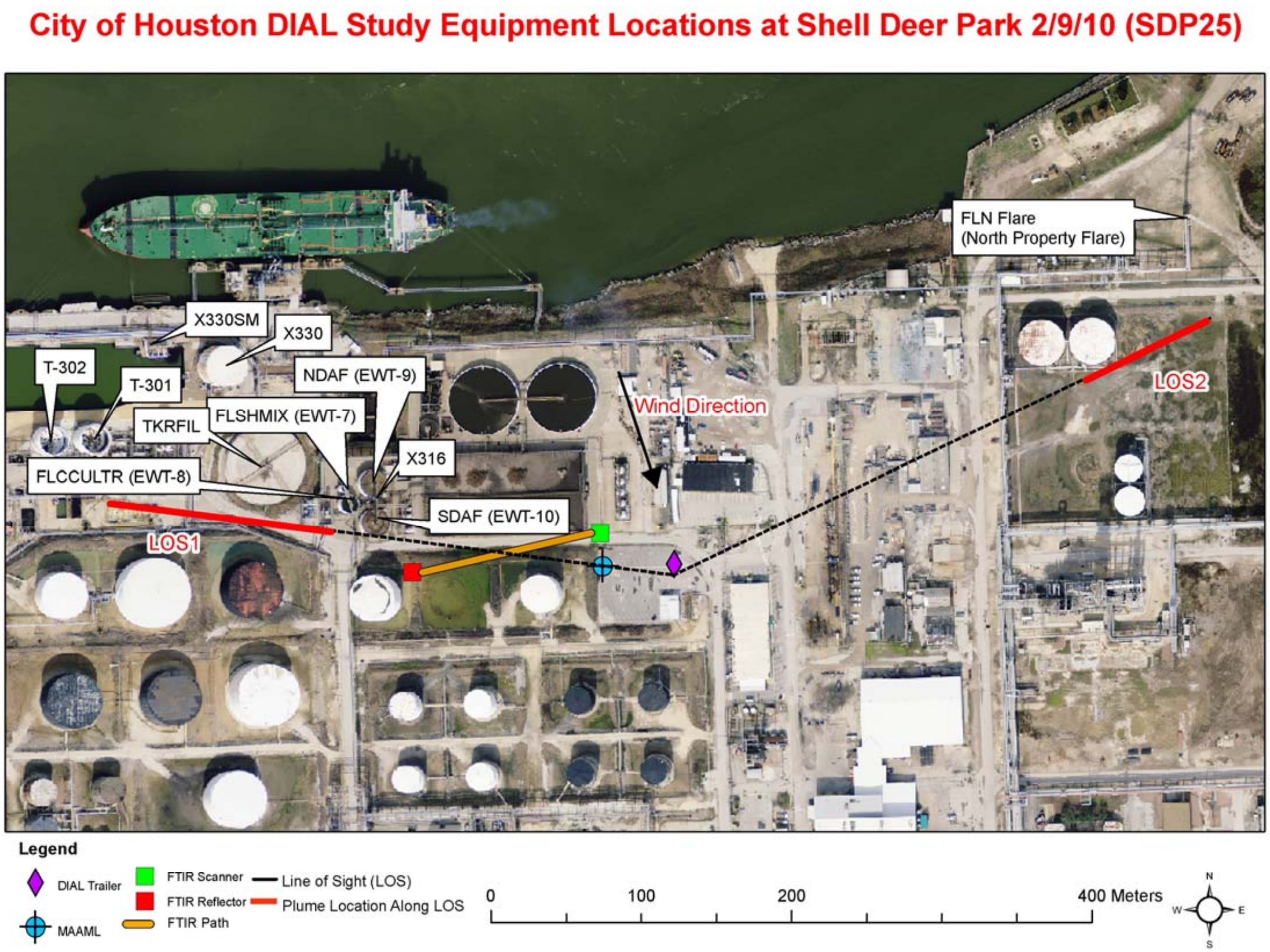
Figure 3.12c Tanks T-OL913 and T-OL920 3/23/2010

3.13 North Property Flare

Table 3.13 North Property Flare (FLN Flare)

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/9/2010	SPD25/LOS2	12:04-12:50	Benzene	2	9:00-16:00	Out (Scan 574)	NA, too few data points	none	*10:46-16:46	No, 0% (Scan 574)	NA, too few data points

* FTIR by Time averaging method (TAM)



City of Houston DIAL Study Equipment Locations at Shell Deer Park 2/9/10 (SDP25)

Figure 3.13a North Property Flare 2/9/2010

3.14 ACU and BEU

Table 3.14 ACU and BEU

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/12/2010	SDP28/LOS1	10:40-16:40	Benzene	27	10:00-16:00	Out (Scan 647)	r =-0.57, p-value =0.18	Ethane, propane, dichlorodifluoromethane, 1-hexene, benzene, toluene, tetrachloroethylene, cumene	11:13-15:57	Yes, 80% (Scan 647)	Benzene nondetect
2/15/2010	SPD28/LOS1	10:18-11:15, 12:21-13:13, 14:18-15:09	Benzene	13	9:00-16:00	Out (Scan 693)	r =0.86 with outlier value p-value = 0.06, and r=0.07 without p-value = 0.93	Benzene, tetrachlorethane	*10:38-16:45	Yes, 100% (Scan 693)	r=0.92 with outlier, p-value=0.0014, r = 0.014 without outlier p-value = 0.98
3/26/2010	SPD35/LOS1	10:53-13:33	VOC	64-65	10:00-13:00	Out (Scan 824)	r =0.44 after excluding one hour when wind changed direction, not significant p-value = 0.38	1,3 butadiene, 1-hexene, benzene	*10:28-12:58	Yes, 40% (Scan 824)	No alkanes detected
3/26/2010	SPD36/LOS1	14:38-17:05	VOC	64-65	14:00-16:00	Out (Scan 836)		Ethylene, propylene, vinyl chloride, methylene chloride, benzene, toluene, 2-methyl pentane, o xylene, m/p xylene, ethylbenzene	*13:02-16:47	Yes, 100% (Scan 836)	

* FTIR by Time averaging method (TAM)

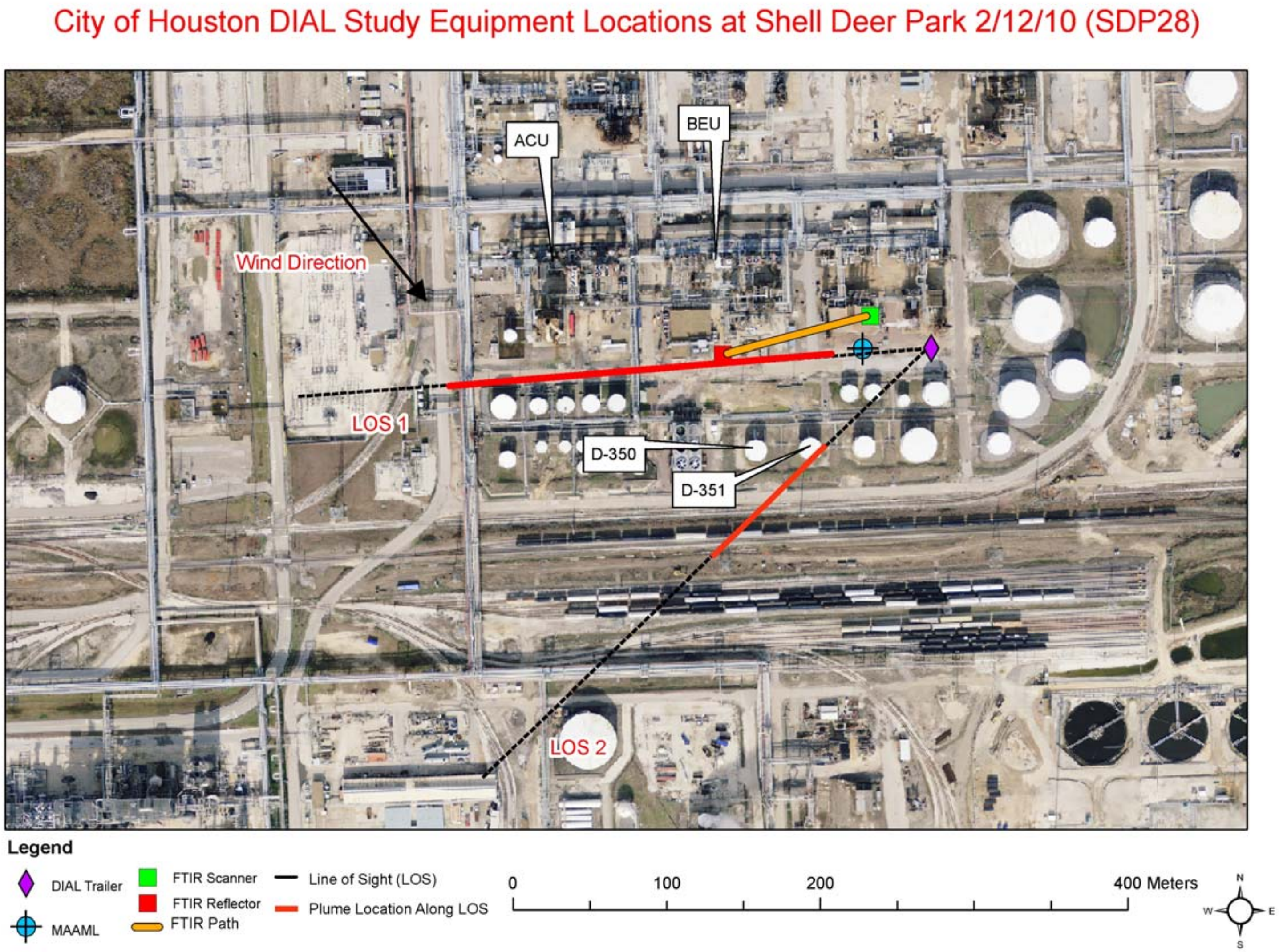


Figure 3.14a ACU and BEU 2/12/2010

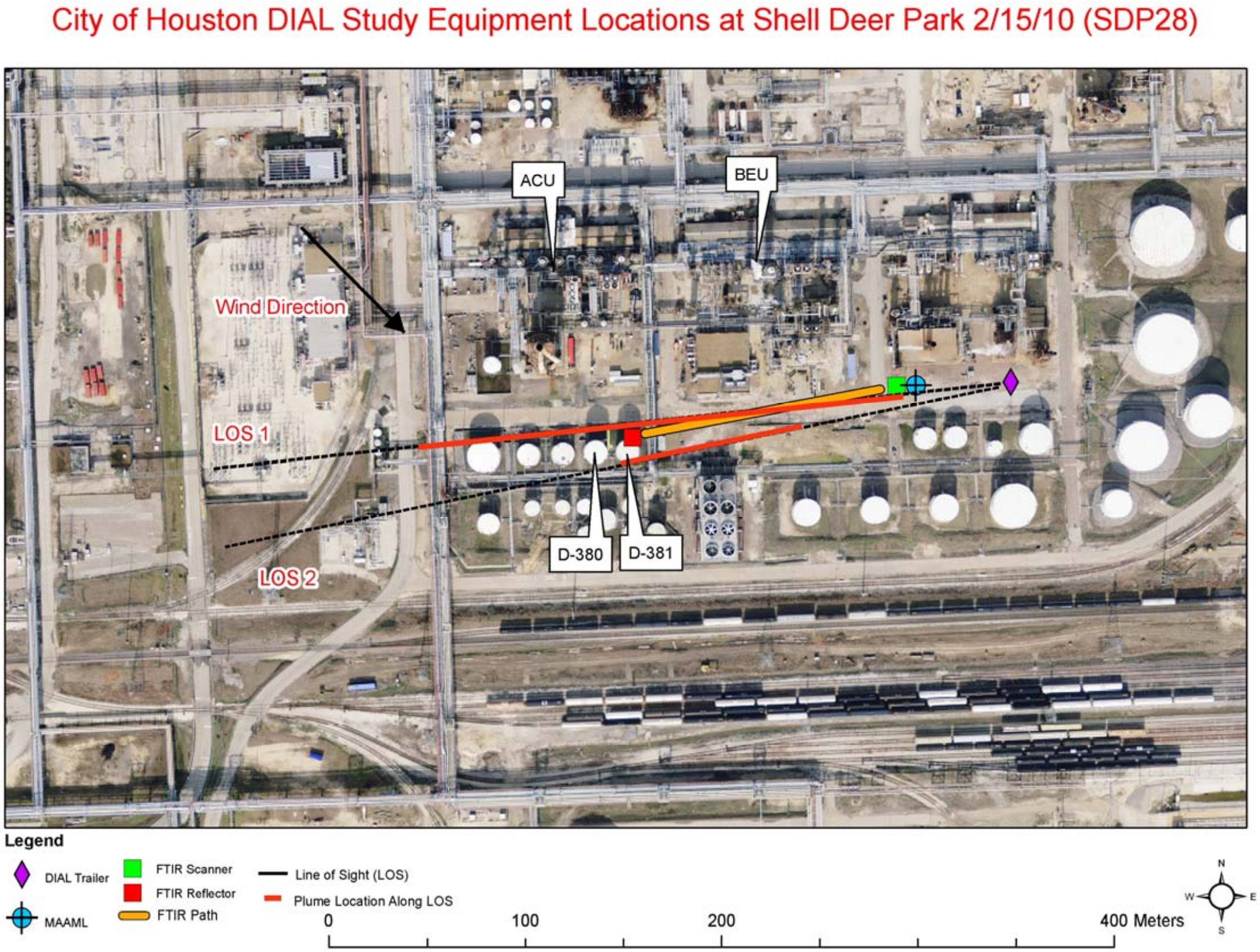


Figure 3.14b ACU and BEU 2/15/2010

Figure 3.14c ACU and BEU 3/26/2010

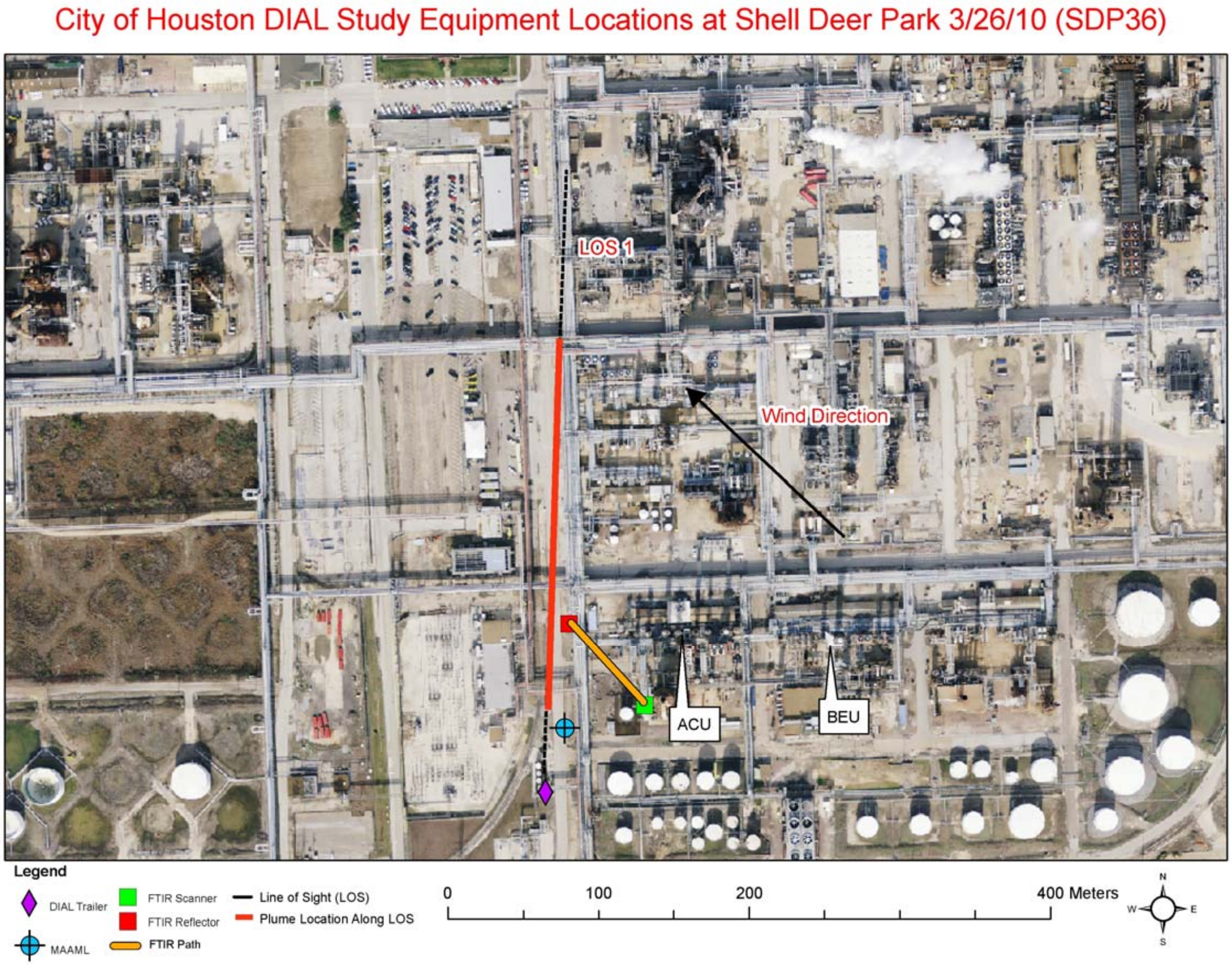


Figure 3.14d ACU and BEU 3/26/2010

3.15 Tanks South of ACU and BEU

Table 3.15 Tanks South of ACU and BEU

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/12/2010	SDP28/LOS2	16:49-17:26	Benzene	25 (possible emission source: D-350 and D-351)	10:00-16:00	Out (Scan 658)	NA, too few data points	Benzene, dichlorodifluoromethane	11:13-15:57	Yes, 10% (Scan 658)	NA, too few data points
2/15/2010	SPD28/LOS2	11:23-12:17, 13:35-14:12, 15:17-17:13	Benzene	29-141 (possible emission source: D-381)	9:00-16:00	Out (Scan 697)	Tank event at hour 12 reported by both MAAML and DIAL is a statistically influential outlier, r = 0.72, p-value = 0.16	Benzene, tetrachloroethylene	*10:38-16:45	Yes, 60% (Scan 697)	Tank event at scan 697 reported by both FTIR and DIAL is a statistically influential outlier, r=0.87 and regression significant p-value <0.0001, after outlier removed, r=-0.41, regression not significant p-value=0.24
3/22/2010	SDP32/LOS1	12:29-13:33, 14:53-15:50	Benzene	5 (possible emission source: D-352)	MAAML not deployed	MAAML not deployed	NA, too few data points	NA	13:52-16:47	No, 0% (Scan 768)	FTIR nondetect

* FTIR by Time averaging method (TAM)

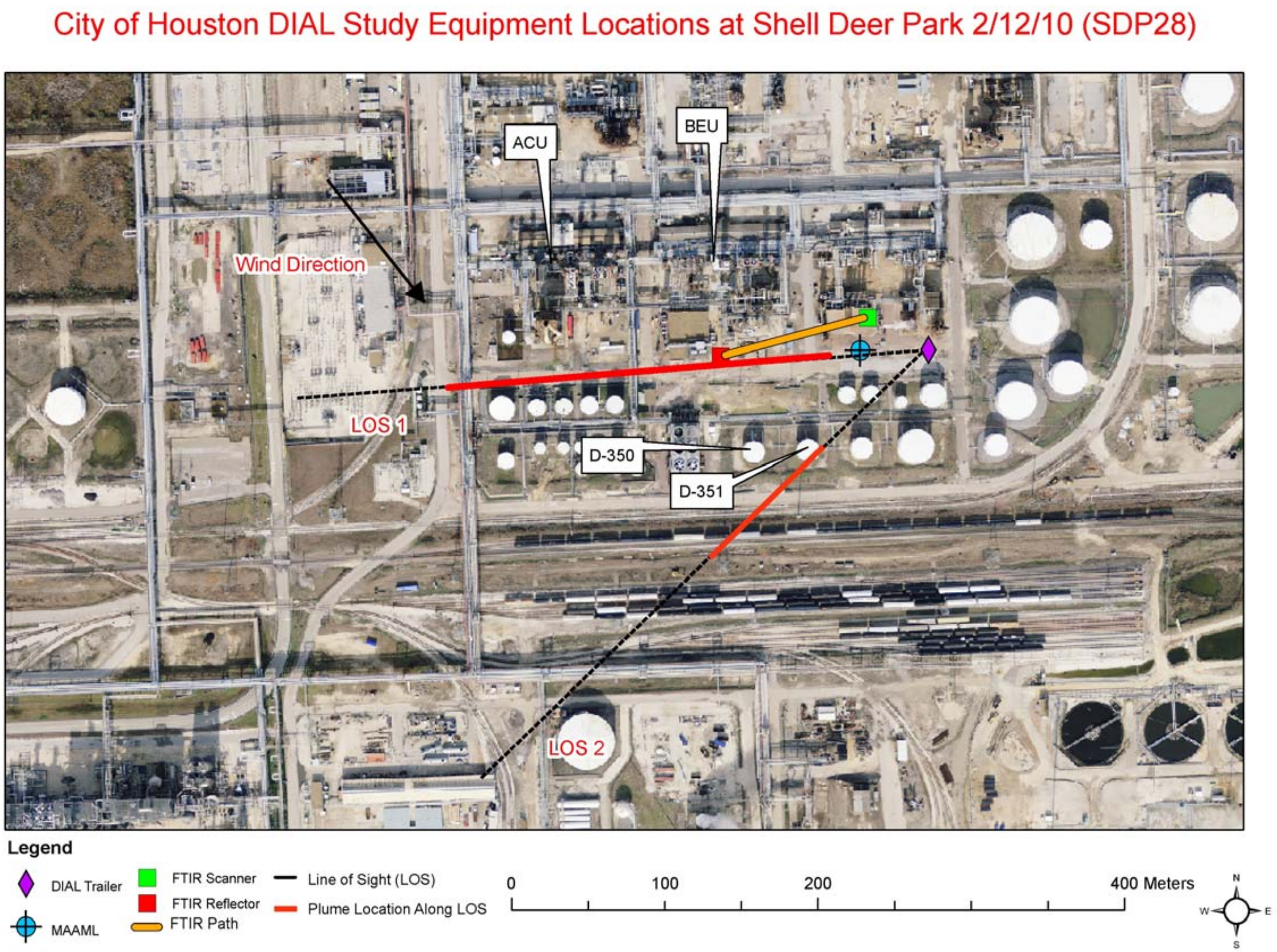

City of Houston DIAL Study Equipment Locations at Shell Deer Park 2/12/10 (SDP28)

Figure 3.15a Tanks South of ACU and BEU 2/12/2010

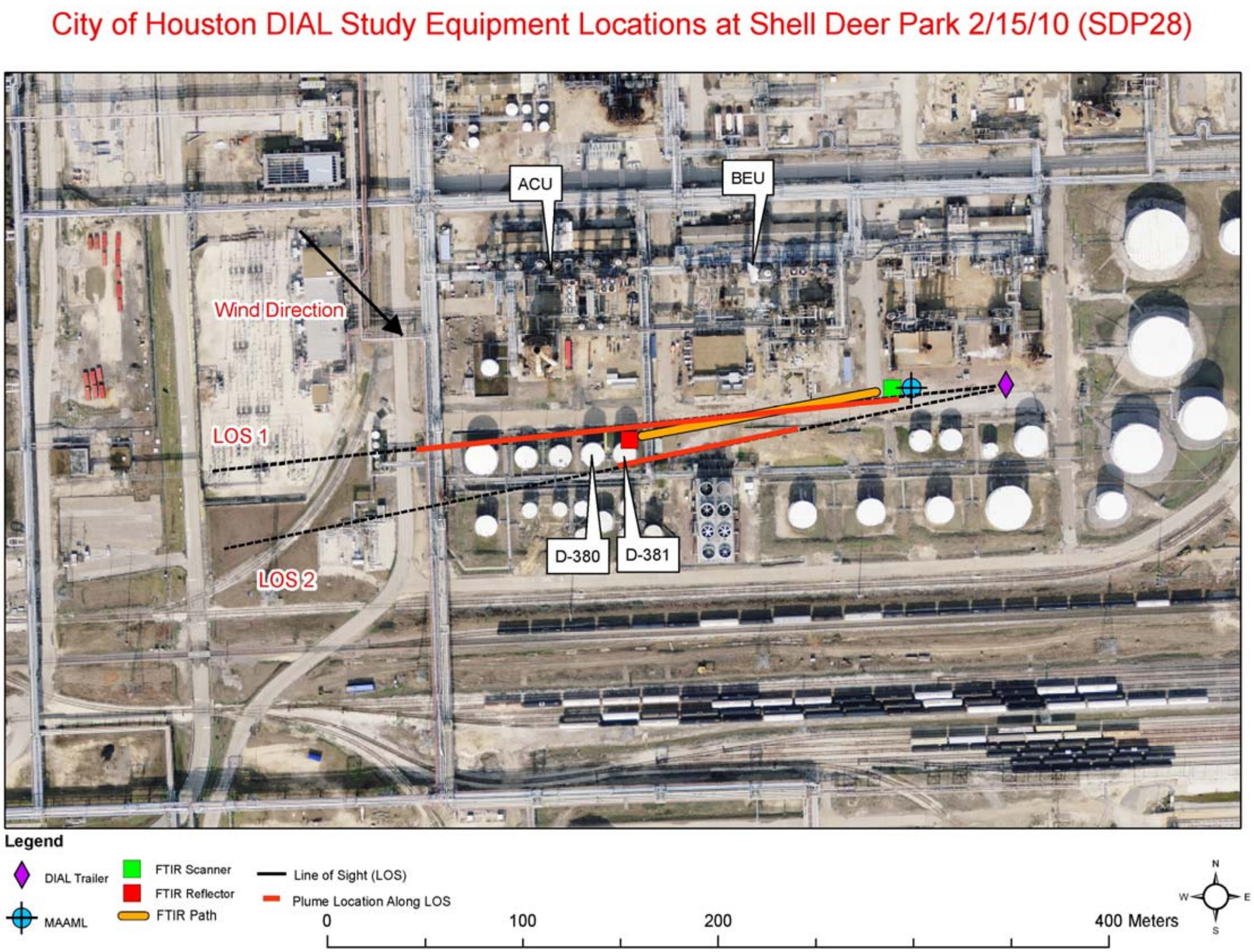


Figure 3.15b Tanks South of ACU and BEU 2/15/2010

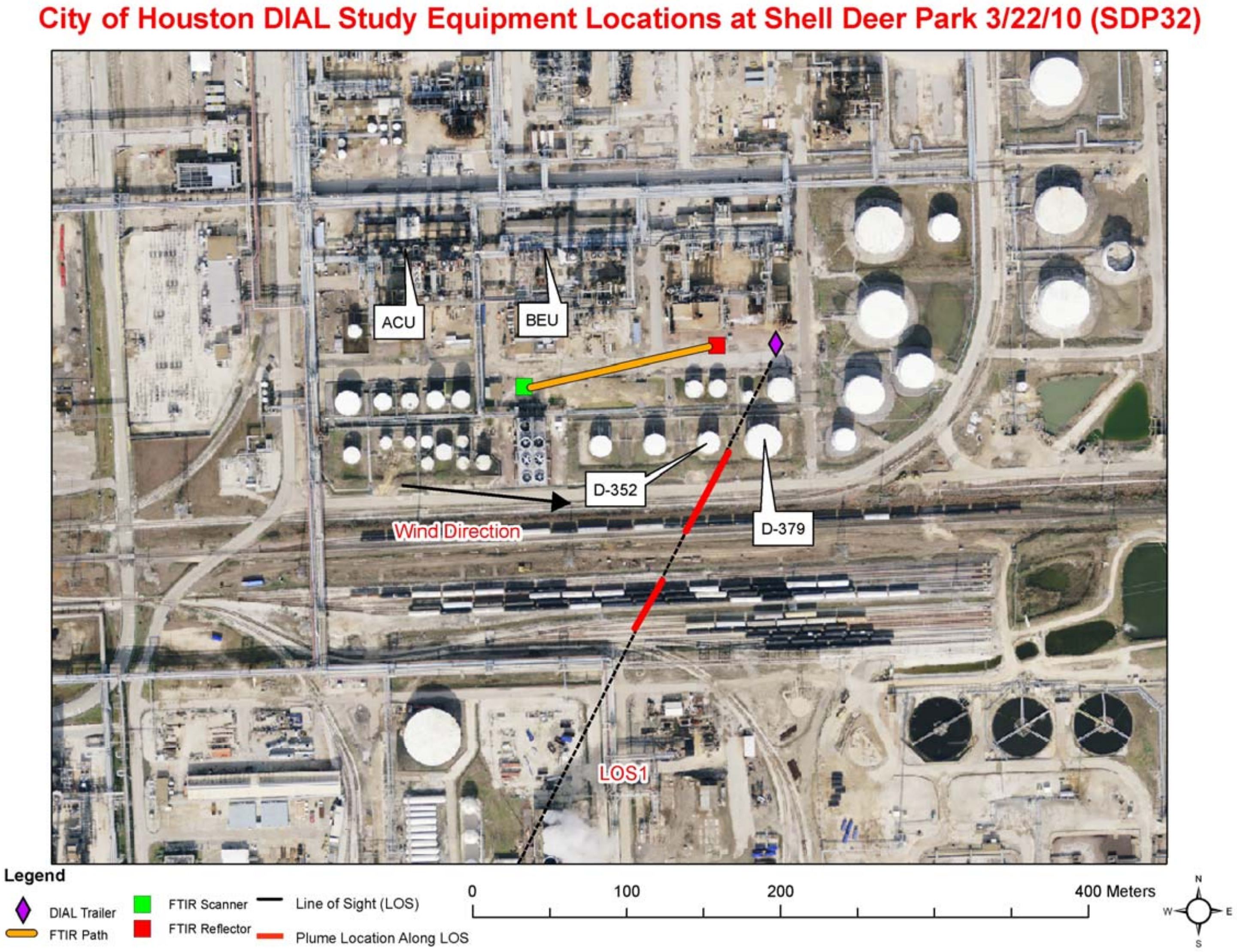


Figure 3.15c Tanks South of ACU and BEU 3/22/2010

3.16 Tanks South of North Wastewater

Table 3.16 Tanks South of North Wastewater (K-302, K-310, K-311, and F-367)

1 Date	2 DIAL Location / LOS	3 DIAL hours	4 DIAL	5 Average DIAL emission rate (lbs/hour)	6 MAAML hours	7 Location of MAAML	8 MAAML correlation with DIAL plume	9 MAAML outliers	10 FTIR hours	11 FTIR aligned with DIAL plume	12 FTIR correlation with DIAL plume
2/13/2010	SPD29/ LOS2	11:14-11:27, 11:44-12:19	Benzene	6	10:00-16:00	Out (Scan 669)	NA, too few data points, benzene ND at hour 15 when FTIR picked up spike	none	11:22-16:43	No, 0% (Scan 669)	All nondetect except 116 ppb benzene at 15:55

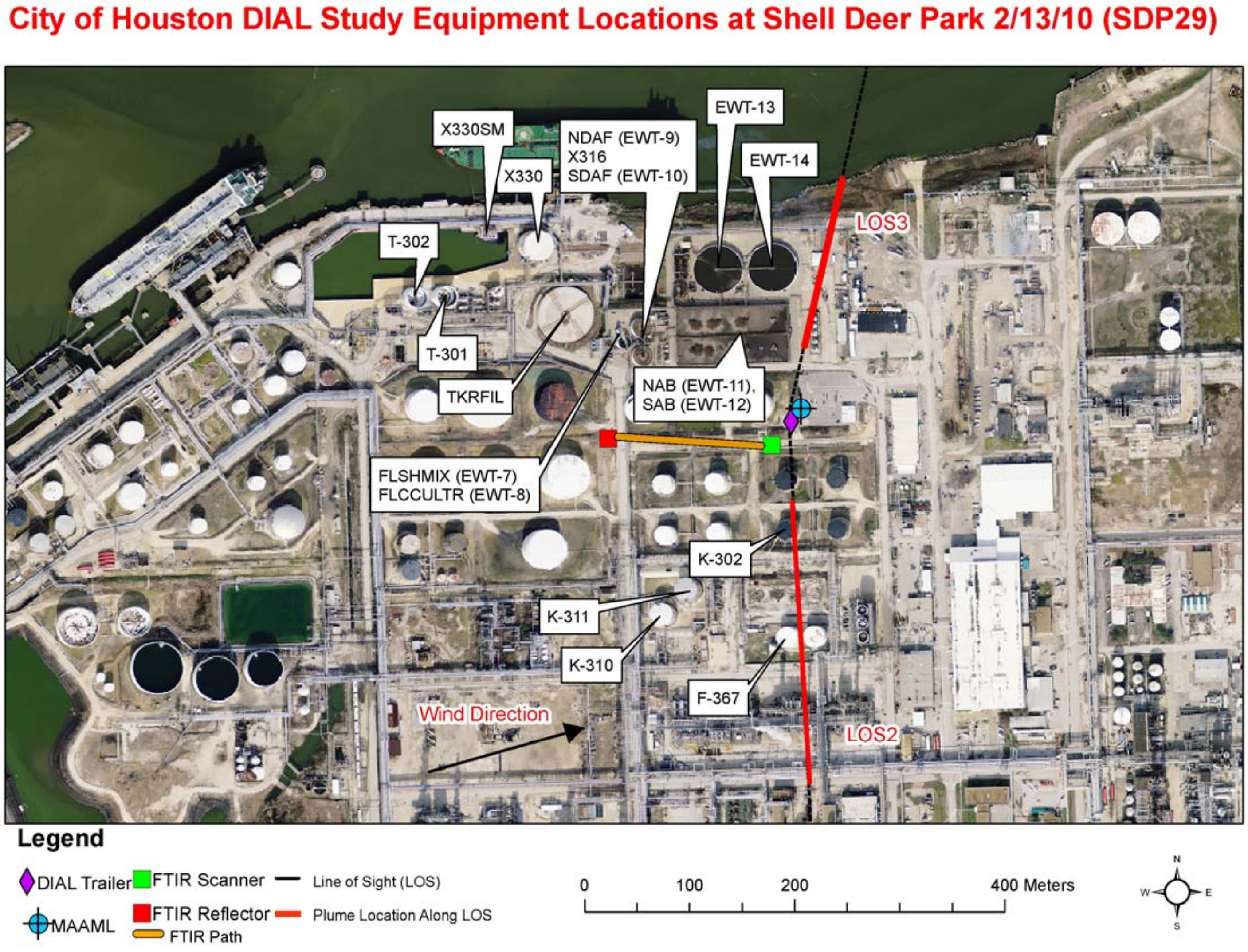


Figure 3.16a Tanks South of North Wastewater 2/13/2010

3.17 Refinery West Tanks

Table 3.17 Refinery West Tanks (A-301, A-309, A-308, F-361, and F-357)

1	2	3	4	5	6	7	8	9	10	11	12
Date	**DIAL Location / LOS**	**DIAL hours**	**DIAL**	**Average DIAL emission rate (lbs/hour)**	**MAAML hours**	**Location of MAAML**	**MAAML correlation with DIAL plume**	**MAAML outliers**	**FTIR hours**	**FTIR aligned with DIAL plume**	**FTIR correlation with DIAL plume**
2/16/2010	SPD30/ LOS1, LOS2†	10:06-12:47, 16:33-16:43	Benzene	5-6	9:00-16:00	Out (Scan 714)	NA, too few data points	Hexane, tetrachloroethylene	10:33-16:46	Yes, 100% (Scan 714)	Too many nondetects in FTIR data

†This Line of Sight (LOS) is not included in the aerial image because it did not measure a significant plume emission rate.

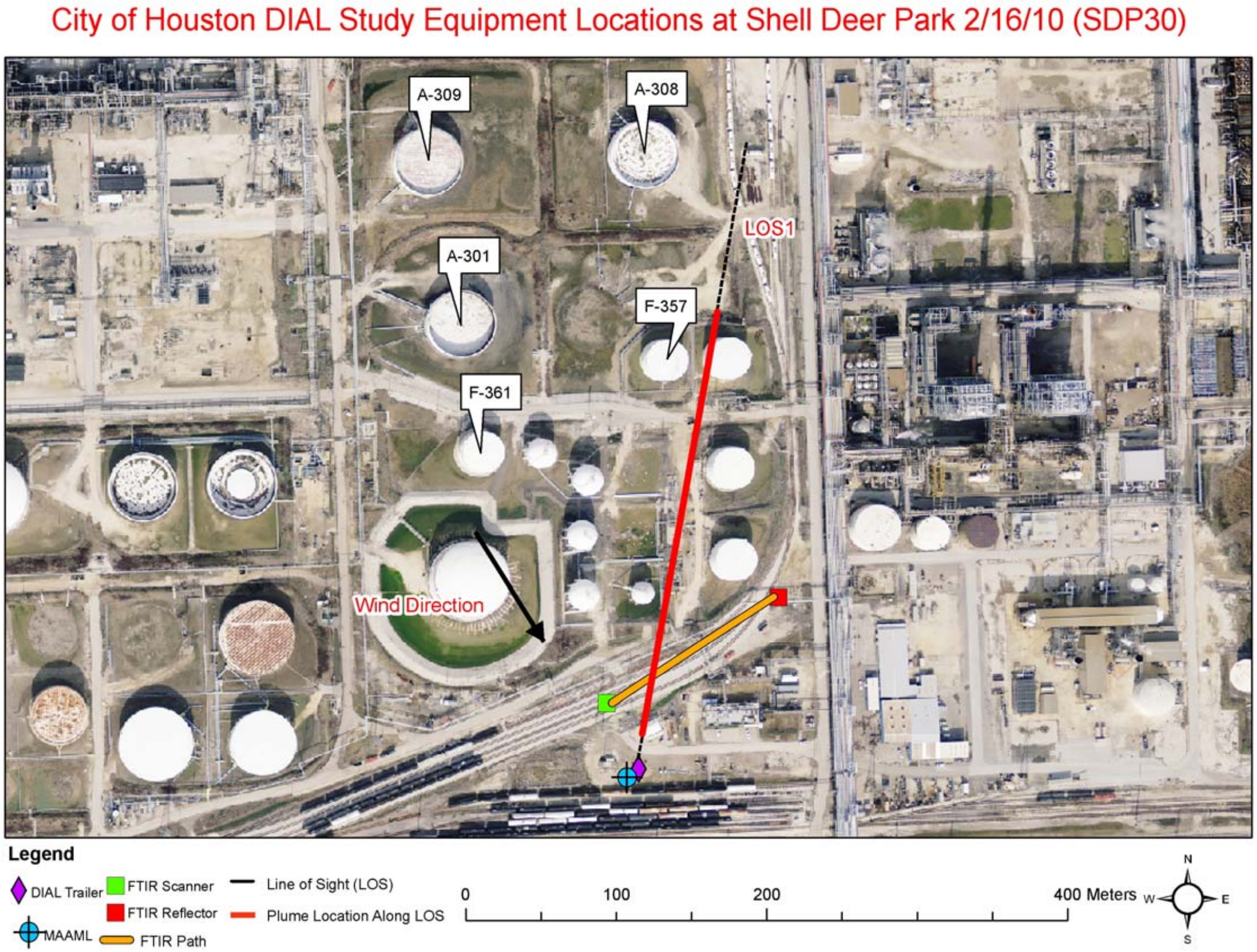


Figure 3.17a Refinery West Tanks 2/16/2010

4. Discussion

This section reports an interpretation of the results with respect to the project objectives.

4.1 Discussion Regarding Report Objective: Evaluate and verify the DIAL system benzene and VOC measurements using the City of Houston's Mobile Ambient Air Monitoring Laboratory (MAAML), canister sampling, and other monitoring/open path measurement techniques.

The analysis discussed in this report that is used to verify DIAL measurements focus on the two techniques used most often simultaneously with DIAL: MAAML and the FTIR (open path). Data from two other measurement techniques used less consistently, UV DOAS and SUMMA canisters, are presented in the appendices D and F respectively.

In order to evaluate and verify the DIAL system emissions measurements with these two techniques, we chose to systematically compare all of the emissions data collected against the concentrations, where there were enough data available to make the comparison while noting the location of the instruments in relation to the DIAL LOS for the scan images provided. As noted previously, although we recognized that relationships would more likely exist when the MAAML was "in" the plume versus "out" and FTIR had good overlap with the DIAL LOS, we chose to systematically examine all comparisons so as not to overlook any information that could be gleaned from this extensive body of data.

Throughout our analysis it became apparent that for various reasons (e.g., location constraints, comparing emissions to concentration under fluctuating wind speed, varying detection limits, sample time durations, and measurement techniques) a simple correlation coefficient did not fully reflect the degree of agreement between the measurements and in some cases correlation coefficients weren't appropriate. Therefore, we further examined the data to more completely answer the question, "How well do the techniques compare?" and "In the future, how can we better design the study so that these techniques can be used to estimate emissions?" The paragraphs below present the correlations found for each technique when the location was in the plume or aligned with the DIAL LOS and the statistically significant correlations when the location was "out" or not aligned. In addition, we highlight some examples of other verification of DIAL via similar pattern (in the face of wind speed changes) and simultaneous identification of spikes. In summary, verification of the DIAL measurements with the MAAML and FTIR measurements was evaluated using: statistical correlation (4.1.1), similar patterns in a time series (4.1.2) and identification of spikes (4.1.3).

4.1.1 Statistical Correlation

While a linear relationship between the DIAL emissions rate and ambient concentration is important to analyze in order to complete this report objective, evaluate and verify DIAL measurements, due to study constraints there were limited times when the MAAML or FTIR were measuring inside the plume or aligned with the DIAL LOS, respectively, and the wind speed was constant with low variability. We present the data from situations where MAAML was in the plume/FTIR aligned and the statistically significant correlations when MAAML was out of the plume/FTIR not aligned.

4.1.1.1 DIAL Emissions Correlation with MAAML

There were two locations and dates where MAAML was measuring concentration “in” the plume based on the scan image and there were enough data to calculate a correlation:

1. Southwest Tanks 1/13/2010, r=0.62, regression not significant, p-value=0.26.

2. North Wastewater 2/5/2010, not linear.

There were two locations and dates where MAAML was “out” of the plume based on the scan image, there were enough data to calculate a correlation, and the correlation was statistically significant (α=0.10):

1. Coker, GOHT, and West Dock Area 1/16/2010, r=-0.95, regression significant, p-value=0.01. The emission rates in this area were low and the wind speed variable.

2. ACU and BEU 2/15/2010, r=0.86, regression significant, p-value=0.06. The MAAML concentration and DIAL emission at hour twelve is an outlier.

In general, these limited cases where MAAML is in the plume indicate that the fixed site point monitor as used here is not a useful technique to validate DIAL emissions. We believe that a better correlation may result if we were to compare DIAL concentration to MAAML concentration, and the heights, measuring times and molecular weights were the same.

The statistically significant strong inverse correlation when the MAAML was outside the plume in example 1 suggests that the plume moved in and out of the DIAL measurement range and when DIAL missed the plume, MAAML picked it up. This scenario could result in DIAL emissions estimates that are biased low.

Statistically significant strong correlations when MAAML was outside of the plume suggest that turbulence caused by structures resulted in plume dispersion beyond the DIAL measurement range and the dispersed plume was detected by MAAML with its lower detection levels. Alternatively, the provided scan image was not representative of the days DIAL measurements for that LOS. In either case the plume may have therefore extended beyond the DIAL measurement capability.

MAAML concentration data may be representative of the relative plume composition and used for potential speciation purposes when: 1. Statistically significant strong inverse correlations were detected between MAAML and DIAL for the DIAL measured species, during time periods that elevated concentrations of the DIAL measured species were measured by MAAML, and 2. statistically significant strong correlations were detected between MAAML and DIAL for the DIAL measured species, for other compounds measured by MAAML that also have statistically significant strong correlations with the DIAL measured species.

4.1.1.2 DIAL Emissions Correlation with FTIR

There were eleven locations and dates where FTIR was measuring concentrations on a line overlapping to some extent with the DIAL LOS based on the plume scan image and there were enough data to calculate a correlation:

1. Coker, GOHT and West Dock Area 2/4/2010, 100% overlap, not linearly related.
2. Coker, GOHT and West Dock Area 3/27/2010, 10% overlap, not linearly related.
3. CR-3 Area 3/25/2010, 90% overlap, not linearly related.
4. North Wastewater 1/25/2010, 5% overlap, r=0.95 and p-value<0.001.
5. North Wastewater 1/30/2010, overlap moves from 40% to 0% to 10%, r=0.56, p-value=0.04.
6. North Wastewater 2/5/2010, overlap moves from 100% to 30%, r=0.66, p-value=0.15.
7. East Wastewater and Flares Area 2/1/2010, overlap 10%, not linearly related.
8. Tank Farm B 2/3/2010, 5% overlap, not linearly related.
9. Tanks T-OL913 and T-OL920 3/23/2010, overlap 100%, not linearly related.
10. ACU and BEU 2/15/2010, 100% overlap, r=0.92, p-value=0.0014, influential outlier, correlation without outlier r=0.014, p-value=0.98.
11. Tanks South of ACU and BEU 2/15/2010, 60% overlap, r=0.87, p-value=0.0001, influential outlier, correlation without outlier r=-0.41, p-value=0.24.

There was one location and date where FTIR was measuring concentrations on a line not overlapping with the DIAL LOS based on the plume scan image and there were enough data to calculate a correlation that was significant. This occurred at the East Tanks Area on January 28. There was a linear relationship that was inverse, r=-.55 with a p-value of 0.02. DIAL was positively correlated with wind direction and FTIR was negatively correlated with wind direction. This suggests that the plume moved in and out of the DIAL measurement range and when the plume moved completely or partially outside of the DIAL range, it moved into the FTIR path. This scenario could result in DIAL emissions estimates that are biased low. The FTIR technique has advantages over MAAML in many ways. It is a similar method of measurement (linear) and the sample duration is shorter and better matches the sample duration of DIAL scans. Beyond better overlap of FTIR and DIAL LOS, the key problem with the use of FTIR for comparison with DIAL in this study was the detection limit. There were many instances when there was good overlap but the FTIR could not detect at low enough concentrations to compare with the DIAL emissions.

The best example of a strong linear relationship between DIAL emission rate and ambient concentration was found at the North Wastewater Area on January 25 (figures 4.1a and 4.1b). The relationship was between DIAL VOC emission rate in lbs/hr and FTIR total alkane (ppb). The time series and the regression lines are presented below. The correlation coefficient r=0.96, the coefficient of determination r^2=0.91 and the regression was significant at p-value <0.001. This indicates that 91% of the variability in emission rates of VOC can be explained from the FTIR total alkane data. This exemplifies the strength of FTIR in verification of DIAL. Because there was strong correlation despite limited overlap, we hypothesize that the DIAL emissions were homogeneous enough that sampling 10% of the plume was adequate to characterize it.

A possible explanation for the strong DIAL emission rate and ambient concentration relationship at this location is that the source of emissions from the North Wastewater Area, was closer to the surface than the other sources measured during this project. Downwind of the North Wastewater Treatment aeration basins and along the FTIR measurement path, on-site personnel noted the presence of some wind turbulence that may have been induced by the basin structure. Emissions from the waste water treatment area may have been well-mixed at the elevation of the FTIR path. In the future, one could consider using an FTIR, and a backwards-Lagrangian Stochastic (bLS) measurement approach to compare FTIR and DIAL measurements on a pounds per hour basis. bLS has been extensively described in the literature, and has been shown to provide reasonable emission rate measurements for near-surface sources. bLS requires the use of 3 dimensional ultrasonic wind measurements, which was not in the scope of the project.

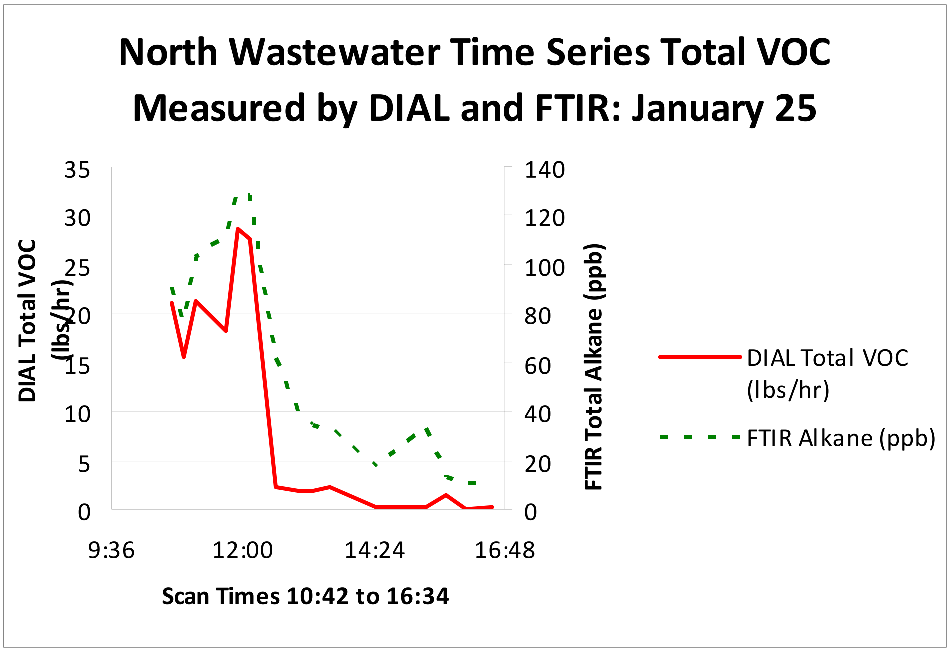


Figure 4.1a North Wastewater Time Series Total VOC Measured by DIAL and FTIR: January 25

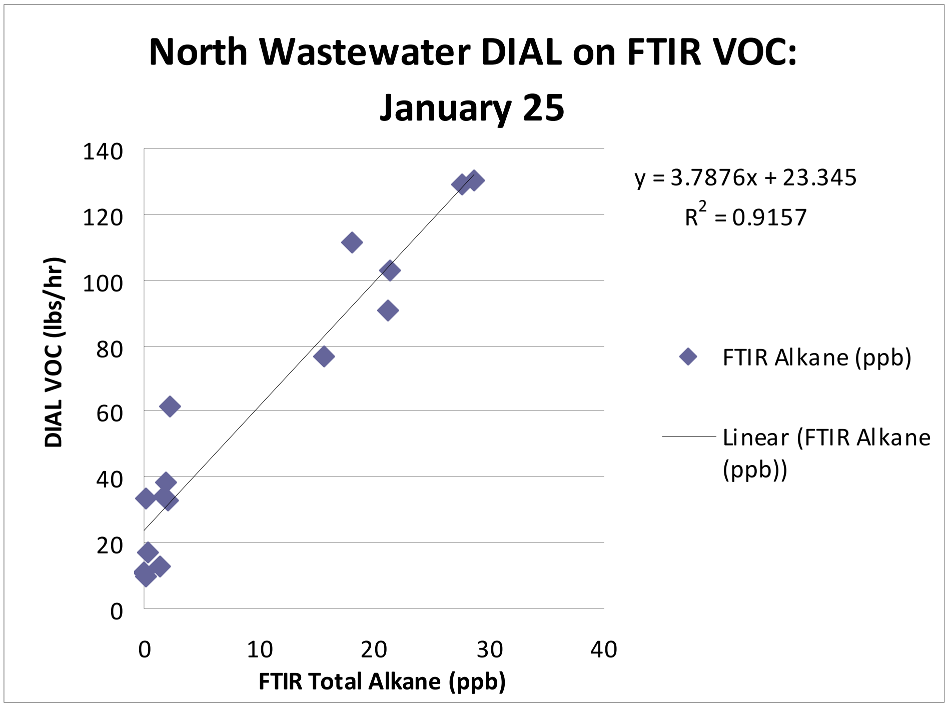


Figure 4.1b North Wastewater DIAL on FTIR VOC: January 25

4.1.1.3 Influential Outliers in Correlations

There are instances noted in the results where there is an influential outlier that pulls the line toward itself. From a statistical perspective the relationship it creates is not sound because the one point provides too much influence. The influential outlier is identified when the slope of the line moves by 10% or more when the relationship is reassessed without the point. When that point is removed, the linear relationship is insignificant and there appears to be no relationship between the DIAL emission rate and the concentration. This is exemplified with the figures 4.1c and 4.1d depicting benzene on February 15 at the ACU/BEU using the MAAML and at the Tanks south of the ACU/BEU using the FTIR.

While the statistical relationship from the overall data needs fortifying, we are optimistic from a practical technical standpoint that at higher emission rates we could develop a statistical model relating emission rate and concentration. The noise at lower emission rates needs to be addressed. If there had been more frequent data points around the peak or at the peak, the relationship would carry more weight. These examples indicate the DIAL emissions and the MAAML and FTIR measurements move in the same direction. In a basic sense, both the MAAML and the FTIR verified the spike that DIAL found on these days.

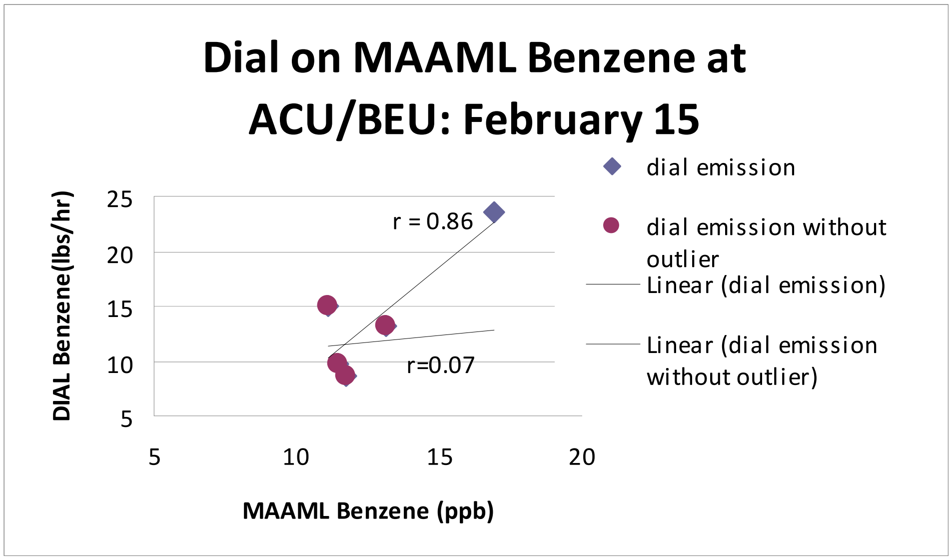


Figure 4.1c DIAL on MAAML Benzene at ACU/BEU: February 15

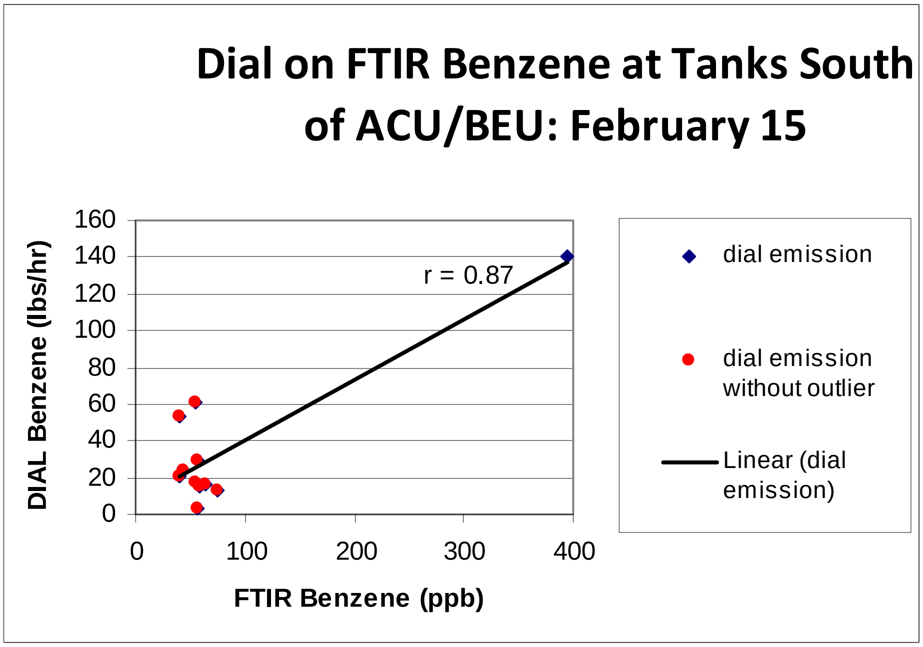


Figure 4.1d DIAL on FTIR Benzene at Tanks South of ACU/BEU: February 15

4.1.2 Similar Pattern

As discussed previously, there are many factors in play that can interfere with correlation (e.g., turbulent eddies, wind speed, varying detection limits, sample durations, shift in location). There were many instances in the time series of the results where although we did not have a strong correlation, we noted similar patterns in the rise and fall of concentration and emission rates. In other words, the patterns were very similar but the rate of change of the different methods was not stationary and therefore, the correlation coefficient (parametric or nonparametric) was low. One example of this occurred on January 13 at the Southwest Tanks (figure 4.1e) beginning at hour 13 and lasting until hour 17. Note that the difference in pattern at the first hour is not a valid starting point for comparison because DIAL did not begin measuring until 12:26.

However, beginning at the pattern at hour 13, we can see similarities in pattern in the two methods. The arrows show that the relationship between the concentration from the MAAML and the DIAL emission rate is not constant. While there were too many non-detects in the FTIR data to assess the DIAL and the FTIR data for this time frame, we look to the FTIR data to help explain the shifting DIAL emission rate and the MAAML concentration relationship over time. During hour 13, the FTIR started measuring many observations above the detection limit. The peak in the FTIR measurements occurred at 13:47. A closer look at this hour reveals a variable molecular weight as reported by the FTIR. The DIAL emissions were calculated assuming a constant molecular weight. Therefore, we note that the changing rate of emissions measured by DIAL and the concentrations measured by the MAAML is at least partially due to the use of a constant molecular weight. To a large extent, variability in the compound mix tended to keep the DIAL VOC mass estimate within an uncertainty range of 14% for this study, as evidenced by the NPL analysis of the many sorbent tube samples.

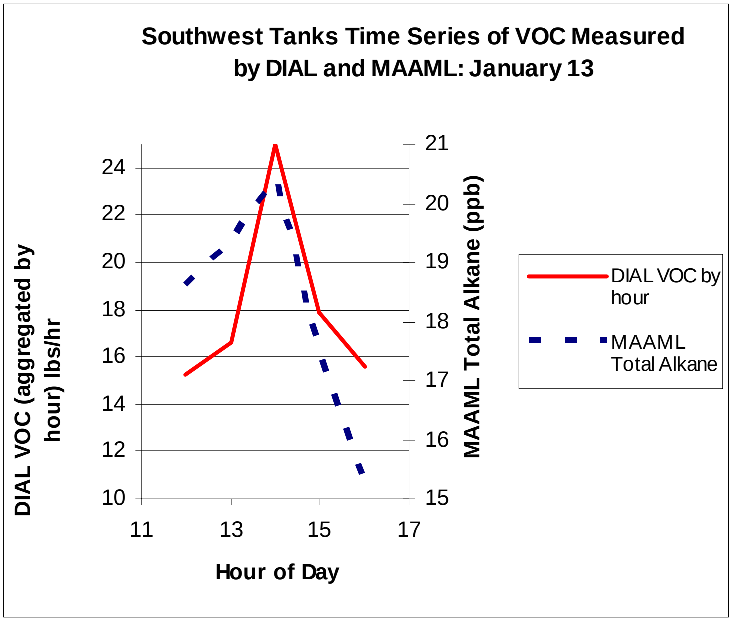


Figure 4.1e Southwest Tanks Time Series of VOC Measured by DIAL and MAAML: January 13

While there are many other examples of similar patterns, in comparison, on January 15 at the Southwest Tanks (figure 4.1f) the DIAL emissions and the MAAML concentration appear unrelated or at best inversely related. When the patterns were similar, the MAAML was found to be located inside the DIAL plume (see the summary table in the results section) and when the patterns appear unrelated, the MAAML was located outside the DIAL plume. This highlights the fact that the location of the MAAML to the DIAL plume is important in a valid verification of DIAL emissions using the MAAML data.

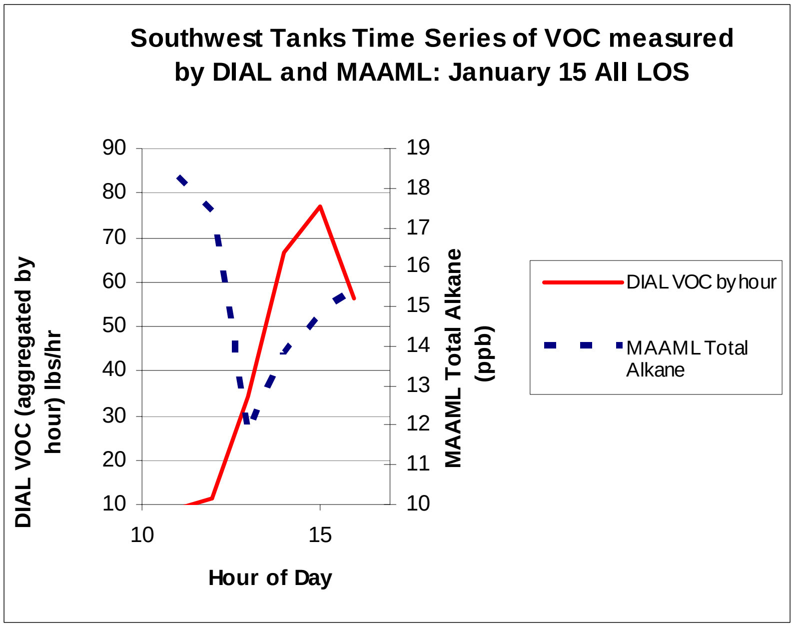


Figure 4.1f Southwest Tanks Time Series of VOC measured by DIAL and MAAML: January 15 All Lines of Sight

Other examples of similar patterns shown below are for East Tanks DIAL emissions compared with the FTIR concentration on January 22 (figure 4.1g), Tanks T-OL913 and T-OL920 DIAL emissions compared with the FTIR concentrations on March 23 (figure 4.1h), and Olefins Process Area DIAL emissions compared with the MAAML data on January 18 (figure 4.1i). The first hour, 10, in the time series of the Olefins Process Area cannot be compared with MAAML because the DIAL emission measurements were not initiated until 10:46. All three figures indicate a shifting relationship. Part of the changing relationship can be explained by a large number of non-detects in the FTIR data. The non-detects were replaced with the detection limit for analysis but this would introduce uncertainty.

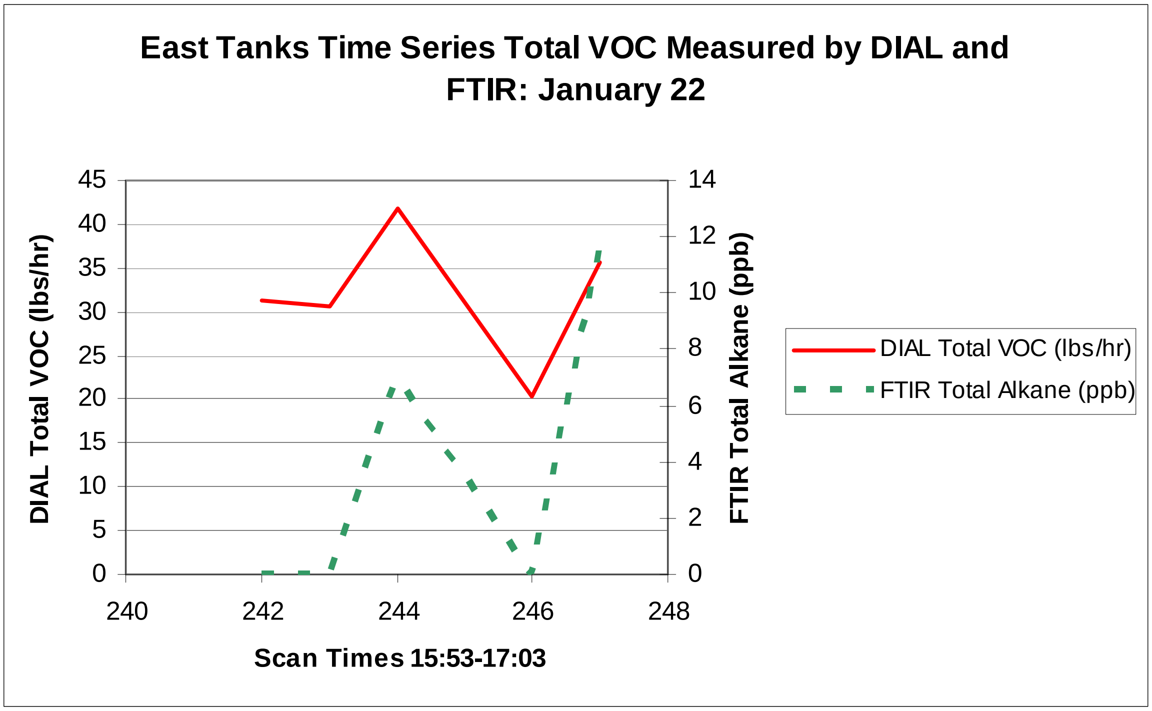


Figure 4.1g East Tanks Time Series Total VOC Measured by DIAL and FTIR: January 22

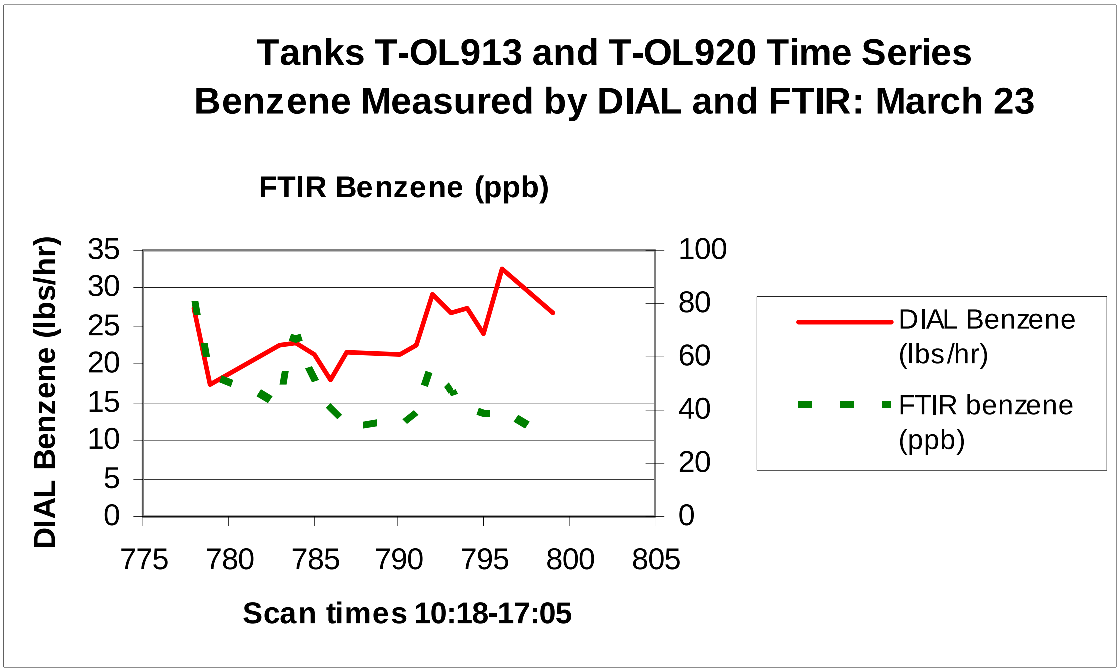


Figure 4.1h Tanks T-OL913 and T-OL920 Time Series Benzene Measured by DIAL and FTIR: March 23

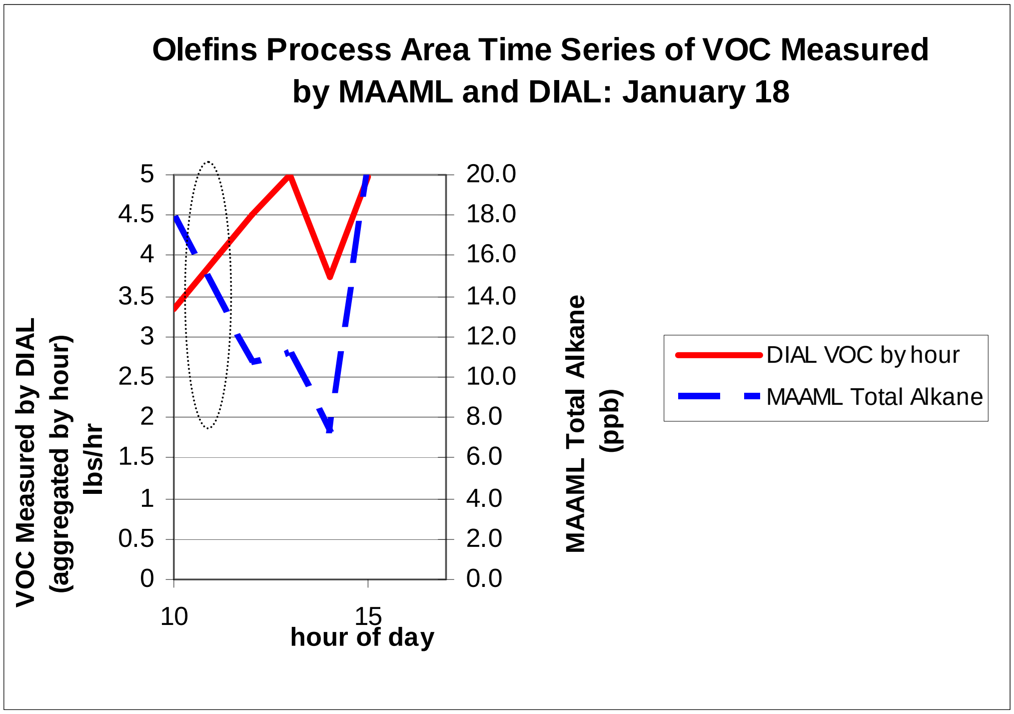


Figure 4.1i Olefins Process Area Time Series of VOC Measured by MAAML and DIAL: January 18

Measurements at the Olefins Process Area on January 18 (figure 4.1i) provide further information. Looking at the entire dataset that compares DIAL emissions to the MAAML concentrations, we find that the two methods are not linearly related. However, we discover that there is a wind shift. Looking at the data without the wind shift, the methods are more closely related. Recognizing that the relationship between DIAL and the FTIR would be less likely to be impacted by a wind shift, we move to analyze how well the FTIR data is related to the DIAL emissions during the wind change. Unfortunately, the FTIR is not in the DIAL plume and as expected it is not linearly related with DIAL. We did find that the FTIR measurements are highly *negatively* correlated with wind direction r=-0.76. This highlights an advantage that FTIR has over the MAAML. The FTIR concentration wind direction relationship can be used to identify sources.

We hypothesize that if the DIAL and the FTIR are aligned, the wind direction shift should impact them equally, if the source is not between them. The East Wastewater and Flares area on February 1 (figure 4.1j) is an example of a situation where both DIAL and FTIR have similar patterns. When the wind direction is plotted along with the time series, we find that DIAL either isn't impacted by wind or is similarly positively correlated with wind direction. Again, FTIR appears negatively correlated with wind direction. The difference here may be that FTIR is only 10% aligned with the DIAL plume.

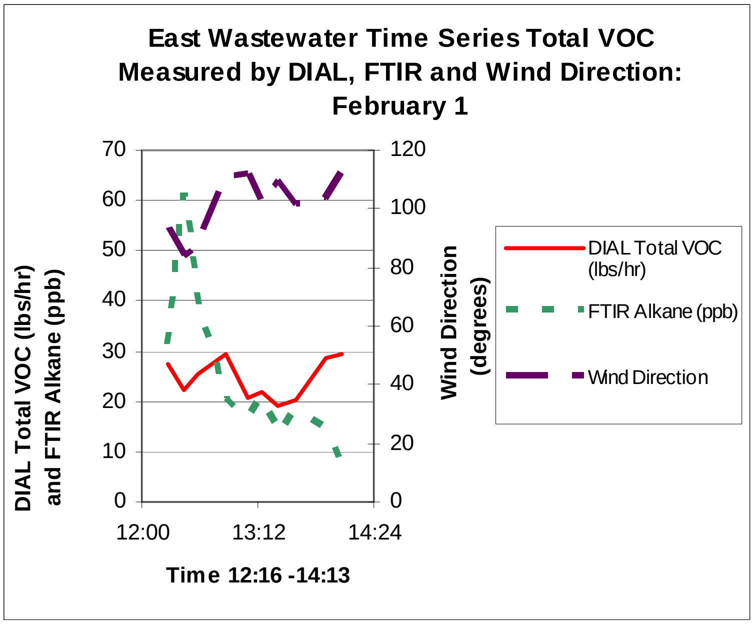


Figure 4.1j East Wastewater Time Series Total VOC Measured by DIAL, FTIR and Wind Direction: February 1

4.1.3 Identification of Spikes

DIAL identified important spikes in emissions as verified by the both the MAAML and the FTIR data. February 15 at the Tanks South of ACU and BEU (figures 4.1k and 4.1l) is a good example of the ability of both methods to find a spike in emission rates. While the linear regressions for this data are not statistically significant without the outlier, both methods were able to verify a spike. FTIR concentrations were much higher than the MAAML concentrations because the event was short term; MAAML reported 16.9 ppb benzene for the hour of peak while FTIR reported 394 ppb benzene at scan 697. MAAML concentrations were averaged over an hour while FTIR were averaged over the DIAL scan time.

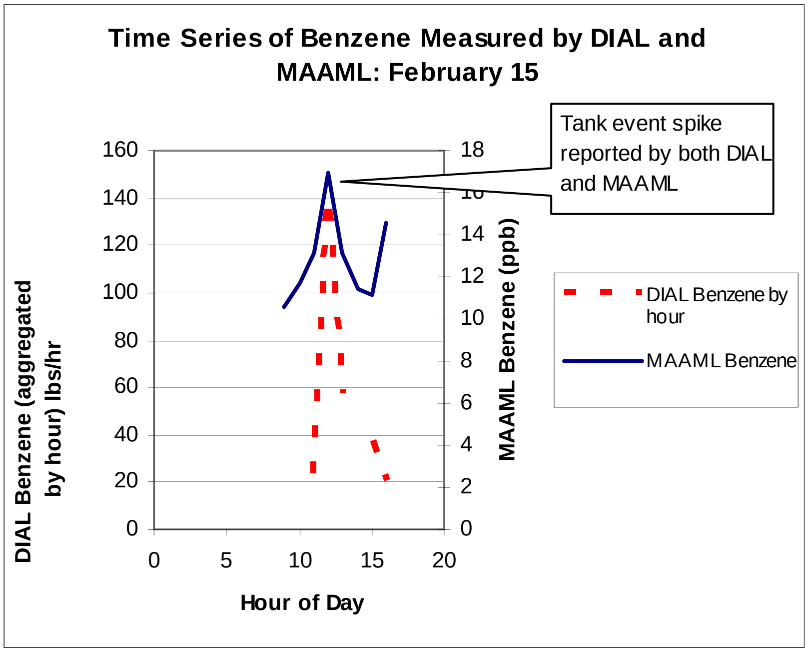


Figure 4.1k Time Series of Benzene Measured by DIAL and MAAML: February 15

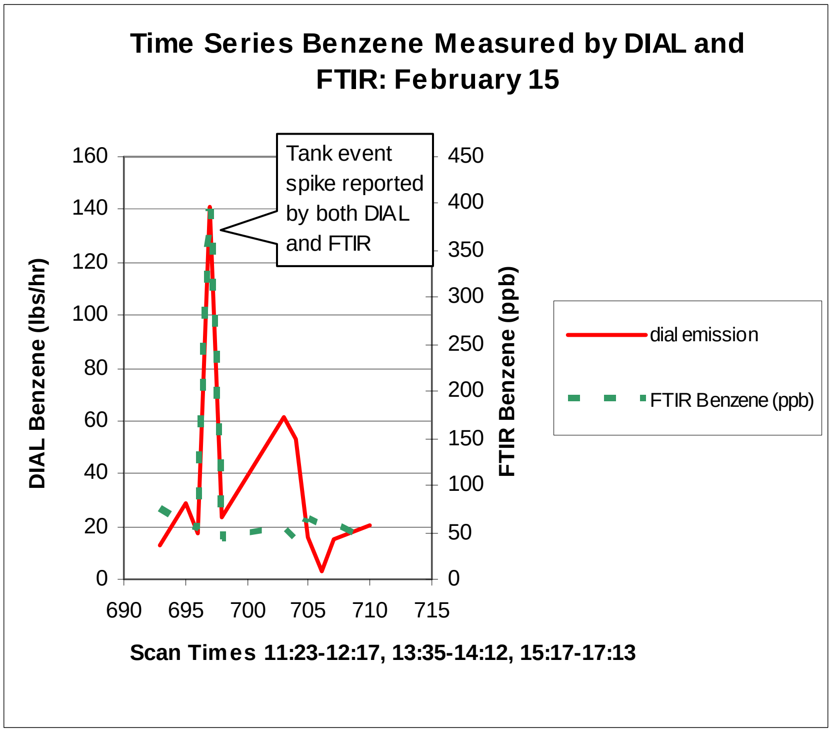


Figure 4.1l Time Series Benzene Measured by DIAL and FTIR: February 15

4.2 Discussion Regarding Report Objective: Develop, improve and demonstrate DIAL System emissions measurement methods for estimating the mass flux of benzene and volatile organic compounds (VOC) from individual emissions sources at a Houston area refinery facility with significant benzene emissions.

4.2.1 Improve Verification Methodology

The process of verification of DIAL emissions with the FTIR and the MAAML measurements discussed in 4.1 has highlighted some important aspects of the DIAL measurement that should be included in methodology of use of DIAL to *improve* verification:

1) Use of a constant molecular weight incorporates bias and results in a shifting relationship between DIAL emissions and the FTIR and MAAML concentrations; therefore, molecular weight should adjust as dictated by the FTIR for best match.
2) Verification of DIAL can only occur when the FTIR is aligned with the DIAL plume.
3) Verification of DIAL emissions at lower emitting sources can only occur when the FTIR detection limit is low enough to avoid non-detects.
4) Verification of DIAL emissions at process units with plumes raised above ground level is not possible when the plume is beyond the reach of the FTIR. In future deployments the FTIR retro-reflector should be elevated to transect the DIAL plume when the plumes are above ground level.

The methodology section (2) presented the methods used and the results section presented the process area emissions (3) satisfying this objective. The following graphs provide a comparison between process areas.

4.2.2. Process Area Comparison

To summarize the range of emission rates of benzene and VOC total alkanes measured by DIAL in each process area during the course of the study we have graphed the emissions using side by side boxplots and calculated an upper 95 percent confidence limit of the mean of each area based on the data distributional shape.

Side by side boxplot figures 4.2a, 4.2b, and 4.2c are shown below. Boxplots indicate, from bottom to top, the low end of the range, the 25th percentile, 50th percentile, and the 75th percentile and the high end of the range. Triangles indicate outliers. There was an extreme outlier in the data set (4,026 lbs/hr) taken when the West Tanks process area was measured that was not included in the statistical graphs and calculations because it was from a different source.

The boxplots indicate that relative to other areas, the lowest benzene emitting areas were the North Property Flare, the Southwest Tanks, the North Wastewater and the Refinery West area. The highest emitting area and the most variable emissions were found from the Tanks South of the ACU/BEU and this area also had an emission that was a statistical outlier. All of the remaining areas had a distribution of benzene emissions skewed high (to the right).

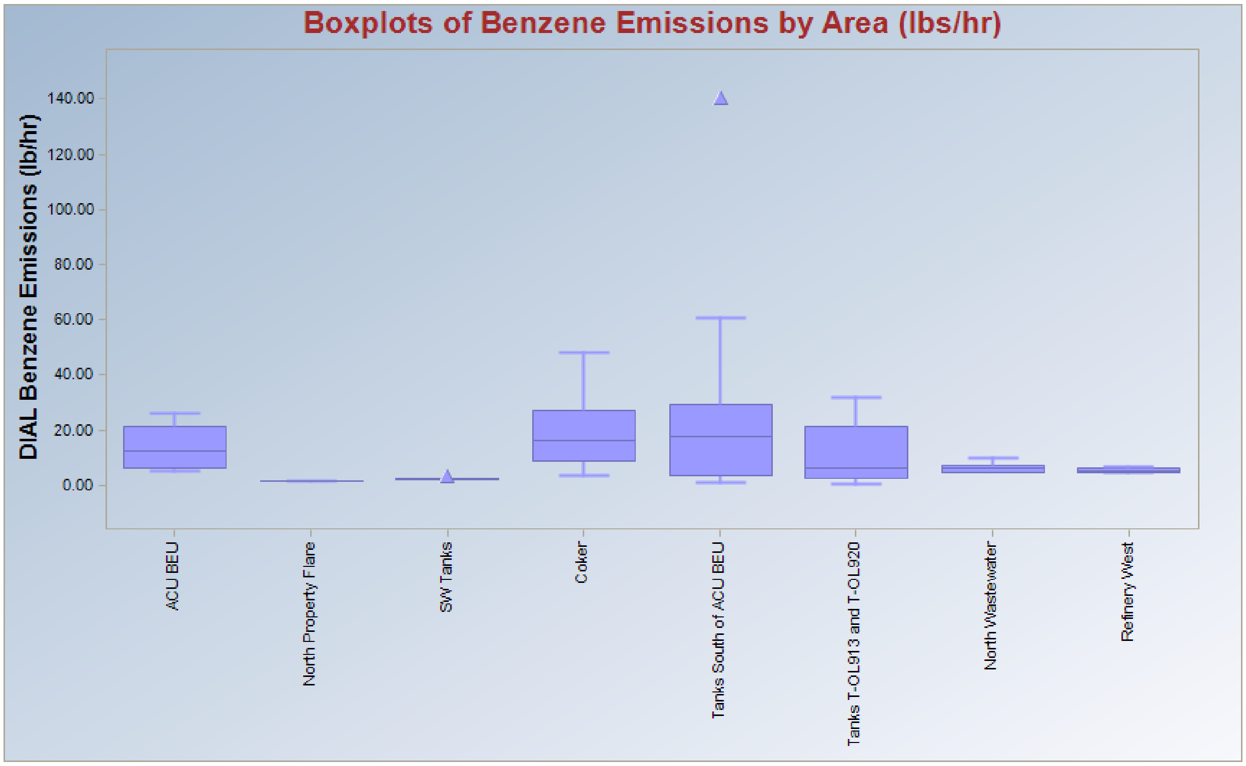


Figure 4.2a Boxplots of Benzene Emissions by Area (lbs/hr)

The range of emission rates of VOCs by area is shown in the side by side boxplots below. The boxplots indicate that relative to other areas, the lowest VOC emitting areas were the Olefins Process Areas, the Olefins Tanks, the Olefins Flares, the Coker, Coker and GOHT, and Tank Farm B followed by the West Dock Area. Emissions of VOC from these areas were all under 15 lbs/hr range of VOC. The highest and most variable area is the North Wastewater Area. These emissions are plotted separately because of the scale relative to the other areas. The next highest emitting area is the ACU/BEU. While this area has outliers on the low end, it is relatively less variable than the other areas which emit more than 15 lbs/hr. The Southwest tanks area emissions distribution is highly variable and skewed to the high end.

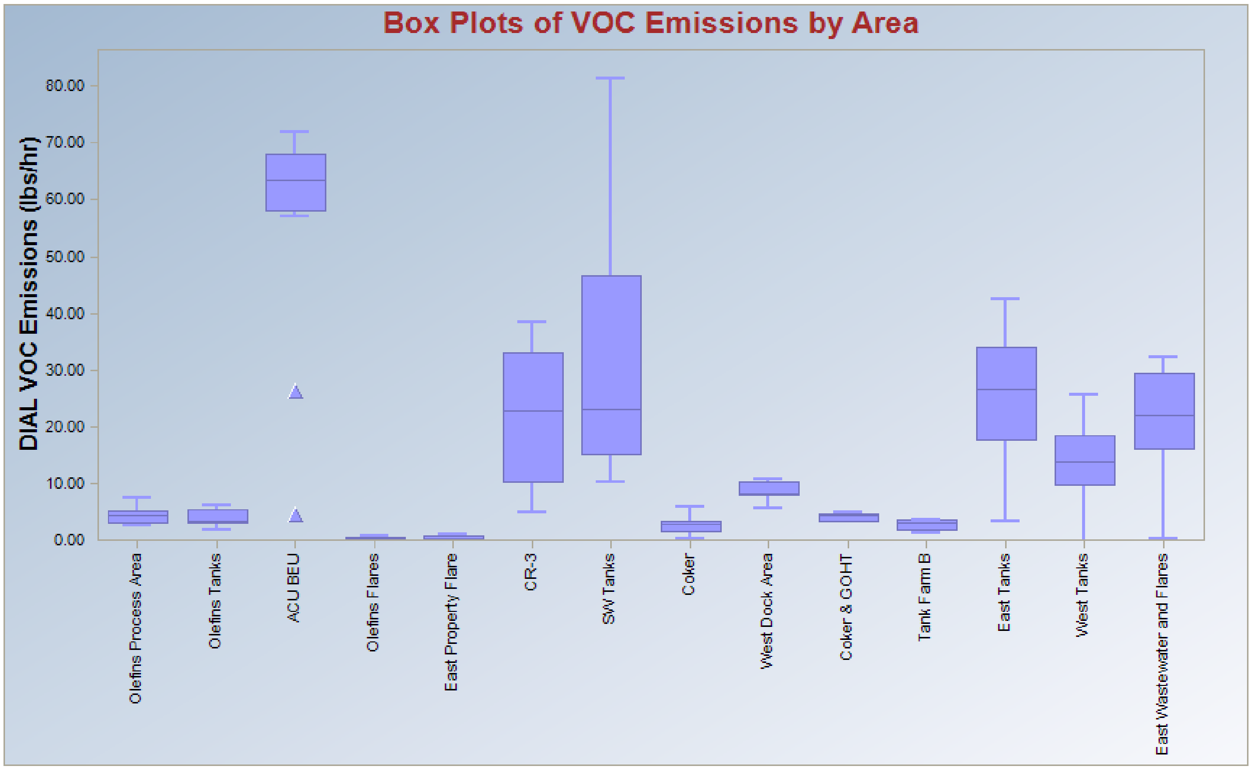


Figure 4.2b Boxplots of VOC Emissions by Area

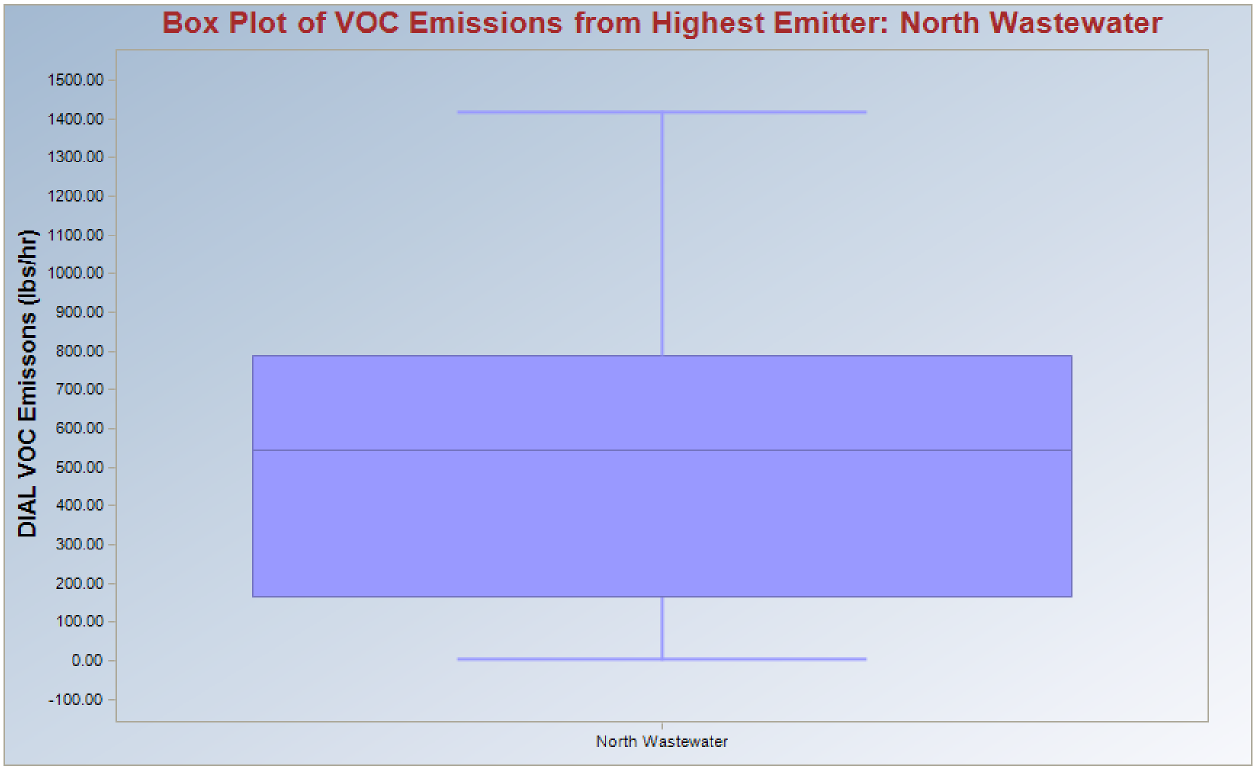


Figure 4.2c Boxplots of VOC Emissions by Area: Highest Emitter

Using the sample data by area, the number of samples, the variability of the samples and the sample distributional shape, the 95th upper confidence limit of the mean statistic was calculated using EPA's ProUCL. The 95th upper confidence limit of the mean is the estimate of the true emissions from the area. Tables 4.2a and 4.2b below list the process area, the distributional shape of the sample data and the 95th upper confidence limit of the mean in lbs/hr from each area. The highest benzene emissions are associated with the Tanks South of the ACU/BEU and the highest VOC emissions are associated with the North Wastewater.

PROUCL Recommended 95th Upper Confidence Limit of Emissions of Benzene by Process Area (lbs/hr)		
ACU BEU	Use 95% Student's-t UCL	16.77
North Property Flare	Too few observations	
SW Tanks	Use 95% Student's-t UCL	3.165
Coker	Use 95% Student's-t UCL	22.21
Tanks South of ACU BEU	Use 95% Approximate Gamma UCL	41.13
Tanks T-OL913 and T-OL920	Use 97.5% Chebyshev (Mean, Sd) UCL	19.76
North Wastewater	Use 95% Student's-t UCL	7.3
Refinery West	Use 95% Student's-t UCL	6.057

Table 4.2a PROUCL Recommended 95th Upper Confidence Limit of Emissions of Benzene by Process Area (lbs/hr)

PROUCL Recommended 95th Upper Confidence Limit of Emissions of VOC by Process Area (lbs/hr)		
Olefins Process Area	Use 95% Student's-t UCL	4.768
Olefins Tanks	Use 95% Student's-t UCL	4.49
ACU BEU	Use 95% Chebyshev (Mean, Sd) UCL	77.48
Olefins Flares	Use 95% Student's-t UCL	0.392
East Property Flare	Use 95% Student's-t UCL	0.474
CR-3	Use 95% Student's-t UCL	27.37
SW Tanks	Use 95% H-UCL	41
Coker	Use 95% Student's-t UCL	2.77
West Dock Area	Use 95% Student's-t UCL	9.568
Coker & GOHT	Use 95% Student's-t UCL	4.582
Tank Farm B	Use 95% Student's-t UCL	3.164
East Tanks	Use 95% Chebyshev (Mean, Sd) UCL	33.62
North Wastewater	Use 99% Chebyshev (Mean, Sd) UCL	1192
West Tanks	Use 95% Student's-t UCL	15.8
East Wastewater and	Use 99% Chebyshev (Mean, Sd) UCL	43.35

Table 4.2b PROUCL Recommended 95th Upper Confidence Limit of Emissions of VOC by Process Area (lbs/hr)

4.2.3 Speciation of DIAL Plume

Use of the MAAML data to speciate the DIAL plume was explored in this study. We hypothesized that if the MAAML was in the DIAL plume and there was good correlation with MAAML benzene (or total VOC) and the DIAL benzene (or total VOC), respectively, then the other MAAML constituents correlated with the DIAL benzene (or total VOC) were present in the DIAL plume. Unfortunately, there were no instances during this study when MAAML was in the plume with good correlation with DIAL based on the scan image. There were days which can be used to demonstrate the speciation, when the MAAML was not recorded as inside the

DIAL plume based on the scan image but there was a positive correlation (r>0.74) and the p-value testing for 0 slope/significant regression was promising (p-value 0.16 or less, recognizing that typically evidence of significance is associated with a p-value of 0.10 or less). These days were:

- Coker, 2/17/2010, hours 12-16, r=0.74 p-value=0.15- Cumene is an outlier.
- East Tanks, 1/23/2010, r=0.73 p-value =0.16- (hour 11 to 13 and hour 15 to 16), ethylene, propylene,n butane, n pentane, 2 methylpentane, hexane, toluene, ethylbenzene, m/p xylene, o xylene, cumene, 1,2,4 trimethylbenzene were outliers.

Tables 4.2c and 4.2d below detail the speciation in terms of correlation with DIAL on these days. On February 17 at the Coker, when DIAL and MAAML have a correlation of benzene of 0.74, the DIAL benzene is relatively correlated with hexane, propylene and toluene and negatively correlated with o-xylene. On January 23 at the East Tanks, when DIAL and MAAML have a correlation of VOC of 0.73, the DIAL VOC is relatively correlated with benzene, hexane, 2-methylpentane, and propane and negatively correlated with 1,2,4-trichlorobenzene. The relatively well correlated constituents may be present in the DIAL plume at concentration ratios similar to what was measured by MAAML.

Correlation of MAAML Chemicals with DIAL Benzene by Hour: Coker on February 17	
Toluene	0.88
propylene	0.81
Hexane	0.76
Benzene	0.74
ethylene	0.63
m/p-xylene	0.60
n-Butane	0.58
2-methylpentane	0.57
ethane	0.57
propane	0.55
n-Pentane	0.27
Cumene	0.14
Methylene Chloride	0.07
acetylene	-0.11
Trichlorofluoromethane	-0.11
1,1,2-Trichlorotrifluoroethane	-0.56
o-Xylene	-0.77

Table 4.2c Correlation of MAAML Chemicals with DIAL Benzene by Hour: Coker on February 17

Correlation of MAAML Chemicals with DIAL VOC by Hour: East Tanks on January 23	
Hexane	0.79
Benzene	0.73
2-methylpentane	0.72
propane	0.72
1,2,4-Trimethylbenzene	0.63
Toluene	0.61
Ethylbenzene	0.60
n-Butane	0.55
n-Pentane	0.55
o-Xylene	0.50
Cumene	0.49
acetylene	0.46
m/p-xylene	0.45
ethane	0.44
1,3,5-Trimethylbenzene	0.43
ethylene	0.25
propylene	0.22
1,2-Dichlorobenzene	-0.15
Trichlorofluoromethane	-0.44
1,3-Dichlorobenzene	-0.90
1,1,2-Trichlorotrifluoroethane	-0.94
1,4-Dichlorobenzene	-0.94
1,2,4-Trichlorobenzene	-0.97

Table 4.2d Correlation of MAAML Chemicals with DIAL VOC by hour: East Tanks on January 23

4.3 Discussion Regarding Report Objective: Identify unanticipated/underestimated sources of benzene and VOC.

The boxplots and the statistics presented in the previous section suggest that in terms of benzene the largest sources come from the Tanks South of the ACU BEU, followed by the Coker, Tanks T-OL913 and T-OL920, and the ACU BEU.

The boxplots and the statistics presented in the previous section suggest that in terms of VOCs the largest sources come from the North Wastewater and West Tanks.

4.4 Discussion Regarding Report Objective: Evaluate emission estimation techniques currently utilized to determine VOC and benzene emission rates by comparing DIAL measurements with estimated emissions.

The 95th upper confidence limit of the mean emissions by process area estimated from the DIAL emission measurements using EPA PROUCL presented in Section 4.2 were compared to the emission rates estimated from emission factors. The 95th upper confidence limit of the mean values reflect the measured data. Based on the current data and associated statistics, the true emissions may be underestimated by a factor of as much as 132 for VOCs and 93 for benzene. See table 4.4a below.

Area		**Date**	**Emission Factor Based Calculation (lbs/hr)**	**VOC (V) or Benzene (B)**	**Estimate of the 95th Upper Confidence Limit of the Mean (lbs/hr)****	**Potential Underestimation Multiplier**
Southwest Tanks	A-333	13-Jan	0.43	V		
	A-330	13-Jan	0.45	V		
	A-332	13-Jan	1.27	V		
		Total	2.15		20.18	9
	A-325	15-Jan	0.22	V		
	A-326	15-Jan	0.34	V		
	Total		0.56		13.15	23
	AP-17	19-Jan	0.46	V		
		Total	0.46		42.6	93
	AP-17	15-Jan	0.25	V		
	AP-16	15-Jan	0.14	V		
	Total		0.39		51.53	132
West Tanks	A-310	1/14	0.17	V		
	G-324-R1	1/14	0.26	V		
	Total		0.43		15.8	37
CR-3		21-Jan	20.67	V		
		25-Mar	20.67	V		
	Average		20.67		27.37	1
East Tanks	J-327	22-Jan	0.14	V		
	J-328	22-Jan	0.12	V		
	J-331*	22-Jan	4.63	V		
	J-332*	22-Jan	4.63	V		
	Total		9.52		37.05	4
	J-327	23-Jan	0.15	V		
	J-328	23-Jan	0.12	V		
	Total		0.27		18.07	67
	J-327	28-Jan	0.11	V		
	J-328	28-Jan	0.16	V		
	J-331*	28-Jan	4.63	V		
	J-332*	28-Jan	4.63	V		
	Total		9.53		35.98	4
Northwest Wastewater		25-Jan	6.5	V		
		30-Jan	15	V		
		5-Feb	11.5	V		
	Average		11		1192	108
		9-Feb	0.019	B		
		13-Feb	0.2	B		
	Average		0.11		7.3	67

* permit limits

** from ProUCL

Table 4.4a Comparison of DIAL measurements with estimated emissions

Area		Date	Emission Factor Based Calculation (lbs/hr)	VOC (V) or Benzene (B)	Estimate of the 95th Upper Confidence Limit of the Mean (lbs/hr)**	Potential Underestimation Multiplier
East Wastewater		1-Feb	5.88	V		
	Total		5.88		43.35	7
Tanks T-OL913 and T-OL920	T-OL913	8-Feb	1.15	B		
	T-OL913	10-Feb	1.17	B		
	T-OL913	23-Mar	1.18	B		
	T-OL920	8-Feb	0.83	B		
	T-OL920	10-Feb	0.83	B		
	T-OL920	23-Mar	0.83	B		
	Total of Tank Averages		2.00		19.76	10
ACU BEU		12-Feb	3.41	B		
		15-Feb	3.41	B		
	Average		3.41		16.77	5
		26-Mar	2.49	V		
	Total		2.49		77.48	31
Tanks South of ACU BEU	D-350	2-Feb	0.03	B		
	D-351	12-Feb	0.09	B		
	D-381	15-Feb	0.3	B		
	D-352	22-Mar	0.02	B		
	Total		0.44		41.13	93

** from ProUCL

Table 4.4a (continued) Comparison of DIAL measurements with estimated emissions

4.5 Discussion Regarding Report Objective: Assess the feasibility of emissions reduction strategies based on the measured impact from the most significant individual benzene emissions sources identified at the selected Houston area sites.

The February 2011 benzene contracts in the US were $4.35/gal, up 51 cents/gal from January and 93 cents/gal from November 2010 (http://www.icis.com/v2/chemicals/9075158/benzene/pricing.html). So a conservative estimate of the value of benzene emissions is $3.00/gal. The benzene emissions measured from Tank D381, a benzene concentrate tank on February 15, 2010 from 11:00 to 17:00 averaged around 40 lbs/hr, when the upwind process unit source emissions were subtracted. The timing of the emissions according to information from the site representatives corresponded with filling of the tank. Assuming a density of 7.365 lbs/gal (temperature of 68˚F and atmospheric pressure) and the conservative $3.00/gal value of benzene, indicates that each time Tank D381 is filled, approximately $80 of benzene is lost to air emissions. If the tank were filled once a week, annual loss from emissions would be $4,200, ignoring breathing losses. If the tank were filled daily, the annual loss from emissions would be $30,000, ignoring breathing losses. Based on the estimated capital and operations cost estimates of various vapor recovery systems, such as a Venturi Jet Ejector vapor recovery system, the feasibility and cost recovery period can be easily calculated.

4.6 Discussion Regarding Report Objective: Assess the cost effectiveness of the DIAL system based on project costs, estimated emissions reduction strategies costs and the estimated cost savings to be realized through preventing the loss of valuable products, intermediates and/or raw materials via the proposed emissions reduction strategies.

To estimate the value of emissions lost, it is assumed that the emitted gas could be used as fuel. Therefore, the value of natural gas is used. The March 2011 spot price for natural gas was \$3.81/mmBTU and the spot price was higher in early 2010 during the project (http://www.eia.doe.gov/oog/info/ngw/ngupdate.asp). The net heating value of natural gas is assumed to be 20,432 BTU/lb (http://www.epa.gov/nvfel/methods/ngfe.pdf). Therefore the estimated value of the emissions is assumed to be approximately \$0.0778/lb. The average total emissions rate measured during the project was 474 lbs/hr VOC (which excludes the high emissions rate wastewater day, 985 lbs/hr, due to a DAF skimmer problem and the high emissions rate tank event, 4,000 lbs/hr scan due to maintenance) and 105 lbs/hr benzene (which excludes the high emissions rate scan from tank D-381 during filling, 141 lbs/hr, and the high emissions rate, 27.1 lbs/hr scan during coker drain phase), for an average total emissions rate of 579 lbs/hr. At an estimated value of \$0.0778/lb, that equates to emissions valued at \$45/hr, \$1,081 per day and \$394,600 per year. If 25% of the measured emissions could be prevented or recovered, assuming the cost of a similar commercial DIAL study would be approximately \$750,000, the payback period for the study, after emissions have been reduced, would be 7.6 years.

5. Conclusions

The data suggest the following conclusions:

Objective 1 Conclusions) Emissions of benzene and VOC from individual emissions sources at a large refinery/chemical plant were successfully measured using DIAL. The comprehensive emissions survey using DIAL was shown to be effective at a large, complex industrial site when combined with a variety of open-path and extractive technologies. There were limitations inherent to the conduct of the study that reduced the value of the data collected. These limitations were primarily related to not having flexible facility access or sufficient access to refinery operating data.

DIAL was shown to be an effective technology for the measurement of mass flux from fugitive, non-point emissions sources. DIAL is limited, however, in that it can only measure the mass flux of a single compound or a class of compounds that absorb energy at a defined wavelength during a scan, preventing DIAL from directly providing information on plume chemical composition. Therefore, additional analysis is necessary to fully characterize the actual plume composition. Additional challenges related to the compositional characterization of the DIAL measured plume include the time period of compositional measurements which may prevent characterization of temporal variations and the fact that the compositional measurement techniques are typically fixed measurement locations, close to ground level. Moving these analytical platforms above ground level for elevated plumes (such as delayed coker plumes) and with wind direction shifts represents a significant challenge.

When DIAL is scanning for total alkanes, emissions of non-alkane hydrocarbons that are important at petroleum refineries (e.g., aromatic compounds such as benzene, toluene and xylenes) can be under-accounted for in the total measured mass flux. The plume compositional analysis (estimated using extractive samples) can be used to estimate total VOC emissions from the total alkane mass flux measurements; however, the accuracy of this adjustment is limited by the accuracy of the extractive compositional analysis relative to the actual composition of the plume during the course of the scan. DIAL is expected to slightly underestimate VOC mass flux. DIAL validation studies conducted using a known mass release have confirmed this slight underestimation (by 3 – 12%), based on six separate studies conducted in Europe (http://www.epa.gov/ttnchie1/efpac/documents/wrkshop_fugvocemissions.pdf). A possible reason for this underestimation is that the DIAL technique assumes that there is no absorption of the pulsed reference laser beam operated at the "off-resonant wavelength" (refer to the description of the DIAL technique provided by NPL in the DIAL QAPP). There may be a relatively small amount of absorption at the "off-resonant wavelength," even though the "off-resonant wavelength" is selected at a wavelength that is not sensitive to the target species concentration.

Use of FTIR or UV-DOAS for surveys of benzene or other individual compounds of interest represents an improvement over the use of DIAL with only extractive techniques for plume compositional characterization for the following reasons:

1) The FTIR can be configured to provide accurate information on plume compositional analysis over the course of the entire DIAL scan. This, however, does require careful

coordination to ensure that the FTIR is aligned along the DIAL scan plane and that the FTIR retroreflector mirror is placed at a distance and height that allows the FTIR beam to be aimed through the plume of interest. Most likely, this requires having a scissor jack or other raised platform readily available for deployment and use, which was not incorporated into this study.

2) While not completely integrated into this study, the FTIR allows for more accurate determination of plume average molecular weight (used in the calculation of mass flux) and to account for the change in average molecular weight of the plume over the course of the scan.
3) Because it can detect a broader range of compounds during the course of a single scan, the FTIR may detect a release that the DIAL does not. While a single path FTIR instrument does not allow for direct measurement of mass flux, detection of a compound of interest, and knowing the time and location of where it was detected, may facilitate additional investigations into location and cause of the release.

The FTIR (operated in accordance with USEPA Method TO-16), could not be used in this study to consistently provide statistical validation of the DIAL measurements. The reasons for this include:

1) The FTIR and DIAL were often taking measurements along similar, but different paths.
2) The FTIR was limited to ground-level measurements (height of approximately 1.5 meters); whereas, the plumes being measured by the DIAL were often elevated.
3) The FTIR and DIAL have different detection limits, with DIAL typically having a lower detection limit for the compound of interest, such as benzene. Therefore, plumes with low concentrations of the target compound(s) may be below the detection limit of the FTIR, yet measured by the DIAL.

While the FTIR could not be used to statistically validate the DIAL measurements, in almost every instance when the DIAL detected emission events (used in the sense of a transient plume, not in the context of the regulatory definition of an event), the FTIR also detected the event in the same location and at the same time.

Use of the MAAML allowed for real-time analysis of plume composition. However, being an extractive point measurement system with limited operational mobility, operation inside of the refinery close to the emission sources proved problematic with respect to plume detection by the MAAML.

It is difficult, if not impossible, to understand whether measured emissions are representative of normal operation. It is similarly difficult to develop good quality emission factors without a complete exchange of information with the facility being surveyed. For example, emissions from a delayed coker are dependent upon many operating factors including residual throughput rates and drum cycle times. If a delayed coker is operating at reduced throughputs or longer batch cycle times at the time of the survey, emissions could be reduced relative to what they would be at higher throughputs or shorter cycle times. However, without adequate access to information on delayed coker operation at the time of the survey and how those operations compare with normal and/or maximum design conditions, it is very difficult to draw conclusions about how representative the measured emissions are.

Objective 2 Conclusions) DIAL emissions were verified by the FTIR concentrations, and less so by the MAAML concentrations, in several ways: linear least squares regression, simultaneous spikes and similar time series patterns. The strongest quantification of verification occurred through least squares linear regression of DIAL VOC emissions (dependent variable) upon concentration from the FTIR alkane concentrations (independent variable) at the North wastewater Area on January 25, r=0.96, regression significant at p-value 0.001. The reason that there were not many more successful least square regression results stems from two main issues:

1) During the statistical analysis, we uncovered multiple examples of influential statistical outliers in regressions. While these outliers may represent real points, a statistical relationship which includes these points would stand up to scrutiny better only if there had been more frequent points around the peak or at the peak. These outliers are real extreme points because they were picked up by both techniques. Their presence just highlights the need for shorter sample duration to obtain more matching points. On the other end of the spectrum, the regressions were often messy at the low concentration/emission areas where the relationship appears noisy. Lower FTIR detection limits may address this noise.

2) There were many instances in which DIAL and the FTIR or the MAAML exhibited similar patterns in the time series but the rise and a fall of concentration and the emission rate did not remain constant. We attributed this drift at least partially to the use of a constant molecular weight in the DIAL emission rate estimates, while the true molecular weight was shifting.

Other important notes on verification of DIAL emissions using either the FTIR or the MAAML are that:

1) The location of the verification measurement must be known with respect to the DIAL plume. The FTIR was by far better suited to verify the plume over the MAAML because of its similar open-path nature, which could be aligned with the DIAL. Note that sources with elevated plumes (e.g., the coker) were not amenable to verification using either method.
2) The change in concentration with wind direction highlights the fact that the FTIR could be used to provide a back trajectory of a source, while the MAAML could not.
3) The MAAML reported hourly concentrations. Therefore, the DIAL scan emissions had to be aggregated up to the hour for comparison and resulted in a loss of precision. Conversely, the FTIR measurements were aggregated up to duration of the scan for DIAL.
4) The MAAML was better than the FTIR at providing speciation data because the MAAML detection limits were lower and it measured a wider range of constituents. The best example of DIAL plume speciation using the MAAML data occurred at the East Tanks on January 23 where toluene accounted for 63% of the total ppb.

Objective 3 Conclusions) The areas with the lowest benzene emissions were the North Property Flare, the Southwest Tanks and the Refinery West. The areas with the lowest VOC emissions were the East Property Flare and the Olefins Flare. The fact that emissions from flares were consistently low in this study may indicate that either the emissions were lower than expected, this method is not suitable to measure emissions from flares, or we did not measure on days when flares were in normal use.

The boxplots and the statistics suggest that in terms of benzene the largest sources of emissions came from the Tanks South of the ACU/BEU area, followed by the Delayed Coker, Tanks T-OL913 and T-OL920, and the ACU/BEU area and in terms of VOCs the largest sources of emissions came from the North Wastewater and West Tanks.

Objective 4 Conclusions) Of the 17 areas where DIAL emissions measurements were conducted, six were compared to VOC emission factor estimates and four were compared to benzene emission factor estimates. In only one process area did emission factors produce a VOC emissions estimate comparable to the DIAL measured results, which was the Catalytic Reformer-3 (CR-3) Unit. Emission factors used to estimate emissions from the Southwest Tanks VOCs produced the most potential underestimated emissions compared to the DIAL measured emissions, off by a factor of 132. The comparison of benzene emission factor estimates to the DIAL measured emissions produced potential underestimated emissions ranging from a factor of 5 at the Aromatics Concentration Unit/Benzene Extraction Unit area, to a factor of 93 for the tanks located south of the ACU/BEU area. These limited comparisons indicate that the emissions factor estimations for process units are better than emissions factors estimations for tanks.

Objective 5 Conclusions) Although the evaluation of emissions reduction strategies did not include costs associated with environmental and public health impacts, the measured impacts from the most significant individual benzene emissions sources identified at the site, such as Tank D381, suggest that there are feasible strategies that could be employed. Emissions reduction alternatives should be evaluated and employed where feasible, for all of the most significant emissions sources identified, including the most significant VOC emissions sources. In some instances additional source information is necessary for reasonable feasibility evaluations (ACU/BEU and Coker). In other instances where the source is well defined and controls are readily available, such as the dissolved air flotation (DAF) unit, the feasibility of various control options could be easily evaluated.

Objective 6 Conclusions) Although the cost effectiveness evaluation of a comprehensive DIAL survey at a large refinery/chemical plant did not include costs associated with environmental and public health impacts, the evaluation based on project costs, estimated emissions reduction strategies costs and the estimated cost savings to be realized through preventing the loss of valuable products, intermediates and/or raw materials indicates that the current DIAL costs may be prohibitively high. If DIAL costs could be reduced, perhaps by having a unit built for dedicated North American service (reducing transportation and travel costs), the potential for significant savings from emissions reductions suggest that the feasibility of conducting comprehensive DIAL surveys at similar sites would significantly improve.

Recommendations

The following recommendations are offered with respect to the conduct of future surveys:

- The pairing of DIAL with FTIR takes advantage of the complementary strengths of these two technologies to allow for improved plume characterization with respect to mass flux and chemical composition. Future investigations should focus on improving the coordinated use of these technologies as well as integration of the collected data. For surveys focused on a single aromatic compound such as benzene, a UV-DOAS instrument can be used in a role similar to FTIR.

- Use of extractive point monitoring systems is of limited use in the context of supporting in-plant surveys of fugitive emission sources where those sources may be significantly elevated, plume dispersion is impacted by nearby facility structures, and access to critical monitoring areas is limited by plant operations or structures. Point monitoring systems are most effective when deployed for conduct of ambient air quality monitoring programs over longer time periods or when conducting mobile surveys, such as those that EPA has conducted in the past using the Trace Atmospheric Gas Analyzer (TAGA) mobile laboratory.

- Surveys at large, complex emission sources such as petroleum refineries need to be conducted with active participation by operations personnel. Ideally, this would include flexible access during the course of the survey to facilitate the free flow of information about activities, events and operating conditions. Perhaps the only way to effectively accomplish this is for the refinery to take lead in conducting the survey.

- To address industry’s concerns that emissions data collected during the course of these types of short-duration surveys are not representative of long-term emissions, permanent open-path installations could be installed to monitor emissions on a long-term basis. While single-beam, open-path instruments do not directly measure mass emission rates, single-beam instruments can be used to estimate mass flux by correlating open-path concentrations with mass flux measured with instruments such as DIAL.

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Appendices

NPL REPORT AS (RES) 050

Differential Absorption Lidar (DIAL) Measurements of VOC and Benzene Emissions from a Refinery Site in Houston, TX, US, January/February/March 2010

DRAFT

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June 2010

Differential absorption Lidar (DIAL) measurements of VOC and benzene emissions from a refinery site in Houston, TX, US, January/February/March 2010

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Analytical Science Division

ABSTRACT

This report presents the results of measurements of the emissions of VOC and benzene from a refinery site in Houston, TX, US, carried out using the NPL Differential Absorption Lidar (DIAL). The measurements were conducted between 13th January and 17th February and between 22nd and 27th March 2010.

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Approved on behalf of NPLML by Martyn Sene, Director, Operations Division

CONTENTS

1 INTRODUCTION

This report presents the results of a measurement campaign carried out using the National Physical Laboratory (NPL) differential absorption lidar (DIAL) system to monitor emission rates of benzene and aliphatic hydrocarbons (C3-C12) from Shell Deer Park refinery and chemical plant in Houston, TX, US, from January to March 2010. The primary objective of the study was to assess emission rates of VOC and benzene from different areas of the site and to identify potential emission sources within these areas. The measurements were carried out in accordance with the QAPP from the 13th January to the 17th February and from the 22nd to the 27th March, 2010. This report covers the measurements undertaken by NPL, and does not cover additional measurements undertaken by other contractors. Measurement of benzene and aliphatic hydrocarbons (in this report aliphatic hydrocarbons are referred to as VOCs - volatile organic compounds) emission rates were made using downwind and upwind scans in a vertical plane.

Figure 1.1 NPL DIAL facility on the Shell Deer Park site in Houston.

A brief overview of the measurement approach and the DIAL measurement locations used during the campaign is given below. Section 2 presents the results of the VOC emission rate measurements while the benzene emission rate measurements are presented in Section 3. Section 4 shows the results from quality assurance measurements of an unknown propane mixture performed on the last day of the campaign, 29th March. Comparison with the Differential Optical Absorption Spectroscopy (DOAS) system is presented in Section 5.

The focus of this report is the presentation of results of measurements of emissions of VOC and benzene from a refinery site. Technical details for the measurement methodology are presented in Annexes 1-3. Annex 1 provides an overview of the DIAL technique, and discusses the calibration and validation procedures. Annex 2 presents the results of speciation measurements of air samples using pumped absorption tubes. Annex 3 presents a series of wind roses to provide a summary of the meteorological conditions present during the campaign.

1.1 OVERVIEW OF MEASUREMENTS APPROACH

The NPL DIAL was used to measure VOC and benzene emission rates from different areas of Shell Deer Park site. Table 1.1 lists the DIAL measurement locations, and provides the GPS locations for each position. These locations are shown in Figure 1.2, VOC locations are in red while benzene locations are in purple.

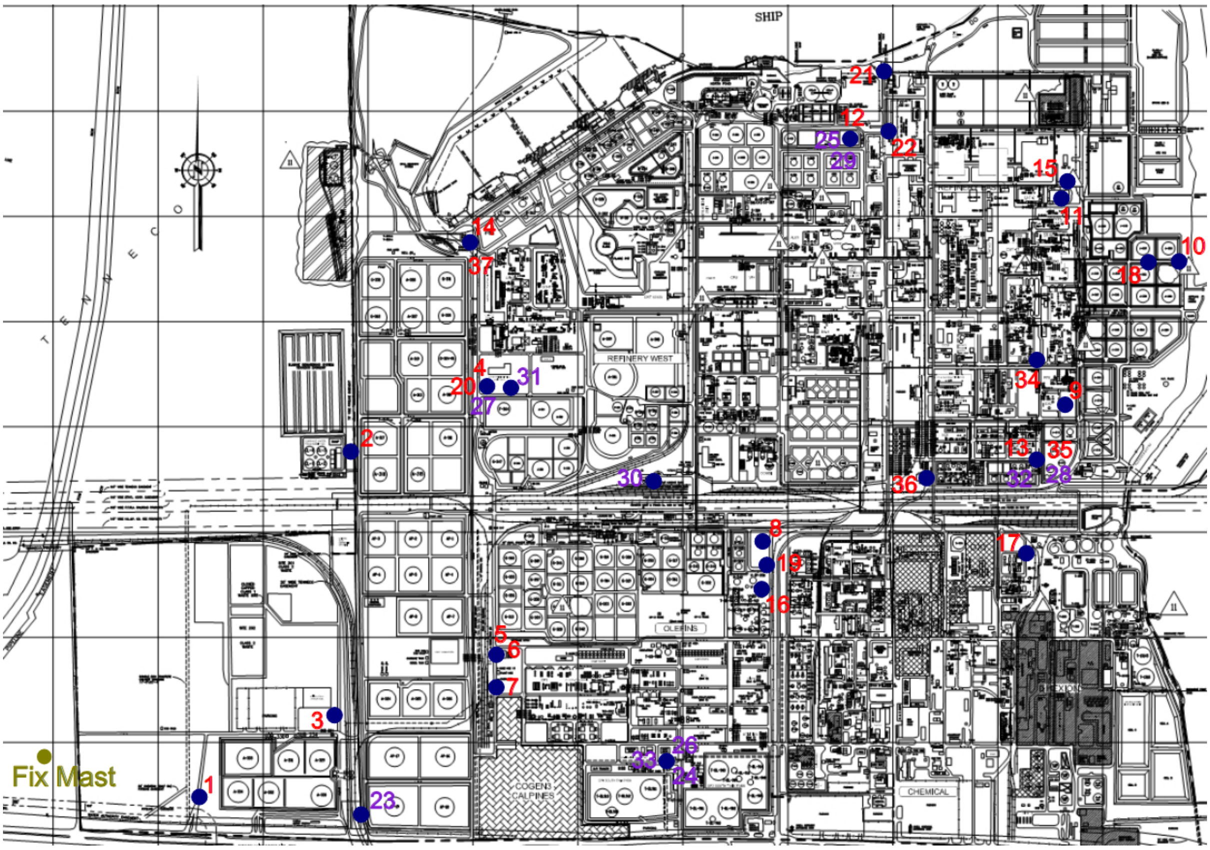

Figure 1.2 DIAL measurement locations and location of fixed meteorological mast. The blue dots represent the DIAL measurement locations and the red and purple numeric labels for each dot indicate the type of measurement (red for VOC and purple for benzene).

Table 1.1 Summary of DIAL measurement locations.

Location	Description	GPS Position	Emission
SDP01	West of Tank A-334	29° 42' 46.01" N - 95° 08' 40.88" W	VOC
SDP02	W of Tanks A-317 and A-318	29° 43' 19.04" N - 95° 08' 24.91" W	VOC
SDP03	NW of Tank AP-17	29° 42' 53.88" N - 95° 08' 26.17" W	VOC
SDP04	SW Corner of Coker Area	29° 43' 25.30" N - 95° 08' 11.00" W	VOC
SDP05	NW of Olefins Process Area	29° 42' 59.83" N - 95° 08' 09.28" W	VOC
SDP06	NW of Olefins Process Area	29° 42' 58.85" N - 95° 08' 09.27" W	VOC
SDP07	West of Olefins Process Area	29° 42' 56.63" N - 95° 08' 09.32" W	VOC
SDP08	NE Corner of Olefins Tanks	29° 43' 10.48" N - 95° 07' 40.69" W	VOC
SDP09	E of Refinery Process	29° 43' 23.40" N - 95° 07' 08.02" W	VOC
SDP10	NE of East Tanks	29° 43' 37.43" N - 95° 06' 56.07" W	VOC
SDP11	NW of East Tanks	29° 43' 43.32" N - 95° 07' 08.35" W	VOC
SDP12	Car Park East of Tank J-320	29° 43' 49.78" N - 95° 07' 31.17" W	VOC
SDP13	N of Tank D-365	29° 43' 18.46" N - 95° 07' 11.21" W	VOC
SDP14	NW Corner of Coker Area	29° 43' 39.02" N - 95° 08' 11.41" W	VOC
SDP15	NW of East Tanks	29° 43' 44.76" N - 95° 07' 07.33" W	VOC
SDP16	NE of Olefins Flares	29° 43' 06.29" N - 95° 07' 40.59" W	VOC
SDP17	NW of East Aeration Basins	29° 43' 09.39" N - 95° 07' 12.42" W	VOC
SDP18	North of Tank J-332	29° 43' 37.51" N - 95° 06' 58.64" W	VOC
SDP19	NE of Olefins Flares	29° 43' 07.92" N - 95° 07' 40.15" W	VOC
SDP20	SW Corner of Coker Area	29° 43' 25.10" N - 95° 08' 10.79" W	VOC
SDP21	NE of Clarifiers	29° 43' 53.57" N - 95° 07' 28.44" W	VOC
SDP22	SE of Clarifiers	29° 43' 49.94" N - 95° 07' 27.73" W	VOC
SDP23	West of Tank AP-19	29° 42' 44.80" N - 95° 08' 23.66" W	Benzene
SDP24	NE of Tank T-OL911	29° 42' 49.75" N - 95° 07' 50.60" W	Benzene
SDP25	Car Park East of Tank J-320	29° 43' 49.33" N - 95° 07' 30.67" W	Benzene
SDP26	NE of Tank T-OL911	29° 42' 49.81" N - 95° 07' 50.29" W	Benzene
SDP27	SW Corner of Coker Area	29° 43' 25.34" N - 95° 08' 10.78" W	Benzene
SDP28	L Street - North of Tank D-365	29° 43' 18.46" N - 95° 07' 11.21" W	Benzene
SDP29	Car Park East of Tank J-320	29° 43' 48.47" N - 95° 07' 32.39" W	Benzene
SDP30	Refinery West Tank Control	29° 43' 16.30" N - 95° 07' 52.45" W	Benzene
SDP31	South of Coker Area	29° 43' 25.02" N - 95° 08' 08.70" W	Benzene
SDP32	L Street - North of Tank D-365	29° 43' 18.44" N - 95° 07' 11.40" W	Benzene
SDP33	NE of Tank T-OL911	29° 42' 49.65" N - 95° 07' 51.08" W	Benzene
SDP34	SE of CR3	29° 43' 27.91" N - 95° 07' 10.74" W	VOC
SDP35	SE of BEU	29° 43' 18.51" N - 95° 07' 10.45" W	VOC
SDP36	SW of ACU	29° 43' 16.78" N - 95° 07' 23.33" W	VOC
SDP37	NW Corner of Coker Area	29° 43' 39.16" N - 95° 08' 11.89" W	VOC

Emission rates were measured as described in Annex 1, by scanning the DIAL measurement beam in a vertical plane downwind of the target sources, and determining the total concentration of VOC or benzene in that plane. The fixed mast (located just outside the SW boundary of the site at the position identified on Figure 1.2) supported two wind sensor packages, at 11 m and 3 m local elevation. The wind field used for the emission rate calculations (see Annex 1) was determined from the speed on the fixed mast (11m and 3m) for most emission rate measurements. The DIAL (12 m) and portable (2 m) wind sensors were used for the wind speed only in location SDP03, SDP35 and SDP36 since they were considered more representative of the local wind speed at these locations. The direction measured from the DIAL sensor was used to define the wind direction for most emission rate measurements. For some locations the DIAL wind was affected by local obstructions, therefore the fixed mast upper or lower sensor or the portable wind sensor was used for the wind direction in these cases. The wind covered most directions over the course of the campaign, as summarized in Annex 3. The wind roses reported in Annex 3 for each location are from the wind sensor used to define the wind direction for the emission rate calculations. Therefore, the wind roses figures indicate heights of 2, 3, 11 and 12 meters for the portable, fixed mast lower, fixed mast upper and DIAL sensor respectively.

1.2 TABLES AND FIGURES

The lines-of-sight (LOS) used at each measurement location are shown in Figures 2.1 to 2.27 for the VOC measurements and in Figures 3.1 to 3.12 for the benzene measurements. These figures also show the average wind direction and the positions of the portable wind sensor. Figures 2.1a to 2.27b and Figures 3.1a to 3.12a show contour plots and visual representations of the emissions observed in the downwind DIAL measurements.

Tables 2.1 to 2.27 report the VOC rates determined for each scan made during the measurement campaign. Tables 3.1 to 3.12 report the benzene rates determined for each scan made during the measurement campaign. The tables also list the locations and the lines-of-sight used for each measurement. Negatives emission rate values can occur because of the random noise on a small signal and these are reported in the tables. However, in the summary Tables 2.28 and 3.13 non-physical negative results are reported as zero. The time reported in each table is local standard time (LST) for the measurements carried out from the 13th January to the 17th February and daylight savings time (DST) for the measurements carried out from the 22nd to the 27th March. The wind directions reported in the tables are from the sensor used for the emission rate calculations. The wind speeds reported in the tables are from the higher of the two sensors used to determine the wind profile.

Emissions from other areas of the site may have been upwind of the measured sources. However, generally these sources have been excluded in two ways. If the upwind sources to be excluded are close to the measured sources, and produce localised plumes, these have been discriminated spatially from the measured rates by selecting the regions of the scanned region to integrate, in order to calculate the emission rate only from the area of interest. Conversely, if the upwind sources are further away and the emissions from them have been measured, this has been removed from the downwind emission rate. In the explanatory text, when the first technique is used, it is normally specified which analysis range has been used. When the second technique is used, the value from the subtraction of an upwind emission from a downwind emission rate and its standard deviation are reported.

Table 2.28 reports the mean and standard deviation of the VOC emission rates measured in each location for each LOS. Table 3.13 reports the mean and standard deviation of the benzene rates measured in each location for each LOS. The standard deviation given in the tables is the standard deviation of the individual emission rate measure from which each mean emission rate value has been determined. The standard deviation will include the effects of the source variability, DIAL measurement uncertainty and the influence of other variable factors such as the wind speed and direction.

2 MEASUREMENTS OF VOC EMISSIONS.

Table 2.1 Emission rate measurements from SDP01 on 13th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
10	SDP01/LOS1	12:26	12:34	4.1	121.7	14.99	Downwind of SW Tanks
11	SDP01/LOS1	12:36	12:45	4.3	119.8	9.89	Downwind of SW Tanks
12	SDP01/LOS1	12:47	12:55	4.9	124.7	20.90	Downwind of SW Tanks
15	SDP01/LOS2	13:09	13:18	4.3	108.1	14.41	Downwind of SW Tanks
16	SDP01/LOS2	13:18	13:27	4.4	120.0	20.52	Downwind of SW Tanks
17	SDP01/LOS2	13:28	13:36	5.0	127.3	11.61	Downwind of SW Tanks
18	SDP01/LOS1	13:41	13:58	4.3	110.5	19.77	Downwind of SW Tanks
22	SDP01/LOS1	14:33	14:42	5.0	110.2	22.15	Downwind of SW Tanks
23	SDP01/LOS1	14:44	14:53	4.7	112.5	23.02	Downwind of SW Tanks
24	SDP01/LOS1	14:55	15:03	5.3	112.8	29.82	Downwind of SW Tanks
25	SDP01/LOS1	15:03	15:12	4.6	113.8	22.81	Downwind of SW Tanks
26	SDP01/LOS1	15:14	15:31	4.8	111.0	11.64	Downwind of SW Tanks
27	SDP01/LOS1	15:32	15:49	5.6	120.0	24.13	Downwind of SW Tanks
28	SDP01/LOS1	15:49	16:05	6.3	122.6	12.87	Downwind of SW Tanks
29	SDP01/LOS1	16:06	16:23	5.5	121.9	13.01	Downwind of SW Tanks
30	SDP01/LOS3	16:25	16:41	5.4	123.2	14.98	Downwind of SW Tanks
31	SDP01/LOS3	16:43	16:55	4.9	120.2	18.68	Downwind of SW Tanks
32	SDP01/LOS3	16:55	17:07	5.0	126.0	23.68	Downwind of SW Tanks
35	SDP01/LOS1	17:26	17:36	4.3	119.7	12.60	Downwind of SW Tanks

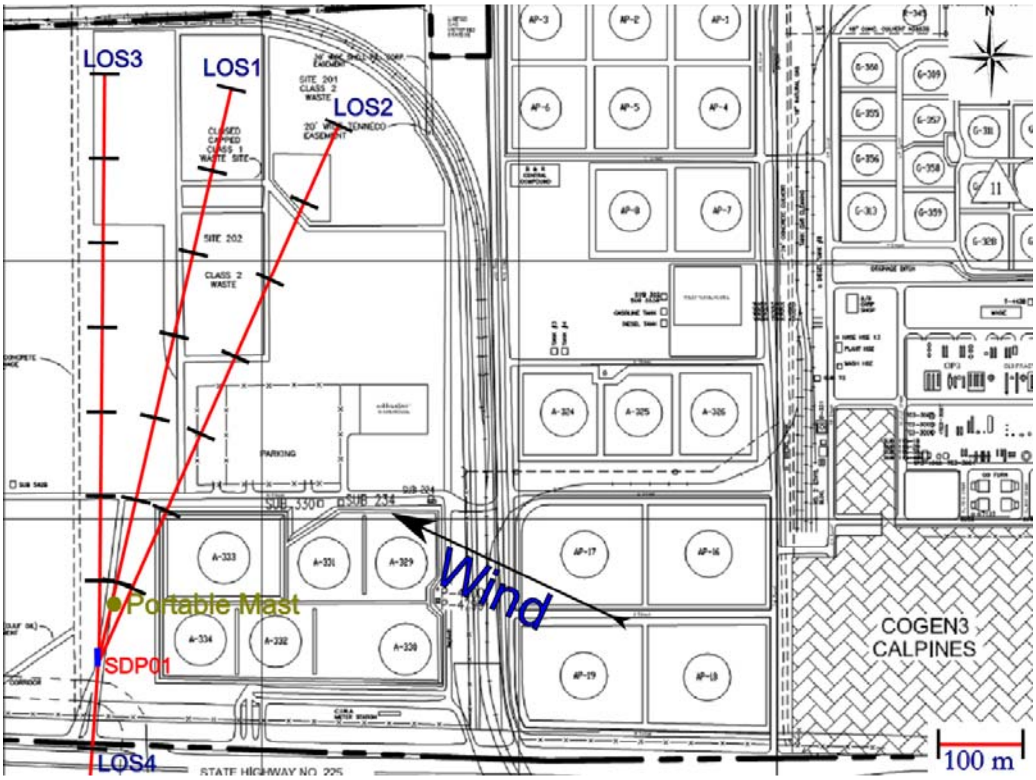

Figure 2.1 Measurement configuration for location SDP01 on 13th of January.

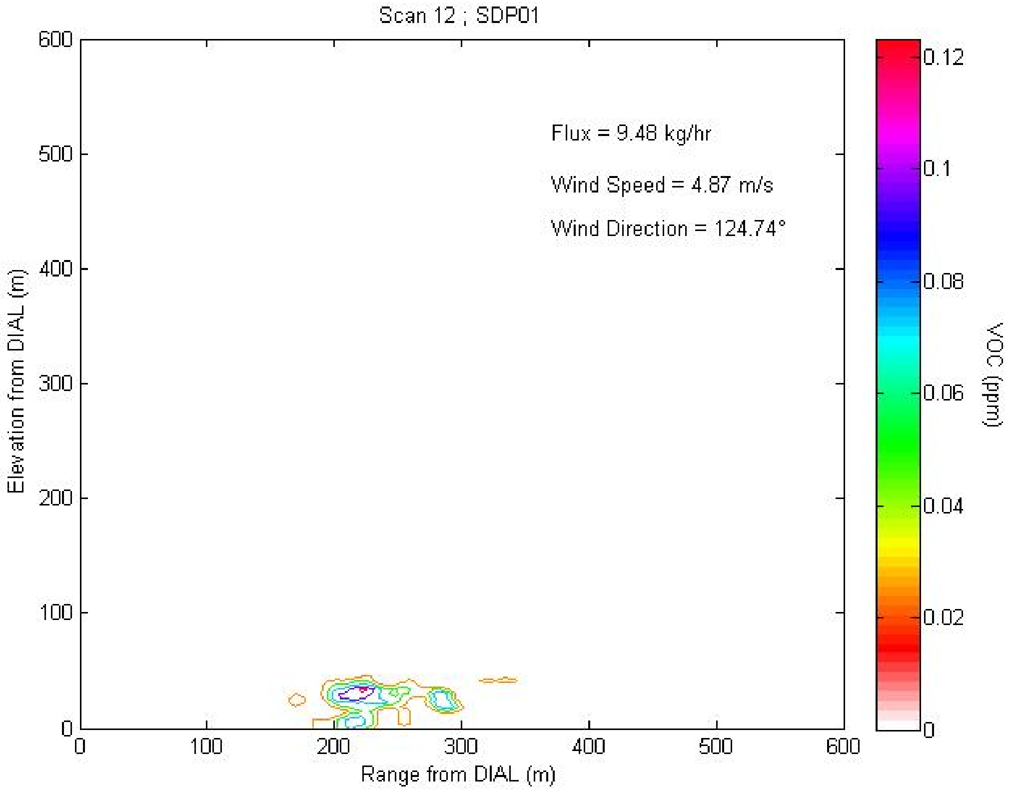

Figure 2.1a1 Contour plot of concentration profile for Scan 12 representing LOS1.

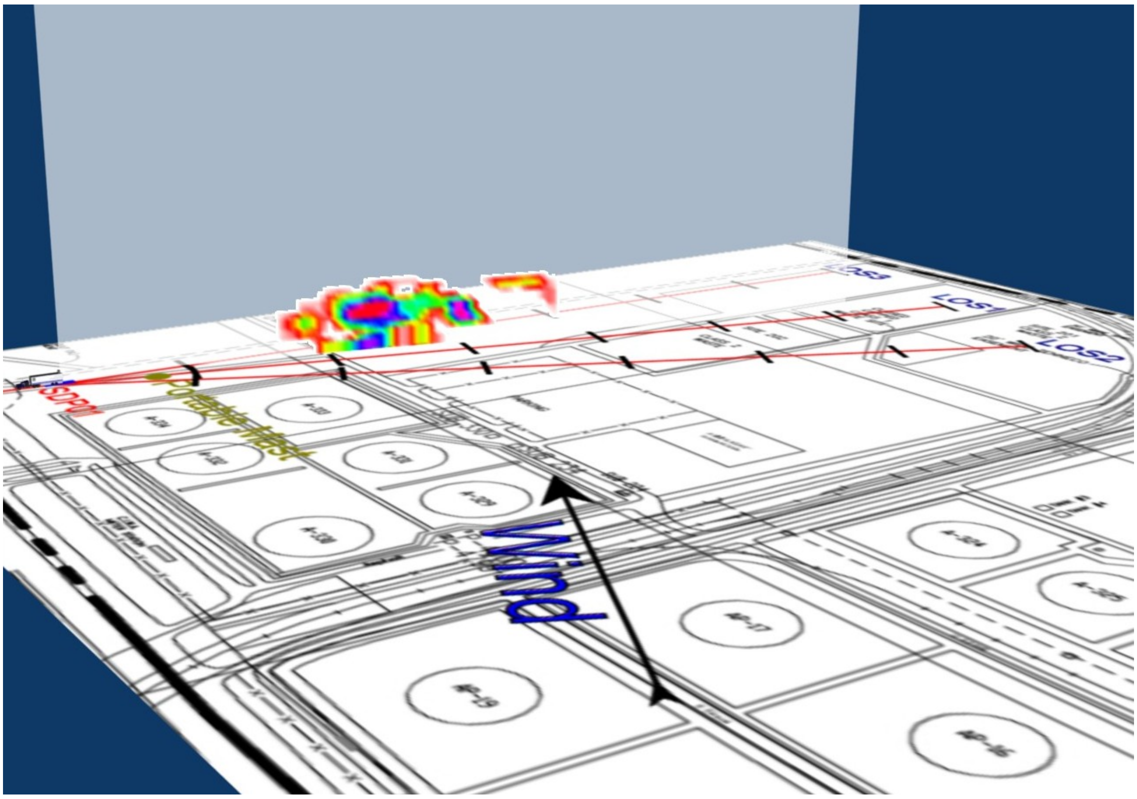

Figure 2.1a2 Visualisation of emission rate measured for Scan 12 representing LOS1.

Table 2.2 Emission rate measurements from SDP02 on 14th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
36	SDP02/LOS1	12:32	12:42	5.6	118.3	9.48	Downwind West Tanks
37	SDP02/LOS1	12:43	12:56	5.9	115.3	11.60	Downwind West Tanks
38	SDP02/LOS1	12:56	13:10	5.8	109.6	19.04	Downwind West Tanks
39	SDP02/LOS1	13:11	13:24	5.7	110.7	22.88	Downwind West Tanks
41	SDP02/LOS1	13:35	13:49	5.4	105.5	16.36	Downwind West Tanks
42	SDP02/LOS1	13:49	14:03	5.7	104.1	17.76	Downwind West Tanks
43	SDP02/LOS1	14:05	14:18	7.0	120.8	15.11	Downwind West Tanks
44	SDP02/LOS2	14:25	14:36	6.9	106.5	10.56	Downwind West Tanks
45	SDP02/LOS2	14:37	14:49	5.9	112.5	16.07	Downwind West Tanks
46	SDP02/LOS2	14:49	15:01	6.3	107.5	22.48	Downwind West Tanks
47	SDP02/LOS2	15:01	15:13	6.1	107.4	17.03	Downwind West Tanks
48	SDP02/LOS2	15:13	15:25	7.1	105.4	9.78	Downwind West Tanks
49	SDP02/LOS2	15:25	15:37	6.8	103.6	13.62	Downwind West Tanks
52	SDP02/LOS2	15:56	16:08	7.3	90.2	4025.80	Downwind West Tanks - Event
53	SDP02/LOS2	16:08	16:20	6.5	94.7	20.52	Downwind West Tanks
54	SDP02/LOS2	16:21	16:32	6.5	96.7	25.89	Downwind West Tanks
55	SDP02/LOS1	16:36	16:45	7.7	99.5	12.40	Downwind West Tanks
56	SDP02/LOS1	16:45	16:54	7.8	98.9	23.24	Downwind West Tanks
57	SDP02/LOS1	16:55	17:03	5.0	88.1	13.79	Downwind West Tanks
58	SDP02/LOS1	17:04	17:12	6.7	98.0	13.07	Downwind West Tanks

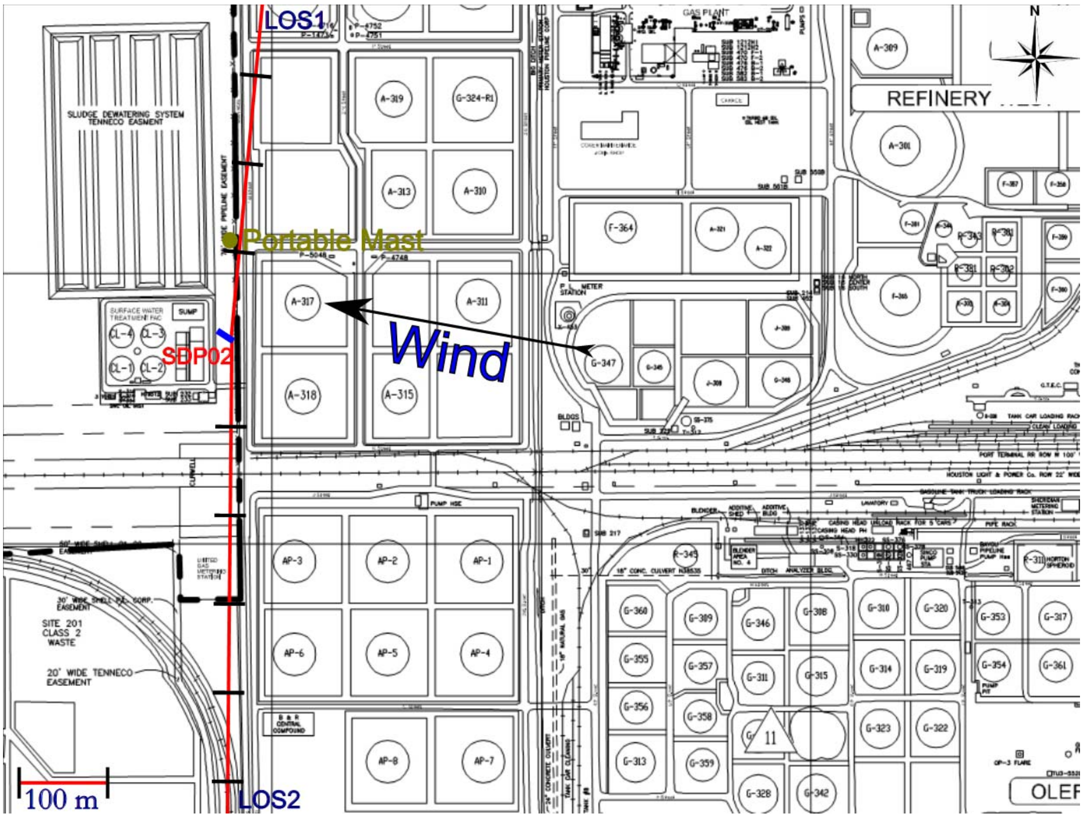

Figure 2.2 Measurement configuration for location SDP02 on 14th of January.

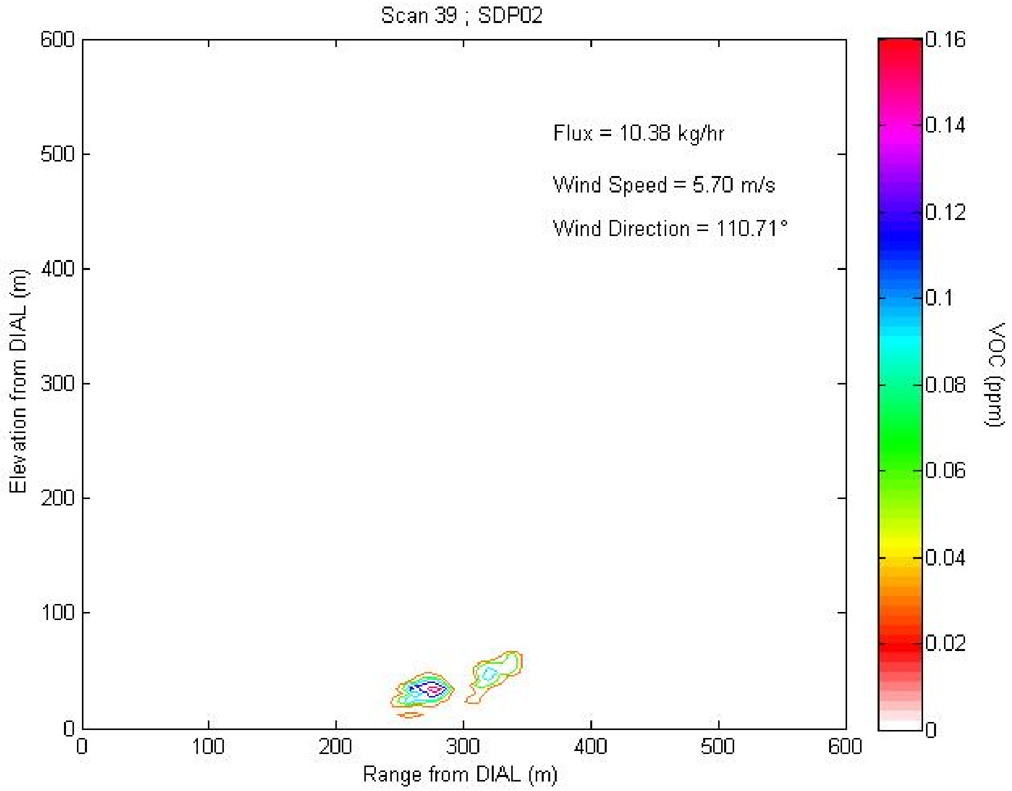

Figure 2.2a1 Contour plot of concentration profile for Scan 39 representing LOS1.

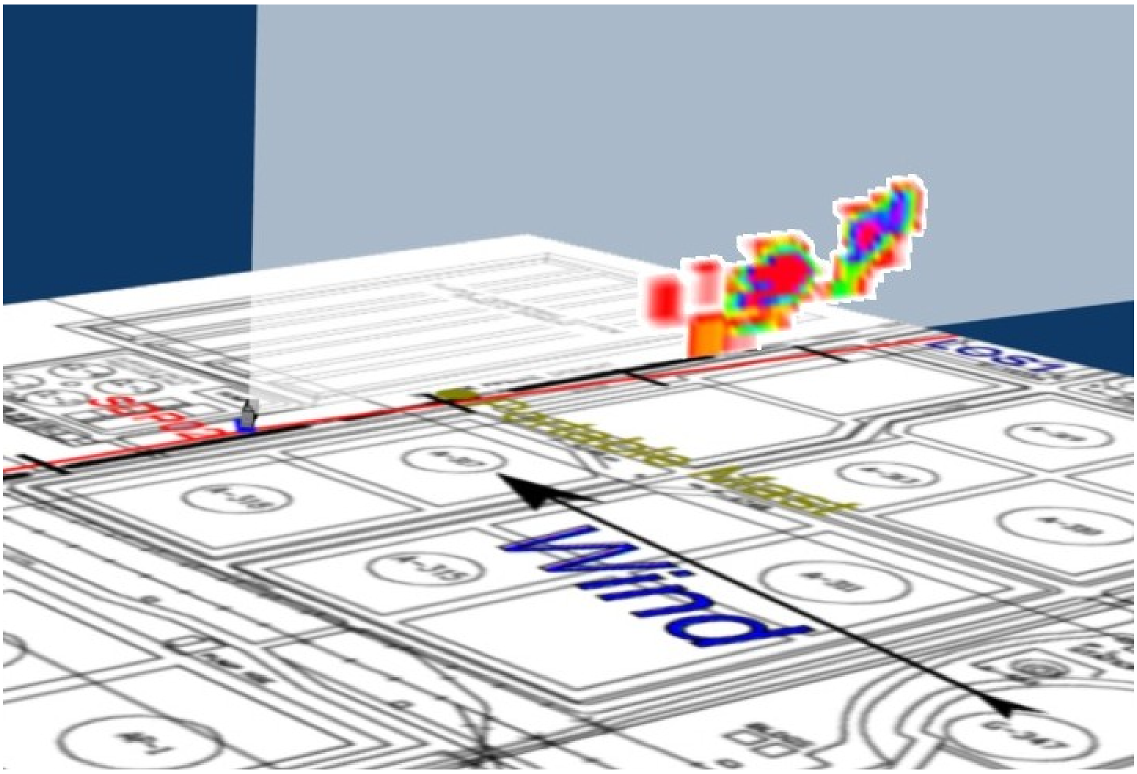

Figure 2.2a2 Visualisation of emission rate measured for Scan 39 representing LOS1.

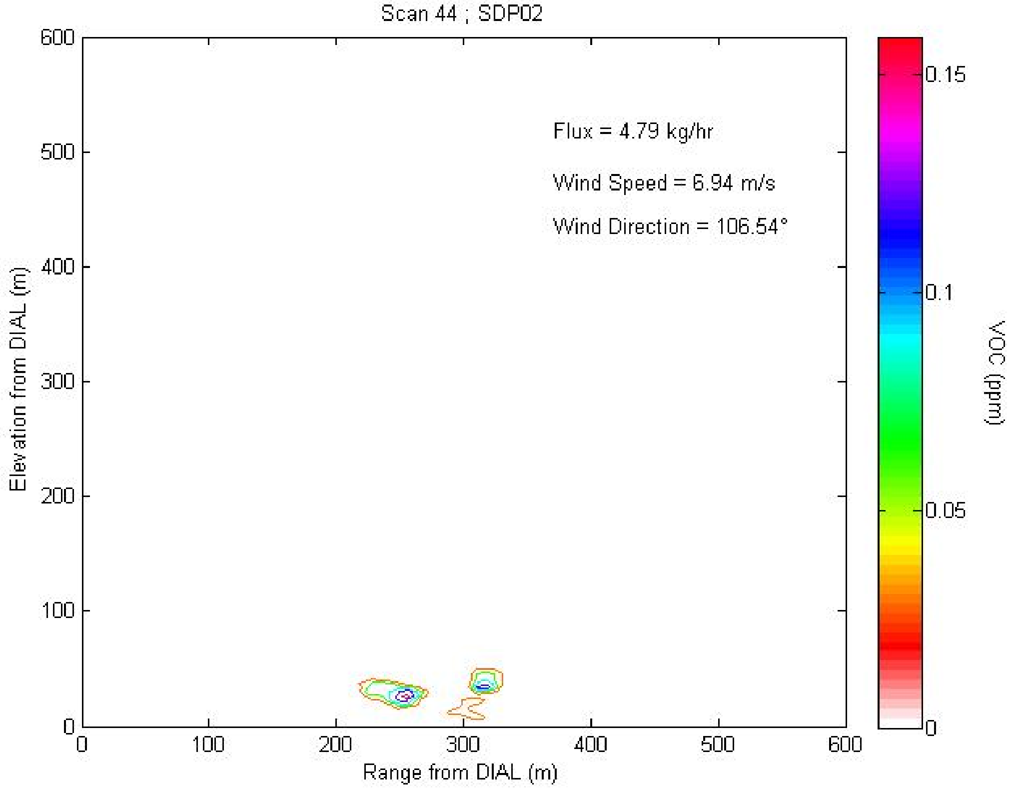

Figure 2.2b1 Contour plot of concentration profile for Scan 44 representing LOS2.

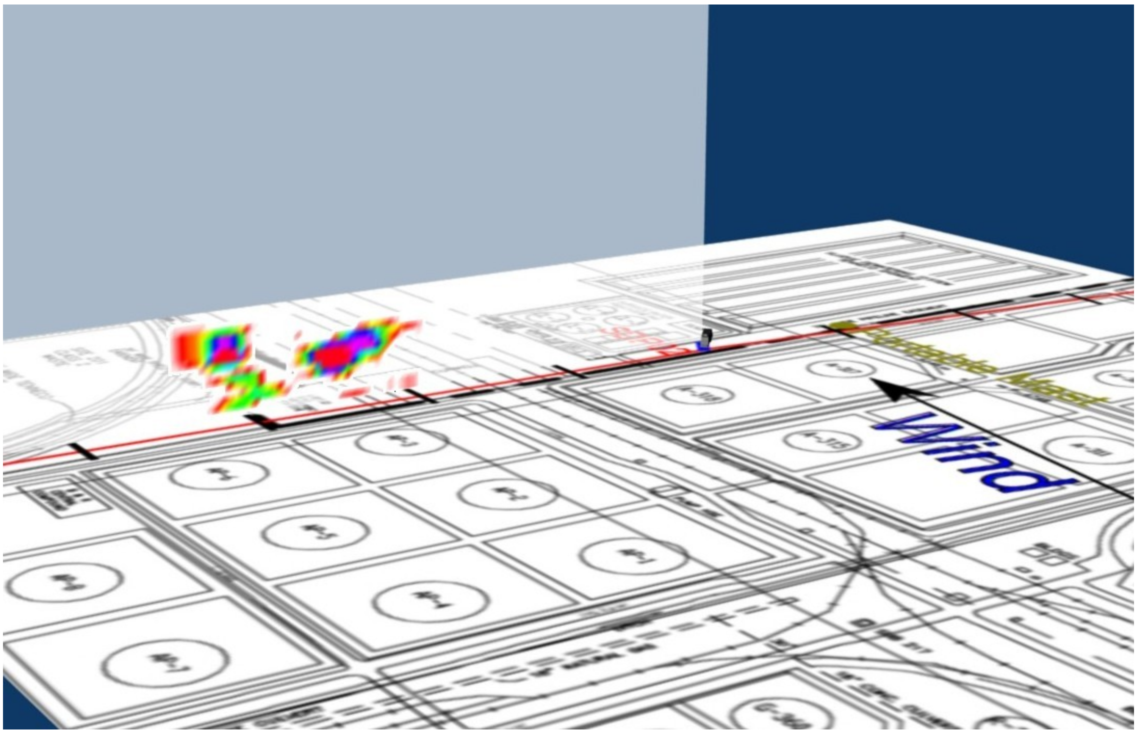

Figure 2.2b2 Visualisation of emission rate measured for Scan 44 representing LOS2.

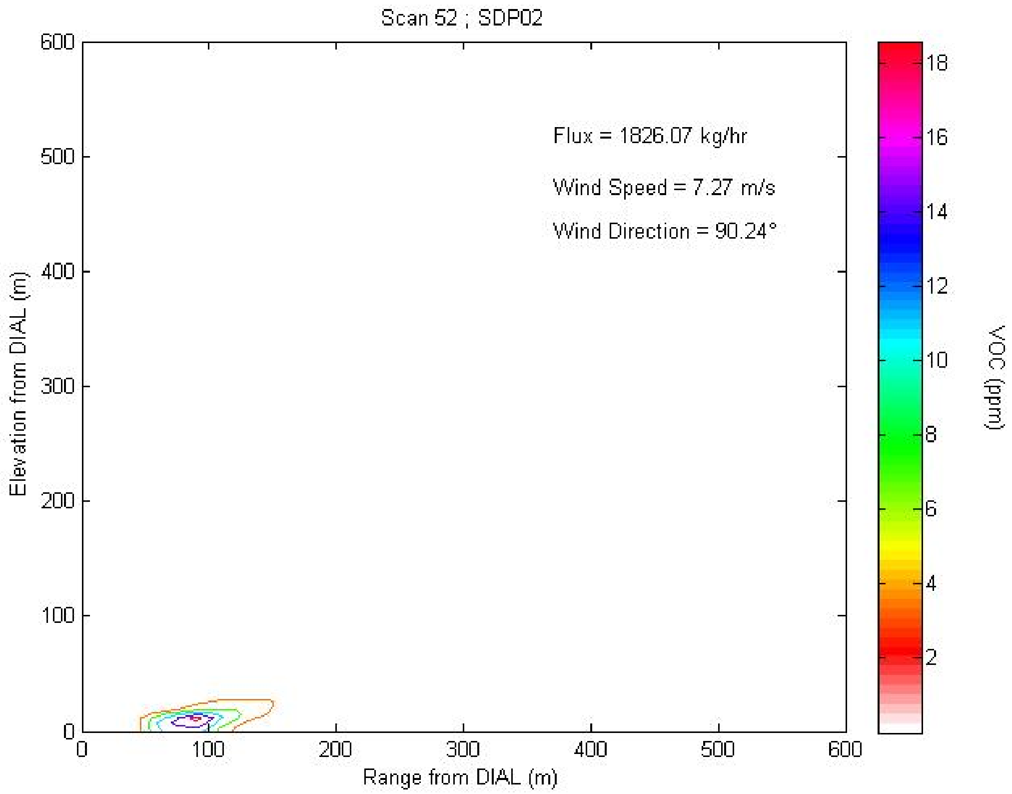

Figure 2.2c1 Contour plot of concentration profile for Scan 52 representing LOS2.

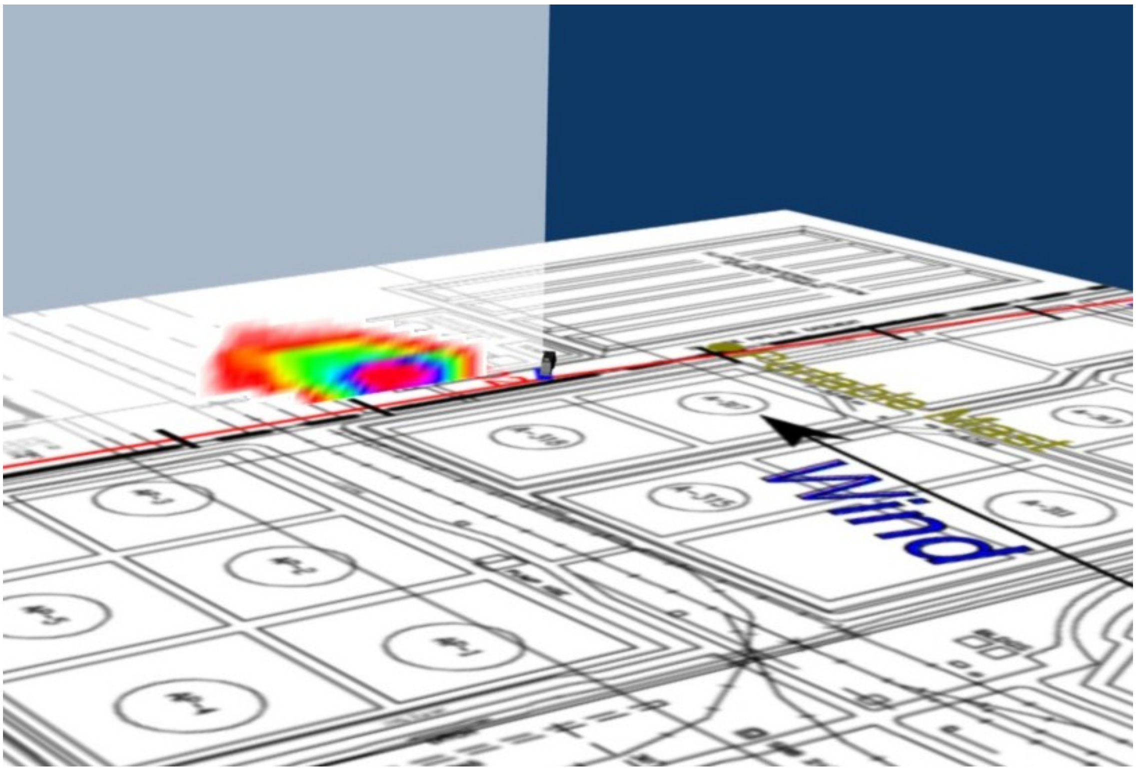

Figure 2.2c2 Visualisation of emission rate measured for Scan 52 representing LOS2.

Table 2.3 Emission rate measurements from SDP03 on 15th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
60	SDP03/LOS1	11:35	11:47	6.7	35.96	7.21	Upwind SW AP Tanks
61	SDP03/LOS1	11:48	12:00	7.4	31.78	10.96	Upwind SW AP Tanks
62	SDP03/LOS1	12:00	12:13	5.9	42.66	6.18	Upwind SW AP Tanks
63	SDP03/LOS1	12:14	12:25	7.3	35.64	14.71	Upwind SW AP Tanks
64	SDP03/LOS1	12:25	12:36	7.6	36.03	6.58	Upwind SW AP Tanks
65	SDP03/LOS1	12:36	12:47	7.6	39.66	14.35	Upwind SW AP Tanks
66	SDP03/LOS1	12:47	12:57	7.9	35.48	14.22	Upwind SW AP Tanks
67	SDP03/LOS1	13:00	13:10	7.2	38.25	14.28	Upwind SW AP Tanks
68	SDP03/LOS1	13:11	13:21	7.0	27.97	9.65	Upwind SW AP Tanks
71	SDP03/LOS2	13:42	13:53	6.7	34.80	46.43	Downwind SW AP Tanks
72	SDP03/LOS2	13:55	14:16	7.6	37.77	67.45	Downwind SW AP Tanks
73	SDP03/LOS2	14:16	14:36	6.2	45.56	81.67	Downwind SW AP Tanks
74	SDP03/LOS2	14:37	14:57	6.7	61.39	51.80	Downwind SW AP Tanks
77	SDP03/LOS3	15:49	16:00	5.1	42.94	76.89	Downwind SW AP Tanks
78	SDP03/LOS3	16:02	16:14	7.1	34.38	45.77	Downwind SW AP Tanks
79	SDP03/LOS3	16:15	16:28	8.2	35.56	50.68	Downwind SW AP Tanks
80	SDP03/LOS3	16:29	16:50	7.0	36.91	71.82	Downwind SW AP Tanks

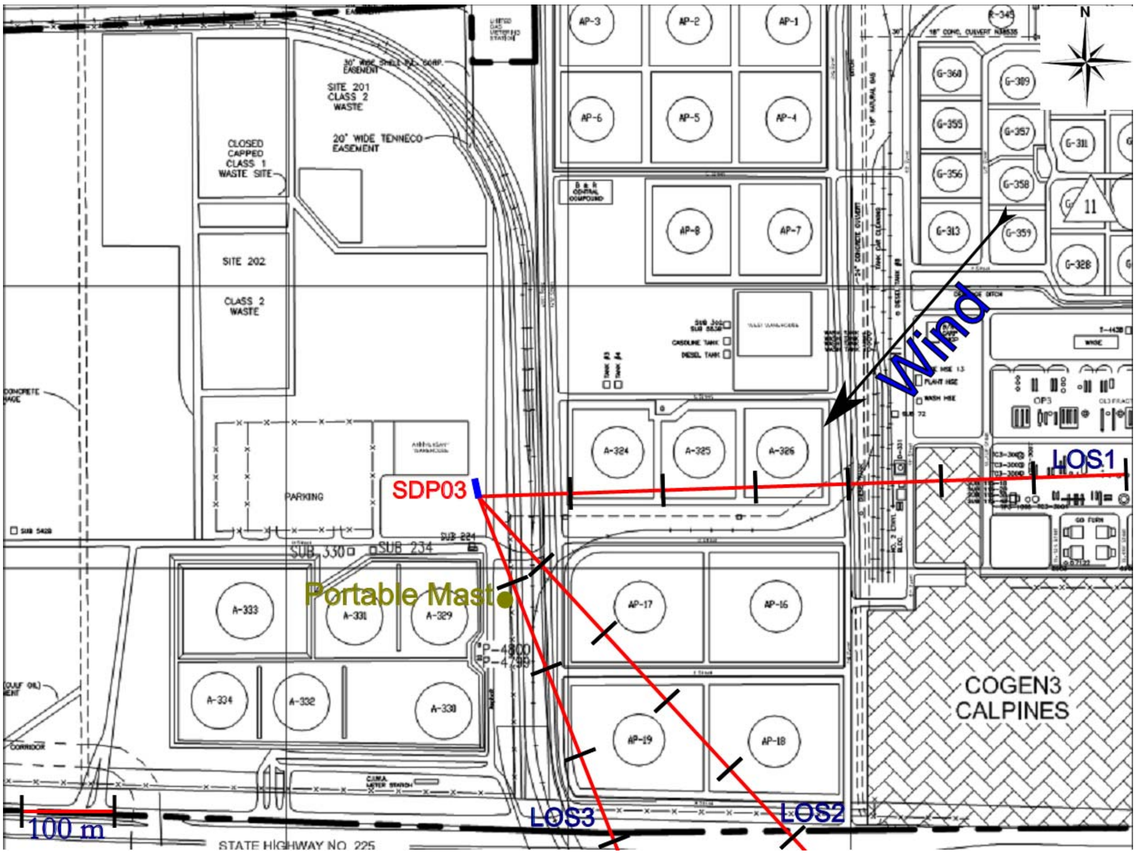

Figure 2.3 Measurement configuration for location SDP03 on 15th of January.

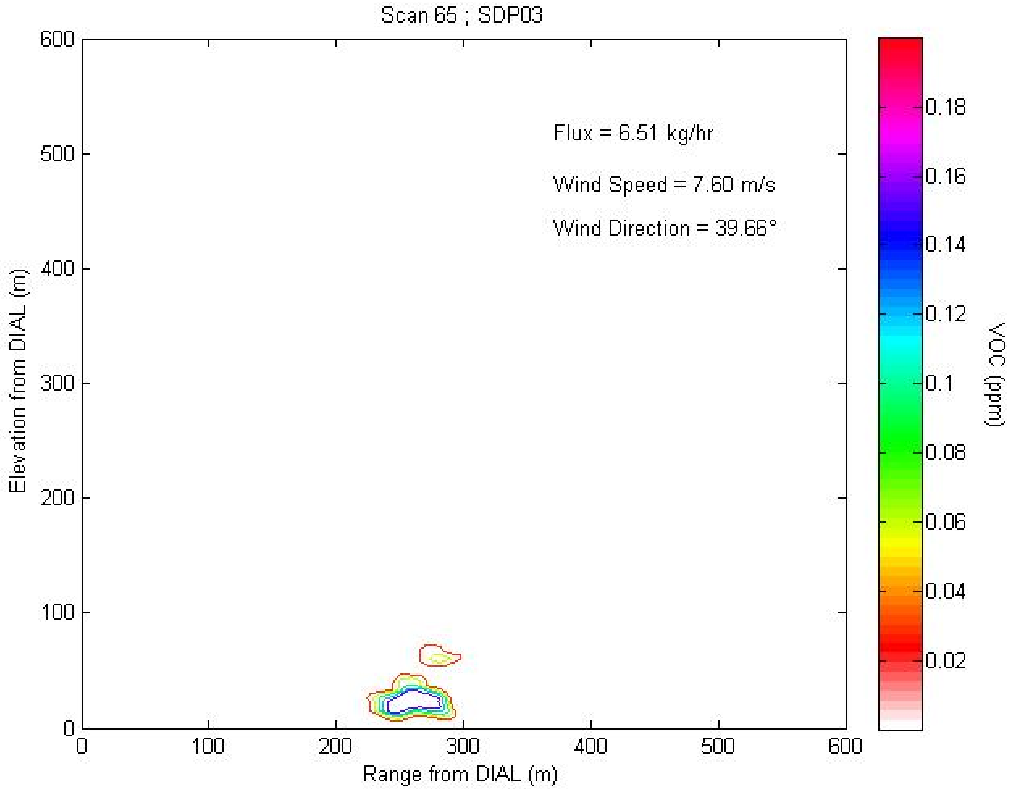

Figure 2.3a1 Contour plot of concentration profile for Scan 65 representing LOS1.

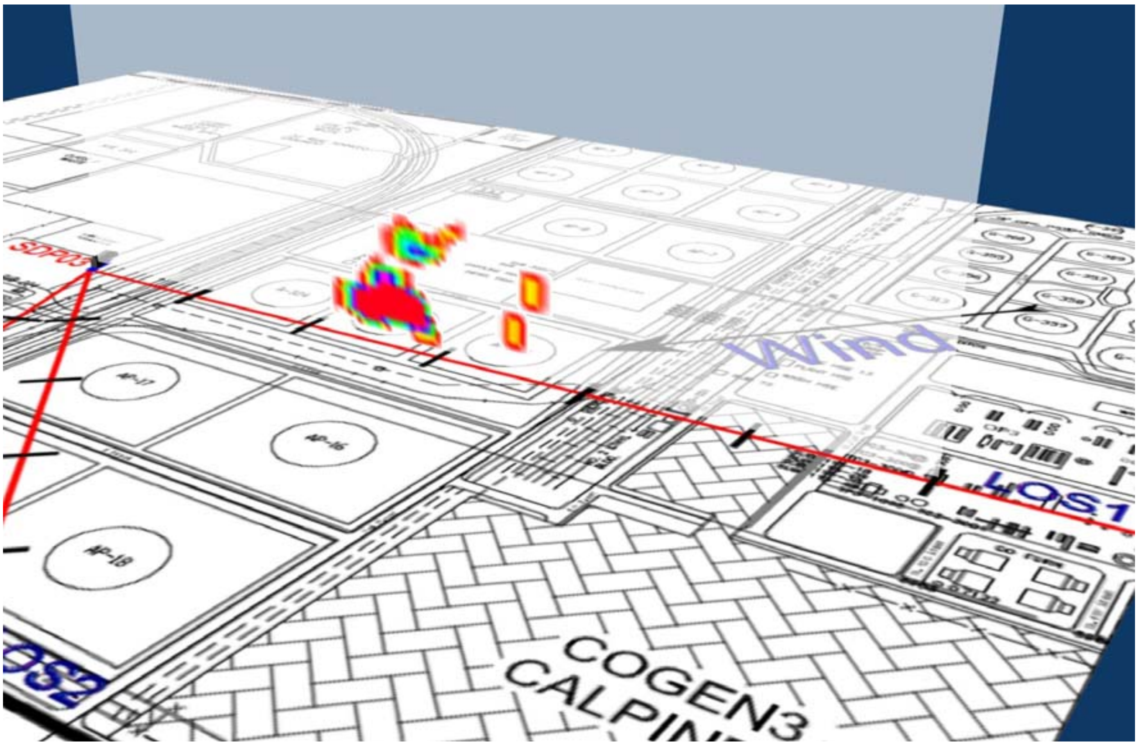

Figure 2.3a2 Visualisation of emission rate measured for Scan 65 representing LOS1.

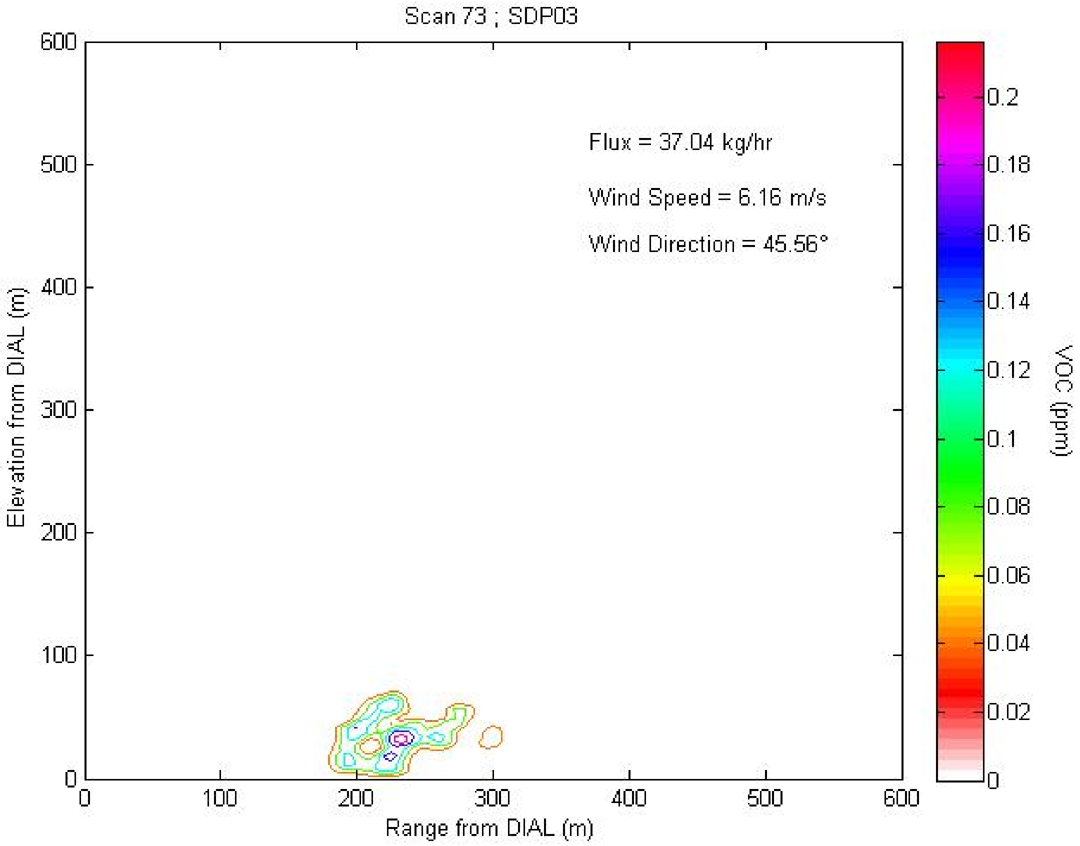

Figure 2.3b1 Contour plot of concentration profile for Scan 73 representing LOS2.

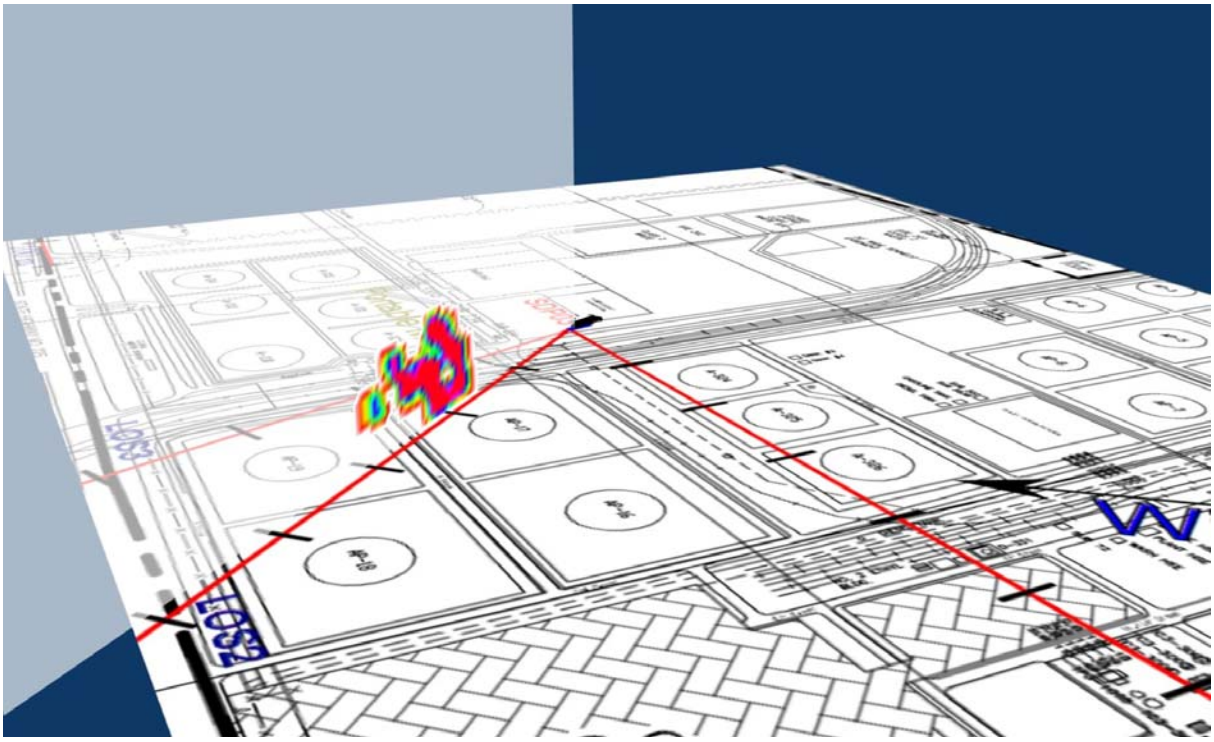

Figure 2.3b2 Visualisation of emission rate measured for Scan 73 representing LOS2.

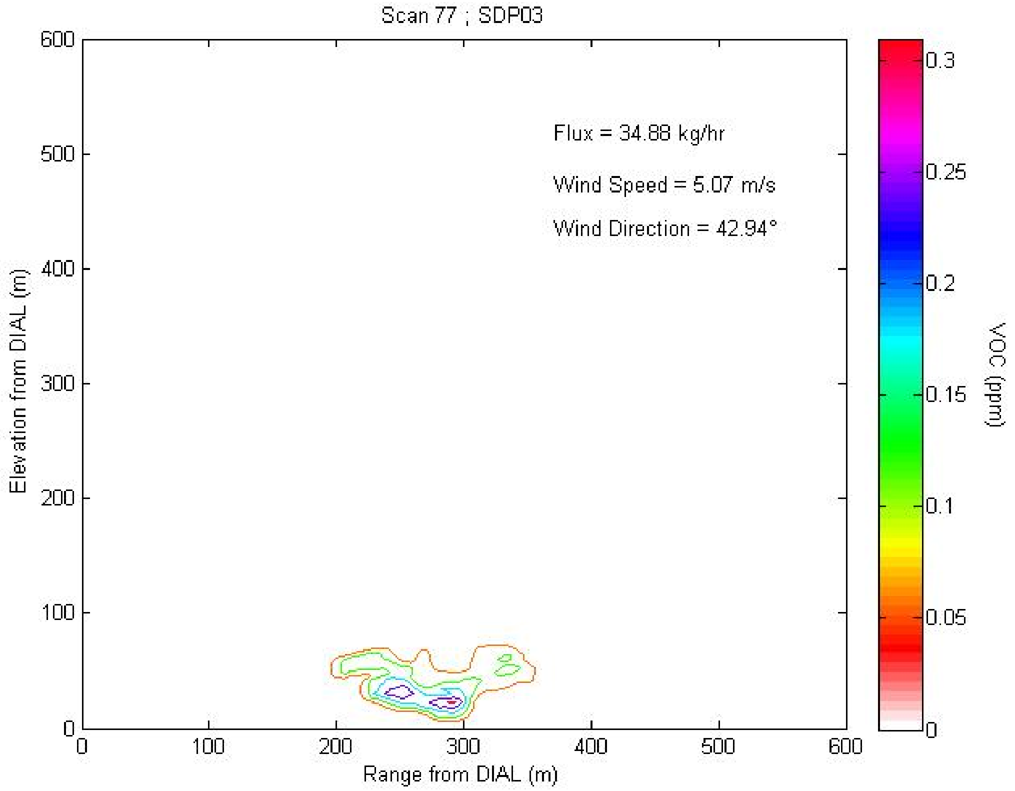

Figure 2.3c1 Contour plot of concentration profile for Scan 77 representing LOS3.

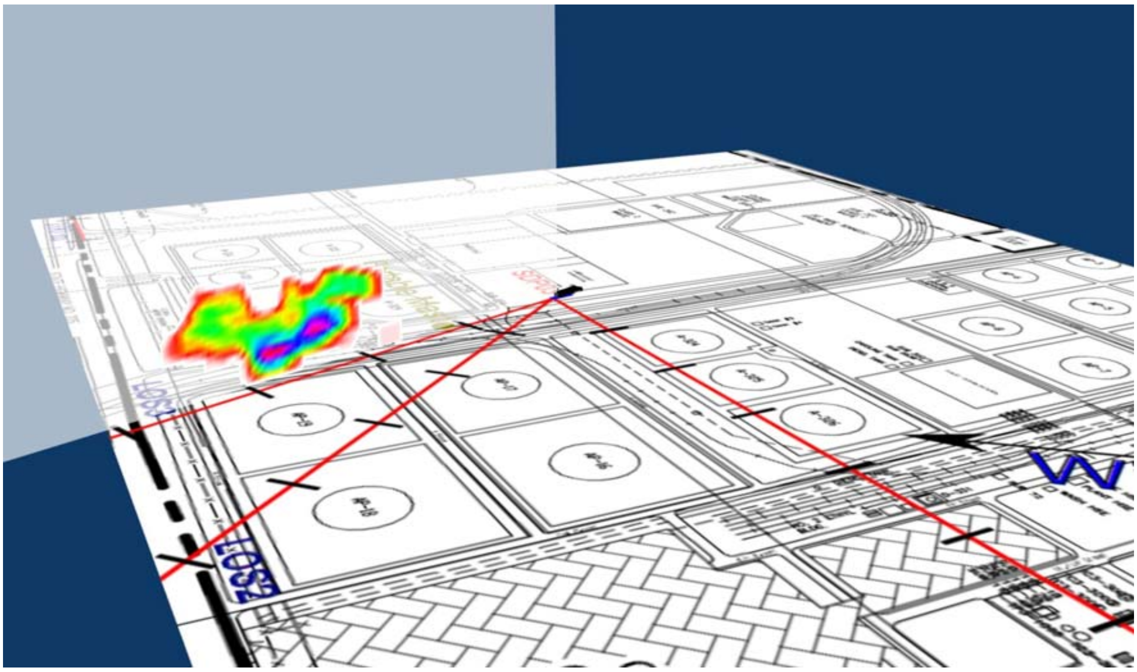

Figure 2.3c2 Visualisation of emission rate measured for Scan 77 representing LOS3.

Table 2.4 Emission rate measurements from SDP04 on 16th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
82	SDP04/LOS1	10:58	11:07	5.9	337.0	0.22	Downwind Coker + Flare
83	SDP04/LOS1	11:08	11:17	5.4	336.6	1.13	Downwind Coker + Flare
84	SDP04/LOS1	11:19	11:28	4.5	331.2	3.13	Downwind Coker + Flare
85	SDP04/LOS1	11:29	11:39	5.2	335.0	3.97	Downwind Coker + Flare
87	SDP04/LOS2	11:48	11:57	5.2	330.6	3.33	Downwind Coker + Flare
88	SDP04/LOS2	11:58	12:09	4.6	335.2	1.02	Downwind Coker + Flare
89	SDP04/LOS2	12:09	12:20	5.1	340.0	2.43	Downwind Coker + Flare
90	SDP04/LOS2	12:23	12:34	4.9	342.3	3.80	Downwind Coker + Flare
91	SDP04/LOS3	12:39	12:50	3.8	349.5	-0.92	Downwind Tanks West of Coker
92	SDP04/LOS3	12:54	13:07	4.3	330.0	0.17	Downwind Tanks West of Coker
93	SDP04/LOS3	13:07	13:21	5.3	330.7	1.17	Downwind Tanks West of Coker
94	SDP04/LOS3	13:21	13:34	4.6	330.5	1.02	Downwind Tanks West of Coker
95	SDP04/LOS3	13:35	13:48	5.6	333.4	0.60	Downwind Tanks West of Coker
102	SDP04/LOS4	14:21	14:38	5.0	320.6	2.82	Downwind Coker
103	SDP04/LOS4	14:38	14:55	6.1	316.3	2.00	Downwind Coker
104	SDP04/LOS4	14:55	15:12	6.6	323.6	0.48	Downwind Coker
105	SDP04/LOS4	15:13	15:29	6.2	318.2	0.60	Downwind Coker
106	SDP04/LOS4	15:31	15:47	5.2	317.1	2.99	Downwind Coker
107	SDP04/LOS4	15:47	16:03	6.4	322.3	1.01	Downwind Coker
108	SDP04/LOS4	16:04	16:20	6.0	331.4	2.88	Downwind Coker
109	SDP04/LOS5	16:23	16:40	6.3	331.6	4.16	Downwind Coker + Flare
110	SDP04/LOS5	16:40	16:57	5.8	326.1	3.76	Downwind Coker + Flare
111	SDP04/LOS5	16:57	17:13	6.3	322.9	2.06	Downwind Coker + Flare

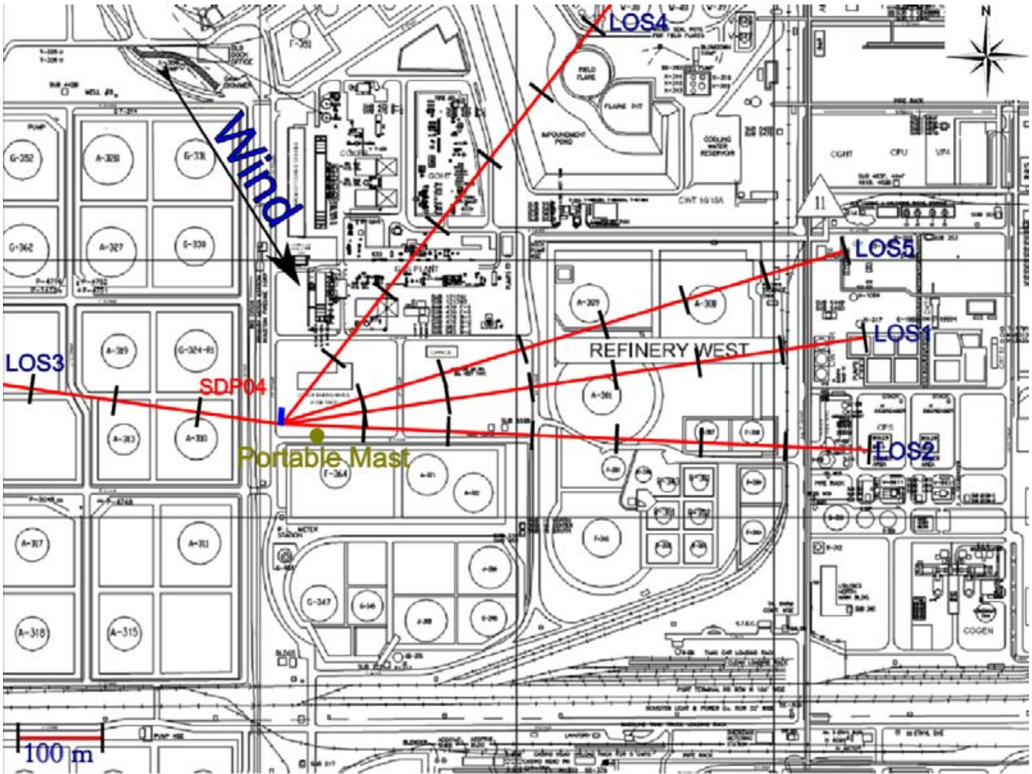

Figure 2.4 Measurement configuration for location SDP04 on 16th of January.

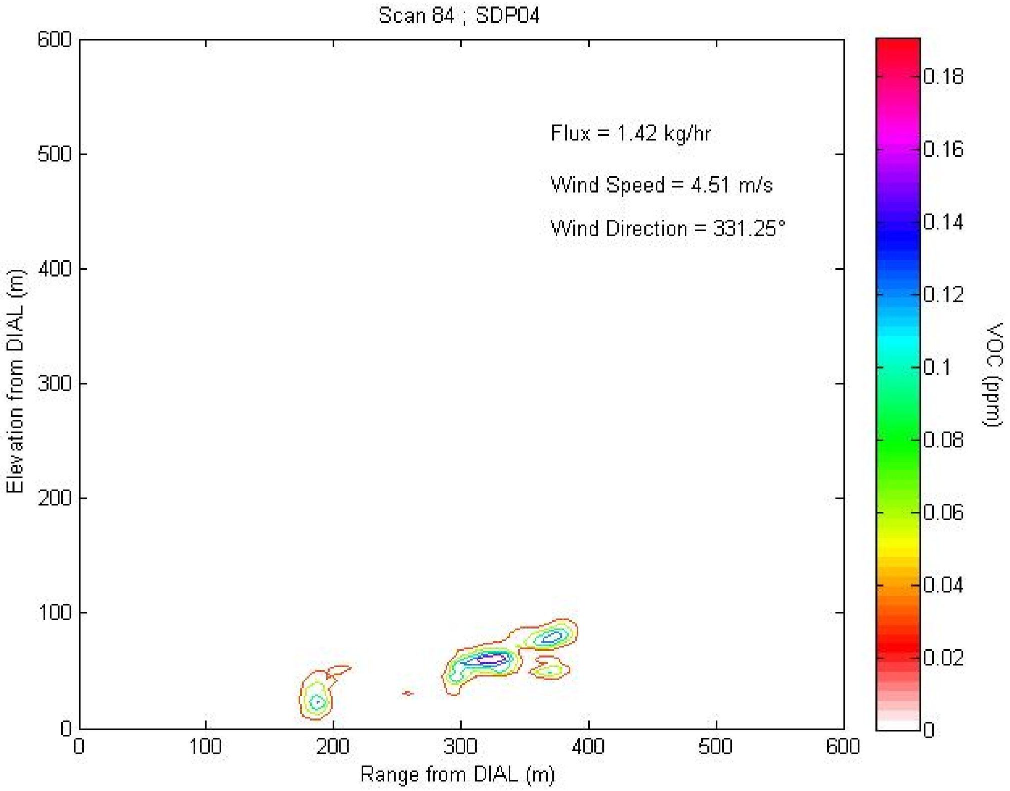

Figure 2.4a1 Contour plot of concentration profile for Scan 84 representing LOS1.

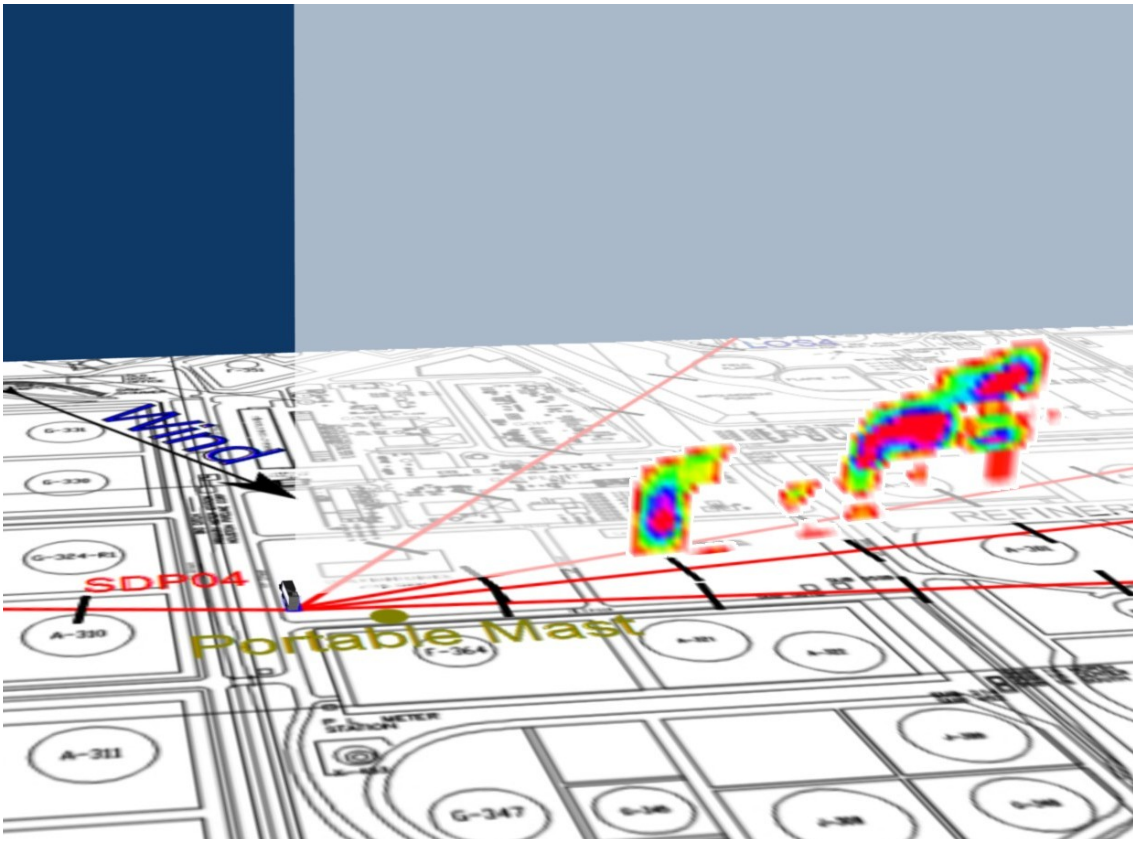

Figure 2.4a2 Visualisation of emission rate measured for Scan 84 representing LOS1.

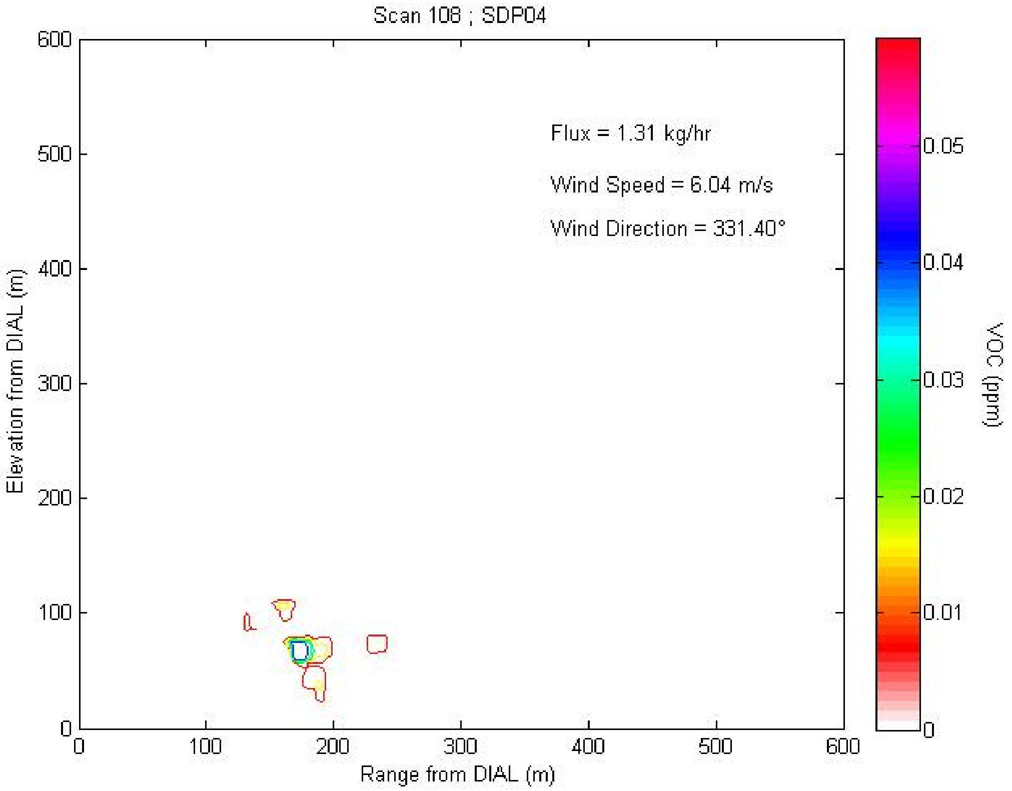

Figure 2.4b1 Contour plot of concentration profile for Scan 108 representing LOS4.

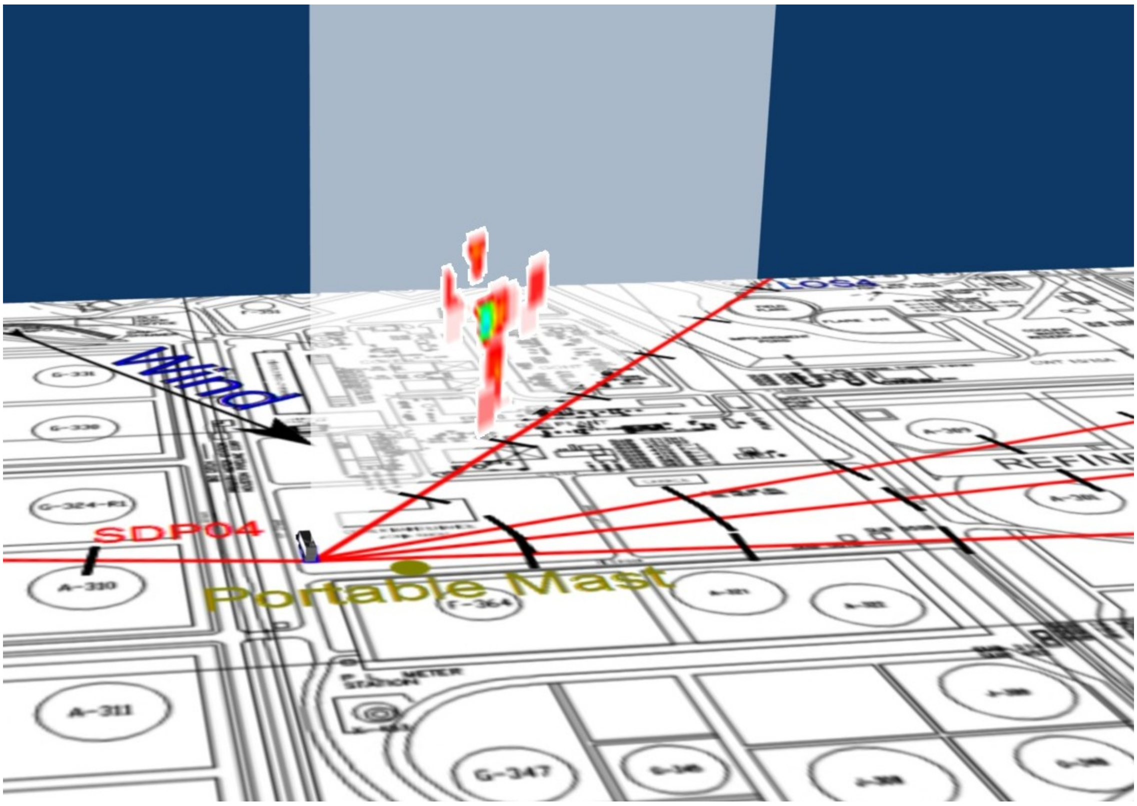

Figure 2.4b2 Visualisation of emission rate measured for Scan 108 representing LOS4.

Table 2.5 Emission rate measurements from SDP05 on 18th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
113	SDP05/LOS1	10:46	10:56	4.2	155.7	3.33	Downwind of Olefins Process Area
114	SDP05/LOS1	10:57	11:07	4.4	178.3	6.67	Downwind of Olefins Process Area
115	SDP05/LOS1	11:08	11:18	4.3	171.4	2.96	Downwind of Olefins Process Area
116	SDP05/LOS1	11:18	11:28	3.7	185.5	2.77	Downwind of Olefins Process Area
118	SDP05/LOS1	11:36	11:48	3.5	183.5	4.47	Downwind of Olefins Process Area
119	SDP05/LOS1	11:48	12:00	4.1	175.3	3.84	Downwind of Olefins Process Area
120	SDP05/LOS1	12:01	12:12	4.3	182.4	5.41	Downwind of Olefins Process Area
121	SDP05/LOS2	12:15	12:26	5.6	188.4	6.20	Downwind of Olefins Process Area
122	SDP05/LOS2	12:26	12:37	6.4	191.2	4.88	Downwind of Olefins Process Area
123	SDP05/LOS2	12:37	12:48	6.4	188.3	3.82	Downwind of Olefins Process Area
124	SDP05/LOS2	12:49	12:57	5.9	186.1	2.26	Downwind of Olefins Process Area
125	SDP05/LOS2	12:57	13:05	5.6	172.9	5.62	Downwind of Olefins Process Area
126	SDP05/LOS2	13:05	13:13	5.1	170.2	4.39	Downwind of Olefins Process Area
127	SDP05/LOS2	13:26	13:38	6.1	191.0	5.96	Downwind of Olefins Process Area
129	SDP05/LOS2	13:45	13:57	6.0	192.3	5.13	Downwind of Olefins Process Area
130	SDP05/LOS2	13:58	14:10	5.2	197.1	4.54	Downwind of Olefins Process Area
131	SDP05/LOS3	14:19	14:31	6.0	189.2	2.35	Downwind of Olefins Process Area
132	SDP05/LOS3	14:31	14:43	6.4	157.8	4.52	Downwind of Olefins Process Area
133	SDP05/LOS3	14:43	14:55	5.9	163.0	5.12	Downwind of Olefins Process Area
134	SDP05/LOS3	14:56	15:07	5.4	132.5	2.95	Downwind of Olefins Process Area
135	SDP05/LOS3	15:08	15:19	4.1	159.9	4.97	Downwind of Olefins Process Area
136	SDP05/LOS4	15:28	15:39	5.6	127.6	1.69	Background
137	SDP05/LOS4	15:39	15:50	3.7	144.7	0.34	Background
138	SDP05/LOS4	15:50	16:02	3.7	105.7	0.81	Background
139	SDP05/LOS4	16:02	16:13	3.9	122.2	-0.22	Background
140	SDP05/LOS4	16:13	16:24	3.9	120.3	-1.00	Background
141	SDP05/LOS4	16:27	16:38	4.4	129.7	0.67	Background
142	SDP05/LOS4	16:38	16:50	4.9	123.6	-0.66	Background

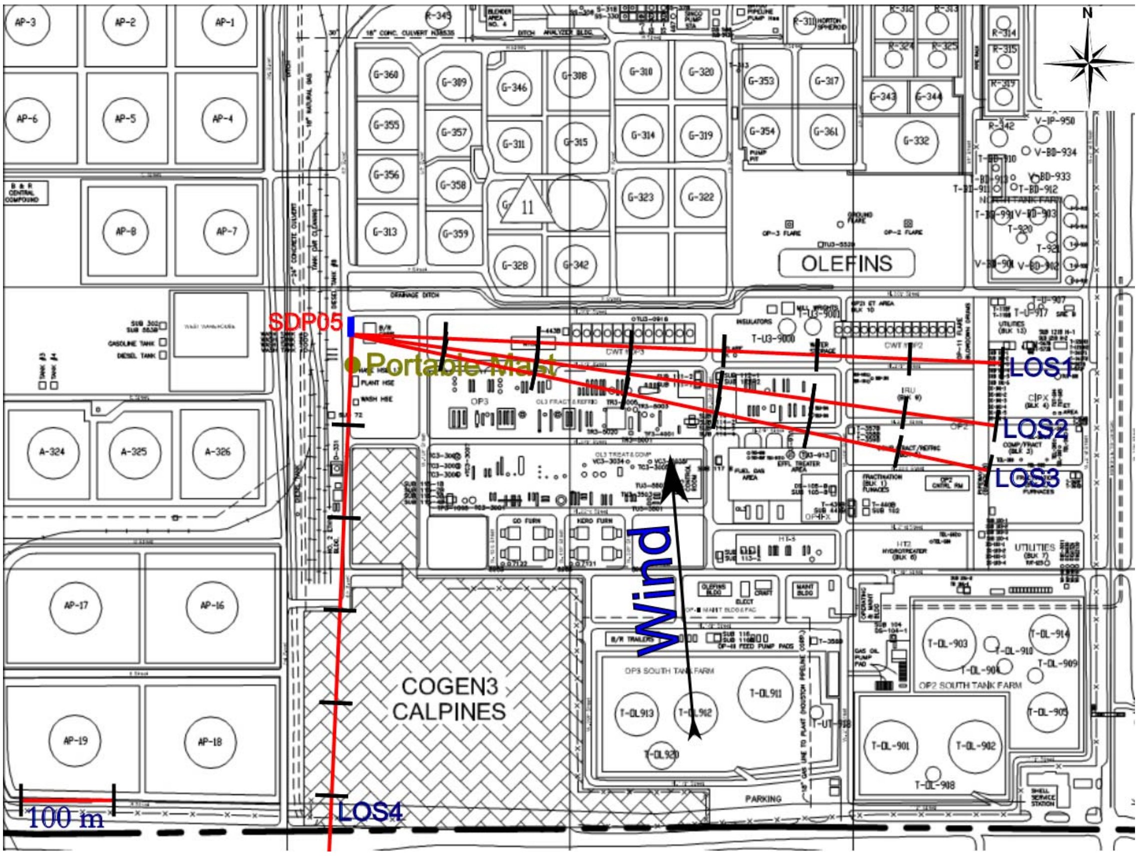

Figure 2.5 Measurement configuration for location SDP05 on 18th of January.

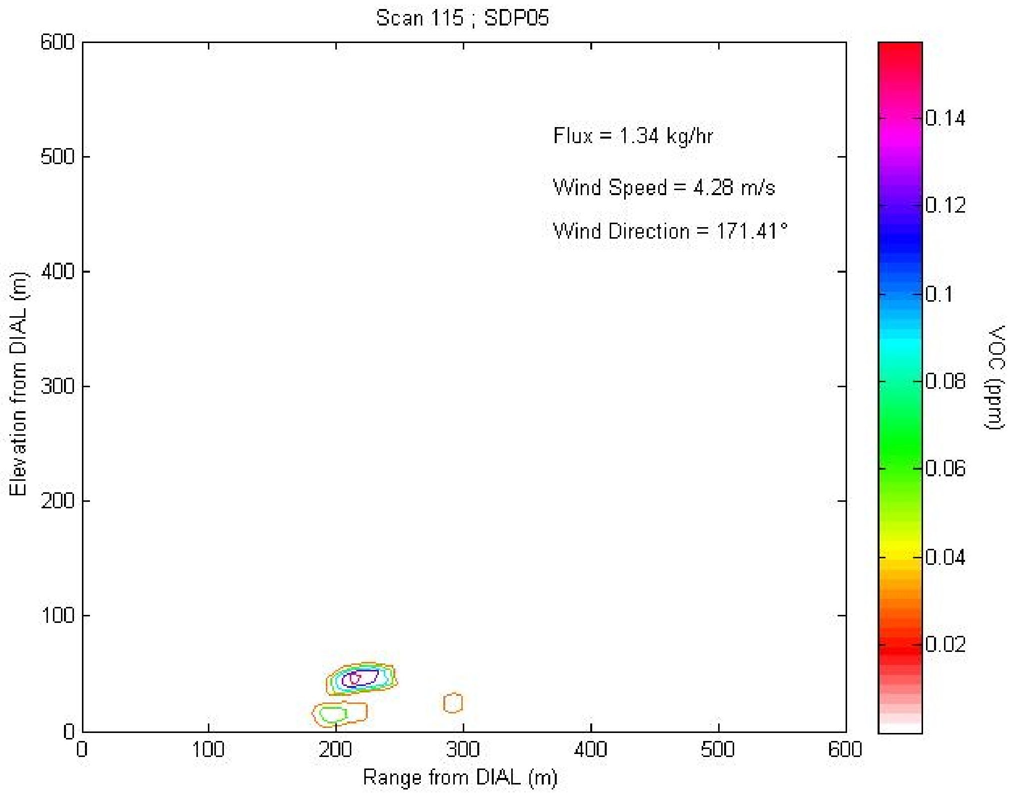

Figure 2.5a1 Contour plot of concentration profile for Scan 115 representing LOS1.

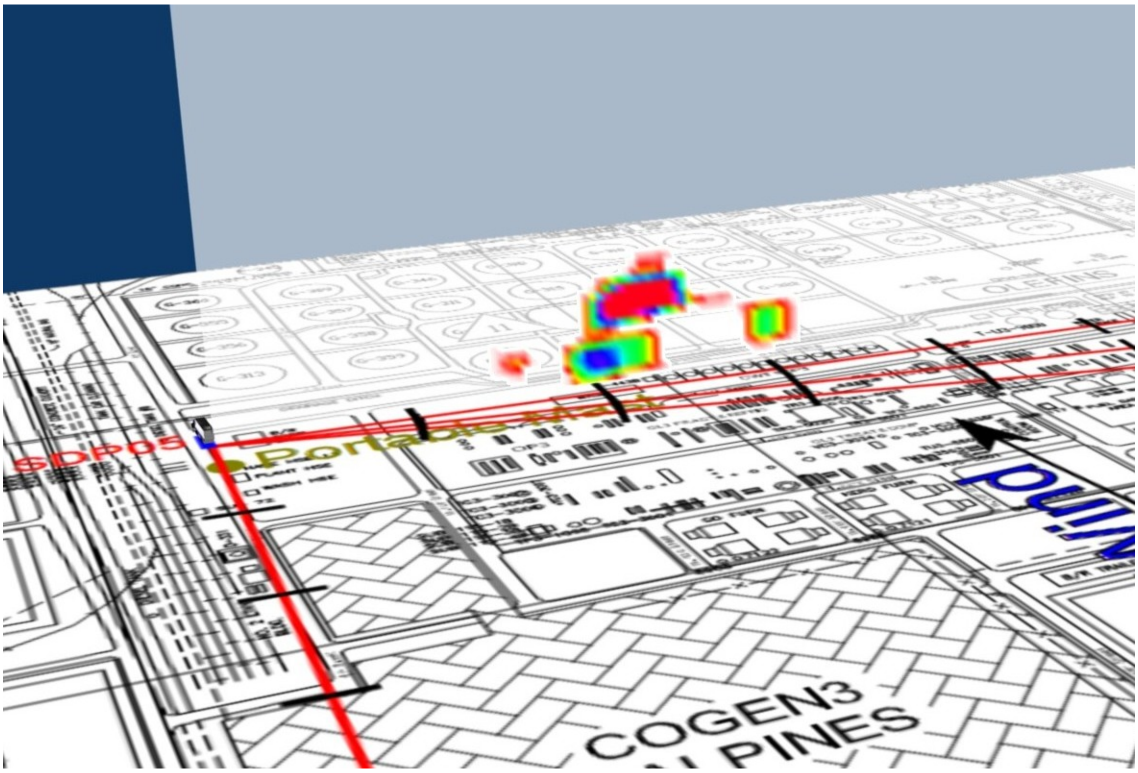

Figure 2.5a2 Visualisation of emission rate measured for Scan 115 representing LOS1.

Table 2.6 Emission rate measurements from SDP06 on 19th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
144	SDP06/LOS1	10:27	10:39	5.3	182.5	4.96	Downwind of Olefins Process Area
145	SDP06/LOS1	10:40	10:51	5.1	180.0	3.10	Downwind of Olefins Process Area
146	SDP06/LOS1	10:51	11:02	4.8	182.7	3.12	Downwind of Olefins Process Area
147	SDP06/LOS1	11:02	11:13	6.1	187.3	4.25	Downwind of Olefins Process Area
148	SDP06/LOS1	11:14	11:26	5.7	175.8	4.95	Downwind of Olefins Process Area
149	SDP06/LOS1	11:27	11:38	6.2	180.0	7.79	Downwind of Olefins Process Area
150	SDP06/LOS1	11:39	11:51	5.5	176.5	4.47	Downwind of Olefins Process Area
153	SDP06/LOS2	12:01	12:13	5.9	180.0	1.41	Background
154	SDP06/LOS2	12:13	12:25	6.2	184.0	-0.35	Background
155	SDP06/LOS2	12:25	12:37	6.2	182.8	-0.61	Background
156	SDP06/LOS3	12:43	12:54	6.0	180.1	46.83	Downwind SW AP Tanks
157	SDP06/LOS3	12:54	13:05	6.3	182.0	37.11	Downwind SW AP Tanks
158	SDP06/LOS3	13:06	13:17	4.8	183.3	43.76	Downwind SW AP Tanks
159	SDP06/LOS1	13:18	13:31	6.3	186.2	3.49	Downwind of Olefins Process Area
160	SDP06/LOS1	13:31	13:43	6.3	172.6	3.06	Downwind of Olefins Process Area
161	SDP06/LOS1	13:43	13:55	5.5	174.7	4.12	Downwind of Olefins Process Area
162	SDP06/LOS1	13:56	14:07	5.9	178.6	6.33	Downwind of Olefins Process Area
163	SDP06/LOS1	14:07	14:18	5.2	179.5	2.43	Downwind of Olefins Process Area

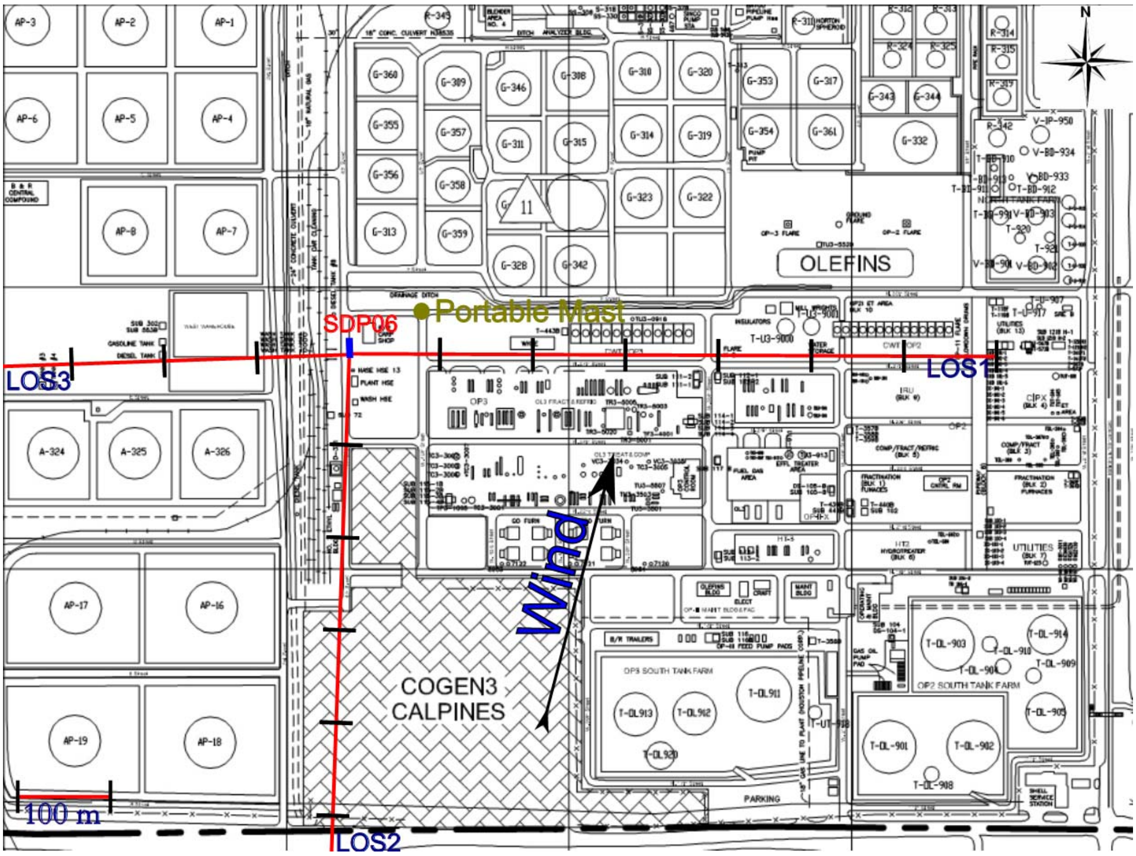

Figure 2.6 Measurement configuration for location SDP06 on 19th of January.

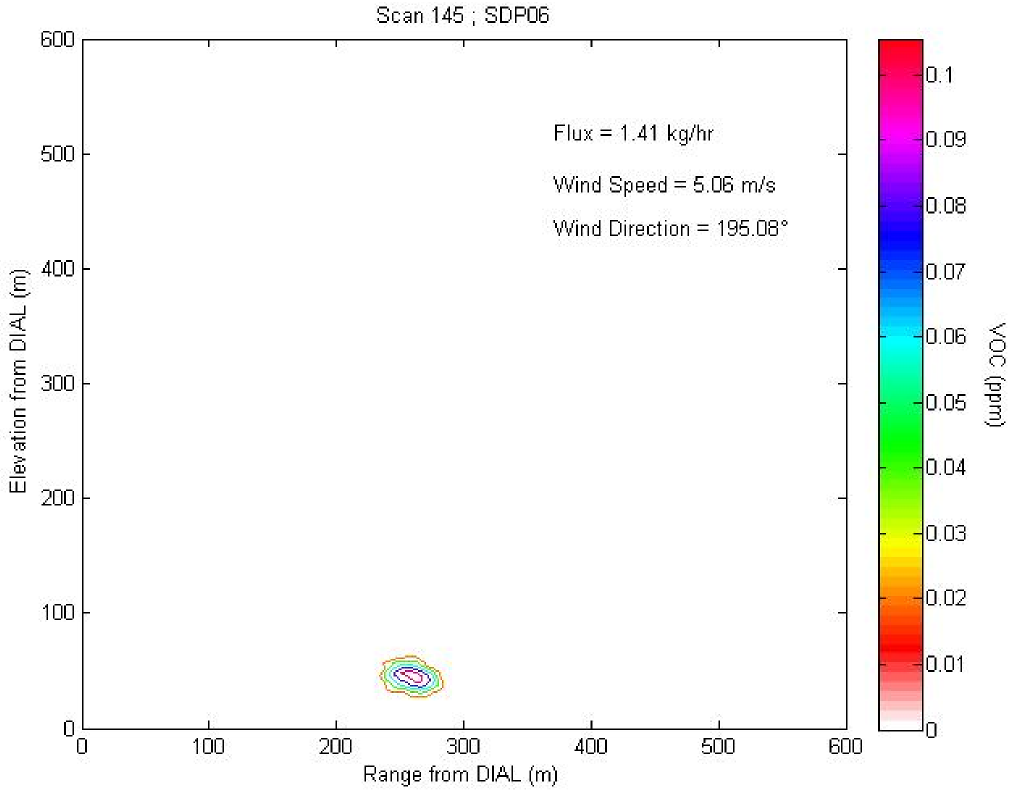

Figure 2.6a1 Contour plot of concentration profile for Scan 145 representing LOS1.

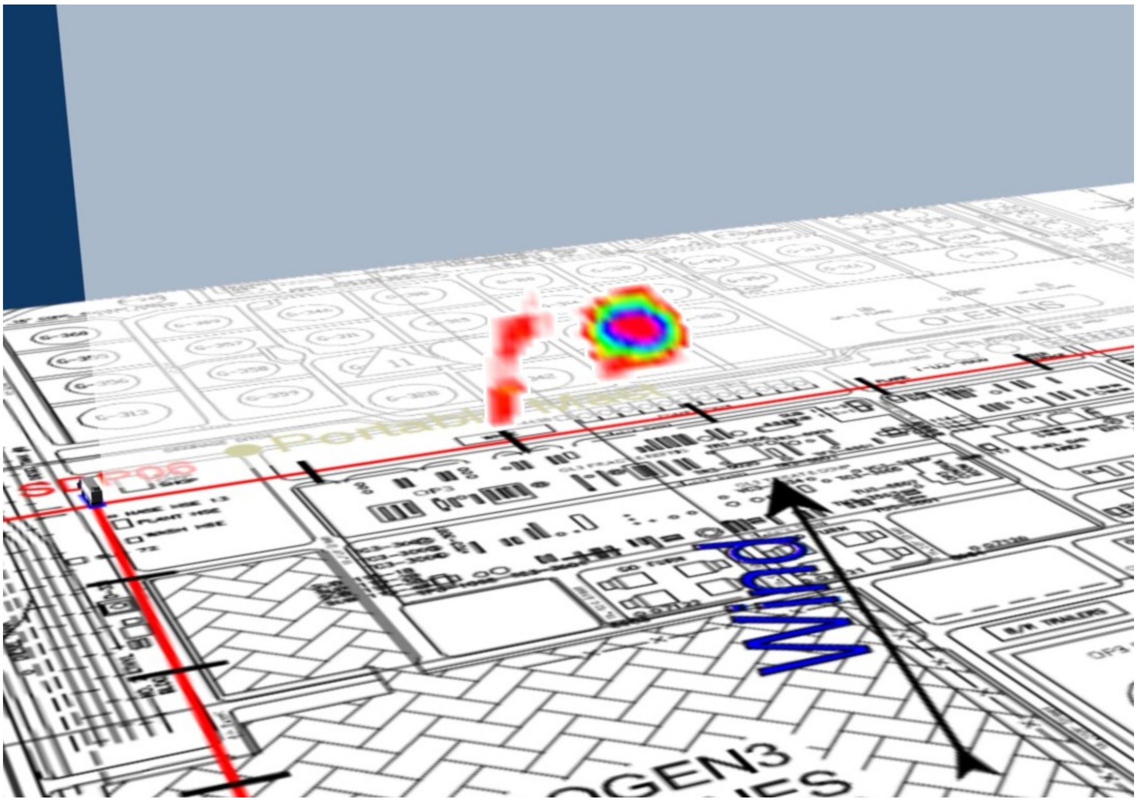

Figure 2.6a2 Visualisation of emission rate measured for Scan 145 representing LOS1.

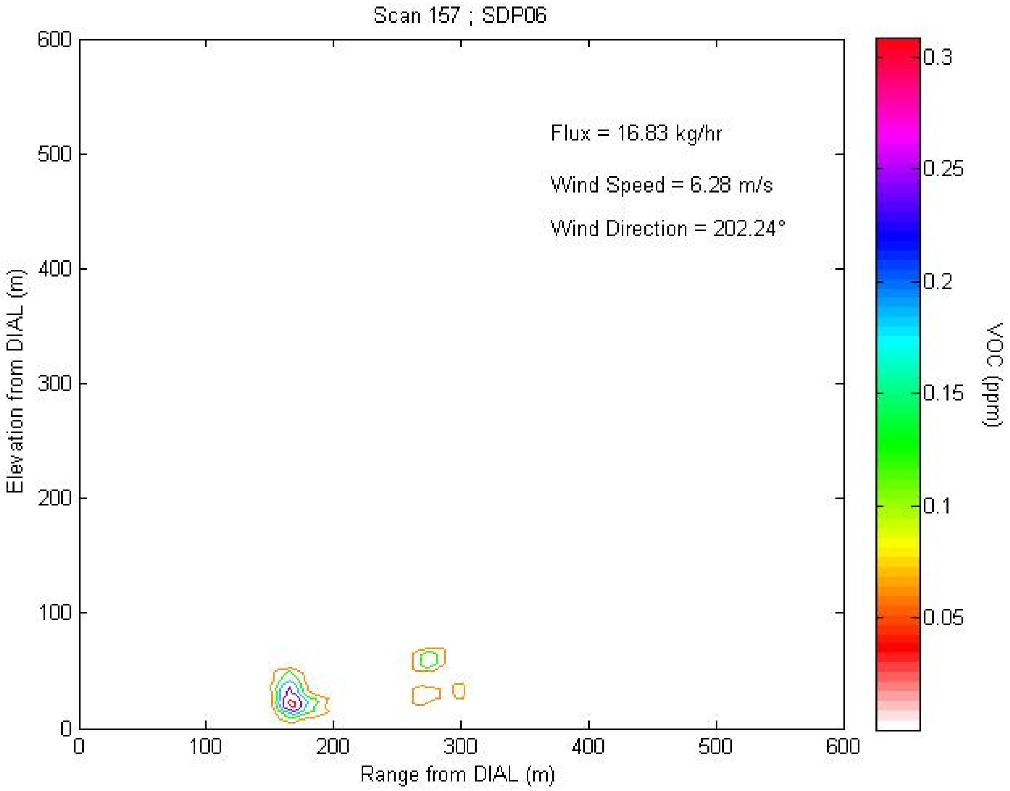

Figure 2.6b1 Contour plot of concentration profile for Scan 157 representing LOS3.

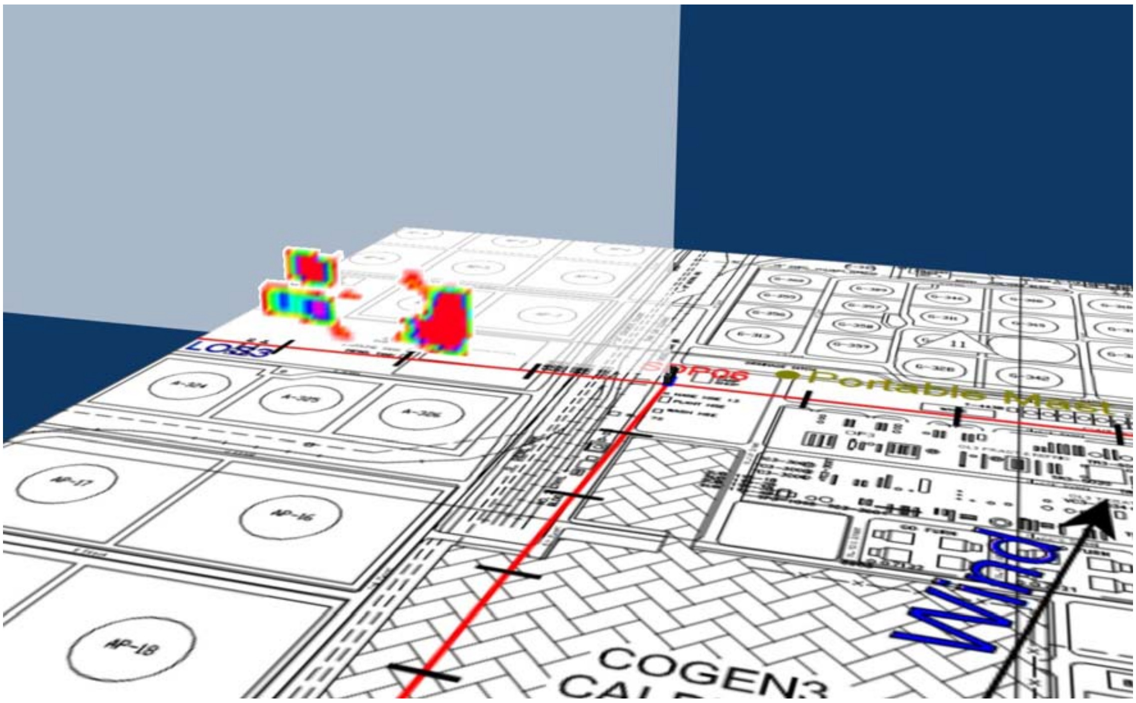

Figure 2.6b2 Visualisation of emission rate measured for Scan 157 representing LOS3.

Table 2.7 Emission rate measurements from SDP07 on 19th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
165	SDP07/LOS1	15:01	15:12	5.8	191.9	-0.42	Upwind of Olefins Process Area
166	SDP07/LOS1	15:18	15:29	6.3	191.6	1.31	Upwind of Olefins Process Area
167	SDP07/LOS1	15:30	15:41	6.6	193.4	0.66	Upwind of Olefins Process Area
168	SDP07/LOS1	15:47	15:59	6.3	195.6	0.15	Upwind of Olefins Process Area
169	SDP07/LOS1	15:59	16:11	5.5	192.2	-0.69	Upwind of Olefins Process Area
172	SDP07/LOS1	16:29	16:41	6.1	192.2	-0.81	Upwind of Olefins Process Area
173	SDP07/LOS1	16:41	16:57	5.2	191.2	-0.53	Upwind of Olefins Process Area

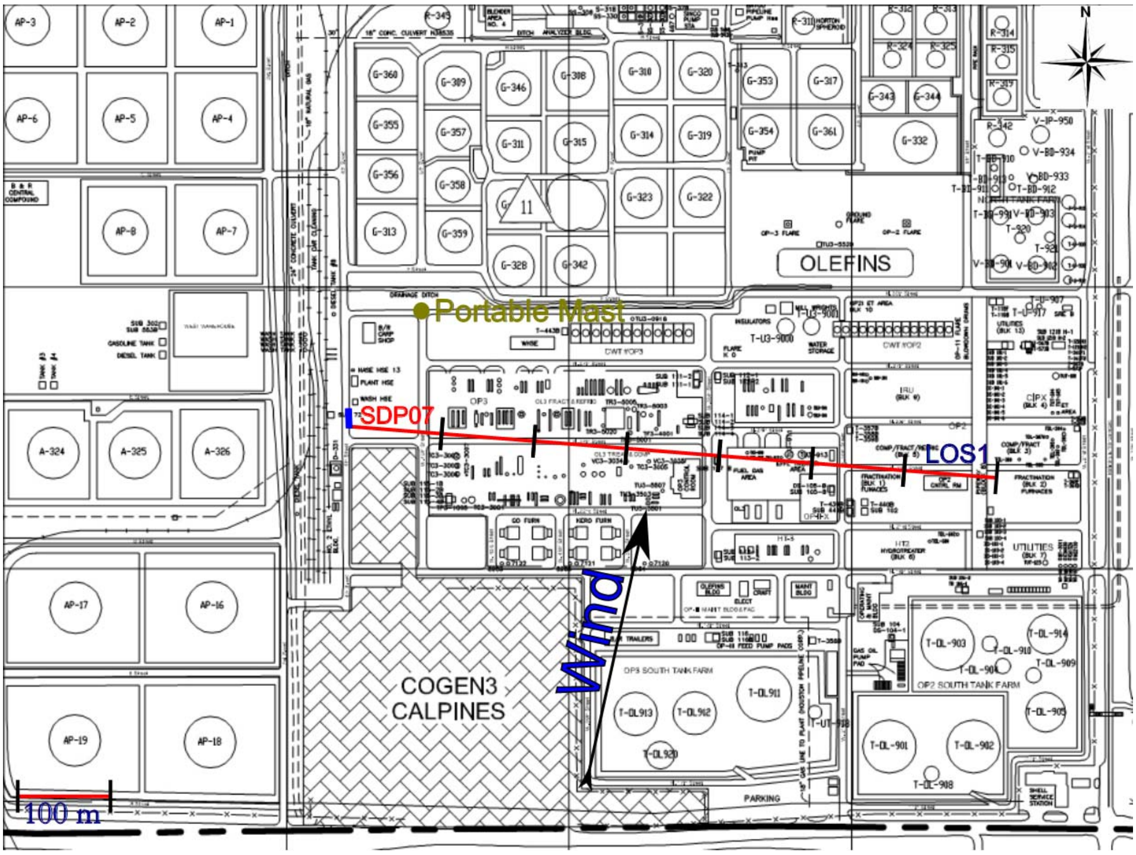

Figure 2.7 Measurement configuration for location SDP07 on 19th of January.

Table 2.8 Emission rate measurements from SDP08 on 20th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
175	SDP08/LOS1	11:57	12:08	6.1	157.5	5.10	Downwind of East Olefins Tanks
176	SDP08/LOS1	12:09	12:20	4.8	160.3	5.26	Downwind of East Olefins Tanks
177	SDP08/LOS1	12:20	12:31	4.7	160.5	6.43	Downwind of East Olefins Tanks
178	SDP08/LOS1	12:32	12:44	5.5	155.3	5.85	Downwind of East Olefins Tanks
179	SDP08/LOS1	12:44	12:55	7.3	158.7	3.52	Downwind of East Olefins Tanks
180	SDP08/LOS1	12:55	13:06	6.2	161.8	3.20	Downwind of East Olefins Tanks
182	SDP08/LOS2	13:22	13:33	4.9	164.9	1.02	Downwind Area E of Olefins Tanks
183	SDP08/LOS2	13:35	13:46	5.3	173.8	1.08	Downwind Area E of Olefins Tanks
184	SDP08/LOS2	13:52	14:03	5.2	162.5	0.50	Downwind Area E of Olefins Tanks
185	SDP08/LOS1	14:06	14:17	5.0	161.9	3.16	Downwind of East Olefins Tanks
186	SDP08/LOS1	14:18	14:30	5.2	168.8	5.53	Downwind of East Olefins Tanks
187	SDP08/LOS1	14:30	14:42	5.1	160.9	3.01	Downwind of East Olefins Tanks
189	SDP08/LOS3	15:00	15:12	5.4	159.7	3.14	Downwind of East Olefins Tanks
190	SDP08/LOS3	15:14	15:25	5.8	162.3	1.63	Downwind of East Olefins Tanks
191	SDP08/LOS3	15:26	15:38	5.7	157.7	3.96	Downwind of East Olefins Tanks
192	SDP08/LOS4	15:42	15:54	5.1	163.2	1.93	Downwind of SE Olefins Tanks
193	SDP08/LOS4	15:55	16:07	5.5	156.0	3.43	Downwind of SE Olefins Tanks
194	SDP08/LOS4	16:07	16:19	5.2	163.5	1.93	Downwind of SE Olefins Tanks
195	SDP08/LOS5	16:29	16:41	5.8	165.8	0.15	Downwind Area E of Olefins Tanks
196	SDP08/LOS5	16:42	16:54	6.3	164.0	-0.13	Downwind Area E of Olefins Tanks
197	SDP08/LOS5	16:54	17:06	6.3	162.5	0.82	Downwind Area E of Olefins Tanks

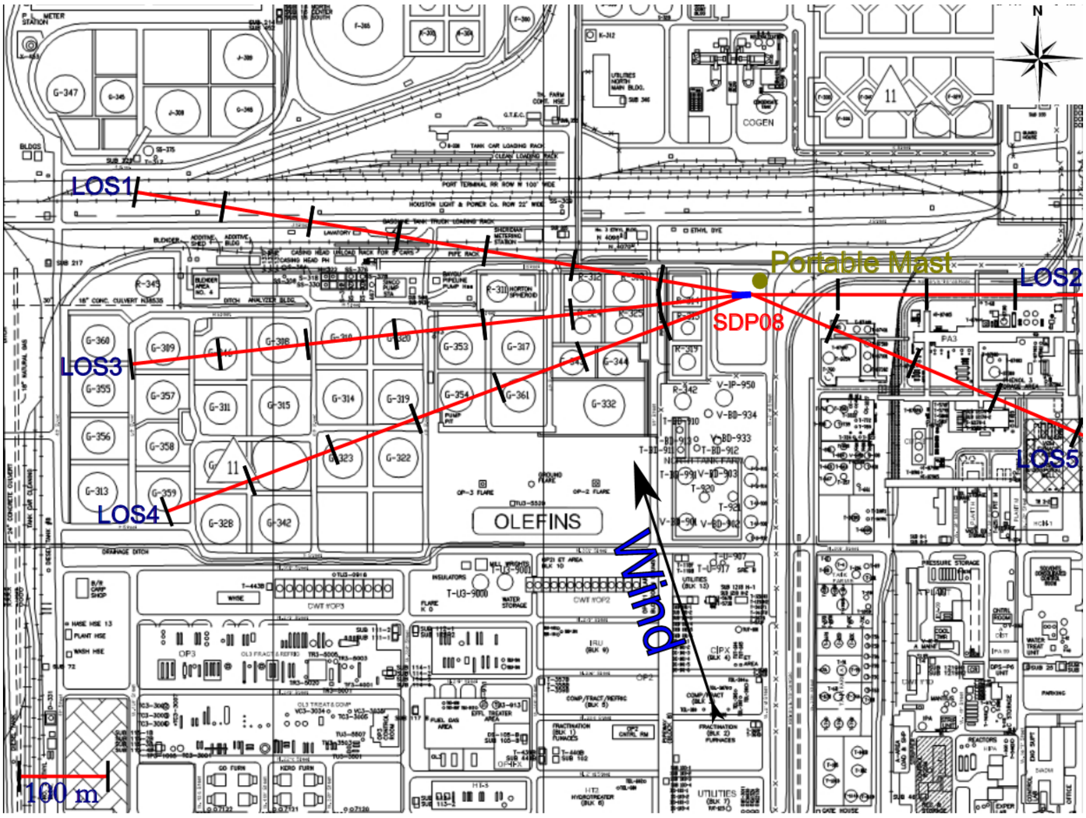

Figure 2.8 Measurement configuration for location SDP08 on 20th of January.

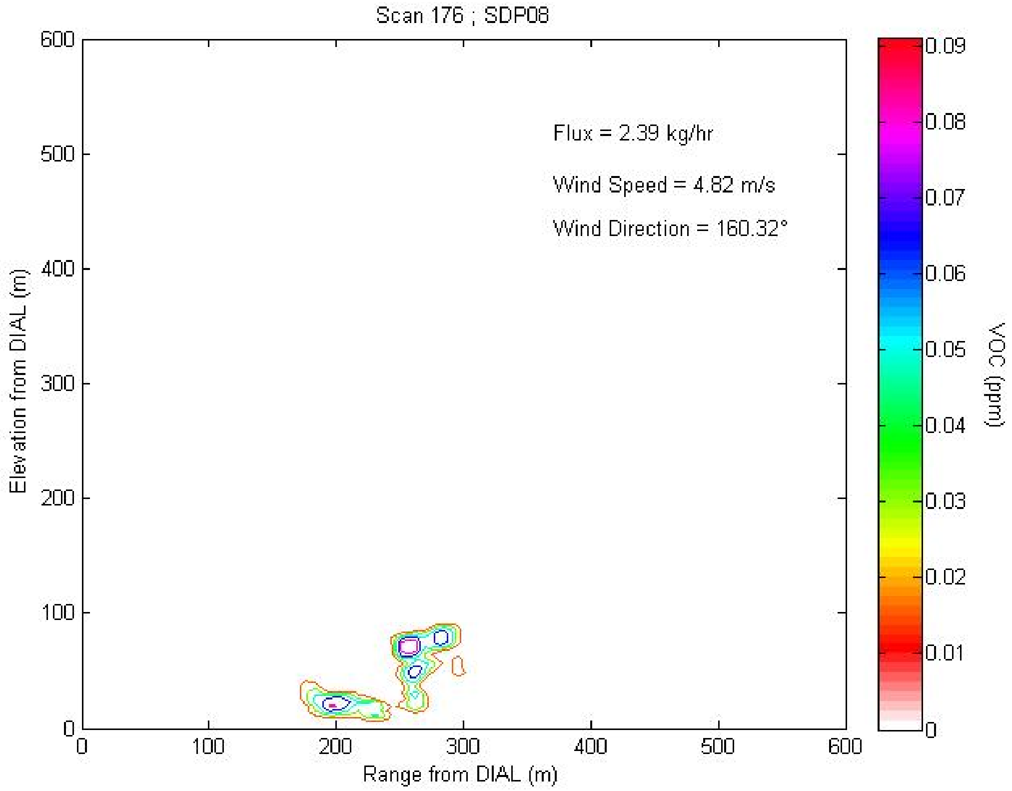

Figure 2.8a1 Contour plot of concentration profile for Scan 176 representing LOS1.

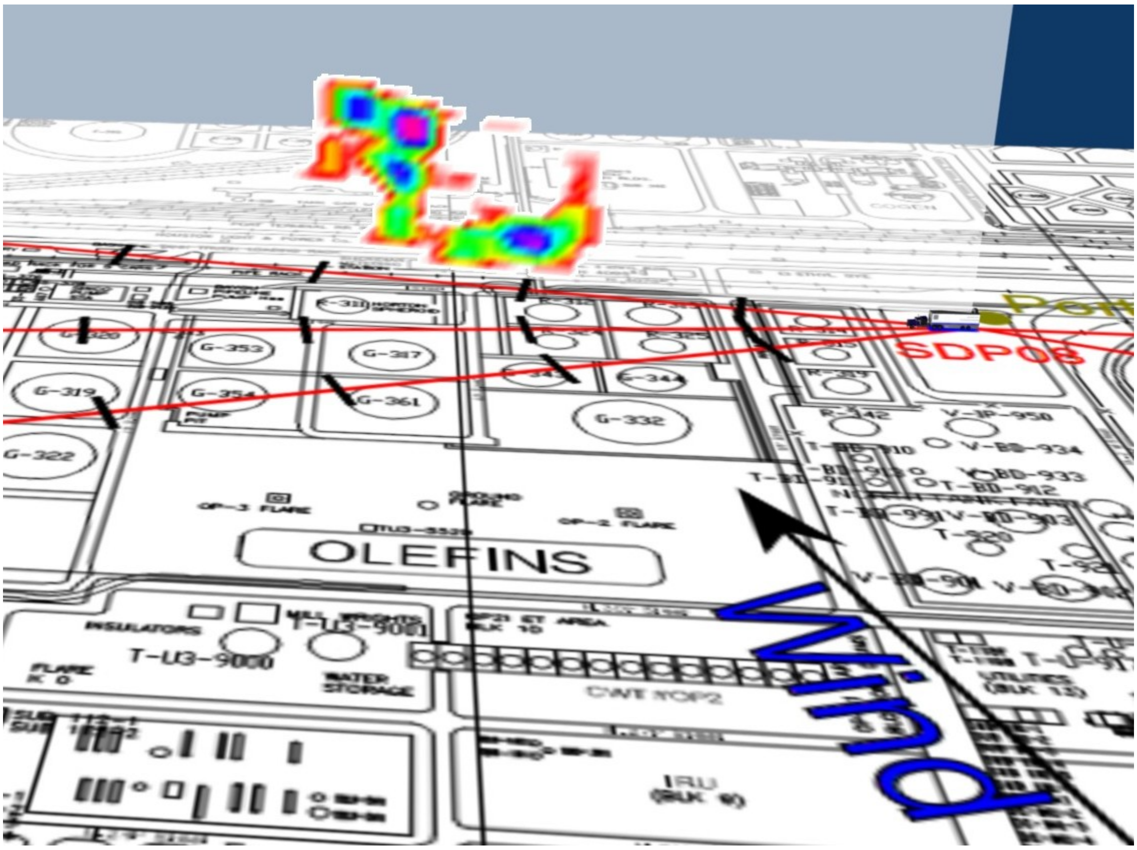

Figure 2.8a2 Visualisation of emission rate measured for Scan 176 representing LOS1.

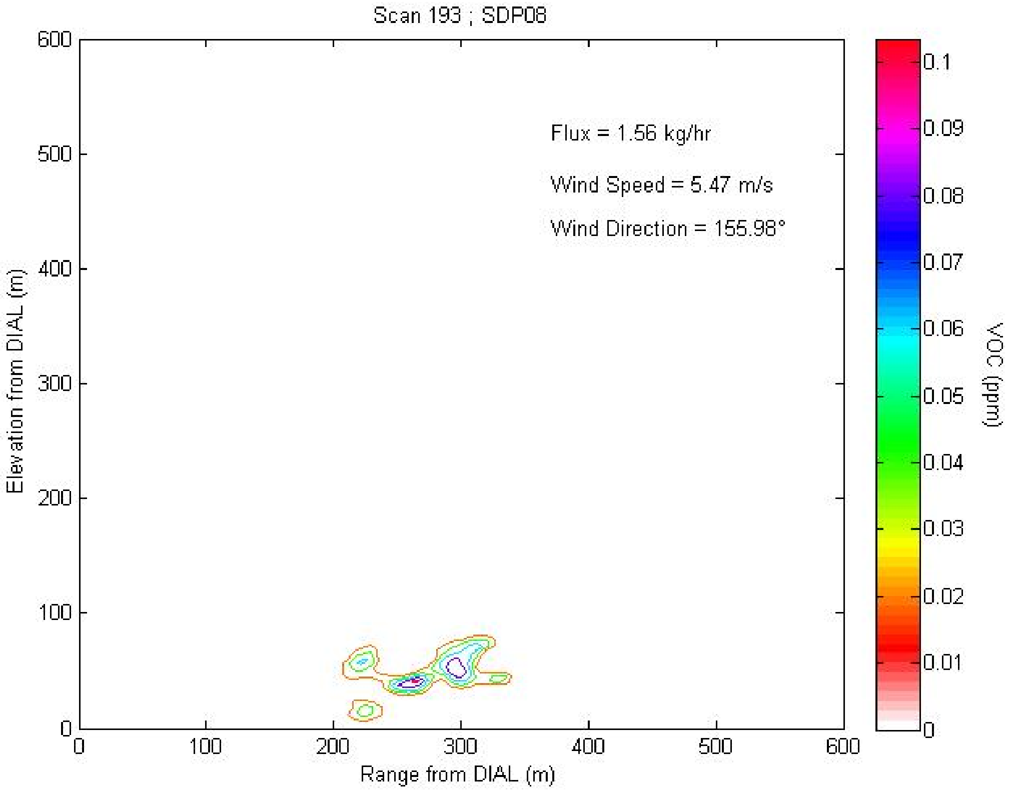

Figure 2.8b1 Contour plot of concentration profile for Scan 193 representing LOS4.

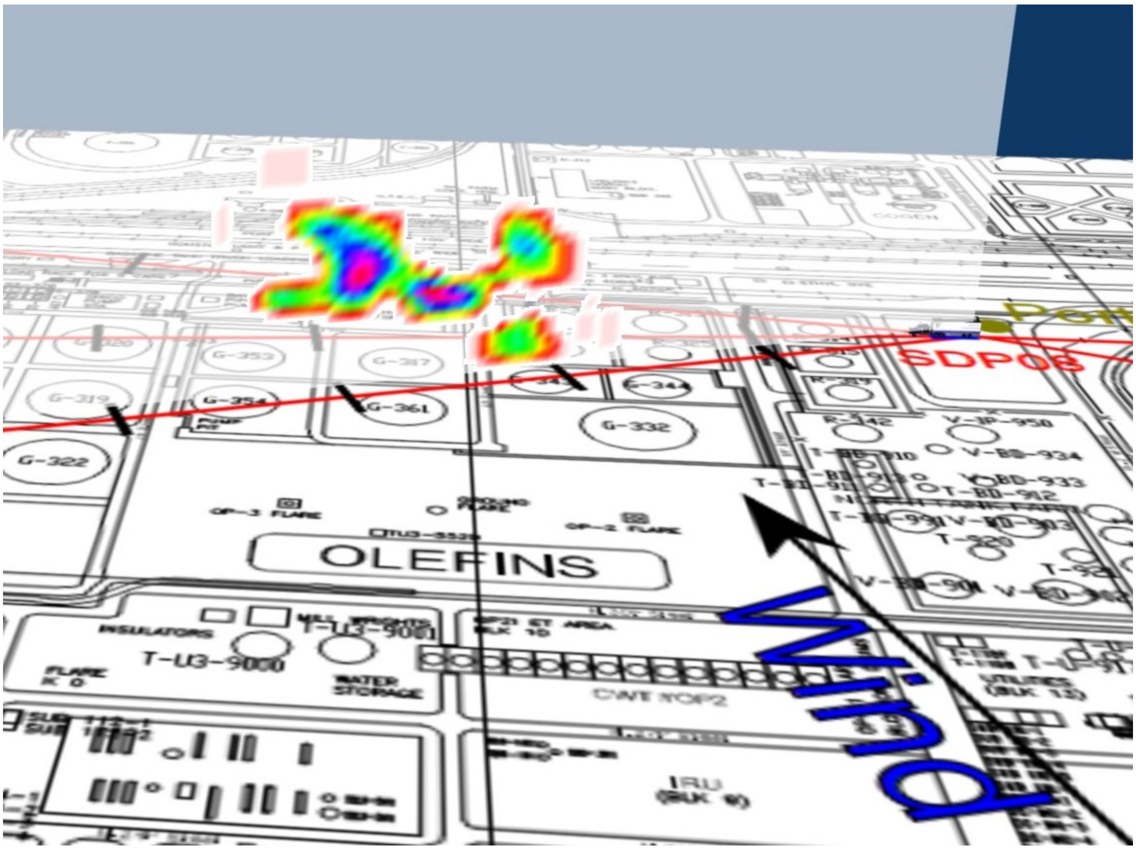

Figure 2.8b2 Visualisation of emission rate measured for Scan 193 representing LOS4.

Table 2.9 Emission rate measurements from SDP09 on 21st of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
199	SDP09/LOS1	11:57	12:07	4.4	289.8	0.88	Upwind of Refinery East Process
200	SDP09/LOS1	12:07	12:16	5.0	296.5	2.72	Upwind of Refinery East Process
201	SDP09/LOS1	12:17	12:26	4.4	279.0	1.13	Upwind of Refinery East Process
202	SDP09/LOS1	12:28	12:37	4.9	272.5	4.56	Upwind of Refinery East Process
203	SDP09/LOS1	12:40	12:49	5.3	287.8	2.29	Upwind of Refinery East Process
204	SDP09/LOS1	12:49	12:59	5.7	317.2	1.90	Upwind of Refinery East Process
207	SDP09/LOS2	13:10	13:22	4.7	275.4	4.66	Downwind of CR3
208	SDP09/LOS2	13:22	13:34	4.5	271.9	10.20	Downwind of CR3
209	SDP09/LOS2	13:35	13:47	4.1	283.7	7.81	Downwind of CR3
210	SDP09/LOS2	13:47	13:58	5.0	262.4	10.29	Downwind of CR3
211	SDP09/LOS2	13:58	14:08	4.9	278.8	7.65	Downwind of CR3
212	SDP09/LOS2	14:10	14:21	4.9	277.0	8.63	Downwind of CR3
214	SDP09/LOS3	14:23	14:28	4.4	282.1	14.36	Downwind of Refinery E Process
215	SDP09/LOS3	14:46	14:58	4.5	273.4	8.76	Downwind of Refinery E Process
216	SDP09/LOS3	14:59	15:11	4.3	276.9	9.57	Downwind of Refinery E Process
217	SDP09/LOS3	15:11	15:23	4.6	274.2	14.92	Downwind of Refinery E Process
218	SDP09/LOS4	15:31	15:43	4.1	276.8	0.22	Downwind Aromatic Units
219	SDP09/LOS4	15:43	15:55	4.6	297.4	0.49	Downwind Aromatic Units
220	SDP09/LOS4	15:56	16:08	4.2	322.3	-1.27	Downwind Aromatic Units
221	SDP09/LOS5	16:18	16:30	3.4	318.7	2.16	Downwind S Refinery E Process
222	SDP09/LOS5	16:31	16:43	4.1	325.4	1.12	Downwind S Refinery E Process
223	SDP09/LOS5	16:43	16:55	4.5	319.0	3.13	Downwind S Refinery E Process

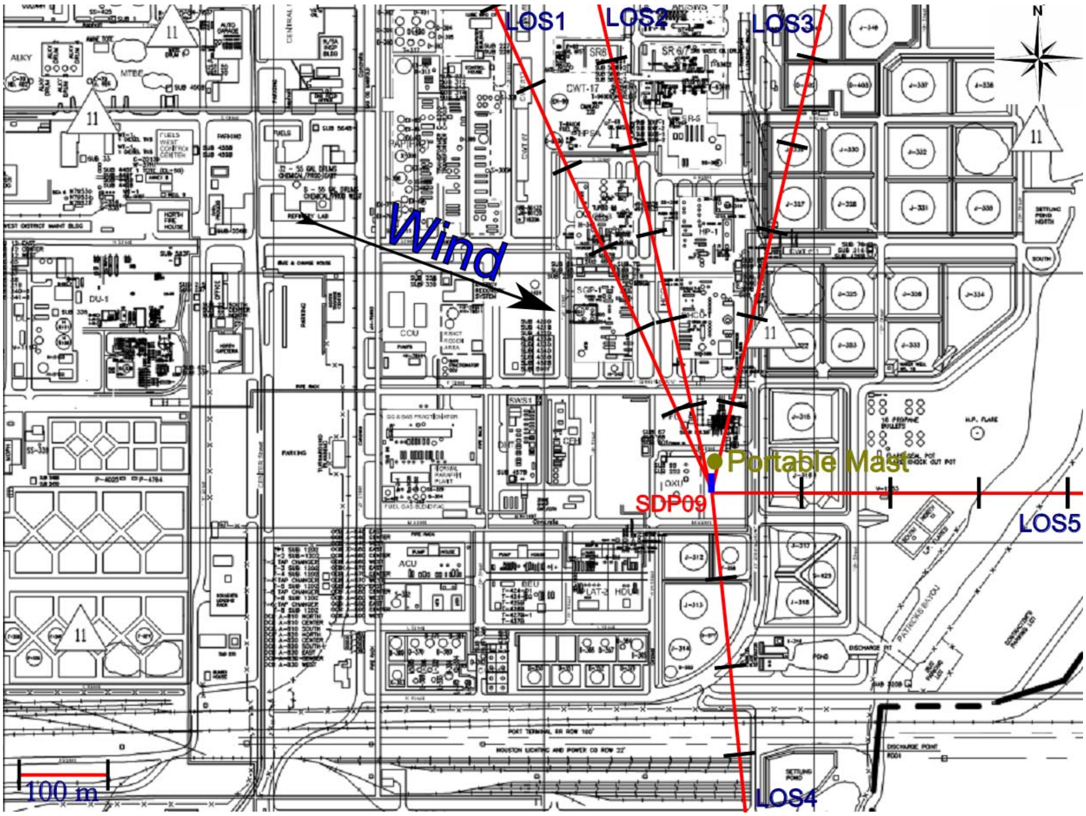

Figure 2.9 Measurement configuration for location SDP09 on 21st of January.

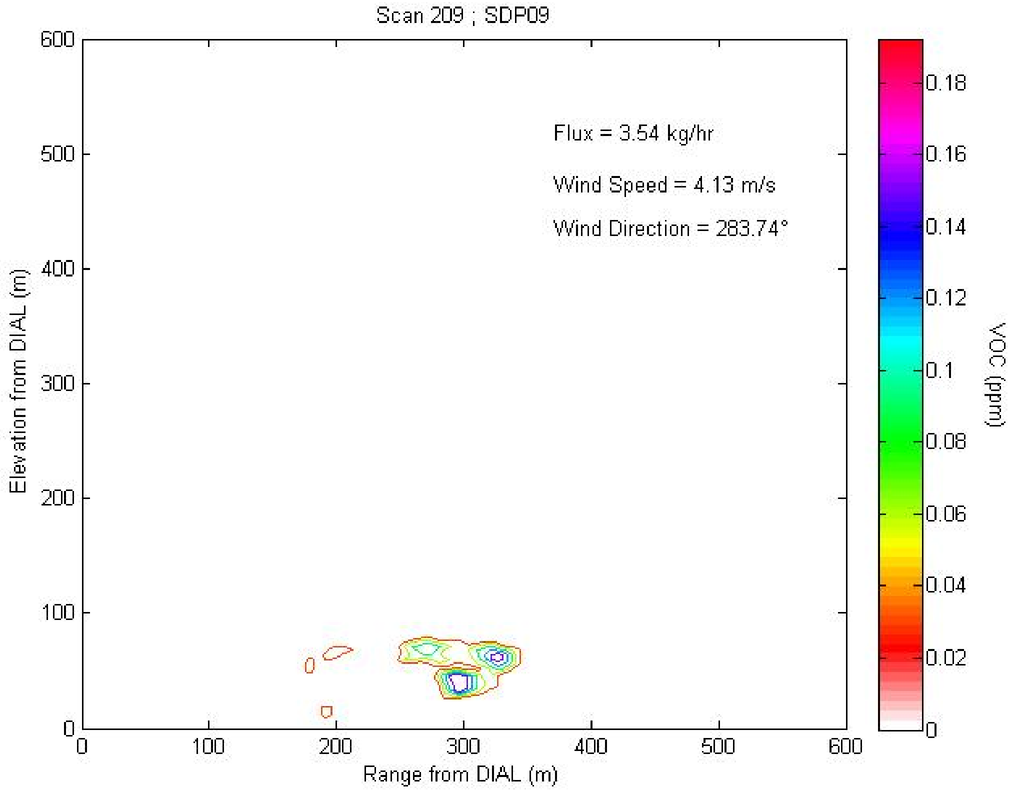

Figure 2.9a1 Contour plot of concentration profile for Scan 209 representing LOS2.

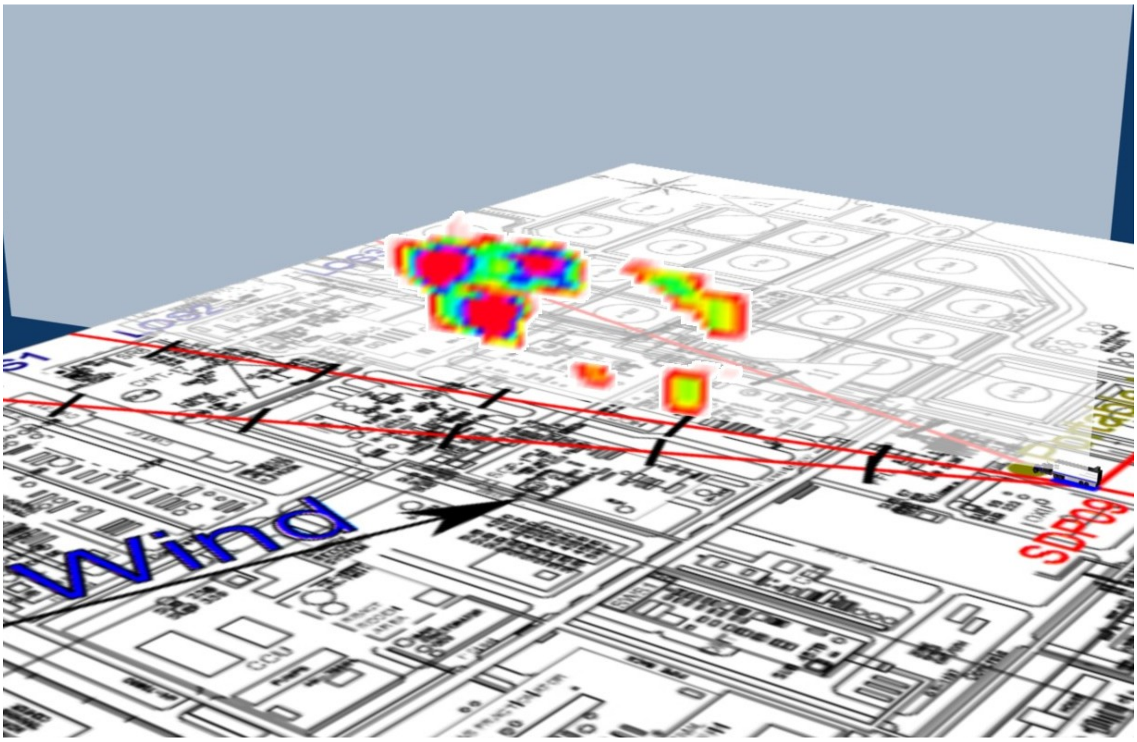

Figure 2.9a2 Visualisation of emission rate measured for Scan 209 representing LOS2.

Table 2.10 Emission rate measurements from SDP10 on 22nd of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
225	SDP10/LOS1	12:07	12:14	5.0	133.4	-0.47	Downwind of Flare
226	SDP10/LOS1	12:28	12:34	4.8	131.4	1.10	Downwind of Flare
227	SDP10/LOS1	12:34	12:46	4.8	131.6	-0.37	Downwind of Flare
228	SDP10/LOS1	12:46	12:58	4.9	134.4	0.15	Downwind of Flare
229	SDP10/LOS2	13:00	13:14	5.2	134.8	0.28	Upwind of Flare
230	SDP10/LOS2	13:14	13:27	4.9	139.3	0.73	Upwind of Flare
231	SDP10/LOS2	13:27	13:41	4.9	133.1	0.06	Upwind of Flare
235	SDP10/LOS1	14:03	14:15	5.6	130.2	0.99	Downwind of Flare
236	SDP10/LOS1	14:15	14:26	5.7	136.0	1.21	Downwind of Flare
237	SDP10/LOS1	14:27	14:38	5.5	137.3	0.40	Downwind of Flare
238	SDP10/LOS2	14:39	14:51	5.8	131.3	1.04	Upwind of Flare
239	SDP10/LOS2	14:51	15:03	5.8	135.8	-1.10	Upwind of Flare
240	SDP10/LOS2	15:03	15:14	6.4	149.1	0.21	Upwind of Flare
242	SDP10/LOS3	15:53	16:04	6.2	152.0	31.40	Downwind of East Tanks
243	SDP10/LOS3	16:06	16:17	5.5	141.7	30.70	Downwind of East Tanks
244	SDP10/LOS3	16:17	16:29	5.7	145.2	41.83	Downwind of East Tanks
246	SDP10/LOS3	16:30	16:41	5.8	147.1	20.22	Downwind of East Tanks
247	SDP10/LOS3	16:41	16:52	5.5	149.8	35.69	Downwind of East Tanks
248	SDP10/LOS3	16:52	17:03	4.6	152.0	23.77	Downwind of East Tanks
251	SDP10/LOS4	17:11	17:20	4.5	146.8	0.49	Upwind of East Tanks
252	SDP10/LOS4	17:20	17:30	4.5	144.2	-0.50	Upwind of East Tanks

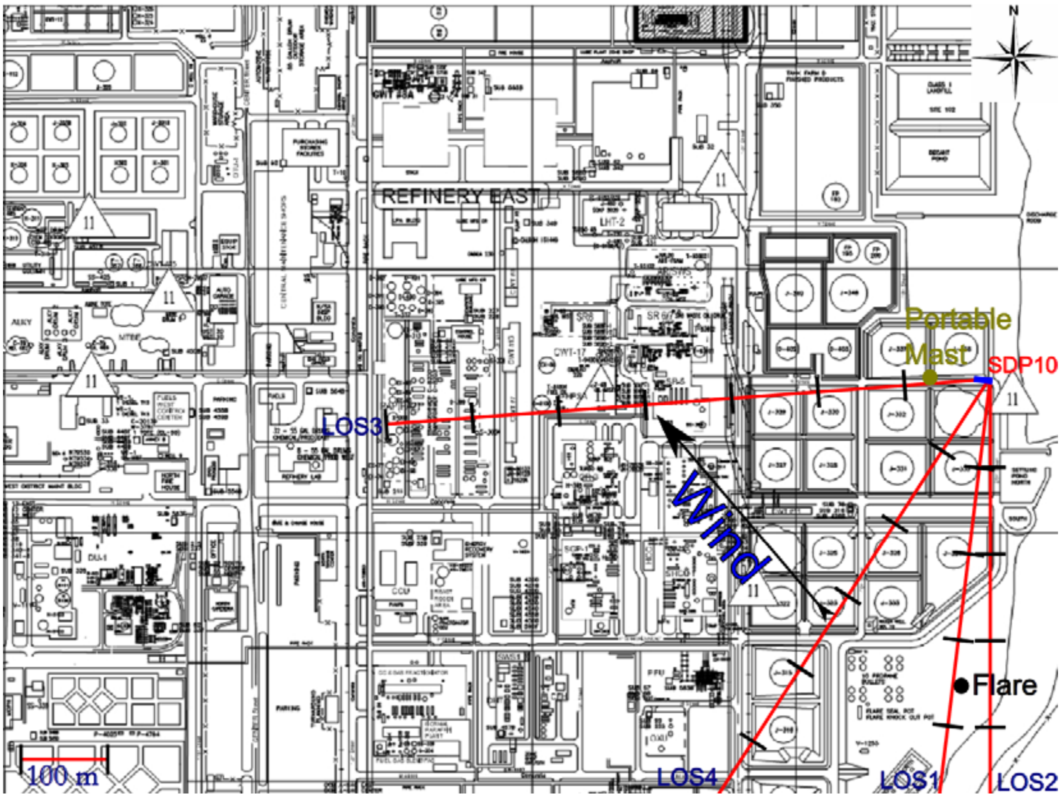

Figure 2.10 Measurement configuration for location SDP10 on 22nd of January.

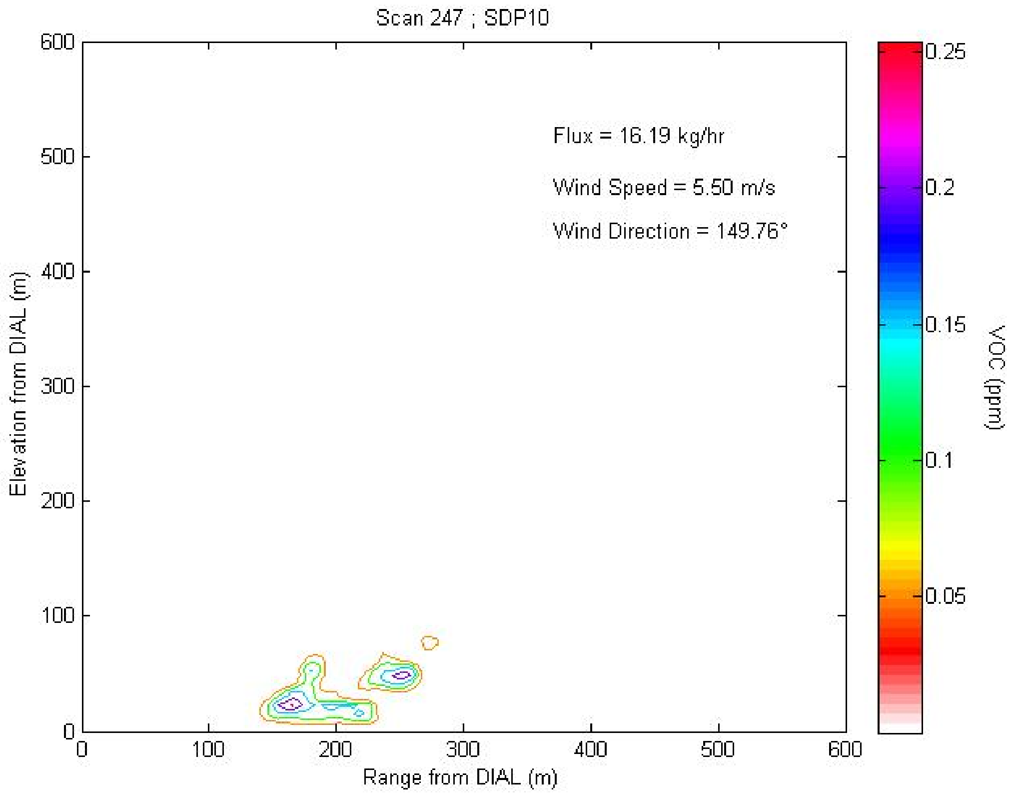

Figure 2.10a1 Contour plot of concentration profile for Scan 247 representing LOS3.

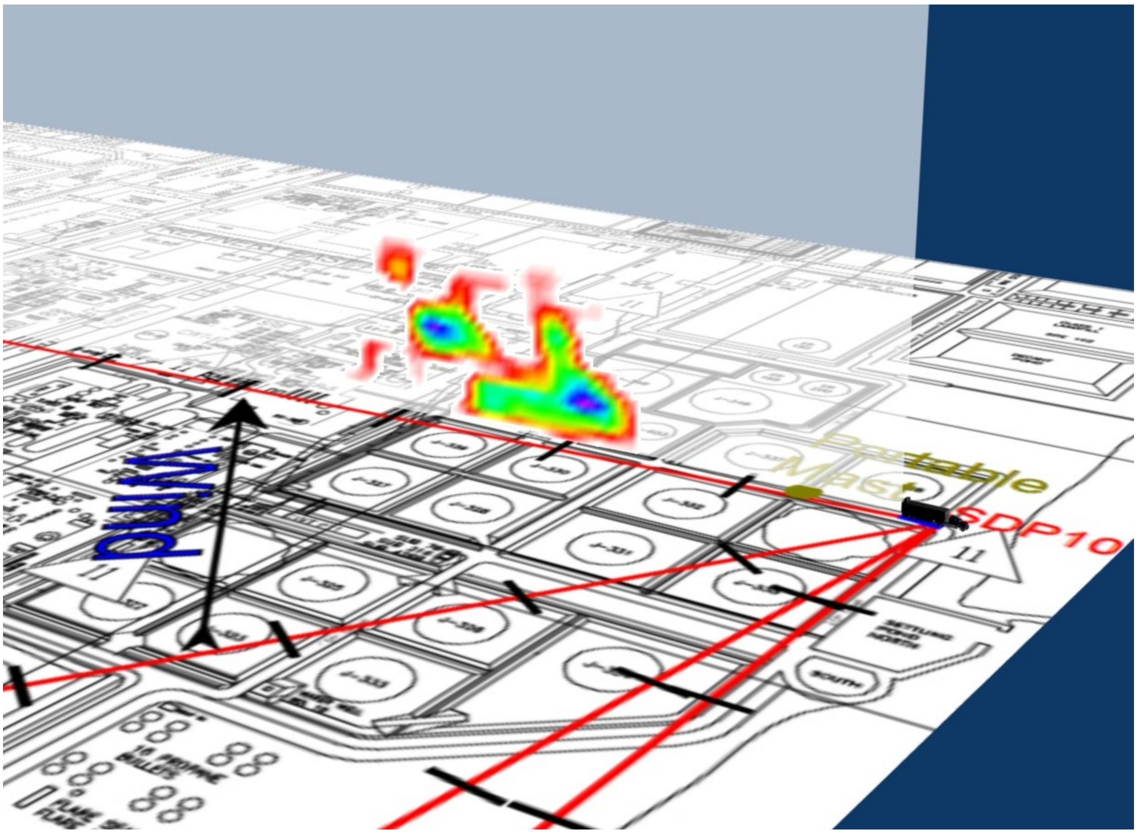

Figure 2.10a2 Visualisation of emission rate measured for Scan 247 representing LOS3.

Table 2.11 Emission rate measurements from SDP11 on 23rd of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
254	SDP11/LOS1	10:57	11:08	5.0	138.9	5.12	Downwind of E of East Tanks
255	SDP11/LOS1	11:09	11:19	5.3	141.1	5.95	Downwind of E of East Tanks
256	SDP11/LOS1	11:19	11:30	5.3	139.8	4.55	Downwind of E of East Tanks
259	SDP11/LOS1	11:49	11:59	4.8	141.1	3.17	Downwind of E of East Tanks
260	SDP11/LOS1	11:59	12:10	4.8	140.9	5.20	Downwind of E of East Tanks
261	SDP11/LOS2	12:15	12:26	3.9	141.8	16.56	Downwind of W of East Tanks
262	SDP11/LOS2	12:27	12:38	4.5	145.3	13.69	Downwind of W of East Tanks
263	SDP11/LOS2	12:40	12:55	4.6	138.7	14.02	Downwind of W of East Tanks
264	SDP11/LOS2	12:56	13:15	3.2	129.7	18.63	Downwind of W of East Tanks
265	SDP11/LOS2	13:17	13:37	4.3	134.1	21.79	Downwind of W of East Tanks
266	SDP11/LOS3	13:50	14:11	5.0	125.6	6.14	Downwind of Refinery E Process
267	SDP11/LOS3	14:13	14:35	5.2	133.4	5.85	Downwind of Refinery E Process
268	SDP11/LOS3	14:35	14:57	3.9	129.4	3.90	Downwind of Refinery E Process
270	SDP11/LOS2	15:50	16:09	1.5	114.8	21.39	Downwind of W of East Tanks
271	SDP11/LOS1	16:13	16:24	2.7	53.2	4.23	Downwind of E of East Tanks
272	SDP11/LOS2	16:28	16:46	2.8	128.9	21.13	Downwind of W of East Tanks
273	SDP11/LOS2	16:47	17:06	3.2	133.2	22.85	Downwind of W of East Tanks

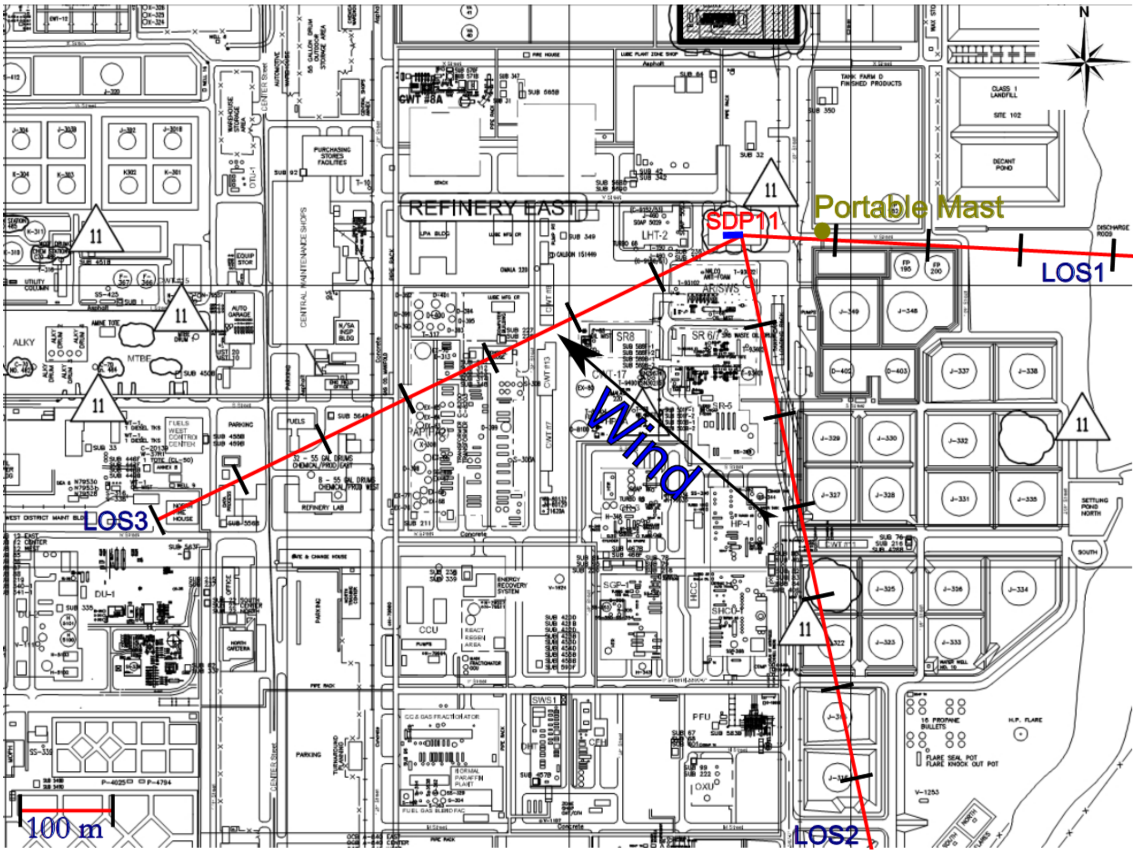

Figure 2.11 Measurement configuration for location SDP11 on 23rd of January.

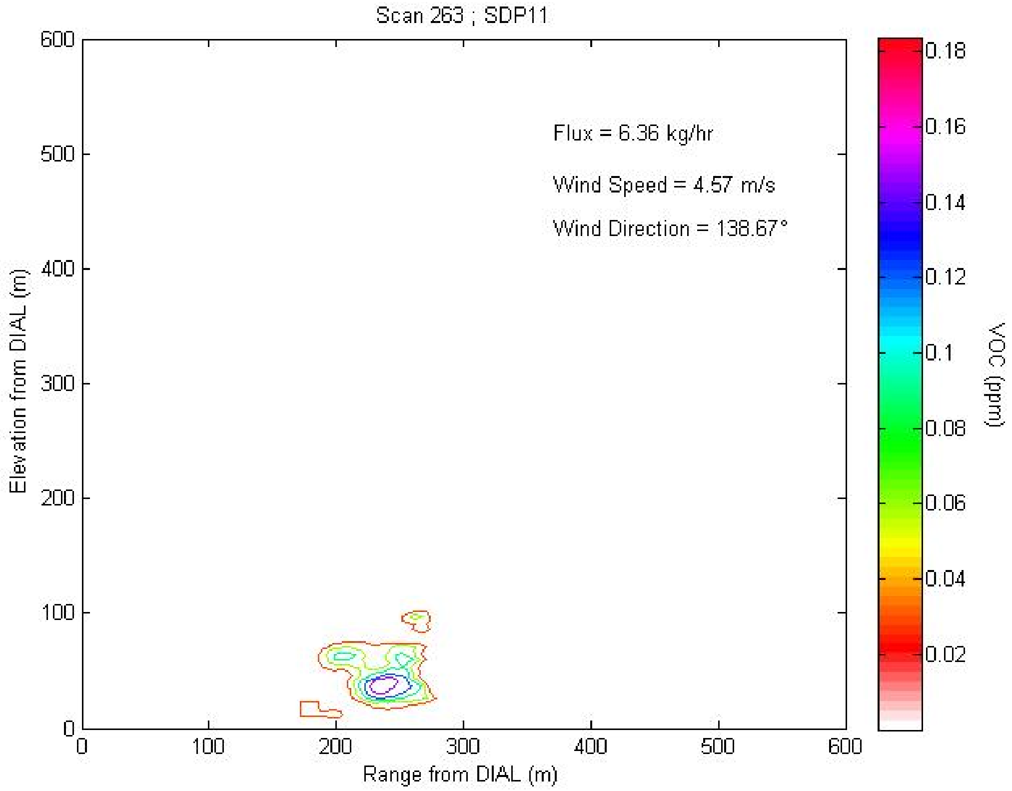

Figure 2.11a1 Contour plot of concentration profile for Scan 263 representing LOS2.

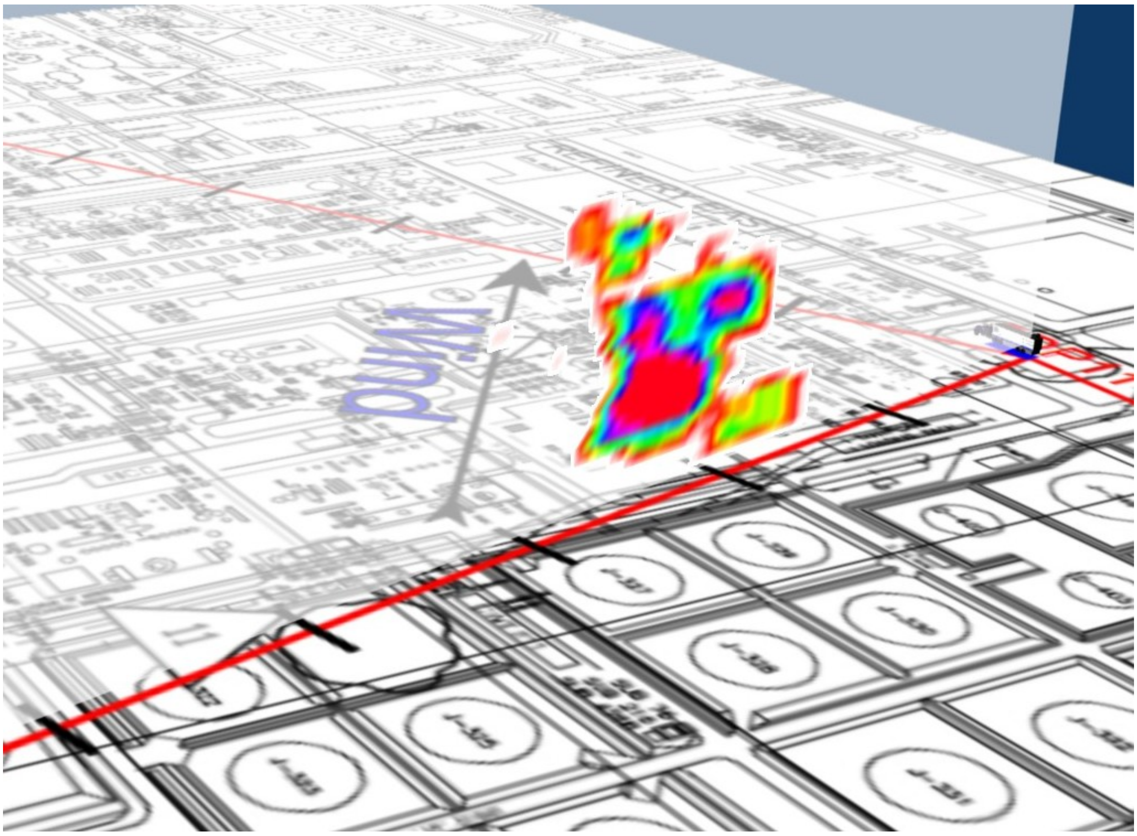

Figure 2.11a2 Visualisation of emission rate measured for Scan 263 representing LOS2.

Table 2.12 Emission rate measurements from SDP12 on 25th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
275	SDP12/LOS1	10:42	10:55	1.4	5.5	21.16	Downwind of Wastewater
276	SDP12/LOS1	10:55	11:08	0.8	29.5	15.57	Downwind of Wastewater
277	SDP12/LOS1	11:08	11:21	0.9	16.0	21.34	Downwind of Wastewater
279	SDP12/LOS1	11:42	11:55	1.2	10.7	18.14	Downwind of Wastewater
280	SDP12/LOS1	11:55	12:08	1.2	22.3	28.64	Downwind of Wastewater
281	SDP12/LOS1	12:09	12:34	1.3	39.1	27.70	Downwind of Wastewater
282	SDP12/LOS1	12:36	12:56	2.0	261.4	2.29	Downwind of Wastewater
283	SDP12/LOS2	13:04	13:13	2.7	250.7	1.90	Downwind of Wastewater
284	SDP12/LOS2	13:17	13:35	2.7	253.8	1.76	Downwind of Wastewater
285	SDP12/LOS2	13:36	13:54	2.1	242.5	2.15	Downwind of Wastewater
291	SDP12/LOS3	14:27	14:46	3.5	190.2	0.28	Upwind J-3018 and K-301 Tanks
294	SDP12/LOS3	15:23	15:42	3.4	101.9	0.26	Upwind J-3018 and K-301 Tanks
295	SDP12/LOS3	15:43	16:01	5.3	106.8	1.47	Upwind J-3018 and K-301 Tanks
296	SDP12/LOS3	16:06	16:32	4.9	109.0	0.07	Upwind J-3018 and K-301 Tanks
297	SDP12/LOS3	16:34	17:01	4.2	116.8	0.22	Upwind J-3018 and K-301 Tanks

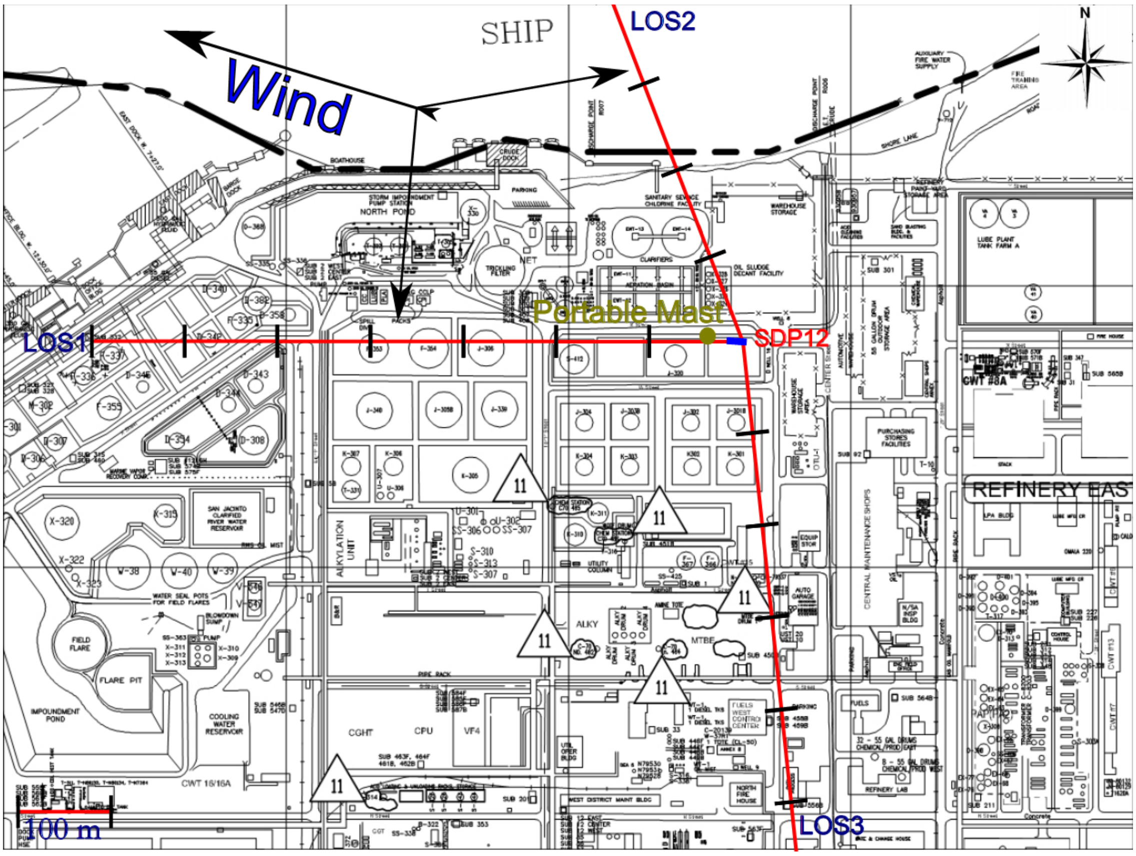

Figure 2.12 Measurement configuration for location SDP12 on 25th of January.

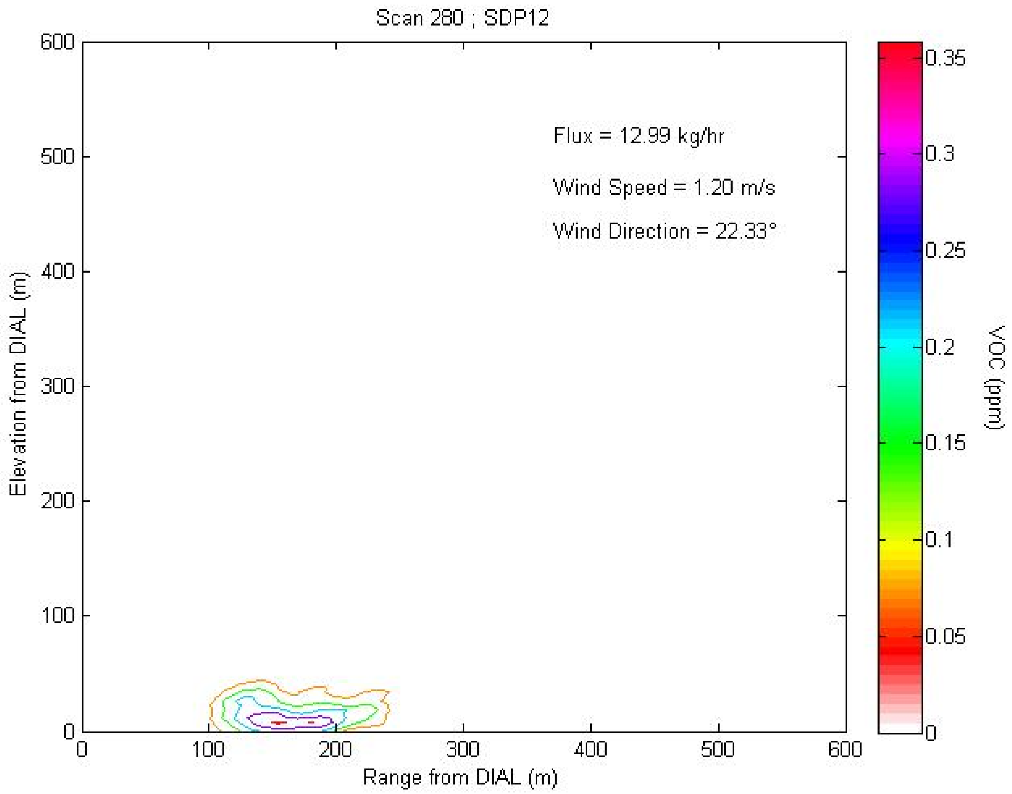

Figure 2.12a1 Contour plot of concentration profile for Scan 280 representing LOS1.

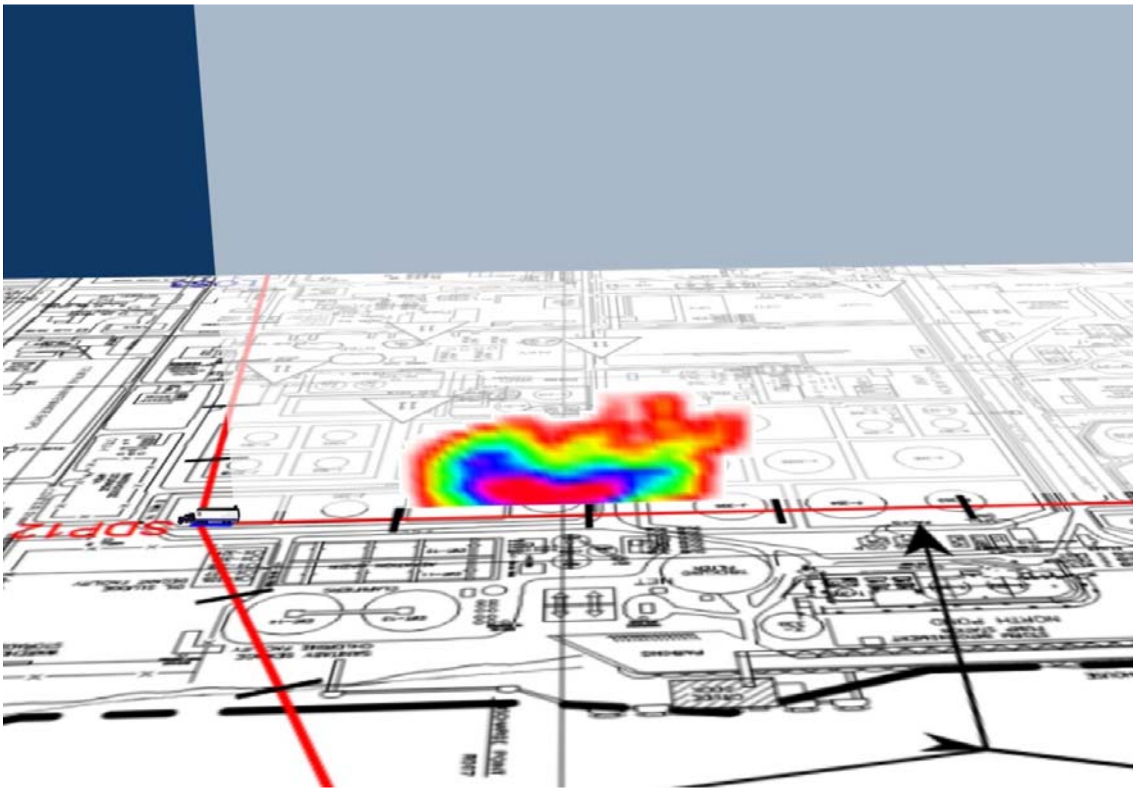

Figure 2.12a2 Visualisation of emission rate measured for Scan 280 representing LOS1.

Table 2.13 Emission rate measurements from SDP13 on 26th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
299	SDP13/LOS1	12:43	12:55	4.1	120.7	-0.34	Upwind of Flare
300	SDP13/LOS1	13:01	13:14	3.9	100.5	0.04	Upwind of Flare
301	SDP13/LOS1	13:14	13:27	4.0	106.5	-0.16	Upwind of Flare
302	SDP13/LOS1	13:32	13:57	3.8	114.4	-0.19	Upwind of Flare
303	SDP13/LOS1	13:59	14:09	4.6	137.0	0.40	Upwind of Flare
307	SDP13/LOS2	14:53	15:03	5.0	145.8	1.24	Downwind of Flare
309	SDP13/LOS2	15:11	15:21	5.1	142.2	1.43	Downwind of Flare
312	SDP13/LOS3	15:50	16:08	4.4	141.9	0.45	Downwind of S of East Tanks
313	SDP13/LOS3	16:10	16:28	4.3	139.3	0.08	Downwind of S of East Tanks
314	SDP13/LOS3	16:28	16:47	4.2	144.4	0.44	Downwind of S of East Tanks

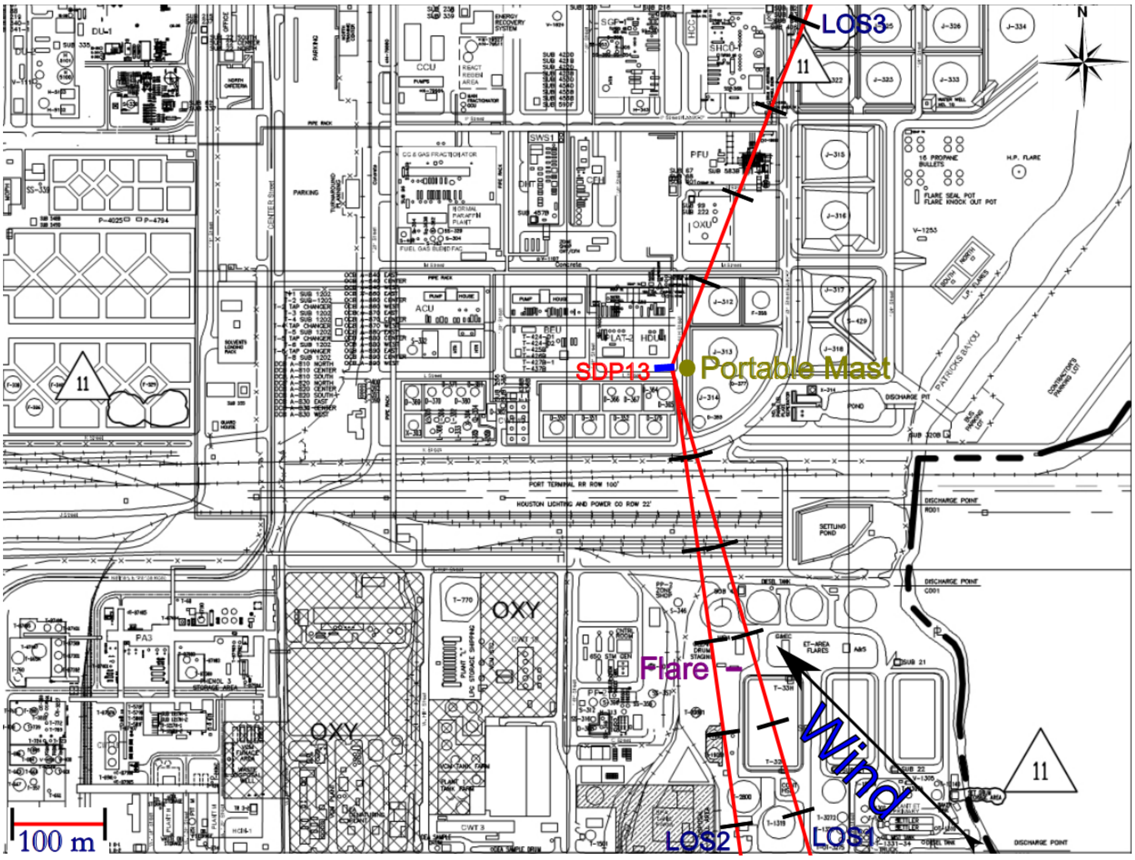

Figure 2.13 Measurement configuration for location SDP13 on 26th of January.

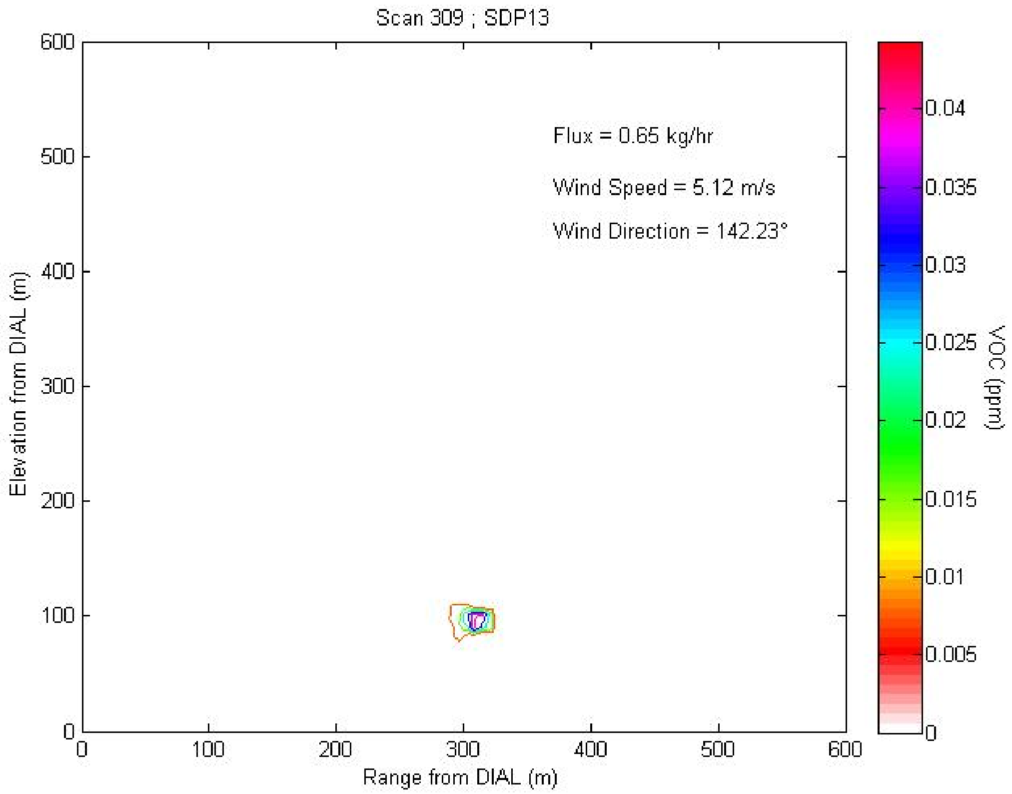

Figure 2.13a1 Contour plot of concentration profile for Scan 309 representing LOS2.

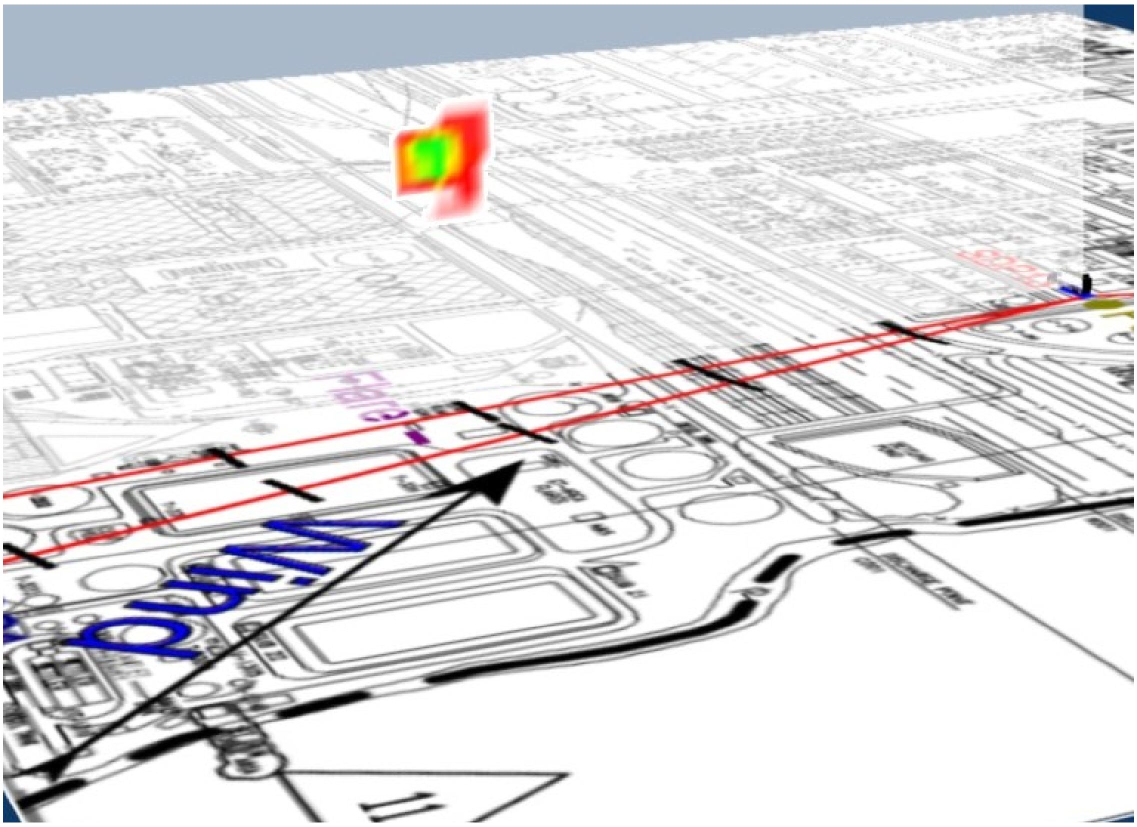

Figure 2.13a2 Visualisation of emission rate measured for Scan 309 representing LOS2.

Table 2.14 Emission rate measurements from SDP14 on 27th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
316	SDP14/LOS1	12:15	12:23	6.0	121.5	7.90	Downwind of Dock Area
317	SDP14/LOS1	12:23	12:31	6.3	122.1	10.64	Downwind of Dock Area
318	SDP14/LOS1	12:32	12:40	6.4	118.7	10.29	Downwind of Dock Area
319	SDP14/LOS2	12:53	13:00	7.4	119.8	1.41	Downwind of NE of Coker Area
320	SDP14/LOS2	13:01	13:13	6.8	119.1	0.10	Downwind of NE of Coker Area
321	SDP14/LOS2	13:14	13:25	7.4	122.9	0.65	Downwind of NE of Coker Area
322	SDP14/LOS2	13:31	13:41	7.6	116.2	0.77	Downwind of NE of Coker Area
323	SDP14/LOS2	13:41	13:50	7.8	122.7	1.39	Downwind of NE of Coker Area
324	SDP14/LOS2	13:52	14:01	7.4	123.4	2.01	Downwind of NE of Coker Area
326	SDP14/LOS3	14:27	14:32	6.0	124.7	0.91	Downwind of SW of Coker Area
327	SDP14/LOS3	14:32	14:37	6.4	126.0	2.66	Downwind of SW of Coker Area
328	SDP14/LOS3	14:37	14:42	6.4	115.8	1.49	Downwind of SW of Coker Area
329	SDP14/LOS4	14:48	14:56	7.6	117.6	8.17	Downwind of Dock Area
330	SDP14/LOS4	14:59	15:06	8.3	118.7	8.82	Downwind of Dock Area
331	SDP14/LOS4	15:07	15:14	8.0	120.6	9.96	Downwind of Dock Area
332	SDP14/LOS1	15:19	15:23	8.7	113.7	11.01	Downwind of Dock Area
333	SDP14/LOS1	15:23	15:28	7.1	123.4	5.46	Downwind of Dock Area
334	SDP14/LOS1	15:28	15:32	7.0	119.3	7.83	Downwind of Dock Area
335	SDP14/LOS1	15:33	15:41	7.7	112.3	6.88	Downwind of Dock Area
336	SDP14/LOS1	15:41	15:49	7.4	125.5	8.03	Downwind of Dock Area
344	SDP14/LOS3	16:53	17:00	6.7	116.7	0.81	Downwind of SW of Coker Area
345	SDP14/LOS3	17:02	17:09	6.4	114.6	1.47	Downwind of SW of Coker Area

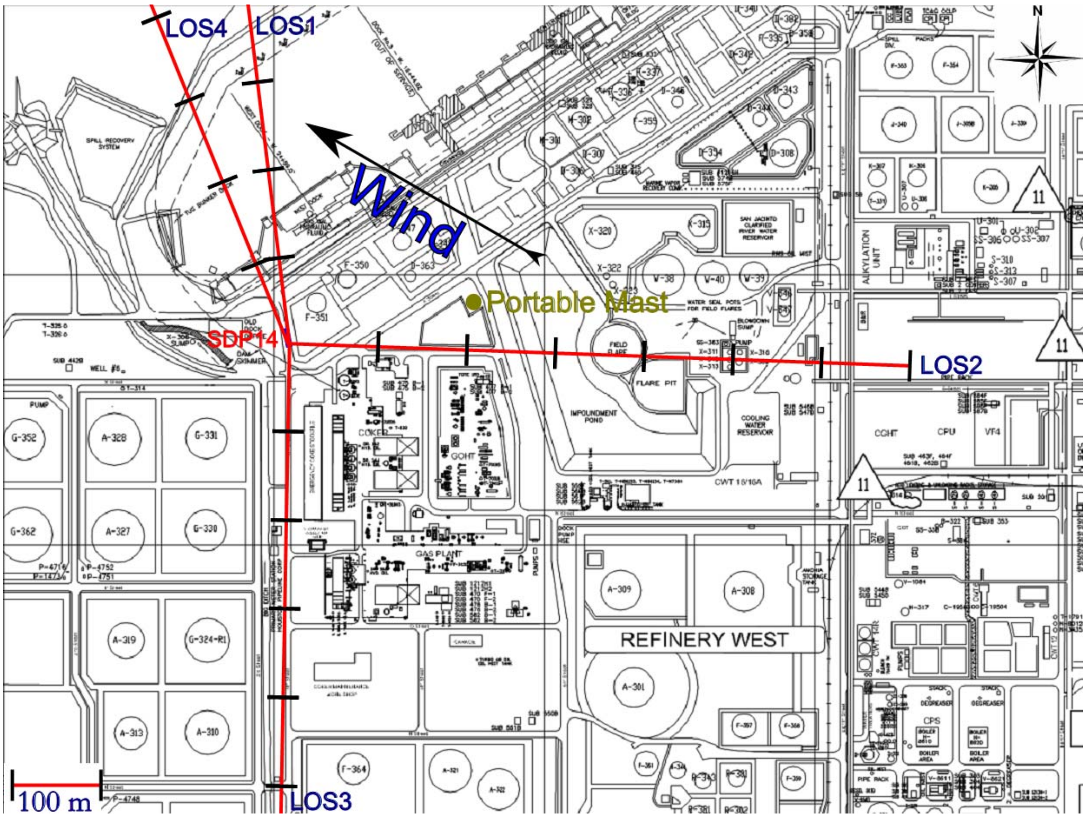

Figure 2.14 Measurement configuration for location SDP14 on 27th of January.

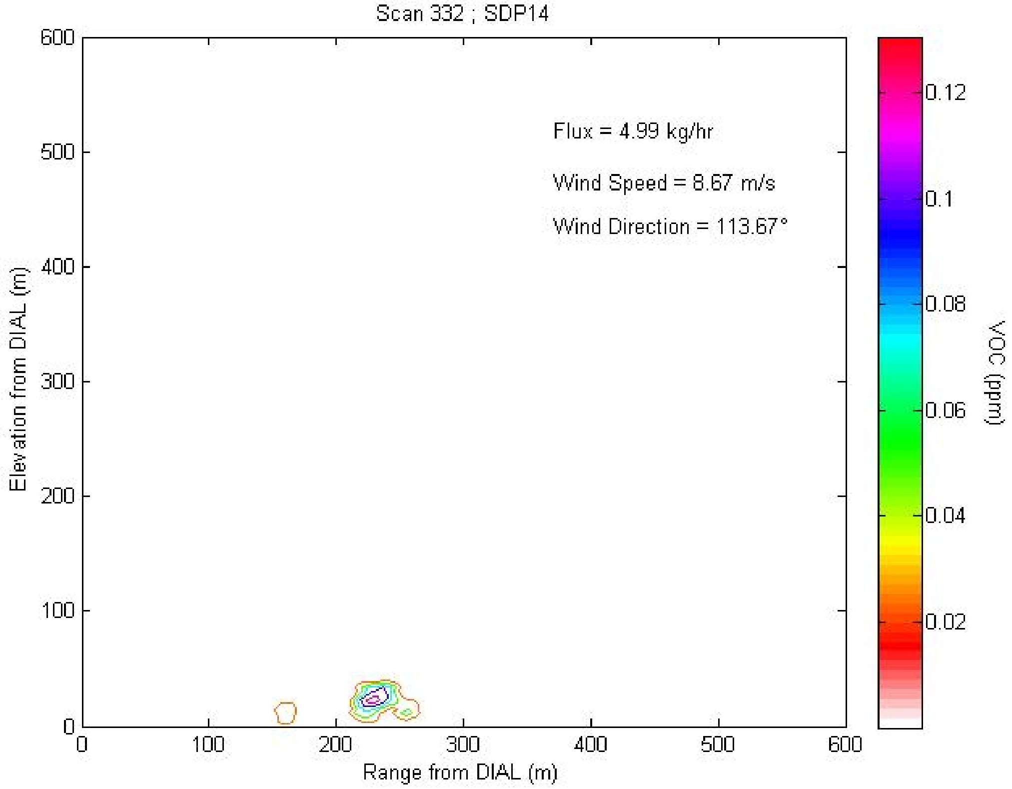

Figure 2.14a1 Contour plot of concentration profile for Scan 332 representing LOS1.

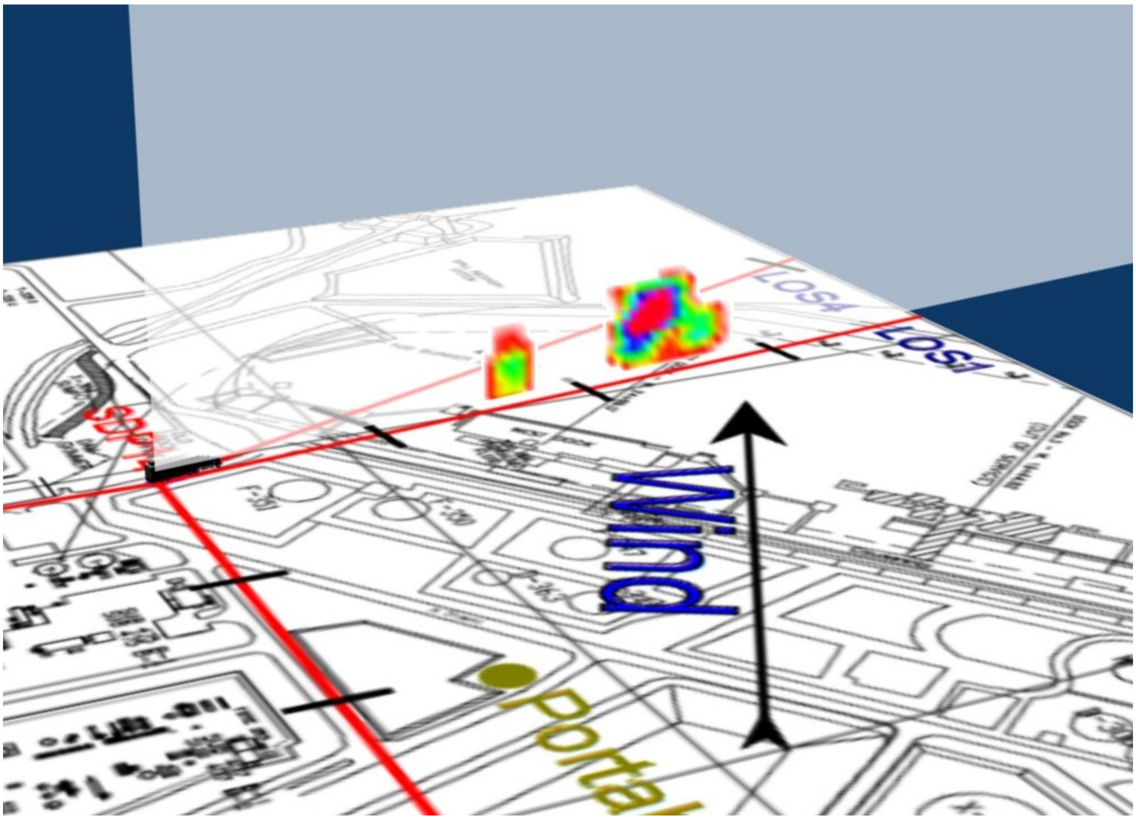

Figure 2.14a2 Visualisation of emission rate measured for Scan 332 representing LOS1.

Table 2.15 Emission rate measurements from SDP15 on 28th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
349	SDP15/LOS1	11:23	11:33	7.5	107.9	34.08	Downwind of East Tanks
350	SDP15/LOS1	11:33	11:43	8.6	102.5	17.74	Downwind of East Tanks
351	SDP15/LOS1	11:48	11:57	7.2	108.7	27.17	Downwind of East Tanks
353	SDP15/LOS1	12:39	12:48	8.1	114.4	32.79	Downwind of East Tanks
354	SDP15/LOS1	12:48	12:58	7.7	109.6	35.37	Downwind of East Tanks
355	SDP15/LOS1	12:59	13:10	8.0	112.5	32.28	Downwind of East Tanks
358	SDP15/LOS1	13:24	13:35	8.9	120.6	42.34	Downwind of East Tanks
359	SDP15/LOS1	13:36	13:47	8.3	116.2	27.56	Downwind of East Tanks
360	SDP15/LOS1	13:48	13:59	8.9	114.2	31.73	Downwind of East Tanks
361	SDP15/LOS1	14:05	14:16	8.1	116.2	23.53	Downwind of East Tanks
362	SDP15/LOS1	14:16	14:27	8.6	117.0	42.61	Downwind of East Tanks
363	SDP15/LOS2	14:39	14:45	7.4	114.0	34.00	Downwind of East Tanks
364	SDP15/LOS2	14:45	14:51	8.3	114.9	35.14	Downwind of East Tanks
365	SDP15/LOS2	14:53	14:59	8.6	119.1	26.72	Downwind of East Tanks
366	SDP15/LOS3	15:06	15:12	8.2	116.5	45.13	Downwind of Refinery E Process
367	SDP15/LOS3	15:13	15:19	9.0	112.2	47.44	Downwind of Refinery E Process
368	SDP15/LOS3	15:20	15:26	8.7	119.7	34.66	Downwind of Refinery E Process
372	SDP15/LOS4	15:46	15:54	8.2	114.6	31.57	Downwind of Refinery E Process
373	SDP15/LOS4	15:54	16:02	8.6	112.9	41.38	Downwind of Refinery E Process
374	SDP15/LOS4	16:03	16:11	7.4	114.0	45.48	Downwind of Refinery E Process
375	SDP15/LOS1	16:17	16:25	8.3	116.0	39.10	Downwind of East Tanks
376	SDP15/LOS1	16:25	16:33	8.0	118.2	40.21	Downwind of East Tanks
377	SDP15/LOS1	16:33	16:41	7.4	115.6	39.85	Downwind of East Tanks

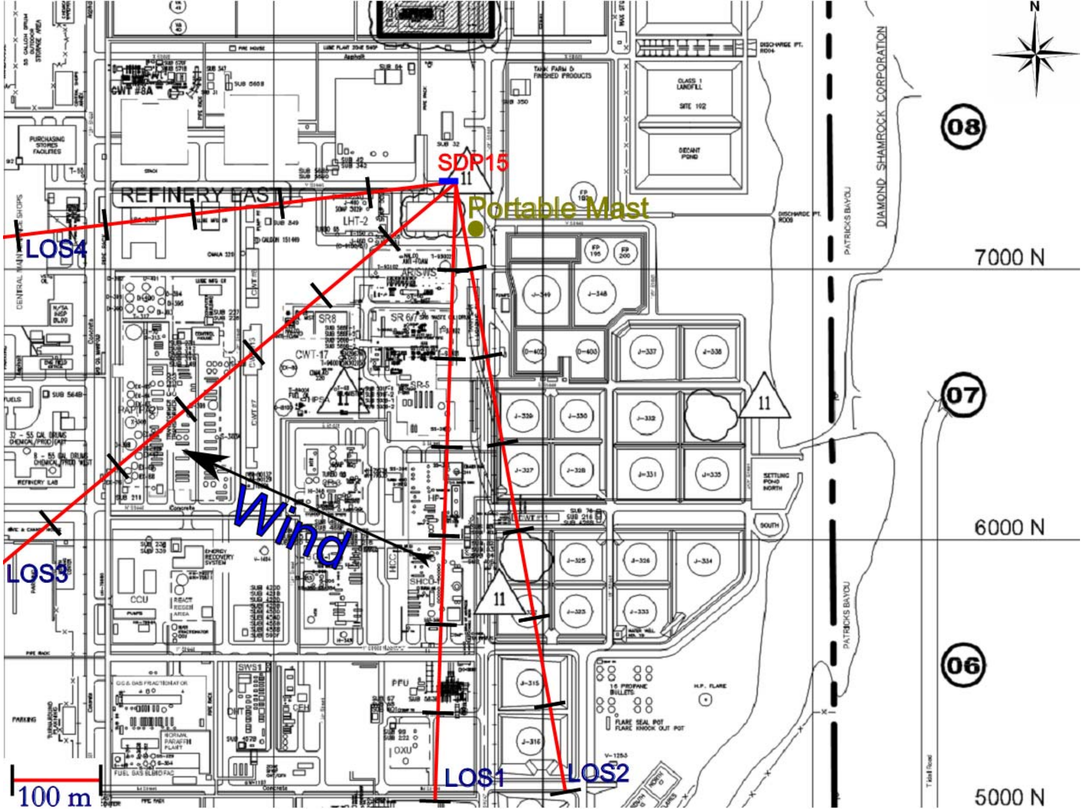

Figure 2.15 Measurement configuration for location SDP15 on 28th of January.

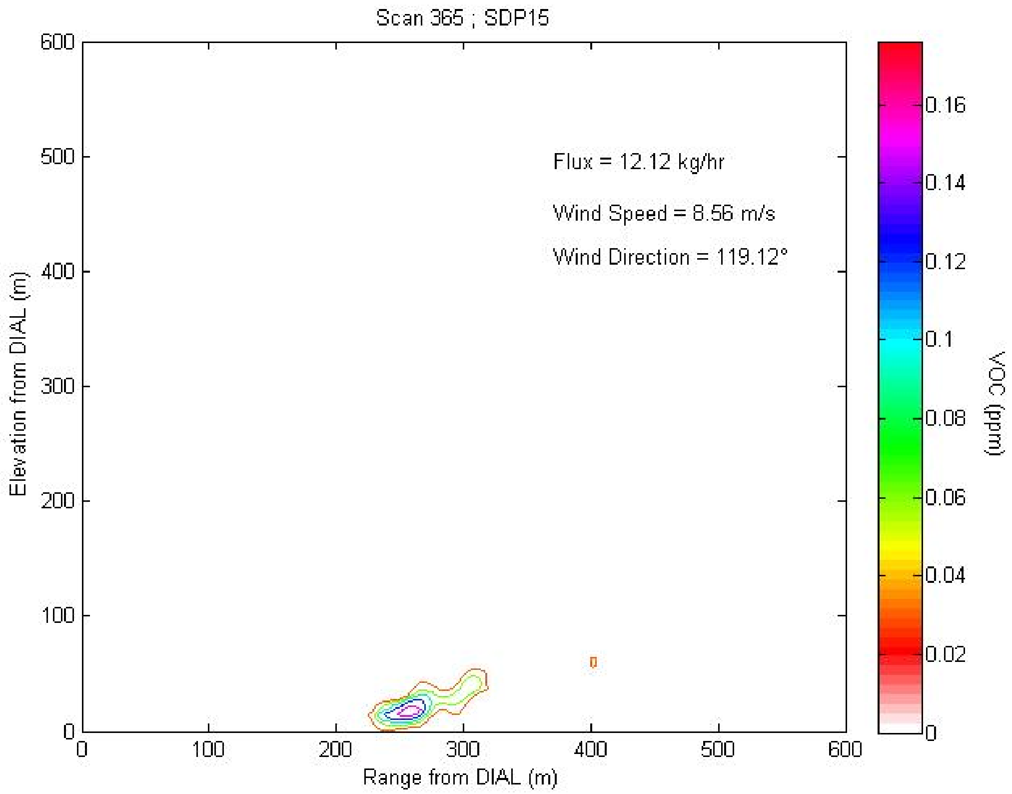

Figure 2.15a1 Contour plot of concentration profile for Scan 365 representing LOS2.

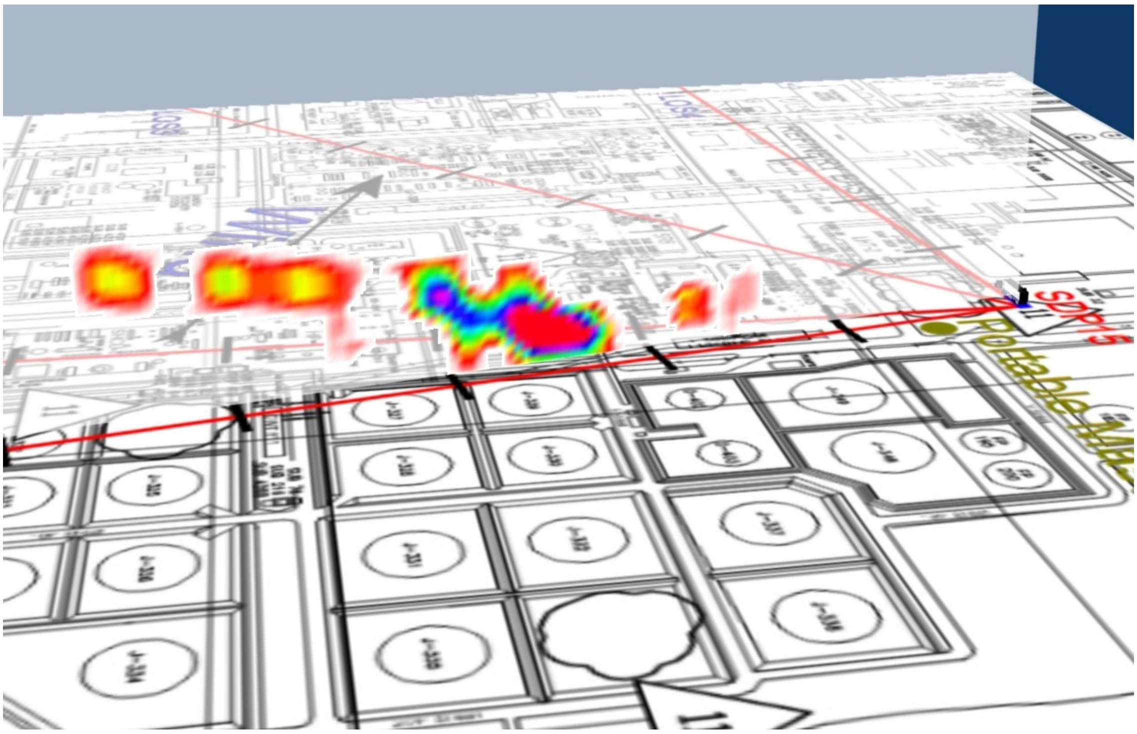

Figure 2.15a2 Visualisation of emission rate measured for Scan 365 representing LOS2.

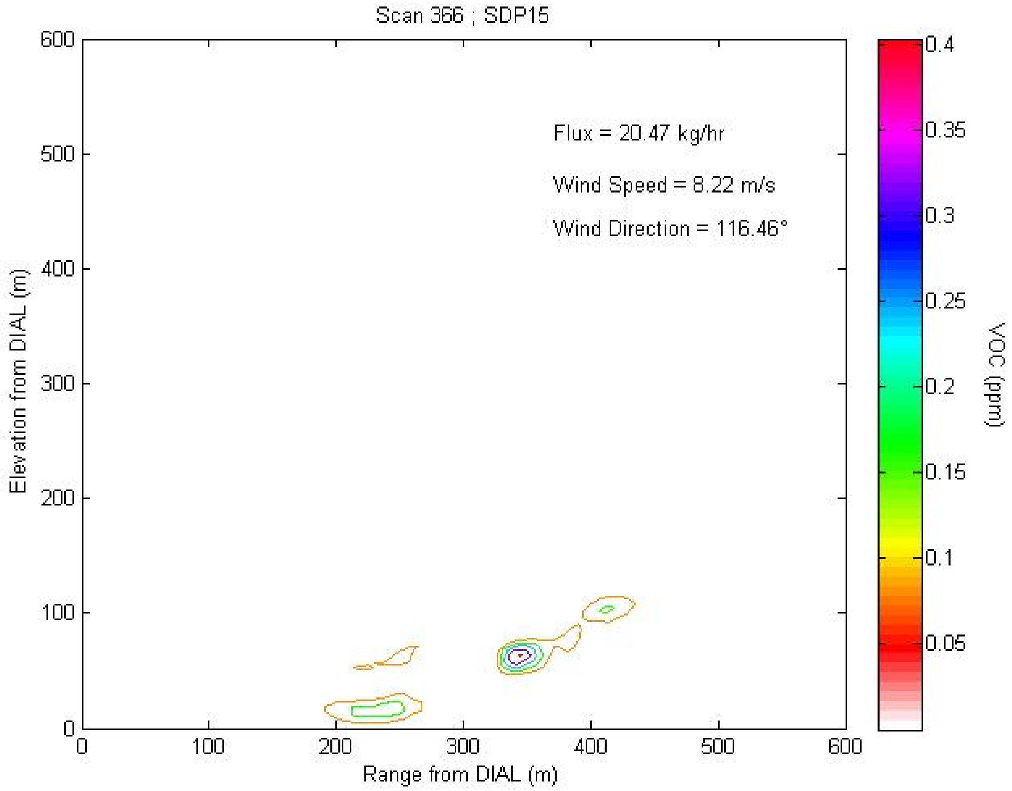

Figure 2.15b1 Contour plot of concentration profile for Scan 366 representing LOS3.

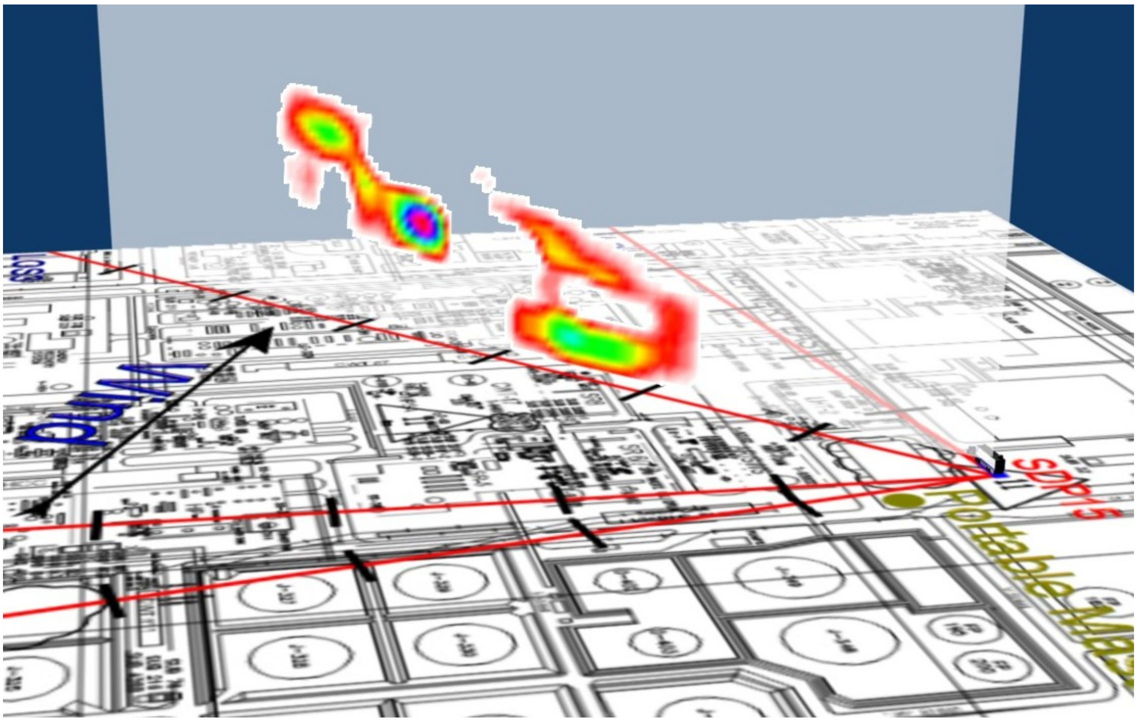

Figure 2.15b2 Visualisation of emission rate measured for Scan 366 representing LOS3.

Table 2.16 Emission rate measurements from SDP16 on 29th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
379	SDP16/LOS1	14:01	14:11	6.6	310.5	0.57	Downwind Olefins OP-2 Flare
380	SDP16/LOS1	14:11	14:30	7.3	312.0	-1.23	Downwind Olefins OP-2 Flare
381	SDP16/LOS2	14:35	14:53	4.9	317.7	-0.98	Downwind Olefins Ground Flare
382	SDP16/LOS2	14:54	15:12	6.9	309.0	0.31	Downwind Olefins Ground Flare
384	SDP16/LOS1	15:25	15:36	7.4	307.9	0.29	Downwind Olefins OP-2 Flare
385	SDP16/LOS1	15:36	15:47	7.3	314.4	-0.65	Downwind Olefins OP-2 Flare
386	SDP16/LOS1	15:48	15:58	7.5	315.5	1.09	Downwind Olefins OP-2 Flare
387	SDP16/LOS1	16:01	16:16	7.3	313.3	0.53	Downwind Olefins OP-2 Flare
388	SDP16/LOS3	16:22	16:37	6.4	324.1	0.14	Downwind Olefins OP-3 Flare
389	SDP16/LOS1	16:44	16:56	6.8	317.5	-0.54	Downwind Olefins OP-2 Flare

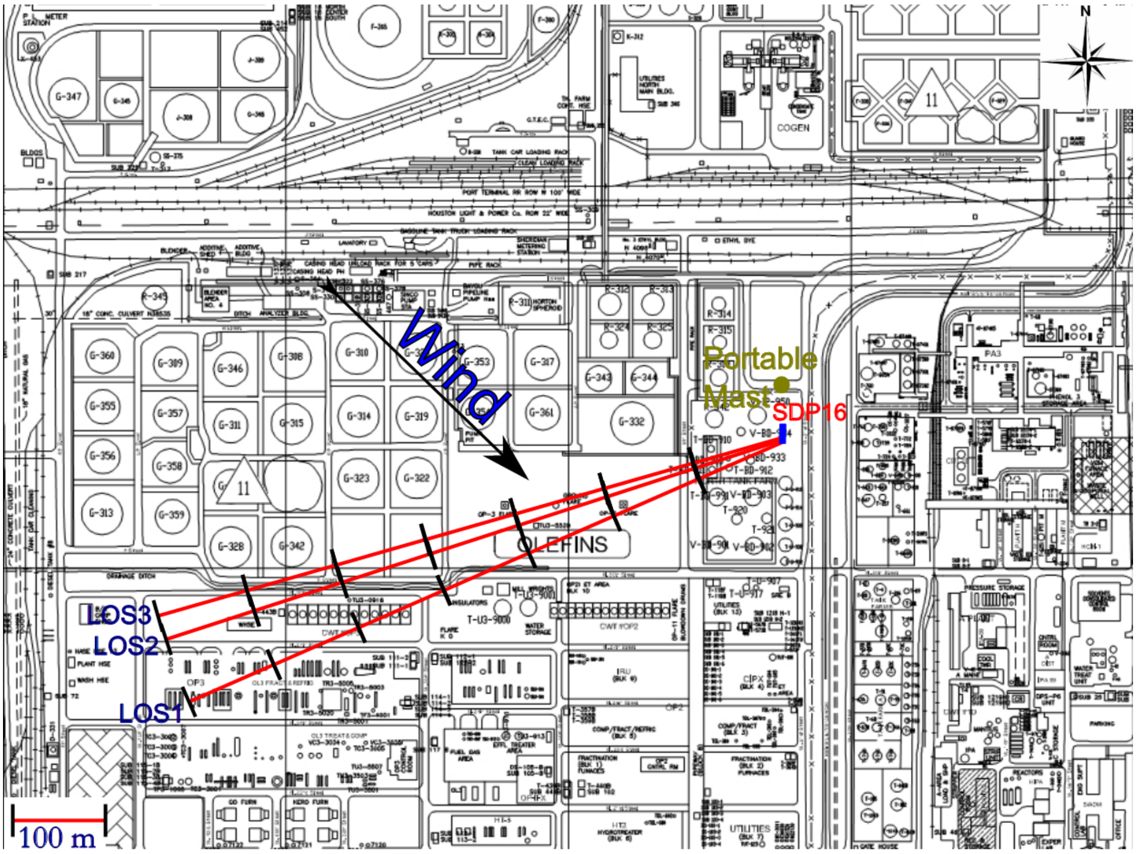

Figure 2.16 Measurement configuration for location SDP16 on 29th of January.

Table 2.17 Emission rate measurements from SDP12 on 30th of January.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
399	SDP12/LOS1	12:26	12:41	5.3	341.4	676.28	Further Downwind of Wastewater
400	SDP12/LOS1	12:48	13:03	6.2	347.8	751.49	Further Downwind of Wastewater
401	SDP12/LOS1	13:15	13:30	5.7	343.0	874.50	Further Downwind of Wastewater
402	SDP12/LOS2	13:35	13:50	5.7	327.8	1347.52	Downwind of Wastewater
404	SDP12/LOS2	13:56	14:11	6.6	338.3	1369.10	Downwind of Wastewater
405	SDP12/LOS2	14:15	14:30	6.4	349.1	926.71	Downwind of Wastewater
406	SDP12/LOS2	14:32	14:47	5.4	339.5	1078.73	Downwind of Wastewater
408	SDP12/LOS3	14:56	15:03	5.5	340.7	-0.65	Upwind of Wastewater
409	SDP12/LOS3	15:03	15:10	5.7	326.9	0.99	Upwind of Wastewater
410	SDP12/LOS3	15:11	15:17	6.2	329.4	0.34	Upwind of Wastewater
411	SDP12/LOS4	15:20	15:27	6.3	332.8	0.22	Upwind of Wastewater
412	SDP12/LOS4	15:27	15:34	5.1	339.9	0.26	Upwind of Wastewater
413	SDP12/LOS4	15:34	15:41	5.7	339.4	0.04	Upwind of Wastewater
414	SDP12/LOS5	15:48	16:05	5.4	328.5	1420.24	Downwind of Wastewater
415	SDP12/LOS5	16:07	16:15	5.1	331.3	1105.51	Downwind of Wastewater
416	SDP12/LOS5	16:15	16:24	4.7	337.2	1054.96	Downwind of Wastewater
417	SDP12/LOS6	16:30	16:39	5.2	328.6	634.67	Further Downwind of Wastewater
418	SDP12/LOS6	16:40	16:49	5.6	340.9	825.76	Further Downwind of Wastewater
419	SDP12/LOS6	16:50	17:01	5.7	339.3	934.07	Further Downwind of Wastewater

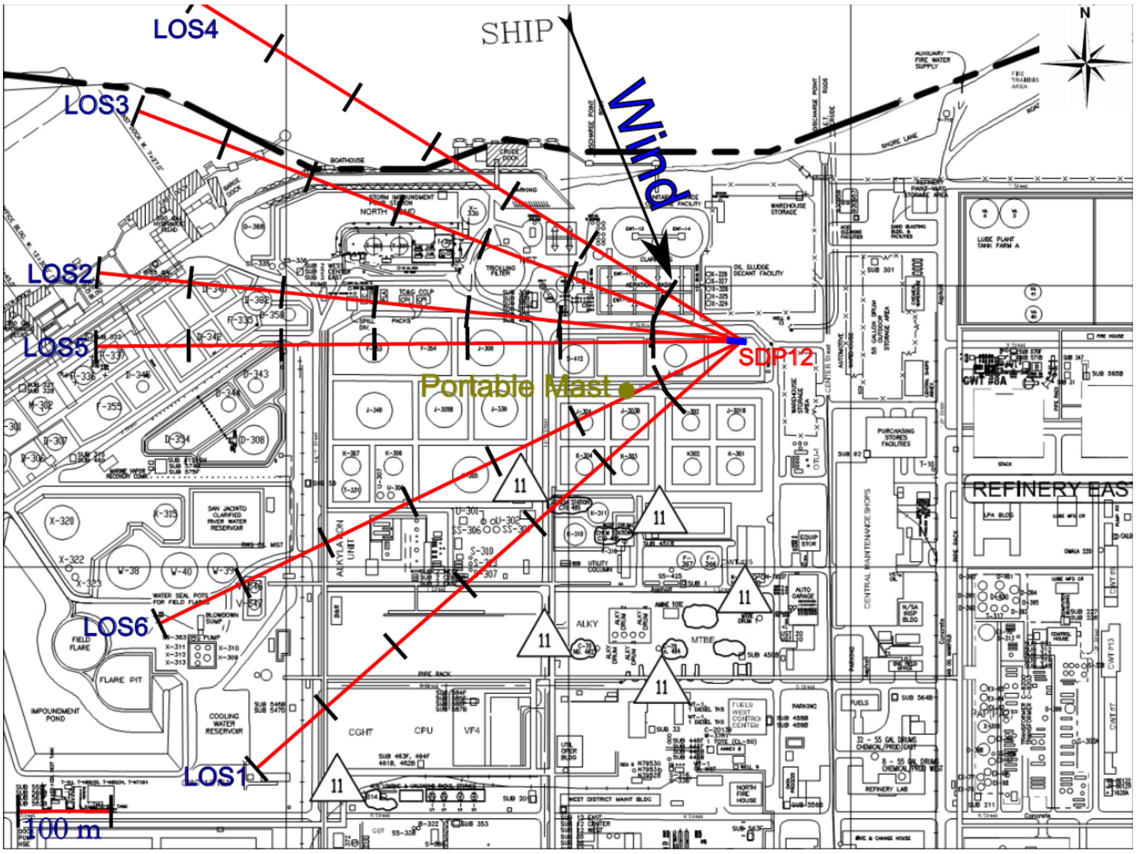

Figure 2.17 Measurement configuration for location SDP12 on 30th of January.

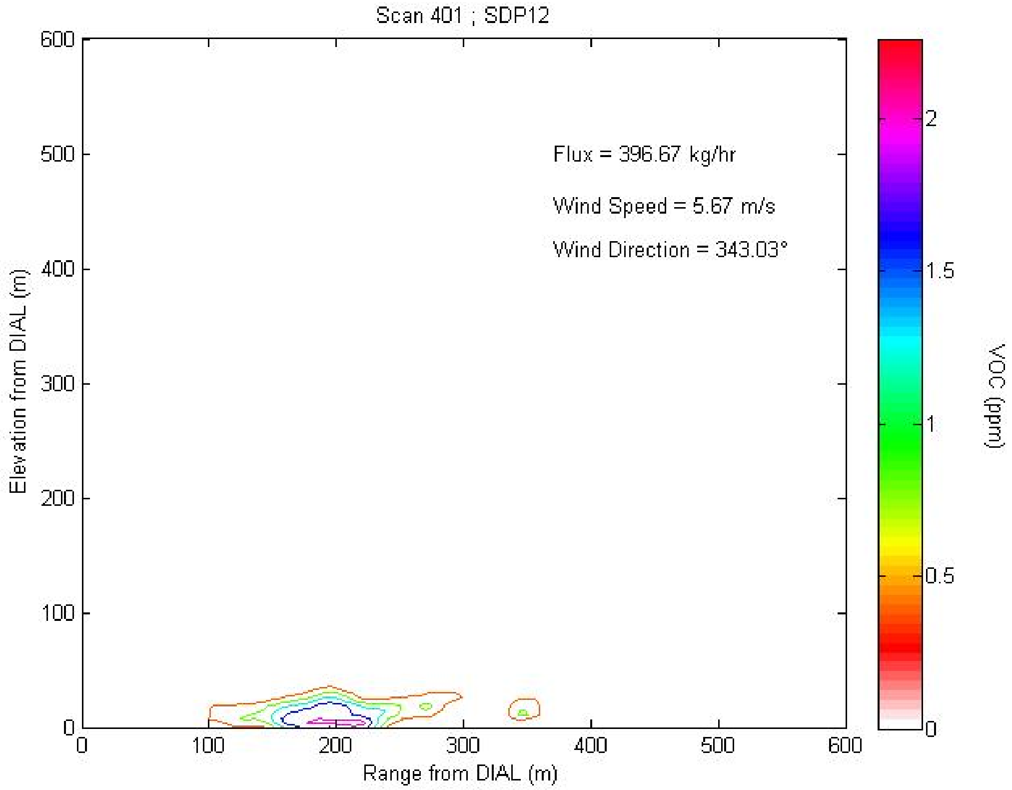

Figure 2.17a1 Contour plot of concentration profile for Scan 401 representing LOS1.

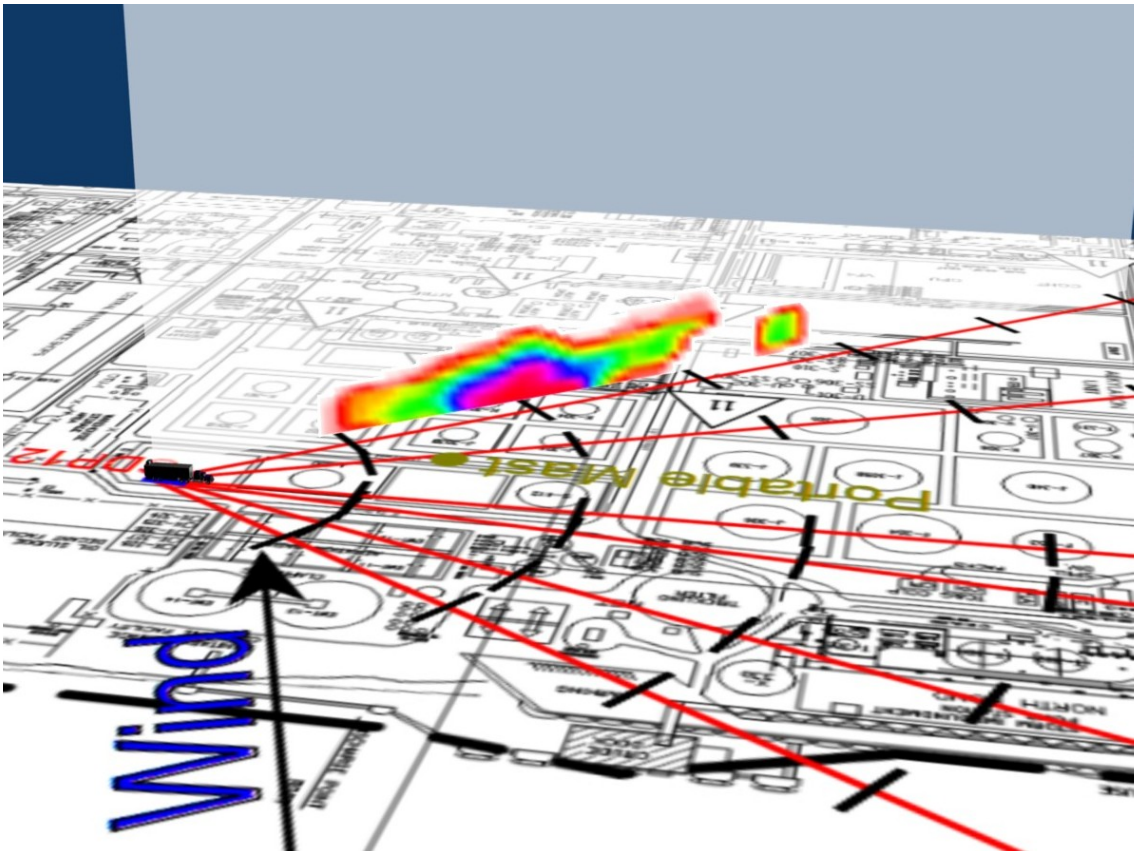

Figure 2.17a2 Visualisation of emission rate measured for Scan 401 representing LOS1.

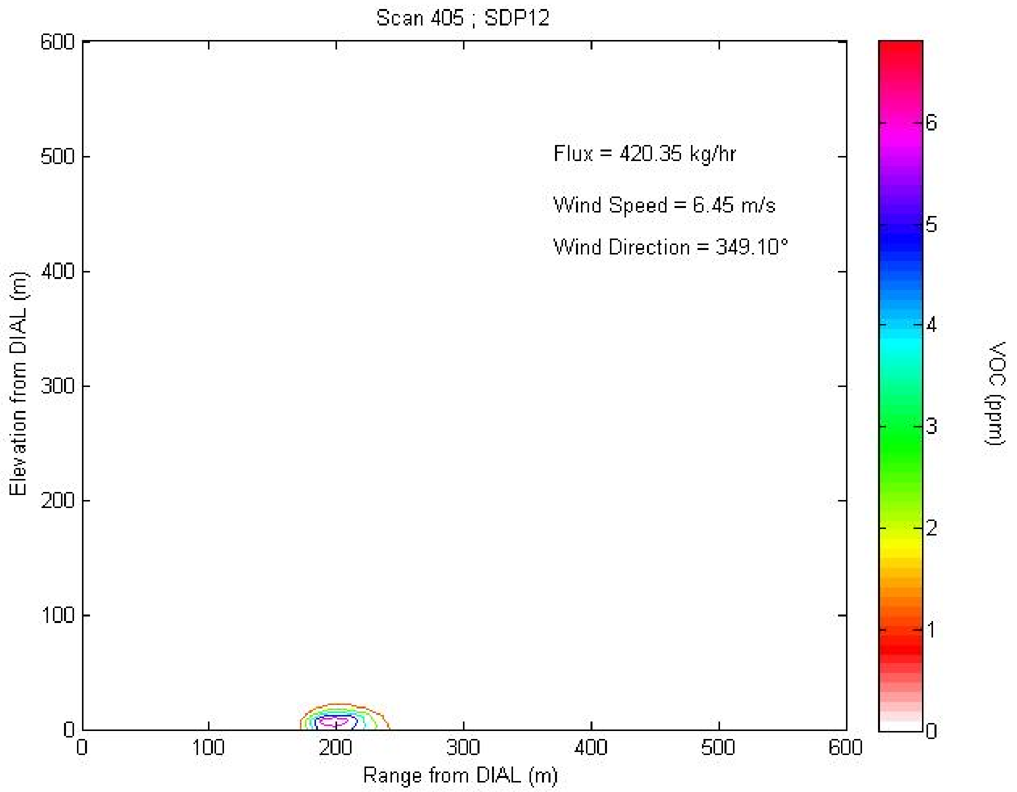

Figure 2.17b1 Contour plot of concentration profile for Scan 405 representing LOS2.

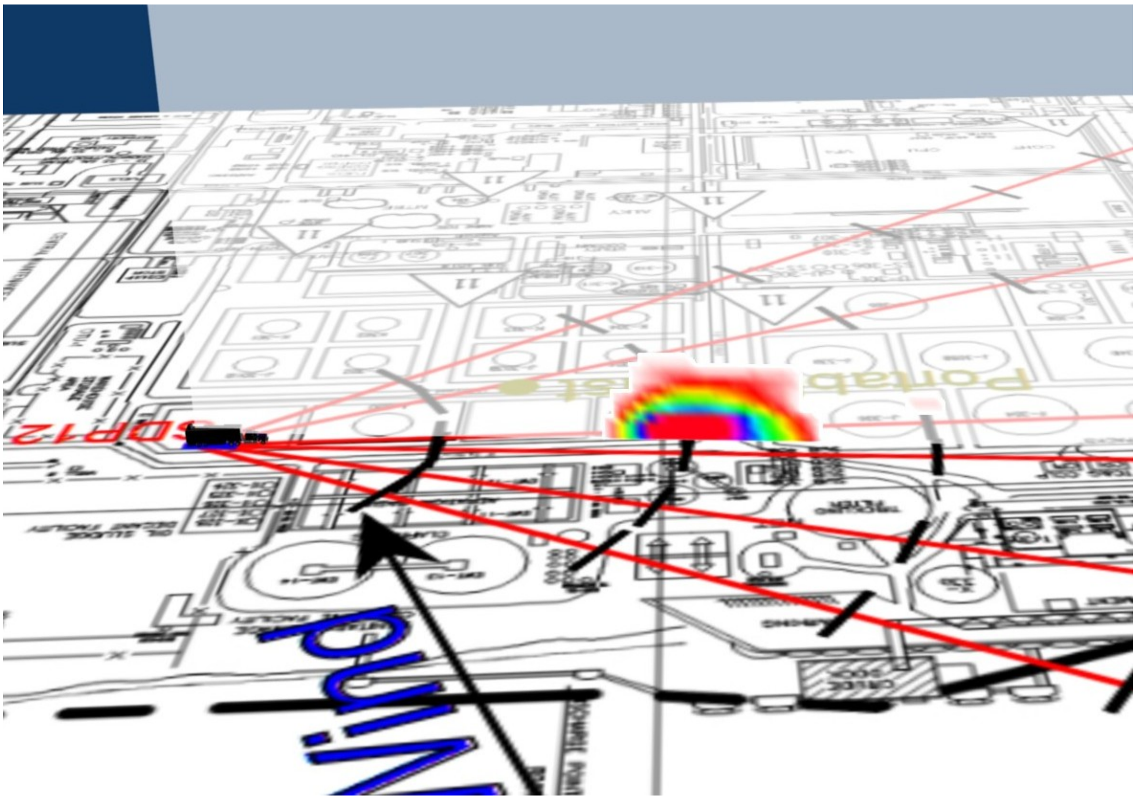

Figure 2.17b2 Visualisation of emission rate measured for Scan 405 representing LOS2.

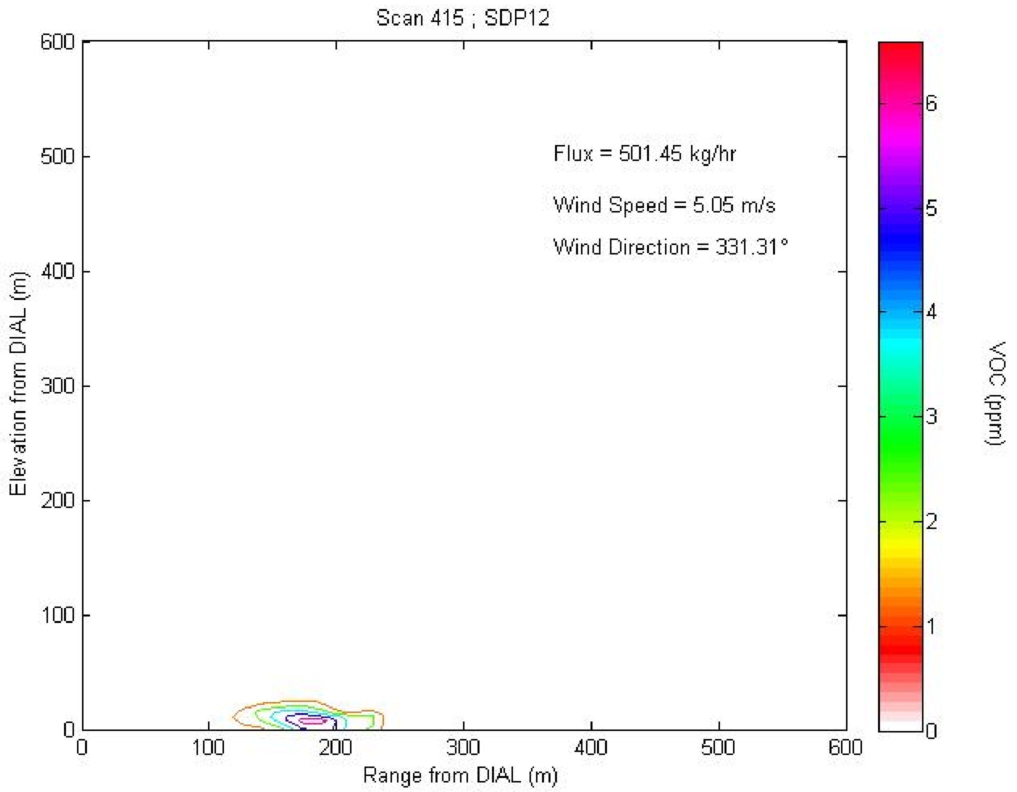

Figure 2.17c1 Contour plot of concentration profile for Scan 415 representing LOS5.

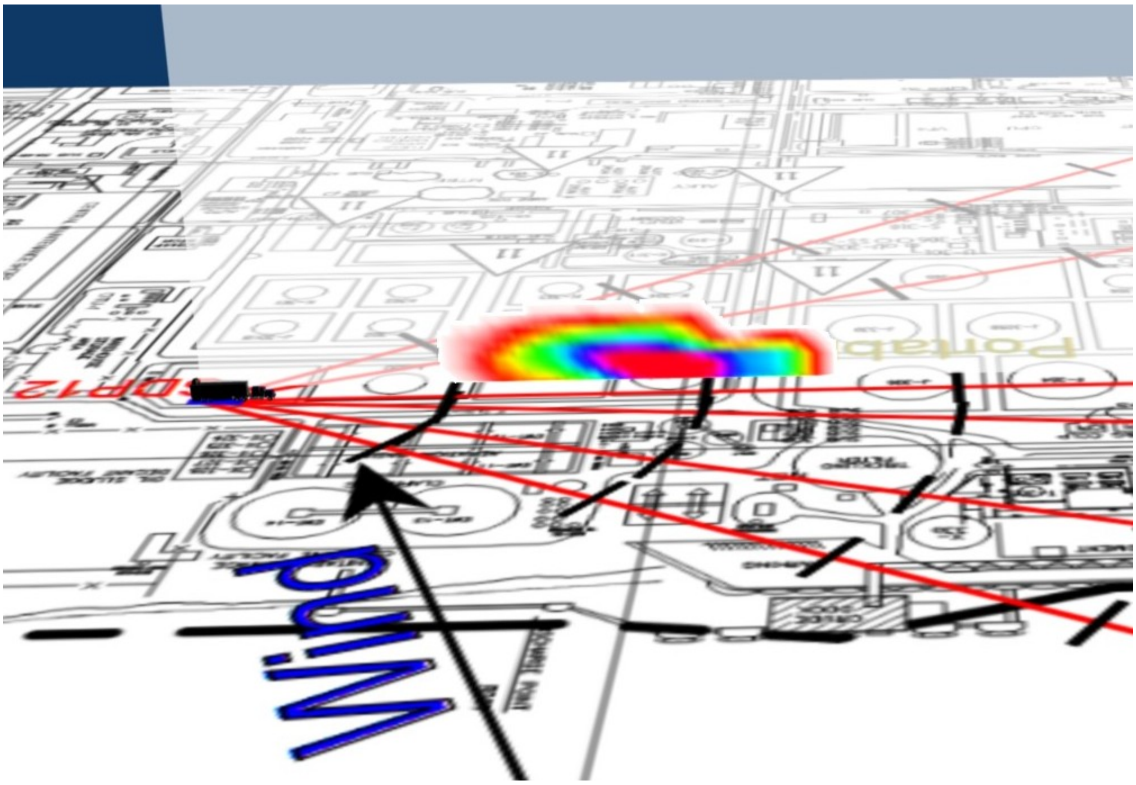

Figure 2.17c2 Visualisation of emission rate measured for Scan 415 representing LOS5.

Table 2.18 Emission rate measurements from SDP17 on 1st of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
421	SDP17/LOS1	12:16	12:26	3.4	93.7	27.43	Downwind of East Wastewater
422	SDP17/LOS1	12:26	12:35	2.9	83.9	22.35	Downwind of East Wastewater
423	SDP17/LOS1	12:35	12:45	3.3	86.9	25.34	Downwind of East Wastewater
424	SDP17/LOS1	12:52	13:01	3.4	111.3	29.55	Downwind of East Wastewater
425	SDP17/LOS2	13:06	13:15	3.9	111.9	20.65	Downwind of East Wastewater
426	SDP17/LOS2	13:15	13:25	3.6	101.7	21.89	Downwind of East Wastewater
427	SDP17/LOS2	13:25	13:34	3.8	109.9	19.18	Downwind of East Wastewater
428	SDP17/LOS2	13:36	13:41	4.5	101.4	20.40	Downwind of East Wastewater
430	SDP17/LOS2	13:54	14:04	3.9	103.9	28.60	Downwind of East Wastewater
431	SDP17/LOS2	14:04	14:13	4.4	112.8	29.33	Downwind of East Wastewater
432	SDP17/LOS3	14:20	14:30	4.6	131.2	1.37	Downwind of Flare
433	SDP17/LOS3	14:30	14:39	4.2	111.6	1.48	Downwind of Flare
434	SDP17/LOS3	14:39	14:49	4.4	88.8	0.29	Downwind of Flare
435	SDP17/LOS4	14:51	15:01	3.9	84.6	1.23	Upwind of Flare
436	SDP17/LOS4	15:01	15:10	4.3	85.0	0.77	Upwind of Flare
440	SDP17/LOS5	15:46	15:55	2.9	80.7	16.17	Downwind of East Wastewater
441	SDP17/LOS5	15:56	16:05	3.1	96.0	32.38	Downwind of East Wastewater
442	SDP17/LOS5	16:05	16:14	4.0	110.6	27.39	Downwind of East Wastewater
443	SDP17/LOS5	16:16	16:25	3.9	79.9	30.17	Downwind of East Wastewater
444	SDP17/LOS5	16:26	16:35	3.3	90.7	29.98	Downwind of East Wastewater
445	SDP17/LOS1	16:37	16:46	3.4	86.3	21.30	Downwind of East Wastewater
446	SDP17/LOS1	16:46	16:56	3.3	86.9	32.23	Downwind of East Wastewater
447	SDP17/LOS1	16:56	17:05	2.8	71.9	22.04	Downwind of East Wastewater

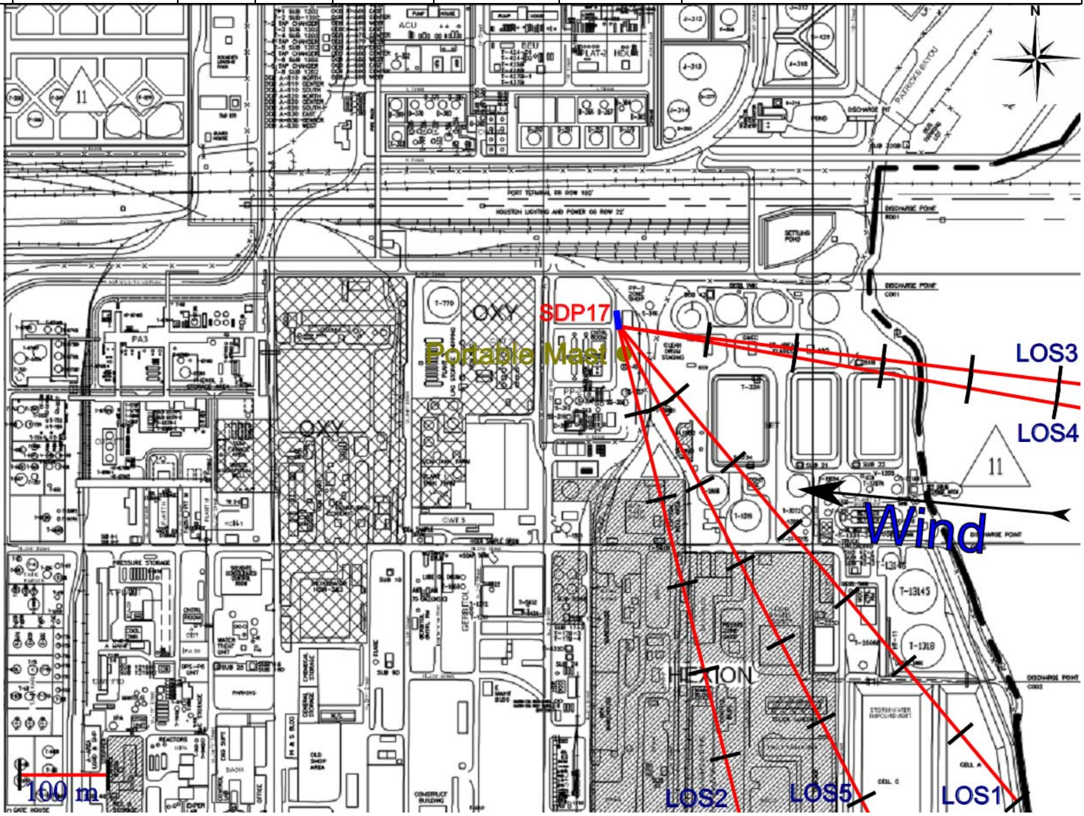

Figure 2.18 Measurement configuration for location SDP17 on 1st of February.

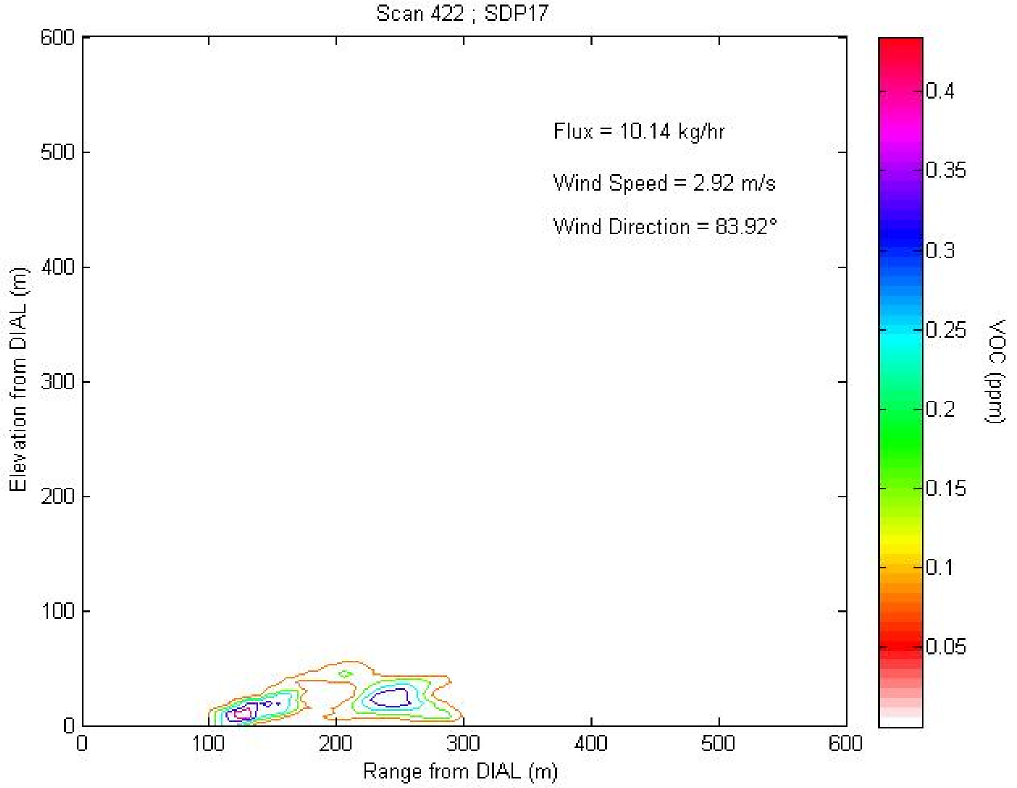

Figure 2.18a1 Contour plot of concentration profile for Scan 422 representing LOS1.

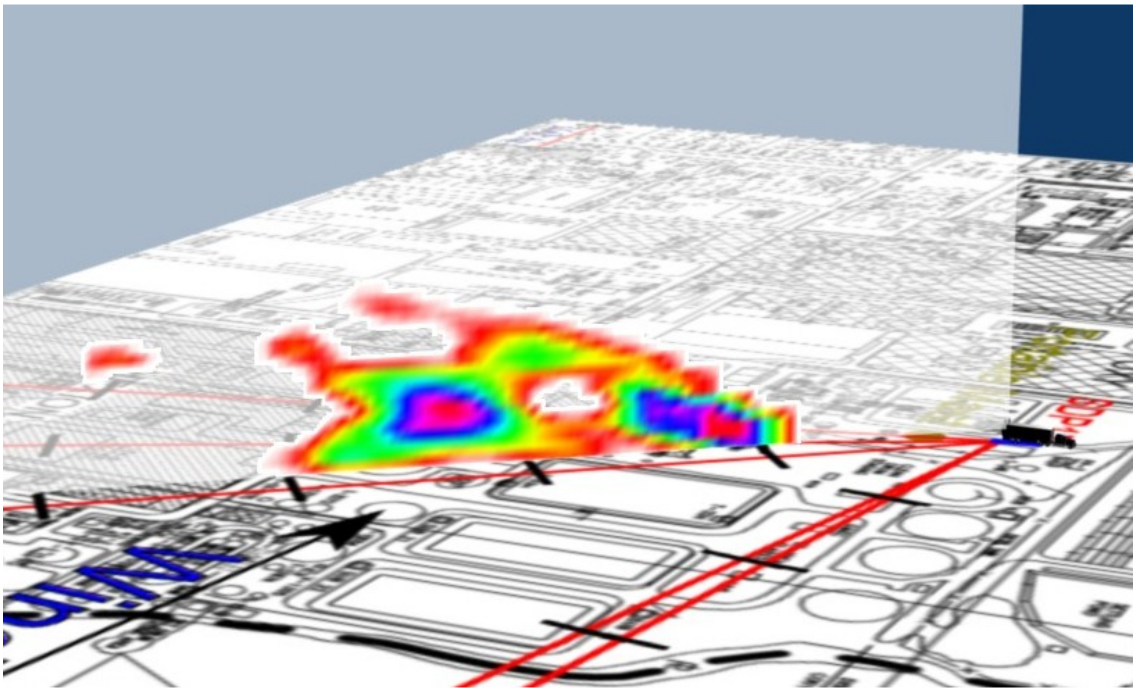

Figure 2.18a2 Visualisation of emission rate measured for Scan 422 representing LOS1.

Table 2.19 Emission rate measurements from SDP18 on 2nd of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
449	SDP18/LOS1	10:54	11:01	3.9	24.9	0.84	Downwind Flare
450	SDP18/LOS1	11:02	11:15	3.6	34.1	0.71	Downwind Flare
451	SDP18/LOS1	11:16	11:39	2.8	40.2	-0.12	Downwind Flare
452	SDP18/LOS1	11:39	11:52	2.3	34.0	0.49	Downwind Flare
454	SDP18/LOS2	12:07	12:20	3.8	12.6	-0.18	Downwind Flare
455	SDP18/LOS2	12:21	12:34	3.3	23.0	0.28	Downwind Flare
456	SDP18/LOS2	12:35	12:48	3.1	29.7	0.11	Downwind Flare
457	SDP18/LOS2	12:49	13:04	3.5	31.7	-0.82	Downwind Flare
458	SDP18/LOS2	13:04	13:19	3.6	24.9	0.24	Downwind Flare
459	SDP18/LOS2	13:19	13:34	3.1	18.9	0.80	Downwind Flare
460	SDP18/LOS2	13:34	13:49	4.3	16.8	-0.36	Downwind Flare
462	SDP18/LOS2	14:02	14:17	4.1	24.6	0.23	Downwind Flare
463	SDP18/LOS2	14:21	14:36	3.6	17.0	-0.15	Downwind Flare
464	SDP18/LOS2	14:36	14:51	3.5	20.1	1.01	Downwind Flare
465	SDP18/LOS2	14:51	15:06	3.5	23.3	0.23	Downwind Flare
466	SDP18/LOS2	15:06	15:21	4.5	17.3	0.17	Downwind Flare
467	SDP18/LOS2	15:21	15:36	5.2	16.7	0.48	Downwind Flare
468	SDP18/LOS2	15:36	15:51	5.1	19.8	0.34	Downwind Flare
469	SDP18/LOS2	15:55	16:18	4.1	15.3	-0.09	Downwind Flare
470	SDP18/LOS2	16:19	16:42	3.8	17.2	0.78	Downwind Flare
471	SDP18/LOS2	16:42	17:05	3.3	11.8	0.63	Downwind Flare

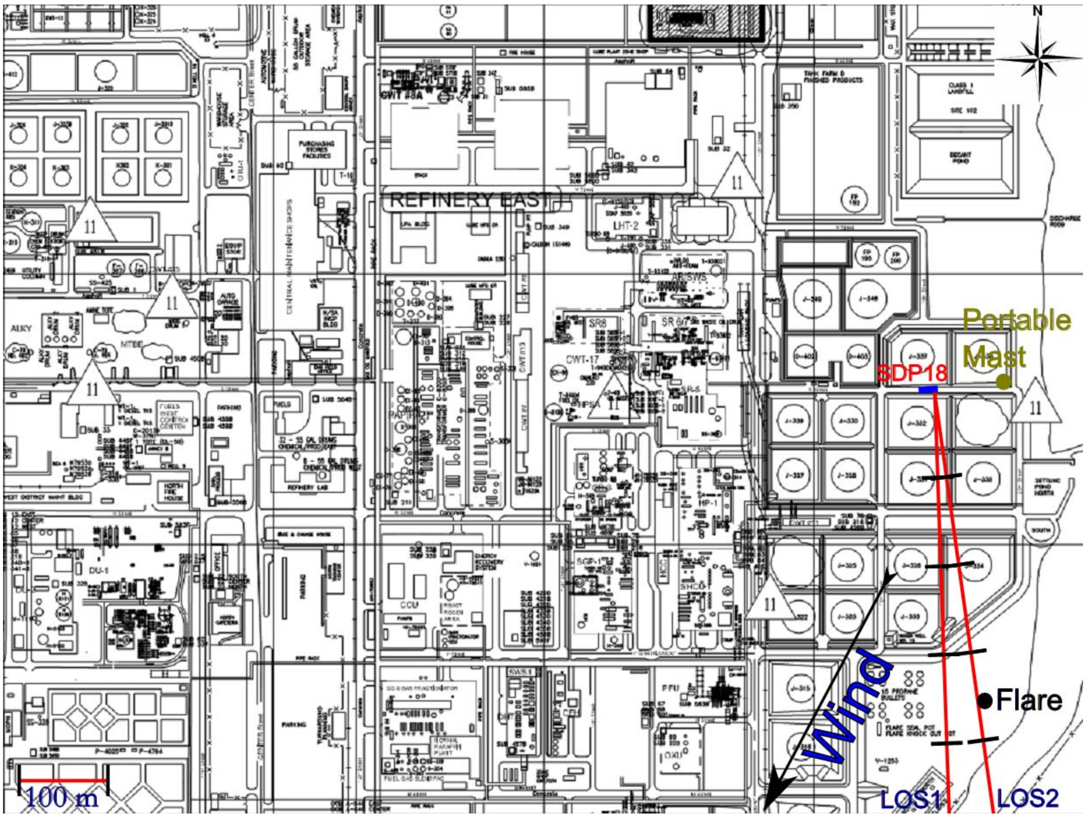

Figure 2.19 Measurement configuration for location SDP18 on 2nd of February.

Table 2.20 Emission rate measurements from SDP19 on 3rd of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
473	SDP19/LOS1	10:30	10:53	8.8	106.3	2.52	Downwind of East Olefins
474	SDP19/LOS1	10:53	11:16	7.6	99.3	1.43	Downwind of East Olefins
475	SDP19/LOS1	11:17	11:44	7.9	98.2	2.46	Downwind of East Olefins
477	SDP19/LOS1	11:56	12:26	7.0	95.1	2.97	Downwind of East Olefins
478	SDP19/LOS1	12:27	13:00	8.0	97.4	3.71	Downwind of East Olefins
479	SDP19/LOS1	13:00	13:27	8.2	112.6	1.72	Downwind of East Olefins
480	SDP19/LOS1	13:27	13:53	9.1	113.6	3.37	Downwind of East Olefins
483	SDP19/LOS1	14:27	14:53	7.3	116.8	3.80	Downwind of East Olefins
484	SDP19/LOS1	14:54	15:21	6.7	112.5	2.98	Downwind of East Olefins
485	SDP19/LOS1	15:21	15:47	7.1	102.8	0.91	Downwind of East Olefins
486	SDP19/LOS1	15:47	16:14	7.3	93.6	3.64	Downwind of East Olefins
487	SDP19/LOS1	16:14	16:40	6.9	86.6	1.31	Downwind of East Olefins
488	SDP19/LOS1	16:41	16:54	6.4	87.6	3.74	Downwind of East Olefins

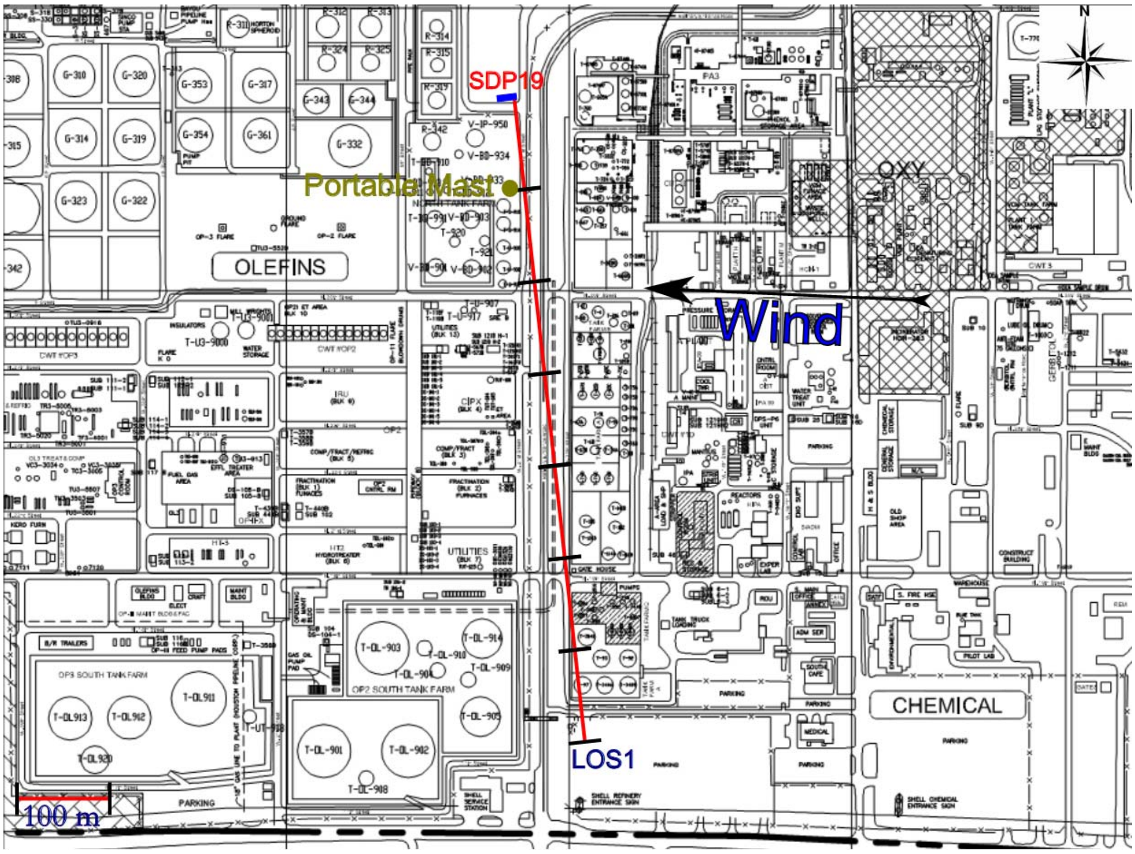

Figure 2.20 Measurement configuration for location SDP19 on 3rd of February.

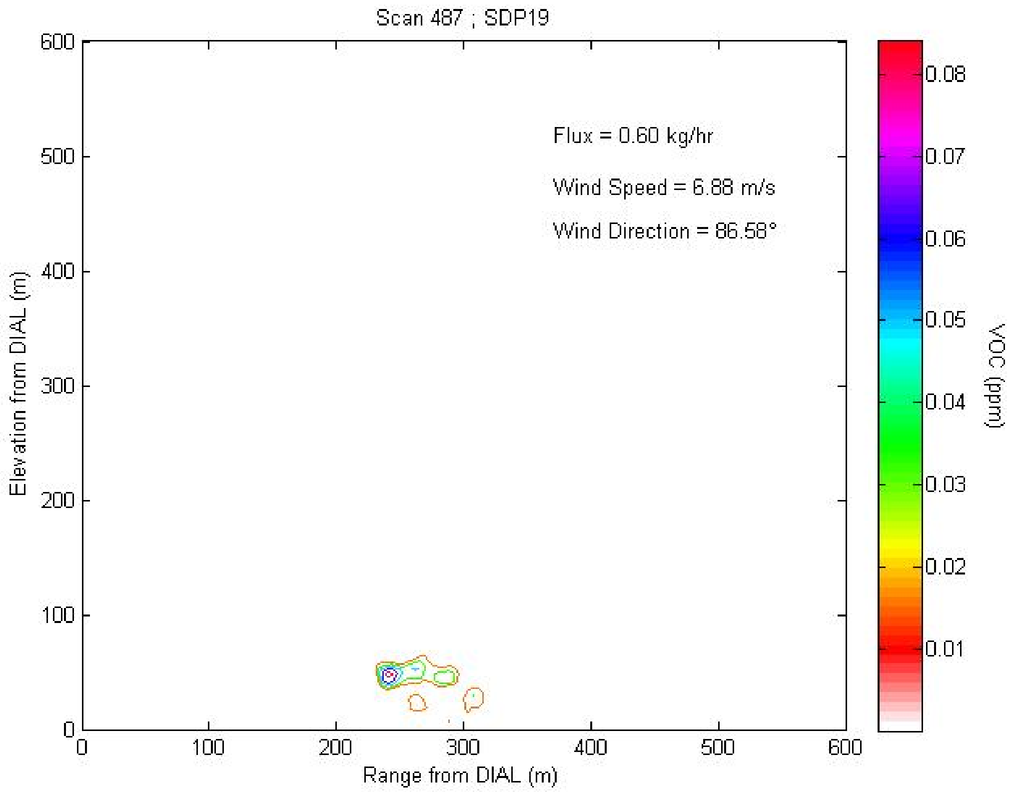

Figure 2.20a1 Contour plot of concentration profile for Scan 487 representing LOS1.

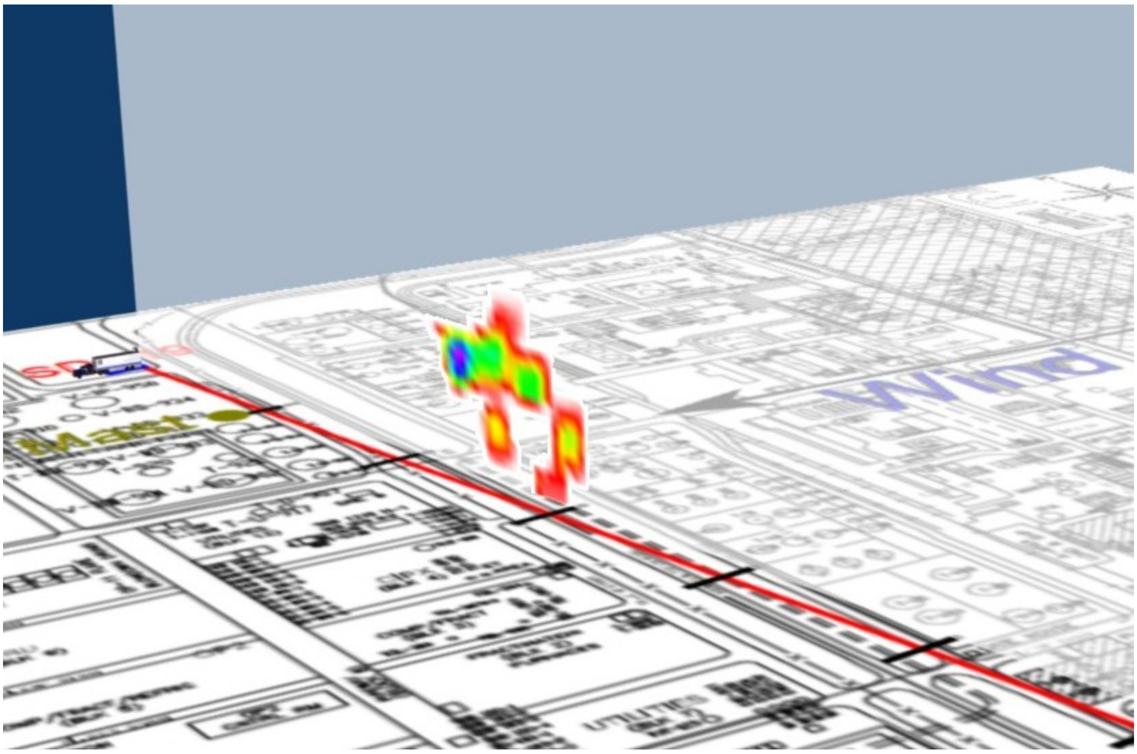

Figure 2.20a2 Visualisation of emission rate measured for Scan 487 representing LOS1.

Table 2.21 Emission rate measurements from SDP20 on 4th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
491	SDP20/LOS1	10:17	10:35	6.0	119.6	3.44	Downwind of Coker
492	SDP20/LOS1	10:36	10:56	6.1	116.1	3.75	Downwind of Coker
493	SDP20/LOS1	10:56	11:16	8.2	116.2	4.33	Downwind of Coker
495	SDP20/LOS2	11:32	11:51	8.8	109.3	2.19	Downwind of Coker
496	SDP20/LOS2	11:51	12:09	9.4	112.1	3.58	Downwind of Coker
497	SDP20/LOS2	12:10	12:28	7.8	105.6	2.75	Downwind of Coker
498	SDP20/LOS2	12:28	12:46	7.2	113.4	3.98	Downwind of Coker
501	SDP20/LOS2	12:54	13:13	5.3	105.1	3.10	Downwind of Coker
503	SDP20/LOS1	13:15	13:22	6.8	105.2	1.36	Downwind of Coker
504	SDP20/LOS1	13:22	13:30	6.9	105.0	3.32	Downwind of Coker
505	SDP20/LOS1	13:30	13:39	7.7	118.6	3.77	Downwind of Coker
506	SDP20/LOS1	13:39	13:47	3.9	116.0	6.07	Downwind of Coker
507	SDP20/LOS2	13:49	14:01	2.0	12.9	0.48	Downwind of Coker
508	SDP20/LOS2	14:01	14:13	2.6	42.4	2.89	Downwind of Coker
509	SDP20/LOS2	14:13	14:25	2.8	354.5	0.21	Downwind of Coker
511	SDP20/LOS3	14:36	14:46	2.0	351.5	1.90	Upwind of Coker
512	SDP20/LOS3	14:47	14:59	1.8	68.9	0.58	Upwind of Coker
513	SDP20/LOS2	15:01	15:13	3.6	41.6	3.21	Downwind of Coker
514	SDP20/LOS2	15:14	15:26	4.6	71.6	3.09	Downwind of Coker
515	SDP20/LOS2	15:26	15:38	3.9	74.8	4.10	Downwind of Coker
516	SDP20/LOS2	15:38	15:50	2.8	77.1	5.09	Downwind of Coker
517	SDP20/LOS2	15:50	16:02	2.6	43.9	1.54	Downwind of Coker
518	SDP20/LOS2	16:02	16:14	2.2	10.7	0.32	Downwind of Coker
519	SDP20/LOS2	16:14	16:26	0.8	103.1	2.68	Downwind of Coker
520	SDP20/LOS2	16:26	16:38	1.5	88.8	4.74	Downwind of Coker
521	SDP20/LOS2	16:38	16:50	1.3	41.8	1.69	Downwind of Coker

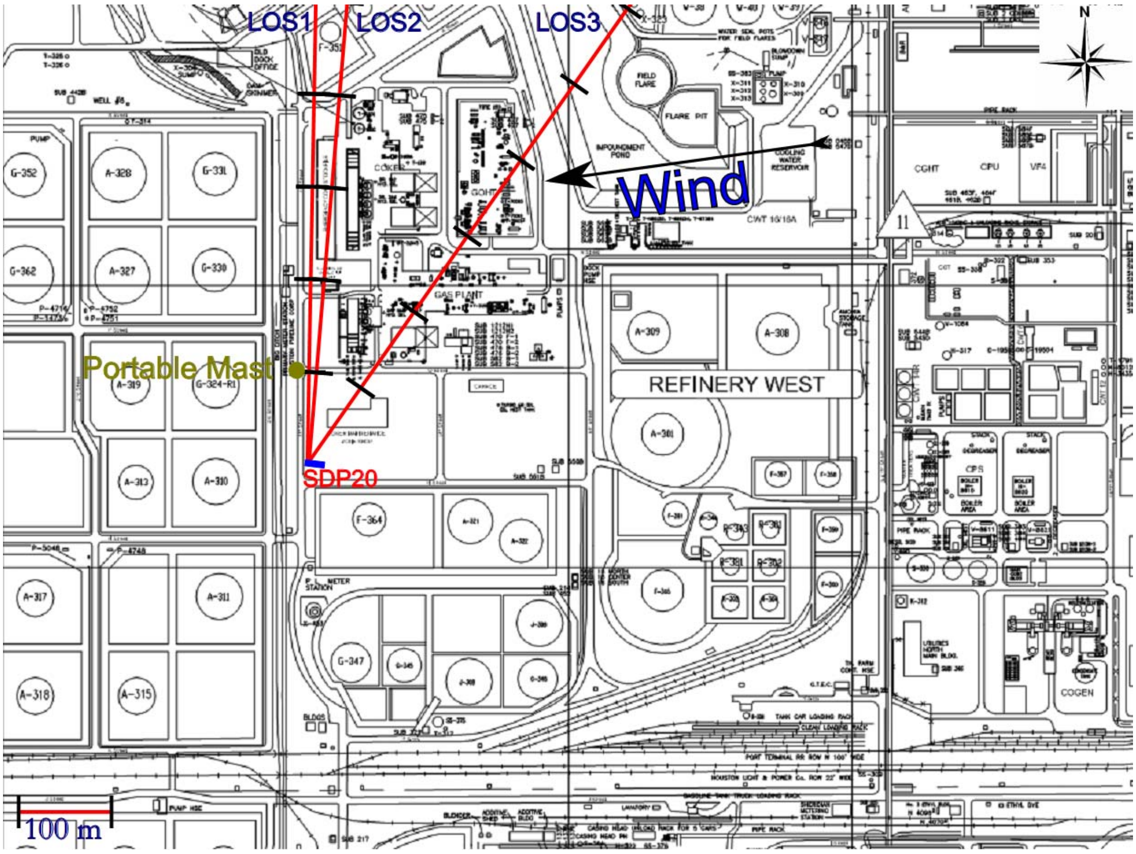

Figure 2.21 Measurement configuration for location SDP20 on 4th of February.

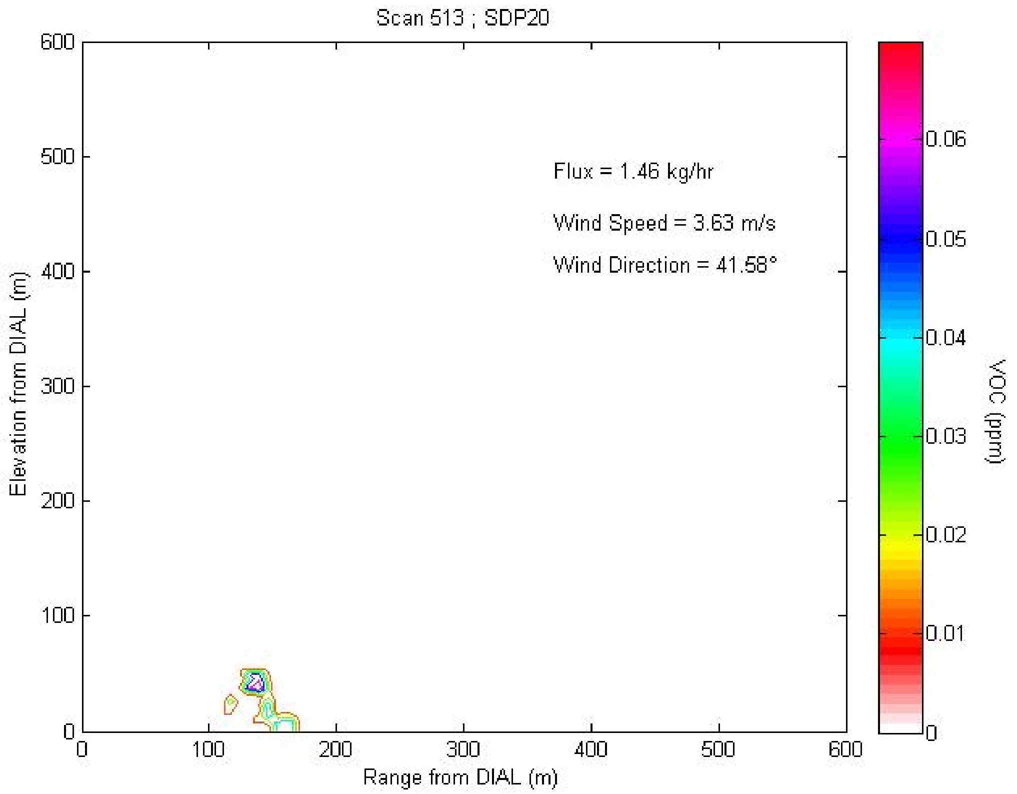

Figure 2.21a1 Contour plot of concentration profile for Scan 513 representing LOS2.

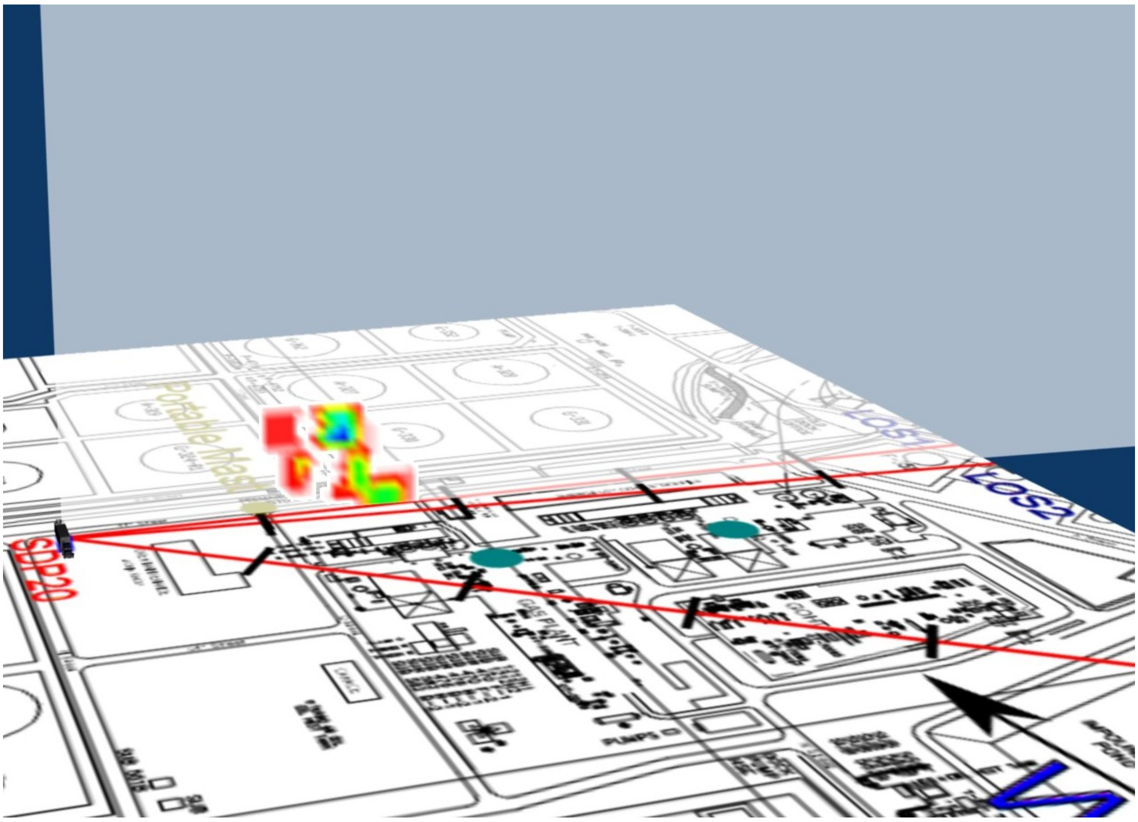

Figure 2.21a2 Visualisation of emission rate measured for Scan 513 representing LOS2.

Table 2.22 Emission rate measurements from SDP21 on 5th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
523	SDP21/LOS1	10:50	11:05	5.1	295.4	462.18	Downwind of Wastewater
524	SDP21/LOS1	11:05	11:20	4.4	298.9	412.93	Downwind of Wastewater
525	SDP21/LOS1	11:21	11:36	4.6	298.9	673.41	Downwind of Wastewater
527	SDP21/LOS1	11:49	12:04	4.8	302.2	678.73	Downwind of Wastewater
528	SDP21/LOS1	12:09	12:26	4.9	289.7	477.45	Downwind of Wastewater
529	SDP21/LOS1	12:26	12:42	4.8	296.9	581.52	Downwind of Wastewater
530	SDP21/LOS1	12:43	12:59	5.4	285.2	384.66	Downwind of Wastewater
531	SDP21/LOS2	13:03	13:20	5.2	297.1	571.02	Downwind of Wastewater
532	SDP21/LOS2	13:20	13:36	5.0	301.4	658.12	Downwind of Wastewater
533	SDP21/LOS2	13:37	13:54	4.7	297.9	602.96	Downwind of Wastewater
534	SDP21/LOS1	13:54	14:11	4.2	300.6	682.69	Downwind of Wastewater

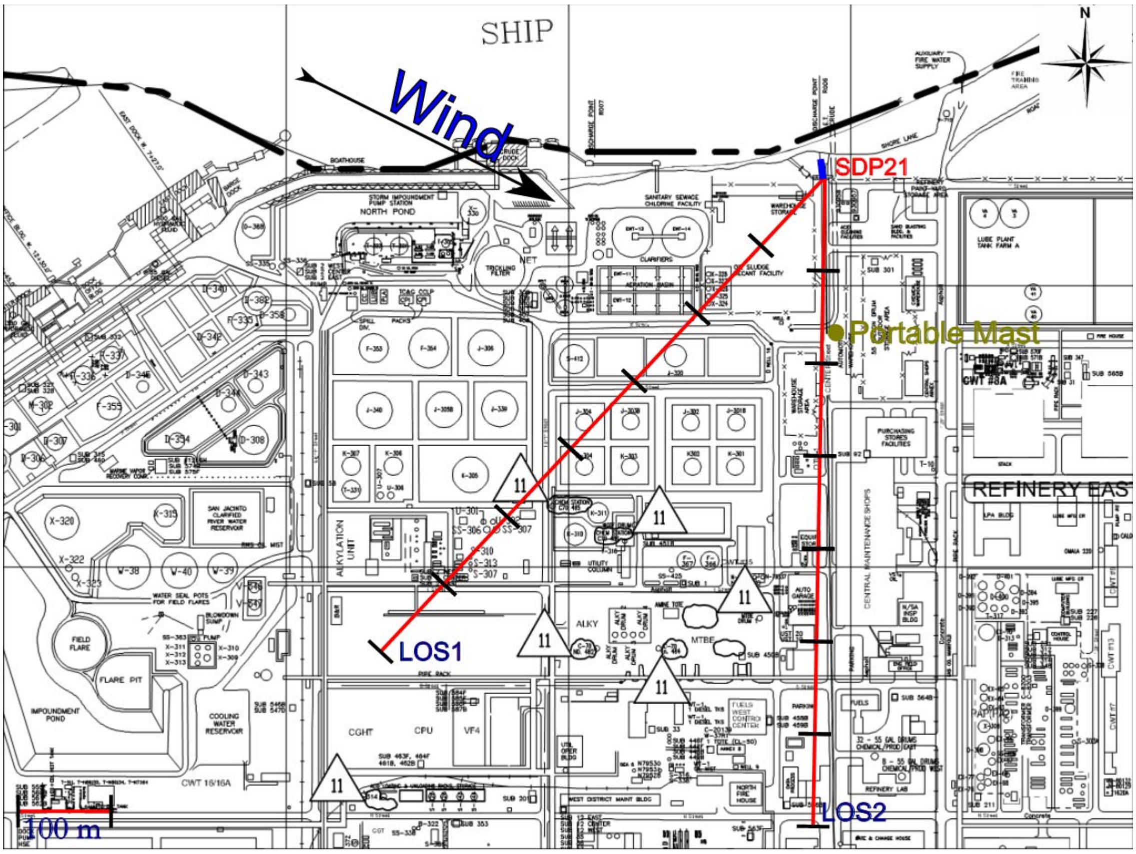

Figure 2.22 Measurement configuration for location SDP21 on 5th of February.

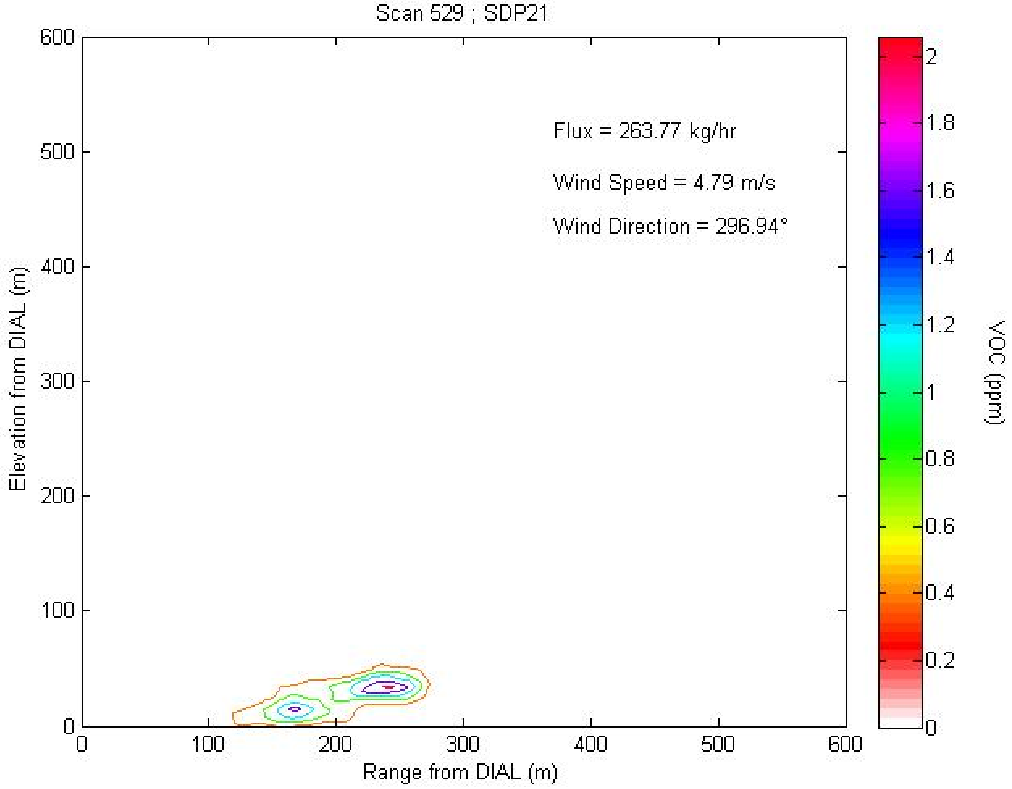

Figure 2.22a1 Contour plot of concentration profile for Scan 529 representing LOS1.

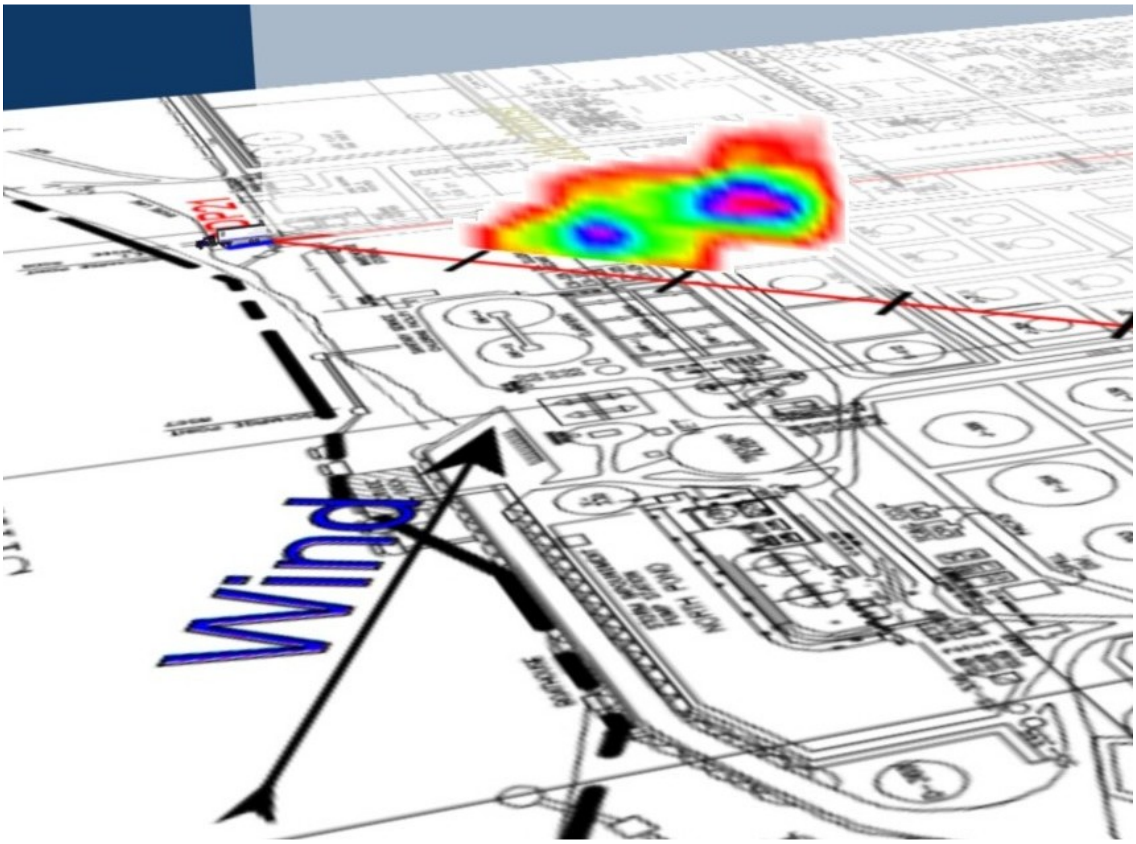

Figure 2.22a2 Visualisation of emission rate measured for Scan 529 representing LOS1.

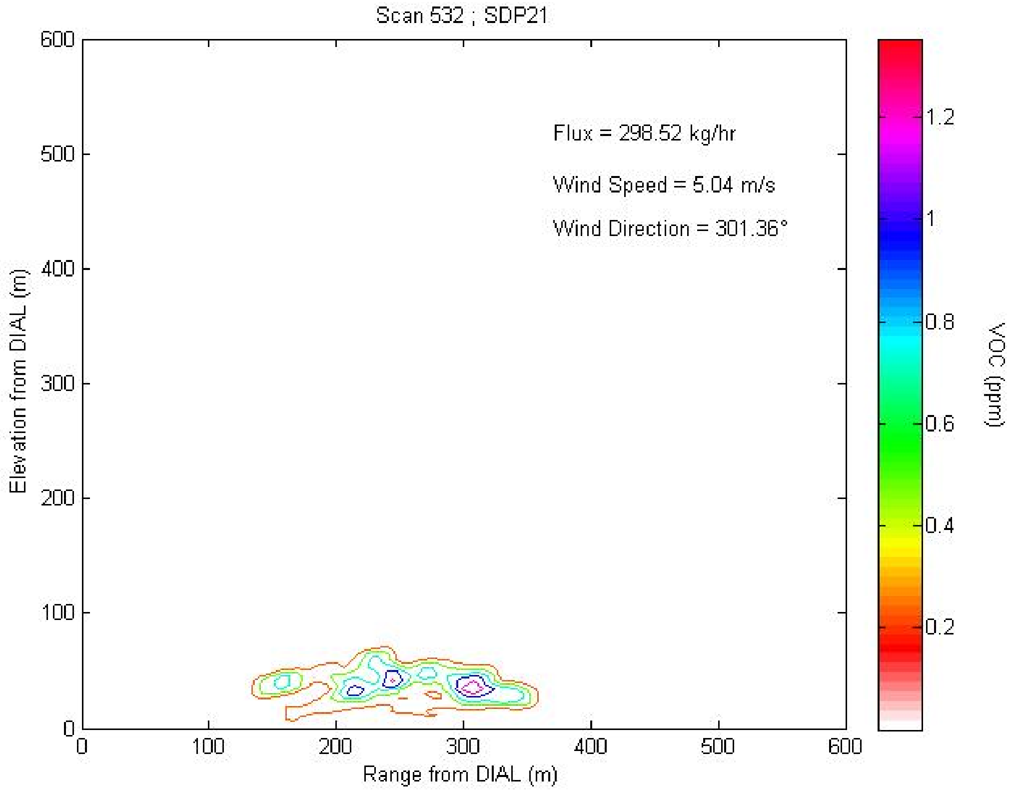

Figure 2.22b1 Contour plot of concentration profile for Scan 532 representing LOS2.

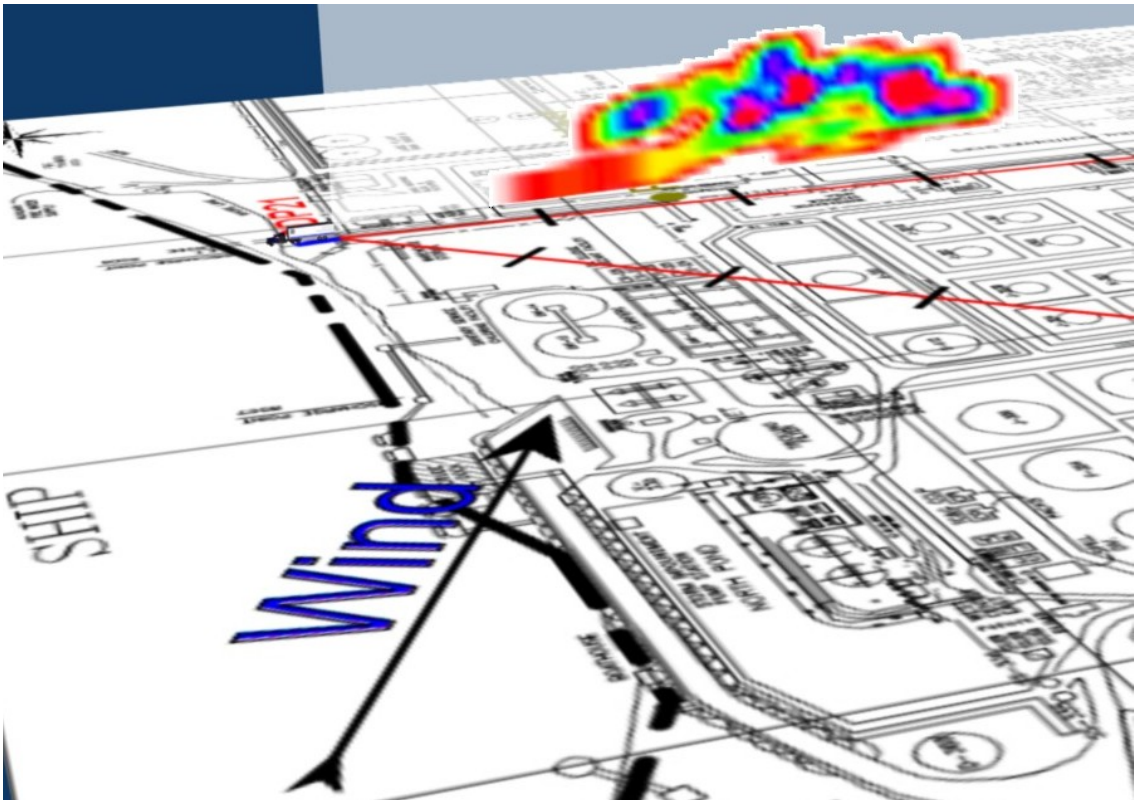

Figure 2.22b2 Visualisation of emission rate measured for Scan 532 representing LOS2.

Table 2.23 Emission rate measurements from SDP22 on 5th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
535	SDP22/LOS1	14:47	15:05	5.3	317.4	514.75	Downwind of Wastewater
536	SDP22/LOS1	15:05	15:23	5.1	314.1	424.67	Downwind of Wastewater
537	SDP22/LOS1	15:28	15:46	4.3	314.0	518.32	Downwind of Wastewater
538	SDP22/LOS1	15:47	16:08	4.0	298.5	303.36	Downwind of Wastewater
540	SDP22/LOS1	16:16	16:36	4.2	305.6	375.29	Downwind of Wastewater
541	SDP22/LOS1	16:36	16:56	5.0	300.4	340.55	Downwind of Wastewater

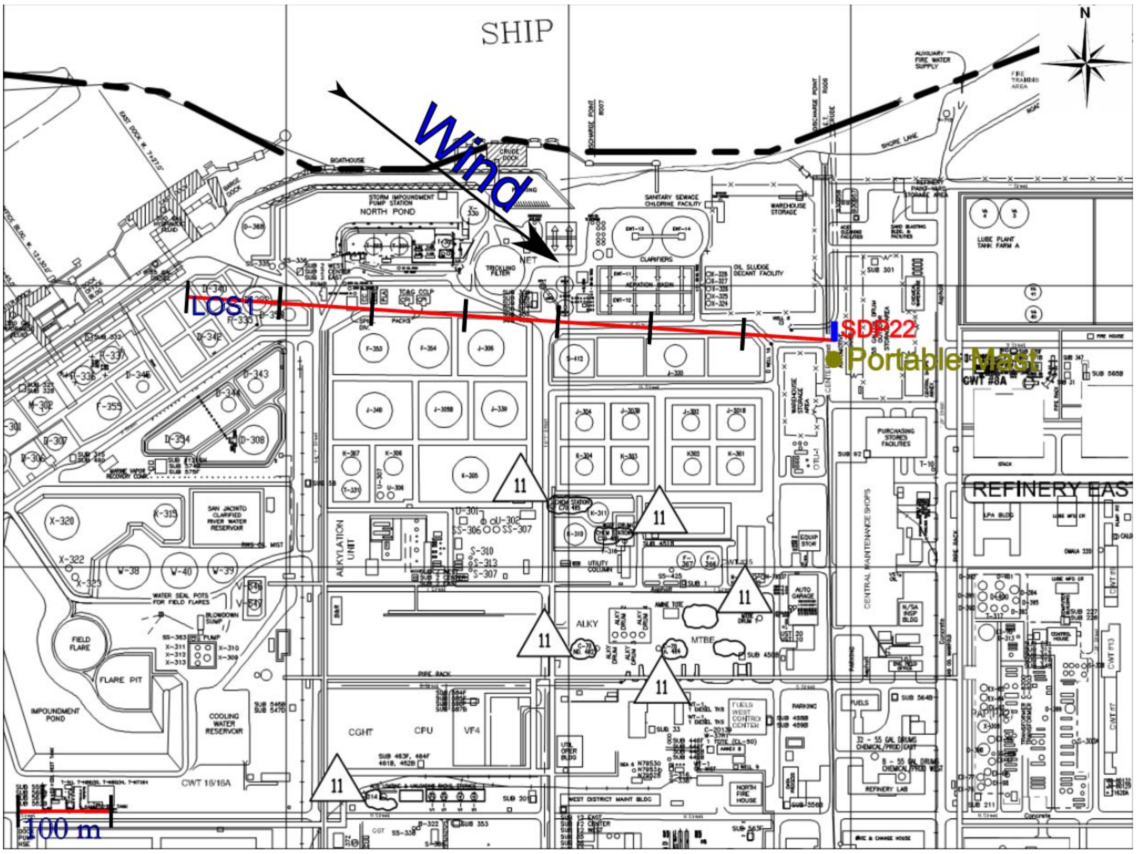

Figure 2.23 Measurement configuration for location SDP22 on 5th of February.

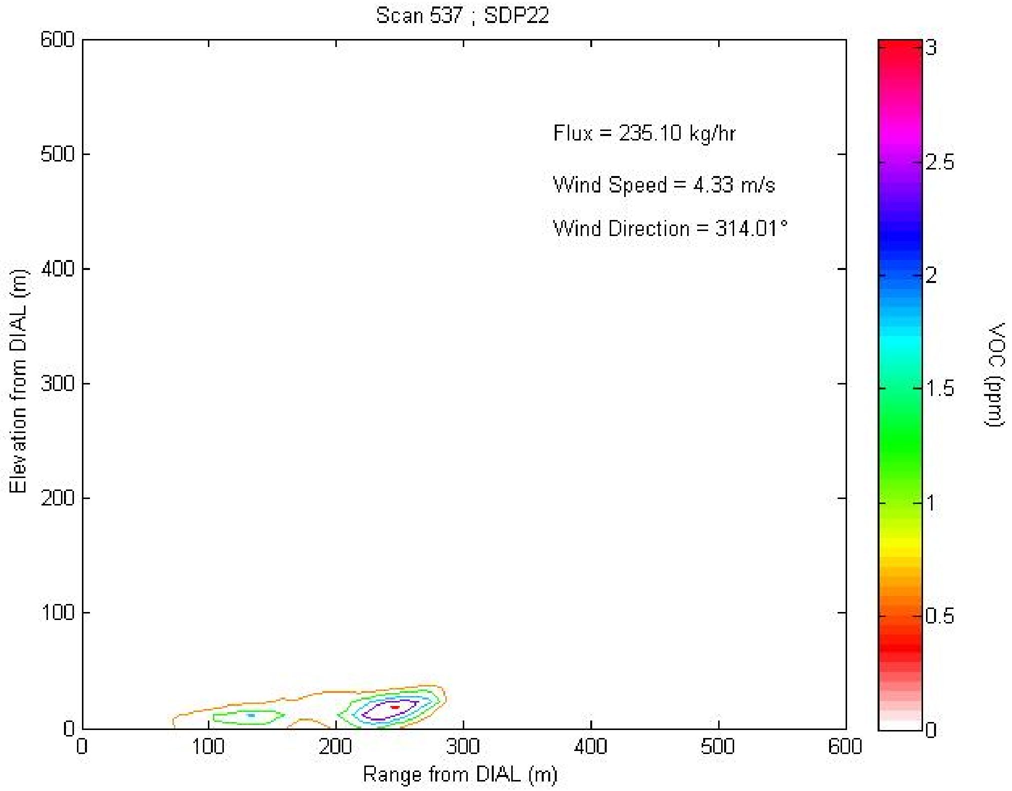

Figure 2.23a1 Contour plot of concentration profile for Scan 537 representing LOS1.

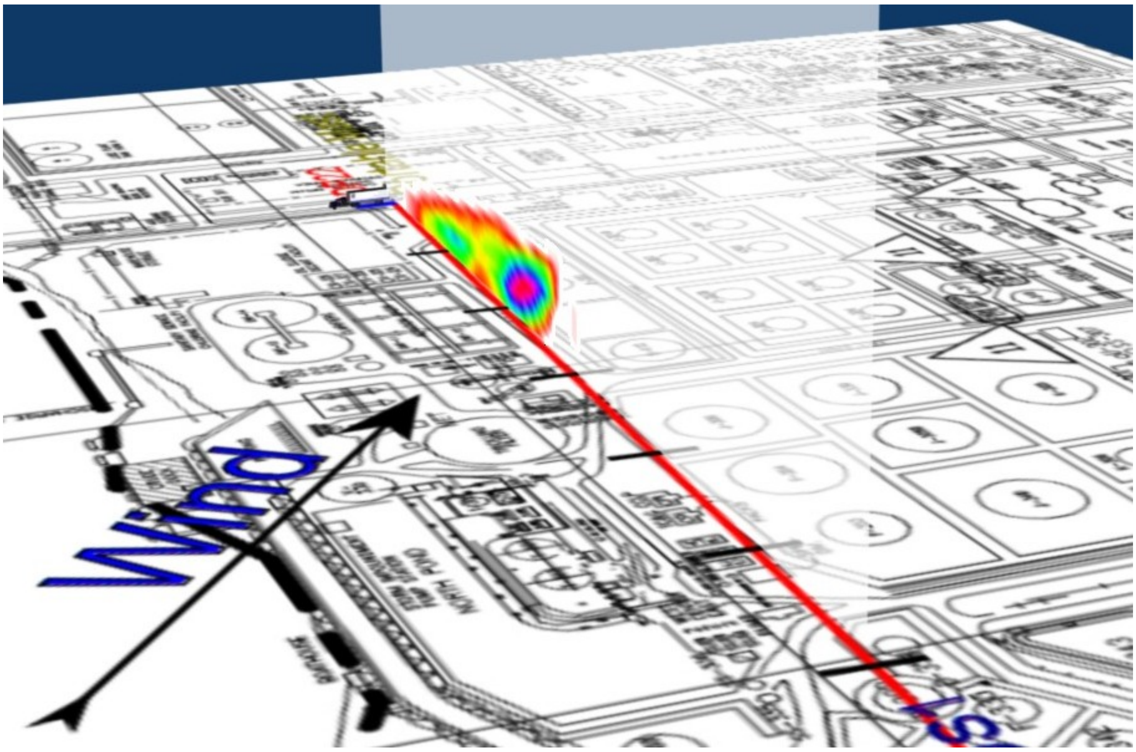

Figure 2.23a2 Visualisation of emission rate measured for Scan 537 representing LOS1.

Table 2.24 Emission rate measurements from SDP34 on 25th of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
803	SDP34/LOS1	10:53	11:11	7.9	303.7	36.75	Downwind of CR3
804	SDP34/LOS1	11:13	11:31	7.3	313.0	20.85	Downwind of CR3
805	SDP34/LOS1	11:32	11:50	7.3	306.7	30.23	Downwind of CR3
807	SDP34/LOS1	11:59	12:19	7.8	308.1	32.93	Downwind of CR3
808	SDP34/LOS1	12:19	12:37	7.7	299.5	21.78	Downwind of CR3
809	SDP34/LOS1	12:37	12:56	7.7	310.5	24.73	Downwind of CR3
810	SDP34/LOS2	13:02	13:20	7.3	307.9	2.84	Upwind of CR3
811	SDP34/LOS2	13:21	13:39	6.7	294.2	0.79	Upwind of CR3
812	SDP34/LOS2	13:39	13:58	7.0	315.5	1.68	Upwind of CR3
814	SDP34/LOS1	14:05	14:23	7.7	306.4	38.54	Downwind of CR3
815	SDP34/LOS1	14:23	14:42	7.4	313.6	35.09	Downwind of CR3
816	SDP34/LOS1	14:42	15:00	7.4	300.2	32.44	Downwind of CR3
817	SDP34/LOS2	15:03	15:21	6.5	305.0	1.89	Upwind of CR3
818	SDP34/LOS2	15:21	15:39	7.1	333.2	0.22	Upwind of CR3
819	SDP34/LOS2	15:39	15:58	7.7	305.6	2.64	Upwind of CR3
820	SDP34/LOS1	15:59	16:17	7.3	321.7	23.48	Downwind of CR3
821	SDP34/LOS1	16:17	16:36	8.0	303.8	22.18	Downwind of CR3
822	SDP34/LOS1	16:36	16:54	7.6	305.1	37.41	Downwind of CR3

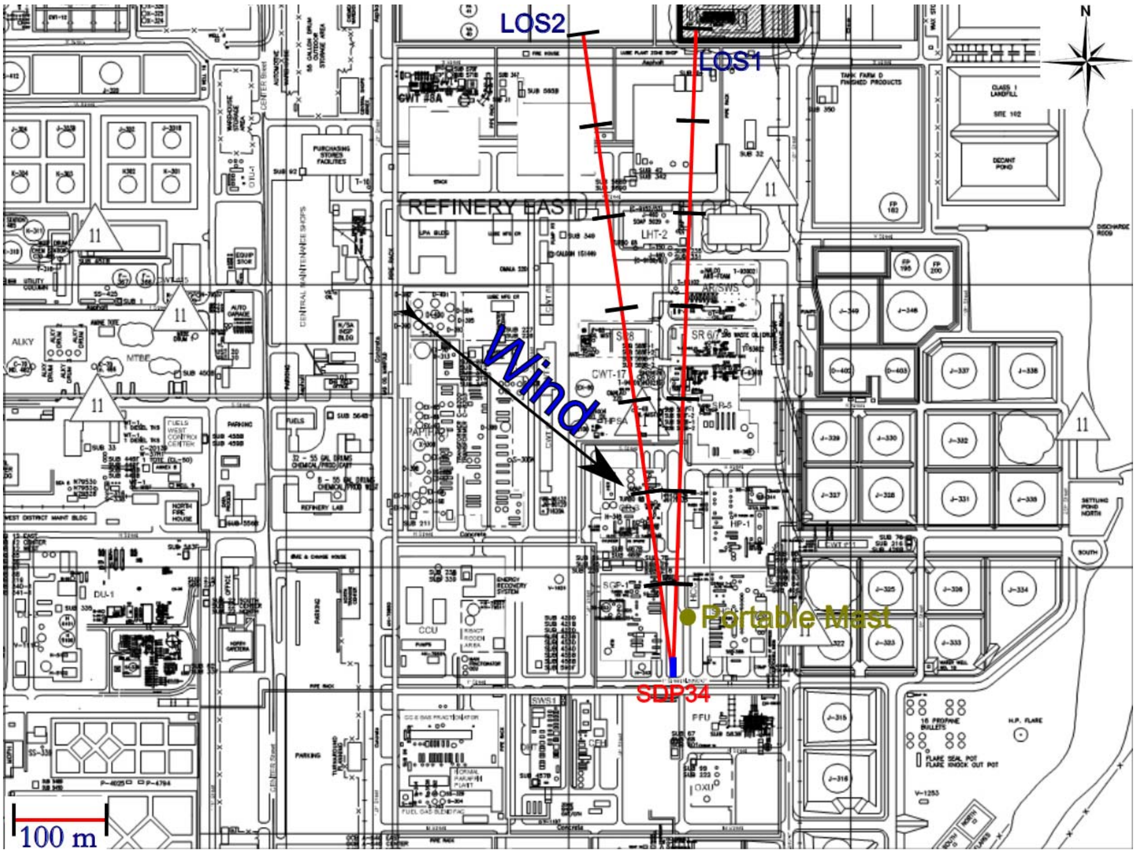

Figure 2.24 Measurement configuration for location SDP34 on 25th of March.

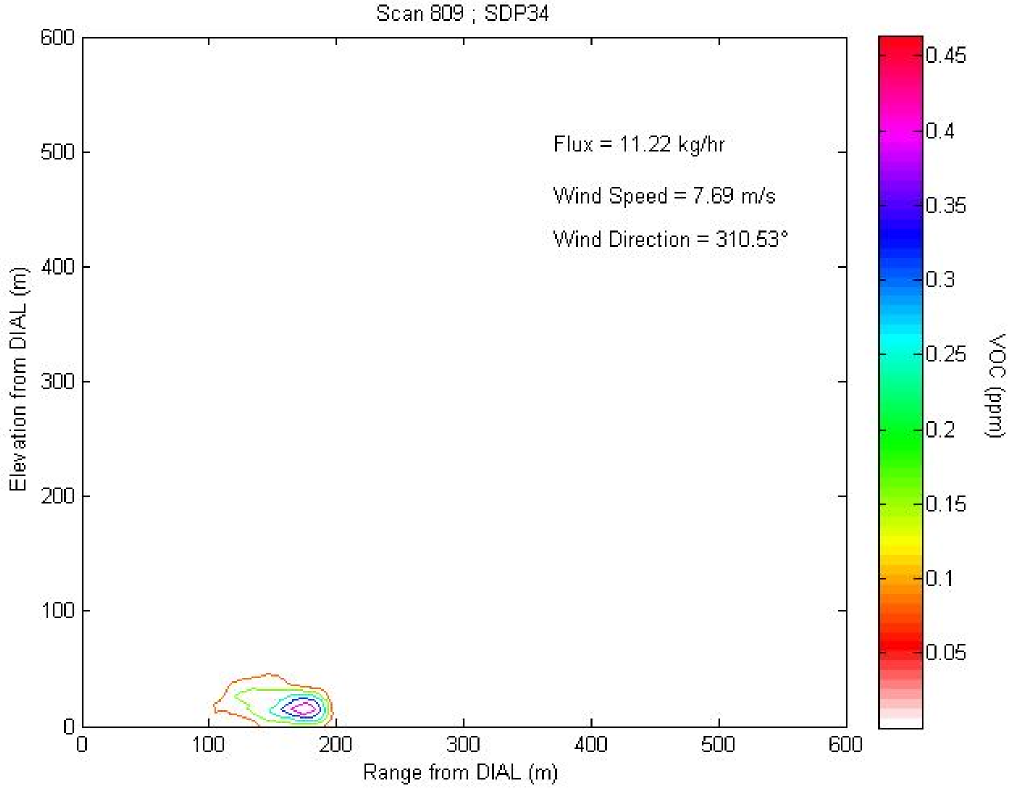

Figure 2.24a1 Contour plot of concentration profile for Scan 809 representing LOS1.

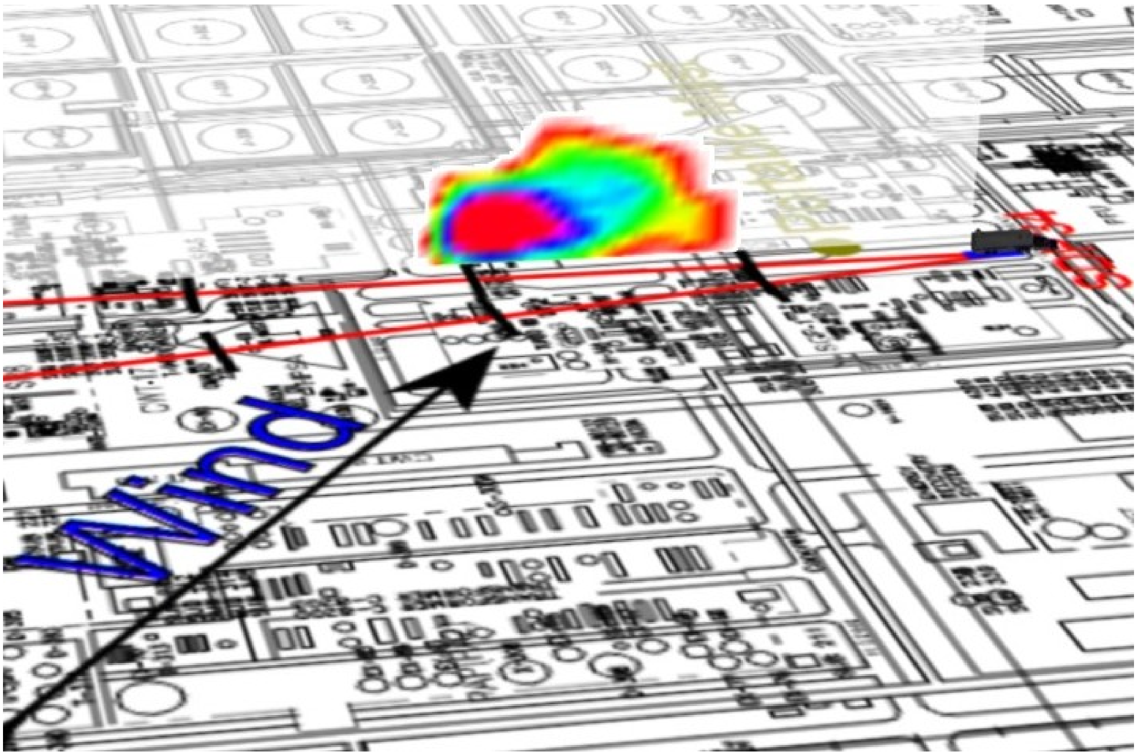

Figure 2.24a2 Visualisation of emission rate measured for Scan 809 representing LOS1.

Table 2.25 Emission rate measurements from SDP35 on 26th of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
824	SDP35/LOS1	10:53	11:12	2.8	10.3	65.29	Downwind of ACU & BEU
825	SDP35/LOS1	11:13	11:32	2.4	6.5	63.33	Downwind of ACU & BEU
826	SDP35/LOS1	11:32	11:51	2.5	17.9	57.29	Downwind of ACU & BEU
827	SDP35/LOS1	11:52	12:10	3.1	26.1	56.82	Downwind of ACU & BEU
829	SDP35/LOS1	12:17	12:35	2.5	50.6	68.97	Downwind of ACU & BEU
830	SDP35/LOS1	12:36	12:55	2.1	27.6	63.55	Downwind of ACU & BEU
831	SDP35/LOS1	12:55	13:13	1.8	12.3	70.09	Downwind of ACU & BEU
832	SDP35/LOS1	13:14	13:33	2.5	119.2	4.69	Downwind of ACU & BEU

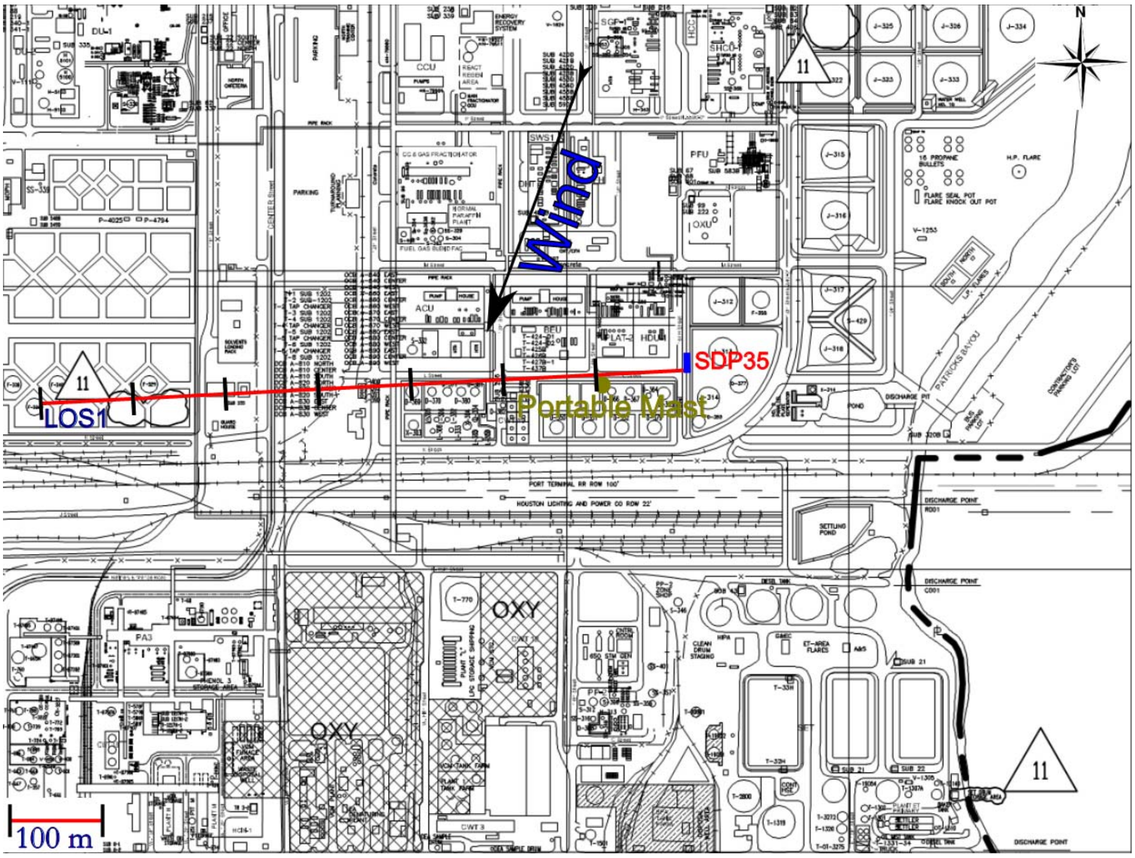

Figure 2.25 Measurement configuration for location SDP35 on 26th of March.

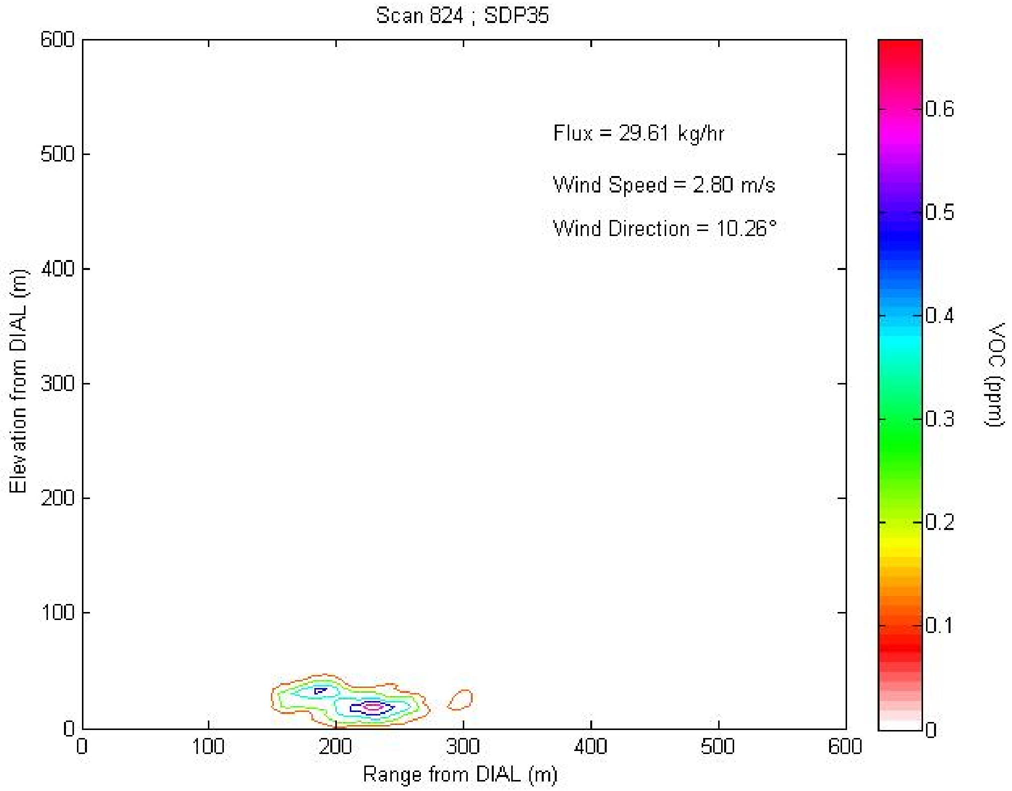

Figure 2.25a1 Contour plot of concentration profile for Scan 824 representing LOS1.

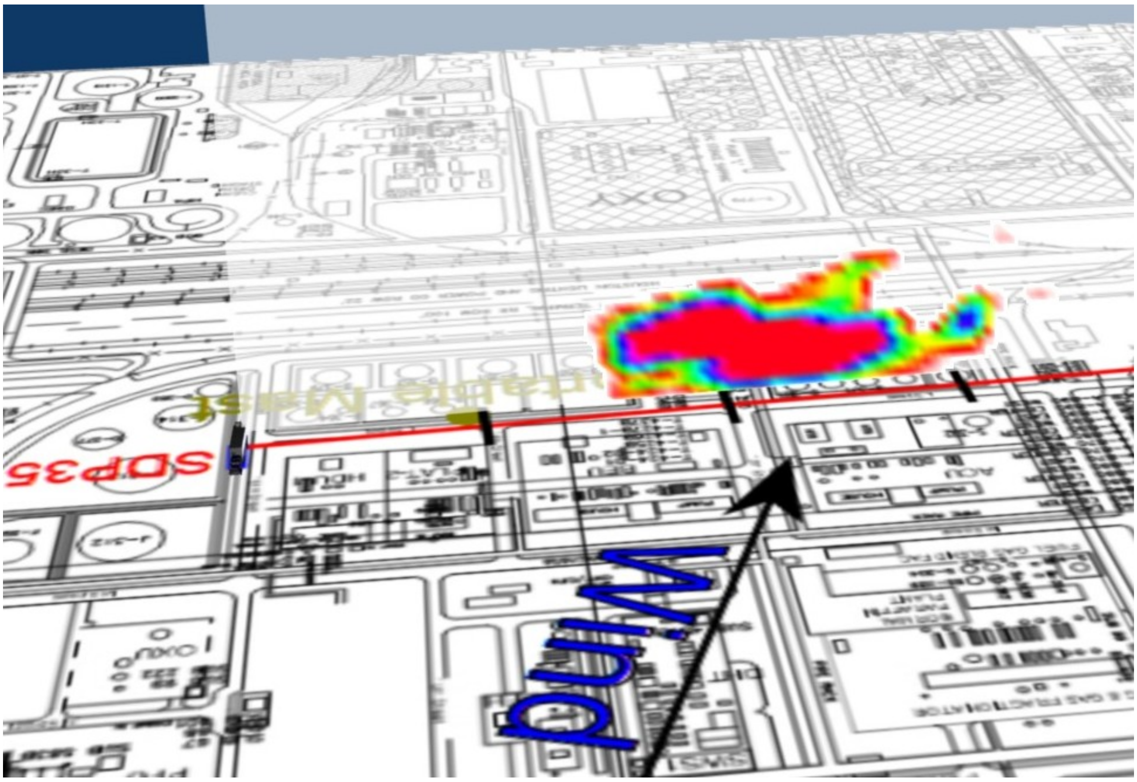

Figure 2.25a2 Visualisation of emission rate measured for Scan 824 representing LOS1.

Table 2.26 Emission rate measurements from SDP36 on 26th of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
833	SDP36/LOS1	14:38	14:56	2.5	138.5	61.74	Downwind of ACU & BEU
835	SDP36/LOS1	15:03	15:21	1.9	127.2	60.60	Downwind of ACU & BEU
836	SDP36/LOS1	15:22	15:40	1.9	110.6	65.25	Downwind of ACU & BEU
837	SDP36/LOS1	15:40	15:59	2.0	115.5	58.71	Downwind of ACU & BEU
838	SDP36/LOS1	16:00	16:18	2.1	127.6	67.36	Downwind of ACU & BEU
839	SDP36/LOS1	16:19	16:38	1.9	119.6	68.71	Downwind of ACU & BEU
840	SDP36/LOS1	16:38	16:56	2.2	119.7	72.21	Downwind of ACU & BEU
841	SDP36/LOS1	16:56	17:05	2.5	143.7	26.30	Downwind of ACU & BEU

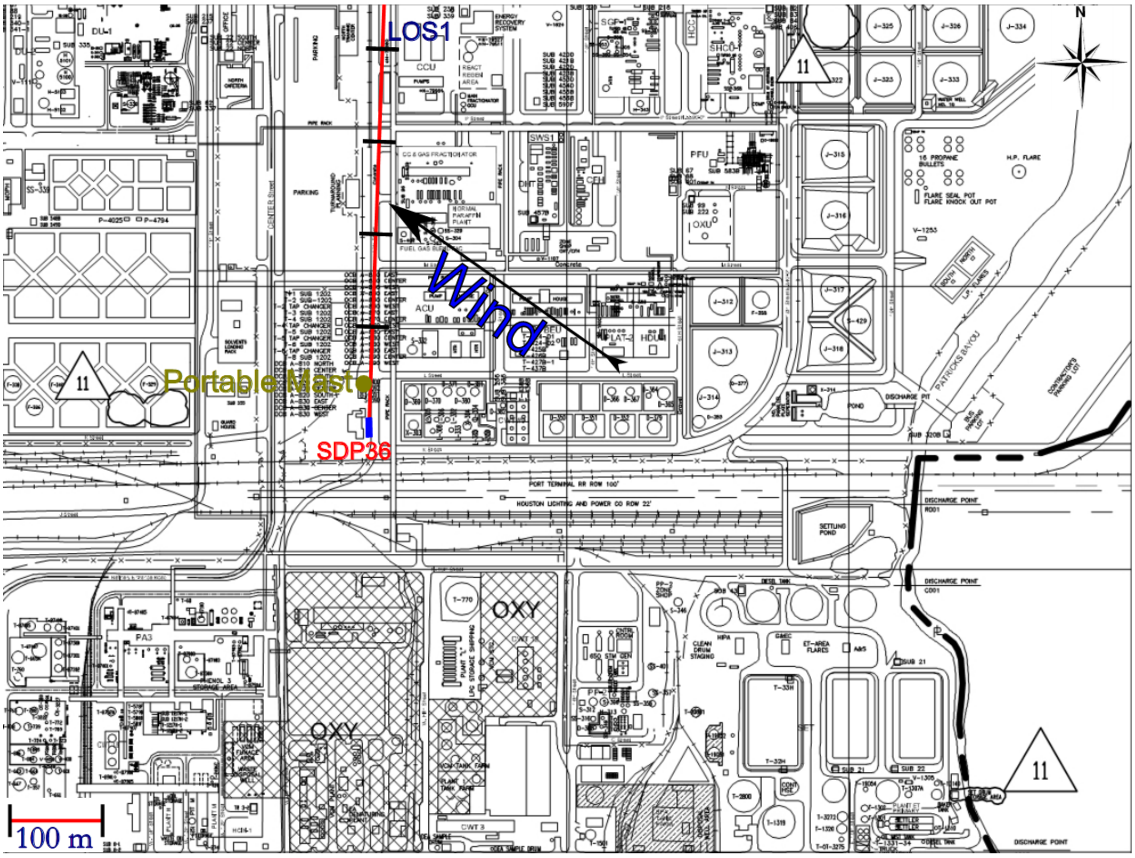

Figure 2.26 Measurement configuration for location SDP36 on 26th of March.

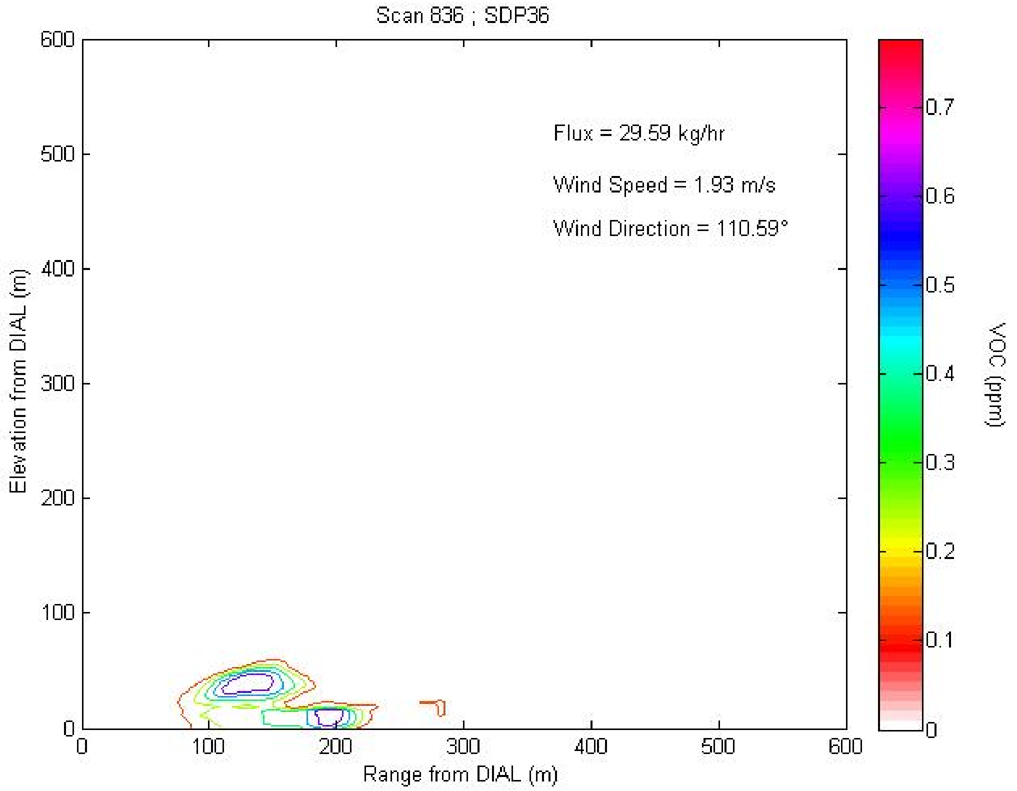

Figure 2.26a1 Contour plot of concentration profile for Scan 836 representing LOS1.

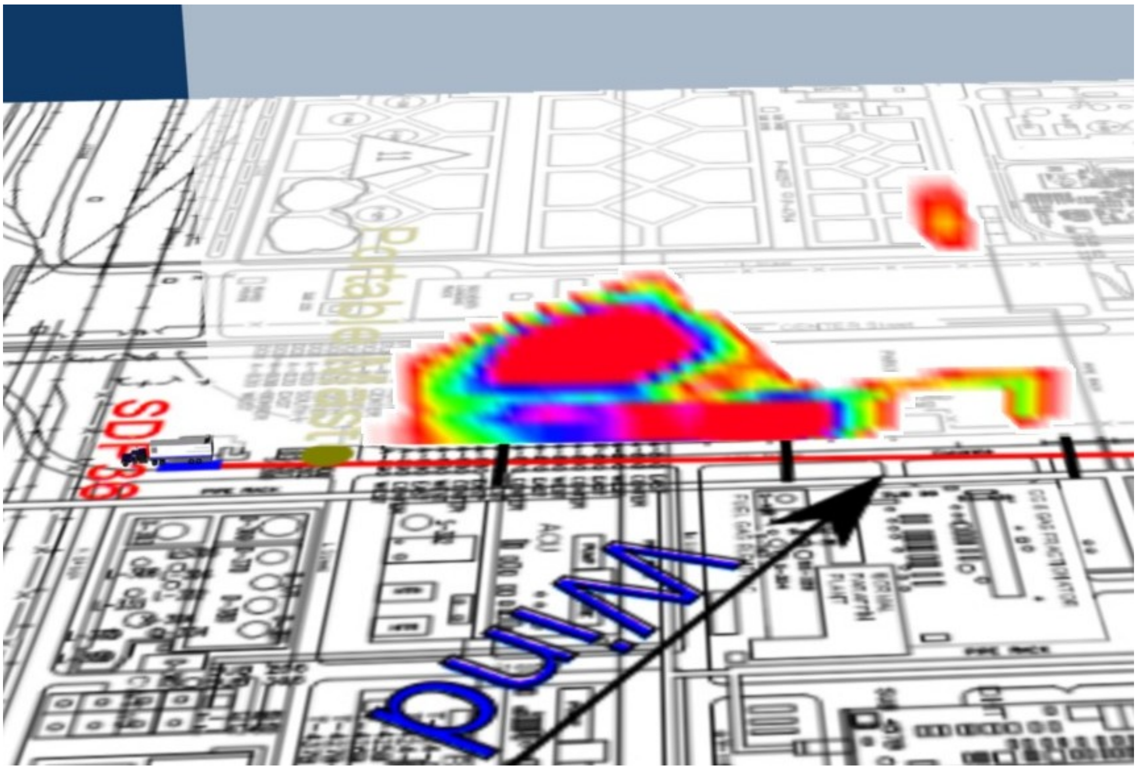

Figure 2.26a2 Visualisation of emission rate measured for Scan 836 representing LOS1.

Table 2.27 Emission rate measurements from SDP37 on 27th of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
843	SDP37/LOS1	09:58	10:08	3.7	216.0	2.50	Downwind of SW Coker Area
844	SDP37/LOS1	10:10	10:19	3.6	227.7	3.38	Downwind of SW Coker Area
845	SDP37/LOS1	10:19	10:29	5.0	214.7	2.86	Downwind of SW Coker Area
847	SDP37/LOS1	10:35	10:45	5.2	203.3	2.61	Downwind of SW Coker Area
848	SDP37/LOS1	10:45	10:55	4.9	211.8	2.59	Downwind of SW Coker Area
849	SDP37/LOS1	10:56	11:07	5.8	222.7	3.59	Downwind of SW Coker Area
850	SDP37/LOS1	11:08	11:18	5.8	213.6	3.36	Downwind of SW Coker Area
851	SDP37/LOS1	11:18	11:28	4.8	214.9	3.74	Downwind of SW Coker Area
852	SDP37/LOS2	11:31	11:40	5.4	209.4	0	Upwind of Coker
853	SDP37/LOS2	11:41	11:49	5.5	198.9	0.58	Upwind of Coker
854	SDP37/LOS2	11:50	11:58	5.6	198.3	0	Upwind of Coker
856	SDP37/LOS3	12:16	12:27	5.2	220.1	2.73	Downwind of Coker & GOHT
857	SDP37/LOS3	12:27	12:39	5.8	215.2	3.16	Downwind of Coker & GOHT
858	SDP37/LOS3	12:40	12:51	5.6	203.3	3.89	Downwind of Coker & GOHT
859	SDP37/LOS1	12:52	13:02	6.1	214.6	3.16	Downwind of SW Coker Area
860	SDP37/LOS1	13:03	13:13	5.7	215.5	1.60	Downwind of SW Coker Area
861	SDP37/LOS1	13:13	13:24	6.3	224.2	2.39	Downwind of SW Coker Area
863	SDP37/LOS1	13:30	13:41	6.4	222.2	3.16	Downwind of SW Coker Area
864	SDP37/LOS1	13:41	13:51	5.3	221.4	2.72	Downwind of SW Coker Area
865	SDP37/LOS3	13:51	14:03	6.2	221.2	4.74	Downwind of Coker & GOHT
866	SDP37/LOS3	14:04	14:15	5.3	217.7	2.95	Downwind of Coker & GOHT
867	SDP37/LOS3	14:16	14:28	4.5	216.7	3.40	Downwind of Coker & GOHT
868	SDP37/LOS3	14:28	14:40	4.9	217.5	4.44	Downwind of Coker & GOHT
869	SDP37/LOS3	14:40	14:52	5.4	215.1	4.55	Downwind of Coker & GOHT
870	SDP37/LOS3	14:53	15:17	4.8	210.9	5.22	Downwind of Coker & GOHT
871	SDP37/LOS3	15:17	15:40	4.8	210.4	3.14	Downwind of Coker & GOHT
872	SDP37/LOS3	15:41	16:04	6.8	208.5	3.86	Downwind of Coker & GOHT
873	SDP37/LOS3	16:04	16:28	6.5	208.6	4.42	Downwind of Coker & GOHT
874	SDP37/LOS3	16:28	16:51	6.3	210.5	4.69	Downwind of Coker & GOHT

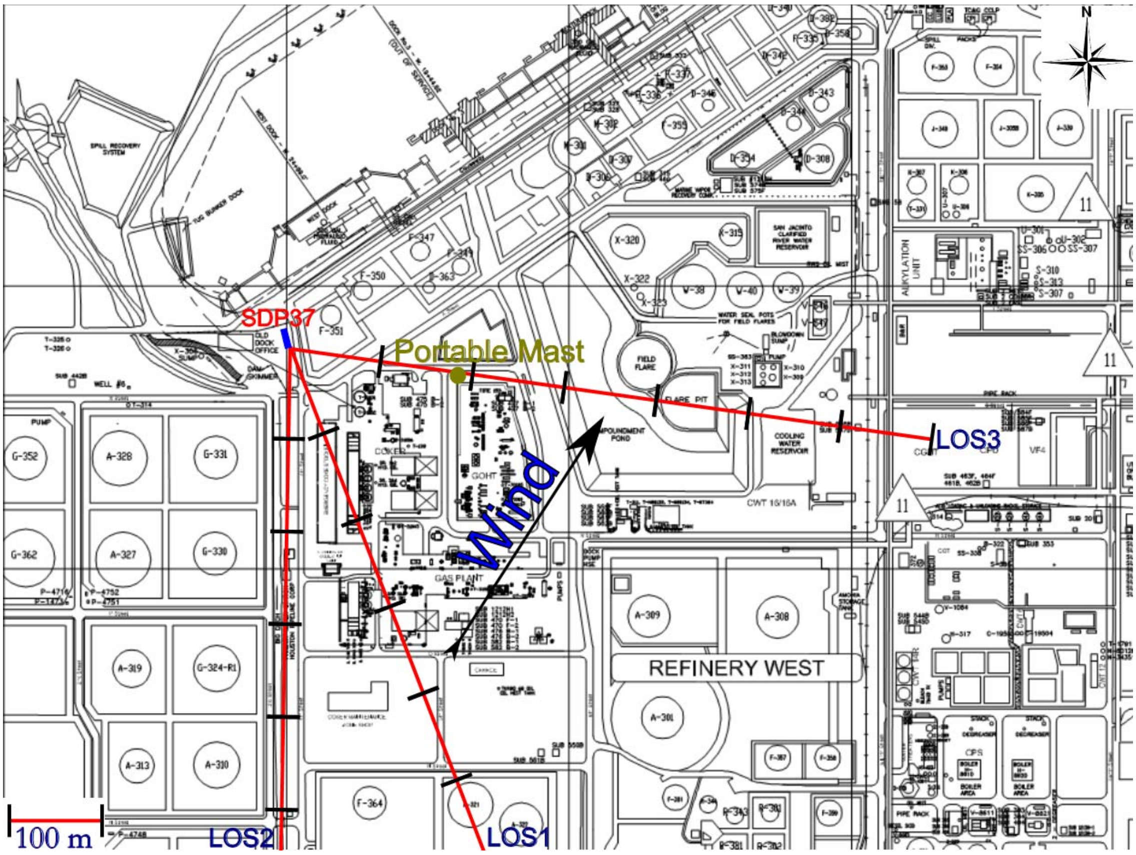

Figure 2.27 Measurement configuration for location SDP37 on 27th of March.

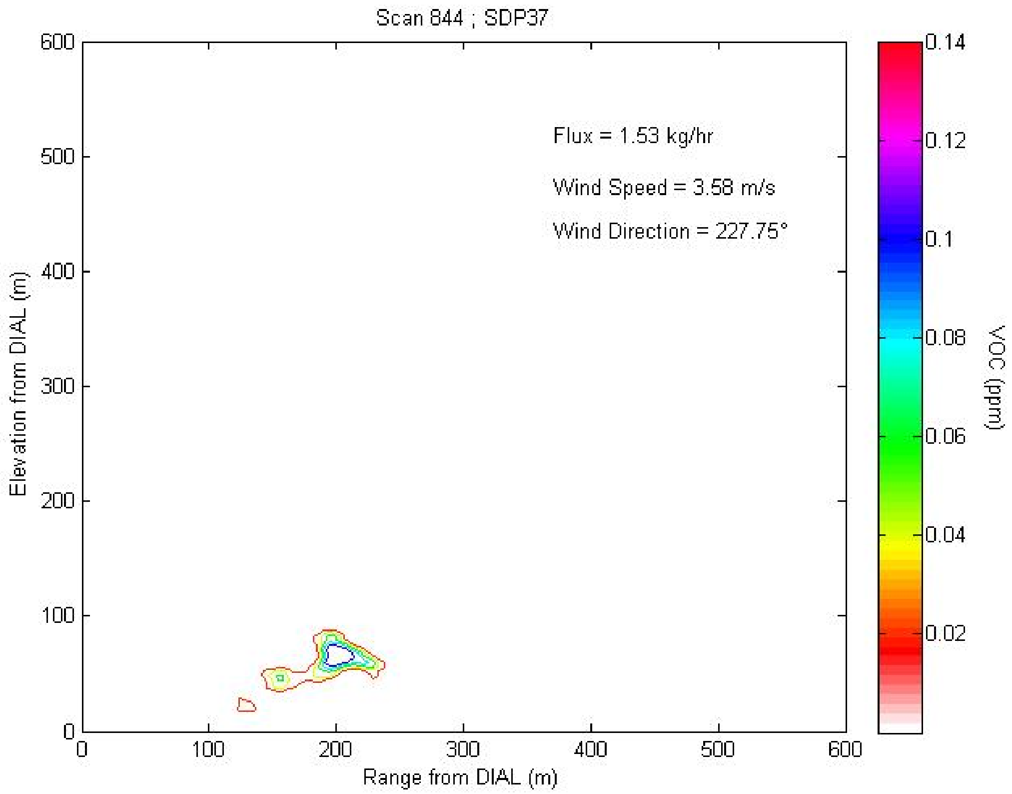

Figure 2.27a1 Contour plot of concentration profile for Scan 844 representing LOS1.

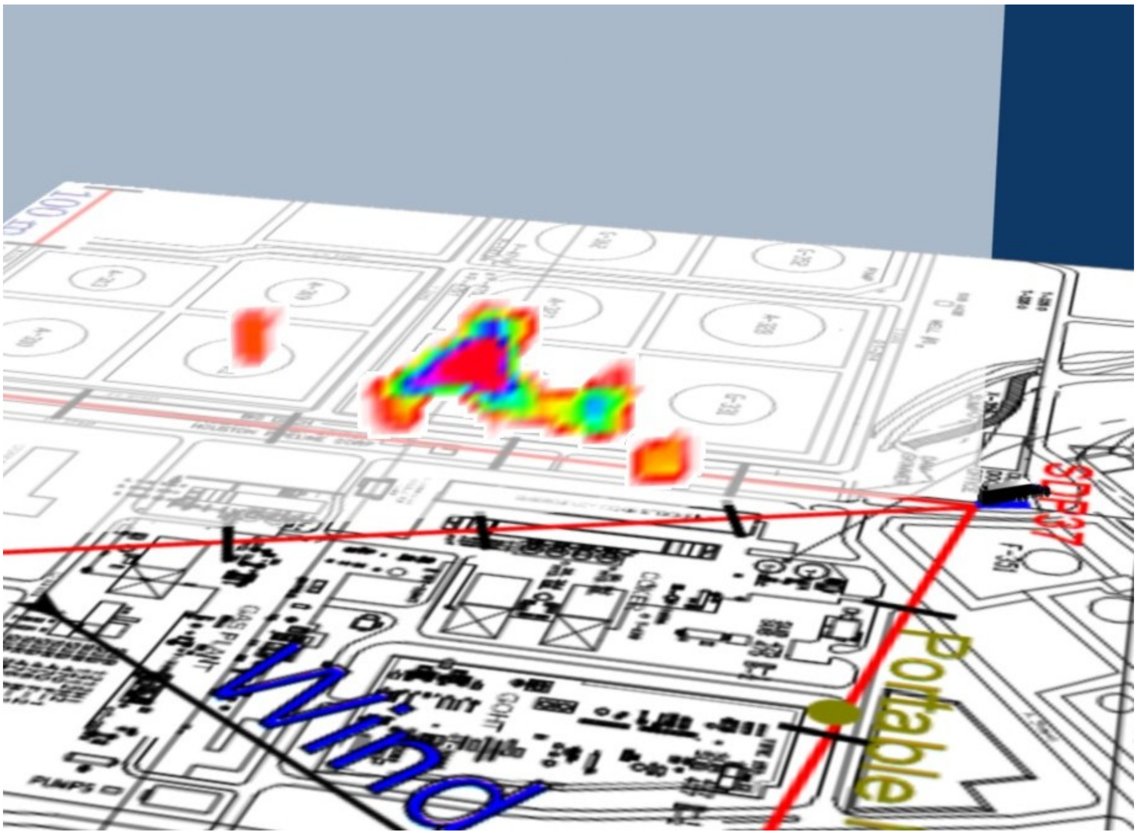

Figure 2.27a2 Visualisation of emission rate measured for Scan 844 representing LOS1.

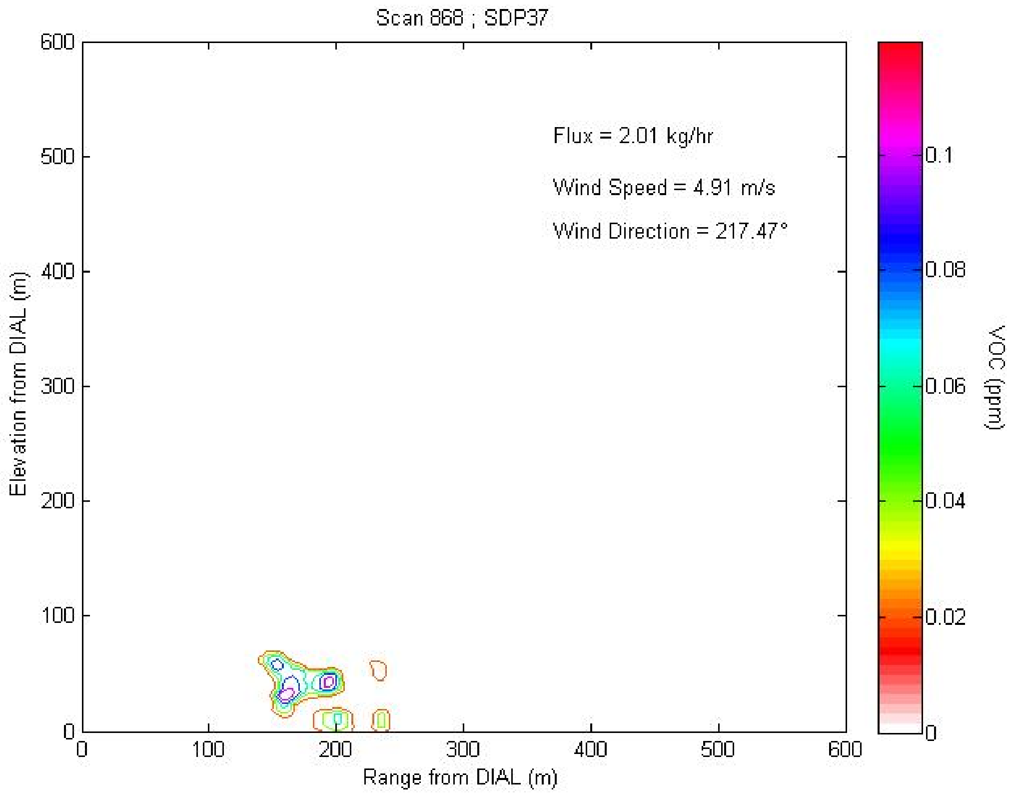

Figure 2.27b1 Contour plot of concentration profile for Scan 868 representing LOS3.

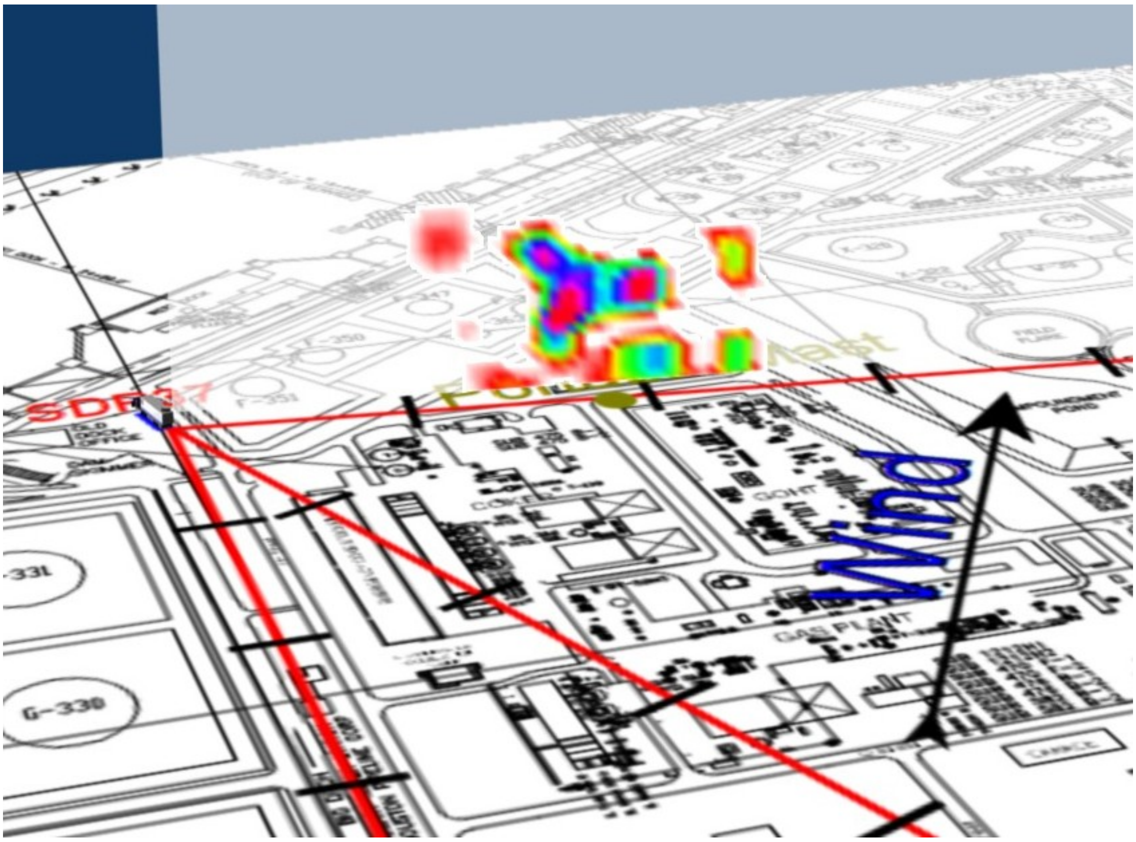

Figure 2.27b2 Visualisation of emission rate measured for Scan 868 representing LOS3.

Table 2.28 **Summary of VOC emission rate measurements.**
*** Scan 282 not included in the average, see text for explanation.**
**** Scans 507, 509 and 518 not included in the average, see text for explanation.**
***** Scan 832 not included in the average, see text for explanation.**
****** For single measurement it is not possible to provide the standard deviation, however, the typical uncertainty for a single measurement is about 20%.**

Date	Location/ LOS/ Figure	Notes	Elevation Angles	Average Flux	Standard Deviation
			degree	lbs/hr	lbs/hr
13-Jan	SDP01/LOS1/Fig 2.1	Downwind of SW Tanks	1 - 10	18.3	6.1
13-Jan	SDP01/LOS2/Fig 2.1	Downwind of SW Tanks	1 - 10	15.5	4.6
13-Jan	SDP01/LOS3/Fig 2.1	Downwind of SW Tanks	1 - 10	19.1	4.4
14-Jan	SDP02/LOS1/Fig 2.2	Downwind West Tanks	2.5 - 12.5	15.9	4.5
14-Jan	SDP02/LOS2/Fig 2.2	Downwind West Tanks	2 - 15	17.0	5.7
14-Jan	SDP02/LOS2/Fig 2.2	Downwind West Tanks - Event	2 - 15	4025.8	
15-Jan	SDP03/LOS1/Fig 2.3	Upwind SW AP Tanks	3 - 15	10.9	3.6
15-Jan	SDP03/LOS2/Fig 2.3	Downwind SW AP Tanks	2.5 - 14.5	61.8	15.9
15-Jan	SDP03/LOS3/Fig 2.3	Downwind SW AP Tanks	2.5 - 15	61.3	15.4
16-Jan	SDP04/LOS1/Fig 2.4	Downwind Coker + Flare	2.5 - 12.5	2.1	1.7
16-Jan	SDP04/LOS2/Fig 2.4	Downwind Coker + Flare	3 - 15	2.6	1.2
16-Jan	SDP04/LOS3/Fig 2.4	Downwind Tanks West of Coker	3 - 10	0.4	0.8
16-Jan	SDP04/LOS4/Fig 2.4	Downwind Coker	7 - 34	1.8	1.1
16-Jan	SDP04/LOS5/Fig 2.4	Downwind Coker + Flare	6 - 33	3.3	1.1
18-Jan	SDP05/LOS1/Fig 2.5	Downwind of Olefins Process Area	3.5 - 30	4.2	1.4
18-Jan	SDP05/LOS2/Fig 2.5	Downwind of Olefins Process Area	4 - 30	4.8	1.2
18-Jan	SDP05/LOS3/Fig 2.5	Downwind of Olefins Process Area	3 - 29	4.0	1.3
18-Jan	SDP05/LOS4/Fig 2.5	Background	4 - 28	0.2	0.9
19-Jan	SDP06/LOS1/Fig 2.6	Downwind of Olefins Process Area	3.5 - 29.5	4.3	1.5
19-Jan	SDP06/LOS2/Fig 2.6	Background	3.5 - 29.5	0.1	1.1
19-Jan	SDP06/LOS3/Fig 2.6	Downwind SW AP Tanks	3.2 - 15.2	42.6	5.0
19-Jan	SDP07/LOS1/Fig 2.7	Upwind of Olefins Process Area	4.2 - 31.2	0.0	0.8
20-Jan	SDP08/LOS1/Fig 2.8	Downwind of East Olefins Tanks	4.5 - 28.5	4.6	1.3
20-Jan	SDP08/LOS2/Fig 2.8	Downwind Area E of Olefins Tanks	2 - 15	0.9	0.3
20-Jan	SDP08/LOS3/Fig 2.8	Downwind of East Olefins Tanks	6 - 19	2.9	1.2
20-Jan	SDP08/LOS4/Fig 2.8	Downwind of SE Olefins Tanks	3.5 - 16.5	2.4	0.9
20-Jan	SDP08/LOS5/Fig 2.8	Downwind Area E of Olefins Tanks	5 - 26	0.3	0.5
21-Jan	SDP09/LOS1/Fig 2.9	Upwind of Refinery East Process	4 - 24	2.2	1.3
21-Jan	SDP09/LOS2/Fig 2.9	Downwind of CR3	4.3 - 26.3	8.2	2.1
21-Jan	SDP09/LOS3/Fig 2.9	Downwind of Refinery E Process	4.2 - 22.2	11.9	3.2
21-Jan	SDP09/LOS4/Fig 2.9	Downwind Aromatic Units	3 - 20	0	0.9
21-Jan	SDP09/LOS5/Fig 2.9	Downwind S Refinery E Process	1 - 17.5	2.1	1.0
22-Jan	SDP10/LOS1/Fig 2.10	Downwind of Flare	4 - 12	0.4	0.7
22-Jan	SDP10/LOS2/Fig 2.10	Upwind of Flare	1 - 15	0.2	0.7
22-Jan	SDP10/LOS3/Fig 2.10	Downwind of East Tanks	3.5 - 21.5	30.6	7.8
22-Jan	SDP10/LOS4/Fig 2.10	Upwind of East Tanks	1.5 - 16.5	0.0	0.7
23-Jan	SDP11/LOS1/Fig 2.11	Downwind of E of East Tanks	3 - 15	4.7	1.0
23-Jan	SDP11/LOS2/Fig 2.11	Downwind of W of East Tanks	3 - 25	18.8	3.6
23-Jan	SDP11/LOS3/Fig 2.11	Downwind of Refinery E Process	1 - 25	5.3	1.2
25-Jan	SDP12/LOS1/Fig 2.12	Downwind of Wastewater	1 - 15	22.1 *	5.2
25-Jan	SDP12/LOS2/Fig 2.12	Downwind of Wastewater	4 - 15	1.9	0.2

25-Jan	SDP12/LOS3/Fig 2.12	Upwind J-3018 and K-301 Tanks	4 - 15	0.5	0.6
26-Jan	SDP13/LOS1/Fig 2.13	Upwind of Flare	3 - 20	0	0.3
26-Jan	SDP13/LOS2/Fig 2.13	Downwind of Flare	15 - 20	1.3	0.1
26-Jan	SDP13/LOS3/Fig 2.13	Downwind of S of East Tanks	6 - 16	0.3	0.2
27-Jan	SDP14/LOS1/Fig 2.14	Downwind of Dock Area	2 - 10	8.5	2.0
27-Jan	SDP14/LOS2/Fig 2.14	Downwind of NE of Coker Area	2 - 15	1.1	0.7
27-Jan	SDP14/LOS3/Fig 2.14	Downwind of SW of Coker Area	4.5 - 13.5	1.5	0.7
27-Jan	SDP14/LOS4/Fig 2.14	Downwind of Dock Area	2 - 10	9.0	0.9
28-Jan	SDP15/LOS1/Fig 2.15	Downwind of East Tanks	0.8 - 15	33.3	7.4
28-Jan	SDP15/LOS2/Fig 2.15	Downwind of East Tanks	0.5 - 11.5	32.0	4.6
28-Jan	SDP15/LOS3/Fig 2.15	Downwind of Refinery E Process	4 - 16	42.4	6.8
28-Jan	SDP15/LOS4/Fig 2.15	Downwind of Refinery E Process	7 - 15	39.5	7.1
29-Jan	SDP16/LOS1/Fig 2.16	Downwind Olefins OP-2 Flare	11 - 36	0.0	0.8
29-Jan	SDP16/LOS2/Fig 2.16	Downwind Olefins Ground Flare	10 - 20	0	0.9
30-Jan	SDP12/LOS1/Fig 2.17	Further Downwind of Wastewater	0 - 8	767.4	100.1
30-Jan	SDP12/LOS2/Fig 2.17	Downwind of Wastewater	0 - 8	1180.5	214.7
30-Jan	SDP12/LOS3/Fig 2.17	Upwind of Wastewater	2.5 - 8.5	0.2	0.8
30-Jan	SDP12/LOS4/Fig 2.17	Upwind of Wastewater	2.5 - 8.5	0.2	0.1
30-Jan	SDP12/LOS5/Fig 2.17	Downwind of Wastewater	0 - 9	1193.6	197.9
30-Jan	SDP12/LOS6/Fig 2.17	Further Downwind of Wastewater	0 - 10	798.2	151.6
1-Feb	SDP17/LOS1/Fig 2.18	Downwind of East Wastewater	3 - 17	25.7	4.2
1-Feb	SDP17/LOS2/Fig 2.18	Downwind of East Wastewater	3 - 23	23.3	4.4
1-Feb	SDP17/LOS3/Fig 2.18	Downwind of Flare	7 - 12	1.0	0.7
1-Feb	SDP17/LOS4/Fig 2.18	Upwind of Flare	7 - 12	1.0	0.3
1-Feb	SDP17/LOS5/Fig 2.18	Downwind of East Wastewater	4 - 20	27.2	6.4
2-Feb	SDP18/LOS1/Fig 2.19	Downwind Flare	3.5 - 8	0.5	0.4
2-Feb	SDP18/LOS2/Fig 2.19	Downwind Flare	4.5 - 12.5	0.2	0.5
3-Feb	SDP19/LOS1/Fig 2.20	Downwind of East Olefins	2.5 23.5	2.7	1.0
4-Feb	SDP20/LOS1/Fig 2.21	Downwind of Coker	0 - 26	3.7	1.4
4-Feb	SDP20/LOS2/Fig 2.21	Downwind of Coker	0.5 - 25.5	3.2 **	1.0
4-Feb	SDP20/LOS3/Fig 2.21	Upwind of Coker	3 - 29	1.2	0.9
5-Feb	SDP21/LOS1/Fig 2.22	Downwind of Wastewater	2.5 - 12.5	544.2	124.9
5-Feb	SDP21/LOS2/Fig 2.22	Downwind of Wastewater	3.5 - 14	610.7	44.1
5-Feb	SDP22/LOS1/Fig 2.23	Downwind of Wastewater	1.5 - 17	412.8	89.7
25-Mar	SDP34/LOS1/Fig 2.24	Downwind of CR3	0 - 15	29.7	6.7
25-Mar	SDP34/LOS2/Fig 2.24	Downwind of CR3	4.5 14.5	1.7	1.0
26-Mar	SDP35/LOS1/Fig 2.25	Downwind of ACU & BEU	1 - 19	63.6 ***	5.2
26-Mar	SDP36/LOS1/Fig 2.26	Downwind of ACU & BEU	2.5 - 18	64.9	4.8
27-Mar	SDP37/LOS1/Fig 2.27	Downwind of SW Coker Area	11 - 26	2.9	0.6
27-Mar	SDP37/LOS2/Fig 2.27	Upwind of Coker	3 - 25	0.1	0.5
27-Mar	SDP37/LOS3/Fig 2.27	Downwind of Coker & GOHT	1.5 - 30	3.9	0.8

The calculations of the VOC emission rate from the different measured areas are described in the following sections.

2.1 MEASUREMENTS OF THE SW TANKS

- SDP01 on the 13th January, SE wind, Table and Figure 2.1.

- LOS1 18.3 lbs/hr, LOS2 15.5 lbs/hr, LOS3 19.1 lbs/hr (see Table 2.28).
- Figures 2.1a1 and a2 visual representation of Scan 12 (LOS1).

The main emission rate is just beyond 200 m from the DIAL suggesting that any of the tanks A-333, A-331, A-330 and A-329 could be the main source of emission. Tank A-332 is also a possible emission source since some of its potential emission could pass north of tank A-333. In theory tank AP-19 is a possible emission source but data from SDP03 show no emission from this tank. The overall emission rate from these tanks can be calculated by averaging the emission rates determined for LOS1, LOS2 and LOS3. The resulting emission rate is 18.0 ± 5.6 lbs/hr

- SDP03 on the 15th January, NE wind, Table and Figure 2.3.

- LOS1 10.9 lbs/hr, LOS2 61.0 lbs/hr, LOS3 61.3 lbs/hr (see Table 2.28).
- Figures 2.3a1, a2, b1, b2, c1 and c2 visual representation of Scans 65 (LOS1), 73 (LOS2) and 77 (LOS3).

The emission plume for LOS1 is in the region 200 - 300 m from the DIAL. Tanks A-325 and A-326 could be the source of emission. The emission source could also be upwind of the tanks although this is less likely considering the width of the measured plume and the fact that other potential sources are farther away from LOS1.

For LOS2 the emission is mainly in the region 200 - 300 m from the DIAL and it includes the upwind emission measured from LOS1. Tanks AP-17 and AP-16 are the likely emission sources, the average emission rate is 50.9 ± 16.4 lbs/hr calculated by subtracting the upwind emission rate measured from LOS1 from the emission from LOS2.

The emission from LOS3 is similar to the emission from LOS2. The overall emission rate from tanks AP-17 and AP-16 can be calculated by averaging the emission rates determined for LOS2 and LOS3 and subtracting the upwind sources measured from LOS1. The resulting emission rate is 50.7 ± 14.9 lbs/hr.

- SDP06/LOS3 on the 19th January, Southerly wind, Table and Figure 2.6.

- LOS3 42.6 lbs/hr (see Table 2.28).
- Figures 2.6a1 and a2 visual representation of Scan 157 (LOS3).

The emission sources measured from SDP06/LOS3 should be similar to the sources measured from SDP03/LOS2 and SDP03/LOS3 apart from tank AP-16 that is not measured from SDP06/LOS3, since any emission from tank AP-16 would be too close to the DIAL position. The measurements from SDP03/LOS2 and SDP03/LOS3 also include any eventual emission upwind of tanks A-325 and A-326, which are not included in measurements from SDP06/LOS3. Hence, we observe decreased emission rate for SDP06/LOS3 compared to SDP03/LOS2 and SDP03/LOS3.

2.2 MEASUREMENTS OF THE WEST TANKS

- SDP02 on the 14th January, easterly wind, Table and Figure 2.2.

- LOS1 15.9 lbs/hr, LOS2 17.0 lbs/hr, LOS2 Event 4025.8 lbs/hr (see Table 2.28).
- Figures 2.2a1, a2, b1, b2, c1 and c2 visual representation of Scan 39 (LOS1), Scan 44 (LOS2) and Scan 52 (LOS2 Event).

The emission for LOS1 is in the region 250 - 350 m from the DIAL suggesting that tanks A-310, A-319 and G-324-R1 could be the source of emission. The emission source could also be upwind of the tanks although this is less likely considering the width of the measured plume and the fact that other potential sources are further away from LOS1.

For LOS2 the emission rate is mainly in the 200 - 350 m region. All the tanks from AP-1 to AP-6 are possible sources of emission. Emission from tanks AP-7 and AP-8 would be beyond the 350 m range and therefore not detected. A strong emission event at about 100 m is observed in Scan 52, see Figures 2.2c1 and c2. This is probably related to the work that was being carried out on tank A-318.

- SDP04/LOS3 on the 16th January, NW wind, Table and Figure 2.4.

\- LOS3 0.4 lbs/hr (see Table 2.28).

Whilst above the detection limit and therefore real, the emission for tank A-319 is very low and hence considered negligible. Tank A-319 is therefore not considered a major source of emission. Any emission from tank G-324-R1 is not detected since it is too close to the DIAL.

2.3 MEASUREMENTS OF THE COKER AND DOCK AREA

- SDP04 on the 16th January, NW wind, Table and Figure 2.4.

\- LOS1 2.1 lbs/hr, LOS2 2.6 lbs/hr, LOS4 1.8 lbs/hr, LOS5 3.3 lbs/hr (see Table 2.28).
\- Figures 2.4a1, a2, b1 and b2 representation of Scans 84 (LOS1) and 108 (LOS4).

The emissions for LOS1, LOS2 and LOS5 are consistently low and show a relatively high standard deviation. As can be seen in Figures 2.4a1 and a2 there are two emission plumes, one at about 200 m and the other approximately 300 - 400 m from the DIAL. The Coker is the most likely emission source.
For LOS4 the emission rate is lower and localized just below 200 m. This emission could be associated with the southern Coker drums 5 and 6.

- SDP14 on the 27th January, SE wind, Table and Figure 2.14.

\- LOS1 8.5 lbs/hr, LOS2 1.1 lbs/hr, LOS3 1.5 lbs/hr, LOS4 9.0 lbs/hr (see Table 2.28).
\- Figures 2.14a1 and a2 visual representation of Scan 332 (LOS1).

The emissions for LOS2 and LOS3 are close to the detection limit. Considering the wind direction and the DIAL position, most of the possible Coker emission would blow towards the DIAL. It is possible that LOS2 catches some emission from the NE part of the Coker area while LOS3 catches some of the emission from the Coker drums 5 and 6 area. Overall these measurements are consistent with the previous measurements from SDP04.

The plume measured from LOS1 is in the region 200 - 250 m from the DIAL and it is consistent with the emission rate measured from LOS4. The West Dock area and tanks D-363, F-347 and F-349 are possible sources for this emission.

- SDP20 on the 4th February, easterly variable wind, Table and Figure 2.21.

\- LOS1 3.7 lbs/hr, LOS2 3.2 lbs/hr, LOS3 1.2 lbs/hr (see Table 2.28).
\- Figures 2.21a1 and a2 visual representation of Scan 513 (LOS2).

The emissions from LOS1 and LOS2 are consistent with each other and localized at 200 m from the DIAL. This is consistent with an emission from the southern Coker drums 5 and 6. In the averaging of the measurements from LOS2, Scans 507, 509 and 518 are not included because the wind is from north and almost parallel to LOS2.

The two measurements from LOS3 are intended to provide an upwind emission rate measurement for these scans of the Coker area. Unfortunately the wind is very variable, for Scan 512 it is almost parallel to LOS3 while for Scan 511 it is from the north.

- SDP37 on the 27th March, SW wind, Table and Figure 2.27.

\- LOS1 2.9 lbs/hr, LOS2 0.1 lbs/hr, LOS3 3.9 lbs/hr (see Table 2.28).
\- Figures 2.27a1, a2, b1 and b2 representation of Scans 844 (LOS1) and 863 (LOS3).

The emission plume for LOS1 is at about 200 m from the DIAL, consistent with emissions from the southern Coker drums 5 and 6.

Given the respective standard deviations the same emission is observed for LOS1 and LOS3. The plume measured from LOS3 is located just below 200 m and is therefore the same source measured from LOS1. These measurements show no appreciable emission from the GOHT area.

For scans from LOS2 an analysis range of 100 - 300 m from the DIAL is chosen in order to have an upwind measurement of the Coker area. No upwind emission is observed.

All the measurements of the Coker area show low emissions and that is consistent with the emission measured from the SW Coker area where drums 5 and 6 are located.

2.4 MEASUREMENTS OF OLEFINS PROCESS AREA

- SDP05 on the 18th January, SSE wind, Table and Figure 2.5.

\- LOS1 4.2 lbs/hr, LOS2 4.8 lbs/hr, LOS3 4.0 lbs/hr, LOS4 0.2 lbs/hr (see Table 2.28).
\- Figures 2.5a1 and a2 visual representation of Scan 115 (LOS1).

The emissions from LOS1, LOS2 and LOS3 show similar values and are localized at about 200 m from the DIAL. The Analyzer House U Vent (LO3AHU), the Analyzer House T Vent (LO3AHT) and the LO3 Unit (LO3FUG) are possible emission sources. The emission rate calculated by averaging all the measurements from LOS1, LOS2 and LOS3 is 4.4 ± 1.3 lbs/hr.

Scans from LOS4 are background measurements showing no emission.

- SDP06 on the 19th January, SSW wind, Table and Figure 2.6.

\- LOS1 4.3 lbs/hr, LOS2 0.1 lbs/hr (see Table 2.28).
\- Figures 2.6a1 and a2 visual representation of Scan 145 (LOS1).

The emission measured at LOS1 is similar to that found from SDP05. The plume is located just before 300 m from the DIAL and it is the same plume observed from SDP05 but shifted due to the different wind direction. The Analyzer House U Vent (LO3AHU), the Analyzer

House T Vent (LO3AHT) and the LO3 Unit (LO3FUG) are possible emission sources. The average emission rate is 4.3 ± 1.5 lbs/hr as reported in Table 2.27.

Scans from LOS2 are background measurements showing no emission.

• SDP07 on the 19th January, SSW wind, Table and Figure 2.7.
- LOS1 0.0 lbs/hr (see Table 2.28).

Measurements from LOS1 are upwind of all the potential emission sources. No emission is detected confirming that the emission observed from SDP05 and SDP06 is coming from the area nearby the Analyzer House U Vent (LO3AHU), the Analyzer House T Vent (LO3AHT) and the LO3 Unit (LO3FUG).

2.5 MEASUREMENTS OF OLEFINS TANKS AREA

• SDP08 on the 20th January, SSE wind, Table and Figure 2.8.
- LOS1 4.6 lbs/hr, LOS2 0.9 lbs/hr, LOS3 2.9 lbs/hr, LOS4 2.4 lbs/hr, LOS5 0.3 lbs/hr (see Table 2.28).
- Figures 2.8a1, a2, b1 and b2 visual representation of Scans 176 (LOS1) and 193 (LOS4).

The emission from LOS4 is a relatively low value and similar to the emission measured from LOS3. The emission plume is in the region 200 - 300 m from the DIAL (Figure 2.8b) indicating tanks G-332 and G-361 are possible sources. It is also possible that the emission source is upwind of these tanks, such as the OP2 and OP3 flares, although measurements from SDP16 showed no emission from the ground (OP3GRFLA) and elevated flares (OP3ELFLA and OP2ELFLA).

The emission from LOS1 is slightly higher than the emission rate measured from LOS3 and LOS4 although the emission rates are similar if the standard deviation associated with the measurements is taken into consideration. Tanks R-311 and R-312 are the only possible sources measured from LOS1 that are not measured from LOS3.

Scans from LOS2 and LOS5 measure the area east of the Olefins tanks. No appreciable emission is detected above the DIAL detection limit.

• SDP16 on the 29th January, NW wind, Table and Figure 2.16.
- LOS1 0.0 lbs/hr, LOS2 -0.3 lbs/hr (see Table 2.28).

The emissions for LOS1 and LOS2 are close to the DIAL detection limit and the very low values are considered negligible. A single scan from LOS3 also shows no emission. The target of the measurements were the OP3 Ground Flare (OP3GRFLA), OP3 Elevated Flare (OP3ELFLA) and OP2 Elevated Flare (OP2ELFLA). The line-of-sights were selected to avoid the steam in the local area.

• SDP19 on the 3rd February, east wind, Table and Figure 2.20.
- LOS1 2.7 lbs/hr (see Table 2.28).
- Figures 2.20a1 and a2 visual representation of Scan 487 (LOS1).

The emission plume is in the 200 - 300 m region. The emission source is most likely in the area called “TANK FARM B” or a source farther upwind of this facility, including the following tanks: T3, T4, T216, T89, T181, T185B, T73C, T69C, T3150, T77B, T198, T189, T188, T344 and T8B.

2.6 MEASUREMENTS OF THE EAST TANKS AND FLARE

- SDP10 on the 22nd January, SE wind, Table and Figure 2.10.

- LOS1 0.0 lbs/hr, LOS2 0.2 lbs/hr, LOS3 30.6 lbs/hr, LOS4 0.0 lbs/hr (see Table 2.28).
- Figures 2.10a1 and a2 visual representation of Scan 247 (LOS3).

The emissions from LOS1, LOS2 and LOS4 are very low and therefore considered negligible. LOS2 is an upwind measurement of the East Property Flare (EP Flare) showing that no emission is coming from the east boundary of the site. LOS1 is a downwind measurement of the flare. LOS4 provides an upwind measurement for LOS3.

For LOS3 the emission rate is mainly in the region 250 - 300 m from the DIAL. All the tanks from J-327 to J-332 are possible sources of emission.

- SDP11 on the 23rd January, SE wind, Table and Figure 2.11.

- LOS1 4.7 lbs/hr, LOS2 18.8 lbs/hr, LOS3 5.3 lbs/hr (see Table 2.28).
- Figures 2.11a1 and a2 visual representation of Scan 263 (LOS2).

The emissions measured the 22nd January from SDP10/LOS3 from tanks J-327 to J-332 are blowing towards the DIAL at the location SDP11. Some of the emission is detected from LOS1 and some from LOS2 for a total emission rate of 23.5 ± 3.7 lbs/hr. This emission rate is lower than the emission rate measured from SDP10/LOS3 as some of the emission passing close to the DIAL may not have intersected the effective measurement path.

Data from LOS3 is analyzed in the 100 - 300 m range from the DIAL, the emission rate is low showing that most of the emission from tanks J-327 to J-332 is passing east of the 100 m mark of LOS3.

- SDP15/LOS1 and LOS2 on the 28th January, SE wind, Table and Figure 2.15.

- LOS1 33.3 lbs/hr, LOS2 32.0 lbs/hr (see Table 2.28).
- Figures 2.15a1 and a2 visual representation of Scan 365 (LOS2).

The main emission measured from LOS1 and LOS2 is in the region 250 - 350 m from the DIAL confirming all the tanks from J-327 to J-332 as probable emission sources. The emission rates measured from LOS1 and LOS2 are similar and agree with the emission measured from SDP10/LOS3.

The emission rate from tanks J-327 to J-332 obtained by averaging the measurements from SDP10/LOS3, SDP15/LOS1 and SDP15/LOS2 is 32.4 ± 7.0 lbs/hr.

- SDP13/LOS3 on the 26th January, SE wind, Table and Figure 2.13.

- LOS3 0.3 lbs/hr (see Table 2.28).

Measurements of the south area of the east tanks are carried out from SDP13/LOS3. The observed emission is very low and considered negligible.

• SDP18 on the 2nd February, NW wind, Table and Figure 2.19.
- LOS1 0.5 lbs/hr, LOS2 0.2 lbs/hr (see Table 2.28).

Scans from LOS1 and LOS2 measure the emission from the East Property Flare (EP Flare). No emissions are found that are above the DIAL detection limit.

2.7 MEASUREMENTS OF THE REFINERY EAST PROCESS AREA

• SDP09 on the 21st January, NW wind, Table and Figure 2.9.
- LOS1 2.2 lbs/hr, LOS2 8.2 lbs/hr, LOS3 11.9 lbs/hr, LOS4 -0.2 lbs/hr, LOS5 2.1 lbs/hr (see Table 2.28).
- Figures 2.9a1 and a2 visual representation of Scan 209 (LOS2).

Measurements from LOS1 are upwind of the Refinery East process area and they show a low emission rate.

For LOS2 the emission rate is localized around 300 m from the DIAL indicating CR-3 as the likely source of such emission. The emission rate from CR-3 is calculated by difference with respect to the upwind sources measured for LOS1 and the emission rate measured for LOS2. The resulting emission rate is 6.0 ± 2.5 lbs/hr.

The emission measured from LOS3 is within the measurement uncertainty and similar to the emission measured with LOS2 and located in the same region. No emission source in the area between LOS2 and LOS3 is detected.

Scans from LOS4 measure the Aromatic Units area. No emissions are observed above the DIAL detection limit.

The main emission measured from LOS5 is in the region 200 - 300 m from the DIAL. The measured emission rate is low and it could possibly be due to emissions from the CR-3, although it seems unlikely considering the distance from the source.

• SDP15/LOS3 and LOS4 on the 28th January, SE wind, Table and Figure 2.15.
- LOS3 42.4 lbs/hr, LOS4 39.5 lbs/hr (see Table 2.28).
- Figures 2.15b1 and b2 visual representation of Scan 366 (LOS3).

The emission from LOS3 is spread in the region 200 - 300 m from the DIAL, probably due to the emission from tanks J-327 to J-332, and at higher elevation at about 350 m from the DIAL. This plume could be associated with emission from the CR-3 area. It is possible to evaluate the high elevation emission rate CR-3 by subtracting the upwind sources from tanks J-327 to J-332 (32.4 ± 7.0 lbs/hr, average from scans from SDP10/LOS3, SDP15/LOS1 and SDP15/LOS2). The resulting emission rate is 9.9 ± 9.8 lbs/hr and, although the uncertainty is as big as the emission, it confirms that is likely to be some emission from CR-3 as observed from SDP09/LOS2.

The emission from LOS4 is similar to the emission measured at LOS3 and it is uniformly spread from the 200 to 450 m region. Tanks J-327 to J-332 and CR-3 are the most likely sources and this is consistent with the broad plume given the sources are a significant distance from LOS4.

- SDP34 on the 25th March, NW wind, Table and Figure 2.24.

- LOS1 29.7 lbs/hr, LOS2 1.7 lbs/hr (see Table 2.28).
- Figures 2.24a1 and a2 visual representation of Scan 809 (LOS1).

The emission plume measured from LOS1 is in the region 100 - 200 m from the DIAL and it is localized in the SE area of CR-3 since the upwind emission rate from LOS2 is very small.

2.8 MEASUREMENTS OF NORTH WASTEWATER AREA

- SDP12 on the 25th January, very variable wind: N, E and W, Table and Figure 2.12.

- LOS1 22.1 lbs/hr, LOS2 1.9 lbs/hr, LOS3 0.5 lbs/hr (see Table 2.28).
- Figures 2.12a1 and a2 visual representation of Scan 280 (LOS1).

Measurements from LOS1 are downwind of the wastewater area with a north wind direction. At the time Scan 282 was taken the wind direction changed to west, therefore this scan is not included in the average emission from LOS1. The emission plume measured from LOS1 is in the region 100 - 200 m from the DIAL indicating emission from the west area of aeration basin and from the aeration tanks west of it.

Measurements at LOS2 are downwind of the wastewater area with a west wind direction. The emission rate is smaller than the emission rate observed from LOS1, which is partly due to some of the emissions being blown too close to the DIAL and therefore not being possible to observe.

Measurements from LOS3 are upwind of tanks J-301B and K-301 with an easterly wind direction. No emissions are observed above the DIAL detection limit.

- SDP12 on the 30th January, NNW wind, Table and Figure 2.17.

- LOS1 767.4 lbs/hr, LOS2 1180.5 lbs/hr, LOS3 0.2 lbs/hr, LOS4 0.2 lbs/hr, LOS5 1193.6 lbs/hr, LOS6 798.2 lbs/hr (see Table 2.28).
- Figures 2.17a1, a2, b1, b2, c1 and c2 visual representation of Scans 401 (LOS1), 405 (LOS2) and 415 (LOS5).

Scans from LOS2 are downwind of the wastewater area and the measured emission rate is significant. The plume is narrowly distributed at 200 m from the DIAL indicating the tanks west of aeration basin as the possible source of emission including SDAF (EWT-10), NDAF (EWT-11), FLCCULTR (EWT-8), FLSHMIX (EWT-7) and X316. This is confirmed by the upwind scans from LOS3 and LOS4 just north of these tanks that show no emission.

The emission from these tanks is about 50 times higher than the emission observed on the 25th January from SDP12/LOS1 the reason is not clear but it could be related to a different operation mode.

Scans from LOS5 are just south of the scans from LOS2 and the emission is similar to that from LOS2. The emission rate calculated by averaging the emission rates determined for LOS2 and LOS5 is 1186.1 ± 190.1 lbs/hr.

Measurements from LOS6 and LOS1 are further downwind of the emission source. As a consequence, the observed plume is diffuse and approximately 200 m wide. The emission rates from LOS6 and LOS1 are similar and smaller than the emission rates measured closer to the source from LOS2 and LOS5. This could be due to the increased distance from the source and the east part the wide plume being too close to the DIAL for LOS1 and LOS6 and therefore not detected. The emission rate calculated by averaging the emission rates determined for LOS1 and LOS6 is 782.8 ± 116.1 lbs/hr.

• SDP21 on the 5th February, NW wind, Table and Figure 2.22.
- LOS1 544.2 lbs/hr, LOS2 610.7 lbs/hr (see Table 2.28).
- Figures 2.22a1 and a2 visual representation of Scans 529 (LOS1) and 532 (LOS2).

The emission plume measured from LOS1 is in the region 100 - 300 m from the DIAL with probably two or more emission sources. Aeration basin and the tanks west of it including SDAF (EWT-10), NDAF (EWT-11), FLCCULTR (EWT-8), FLSHMIX (EWT-7) and X316 are possible sources as emission from them was already observed from SDP12 on the 25th and 30th of January. Considering the wind direction and the width of the plume, the tanks north of aeration basin and the trickling filter cannot be excluded as sources of emission.

The emission from LOS2 is similar to the emission measured from LOS1. The plume is spread over 150 to 350 m region confirming the observations made for the scans carried out from LOS1.

The overall emission calculated by averaging the emission rates determined for LOS1 and LOS2 is 562.3 ± 110.8 lbs/hr. This value is just about comparable with the emission rate measured on the 30th January from SDP12/LOS1 and SDP12/LOS6 (782.8 ± 116.1 lbs/hr) but it is lower than the emission rate measured on the 30th January from SDP12/LOS2 and SDP12/LOS5, 1186.1 ± 190.1 lbs/hr.

• SDP22 on the 5th February, NW wind, Table and Figure 2.23.
- LOS1 412.8 lbs/hr (see Table 2.28).
- Figures 2.23a1 and a2 visual representation of Scan 537 (LOS1).

The emission plume measured from LOS1 is in the region 100 - 300 m from the DIAL with clearly two clear emission sources. The strongest emission in the 200 - 300 m region is likely to be from the tanks west of aeration basin while the emission in the 100 - 200 m region is likely to be from aeration basin. Considering the wind direction and the width of the plume, the tanks north of aeration basin and the trickling filter can be excluded as sources of emission. The most likely emission sources are the units SDAF (EWT-10), NDAF (EWT-11), FLCCULTR (EWT-8), FLSHMIX (EWT-7) and X316.

The emission measured from SDP22/LOS1 is slightly lower than the emission observed from SDP21/LOS1 and LOS2.

2.9 MEASUREMENTS OF EAST WASTEWATER AREA AND FLARES

- SDP17 on the 1st February, E wind, Table and Figure 2.18.

- LOS1 25.7 lbs/hr, LOS2 23.3 lbs/hr, LOS3 1.0 lbs/hr, LOS4 1.0 lbs/hr, LOS5 27.2 lbs/hr (see Table 2.28).
- Figures 2.18a1 and a2 visual representation of Scan 422 (LOS1).

The emission plume measured from LOS1 is in the region 100 - 300 m from the DIAL with two clear emission sources. The first source, in the 100 - 200 m range, is most likely due to the aeration basins east of LOS1. The second source, in the 200 - 300 m region, is from the area south of the aeration basins. This could include the following units: A-13113, A-1304, T-1372, T-1331, T1332, T-1333, T1334, T-1310, T-320, NAPI and SAPI.

The emission rate measured from LOS2 and LOS5 are similar and agree with the emission measured from LOS1, confirming the observations made for LOS1.

Scans from LOS3 and LOS4 are downwind and upwind measurements of the A&S Flare (A1301) north of the aeration basins. For these measurements the wind is not favourable since it is almost parallel to the LOSs. The emission rate is very low and close to the DIAL detection limit, moreover there is no appreciable difference between the upwind and downwind emission rate measurements.

- SDP13/LOS1 and LOS2 on the 26th January, SE wind, Table and Figure 2.13.

- LOS1 1.3 lbs/hr, LOS2 -0.1 lbs/hr (see Table 2.28).
- Figures 2.13a1 and a2 visual representation of Scan 309 (LOS1).

Scans from LOS1 are downwind measurements of the HIPA Flare (A1313) located at the NW corner of the western aeration basin as indicted in Figure 2.13. The measured emission rate is very low and, although it is close to the DIAL detection limit, it is higher than the upwind emission rate measured from LOS2.

These scans specifically target the flare at about 100 m elevation, therefore the emission from the aeration basins observed on the 1st of February from SDP17 is not observed in these scans, as they are at higher elevation angles.

2.10 MEASUREMENTS OF ACU & BEU AREA

- SDP35 on the 26th March, NNE wind, Table and Figure 2.25.

- LOS1 63.6 lbs/hr (see Table 2.28).
- Figures 2.25a1 and a2 visual representation of Scan 824 (LOS1).

The emission plume measured from LOS1 is in the region 150 - 250 m from the DIAL with possibly two emission sources that can be identified as the BEU area and the ACU area.
At the time Scan 832 was taken the wind direction changed toward east, therefore this scan is not included in the average emission from LOS1.

- SDP36 on the 26th March, SE wind, Table and Figure 2.26.

- LOS1 64.9 lbs/hr (see Table 2.28).

- Figures 2.26a1 and a2 visual representation of Scan 836 (LOS1).

The emission plume measured from LOS1 is from just before 100 m up to just beyond 200 m from the DIAL with probably two emission sources. Similar to the measurements from SDP35/LOS1, the two sources are likely to be the BEU area and the ACU area. Moreover, the emission rate measured from SDP36 is similar to the emission measured from SDP35.

3 MEASUREMENTS OF BENZENE EMISSIONS.

Table 3.1 Emission rate measurements from SDP23 on 8th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
545	SDP23/LOS1	10:55	11:06	8.3	143.4	2.41	Downwind SW AP Tanks
546	SDP23/LOS1	11:07	11:18	7.8	154.6	2.72	Downwind SW AP Tanks
547	SDP23/LOS1	11:19	11:30	7.8	148.7	1.87	Downwind SW AP Tanks
548	SDP23/LOS2	11:33	11:44	7.0	152.0	2.00	Downwind SW AP Tanks
549	SDP23/LOS2	11:45	11:56	7.9	149.2	2.67	Downwind SW AP Tanks
550	SDP23/LOS2	11:56	12:07	8.6	146.5	3.84	Downwind SW AP Tanks

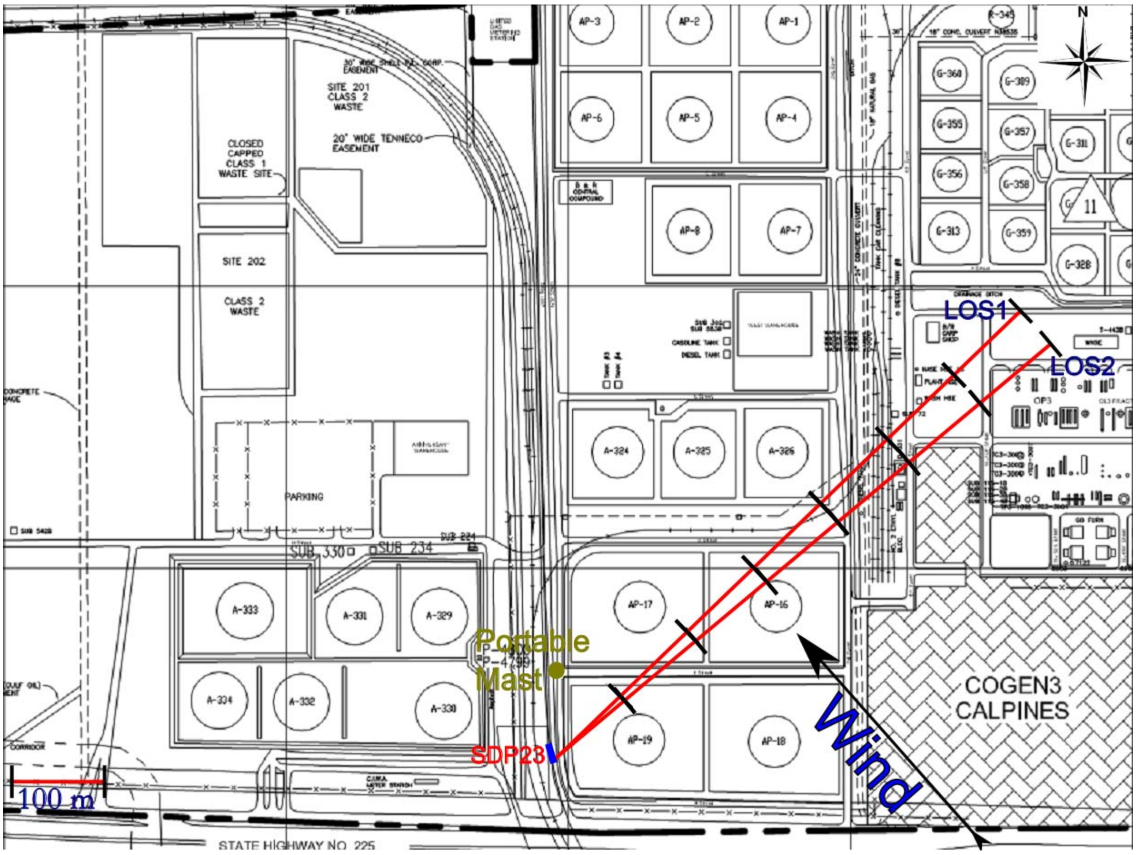

Figure 3.1 Measurement configuration for location SDP23 on 8th of February.

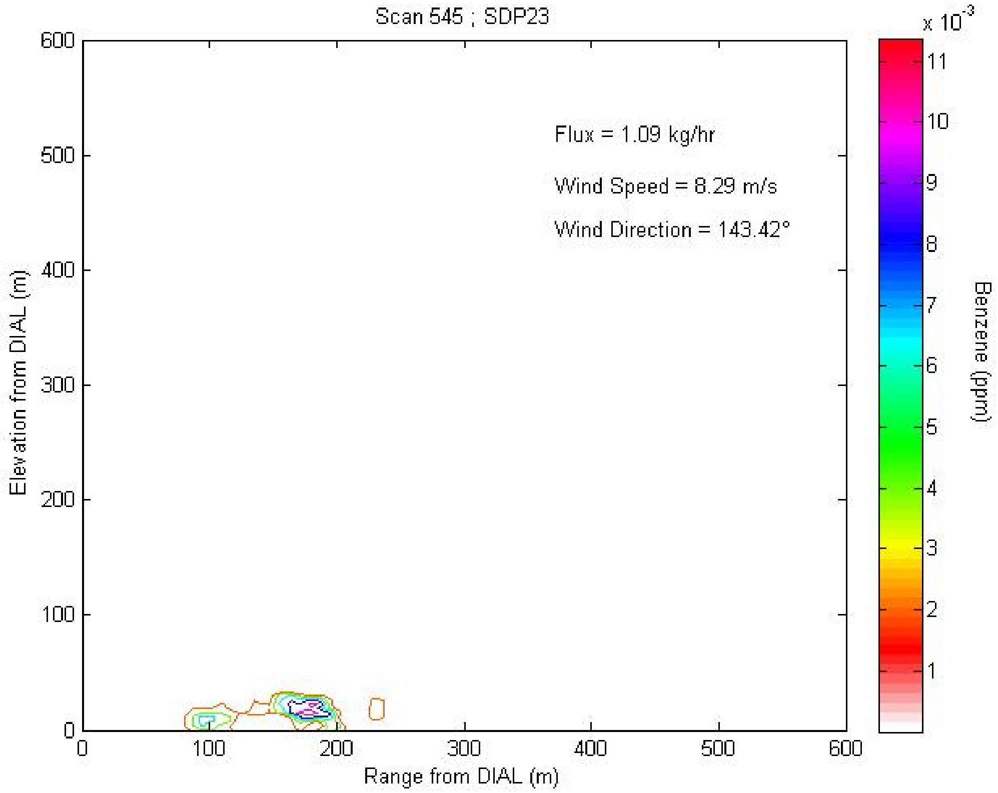

Figure 3.1a1 Contour plot of concentration profile for Scan 545 representing LOS1.

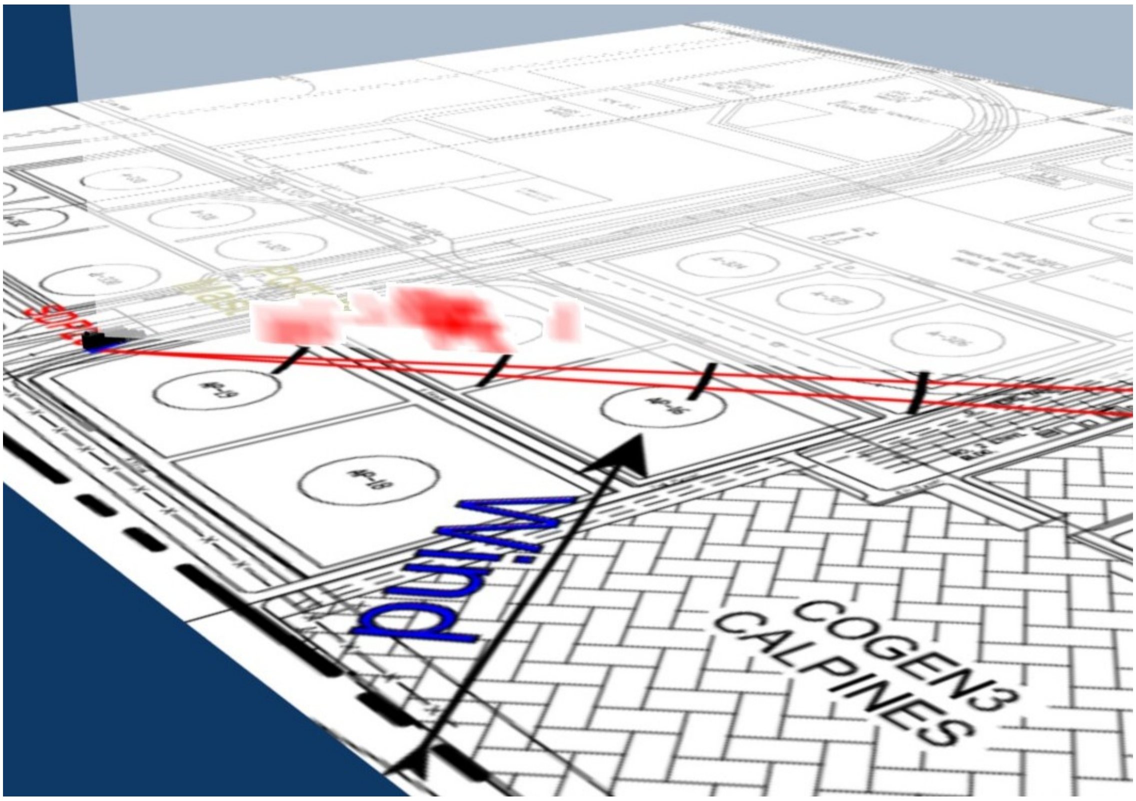

Figure 3.1a2 Visualisation of emission rate measured for Scan 545 representing LOS1.

Table 3.2 Emission rate measurements from SDP24 on 8th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
552	SDP24/LOS1	14:15	14:24	6.8	139.5	4.85	Downwind of T-OL913 Tank
553	SDP24/LOS1	14:25	14:34	6.6	142.4	4.85	Downwind of T-OL913 Tank
554	SDP24/LOS1	14:34	14:43	5.3	144.0	4.09	Downwind of T-OL913 Tank
555	SDP24/LOS1	14:47	15:05	6.6	146.2	6.64	Downwind of T-OL913 Tank
557	SDP24/LOS1	15:18	15:33	5.8	145.7	6.55	Downwind of T-OL913 Tank
558	SDP24/LOS1	15:33	15:48	6.6	141.2	5.56	Downwind of T-OL913 Tank
560	SDP24/LOS1	15:49	15:52	5.5	152.1	8.50	Downwind of T-OL913 Tank
561	SDP24/LOS1	16:08	16:23	6.3	160.2	8.56	Downwind of T-OL913 Tank
562	SDP24/LOS1	16:23	16:38	6.0	149.8	1.44	Downwind T-OL913 Low Elevation
563	SDP24/LOS1	16:38	16:53	7.2	142.2	1.08	Downwind T-OL913 Low Elevation
564	SDP24/LOS1	16:53	17:08	5.9	134.7	0.82	Downwind T-OL913 Low Elevation
565	SDP24/LOS1	17:08	17:23	5.4	130.5	1.26	Downwind T-OL913 Low Elevation

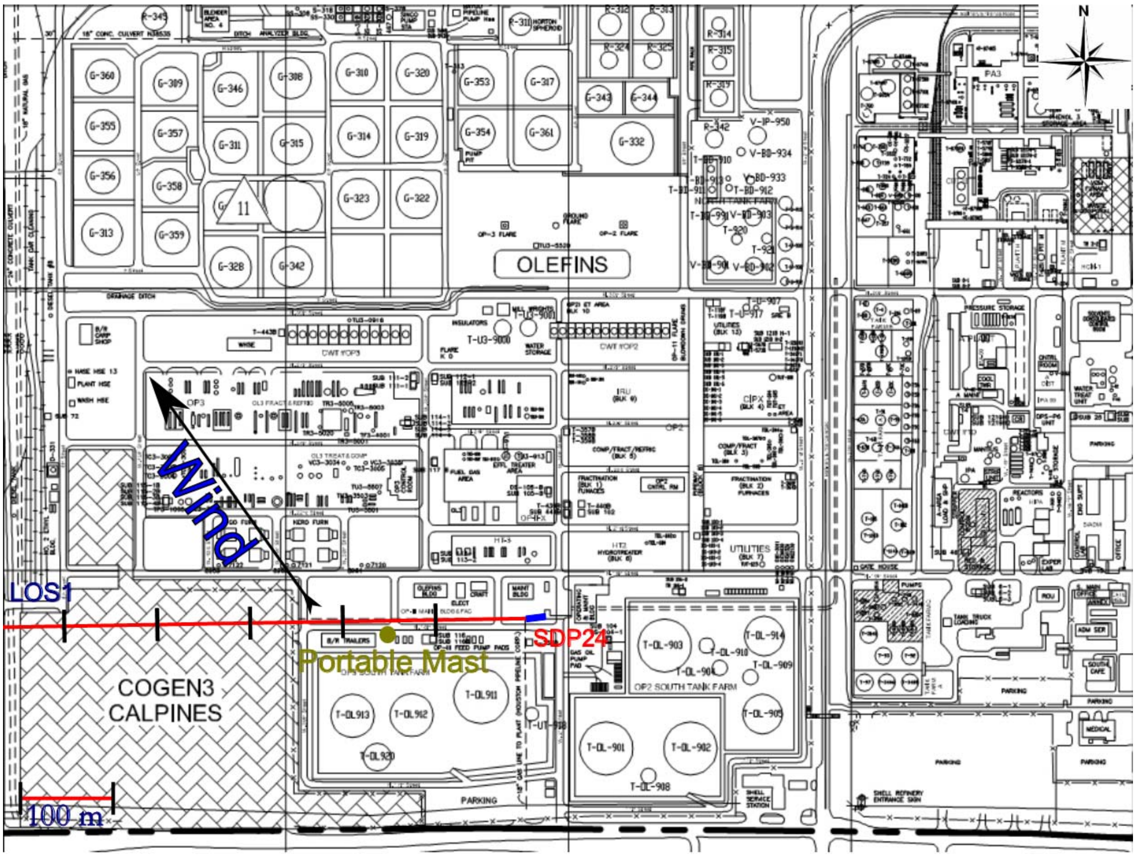

Figure 3.2 Measurement configuration for location SDP24 on 8th of February.

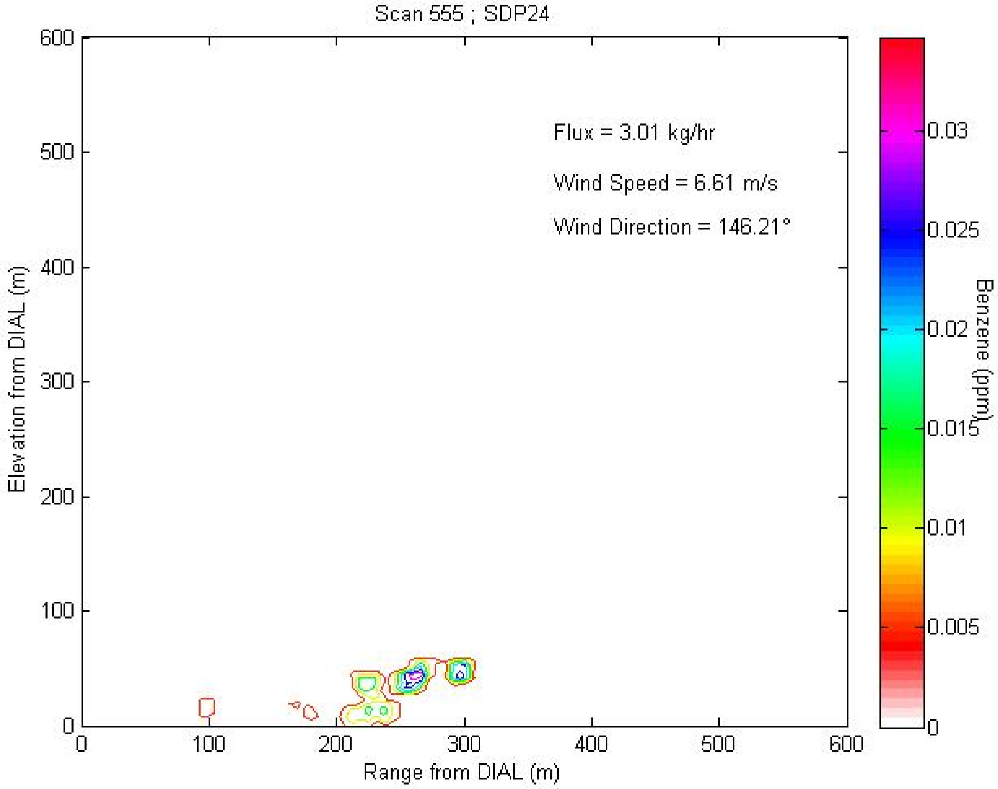

Figure 3.2a1 Contour plot of concentration profile for Scan 555 representing LOS1.

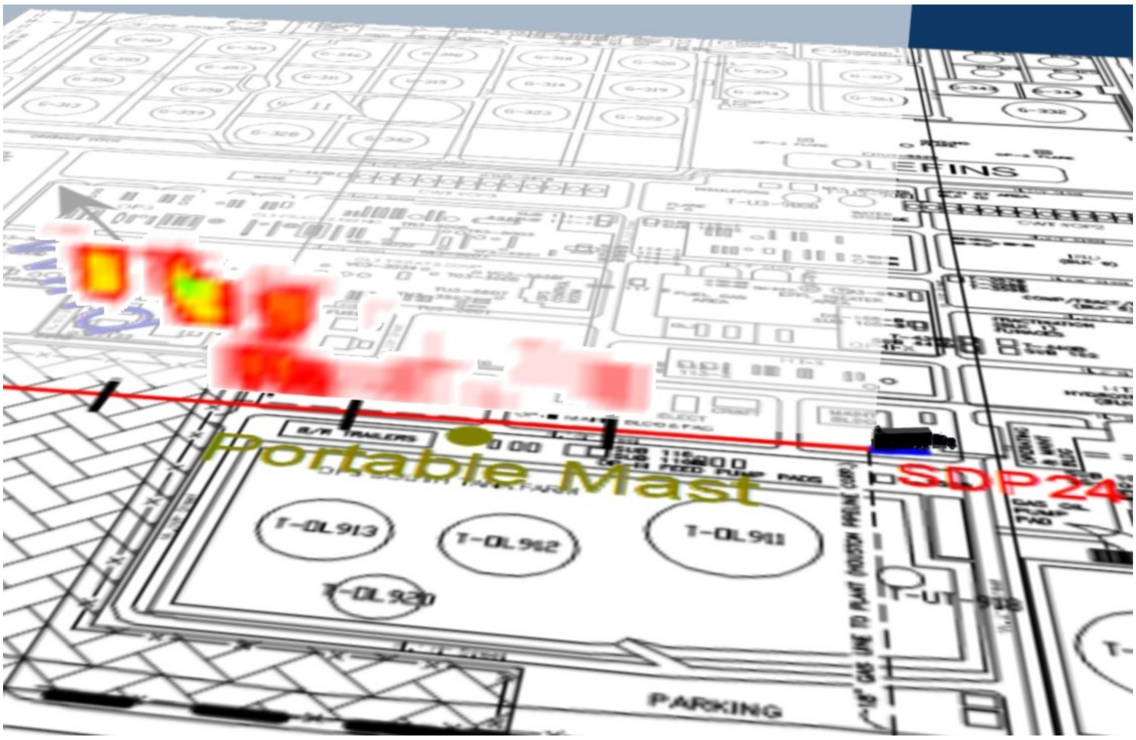

Figure 3.2a2 Visualisation of emission rate measured for Scan 555 representing LOS1.

Table 3.3 Emission rate measurements from SDP25 on 9th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
567	SDP25/LOS1	10:42	10:56	6.6	351.2	9.30	Downwind of Wastewater
568	SDP25/LOS1	10:57	11:15	6.7	350.3	10.29	Downwind of Wastewater
570	SDP25/LOS1	11:22	11:41	6.0	340.3	7.47	Downwind of Wastewater
571	SDP25/LOS1	11:41	11:59	6.2	351.9	7.47	Downwind of Wastewater
572	SDP25/LOS2	12:04	12:14	7.2	334.9	1.70	Downwind of Flare
574	SDP25/LOS2	12:19	12:29	7.0	336.7	1.14	Downwind of Flare
575	SDP25/LOS2	12:29	12:39	6.7	342.6	1.71	Downwind of Flare
576	SDP25/LOS2	12:40	12:50	6.6	353.2	1.48	Downwind of Flare
579	SDP25/LOS1	13:10	13:28	7.3	336.4	6.46	Downwind of Wastewater
580	SDP25/LOS1	13:28	13:46	7.8	342.6	7.36	Downwind of Wastewater
581	SDP25/LOS1	13:47	14:05	7.4	349.3	5.20	Downwind of Wastewater
582	SDP25/LOS1	14:06	14:24	7.2	345.4	6.53	Downwind of Wastewater
583	SDP25/LOS1	14:24	15:01	6.6	349.9	5.26	Downwind of Wastewater
584	SDP25/LOS1	15:01	15:37	6.5	357.4	4.82	Downwind of Wastewater
585	SDP25/LOS1	15:37	15:55	5.9	357.7	6.46	Downwind of Wastewater
587	SDP25/LOS1	16:02	16:20	5.9	353.4	4.47	Downwind of Wastewater
588	SDP25/LOS1	16:20	16:39	5.0	342.0	4.43	Downwind of Wastewater
589	SDP25/LOS1	16:39	16:57	4.7	337.7	4.69	Downwind of Wastewater

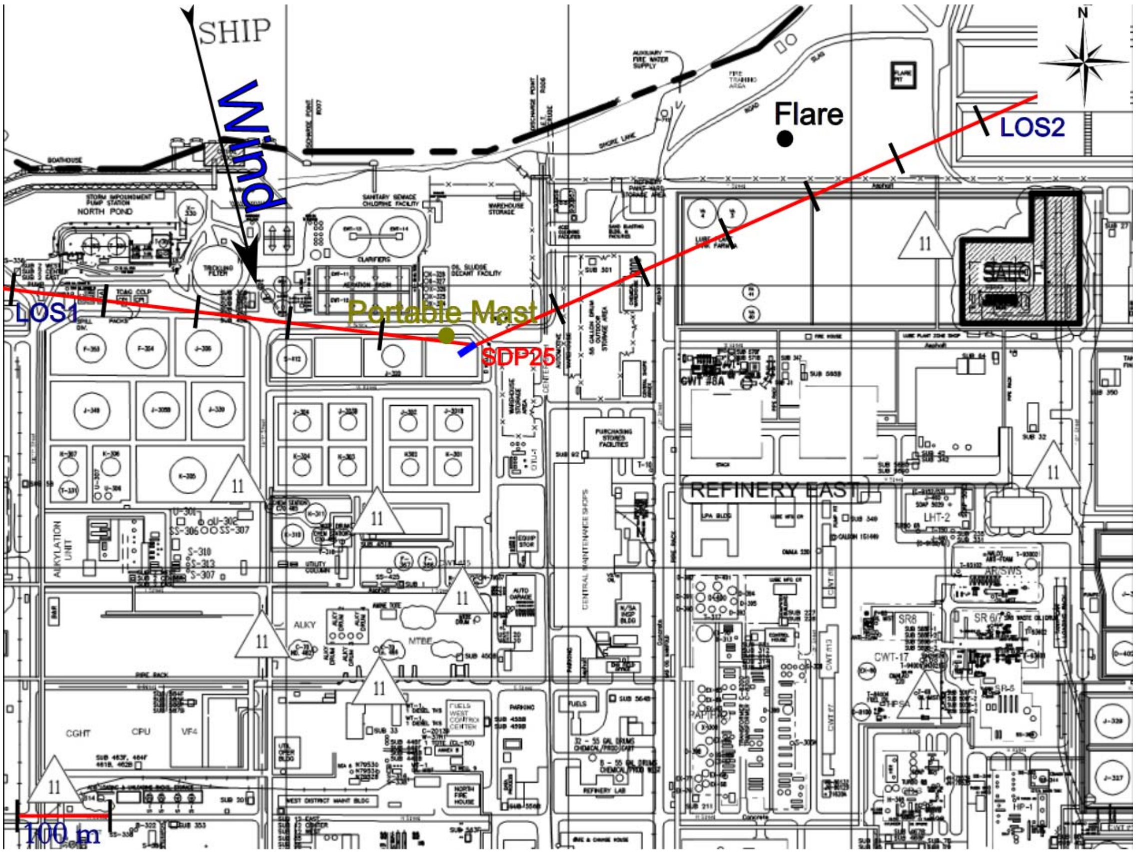

Figure 3.3 Measurement configuration for location SDP25 on 9th of February.

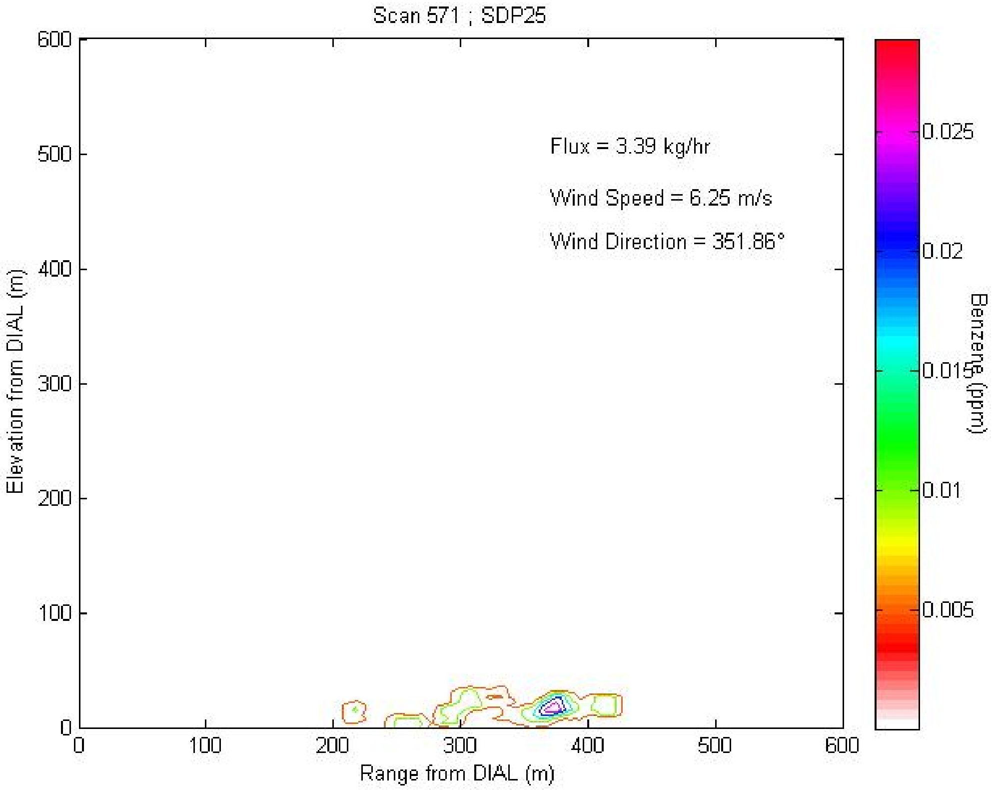

Figure 3.3a1 Contour plot of concentration profile for Scan 571 representing LOS1.

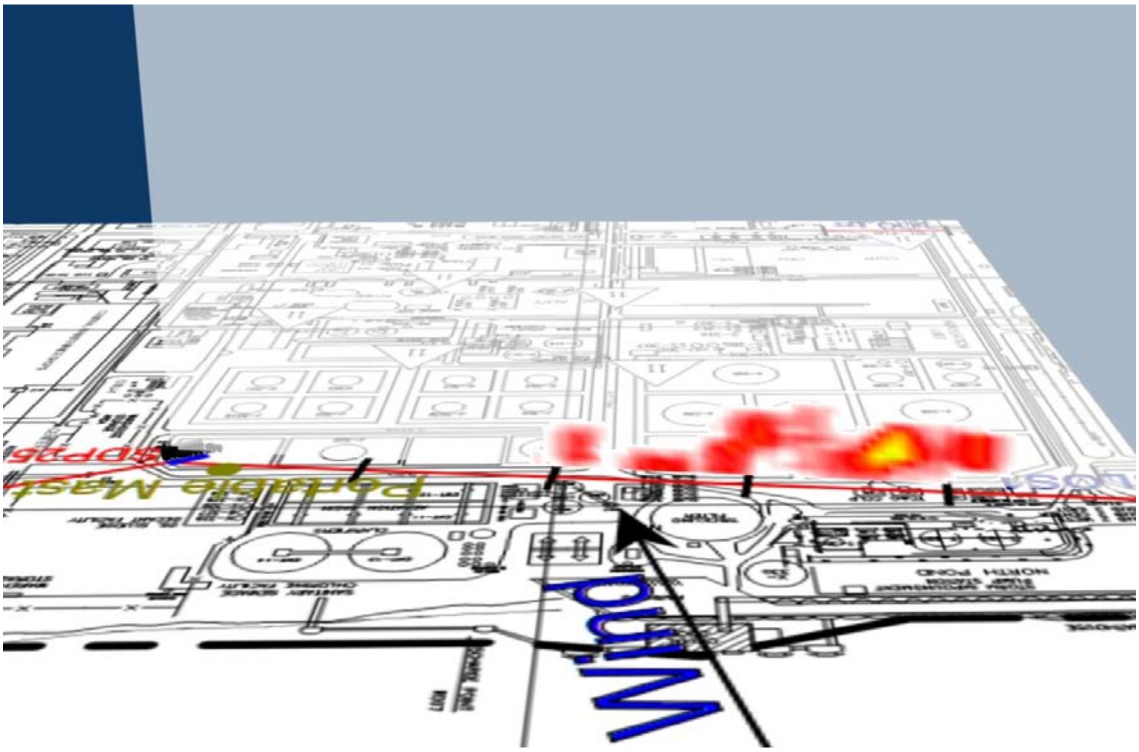

Figure 3.3a2 Visualisation of emission rate measured for Scan 571 representing LOS1.

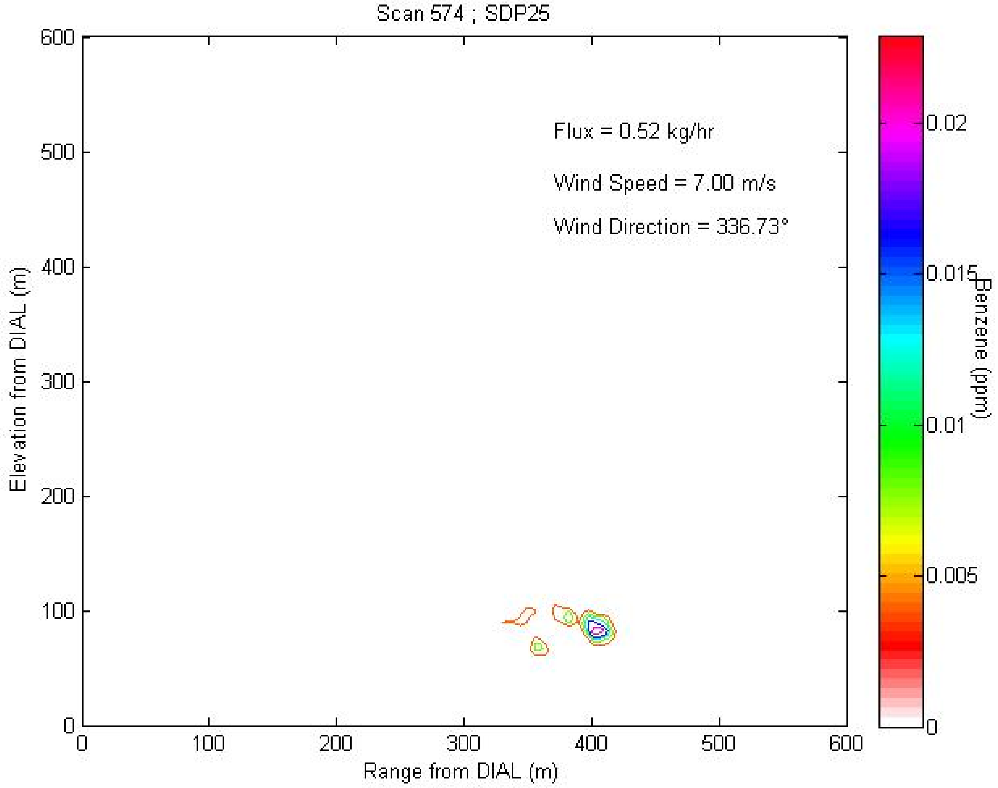

Figure 3.3b1 Contour plot of concentration profile for Scan 574 representing LOS2.

Figure 3.3b2 Visualisation of emission rate measured for Scan 574 representing LOS2.

Table 3.4 Emission rate measurements from SDP26 on 10th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
590	SDP26/LOS1	09:55	10:05	6.1	97.4	0.06	Downwind T-OL913 Low Emission
591	SDP26/LOS1	10:06	10:16	4.3	105.2	0.20	Downwind T-OL913 Low Emission
592	SDP26/LOS1	10:16	10:26	4.4	110.6	0.26	Downwind T-OL913 Low Emission
594	SDP26/LOS1	10:35	10:48	3.5	113.0	0.07	Downwind T-OL913 Low Emission
595	SDP26/LOS1	10:48	11:01	3.1	127.7	2.48	Downwind T-OL913 High Emission
596	SDP26/LOS1	11:02	11:12	3.2	113.4	0.13	Downwind T-OL913 Low Emission
597	SDP26/LOS1	11:12	11:22	3.1	123.5	2.96	Downwind T-OL913 High Emission
598	SDP26/LOS1	11:22	11:32	2.8	136.6	5.17	Downwind T-OL913 High Emission
599	SDP26/LOS1	11:33	11:46	3.0	103.4	1.21	Downwind T-OL913 High Emission
600	SDP26/LOS1	11:46	11:59	2.7	111.7	1.35	Downwind T-OL913 High Emission
601	SDP26/LOS1	12:00	12:13	1.7	148.2	3.58	Downwind T-OL913 High Emission
602	SDP26/LOS1	12:14	12:31	1.8	202.2	7.89	Downwind T-OL913 High Emission
604	SDP26/LOS1	12:39	12:56	1.9	113.9	2.92	Downwind T-OL913 High Emission
605	SDP26/LOS1	12:56	13:13	2.1	114.9	3.20	Downwind T-OL913 High Emission
606	SDP26/LOS1	13:13	13:30	1.9	120.0	2.85	Downwind T-OL913 High Emission
607	SDP26/LOS1	13:30	13:47	1.6	148.8	5.55	Downwind T-OL913 High Emission
608	SDP26/LOS1	13:47	14:04	1.1	127.2	0.88	Downwind T-OL913 Low Emission
609	SDP26/LOS1	14:04	14:21	0.3	226.5	0.95	Downwind T-OL913 Low Emission
610	SDP26/LOS1	14:21	14:37	1.3	218.8	4.17	Downwind T-OL913 High Emission
611	SDP26/LOS1	14:40	14:56	1.0	210.4	2.68	Downwind T-OL913 High Emission
612	SDP26/LOS1	14:57	15:15	1.0	219.5	3.19	Downwind T-OL913 High Emission
613	SDP26/LOS1	15:16	15:38	0.6	161.7	2.55	Downwind T-OL913 High Emission
614	SDP26/LOS1	15:38	16:00	1.9	182.2	7.76	Downwind T-OL913 High Emission
615	SDP26/LOS1	16:00	16:22	2.0	166.0	8.84	Downwind T-OL913 High Emission
616	SDP26/LOS1	16:22	16:43	1.5	174.1	8.86	Downwind T-OL913 High Emission
617	SDP26/LOS1	16:43	17:05	1.5	172.6	7.86	Downwind T-OL913 High Emission

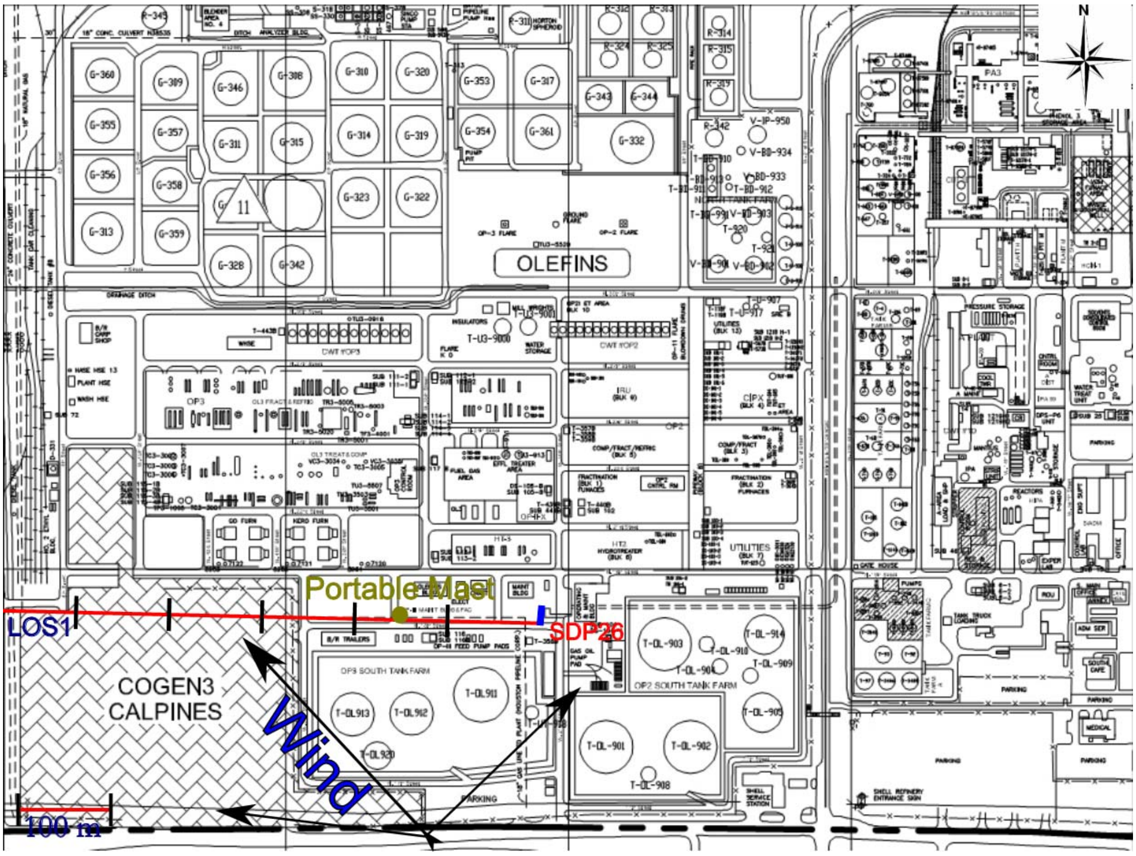

Figure 3.4 Measurement configuration for location SDP26 on 10th of February.

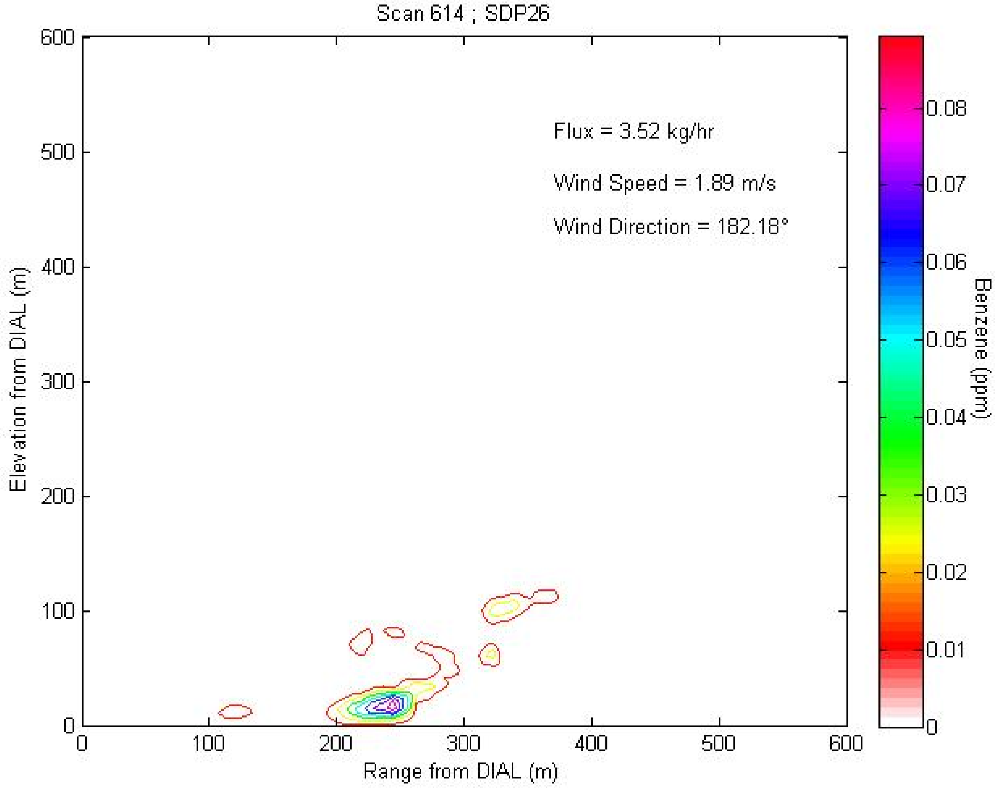

Figure 3.4a1 Contour plot of concentration profile for Scan 614 representing LOS1.

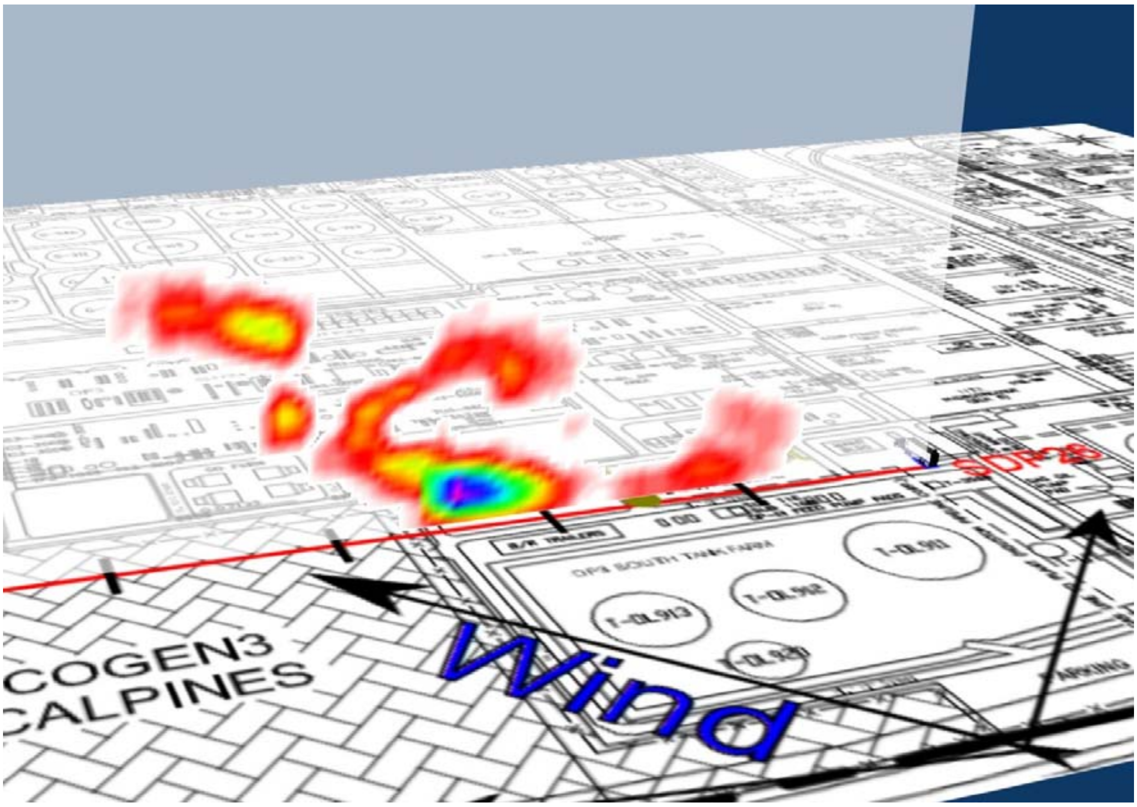

Figure 3.4a2 Visualisation of emission rate measured for Scan 614 representing LOS1.

Table 3.5 Emission rate measurements from SDP27 on 11th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
620	SDP27/LOS1	11:22	11:41	6.3	92.4	11.85	Downwind of the Coker
621	SDP27/LOS1	11:41	12:00	7.4	111.3	14.98	Downwind of the Coker
622	SDP27/LOS1	12:00	12:18	7.7	97.8	15.97	Downwind of the Coker
624	SDP27/LOS1	12:27	12:46	6.8	79.3	14.04	Downwind of the Coker
625	SDP27/LOS1	12:47	13:05	6.4	71.2	16.15	Downwind of the Coker
626	SDP27/LOS1	13:06	13:24	6.2	90.5	12.80	Downwind of the Coker
627	SDP27/LOS1	13:24	13:43	7.5	106.6	10.17	Downwind of the Coker
628	SDP27/LOS1	13:43	14:01	8.2	106.6	16.78	Downwind of the Coker
629	SDP27/LOS1	14:02	14:20	6.9	98.1	7.91	Downwind of the Coker
631	SDP27/LOS2	14:32	14:48	6.5	101.9	3.26	Downwind of the Coker
632	SDP27/LOS2	14:49	15:02	6.4	107.6	5.26	Downwind of the Coker
633	SDP27/LOS2	15:42	15:58	7.8	74.6	26.95	Downwind of the Coker - Event
634	SDP27/LOS3	16:00	16:10	6.6	72.1	6.16	Downwind of the Coker
635	SDP27/LOS3	16:10	16:20	7.3	75.1	4.13	Downwind of the Coker
636	SDP27/LOS3	16:20	16:30	7.2	85.0	3.86	Downwind of the Coker
637	SDP27/LOS2	16:31	16:47	6.3	74.2	7.09	Downwind of the Coker

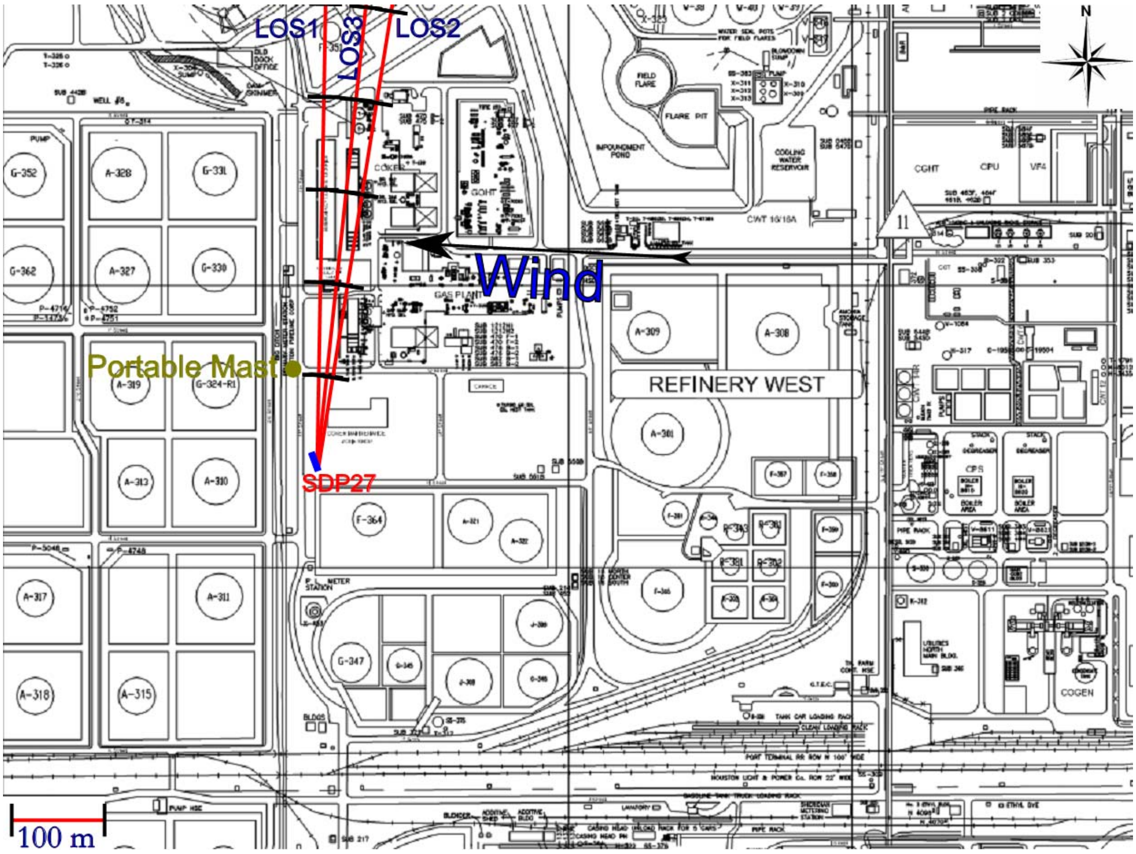

Figure 3.5 Measurement configuration for location SDP27 on 11th of February.

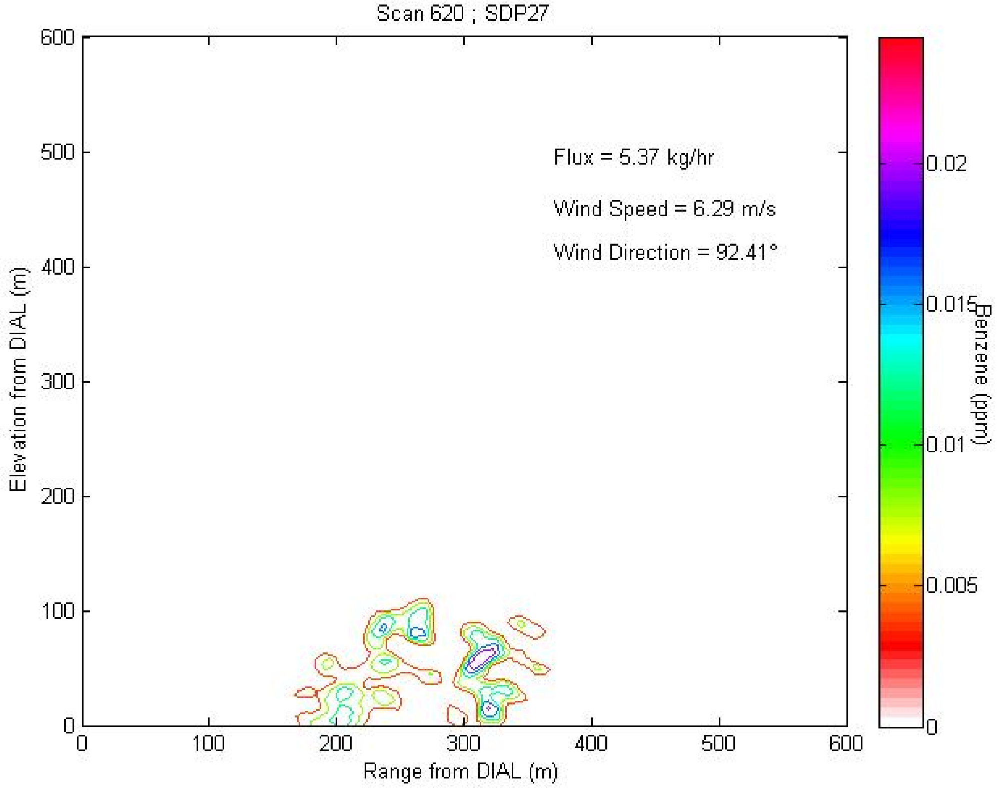

Figure 3.5a1 Contour plot of concentration profile for Scan 620 representing LOS1.

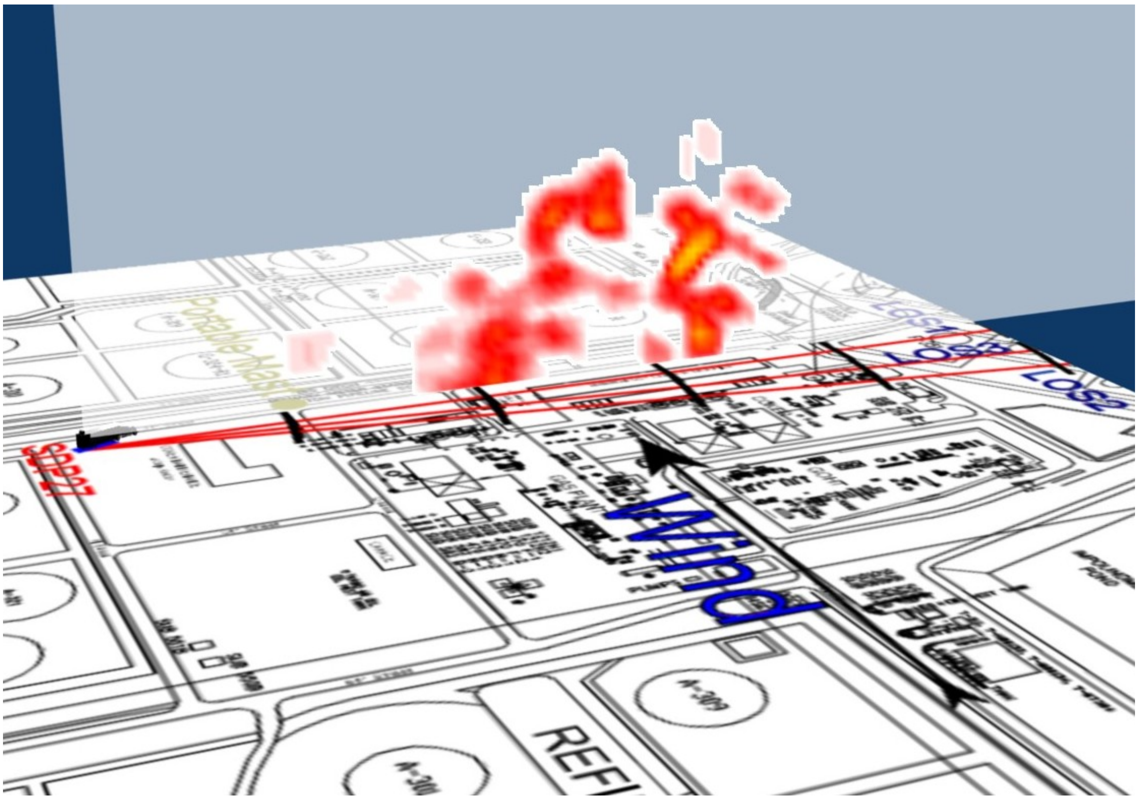

Figure 3.5a2 Visualisation of emission rate measured for Scan 620 representing LOS1.

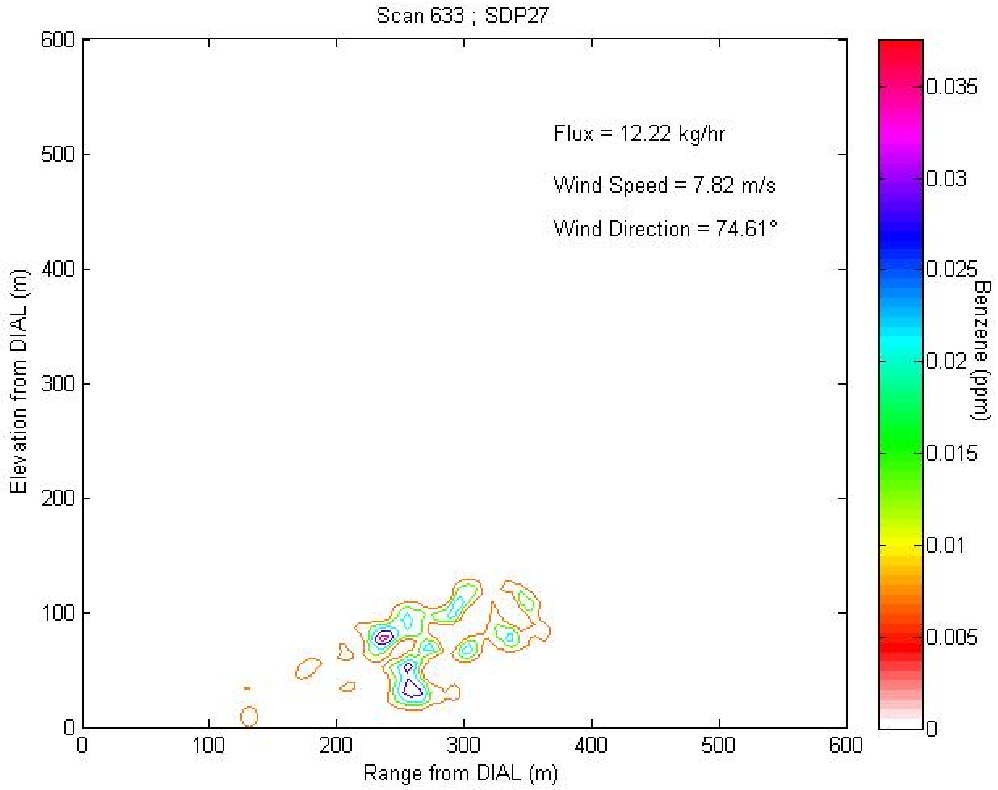

Figure 3.5b1 Contour plot of concentration profile for Scan 633 representing LOS2.

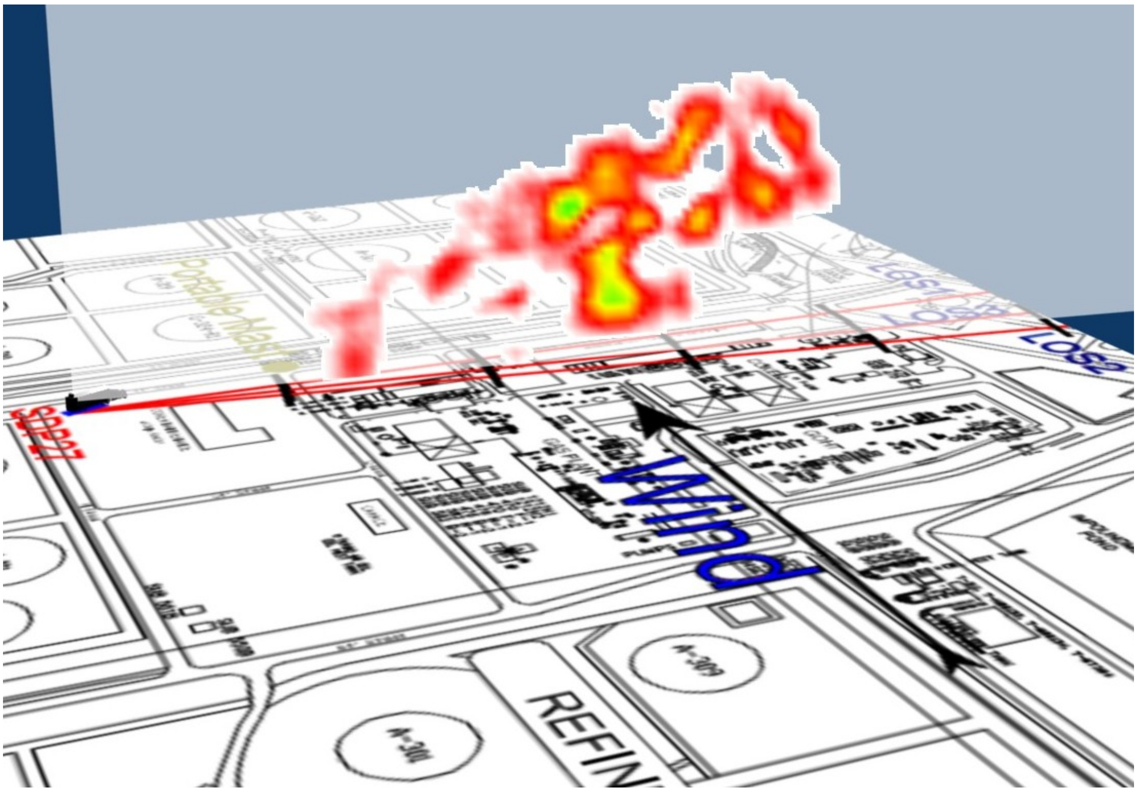

Figure 3.5b2 Visualisation of emission rate measured for Scan 633 representing LOS2.

Table 3.6 Emission rate measurements from SDP28 on 12th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
640	SDP28/LOS1	10:40	10:49	4.7	14.2	9.56	Downwind ACU & BEU 3.5°- 8.5°
641	SDP28/LOS1	10:50	11:00	5.7	339.8	11.47	Downwind ACU & BEU 3.5°- 8.5°
642	SDP28/LOS1	11:00	11:10	5.5	333.0	11.40	Downwind ACU & BEU 3.5°- 8.5°
643	SDP28/LOS1	11:14	11:39	5.7	354.5	16.68	Downwind ACU & BEU 3.5°- 10.5°
644	SDP28/LOS1	11:42	12:12	5.9	354.8	17.79	Downwind ACU & BEU 3.5°- 13.5°
646	SDP28/LOS1	12:25	12:50	6.4	346.4	20.44	Downwind ACU & BEU 3.5°- 17.5°
647	SDP28/LOS1	12:52	13:17	6.4	326.8	21.92	Downwind ACU & BEU 3.5°- 17.5°
648	SDP28/LOS1	13:19	13:44	5.7	329.8	21.26	Downwind ACU & BEU 3.5°- 17.5°
649	SDP28/LOS1	13:52	14:05	5.6	337.6	5.53	Downwind ACU & BEU 0°- 3.5°
650	SDP28/LOS1	14:07	14:20	5.3	325.7	6.25	Downwind ACU & BEU 0°- 3.5°
651	SDP28/LOS1	14:21	14:34	4.6	307.2	5.13	Downwind ACU & BEU 0°- 3.5°
654	SDP28/LOS1	15:22	15:47	4.9	311.3	4.65	ACU & BEU No 100-200m Plume
655	SDP28/LOS1	15:49	16:14	4.9	312.2	5.63	ACU & BEU No 100-200m Plume
656	SDP28/LOS1	16:15	16:40	4.8	302.2	4.60	ACU & BEU No 100-200m Plume
657	SDP28/LOS2	16:49	17:00	5.1	313.2	26.62	Downwind D-350 and D-351 Tanks
658	SDP28/LOS2	17:01	17:13	4.8	311.4	24.74	Downwind D-350 and D-351 Tanks
659	SDP28/LOS2	17:14	17:26	4.7	303.6	24.45	Downwind D-350 and D-351 Tanks

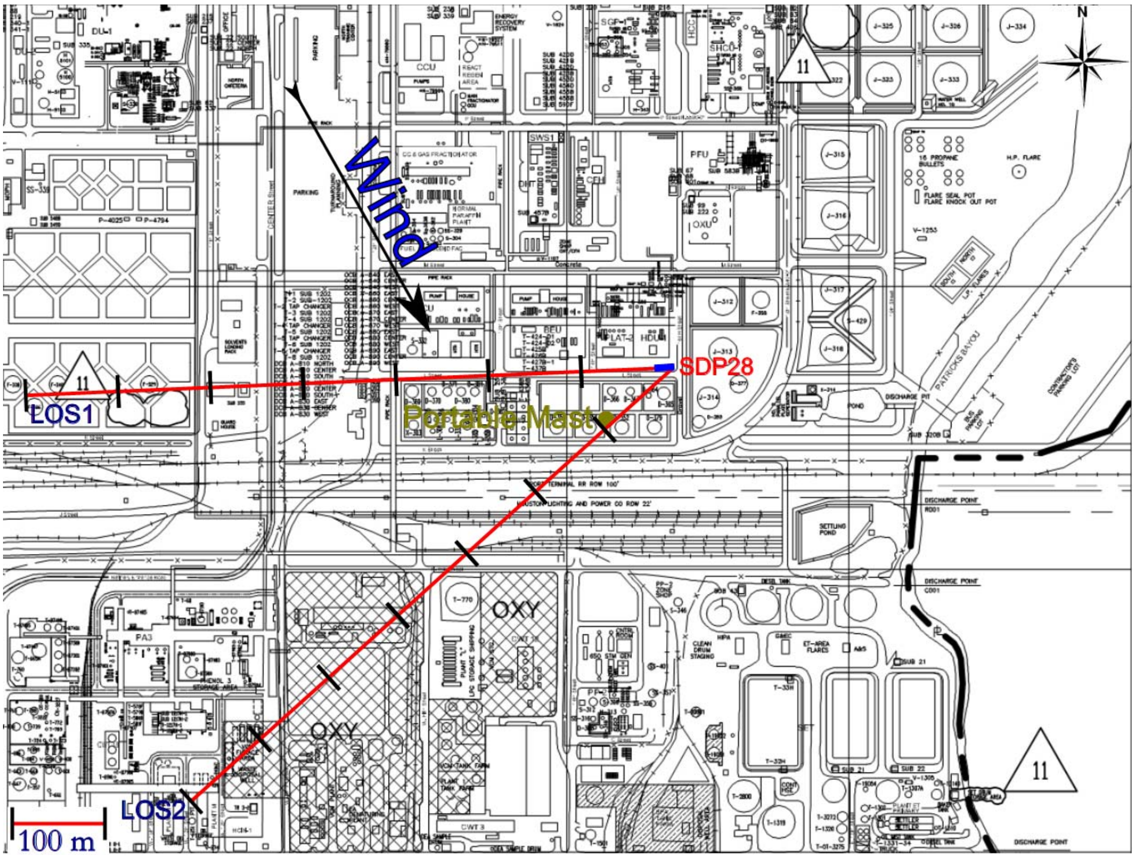

Figure 3.6 Measurement configuration for location SDP28 on 12th of February.

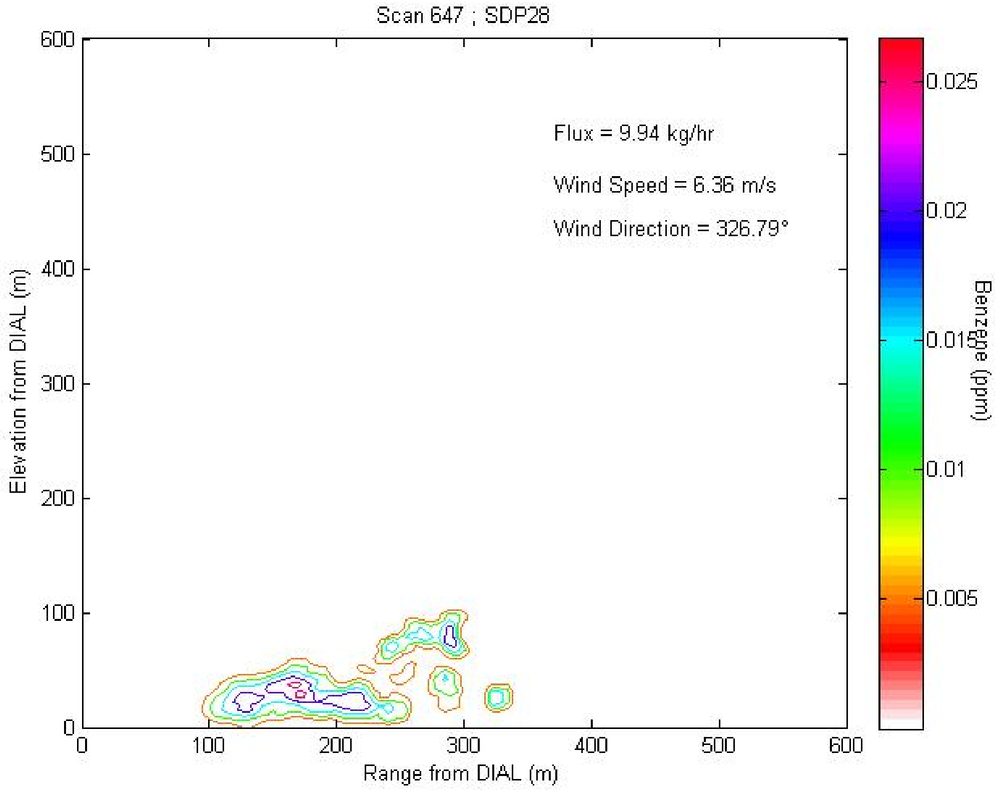

Figure 3.6a1 Contour plot of concentration profile for Scan 647 representing LOS1.

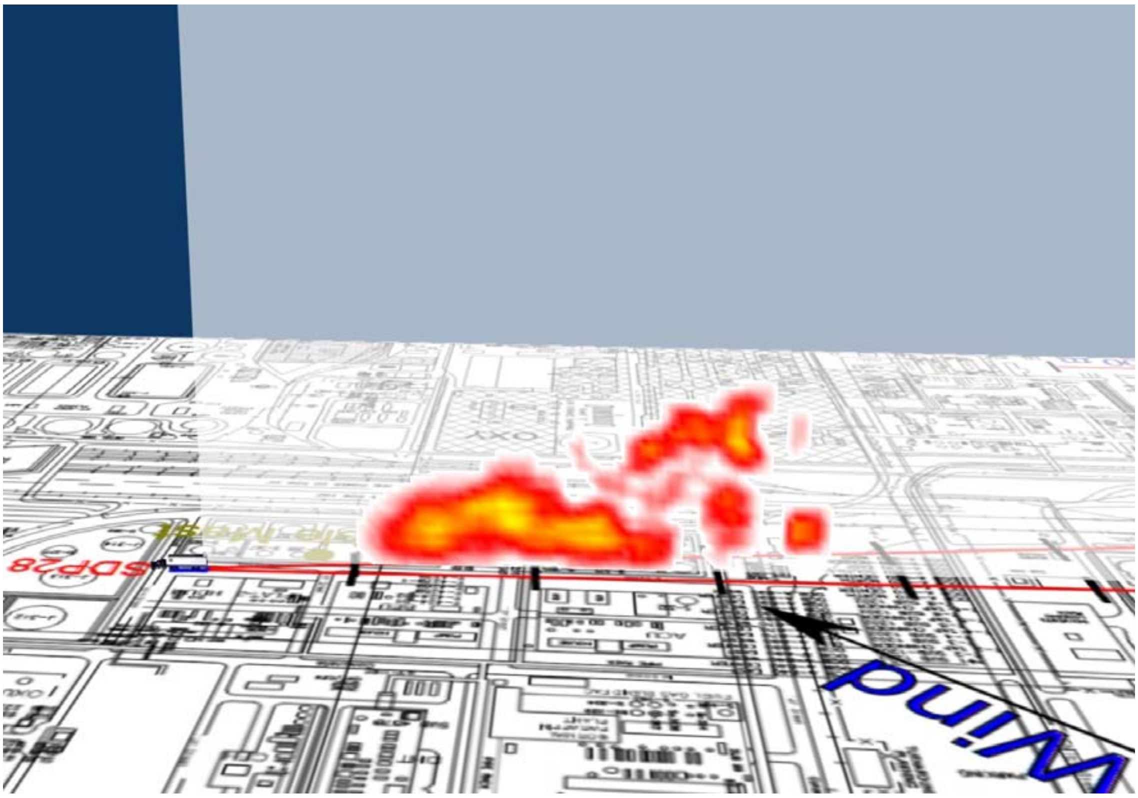

Figure 3.6a2 Visualisation of emission rate measured for Scan 647 representing LOS1.

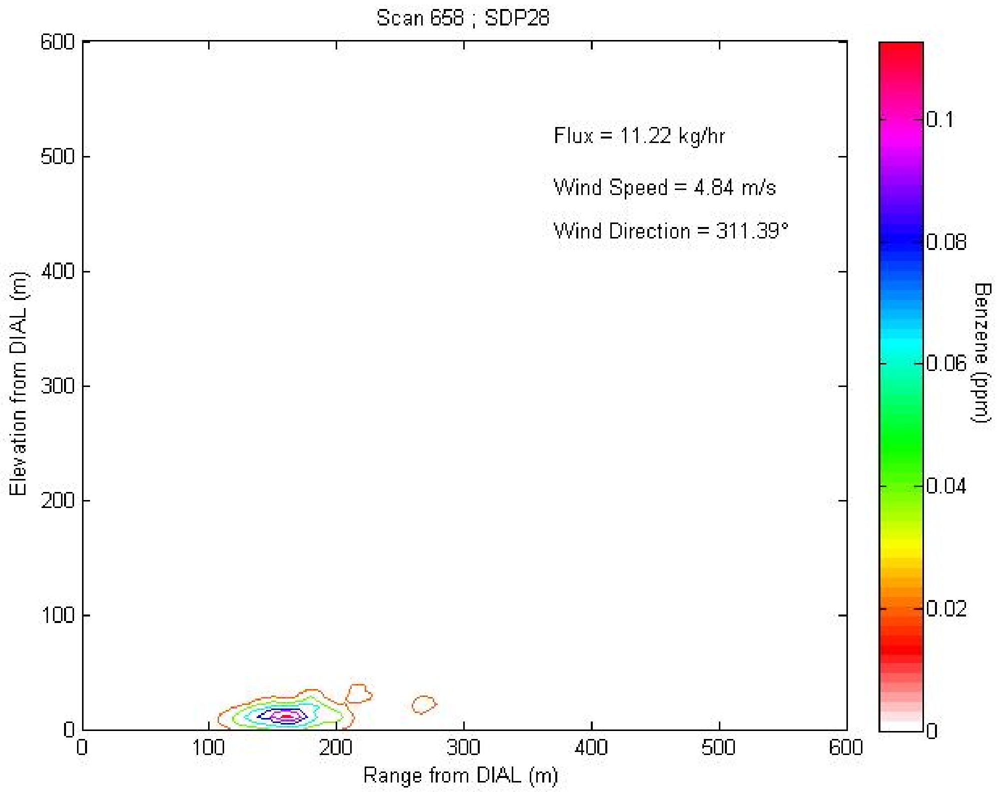

Figure 3.6b1 Contour plot of concentration profile for Scan 658 representing LOS2.

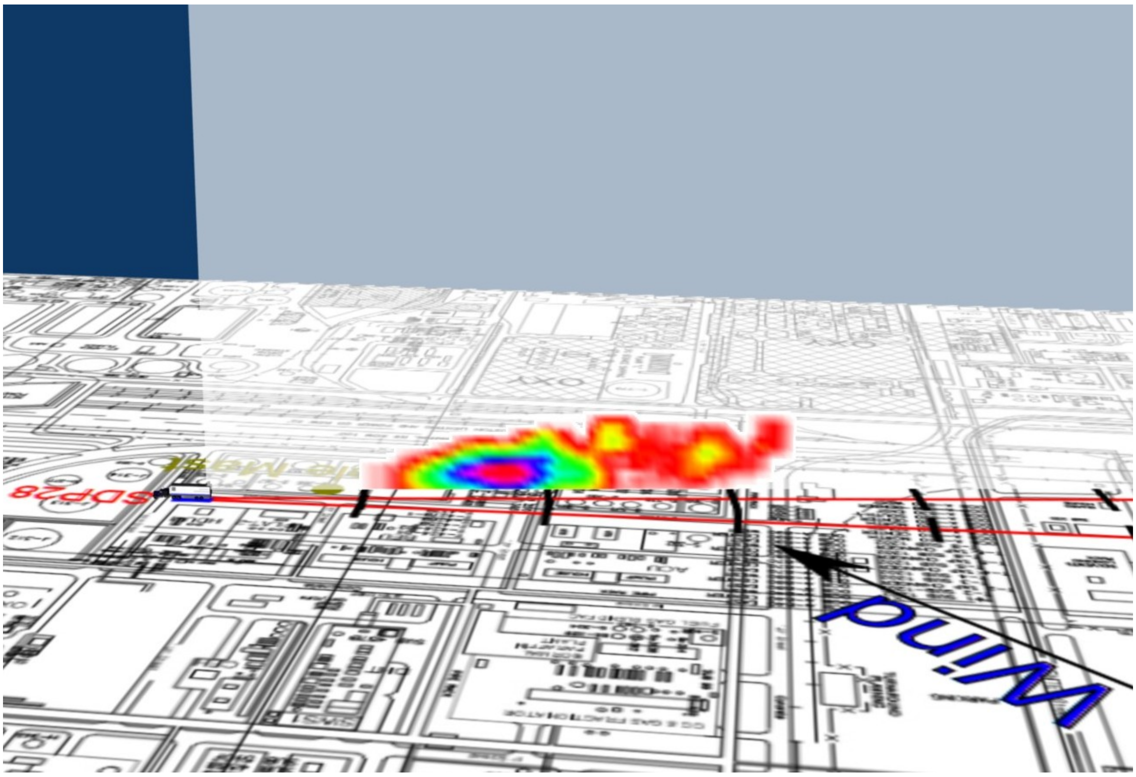

Figure 3.6b2 Visualisation of emission rate measured for Scan 658 representing LOS2.

Table 3.7 Emission rate measurements from SDP29 on 13th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
664	SDP29/LOS1	10:53	11:06	2.8	255.5	0.59	Downwind of J-339 Tank
666	SDP29/LOS2	11:14	11:27	3.2	244.0	4.97	Downwind of K-302 Tank
667	SDP29/LOS1	11:29	11:43	2.8	257.1	0.52	Downwind of J-339 Tank
668	SDP29/LOS2	11:44	12:01	2.7	237.4	4.33	Downwind of K-302 Tank
669	SDP29/LOS2	12:02	12:19	2.8	245.9	7.69	Downwind of K-302 Tank
670	SDP29/LOS1	12:20	12:33	2.8	243.5	0.22	Downwind of J-339 Tank
672	SDP29/LOS3	12:53	13:05	1.9	253.0	2.55	Downwind of Wastewater
673	SDP29/LOS3	13:05	13:17	2.4	279.3	3.94	Downwind of Wastewater
674	SDP29/LOS3	13:18	13:30	2.4	287.1	3.74	Downwind of Wastewater
676	SDP29/LOS3	13:54	14:05	2.6	251.9	3.81	Downwind of Wastewater
677	SDP29/LOS3	14:09	14:24	2.6	248.7	4.62	Downwind of Wastewater
678	SDP29/LOS3	14:25	14:40	2.4	258.6	4.88	Downwind of Wastewater
680	SDP29/LOS4	14:47	14:47	1.8	259.4	0.49	Between J-304 and J-303B Tanks
681	SDP29/LOS4	15:00	15:11	2.0	262.0	0.63	Between J-304 and J-303B Tanks
682	SDP29/LOS4	15:13	15:29	1.5	251.4	0.29	Between J-304 and J-303B Tanks
683	SDP29/LOS1	15:36	15:49	3.3	251.6	0.61	Downwind of J-339 Tank
684	SDP29/LOS1	15:50	16:03	2.0	245.9	0.24	Downwind of J-339 Tank
685	SDP29/LOS1	16:06	16:19	3.1	242.1	0.52	Downwind of J-339 Tank
687	SDP29/LOS3	16:27	16:42	2.6	230.0	3.87	Downwind of Wastewater

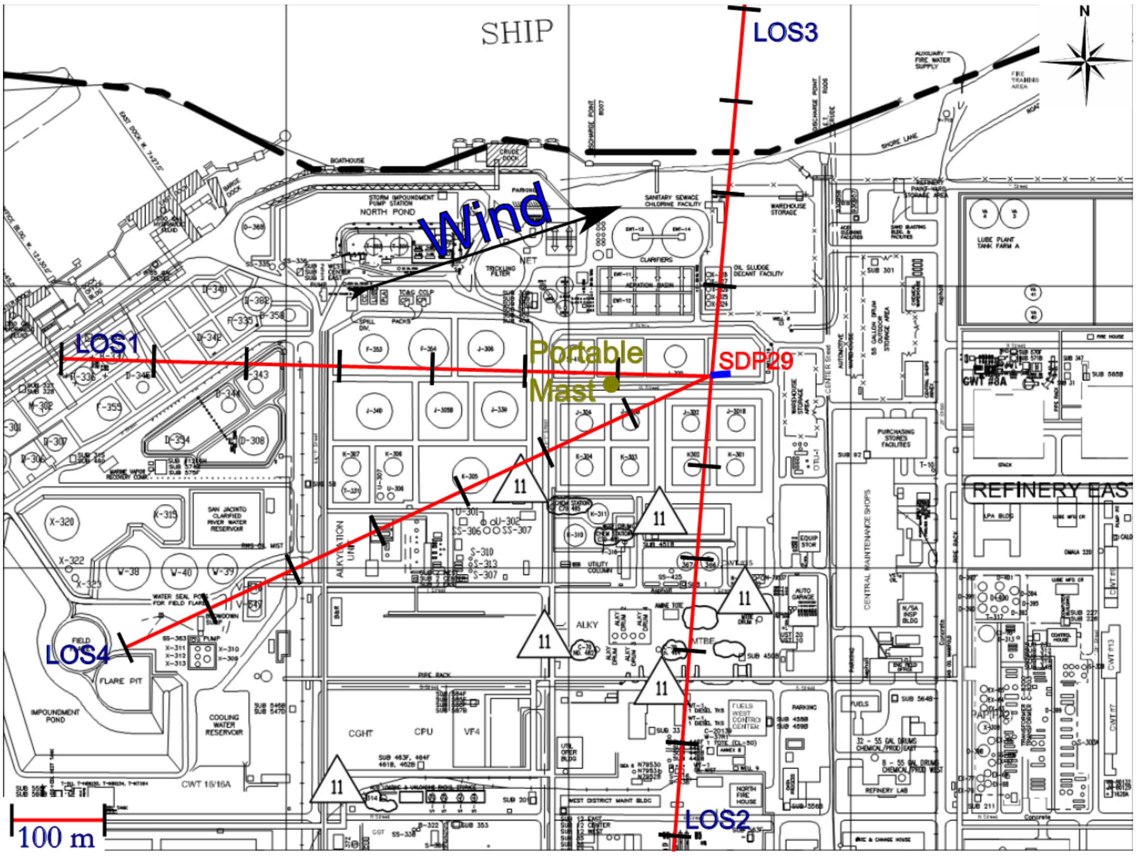

Figure 3.7 Measurement configuration for location SDP29 on 13th of February.

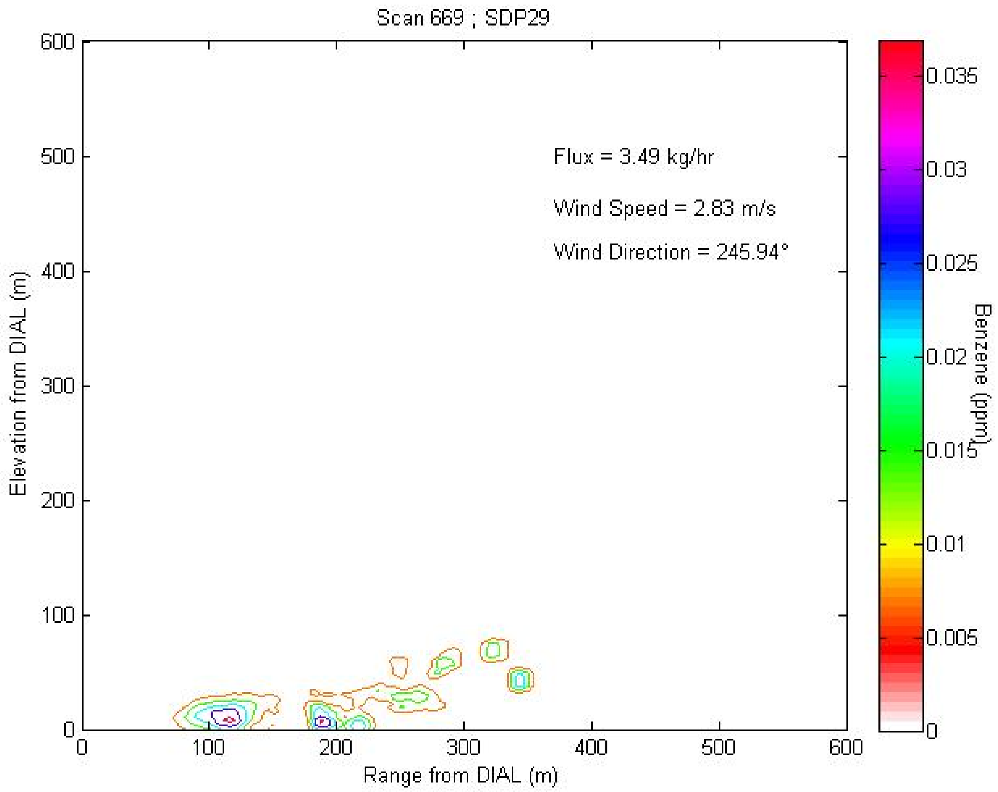

Figure 3.7a1 Contour plot of concentration profile for Scan 669 representing LOS2.

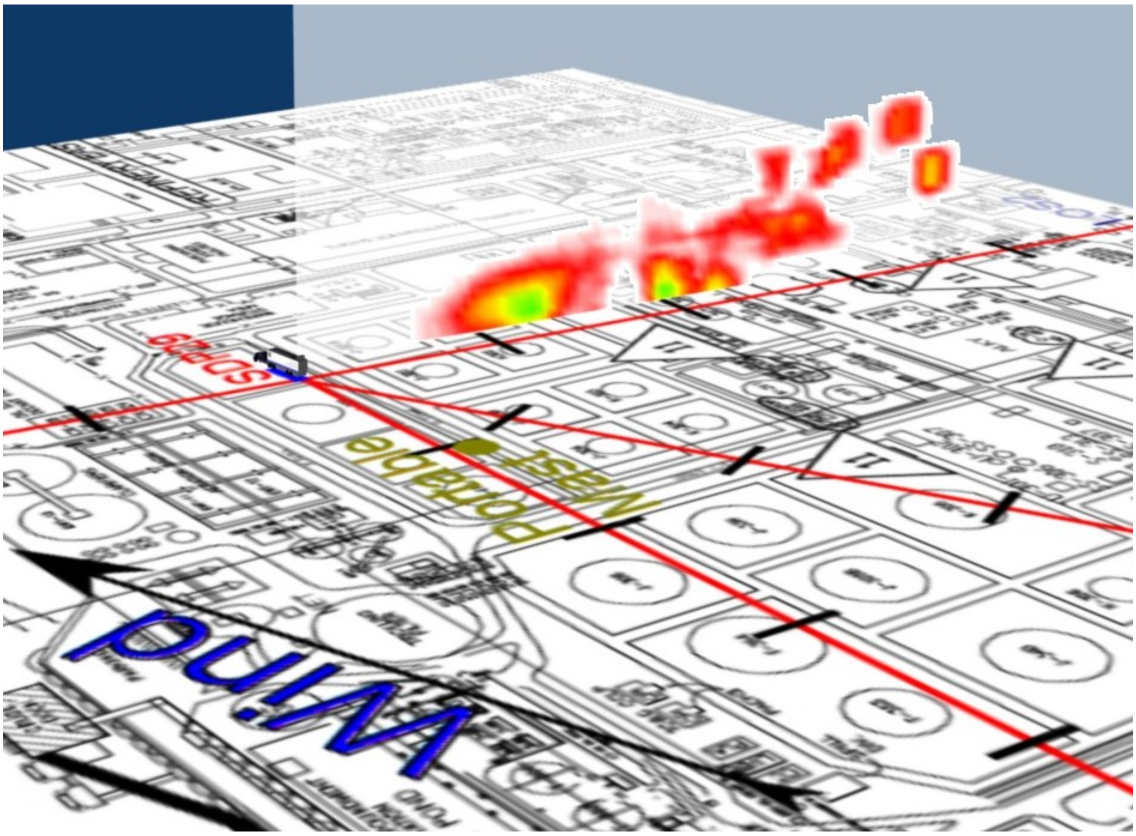

Figure 3.7a2 Visualisation of emission rate measured for Scan 669 representing LOS2.

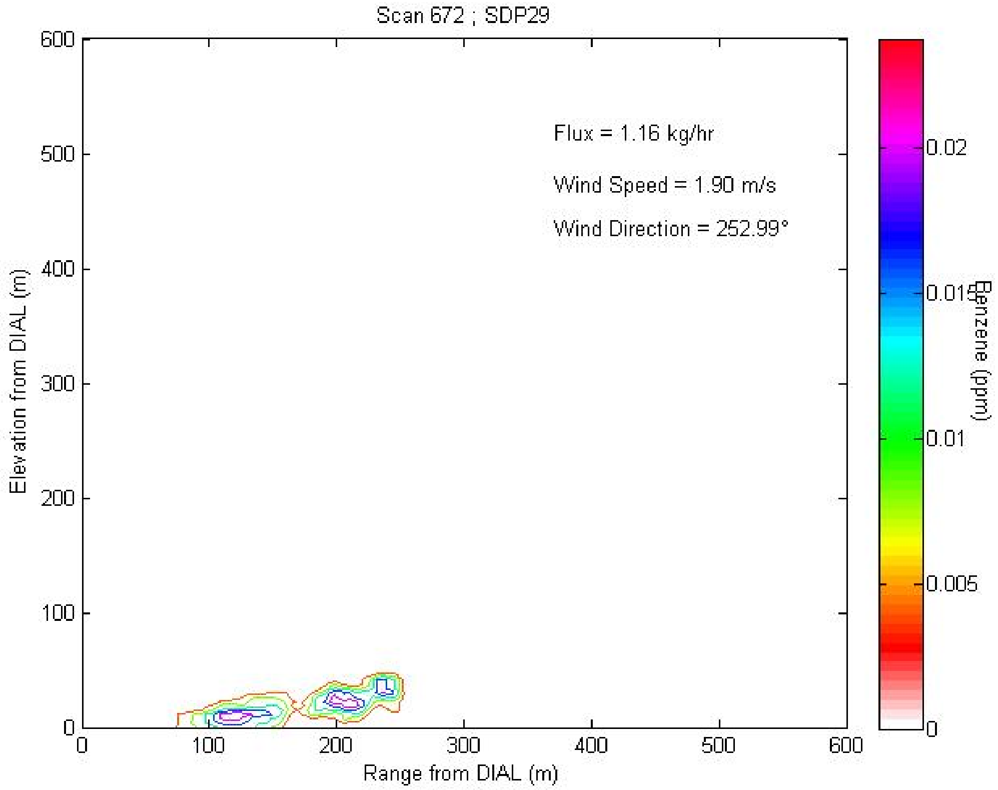

Figure 3.7b1 Contour plot of concentration profile for Scan 672 representing LOS3.

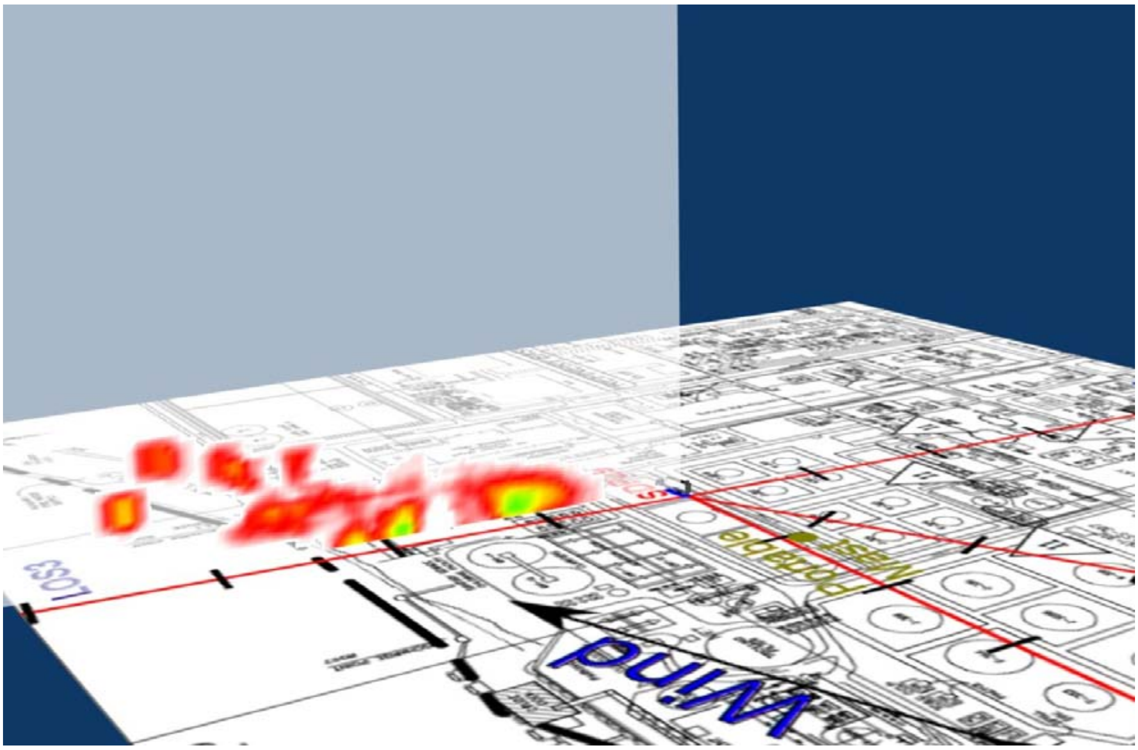

Figure 3.7b2 Visualisation of emission rate measured for Scan 672 representing LOS3.

Table 3.8 Emission rate measurements from SDP28 on 15th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
692	SDP28/LOS1	10:18	10:30	5.9	299.6	4.62	Downwind ACU & BEU
693	SDP28/LOS1	10:36	10:53	6.0	313.1	12.61	Downwind ACU & BEU
694	SDP28/LOS1	10:55	11:15	6.3	320.0	23.65	Downwind ACU & BEU
695	SDP28/LOS2	11:23	11:38	6.5	319.0	29.10	Downwind of D-381 Tank
696	SDP28/LOS2	11:40	11:58	6.1	316.9	17.54	Downwind of D-381 Tank
697	SDP28/LOS2	11:59	12:17	6.3	314.2	140.88	Downwind of D-381 Tank - Event
698	SDP28/LOS1	12:21	12:41	7.1	318.6	23.56	Downwind ACU & BEU
699	SDP28/LOS1	12:53	13:13	6.4	310.5	13.17	Downwind ACU & BEU
703	SDP28/LOS2	13:35	13:53	7.7	310.5	61.06	Downwind of D-381 Tank
704	SDP28/LOS2	13:54	14:12	7.3	315.4	53.35	Downwind of D-381 Tank
705	SDP28/LOS1	14:18	14:33	7.5	319.8	16.23	Downwind ACU & BEU
706	SDP28/LOS1	14:36	14:44	7.6	317.9	3.16	Downwind ACU & BEU
707	SDP28/LOS1	14:45	15:09	7.1	308.3	15.00	Downwind ACU & BEU
708	SDP28/LOS2	15:17	15:38	7.4	312.0	42.59	Downwind of D-381 Tank
709	SDP28/LOS2	15:46	16:11	7.3	309.1	32.08	Downwind of D-381 Tank
710	SDP28/LOS2	16:19	16:37	6.4	319.5	20.51	Downwind of D-381 Tank
711	SDP28/LOS2	17:03	17:13	5.6	311.1	11.54	Downwind of D-381 Tank

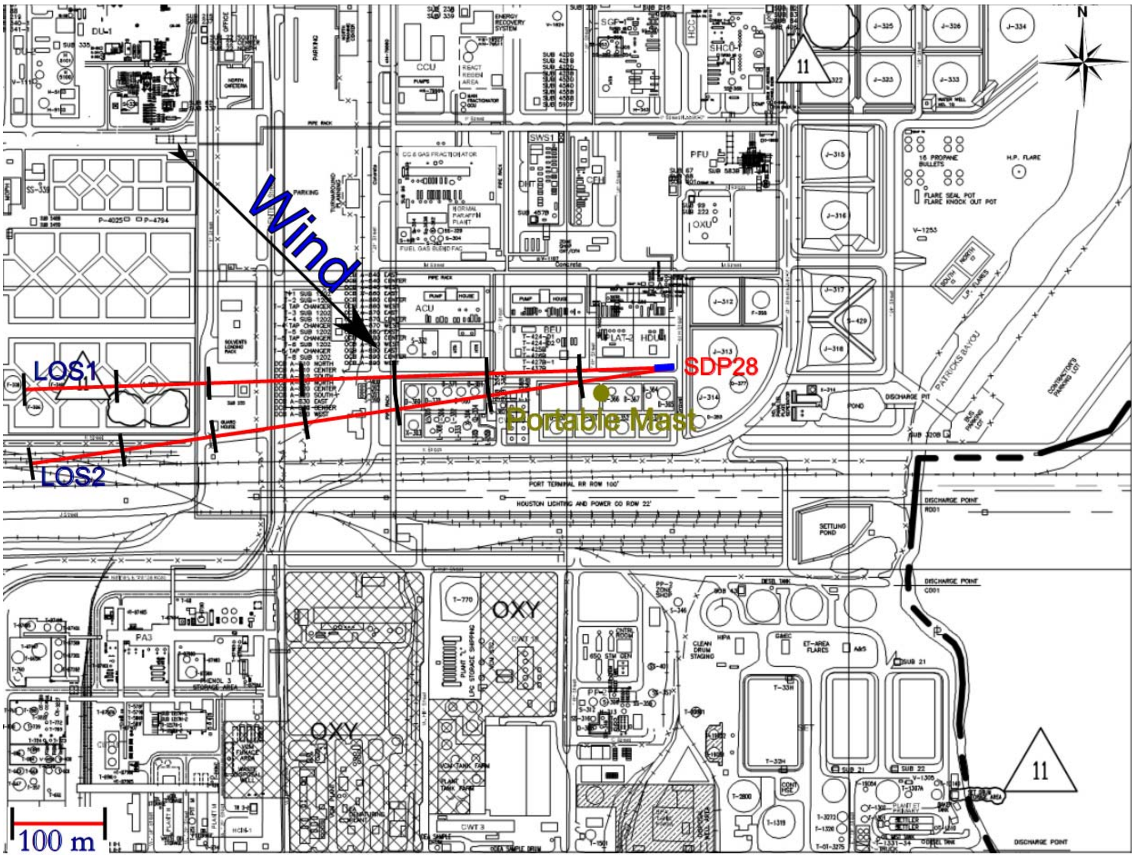

Figure 3.8 Measurement configuration for location SDP28 on 15th of February.

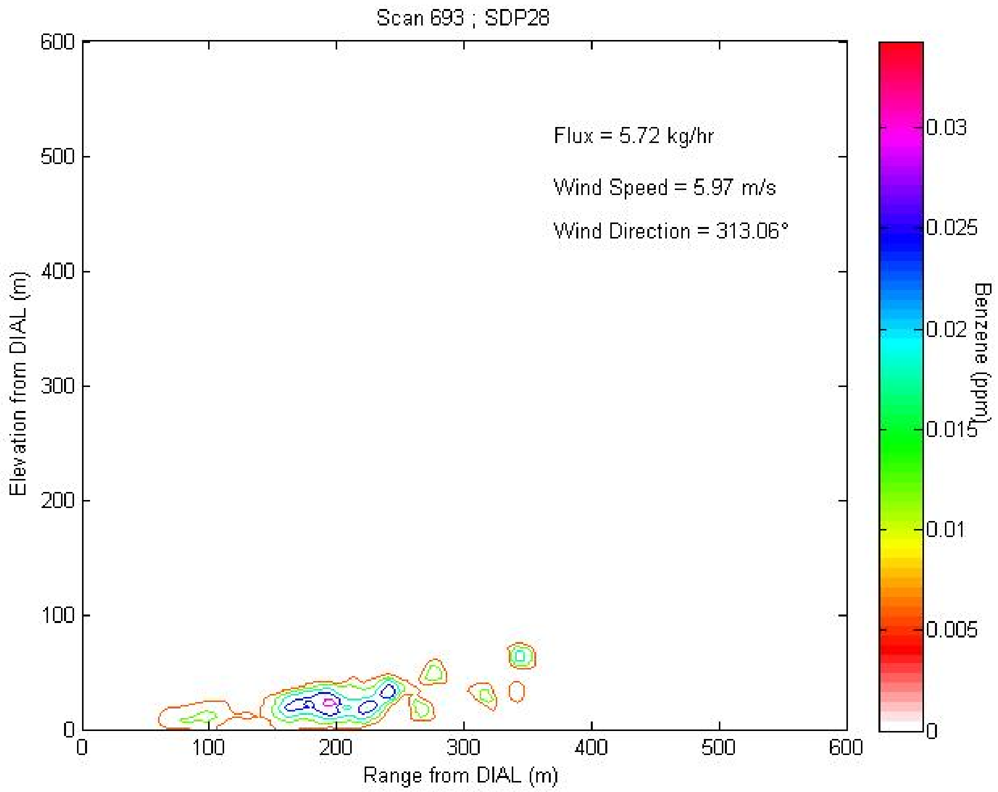

Figure 3.8a1 Contour plot of concentration profile for Scan 693 representing LOS1.

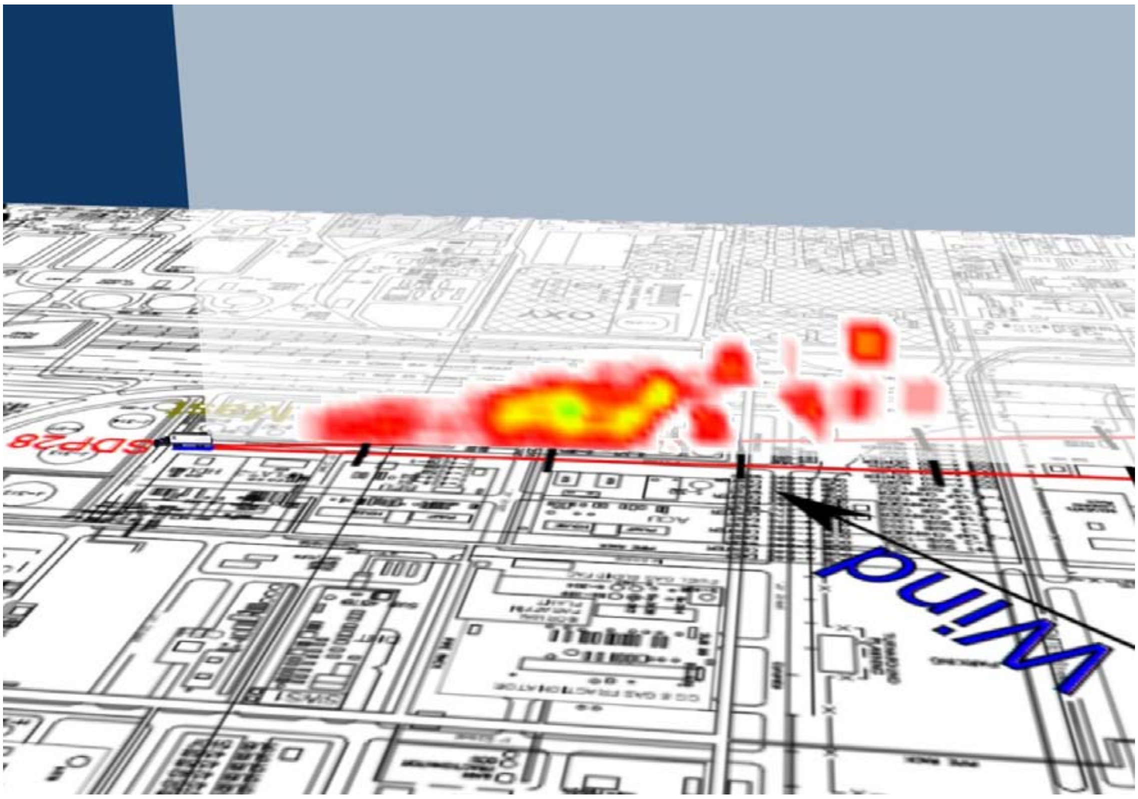

Figure 3.8a2 Visualisation of emission rate measured for Scan 693 representing LOS1.

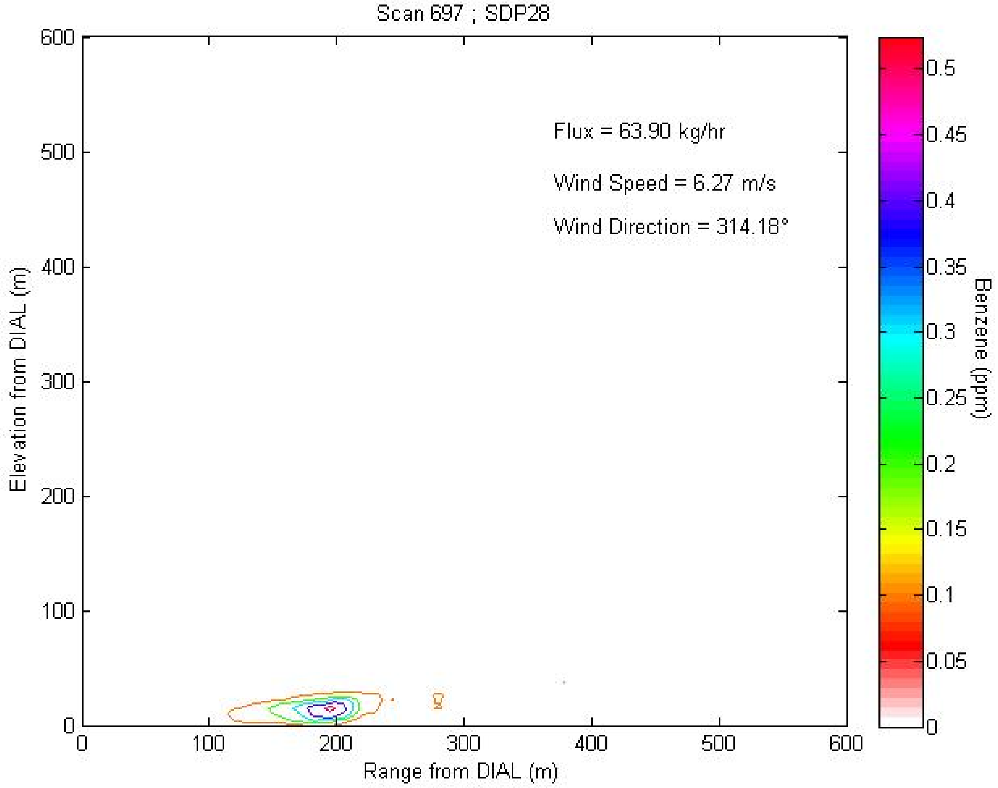

Figure 3.8b1 Contour plot of concentration profile for Scan 697 representing LOS2.

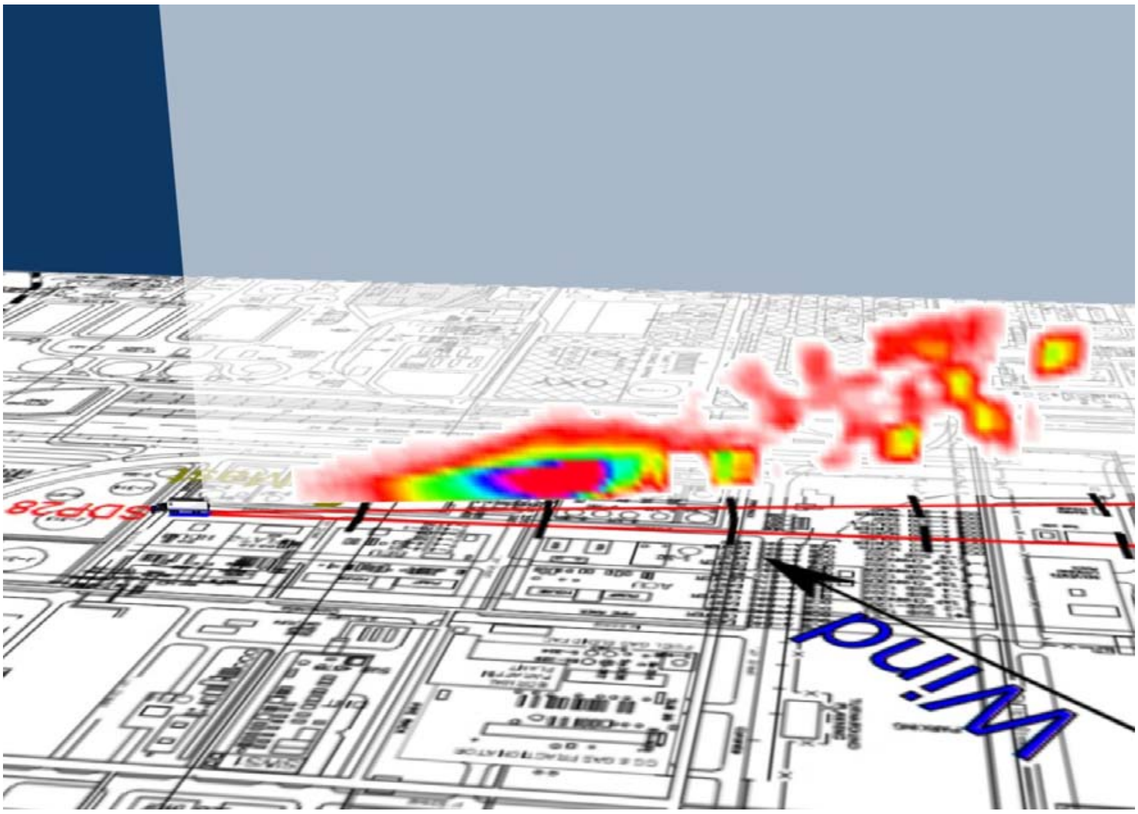

Figure 3.8b2 Visualisation of emission rate measured for Scan 697 representing LOS2.

Table 3.9 Emission rate measurements from SDP30 on 16th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
714	SDP30/LOS1	10:06	10:17	3.5	341.2	4.27	Downwind Refinery West Tanks
715	SDP30/LOS1	10:19	10:30	3.4	339.5	7.39	Downwind Refinery West Tanks
716	SDP30/LOS1	10:31	10:43	3.0	338.2	5.41	Downwind Refinery West Tanks
717	SDP30/LOS2	10:52	11:10	1.7	335.4	4.73	Downwind Refinery West Tanks
718	SDP30/LOS2	11:12	11:30	2.7	322.9	6.26	Downwind Refinery West Tanks
719	SDP30/LOS2	11:31	11:49	2.8	319.2	6.58	Downwind Refinery West Tanks
720	SDP30/LOS1	11:52	12:04	3.9	292.1	5.07	Downwind Refinery West Tanks
721	SDP30/LOS1	12:05	12:25	4.1	292.8	4.38	Downwind Refinery West Tanks
722	SDP30/LOS1	12:27	12:47	4.2	327.6	4.48	Downwind Refinery West Tanks
727	SDP30/LOS3	14:10	14:23	4.8	331.1	0.43	Upwind Refinery West Tanks
728	SDP30/LOS3	14:34	14:47	4.6	325.7	1.14	Upwind Refinery West Tanks
731	SDP30/LOS3	16:08	16:21	5.6	334.8	0.98	Upwind Refinery West Tanks
732	SDP30/LOS2	16:33	16:43	5.2	337.8	5.88	Downwind Refinery West Tanks

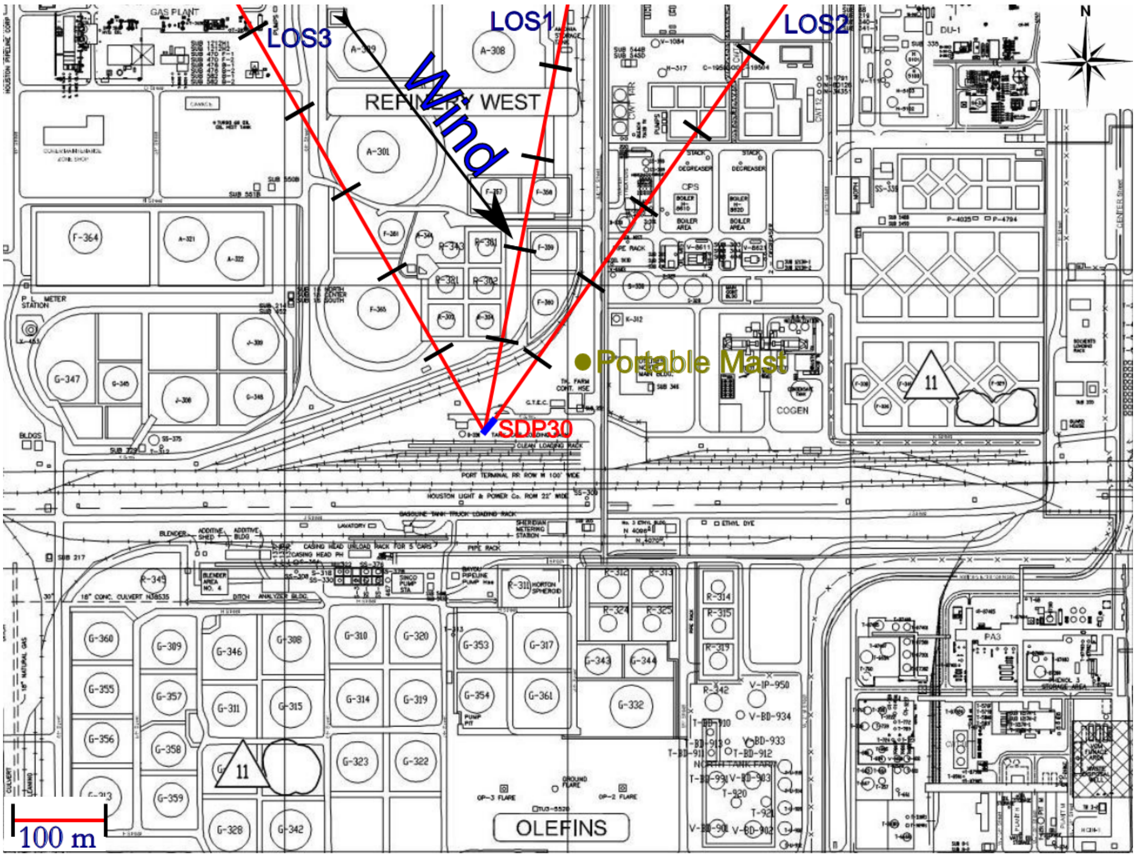

Figure 3.9 Measurement configuration for location SDP30 on 16th of February.

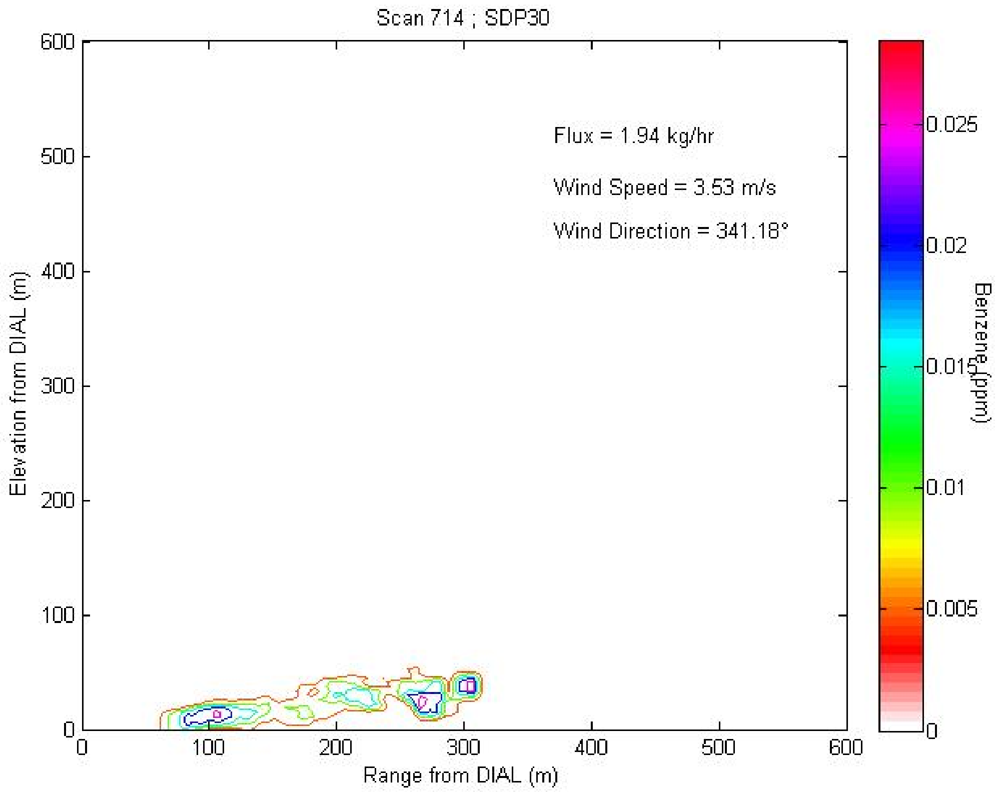

Figure 3.9a1 Contour plot of concentration profile for Scan 714 representing LOS1.

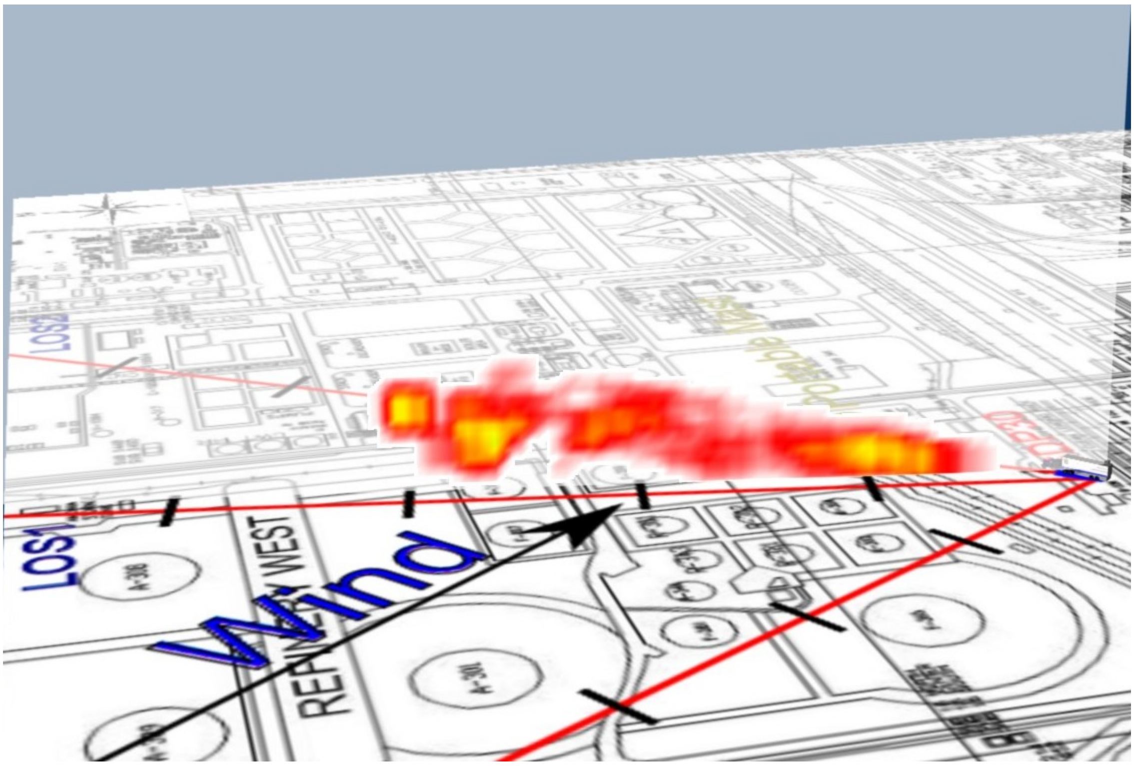

Figure 3.9a2 Visualisation of emission rate measured for Scan 714 representing LOS1.

Table 3.10 Emission rate measurements from SDP31 on 17th of February.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
736	SDP31/LOS1	10:06	10:23	2.7	311.6	14.99	Downwind of Coker
737	SDP31/LOS1	10:24	10:41	3.9	317.3	17.69	Downwind of Coker
738	SDP31/LOS1	10:42	11:01	4.0	330.0	20.86	Downwind of Coker
739	SDP31/LOS1	11:02	11:24	4.7	319.9	27.13	Downwind of Coker
740	SDP31/LOS2	11:29	11:43	5.2	321.3	-0.24	Upwind of Coker
741	SDP31/LOS2	11:43	11:57	5.7	321.0	0.20	Upwind of Coker
742	SDP31/LOS2	11:59	12:12	5.4	322.1	0.35	Upwind of Coker
743	SDP31/LOS3	12:19	12:34	5.3	318.3	34.26	Downwind of Coker
744	SDP31/LOS3	12:40	12:55	5.2	325.7	37.03	Downwind of Coker
745	SDP31/LOS3	12:56	13:11	5.3	325.1	37.97	Downwind of Coker
748	SDP31/LOS3	13:36	13:58	4.3	334.5	27.60	Downwind of Coker
749	SDP31/LOS3	13:59	14:20	3.7	331.5	20.23	Downwind of Coker
750	SDP31/LOS3	14:22	14:47	2.9	338.5	22.54	Downwind of Coker
751	SDP31/LOS3	14:56	15:16	4.7	325.4	48.83	Downwind of Coker
752	SDP31/LOS1	15:19	15:38	4.3	331.1	29.82	Downwind of Coker
753	SDP31/LOS2	15:48	16:07	4.1	331.1	-0.11	Upwind of Coker
754	SDP31/LOS1	16:14	16:33	3.9	328.8	22.11	Downwind of Coker
755	SDP31/LOS3	16:36	16:54	4.1	343.9	34.61	Downwind of Coker

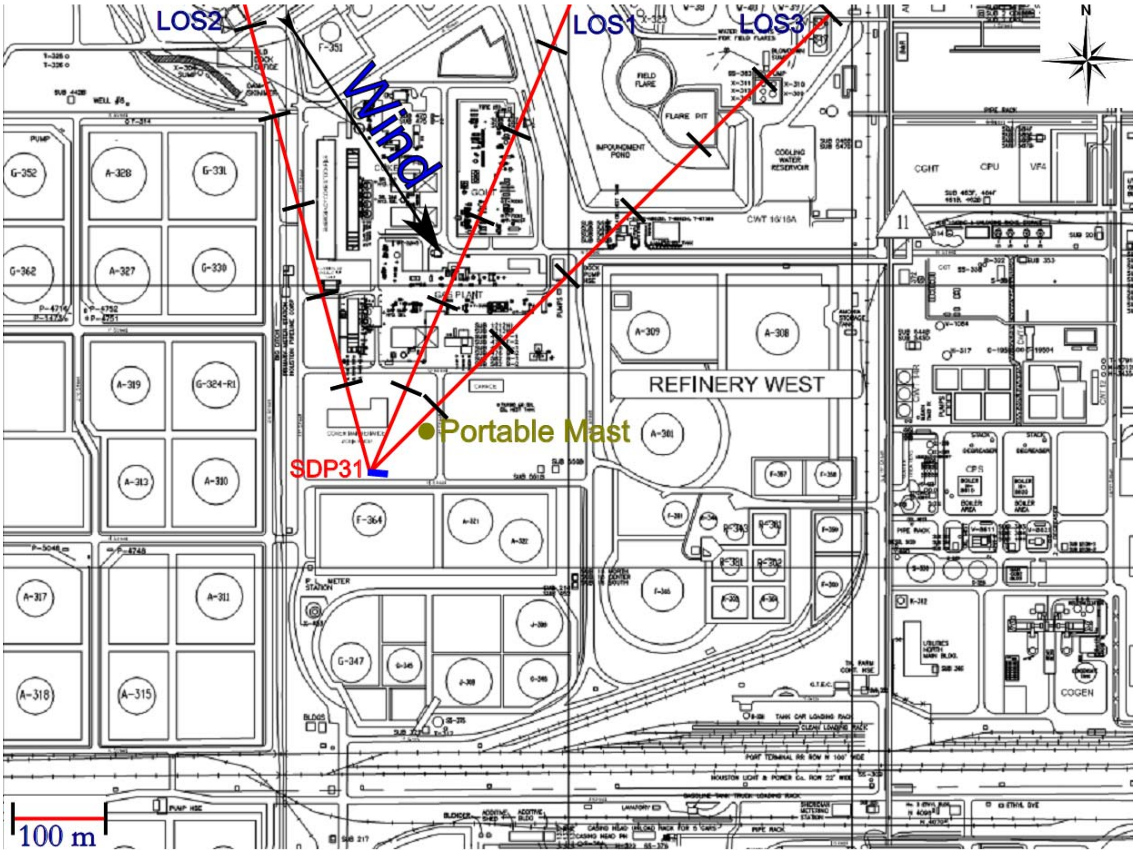

Figure 3.10 Measurement configuration for location SDP31 on 17th of February.

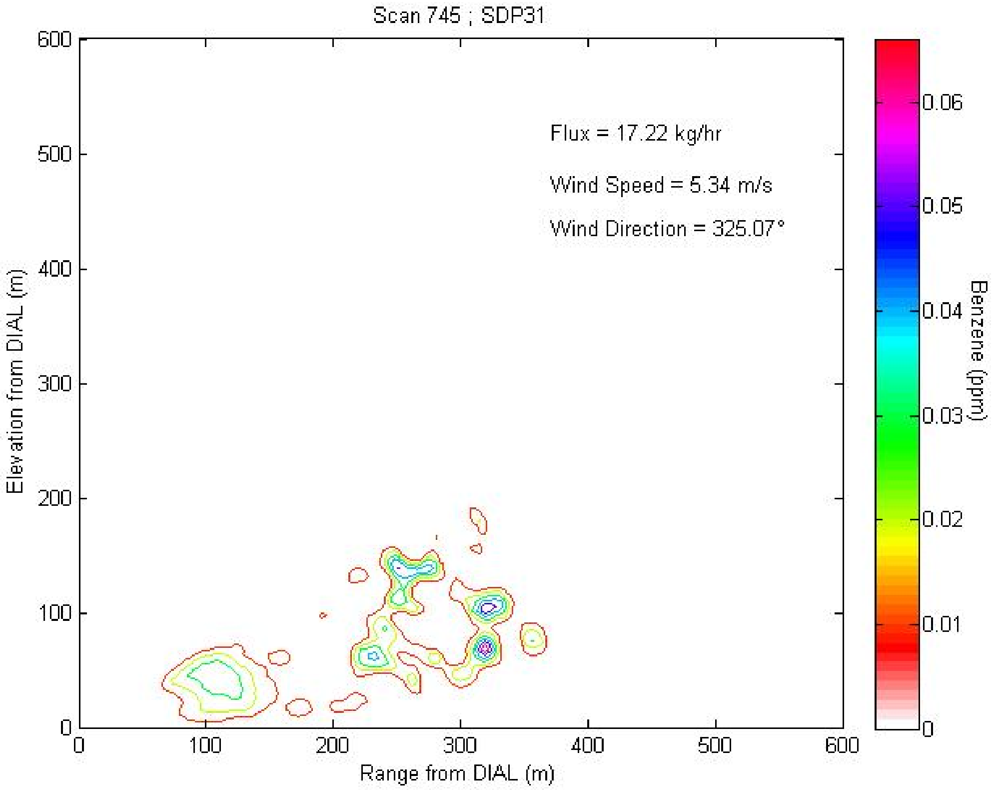

Figure 3.10a1 Contour plot of concentration profile for Scan 745 representing LOS3.

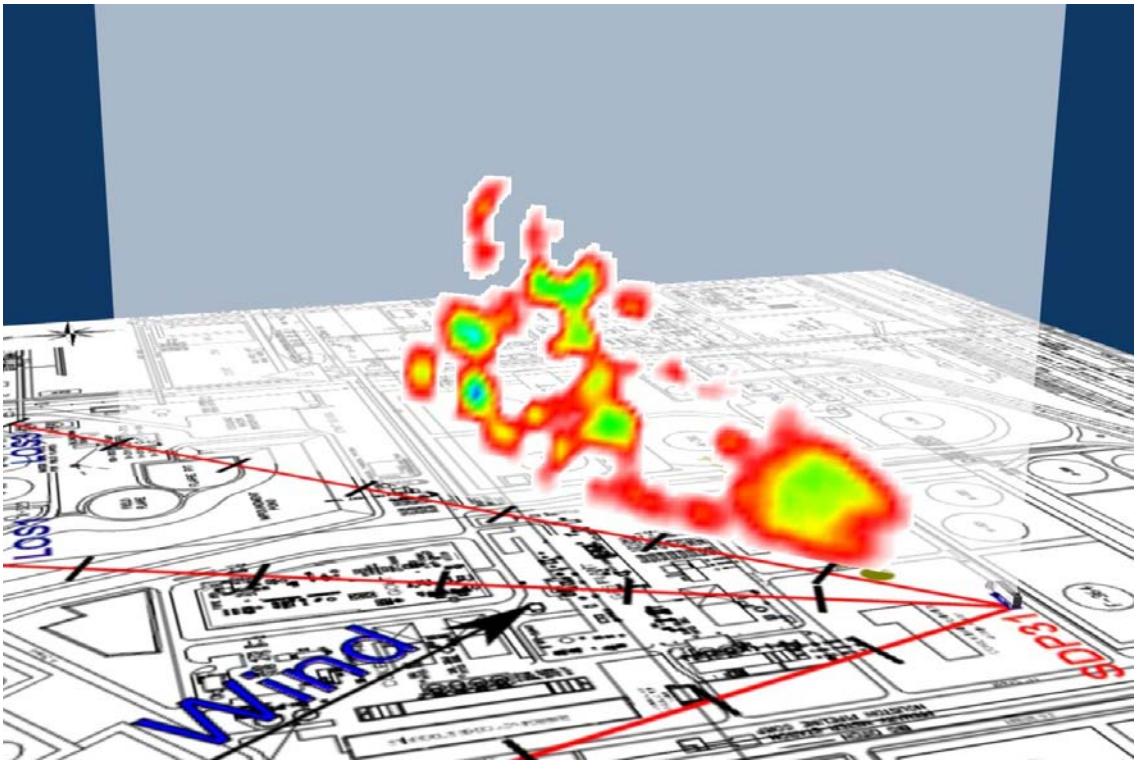

Figure 3.10a2 Visualisation of emission rate measured for Scan 745 representing LOS3.

Table 3.11 Emission rate measurements from SDP32 on 22nd of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
758	SDP32/LOS1	12:29	12:47	4.9	273.1	11.70	Downwind of D-352 Tank
759	SDP32/LOS1	12:58	13:14	4.5	294.2	3.56	Downwind of D-352 Tank
760	SDP32/LOS1	13:15	13:33	4.8	287.8	2.68	Downwind of D-352 Tank
764	SDP32/LOS2	13:57	14:15	4.6	296.0	0.04	Upwind of D-352 Tank
765	SDP32/LOS2	14:15	14:34	4.2	269.2	-0.07	Upwind of D-352 Tank
766	SDP32/LOS2	14:34	14:52	5.0	271.4	0.04	Upwind of D-352 Tank
768	SDP32/LOS1	14:53	15:11	4.9	281.7	5.75	Downwind of D-352 Tank
769	SDP32/LOS1	15:12	15:31	5.1	275.5	4.00	Downwind of D-352 Tank
770	SDP32/LOS1	15:32	15:50	5.3	285.7	2.71	Downwind of D-352 Tank
772	SDP32/LOS3	15:54	16:11	4.7	277.6	1.83	Downwind of D-379 Tank
773	SDP32/LOS3	16:11	16:28	4.2	273.5	0.46	Downwind of D-379 Tank
774	SDP32/LOS3	16:29	16:45	3.9	296.8	0.53	Downwind of D-379 Tank
775	SDP32/LOS2	16:46	17:04	4.1	302.4	0.05	Upwind of D-352 Tank
776	SDP32/LOS2	17:05	17:24	3.8	275.6	-0.01	Upwind of D-352 Tank

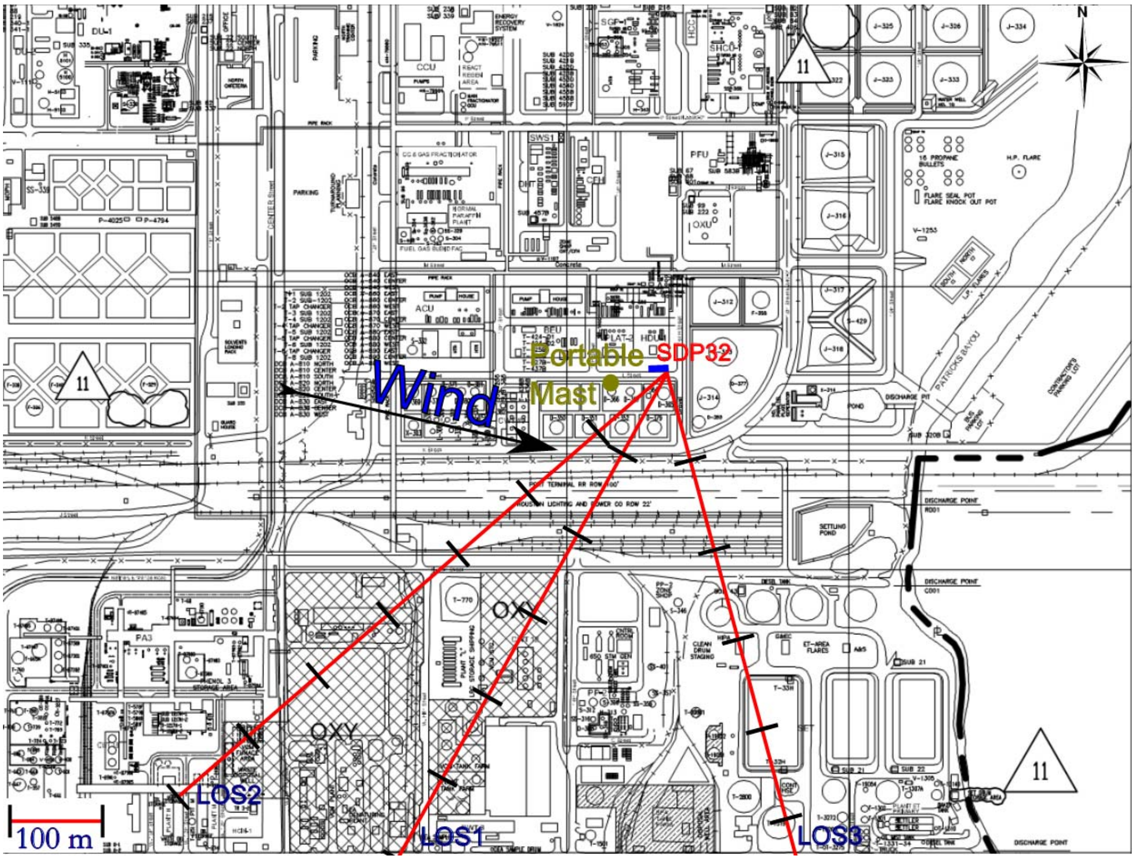

Figure 3.11 Measurement configuration for location SDP32 on 22nd of March.

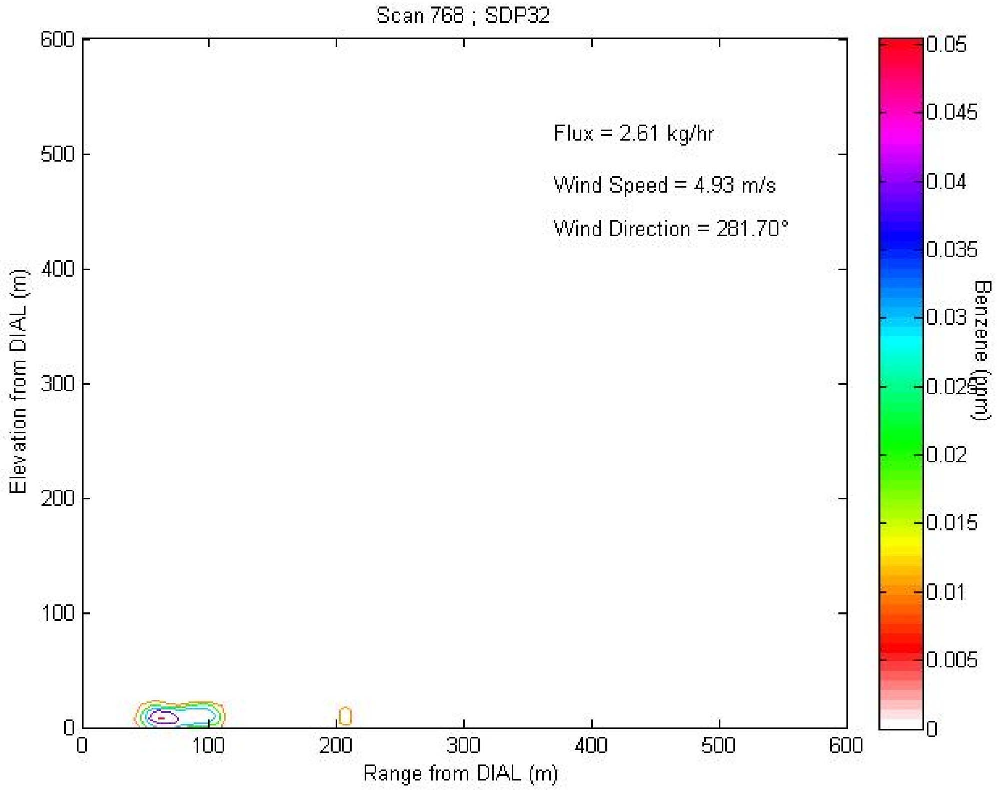

Figure 3.11a1 Contour plot of concentration profile for Scan 768 representing LOS1.

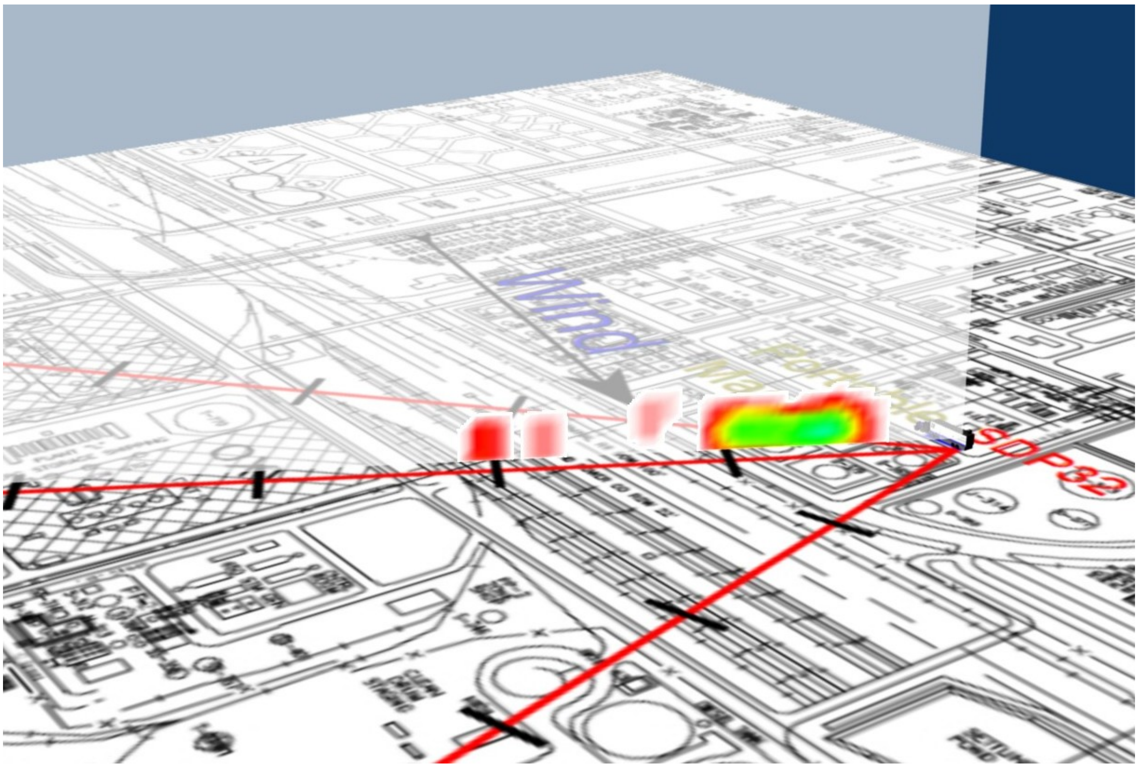

Figure 3.11a2 Visualisation of emission rate measured for Scan 768 representing LOS1.

Table 3.12 Emission rate measurements from SDP33 on 23rd of March.

Scan ID	Location / LOS	Start Time	End Time	Wind Speed	Wind Direction	Emission Rate	Notes
				m/s	Degrees	lbs/hr	
778	SDP33/LOS1	10:18	10:37	4.7	205.3	27.46	Downwind of T-OL913 Tank
779	SDP33/LOS1	10:37	10:56	4.7	192.7	17.50	Downwind of T-OL913 Tank
780	SDP33/LOS1	10:59	11:18	4.7	183.0	29.87	Downwind of T-OL913 Tank
783	SDP33/LOS1	11:26	11:44	3.9	192.0	22.43	Downwind of T-OL913 Tank
784	SDP33/LOS1	11:44	12:03	3.5	188.0	22.78	Downwind of T-OL913 Tank
785	SDP33/LOS1	12:03	12:21	3.7	188.4	21.22	Downwind of T-OL913 Tank
786	SDP33/LOS1	12:22	12:40	3.3	163.5	17.85	Downwind of T-OL913 Tank
787	SDP33/LOS1	12:40	12:59	3.4	156.5	21.62	Downwind of T-OL913 Tank
788	SDP33/LOS1	12:59	13:17	4.0	158.5	21.20	Downwind of T-OL913 Tank
790	SDP33/LOS1	13:36	13:54	3.6	164.9	21.18	Downwind of T-OL913 Tank
791	SDP33/LOS1	13:54	14:13	4.1	165.7	22.66	Downwind of T-OL913 Tank
792	SDP33/LOS1	14:13	14:31	4.7	167.5	29.08	Downwind of T-OL913 Tank
793	SDP33/LOS1	14:31	14:50	4.7	164.0	26.65	Downwind of T-OL913 Tank
794	SDP33/LOS1	14:50	15:08	4.6	166.3	27.38	Downwind of T-OL913 Tank
795	SDP33/LOS1	15:08	15:27	5.3	174.6	24.11	Downwind of T-OL913 Tank
796	SDP33/LOS1	15:27	15:45	5.7	189.2	32.50	Downwind of T-OL913 Tank
798	SDP33/LOS1	15:51	16:10	5.6	178.8	29.25	Downwind of T-OL913 Tank
799	SDP33/LOS1	16:10	16:28	5.8	161.8	26.92	Downwind of T-OL913 Tank
800	SDP33/LOS1	16:28	16:47	5.4	174.2	29.66	Downwind of T-OL913 Tank
801	SDP33/LOS1	16:47	17:05	5.9	164.6	25.72	Downwind of T-OL913 Tank

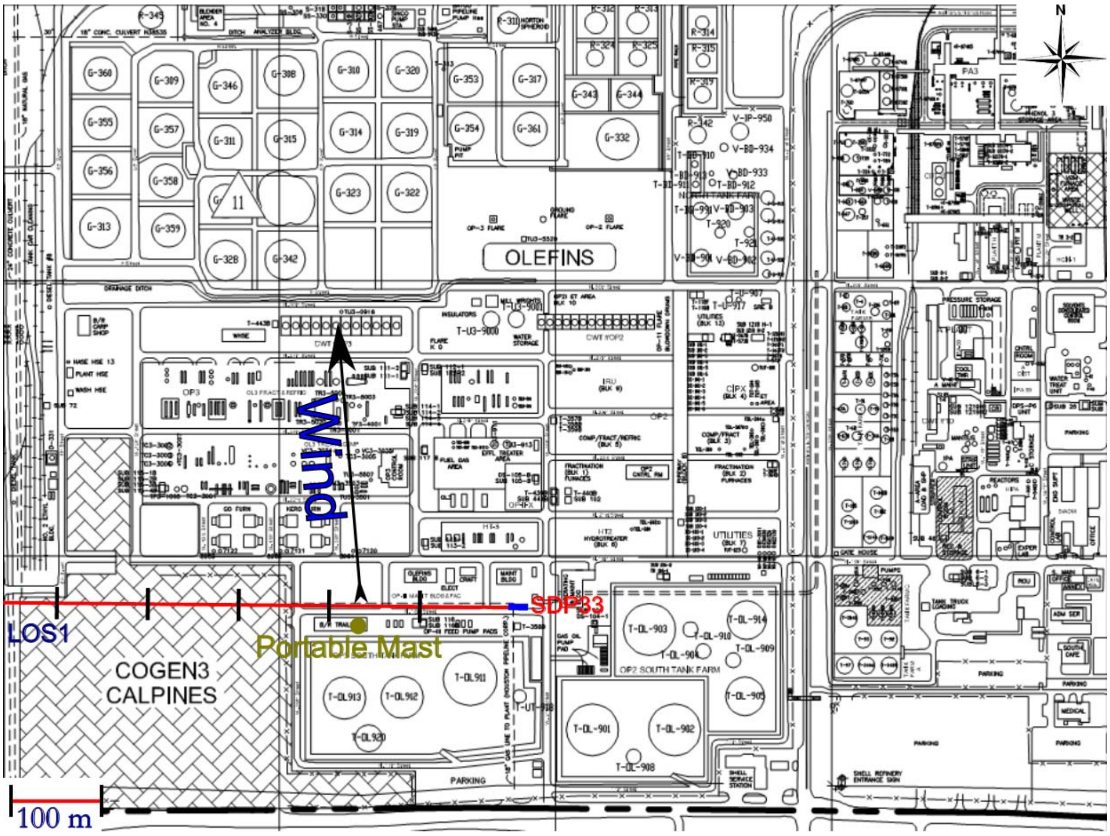

Figure 3.12 Measurement configuration for location SDP33 on 23rd of March.

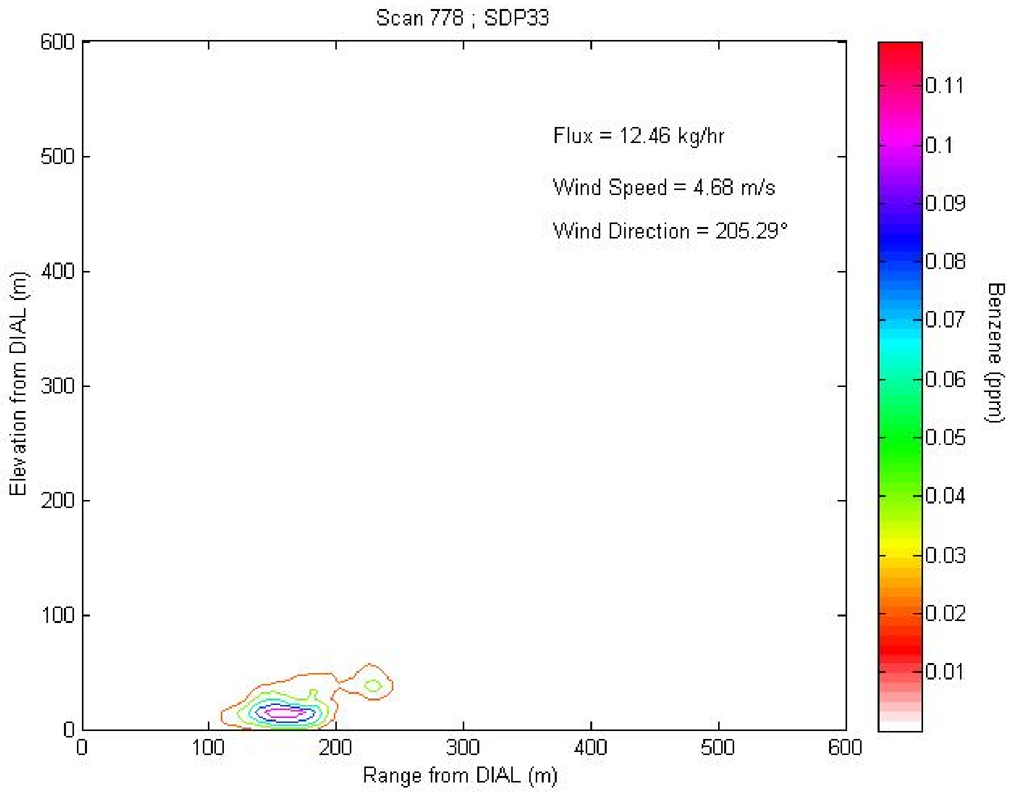

Figure 3.12a1 Contour plot of concentration profile for Scan 778 representing LOS1.

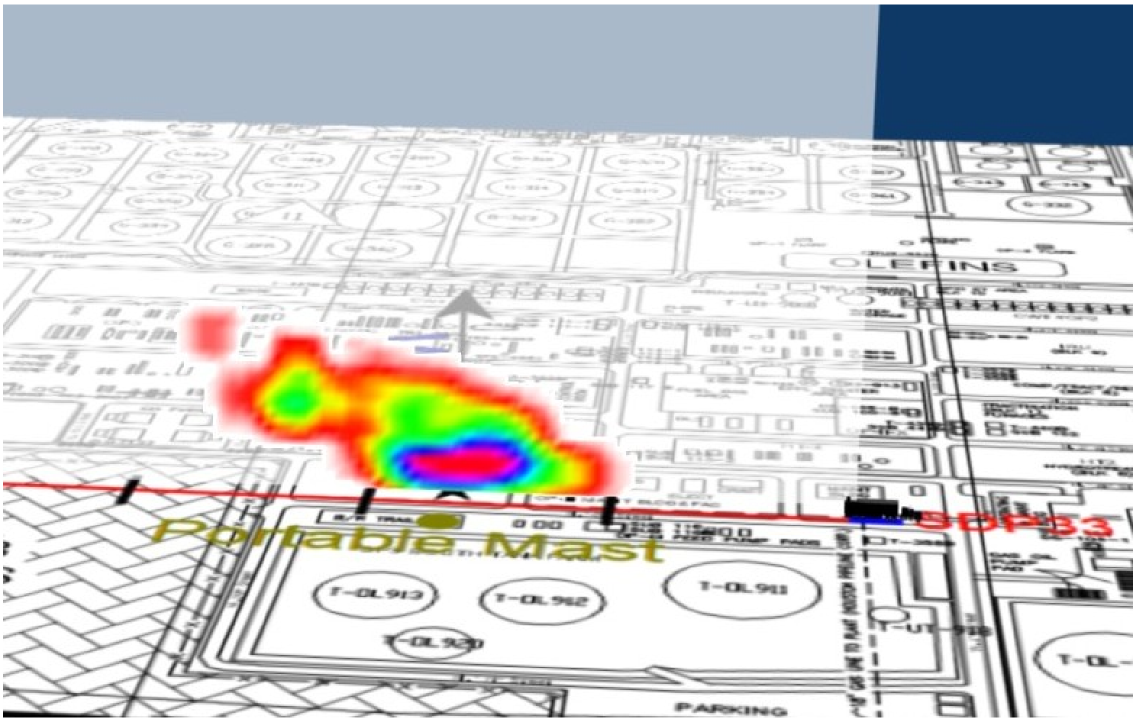

Figure 3.12a2 Visualisation of emission rate measured for Scan 778 representing LOS1.

Table 3.13 **Summary of benzene emission rate measurements.**
*** For single measurement it is not possible to provide the standard deviation, however, the typical uncertainty for a single measurement is about 20%.**

Date	Location/ LOS/ Figure	Notes	Elevation Angles	Average Flux	Standard Deviation
			degree	lbs/hr	lbs/hr
8-Feb	SDP23/LOS1/Fig 3.1	Downwind SW AP Tanks	2 - 8	2.3	0.4
8-Feb	SDP23/LOS2/Fig 3.1	Downwind SW AP Tanks	1.7 - 7.7	2.8	0.9
8-Feb	SDP24/LOS1/Fig 3.2	Downwind of T-OL913 Tank	2.6 - 10.6	6.2	1.7
8-Feb	SDP24/LOS1/Fig 3.2	Downwind T-OL913 Low Elevation	2.6 - 4.6	1.2	0.3
9-Feb	SDP25/LOS1/Fig 3.3	Downwind of Wastewater	0 - 5	6.4	1.8
9-Feb	SDP25/LOS2/Fig 3.3	Downwind of Flare	10 - 15	1.5	0.3
10-Feb	SDP26/LOS1/Fig 3.4	Downwind T-OL913 Low Emission	2 - 21	0.4	0.4
10-Feb	SDP26/LOS1/Fig 3.4	Downwind T-OL913 High Emission	2 - 21	4.5	2.5
11-Feb	SDP27/LOS1/Fig 3.5	Downwind of the Coker	0 - 21	13.4	3.0
11-Feb	SDP27/LOS2/Fig 3.5	Downwind of the Coker	2 - 21	5.2	1.9
11-Feb	SDP27/LOS2/Fig 3.5	Downwind of the Coker - Event	2 - 21	27.0	
11-Feb	SDP27/LOS3/Fig 3.5	Downwind of the Coker	2 - 21	4.7	1.3
12-Feb	SDP28/LOS1/Fig 3.6	Downwind ACU & BEU 3.5°- 8.5°	3.5 - 8.5	10.8	1.1
12-Feb	SDP28/LOS1/Fig 3.6	Downwind ACU & BEU 3.5°- 17.5°	3.5 - 17.5	21.2	0.7
12-Feb	SDP28/LOS1/Fig 3.6	Downwind ACU & BEU 0°- 3.5°	0 - 3.5	5.6	0.6
12-Feb	SDP28/LOS1/Fig 3.6	ACU & BEU No 100-200m Plume	0 - 17.5	5.0	0.6
12-Feb	SDP28/LOS2/Fig 3.6	Downwind D-350 and D-351 Tanks	2 - 8	25.3	1.2
13-Feb	SDP29/LOS1/Fig 3.7	Downwind of J-339 Tank	3 - 10	0.5	0.2
13-Feb	SDP29/LOS2/Fig 3.7	Downwind of K-302 Tank	1 - 12	5.7	1.8
13-Feb	SDP29/LOS3/Fig 3.7	Downwind of Wastewater	2.5 - 10.5	3.9	0.7
13-Feb	SDP29/LOS4/Fig 3.7	Between J-304 and J-303B Tanks	4 - 13	0.5	0.2
15-Feb	SDP28/LOS1/Fig 3.8	Downwind ACU & BEU	2 - 15	12.8	7.9
15-Feb	SDP28/LOS2/Fig 3.8	Downwind of D-381 Tank	3 - 15	28.9	17.6
15-Feb	SDP28/LOS2/Fig 3.8	Downwind of D-381 Tank - Event	3 - 15	140.9	
16-Feb	SDP30/LOS1/Fig 3.9	Downwind Refinery West Tanks	4 - 15	5.2	1.2
16-Feb	SDP30/LOS2/Fig 3.9	Downwind Refinery West Tanks	5.5 - 15.5	5.9	0.8
16-Feb	SDP30/LOS3/Fig 3.9	Upwind Refinery West Tanks	5 - 14	0.8 *	0.4
17-Feb	SDP31/LOS1/Fig 3.10	Downwind of Coker	7 - 30	22.1	5.6
17-Feb	SDP31/LOS2/Fig 3.10	Upwind of Coker	7 - 30	0.0	0.3
17-Feb	SDP31/LOS3/Fig 3.10	Downwind of Coker	6 - 30	30.6	7.1
22-Mar	SDP32/LOS1/Fig 3.11	Downwind of D-352 Tank	2 - 20	5.1	3.4
22-Mar	SDP32/LOS2/Fig 3.11	Upwind of D-352 Tank	2 - 20	0.0	0.1
22-Mar	SDP32/LOS3/Fig 3.11	Downwind of D-379 Tank	2 - 20	0.9	0.8
23-Mar	SDP33/LOS1/Fig 3.12	Downwind of T-OL913 Tank	3 - 18.5	24.9	4.2

The calculations of the benzene emission rate from the different measured areas are described in the following sections.

3.1 MEASUREMENTS OF THE SW AP TANKS

- SDP23 on the 8th February, SE wind, Table and Figure 3.1.

- LOS1 2.3 lbs/hr, LOS2 2.8 lbs/hr (see Table 3.13).
- Figures 3.1a1 and a2 visual representation of Scan 545 (LOS1).

Similar emission rates are found from LOS1 and LOS2 and being in the region 100 - 200 m from the DIAL it is proposed that tank AP-18 is the main emission source with a possible contribution from tank AP-19.

3.2 MEASUREMENTS OF THE OP3 SOUTH TANK FARM AREA

- SDP24 on the 8th February, SE wind, Table and Figure 3.2.

\- LOS1 6.2 lbs/hr, LOS1 low elevation angle 1.2 lbs/hr (see Table 3.13).
\- Figures 3.2a1 and a2 visual representation of Scan 555 (LOS1).

The emission plume for LOS1 is in the region 200 - 300 m from the DIAL, and the main emission is detected at higher elevation angle just above the buildings in the “Cogen3 Calpines” area. This is confirmed by the scans carried out scanning only at the lower elevation angles that show a low emission rate, 1.2 lbs/hr compared with 6.2 lbs/hr from all the elevation angles. Tanks T-OL913 and T-OL920 are possible sources of emission.

- SDP26 on the 10th February, very variable wind from E to SW, Table and Figure 3.4.

\- LOS1 high emission 4.5 lbs/hr, LOS1 low emission 0.4 lbs/hr (see Table 3.13).
\- Figures 3.4a1 and a2 visual representation of Scan 614 (LOS1).

The measurements were very difficult because of the high variability of the wind direction. The scans have been divided into high emission scans when the wind direction is from SSW to SSE and low emission scans when the wind is from east. Because of the wind variability, the scan division is not straightforward and some of the scans chosen as high emission have a relatively low emission. As consequence, the standard deviation of the high emission scans is relatively large. Nonetheless, the emission rate is similar to the emission measured from SDP24. Figures 3.4a1 and a2 show a plume in the region 200 - 250 m from the DIAL for a wind coming from south confirming tanks T-OL913 and T-OL920 as possible emission sources.

- SDP33 on the 23rd March, S wind, Table and Figure 3.12.

\- LOS1 24.9 lbs/hr (see Table 3.13).
\- Figures 3.12a1 and a2 visual representation of Scan 778 (LOS1).

The emission plume is at 200 m from the DIAL for wind from SSE and at about 150 m from the DIAL for wind from the SSW as in Figures 3.12a1 and a2. The measured emission rate is higher than the emission rate measured from SDP24 and SDP26. This difference could be real or possibly some of the emission rate in the previous scans wasn’t detected because of the buildings in the “Cogen3 Calpines” area obstructing the DIAL LOS at lower elevation angles. Both tanks T-OL913 and T-OL920 are possible emission sources.

3.3 MEASUREMENTS OF NORTH WASTEWATER AREA

- SDP25 on the 9th February, NNW wind, Table and Figure 3.3.

\- LOS1 6.4 lbs/hr, LOS2 1.5 lbs/hr (see Table 3.13).
\- Figures 3.3a1, a2, b1 and b2 visual representation of Scans 571 (LOS1) and 574 (LOS2).

The emission for LOS1 is in the region 250 - 400 m from the DIAL suggesting multiple sources including the trickling filter (TKRFIL), SDAF (EWT-10), NDAF (EWT-11), FLCCULTR (EWT-8), FLSHMIX (EWT-7), X316, X-330, X330SM, CCLP (T-301) and TC&G (T-302).

Scans along LOS2 measure the emission from the North Property Flare (FLN FLARE) as marked in Figure 3.3. The emission rate is very low and close to the DIAL detection limit emission rate. However, a small plume is consistently detected at 400 m range from the DIAL.

- SDP29 on the 13th February, WSW wind, Table and Figure 3.7.

- LOS1 0.5 lbs/hr, LOS2 5.7 lbs/hr, LOS3 3.9 lbs/hr, LOS4 0.5 lbs/hr (see Table 3.13).
- Figures 3.7a1, a2, b1 and b2 visual representation of Scans 669 (LOS2) and 672 (LOS3).

The emission plume measured from LOS3 is in the region 100 - 250 m from the DIAL showing possibly two emission sources. The plume from just below 100 m to about 150 m from the DIAL could arise from any of the following sources: the trickling filter (TKRFIL), SDAF (EWT-10), NDAF (EWT-11), FLCCULTR (EWT-8), FLSHMIX (EWT-7), X316, EWT-13, EWT-14, NAB (EWT-11) and SAB (EWT-12). The emission in the region 150 - 250 m from the DIAL is possibly coming from an area east of the trickling filter as observed from SDP25/LOS1 including X-330, X330SM, CCLP (T-301) and TC&G (T-302). The emission rate is similar to the emission measured from SDP25/LOS1 taking into consideration that the emission sources are at significant distance from the DIAL locations and LOSs.

Scans along LOS1 and LOS4 measure the area just south of wastewater and they don’t show any emission above the DIAL detection limit.

Scans from LOS2 measure the emission from the east part of the area south of wastewater. The emission plume is wide from ranges less than 100 m to beyond 300 m from the DIAL. It is difficult to pinpoint the emission sources that could be nearby in the area between LOS1 and LOS4. The source of the plume at about 100 m could be tank K-302 or the area with tanks K-310 and K-311 or possibly even upwind of them. The source of the plume at about 200 m and above could be the tank F-367 or a source upwind of it.

3.4 MEASUREMENTS OF THE COKER AREA

- SDP27 on the 11th February, E wind, Table and Figure 3.5.

- LOS1 13.4 lbs/hr, LOS2 5.2 lbs/hr, LOS2 event (Scan 633) 27.0 lbs/hr, LOS3 4.7 lbs/hr (see Table 3.13).
- Figures 3.5a1, a2, b1 and b2 visual representation of Scans 620 (LOS1) and 633 (LOS2).

Scans from LOS1 are downwind of all the Coker area. The observed emission is wide and at high elevation and it is divided in two plumes. Considering the wind direction, the first plume could be associated to southern Coker drums 5 and 6 and the second to the northern Coker drums 1, 2, 3 and 4.

Measurements along LOS2 and LOS3 are downwind of southern Coker drums 5 and 6 and upwind of northern Coker drums 1, 2, 3 and 4. The emission rates measured from LOS1 and LOS2 are similar and related to the emission from the Coker drums 5 and 6 area. It is possible to estimate the emission of the Coker drums 1, 2, 3 and 4 area from difference with respect to the average emission rate measured from LOS2 and LOS3 (5.0 ±1.5 lbs/hr) to the emission rate measured from LOS1. The resulting emission rate from the Coker drums 1, 2, 3 and 4 area is 8.4 ± 3.4 lbs/hr.

A higher emission was measured from LOS2 during Scan 633 from 15:42 to 15:48. This event correlates with the drain phase of the Coker drum 5 cycle.

• SDP31 on the 17th February, E wind, Table and Figure 3.10.
- LOS1 22.1 lbs/hr, LOS2 0.0 lbs/hr, LOS3 30.6 lbs/hr (see Table 3.13).
- Figures 3.10a1, a2, b1 and b2 visual representation of Scan 745 (LOS3).

Scans from LOS2 area upwind of the Coker area, no emission is detected above the DIAL detection limit.

The measurements from LOS1 and LOS3 are downwind of the Coker area. The emission plume is wide, from before 100 m to beyond 300 m range from the DIAL. The emission rates measured from LOS1 and LOS3 are similar. The plume around 100 m from the DIAL could be associated with emission from the southern Coker area. The plume beyond 200 m from the DIAL could be from the northern Coker area and the GOHT although it is possible that other sources north of the Coker are contributing to the measured emission rate such as the West Dock and tanks F-347, F-349 and D-363. This could explain why the emission rate is higher compared with the emission rate measured from SDP27/LOS1.

3.5 MEASUREMENTS OF ACU & BEU AREA

• SDP28 on the 12th February, NW wind, Table and Figure 3.6.
- LOS1 26.8 lbs/hr, LOS1 no 100-200 m plume 5.0 lbs/hr, LOS2 25.3 lbs/hr (see Table 3.13).
- Figures 3.6a1, a2, b1 and b2 visual representation of Scans 647 (LOS1) and 658 (LOS2).

The measurements from LOS1 are downwind of the BEU and ACU area. The observed plume is wide and at high elevation, consequently for some of the scans the elevation angle isn’t high enough to detect the whole plume. The total emission is calculated by adding the average emission rate from Scans 646 to 648 to the average emission rate from Scans 649 to 651 obtaining an emission of 26.8 ± 0.9 lbs/hr.

Scans 654 to 656 from LOS1 show lower emission with respect to the other scans from LOS1. The plume in the 100 - 200 m region that is observed in previous scans doesn’t appear in Scans 654 to 656. This is possibly due to the plume source ceasing benzene emission or because the wind shift toward west is enough to move the emission rate towards the DIAL during Scans 654 to 656. The latter case is the most likely if the emission source was far away from LOS1, i.e. north of ACU and EBU area.

Scans along LOS2 are downwind of tanks D-350 and D-351 and they are carried out just after Scans 654 to 656 and can therefore be used as upwind measurements. The plume is in the region 100 - 200 m from the DIAL suggesting that tank D-350 is the most likely emission source. The fact that the plume measured from LOS2 is smaller than the plume observed from LOS1 before Scans 654 to 656 (compare Figures 3.6a1 and 3.6b1) confirms that the source of emission measured from LOS1 before Scans 654 to 656 is not present in LOS2. The average emission rate measured from LOS2 after the subtraction of the upwind emission rate from Scans 654 to 656 is 20.3 ± 1.3 lbs/hr.

• SDP28 on the 15th February, NW wind, Table and Figure 3.8.
- LOS1 12.8 lbs/hr, LOS2 28.9 lbs/hr, LOS2 event 140.9 lbs/hr (see Table 3.13).
- Figures 3.8a1, a2, b1 and b2 visual representation of Scans 693 (LOS1) and 697 (LOS2).

The measurements from LOS1 are downwind of the BEU and ACU area. The measured emission rate is very variable during the day, as low as about 3 lbs/hr and as high as 23 lbs/hr. This is similar to the low and high emission measurements carried out from SDP28/LOS1 on the 12th February. The plume is wide and centred at about 200 m from the DIAL implying that the ACU area is the main emission source.

Scans from LOS2 are downwind of tank D-381 and just south of LOS1. The average emission rate from the first two scans, Scans 695 and 696, is 23.3 ± 8.2 lbs/hr and it is similar to that measured at LOS1, 12.8 ± 7.9 lbs/hr. High emission rate is measured in Scan 697 (140.9 lbs/hr) and slowly decreases during the day towards the emission measured before the event and similar to what is measured from LOS1. After the event in Scan 697 the emission rates measured from LOS2 are: 61.1, 53.3, 42.6, 32.1, 20.5 and 11.5 lbs/hr. Between these scans some measurements from LOS1 are taken showing lower emission with respect to the emission rates at LOS2 (compare scans 698 (23.6 lbs/hr) and 699 (13.2 lbs/hr) from LOS1 with scans 703 (61.1 lbs/hr) and 704 (53.3 lbs/hr) from LOS2 just after the event on Scan 697) and similar to the measurements from LOS1 taken before the event. This implies that the source of the event is in the area between LOS1 and LOS2 at about 200 m from the DIAL with tanks D-381 and D-380 the most likely sources of emissions.

• SDP32 on the 22nd March, W wind, Table and Figure 3.11.
- LOS1 5.1 lbs/hr, LOS2 0.0 lbs/hr, LOS3 0.9 lbs/hr (see Table 3.13).
- Figures 3.11a1 and a2 visual representation of Scan 768 (LOS1).

The emission plume from LOS1 is just above 50 m from DIAL suggesting tank D-352 as the source. This is confirmed by the upwind emission rate of tanks D-352 taken from LOS2 showing no emission. The emissions from the ACU and BEU area observed from SDP28 would pass north of the DIAL.

Scans from LOS3 show little emission rate, probably because the emission from tank D-352 is passing too close to the DIAL, particularly if it passes north of tank D-379.

3.6 MEASUREMENTS OF THE REFINERY WEST TANKS

• SDP30 on the 16th February, NW wind, Table and Figure 3.9.
- LOS1 5.2 lbs/hr, LOS2 5.9 lbs/hr, LOS3 0.8 lbs/hr (see Table 3.13).
- Figures 3.9a1 and a2 visual representation of Scan 714 (LOS1).

The emission plume measured from LOS1 is wide from before 100 m to about 300 m from the DIAL. The upwind measurements from LOS3 show no emission above the DIAL detection limit. Therefore all the tanks between LOS1 and LOS3 are possible sources of the emission detected from LOS1 including A-301, A-309, F-369, F-308 and F-357.

The emission from LOS2 is similar to the emission measured from LOS1.

4 MEASUREMENTS OF UNKNOWN PROPANE MIXTURE.

City of Houston provided a compressed gas cylinder containing an unknown concentration of propane. The concentration of this gas was assessed using the on-line spectral monitoring capability of the NPL DIAL system. A 198 mm gas cell was filled unknown gas sample and the infrared wavelength of the DIAL system was scanned through the main propane absorption around 2970 cm^{-1} and the absorption through the cell was measured. This was then compared to the absorption measured when the cell was filled with NPL's gravimetrically-traceable reference gas mixture used throughout the campaign for on-line calibration and diagnostics. As one of the main sources of potential uncertainty for such measurements is repeatability due to the manual filling of the gas cell this procedure was repeated several times.

A non-linear least squares fitting procedure was used to determine the appropriate concentration scaling factor to match the two absorptions, and determine the uncertainty in the fits. Figure 4.1 shows the excellent agreement between the two measured absorptions when the NPL concentration is scaled by a factor of 2.04. The thin lines on this plot show the 1-sigma standard deviation limits of the fits, indicating that the two measurements are completely consistent across the entire spectral scan.

The concentration of the NPL reference standard is 2878.84 ppmv, so the inferred concentration of the unknown propane mixture is 5873 (+/-576) ppmv.

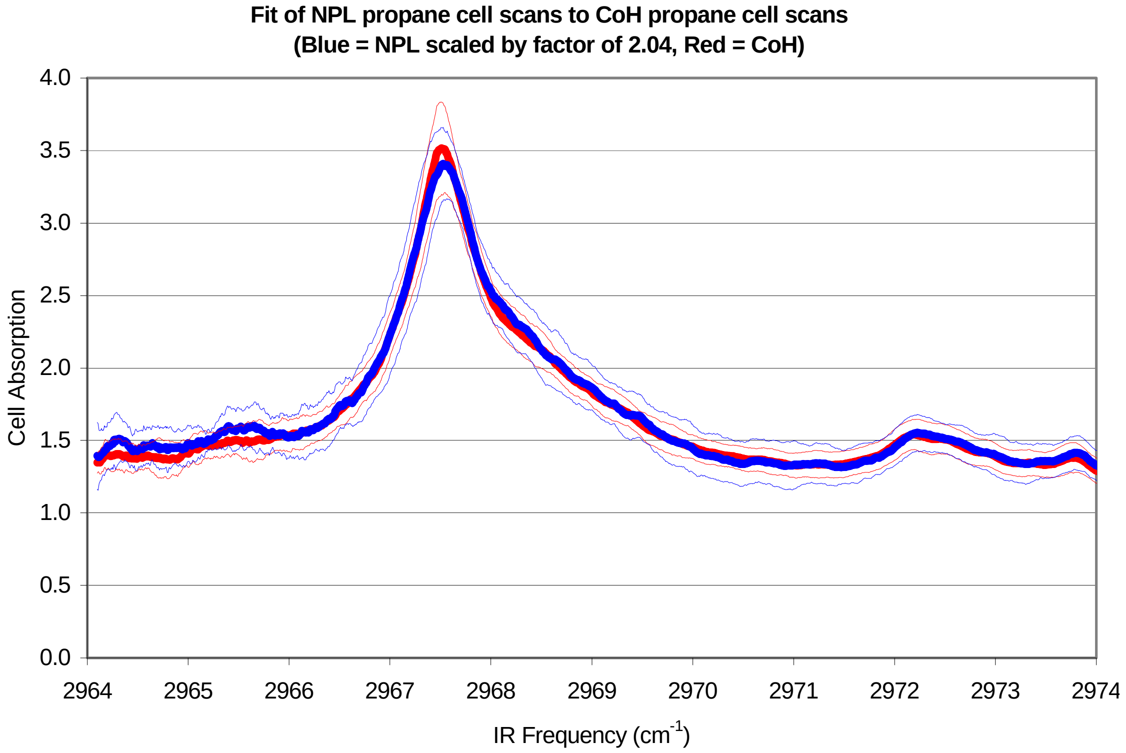

Figure 4.1 NPL reference standard absorption scaled by a factor of 2.04 (blue line) compared with the absorption from an unknown propane mixture (red line).

5 DIAL AND DOAS MEASUREMENTS COMPARISON.

EPA carried out benzene Differential Optical Absorption Spectroscopy (DOAS) measurements on the 8th, 9th and 10th of February. On the 8th of February the DIAL was in location SDP24 and it was measuring the emission from the OP3 south tank farm area, see Figure 3.2. The DOAS was located at about 80 m from the DIAL and the path was 168 m alongside the DIAL measuring line, LOS1. To compare the DIAL to the DOAS data, for each DIAL scan the benzene concentration measured at the lowest elevation angle is averaged over a 150 m measurement path from the starting point of DIAL measurements just before 100 m in LOS1. Figure 5.1 shows the results of the benzene concentrations measured by DIAL and DOAS, plotted as a time series of average concentrations over a 168 m DOAS measurement path and a 150 m DIAL measurement path.

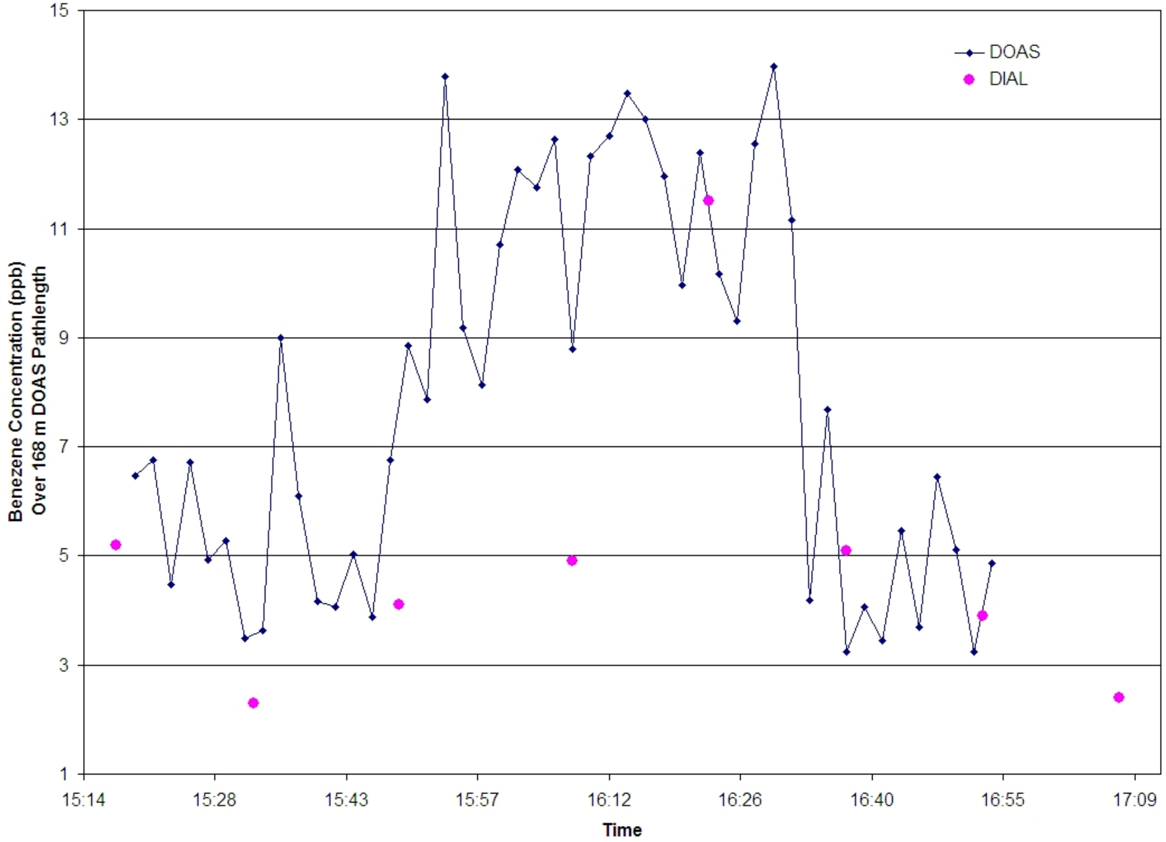

Figure 5.1 DIAL and DOAS measurements comparison on the 8th of February.

On the 10th of February the DIAL was in location SDP26 and it was measuring the emission from the OP3 south tank farm area, see Figure 3.4. The DIAL scanning line was similar to LOS1 in SDP24 and the DOAS was in the same position as the 8th of February until 13:30. Figure 5.2 shows the results of the benzene concentrations measured by DIAL and DOAS, plotted as a time series of average concentrations over a 168 m DOAS measurement path and a 150 m DIAL measurement path. After 13:30 the DOAS was moved further with respect to the DIAL, at about 125 m from it, measuring over a pathlength of 124 m. The DIAL benzene concentration is then averaged over a 124 m measurement path with the starting point at 124 m from the DIAL. Figure 5.3 shows the results of the benzene concentrations measured by DIAL and DOAS, plotted as a time series of average concentrations over a 124 m measurement path. As can be seen in Figures 5.1, 5.2 and 5.3, the agreement between the DIAL and the DOAS data is good and the two techniques see similar temporal variation in the benzene concentration.

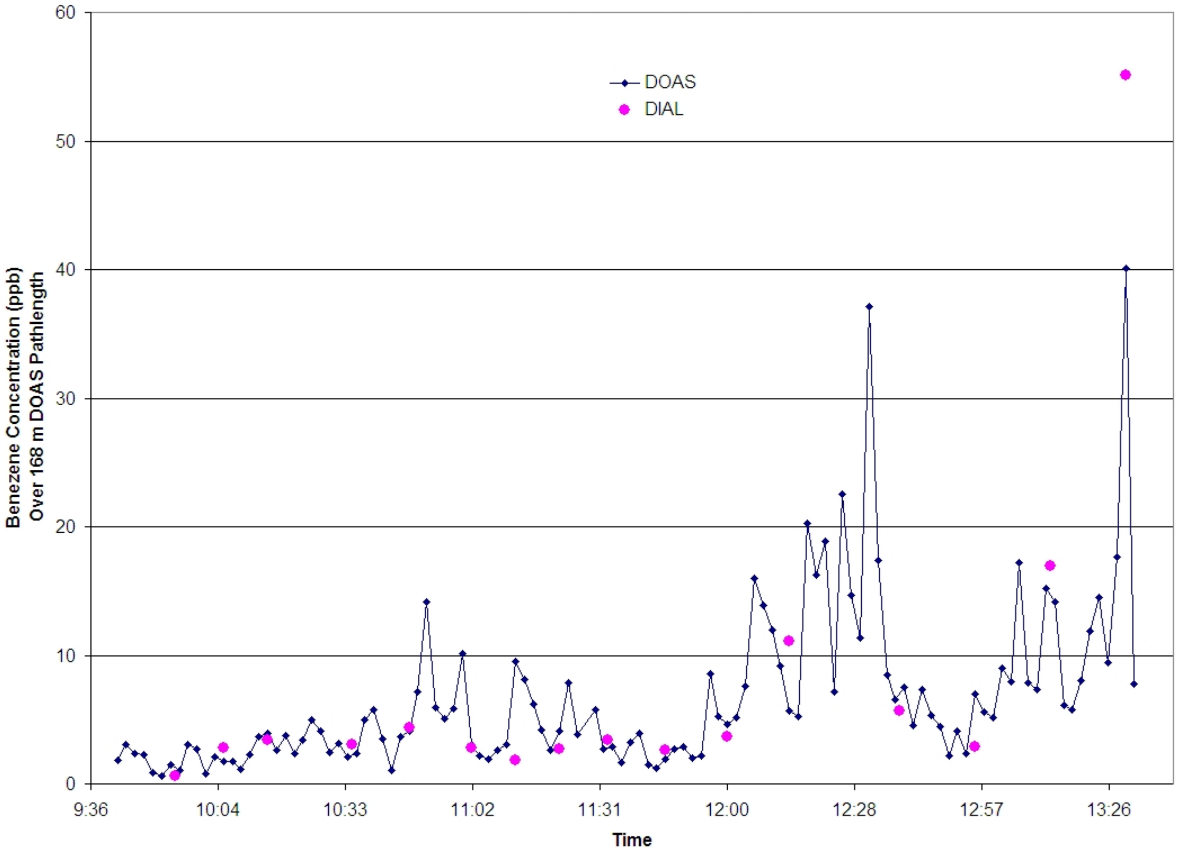

Figure 5.2 DIAL and DOAS measurements comparison on the 10th of February until 13:30.

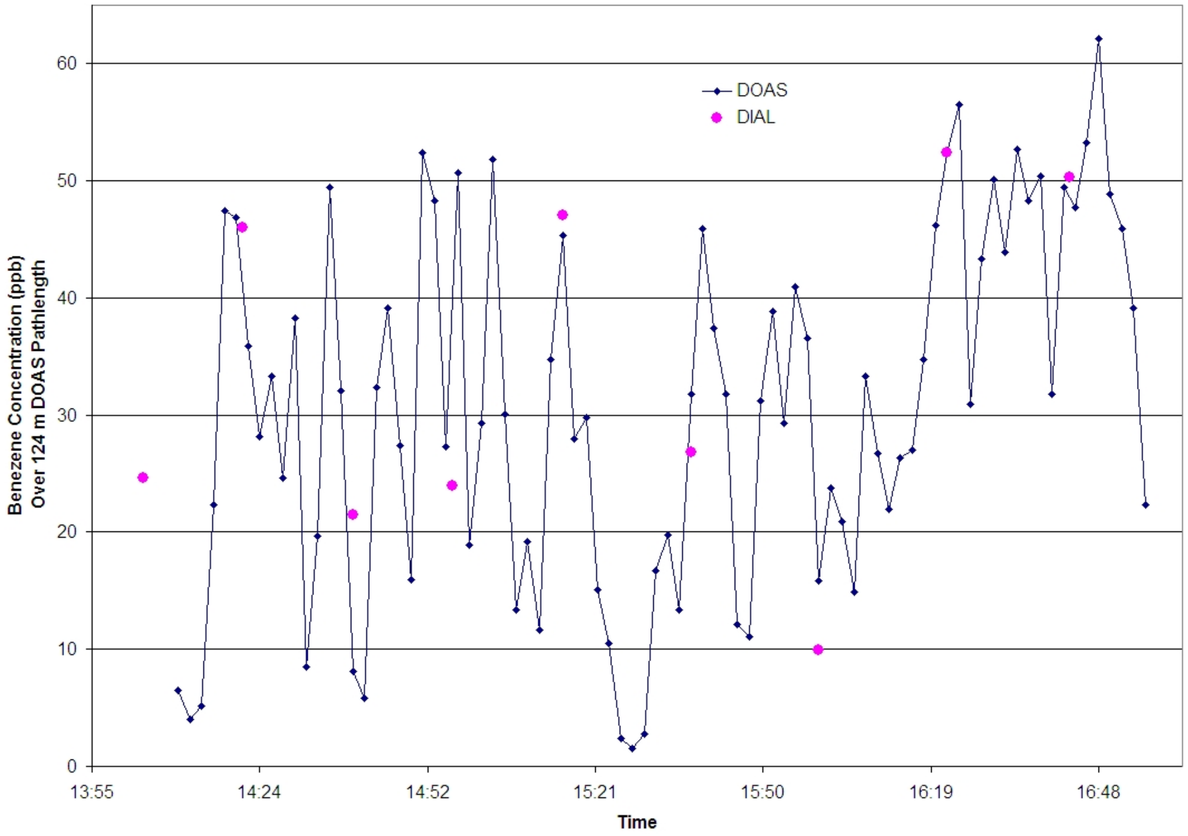

Figure 5.3 DIAL and DOAS measurements comparison on the 10th of February from 14:00.

On the 9th of February the DIAL was in location SDP25 and it was measuring the emission from the north wastewater area, see Figure 3.3. The DOAS was located at about 60 m from the DIAL and the path was 148 m alongside the DIAL measuring line, LOS1. To compare the DIAL to the DOAS data, for each DIAL scan the benzene concentration measured at the lower elevation angle is averaged over a 110 m measurement path from the starting point of DIAL measurements just before 100 m in LOS1. Figure 5.4 shows the results of the benzene concentrations measured by DIAL and DOAS, plotted as a time series of average concentrations over a 148 m DOAS measurement path and a 110 m DIAL measurement path. The benzene concentration is low and close to the DIAL detection limit and in few cases it is below the detection limit. The small differences between the DIAL and DOAS data could be due to the different measurement path lengths.

When the DOAS measured the high concentration peak, the DIAL was scanning at higher elevation angles. The peak observed by the DOAS could be from the same emission source measured by the DIAL beyond the 200 m range (e.g. see Figure 3.3a) that temporally moved closer than 200 m possibly as consequence of a temporary change in the local wind.

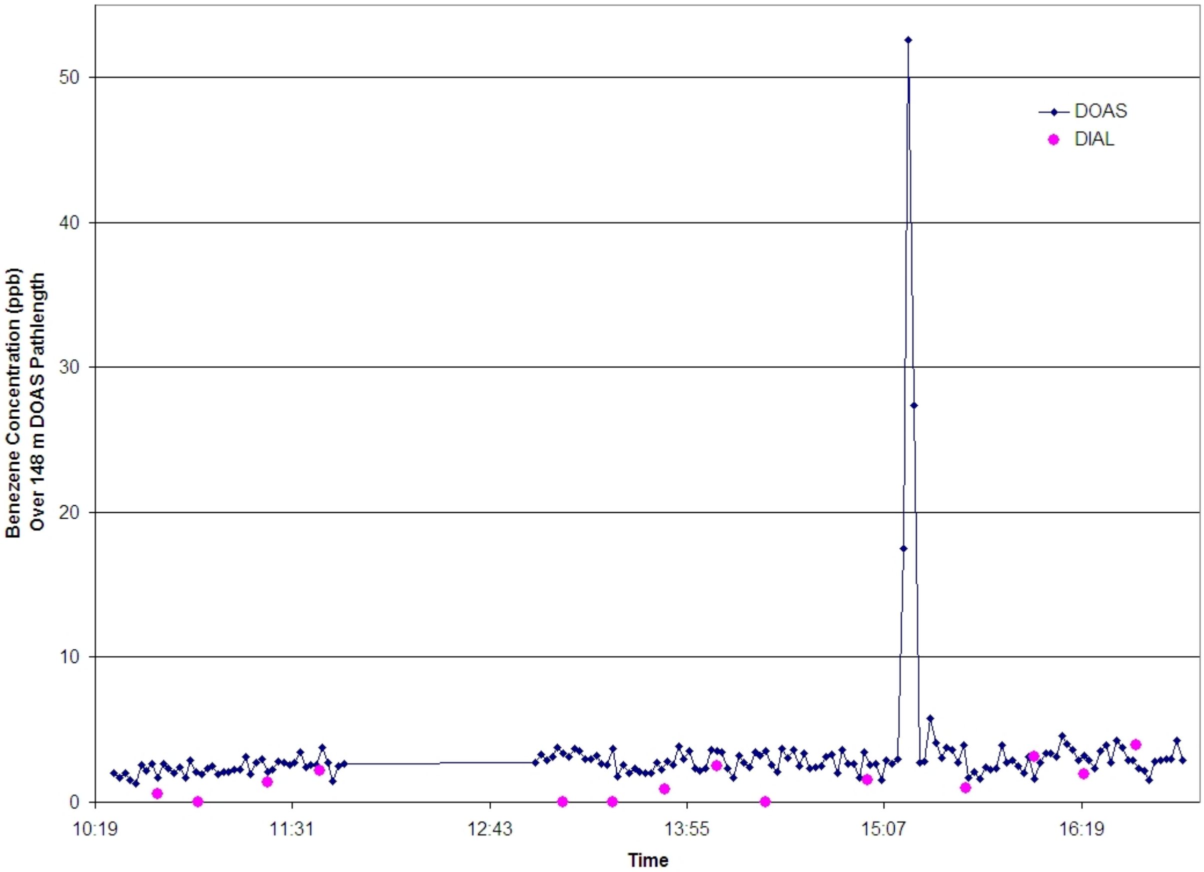

Figure 5.4 DIAL and DOAS measurements comparison on the 9th of February.

6 ANNEX 1: DESCRIPTION OF THE DIAL TECHNIQUE

6.1 OVERVIEW OF THE DIAL TECHNIQUE

The Differential Absorption Lidar (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.

6.2 DESCRIPTION OF THE THEORY OF DIAL MEASUREMENTS

The atmospheric return signal measured by a DIAL system is given by the Light Detection and Ranging (Lidar) equation, a simplified form of which is given in Equation 1.

$$P_x(r) = E_x \frac{D_x}{r^2} B_x(r) \exp\{-2\int_0^r [A_x(r') + \alpha_x C(r')] d'r\} \qquad \textbf{(1)}$$

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 at wavelength x.

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 are 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.

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

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 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).

$$C(r) = \frac{dCL(r)}{dr} \qquad \textbf{(3)}$$

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).

6.3 DESCRIPTION OF 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 10 m 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 10 Hz and an output laser pulse duration of ~10 ns. 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 high speed digitisers. The digitisers are clocked using a clock generator triggered by an optical detector in the transmission chain. 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 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 levels 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 by multiplying the log of the ratio of the returned normalised signals by the differential absorption.

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.
In order to better visualise the data the integrated concentration profiles are piecewise differentiated with a selectable range resolution, to give the range-resolved concentration along the line-of-sight.

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 due to 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:

(a) 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.

(b) This product is computed at all points within the measured concentration profile, to form a two-dimensional array of data.

(c) 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. The Log wind profile is used to describe the vertical distribution of the wind. Two wind speeds at different highs, usually from the fix mast sensors, are used to calculate the wind profile. The calculated wind field is then combined with the measured gas concentration profile using the procedure described above.

A summary of the ultraviolet and infrared performance capabilities of the NPL DIAL facility are given in Tables A1.1 and A1.2. 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 – 50 metres 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 a $(\text{range})^{-2}$ function, the sensitivity is also a function of range. The sensitivity values given in the table apply at a range of 200 metres, 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 nitric oxide 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 dependant on the particular loading of the atmosphere, and this can vary dramatically over relatively short timescales.

The NPL DIAL has a theoretical range resolution of 3.75 metres along the measurement beam, and a vertical and horizontal scan resolution which can be less than 1 metre at 100 metres. 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 20-30 m.

The DIAL is able to make measurements of a wide range of compounds, including benzene and other aromatics, individual VOCs and total VOCs, see Tables 2a and 2b. The methodology for obtaining measurements of the total VOC content from C3 to C15 is provided below. It consists of the combination of DIAL measurements with air sampling and GC analysis. The system is able to monitor individual aromatic compounds and VOC species, which have absorption features in the IR and UV 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 A1.2 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 volatile organic compounds (VOCs) 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 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.

Although the general hydrocarbon measurement provides a good estimate of the overall amount of hydrocarbons present, the accuracy of this measurement can be improved, and the total VOC concentration calculated, by combining the DIAL measurements with the results of gas chromatography (GC) analysis of the emitted gases. The standard procedure for this involves taking whole air samples around the site in locations where the DIAL measurements show the emitted plumes are present. The VOCs present in these samples are identified and quantified by GC analysis. The results provide the relative levels of all the VOCs present with a concentration of 0.1 ppb or higher. The results of this analysis are combined with NPL's unique spectral library of quantified infrared absorptions of an extensive set of VOCs to calculate the combined absorption coefficient for the actual VOC mixture present at the site. Appling this absorption coefficient to the DIAL results enables the total VOC emission rates to be calculated.

Table A1.1 Ultraviolet capability of NPL DIAL Facility

Species	Sensitivity(1)	Maximum range(2)
Nitric oxide	5 ppb	500 m
Sulphur dioxide	10 ppb	3 km
Ozone	5 ppb	2 km
Benzene	10 ppb	800 m
Toluene	10 ppb	800 m

Table A1.2 Infrared capability of NPL DIAL Facility

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

(1) The concentration sensitivities apply for measurements of a 50 metre wide plume at a range of 200 metres, under typical meteorological conditions.
(2) The range value represents the typical working maximum range for the NPL DIAL system.

6.4 RELATIONSHIP BETWEEN EMISSION RATE AND CONCENTRATIONS

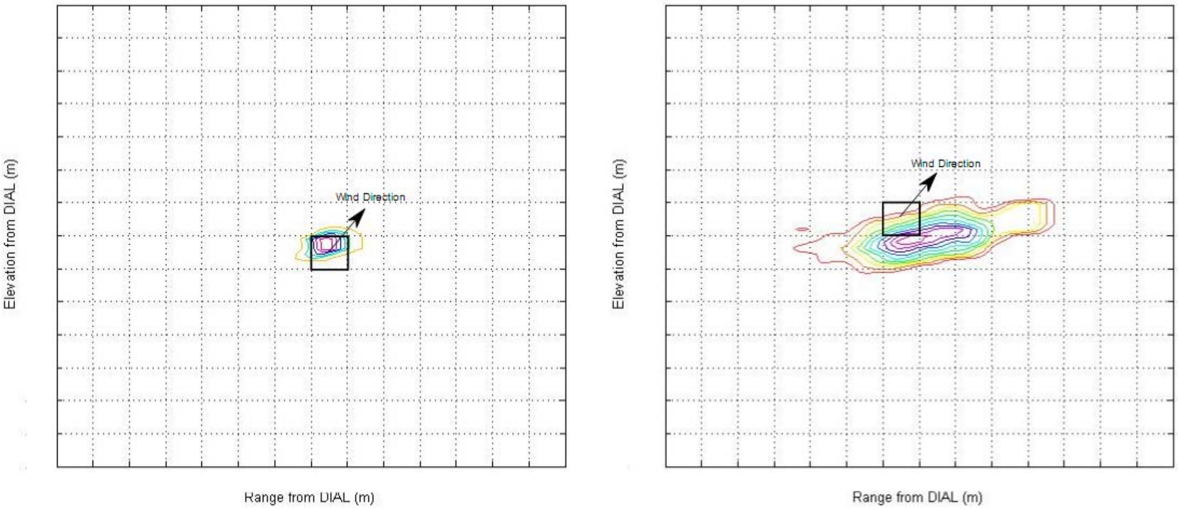

Figure A1.2 Illustration of the emission rate calculation approach

Where concentrations are provided as an indication of the levels observed in a measurement scan, the reported concentration 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 3.75 m, so each cell is 3.75 m square. Figure A1.2 shows how the emission rate is calculated: the concentration assigned to each cell is multiplied by the perpendicular wind field determined for that cell, and then the individual emission rates are summed to give the total emission rate through the plane. This figure 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 then the large plume.

Figure A1.3 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 normal to the plane of the measurements. If only the concentration profile were observed the left 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.

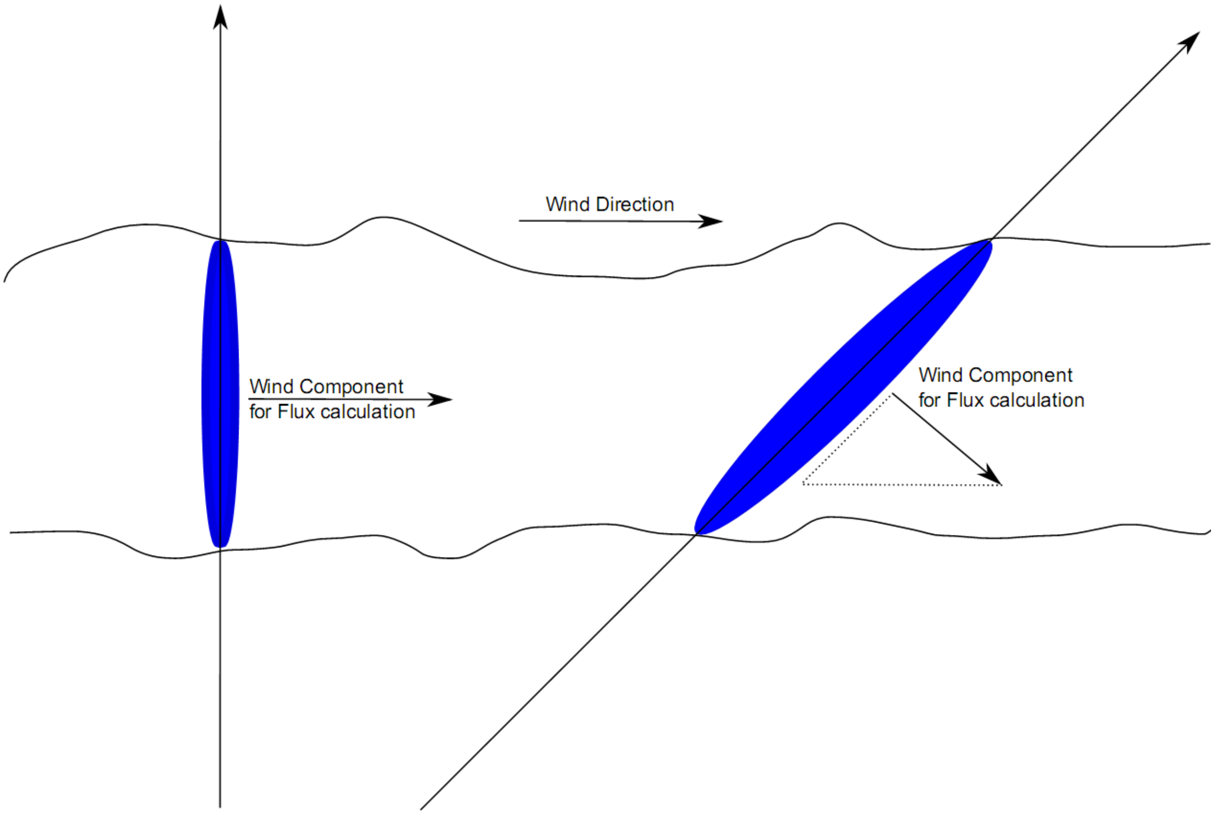

Figure A1.3 Schematic showing relationship between emission rate and wind direction

6.5 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 system also employs a wavemeter to monitor the wavelengths transmitted during operation. 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 detailed below:

i) Intercomparisons have been carried out in the vicinity of chemical and petrochemical plants where a large number of different volatile organic species are present. In these intercomparisons, the DIAL radiation 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 VOCs 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%.

ii) 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%.

iii) DIAL Measurements of controlled releases of methane from a stack agreed with the known emission rates to within ± 15%.

6.6 NPL OPEN-PATH CALIBRATION FACILITY

NPL has also developed and operate a full-scale facility for the calibration of open path monitors, including DIAL. This consists of a 10 m long windowless cell able to maintain a uniform, independently-monitored concentration of a gaseous species along its length. This provides a known controlled section of the atmosphere with traceable concentration over a defined range (10m). The absence of windows removes reflections and other artefacts from measurements made using optical techniques, providing a direct way to validate and assess the calibration of DIAL instruments.

The calibration facility is windowless with a 1 m diameter, to minimise any beam reflections from the cell walls and ends. At each end of the cell is an annular calibration-gas feed ring with multiple outlets injecting the calibration gas mixture into the cell. A ring of tangential fans around the centre of the cell extract gas and entrained air pulled in through the open ends of the cell. This ensures the backscatter in the cell approximates to the ambient air conditions. Each fan has a long exhaust tube to avoid recirculation of the gas into the cell.

This facility has been employed to directly validate VOC measurements by the NPL DIAL facility [2].

Figure A1.1 The NPL 10m calibration cell.

The facility provides the ability to generate a defined concentration path and so it also provides range-resolution validation for DIAL and lidar instruments. The system was used to validate the DIAL with a number of measurements of propane and methane, as a part of its acceptance tests for Siemens, Shell and British Gas.

[1] Measurements of the Emissions to Atmosphere of Volatile Organic Compounds from the Hellenic Aspropyrgos Oil Refinery; T D Gardiner, M.J.T. Milton, R.A. Robinson, P.T.Woods, A.S.Andrews, H. D'Souza, D Alfonso, N.R Swann; NPL Report QM S99, Sept 1996.

[2] Calibration of DIAL and Open Path Systems Using External Gas Cells; M.J.T. Milton, P.T. Woods, R.H. Partridge, B.A Goody; Proc. Europto, Munich 1995.

7 ANNEX 2: SPECIATION OF VOC MEASUREMENTS

The DIAL measures VOCs by measuring the differential absorption of two wavelengths of light. The wavelengths used, at around 3000 cm^{-1}, are chosen to measure, in effect, the C-H stretch in the hydrocarbons for C3 and above. The sensitivity of the DIAL is slightly different for different hydrocarbons, and for example an oxygenated hydrocarbon will give a different absorption per mass than a straight chain alkane. The differential absorption strength used in the DIAL measurements was calibrated to give a mass emission rate for gasoline vapour. A different 'cocktail' of hydrocarbons could give a slightly different response per unit mass. Air samples were taken at locations which would provide an indication of the actual speciation of the emission rates sampled by the DIAL. If the actual (relative) composition is known from the air sample analyses, then it is possible to check that the absorption coefficients used are appropriate for the actual hydrocarbon mixture present.

Air samples were taken at a number of locations around the plant over the course of the measurement campaign. Figure A2.1 show the locations of each numbered sample. The Air samples were taken using pumped Perkin Elmer Automatic Thermal Desorption (ATD) tubes. The ATD tubes were sampled at a flow rate of 40ml/min to enable a reasonable duration of sample to be taken – typically 30 to 40 minutes. The samples were taken at a height of approximately 2m by mounting the sampling array on a tripod.

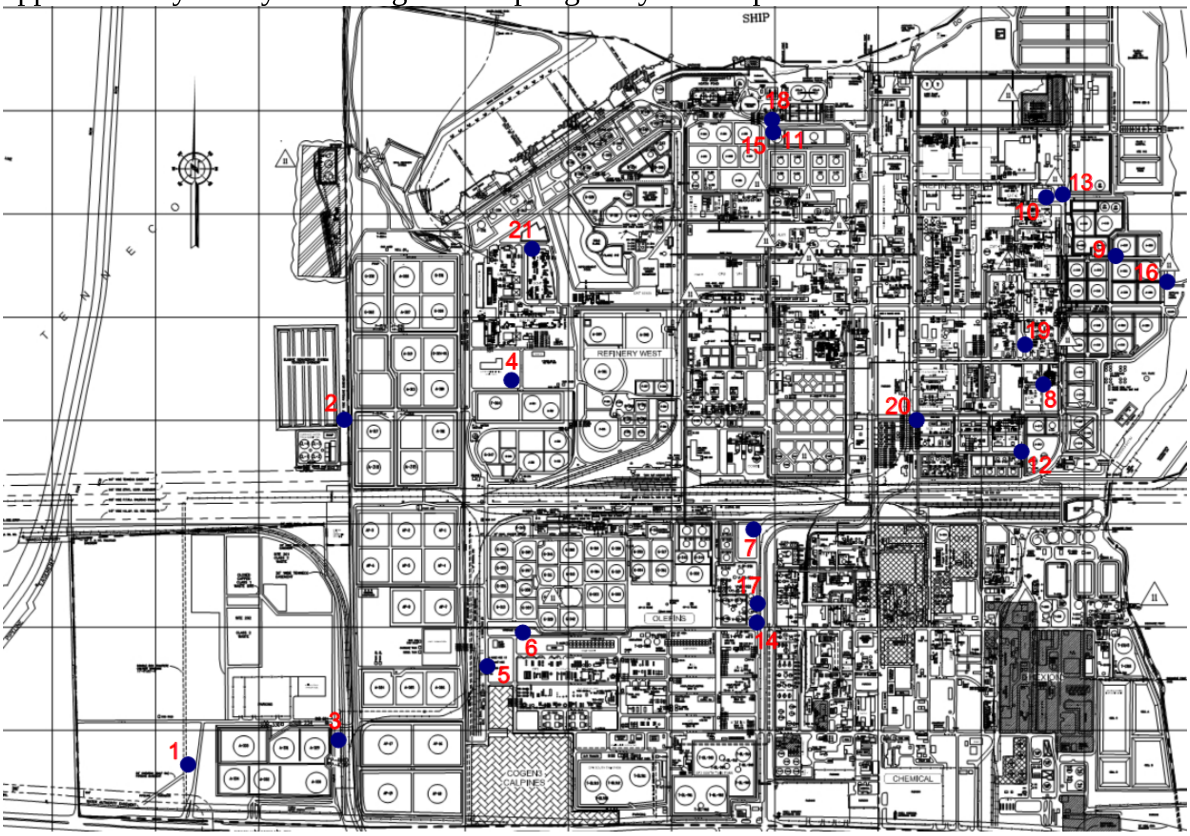

Figure A2.1 Pumped sample tube locations

The sampler tubes were approximately 6mm in diameter and 90mm long. The sampler tubes contained approximately 200 milligrams to 300 milligrams of sorbent. Two sorbent tubes were used in series containing two sorbent materials used, a porous polymer (Tenax TA) and a carbon black (Carbopack X). Different sorbents are needed to cover the diverse boiling point ranges and chemical functional groups of VOCs, and this combination gives a maximum Carbon number range of C_3-C_{22}.

Table A2.1 Results of VOC Speciation Measurements

Sample #	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Date	**13-Jan-10**	**14-Jan-10**	**15-Jan-10**	**16-Jan-10**	**18-Jan-10**	**19-Jan-10**	**20-Jan-10**
Start Time	16:29	14:40	14:05	14:52	14:10	15:55	15:10
End Time	16:59	15:15	14:40	15:24	14:45	16:28	15:46
Species	**Mass Concentration (ug / m3)**						
PROPANE	14.2	5.1	7.6	12.2	9.2	3.9	5.9
PROPENE	2.3	3.8	3.3	3.8	3.2	5.5	3.4
i-BUTANE	5.4	22.4	9.3	4.0	43.8	3.1	12.0
n-BUTANE	14.1	16.6	13.5	6.3	50.4	4.6	15.1
trans-2-BUTENE	0.0	0.0	1.8	0.0	4.9	0.0	0.0
1-BUTENE	0.0	1.7	1.9	0.0	4.7	0.0	1.6
2-Me-PROPENE	1.5	10.7	4.5	0.0	9.2	4.3	13.3
cis-2-BUTENE	0.0	0.0	1.5	0.0	3.1	0.0	0.0
C4 olefin	0.0	0.0	0.0	0.0	0.0	0.0	0.0
i-PENTANE	12.2	14.9	18.3	3.0	36.2	6.9	9.6
n-PENTANE	0.6	0.0	1.5	0.0	15.1	1.5	6.0
C6 alkanes	4.9	19.8	7.1	1.5	34.8	6.1	18.8
2-METHYL_BUTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ETHANOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ISOPROPYL ALCOHOL	5.0	4.1	4.0	0.0	0.0	6.6	0.0
2-METHYL-2-PROPANOL	4.5	5.3	0.0	0.0	0.0	6.3	0.0
2,3 DI METHYL BUTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2-METHYL PENTANE	14.5	14.3	15.2	0.0	0.0	12.5	0.0
3-METHYL PENTANE	8.2	7.2	8.1	0.0	0.0	7.3	0.0
n-HEXANE	23.8	18.6	14.4	0.0	0.0	18.0	0.0
METHYL-CYCLOPENTANE	8.5	8.3	7.9	0.0	0.0	7.6	0.0
CYCLOHEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 METHYL HEXANE	11.3	10.3	8.2	0.0	0.0	10.0	4.2
BENZENE	8.2	8.6	10.9	2.4	4.4	7.9	1.1
2-METHYL HEXANE	6.1	4.2	4.3	0.0	0.0	0.0	0.0
ISO OCTANE	0.0	5.3	0.0	0.0	0.0	0.0	0.0
n-HEPTANE	15.2	6.8	7.4	0.0	0.0	9.3	0.0
2,5 DI METHYL HEXANE	5.2	0.0	0.0	0.0	0.0	0.0	0.0
2,4 DI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,2 DI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3,4 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3,3 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,2,3 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOLUENE	28.9	29.7	31.9	0.0	0.0	46.4	0.0
2,25 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-OCTANE	8.4	5.4	10.6	0.0	0.0	6.4	0.0
2,4,4 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3,5 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,4 DI METHYL HEPTANE	0.0	5.1	0.0	0.0	0.0	4.1	0.0
2,6 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,5 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ETHYLBENZENE	6.7	7.6	7.2	0.0	0.0	9.5	0.0
C10 ALKANE 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C10 ALKANE 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,2,4 TRI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M/P-XYLENE	12.7	14.1	13.1	0.0	0.0	15.0	0.0
NONANE	6.9	6.0	8.1	0.0	0.0	4.2	0.0
STYRENE	8.5	9.8	7.1	0.0	0.0	13.0	0.0
O-XYLENE	4.5	5.4	4.7	0.0	0.0	5.4	0.0
C11 ALKANE 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 ETHYL 4 METHYL BENZENE	0.0	0.0	5.2	33.5	0.0	0.0	0.0
C11 ALKANE 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-DECANE	5.7	5.0	5.8	0.0	0.0	6.7	0.0
n-UNDECANE	7.2	4.8	5.1	0.0	0.0	10.2	0.0
n-DODECANE	11.0	10.8	8.5	0.0	0.0	16.0	0.0
TRIDECANE	8.6	7.6	5.4	0.0	0.0	12.5	0.0

Sample #	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Date	**21-Jan-10**	**22-Jan-10**	**23-Jan-10**	**25-Jan-10**	**26-Jan-10**	**28-Jan-10**	**29-Jan-10**
Start Time	14:47	16:05	12:48	12:47	14:25	14:15	14:41
End Time	15:17	16:41	13:19	13:18	14:54	14:48	15:12
Species	**Mass Concentration (ug / m3)**						
PROPANE	5.6	13.9	9.6	8.1	6.8	4.7	15.6
PROPENE	3.1	2.1	3.0	1.8	1.8	3.0	25.0
i-BUTANE	15.8	10.9	29.7	11.1	14.1	6.4	6.7
n-BUTANE	16.9	26.3	31.5	8.0	5.6	6.6	8.7
trans-2-BUTENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1-BUTENE	0.0	0.0	2.0	0.0	0.0	0.0	0.0
2-Me-PROPENE	14.4	1.9	3.1	1.4	23.9	0.0	0.0
cis-2-BUTENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C4 olefin	0.0	0.0	0.0	0.0	0.0	0.0	0.0
i-PENTANE	21.9	18.5	35.9	5.6	2.9	8.3	21.7
n-PENTANE	8.7	32.6	34.8	0.0	2.3	9.7	9.6
C6 alkanes	47.1	5.9	8.5	6.5	6.2	0.0	3.4
2-METHYL_BUTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ETHANOL	11.9	0.0	0.0	8.0	0.0	0.0	0.0
ISOPROPYL ALCOHOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2-METHYL-2-PROPANOL	0.0	0.0	0.0	0.0	5.9	0.0	0.0
2,3 DI METHYL BUTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2-METHYL PENTANE	6.1	8.6	27.9	0.0	0.0	7.3	15.8
3-METHYL PENTANE	0.0	4.3	12.4	0.0	0.0	0.0	9.8
n-HEXANE	0.0	13.4	27.6	0.0	0.0	0.0	38.5
METHYL-CYCLOPENTANE	4.6	5.4	11.4	0.0	3.9	0.0	18.1
CYCLOHEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 METHYL HEXANE	5.8	6.7	11.7	4.0	0.0	0.0	13.8
BENZENE	5.4	4.4	11.7	2.9	26.4	3.5	11.3
2-METHYL HEXANE	0.0	0.0	4.5	0.0	0.0	0.0	7.7
ISO OCTANE	0.0	0.0	0.0	0.0	0.0	0.0	18.1
n-HEPTANE	4.1	8.4	5.7	0.0	0.0	0.0	16.9
2,5 DI METHYL HEXANE	0.0	4.6	9.0	0.0	0.0	0.0	6.7
2,4 DI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,2 DI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3,4 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	5.9
2,3,3 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	4.9
2,2,3 TRI METHYL PENTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOLUENE	15.3	4.6	1133.0	7.2	0.0	98.2	7.3
2,25 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-OCTANE	0.0	5.1	0.0	0.0	0.0	0.0	5.3
2,4,4 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3,5 TRI METHYL HEXANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,4 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,6 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,5 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ETHYLBENZENE	0.0	0.0	20.8	0.0	0.0	0.0	0.0
C10 ALKANE 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C10 ALKANE 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,2,4 TRI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M/P-XYLENE	6.7	4.2	7.6	0.0	0.0	0.0	5.2
NONANE	0.0	8.3	0.0	0.0	0.0	0.0	0.0
STYRENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O-XYLENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C11 ALKANE 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 ETHYL 4 METHYL BENZENE	6.6	0.0	96.9	0.0	0.0	9.2	4.3
C11 ALKANE 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-DECANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-UNDECANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
n-DODECANE	0.0	0.0	0.0	0.0	7.7	0.0	12.6
TRIDECANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Sample #	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Date	**30-Jan-10**	**2-Feb-10**	**3-Feb-10**	**5-Feb-10**	**25-Mar-10**	**26-Mar-10**	**27-Mar-10**
Start Time	14:35	14:18	15:10	15:35	16:06	16:39	14:47
End Time	15:15	14:51	15:42	16:07	16:35	17:09	15:17
Species	**Mass Concentration (ug / m3)**						
PROPANE	12.1	13.2	6.6	15.6	71.2	6.7	5.2
PROPENE	1.2	2.0	2.0	1.8	0.8	4.0	1.5
i-BUTANE	1170.9	24.0	18.1	64.0	39.6	18.0	7.3
n-BUTANE	437.4	49.8	7.9	43.9	49.9	10.0	10.8
trans-2-BUTENE	0.0	0.0	0.0	4.6	0.0	0.0	0.9
1-BUTENE	0.0	0.0	1.6	4.9	0.0	0.0	1.8
2-Me-PROPENE	1.5	7.0	20.3	10.6	0.3	3.6	2.1
cis-2-BUTENE	0.0	0.0	0.0	4.7	0.0	0.0	0.0
C4 olefin	0.0	0.0	0.0	4.0	0.0	0.5	0.0
i-PENTANE	256.1	17.8	6.1	251.4	6.3	8.4	5.6
n-PENTANE	6.6	21.6	2.7	400.2	2.3	4.1	4.6
C6 alkanes	8910.0	69.0	16.1	104.0	1.4	3.1	3.8
2-METHYL_BUTANE	0.0	0.0	0.0	0.0	4.6	5.8	2.7
ETHANOL	0.0	11.3	10.5	0.0	0.0	0.0	0.0
ISOPROPYL ALCOHOL	0.0	0.0	0.0	4.4	0.0	0.0	0.0
2-METHYL-2-PROPANOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3 DI METHYL BUTANE	51.2	0.0	0.0	0.0	0.0	0.0	0.0
2-METHYL PENTANE	51.3	0.0	0.0	121.3	14.4	16.6	8.8
3-METHYL PENTANE	23.3	0.0	0.0	42.8	6.9	8.3	4.6
n-HEXANE	0.0	0.0	9.0	87.5	11.7	14.9	17.6
METHYL-CYCLOPENTANE	149.6	0.0	0.0	37.6	2.8	12.3	9.1
CYCLOHEXANE	0.0	0.0	0.0	0.0	17.6	17.2	11.5
2 METHYL HEXANE	17.5	0.0	0.0	24.2	0.0	0.0	0.0
BENZENE	98.7	2.8	3.1	33.6	6.8	12.6	3.4
2-METHYL HEXANE	12.1	0.0	0.0	7.2	0.0	0.0	0.0
ISO OCTANE	2008.7	0.0	0.0	62.2	0.0	0.0	0.0
n-HEPTANE	0.0	0.0	0.0	11.5	0.0	0.0	7.4
2,5 DI METHYL HEXANE	528.7	0.0	0.0	16.4	0.0	0.0	0.0
2,4 DI METHYL HEXANE	437.8	0.0	0.0	6.8	0.0	0.0	0.0
2,2 DI METHYL HEXANE	197.1	0.0	0.0	6.2	0.0	0.0	0.0
2,3,4 TRI METHYL PENTANE	0.0	0.0	0.0	40.4	0.0	0.0	0.0
2,3,3 TRI METHYL PENTANE	0.0	0.0	0.0	52.8	0.0	0.0	0.0
2,2,3 TRI METHYL PENTANE	2260.8	0.0	0.0	0.0	0.0	0.0	0.0
2 METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOLUENE	7.3	0.0	13.2	47.3	30.8	18.1	8.5
2,25 TRI METHYL HEXANE	357.4	0.0	0.0	4.7	0.0	0.0	0.0
n-OCTANE	0.0	0.0	0.0	9.4	0.0	0.0	5.5
2,4,4 TRI METHYL HEXANE	12.4	0.0	0.0	0.0	0.0	0.0	0.0
2,3,5 TRI METHYL HEXANE	67.8	0.0	0.0	0.0	0.0	0.0	0.0
2,4 DI METHYL HEPTANE	6.5	0.0	0.0	0.0	0.0	0.0	0.0
2,6 DI METHYL HEPTANE	8.9	0.0	0.0	0.0	0.0	0.0	0.0
2,5 DI METHYL HEPTANE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2,3 DI METHYL HEPTANE	17.1	0.0	0.0	0.0	0.0	0.0	0.0
ETHYLBENZENE	6.2	0.0	0.0	15.1	0.0	4.9	0.0
C10 ALKANE 1	37.5	0.0	0.0	0.0	0.0	0.0	0.0
C10 ALKANE 2	30.3	0.0	0.0	0.0	0.0	0.0	0.0
2,2,4 TRI METHYL HEPTANE	67.4	0.0	0.0	0.0	0.0	0.0	0.0
M/P-XYLENE	0.0	0.0	4.2	37.4	7.8	19.6	5.0
NONANE	4.9	0.0	5.0	11.8	0.0	0.0	0.0
STYRENE	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O-XYLENE	7.2	0.0	0.0	18.5	0.0	5.1	0.0
C11 ALKANE 1	9.0	0.0	0.0	0.0	0.0	0.0	0.0
1 ETHYL 4 METHYL BENZENE	12.6	0.0	0.0	42.6	25.6	0.0	0.0
C11 ALKANE 2	117.5	0.0	0.0	0.0	0.0	0.0	0.0
n-DECANE	0.0	0.0	0.0	16.0	0.0	0.0	0.0
n-UNDECANE	22.5	0.0	0.0	16.9	0.0	0.0	0.0
n-DODECANE	7.6	0.0	8.6	44.6	0.0	0.0	0.0
TRIDECANE	0.0	0.0	0.0	22.0	0.0	0.0	0.0

7.1 SPECIATION RESULTS FROM THE ATD TUBE SAMPLES

Table A2.1 presents the results from the ATD tube analyses. The tube analyses were carried out by NPL's in house accredited analysis laboratory. Different methods of analysis were used for the Carbopack X (light hydrocarbons) tubes and the Tenax (heavy hydrocarbons) tubes. The Carbopack X method of analysis was based on EN ISO 16017-2 and was carried out using UKAS (United Kingdom Accreditation Service) accredited method QPDQM/B/526. This method combines Automatic Thermal Desorption with Gas Chromatography (GC), with a Flame Ionisation Detector (FID).

The analysis instrument used is an Automated Thermal Desorber autosampler coupled to a Gas Chromatograph usually with a flame ionisation detector. The VOCs are released from the sampler tube using a heated oven in an inert gas stream of helium. The VOCs are refocused onto a small cold trap prior to transfer onto the gas chromatography column. Generally a coated fused silica gas chromatography column of diameter 320 micrometers and length 60 meters is used to separate the individual VOCs collected. Using VOC standard materials, the identification of the individual VOC components are compared to the column elution time (retention time) of the standard VOC materials. The mass of VOCs collected is quantified using the flame ionisation detector. A series of calibrations standards are used to calibrate the flame ionisation detector response. The concentration of the VOC in ambient air is then calculated from the mass collected and the volume of air sampled.

A similar procedure was used for the Tenax analyses, but in this case mass spectrometric (MS) detection was used after the GC separation instead of a FID. MS detection provides additional information on the mass of ionized fragments from the different species while retaining the elution separation of the gases, which assists in the species identification within the potentially complex mixture of heavy organic components.

The results in Table A2.1 show the range of different species present in the ambient atmosphere around the refinery. A simplified way of visualising the different distributions is to look at the distributions in terms of the fractions of different types of species present – as shown in Figure A2.2 which shows the mass percentages of the amount of saturated, unsaturated and aromatic hydrocarbons, together with any residual other VOCs, principally alcohols. In general the samples give a good representation of the general VOC mixture present in that area of the refinery. An exception to this is samples 10 and 13 which measured the high levels of toluene seen from a localised source in that particular area.

In order to confirm the suitability of the absorption coefficients used, the molecular mass and volume absorption coefficient for each individual component in the mixture was calculated using NPL's spectroscopic database, and the average values for the general refinery mixtures compared to those of the reference gravimetric measurements of gasoline vapour used for the DIAL emission rate measurements. The average molecular mass for the general refinery samples is 75.1 ± 10.1 compared to the gravimetric gasoline vapour molecular mass of 73.3. The average optical absorption coefficient for the samples is 1.23 ± 0.31 $(\text{ppm.km})^{-1}$ compared to the gasoline absorption coefficient of 1.47 $(\text{ppm.km})^{-1}$. So both results are consistent within the variability of the measurements.

A similar consistency check of the average molecular mass can be made with the results from the C4/C8 ratio measurements from the open-path FTIR made by Environ. These data give an average molecular mass of 70.3 ± 13.6, which is also consistent with the gasoline value of 73.3.

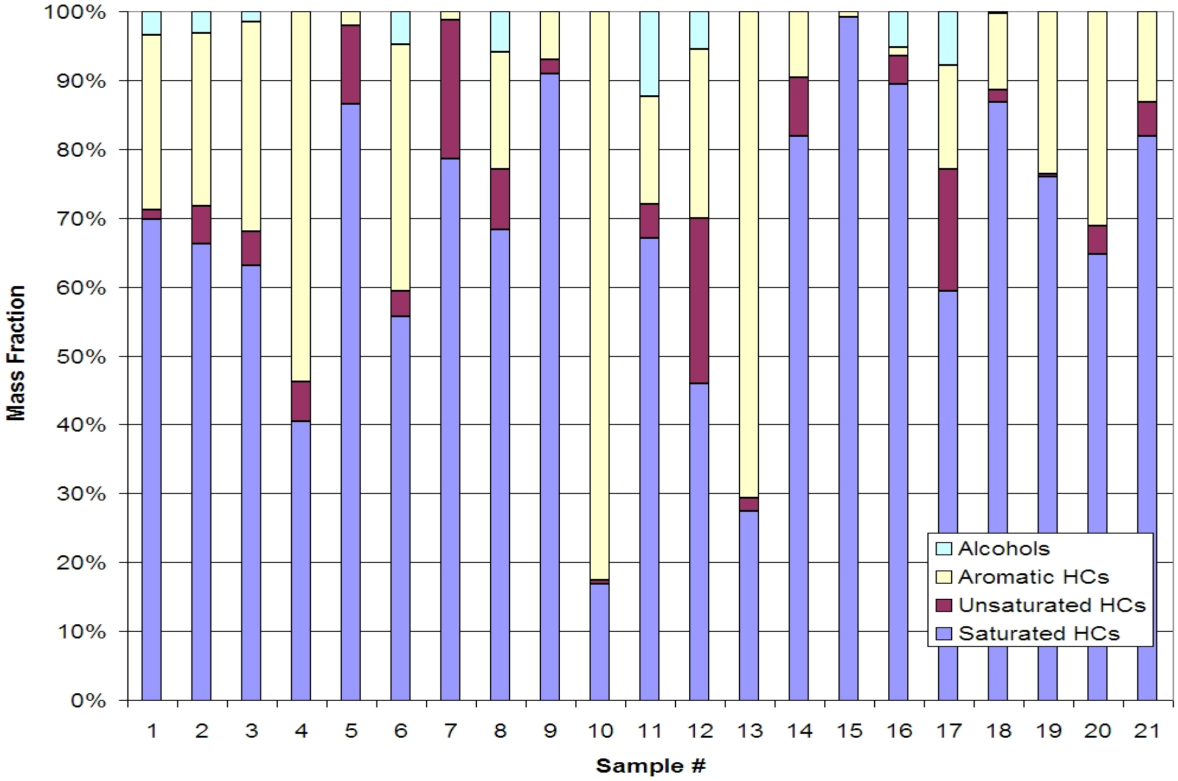

Figure A2.2 Percentage by mass of main types of VOCs in ATD samples

8 ANNEX 3: METEOROLOGICAL MEASUREMENTS

Wind data were collected from a fixed mast located just outside the SW boundary of the site. The location is shown in Figure 1.2. Figure A3.1 shows a picture of the meteorological mast. Wind speed and direction measurements were collected at two elevations, 11 m and 3 m. The DIAL (12 m) and portable (2 m) wind sensors were also used.

Figure A3.1 The NPL meteorological mast.

The following figures present the average wind roses for the measurement periods on each location from the 13th January to the 17th February and from the 22nd to the 27th March 2010.

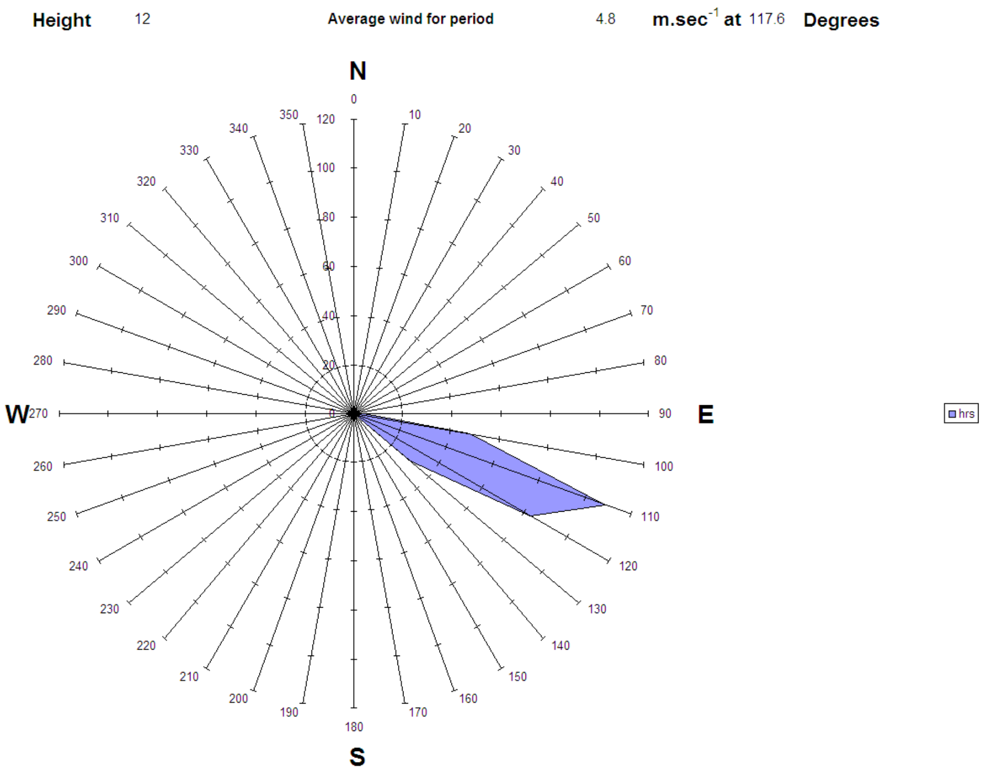

Figure A3.2 Wind rose for 13th January during measurements from SDP1, 12:24 - 17:36

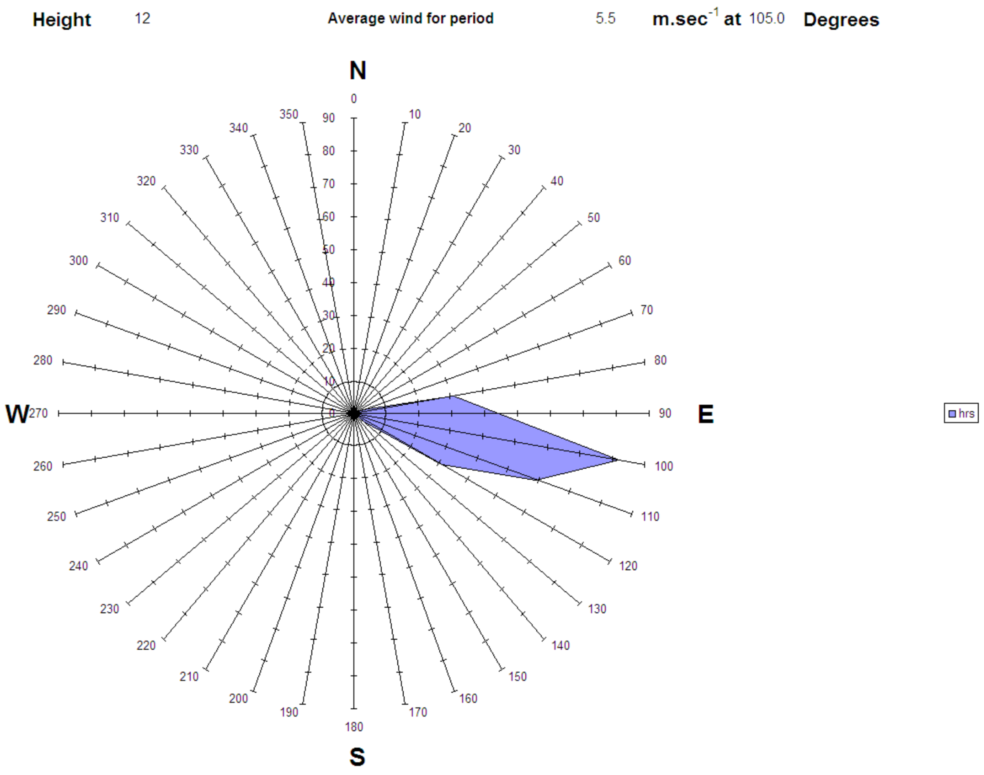

Figure A3.3 Wind rose for 14th January during measurements from SDP2, 12:32 - 17:04

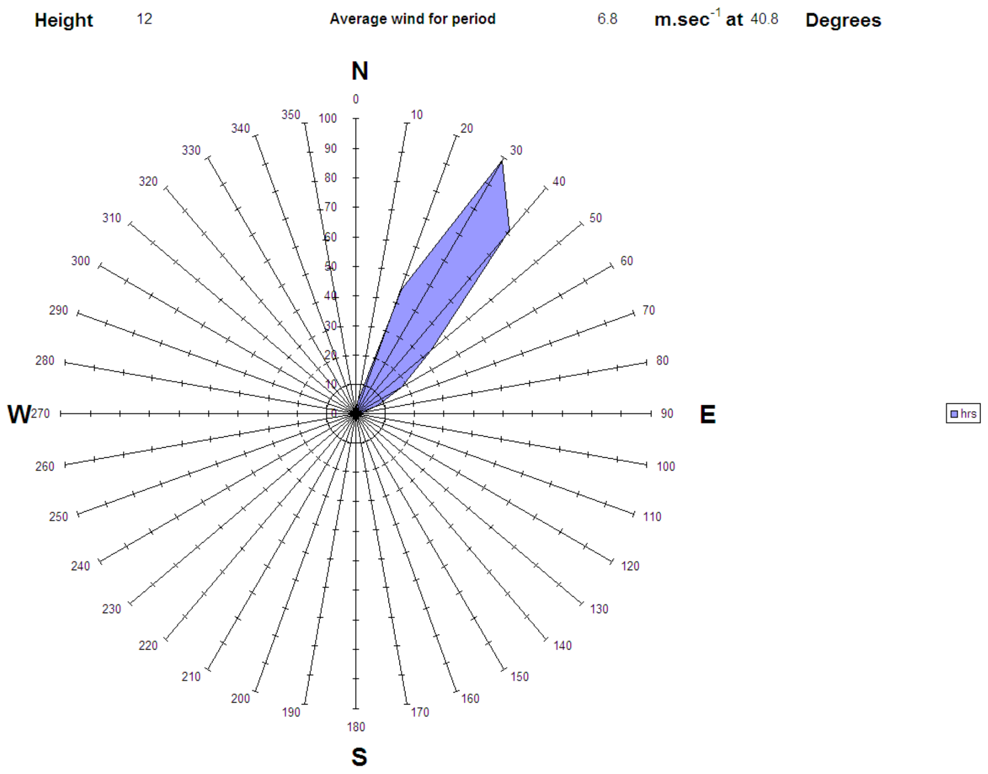

Figure A3.4 Wind rose for 15th January during measurements from SDP3, 11:35 - 16:50

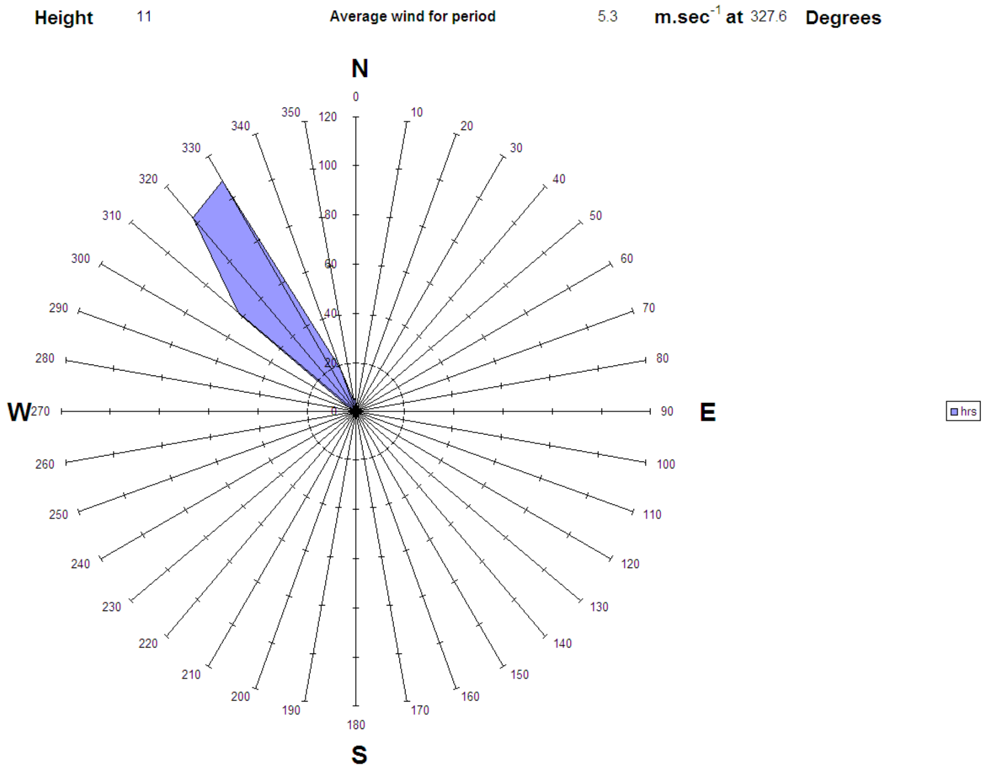

Figure A3.5 Wind rose for 16th January during measurements from SDP4, 10:58 - 17:13

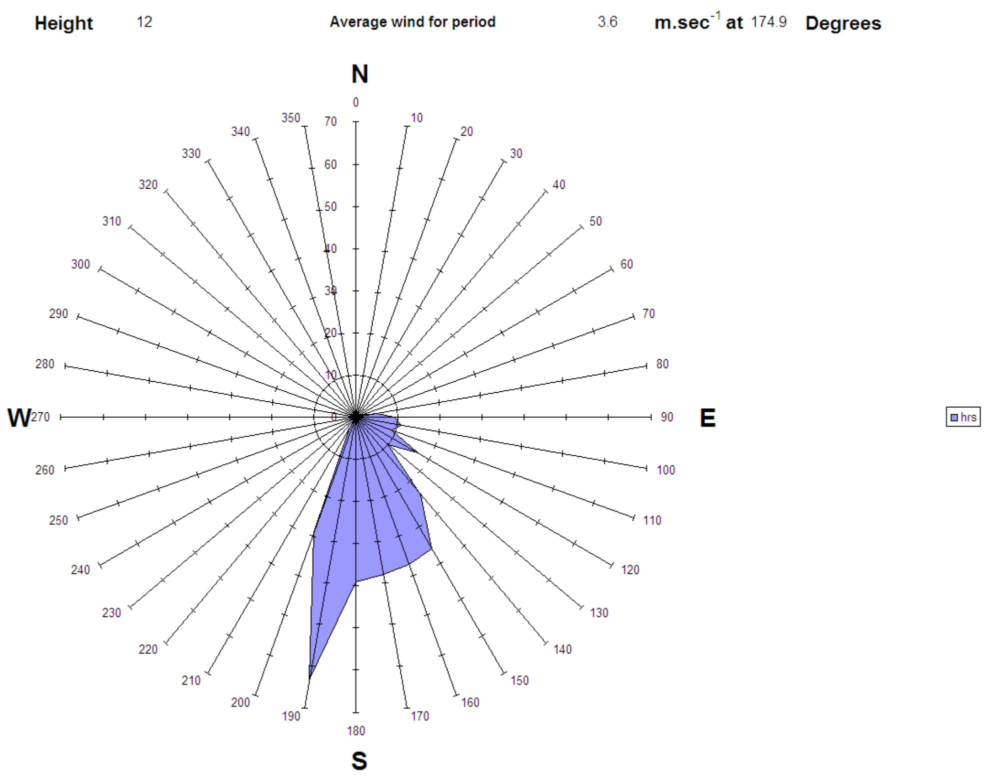

Figure A3.6 Wind rose for 18th January during measurements from SDP5, 10:46 - 16:50

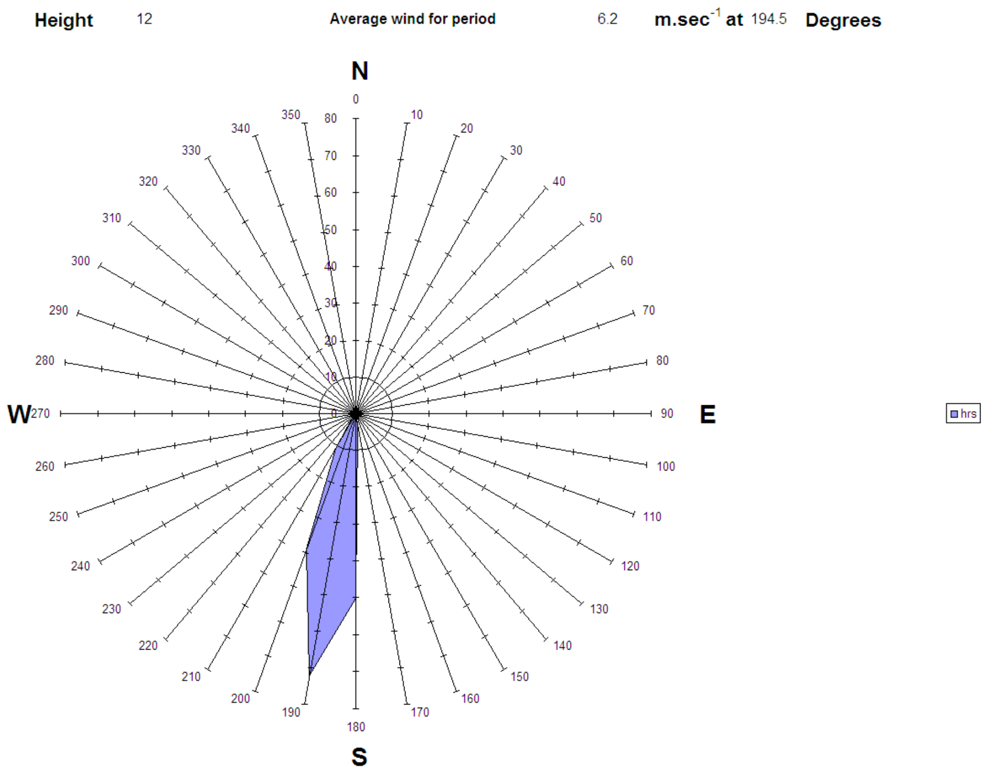

Figure A3.7 Wind rose for 19th January during measurements from SDP6, 10:27 - 14:18

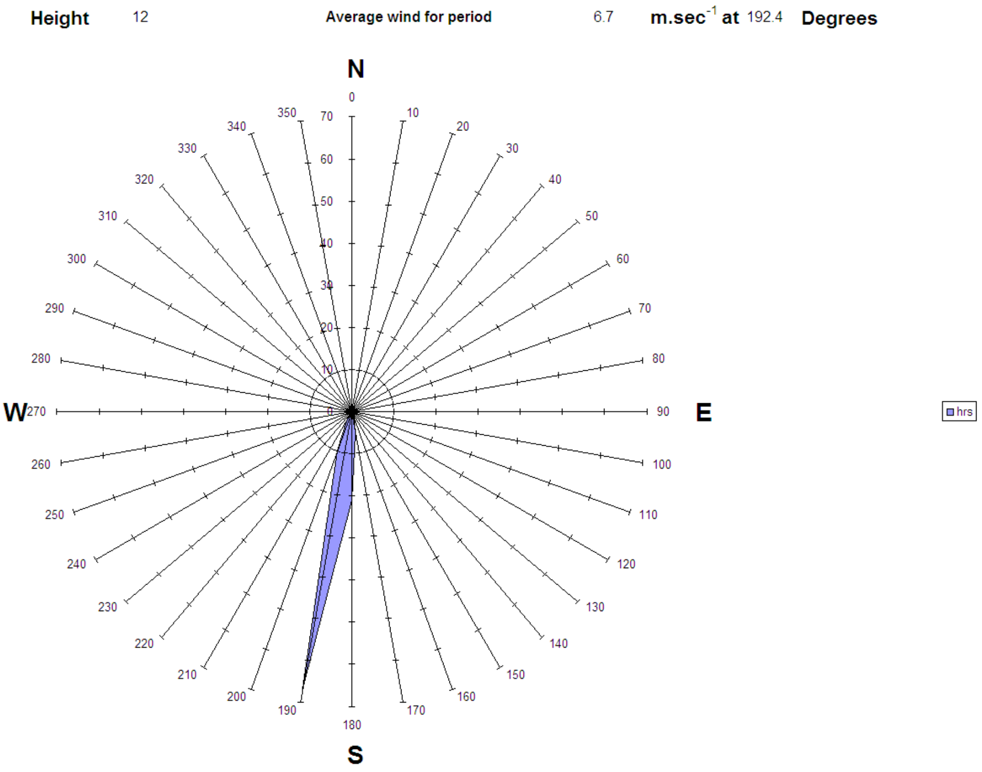

Figure A3.8 Wind rose for 19th January during measurements from SDP7, 15:01 - 16:57

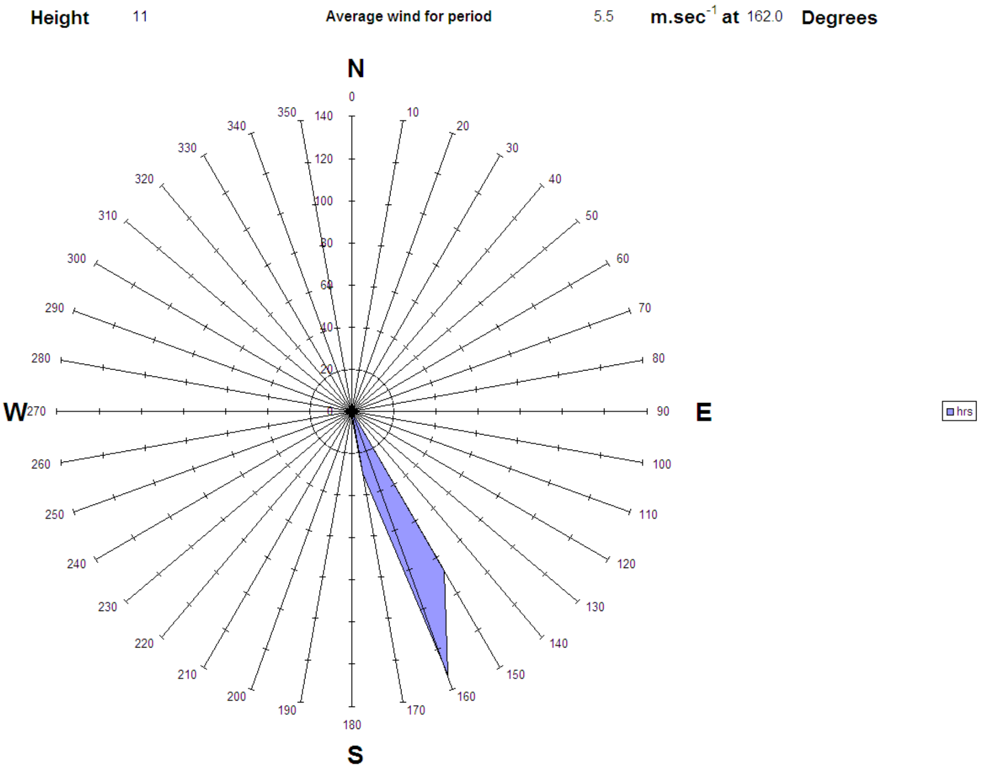

Figure A3.9 Wind rose for 20th January during measurements from SDP8, 11:57 - 17:06

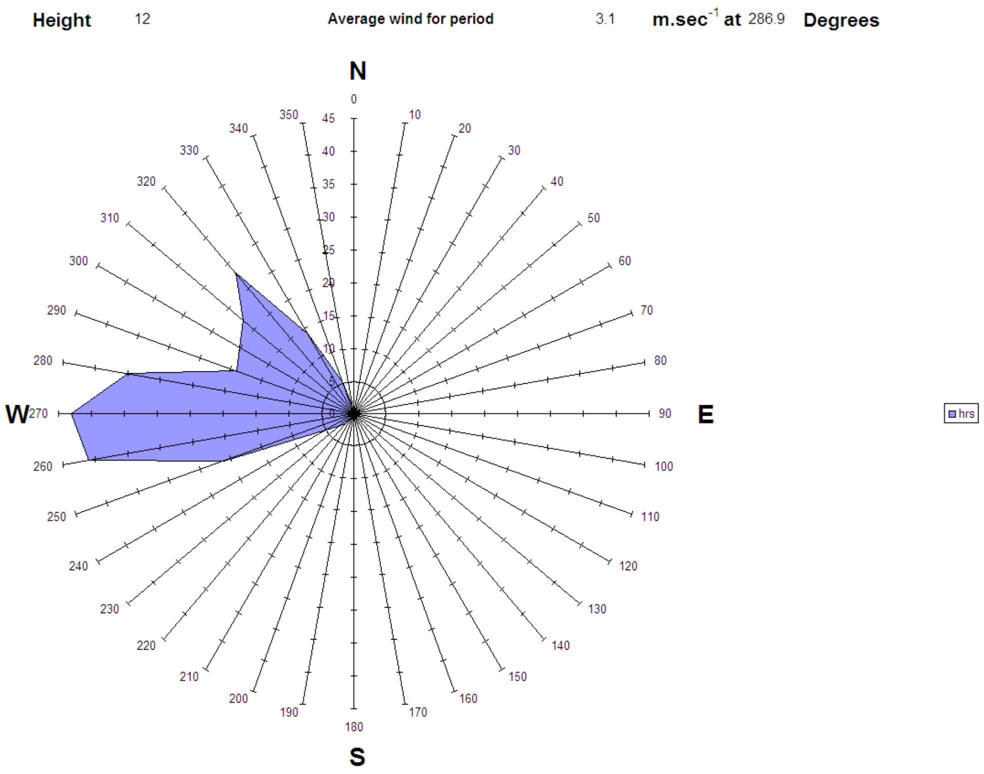

Figure A3.10 Wind rose for 21st January during measurements from SDP9, 11:57 - 16:55

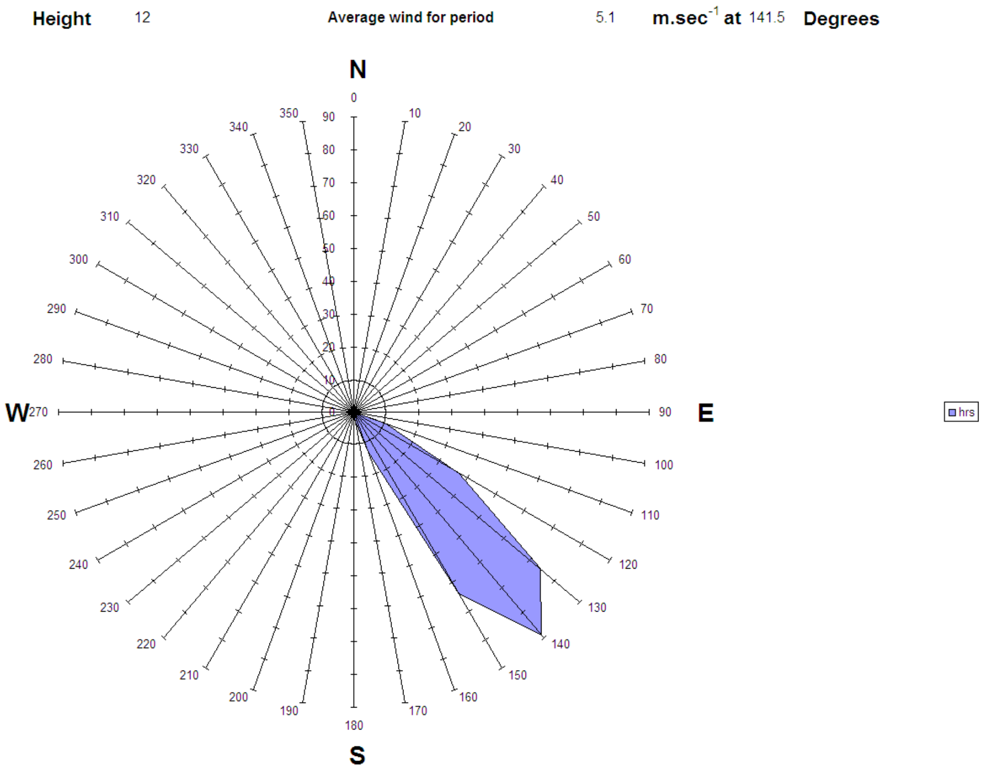

Figure A3.11 Wind rose for 22nd January during measurements from SDP10, 12:07 - 17:30

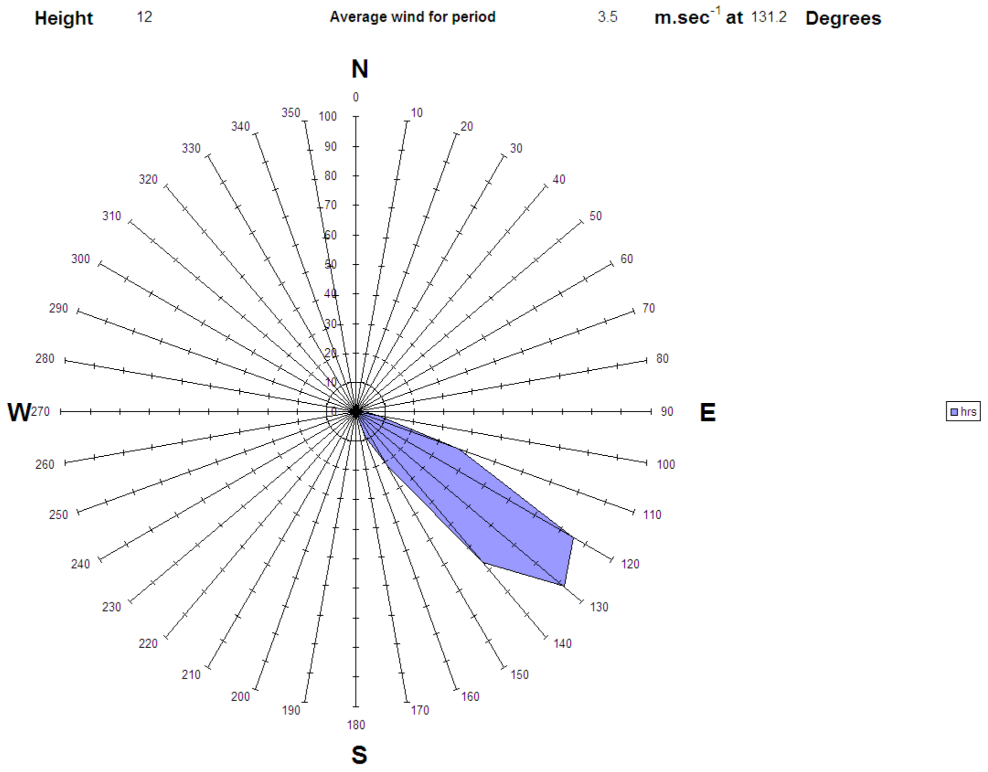

Figure A3.12 Wind rose for 23rd January during measurements from SDP11, 10:57 - 17:06

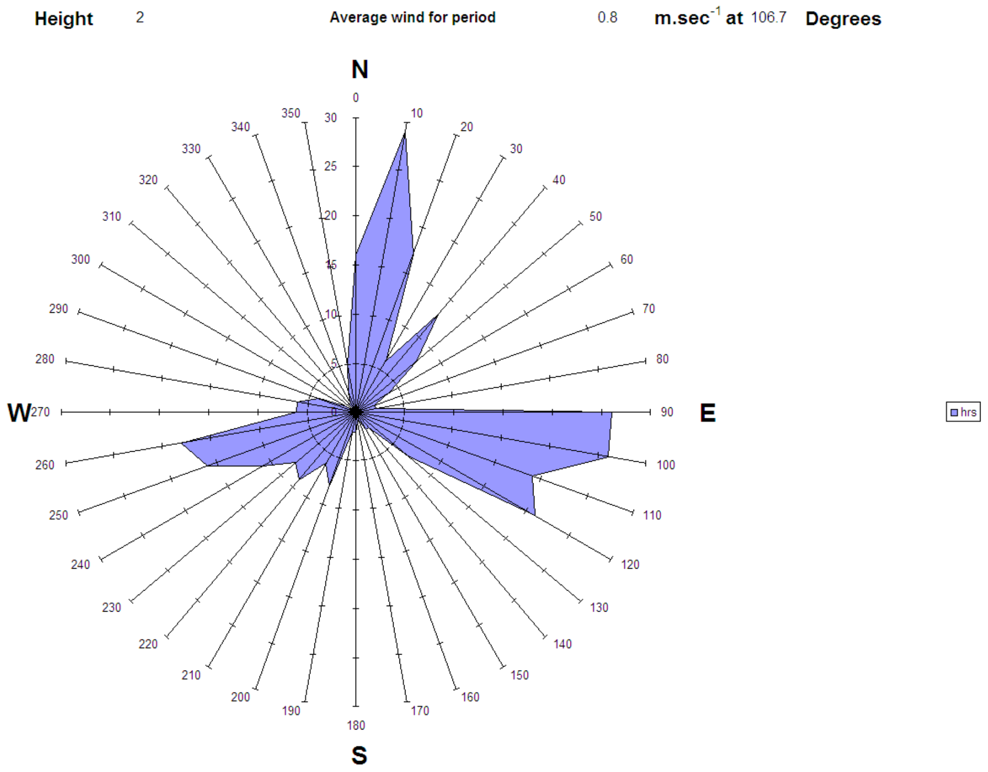

Figure A3.13 Wind rose for 25th January during measurements from SDP12, 10:42 - 17:01

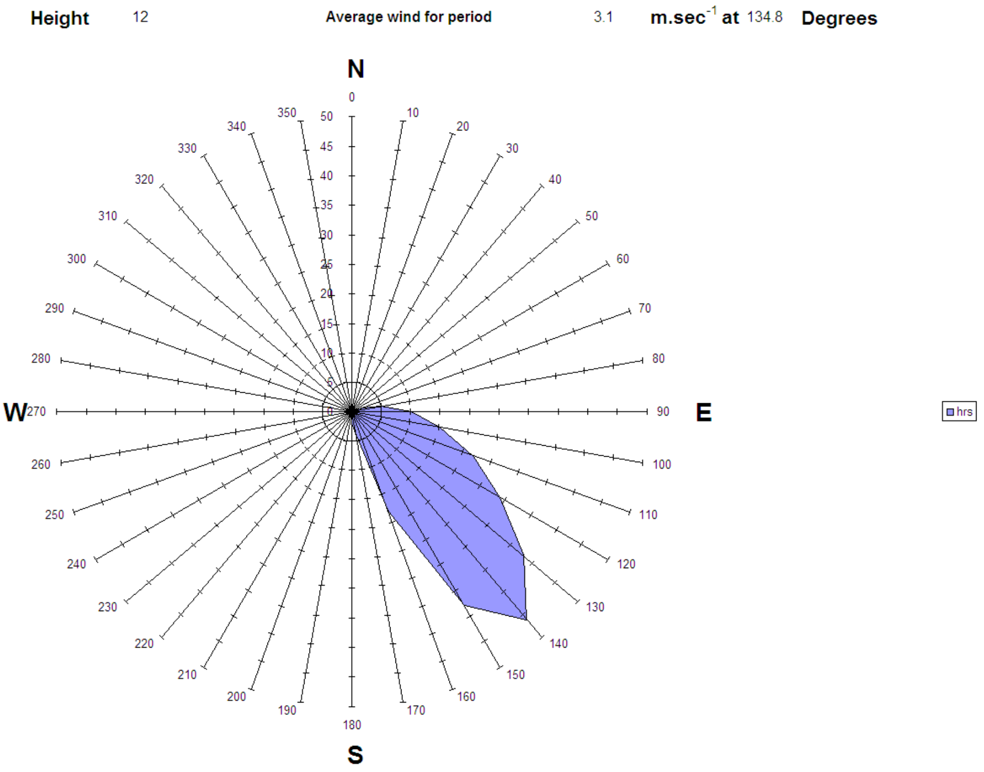

Figure A3.14 Wind rose for 26th January during measurements from SDP13, 12:43 - 16:47

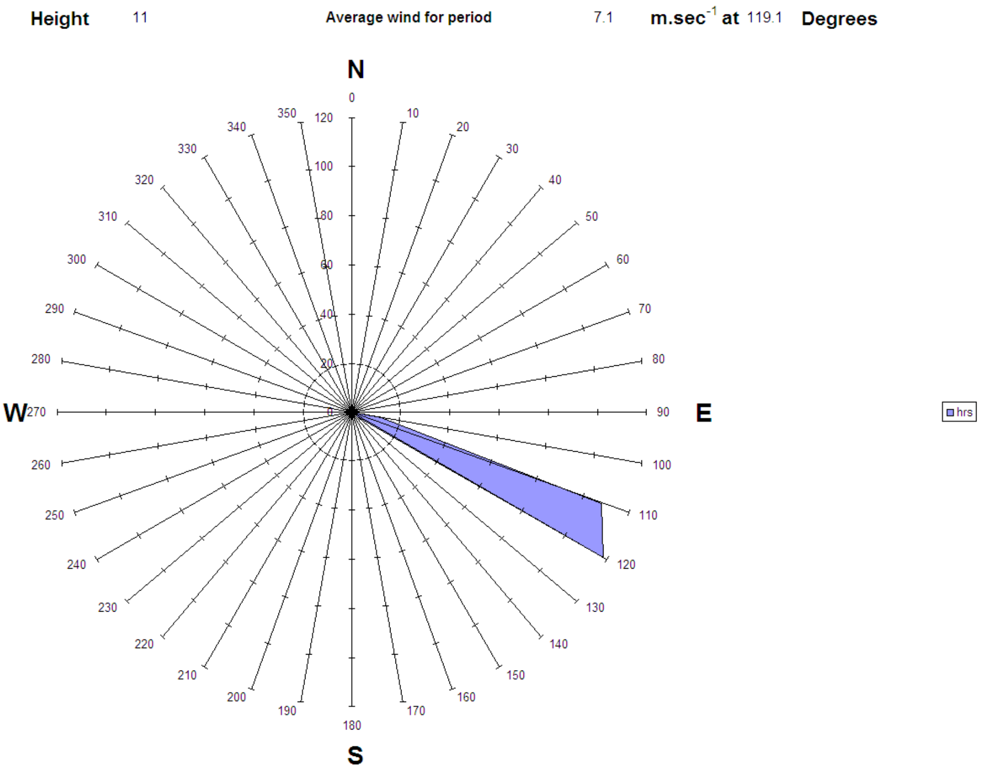

Figure A3.15 Wind rose for 27th January during measurements from SDP14, 12:15 - 17:09

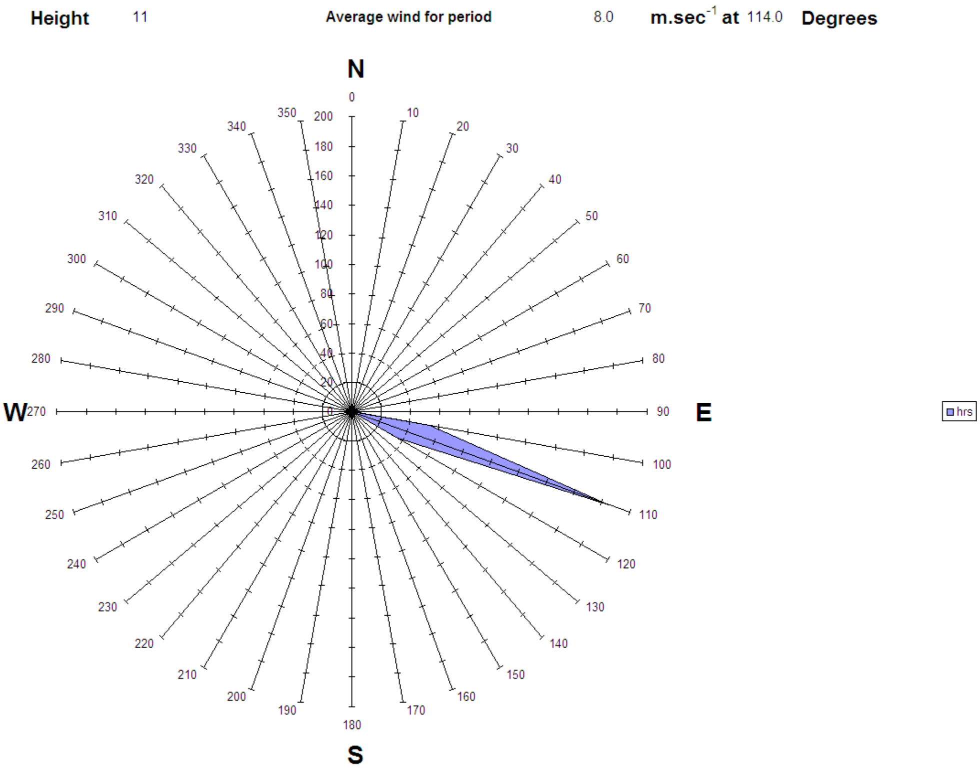

Figure A3.16 Wind rose for 28th January during measurements from SDP15, 11:23 - 16:41

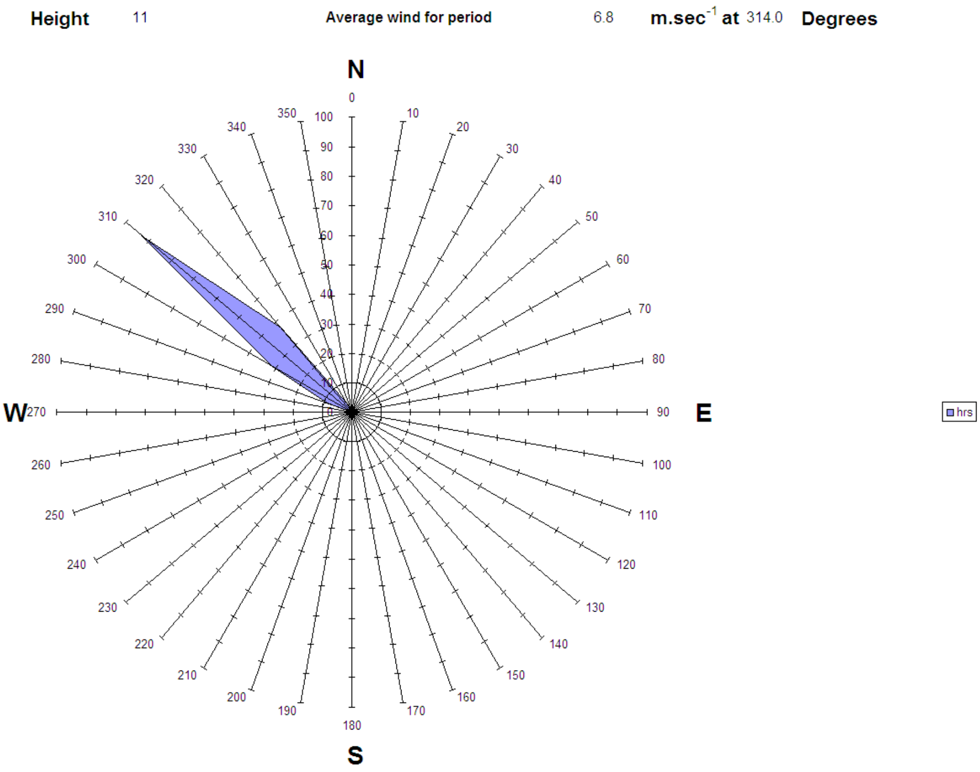

Figure A3.17 Wind rose for 29th January during measurements from SDP16, 14:01 - 16:56

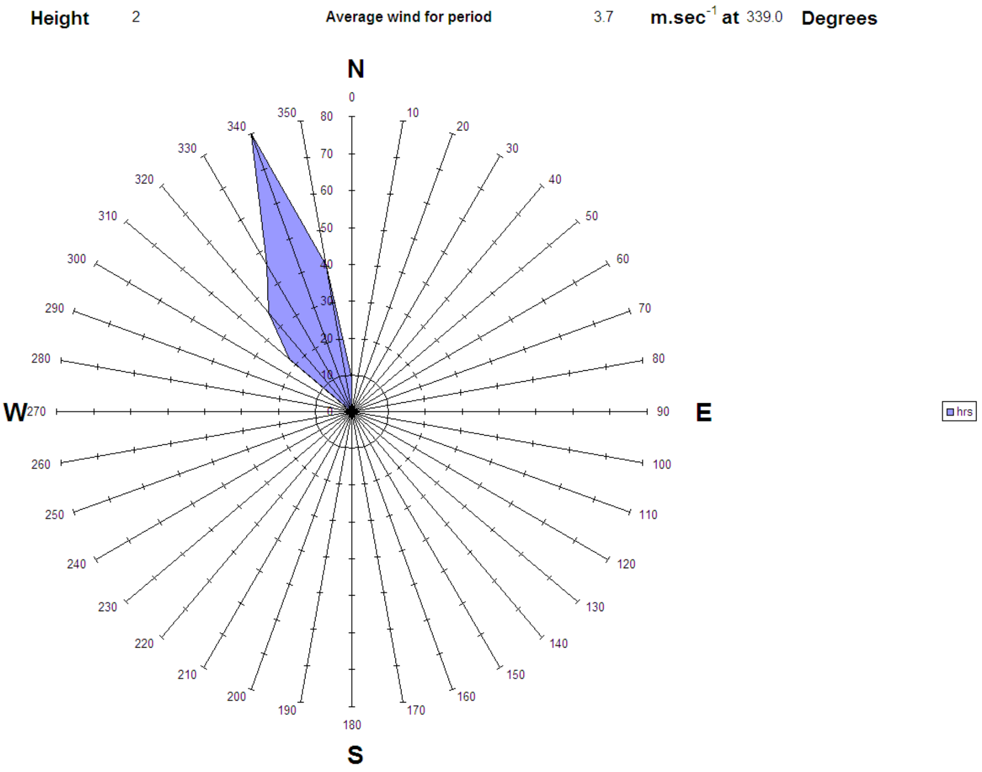

Figure A3.18 Wind rose for 30th January during measurements from SDP12, 12:26 - 17:01

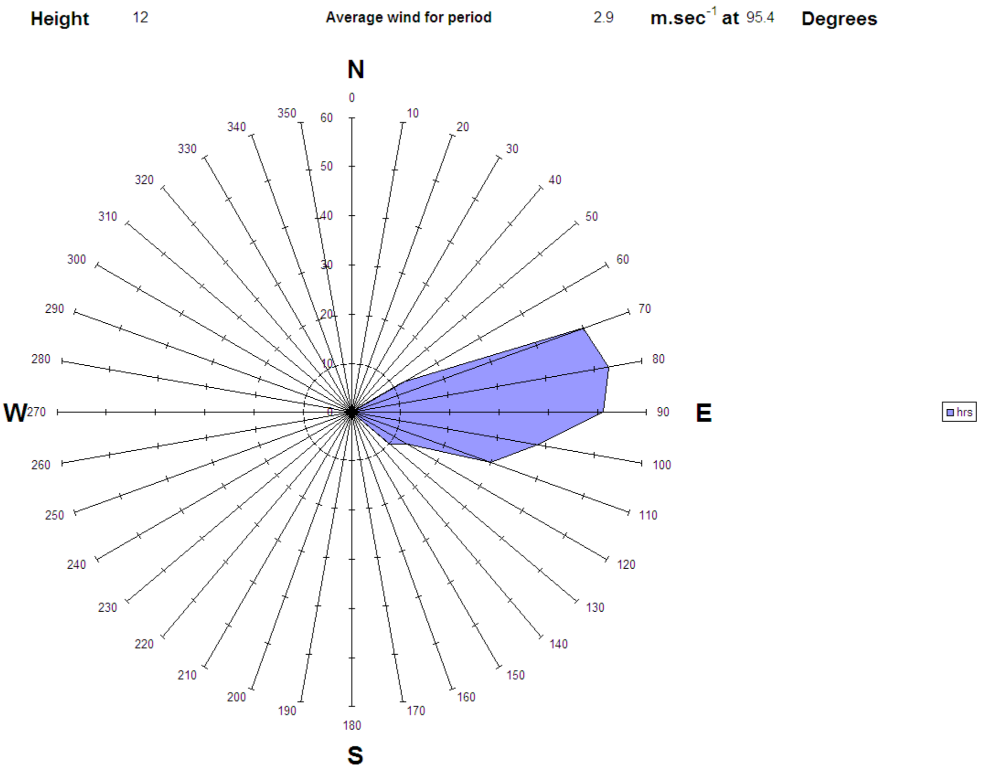

Figure A3.19 Wind rose for 1st February during measurements from SDP17, 12:16 - 17:05

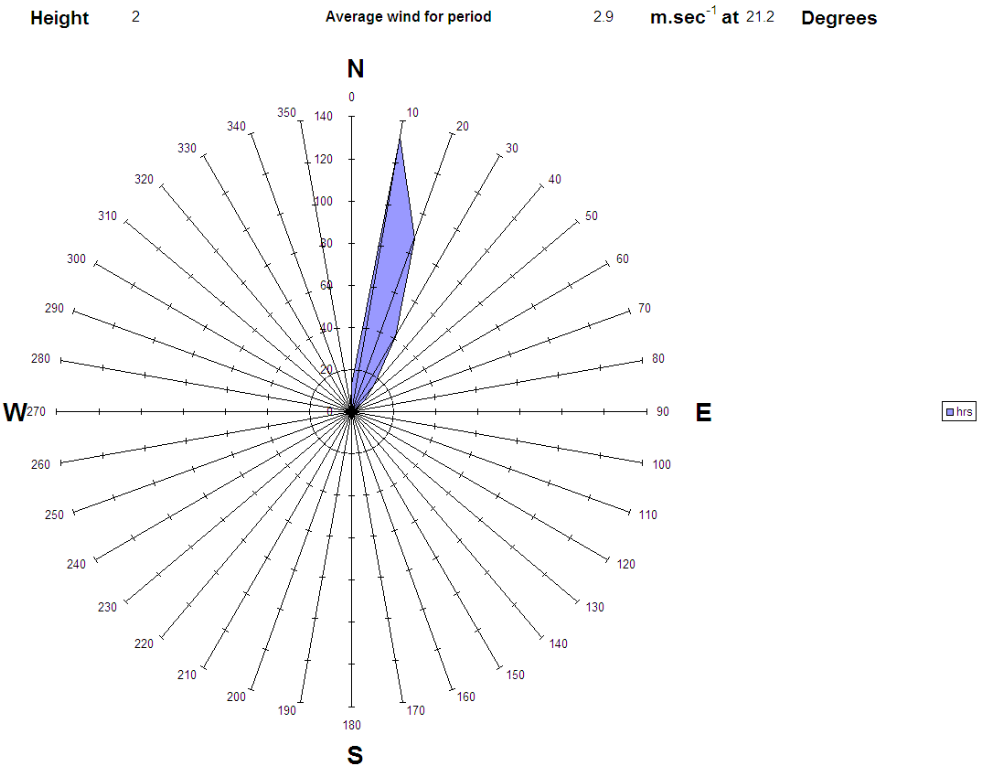

Figure A3.20 Wind rose for 2nd February during measurements from SDP18, 10:54 - 17:05

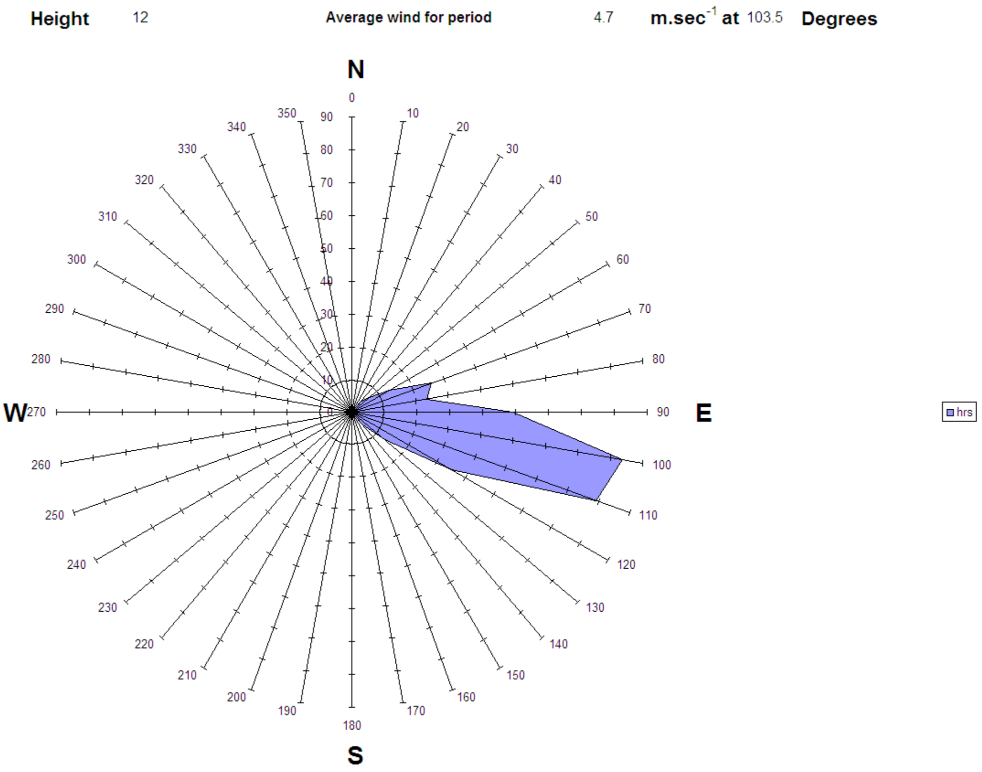

Figure A3.21 Wind rose for 3rd February during measurements from SDP19, 10:30 - 16:54

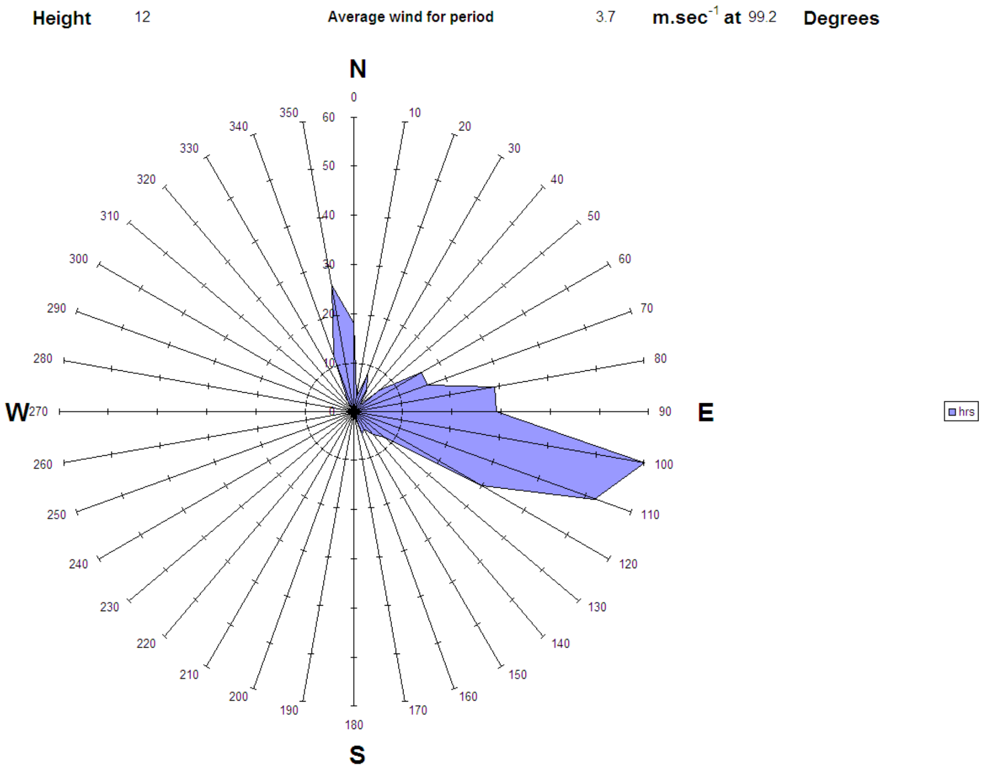

Figure A3.22 Wind rose for 4th February during measurements from SDP20, 10:17 - 16:50

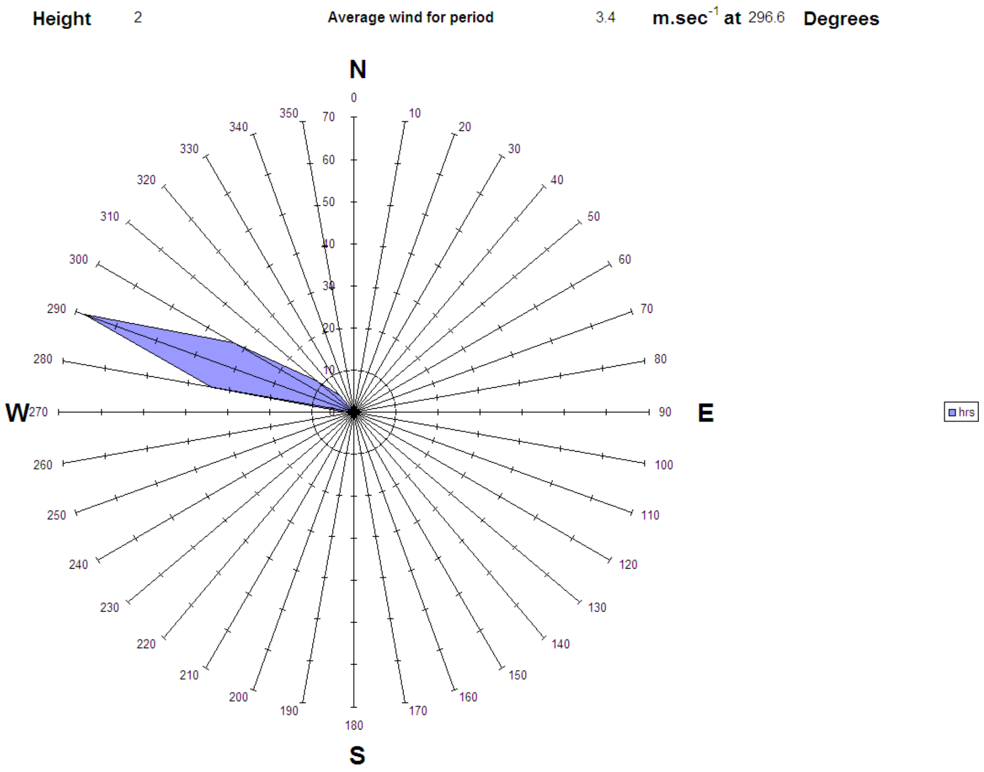

Figure A3.23 Wind rose for 5th February during measurements from SDP21, 10:50 - 14:11

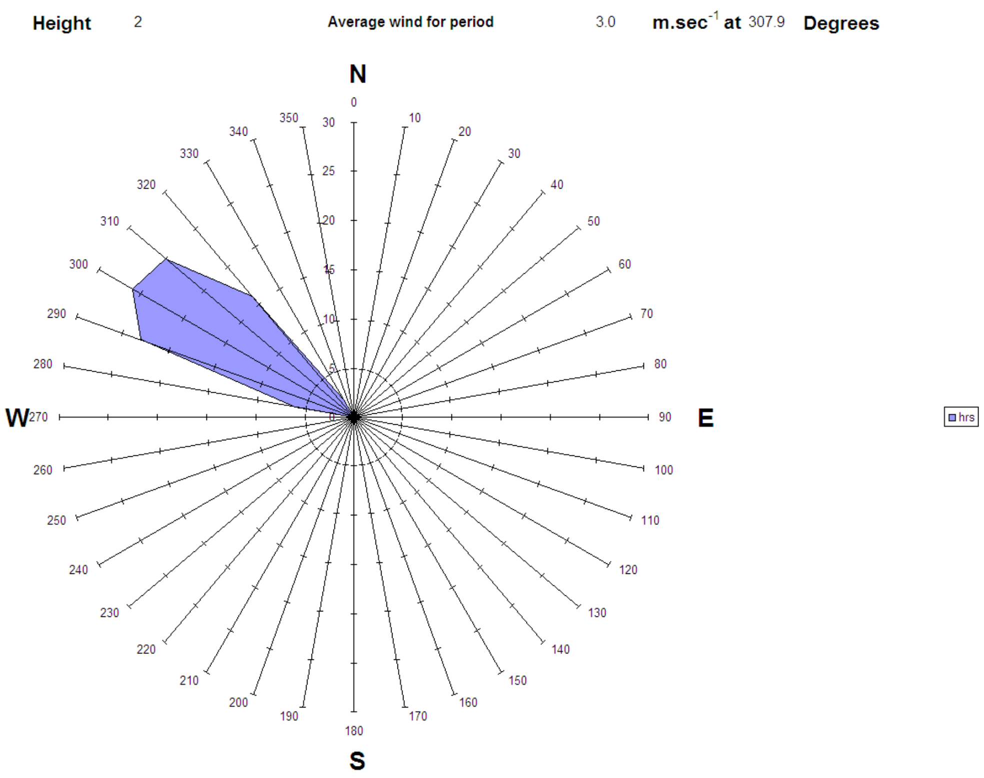

Figure A3.24 Wind rose for 5th February during measurements from SDP22, 14:47 - 16:56

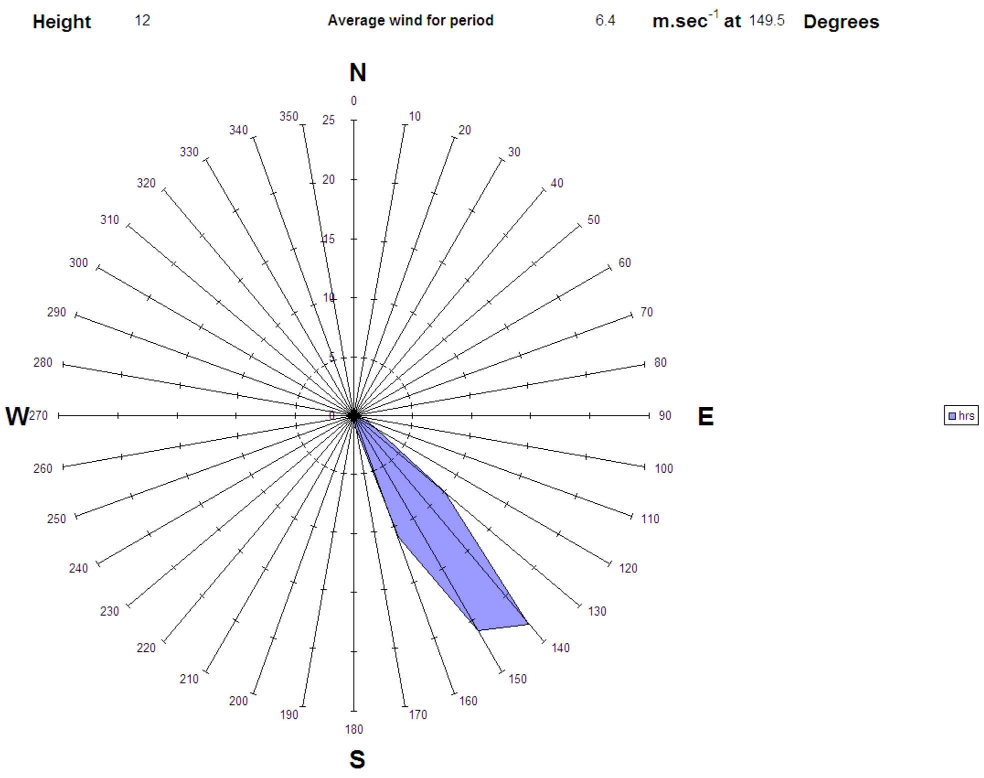

Figure A3.25 Wind rose for 8th February during measurements from SDP23, 10:55 - 12:07

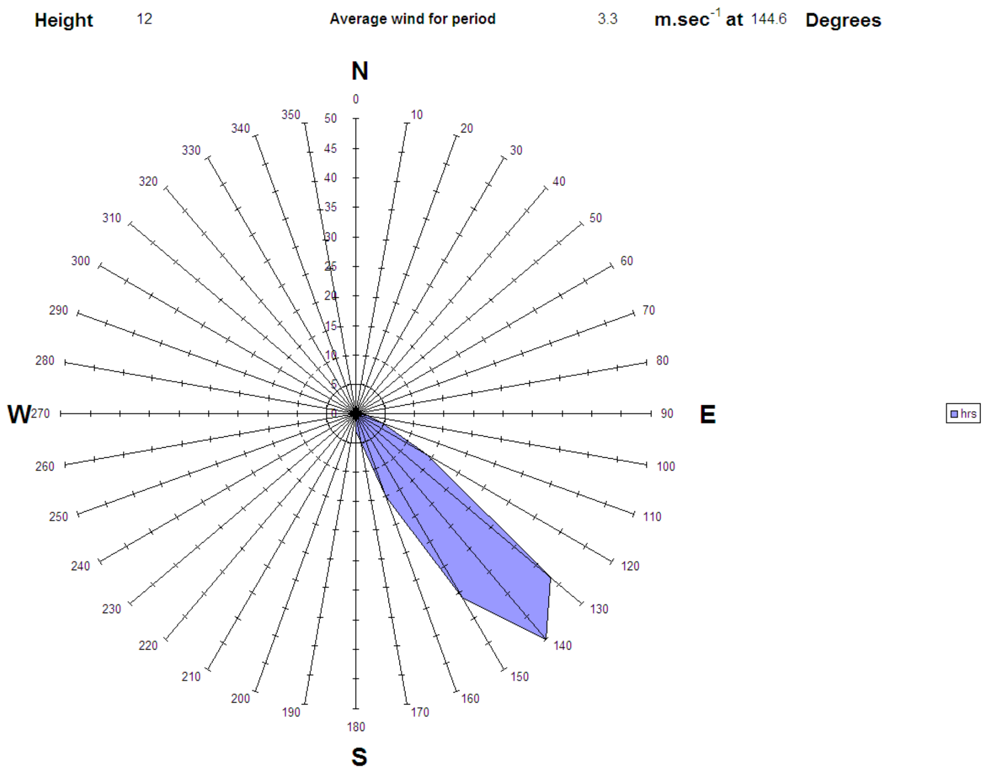

Figure A3.26 Wind rose for 8th February during measurements from SDP24, 14:15 - 17:23

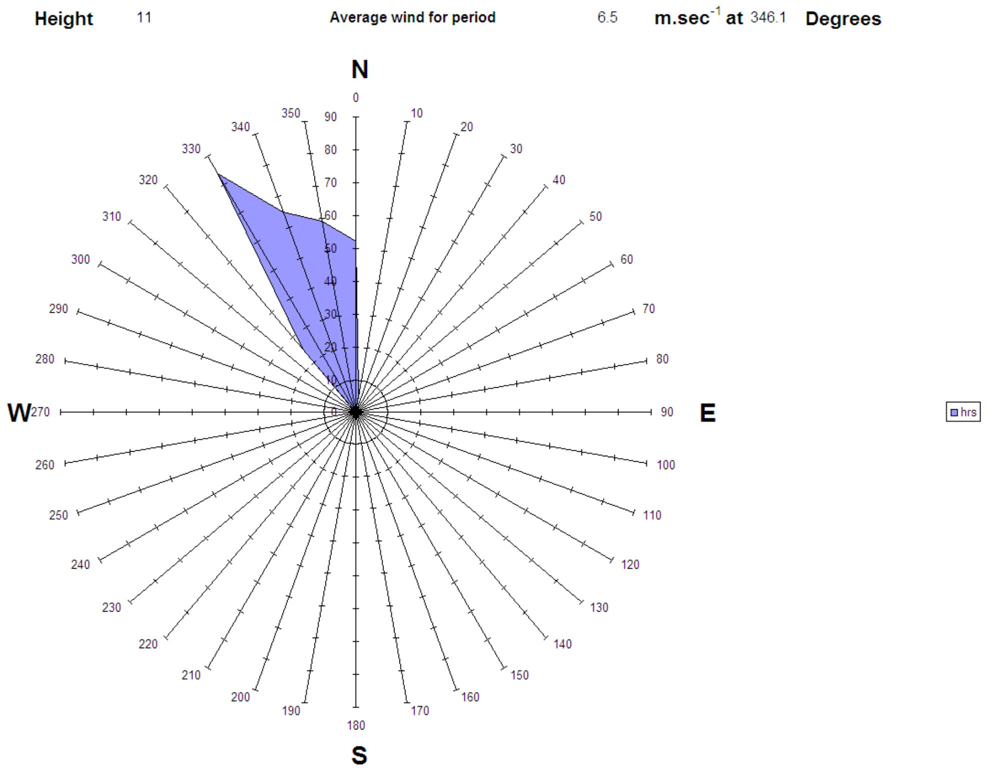

Figure A3.27 Wind rose for 9th February during measurements from SDP25, 10:42 - 16:57

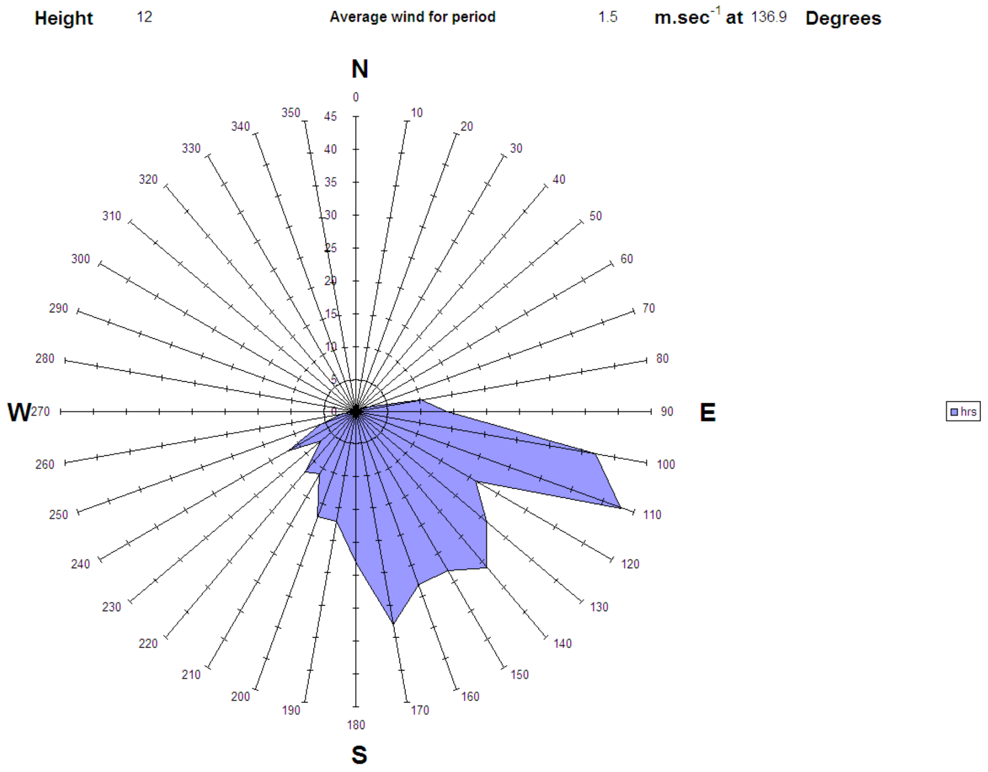

Figure A3.28 Wind rose for 10th February during measurements from SDP26, 9:55 - 17:05

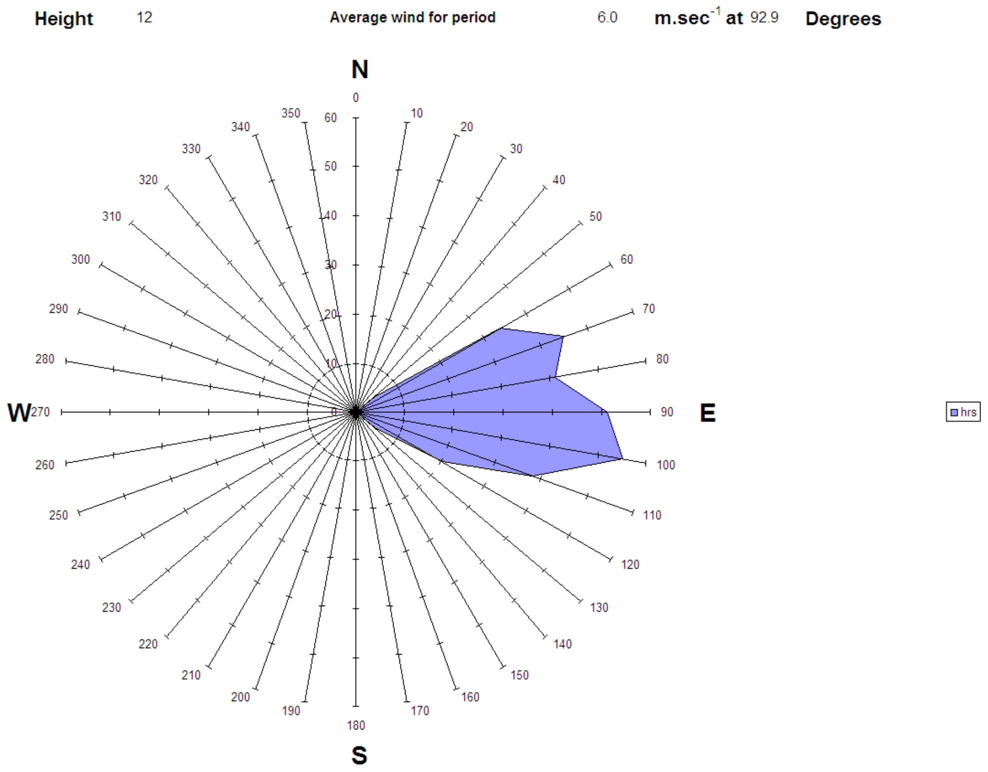

Figure A3.29 Wind rose for 11th February during measurements from SDP27, 11:22 - 16:47

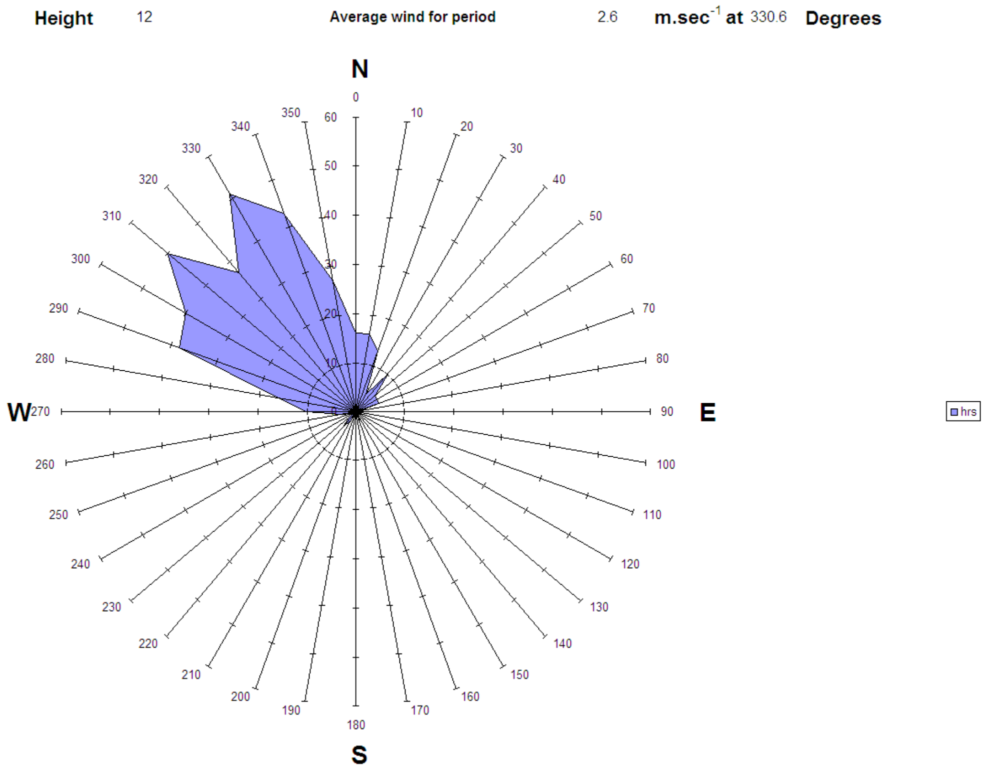

Figure A3.30 Wind rose for 12th February during measurements from SDP28, 10:40 - 17:26

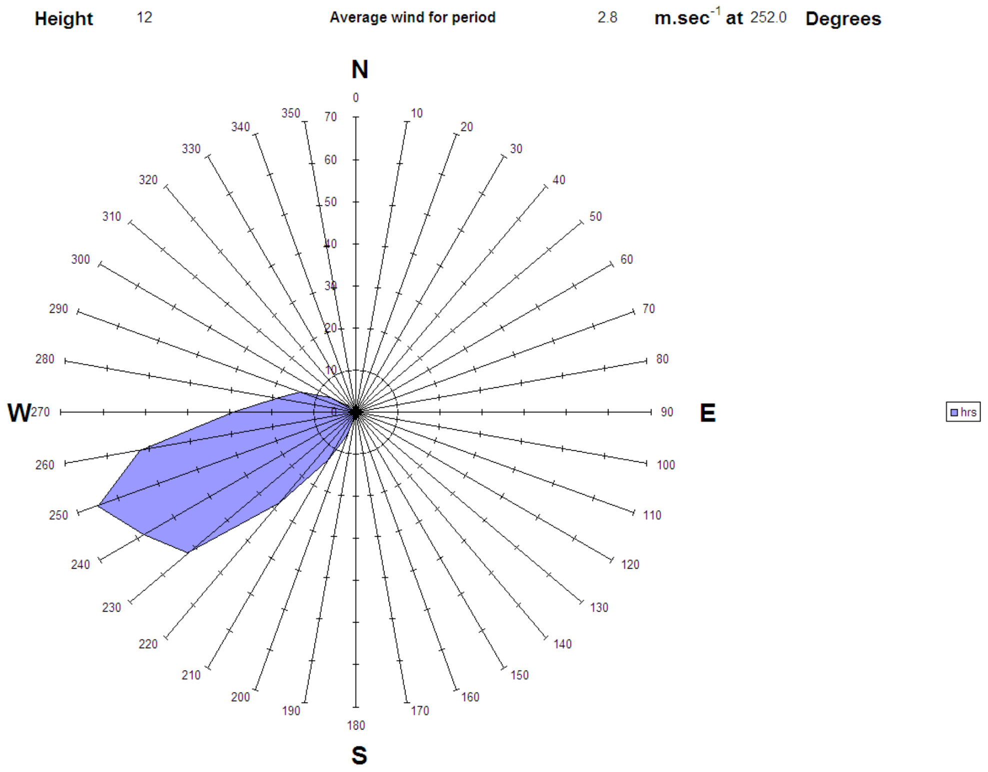

Figure A3.31 Wind rose for 13th February during measurements from SDP29, 10:53 - 16:42

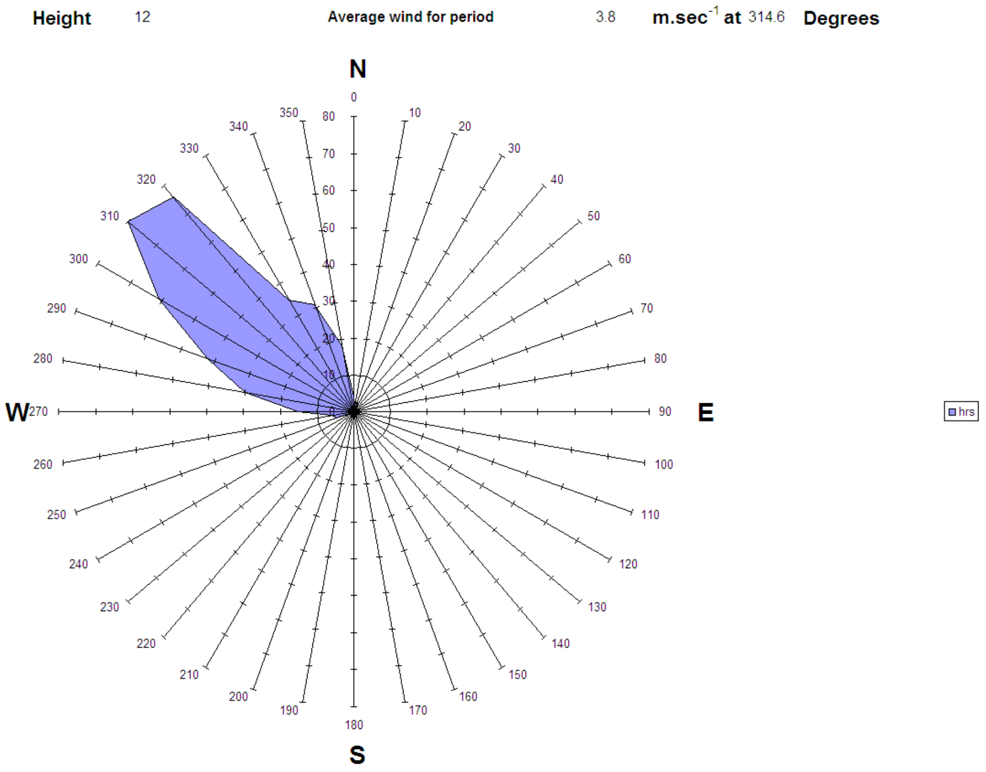

Figure A3.32 Wind rose for 15th February during measurements from SDP28, 10:18 - 17:13

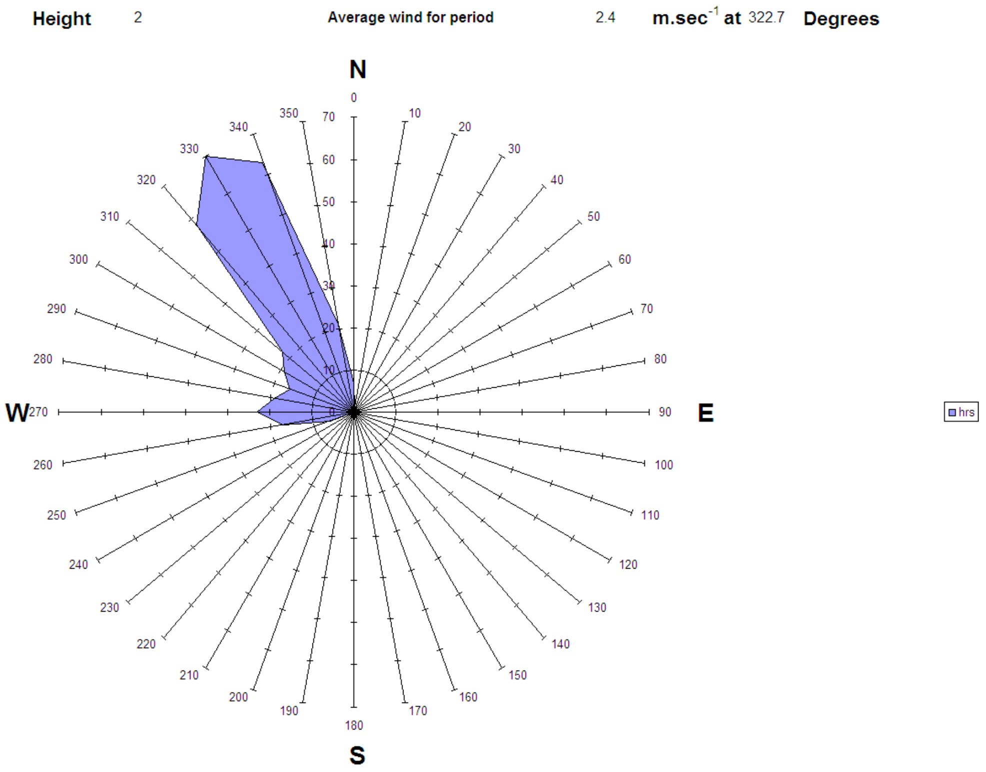

Figure A3.33 Wind rose for 16th February during measurements from SDP30, 10:06 - 16:43

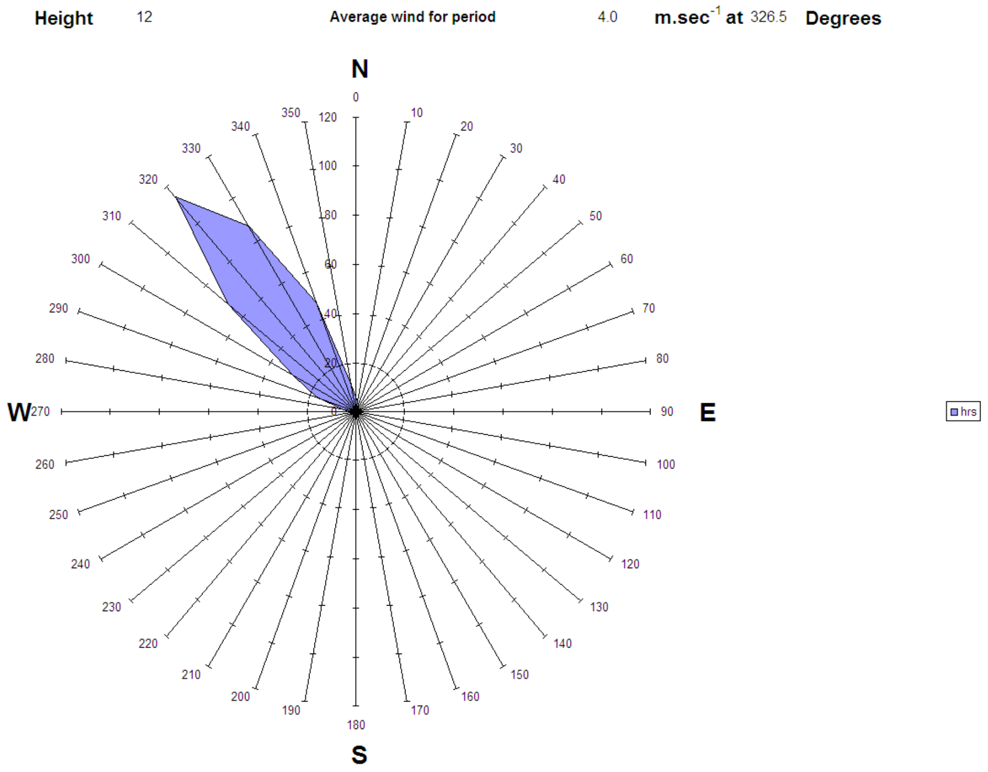

Figure A3.34 Wind rose for 17th February during measurements from SDP31, 10:06 - 16:54

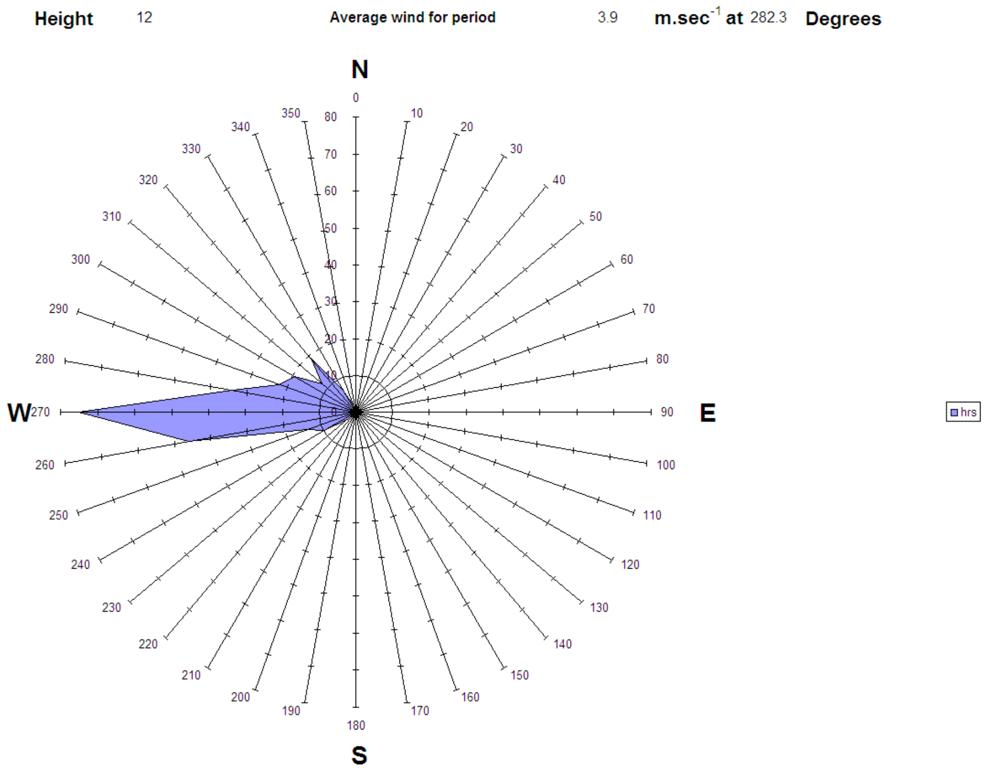

Figure A3.35 Wind rose for 22nd March during measurements from SDP32, 12:29 - 17:24

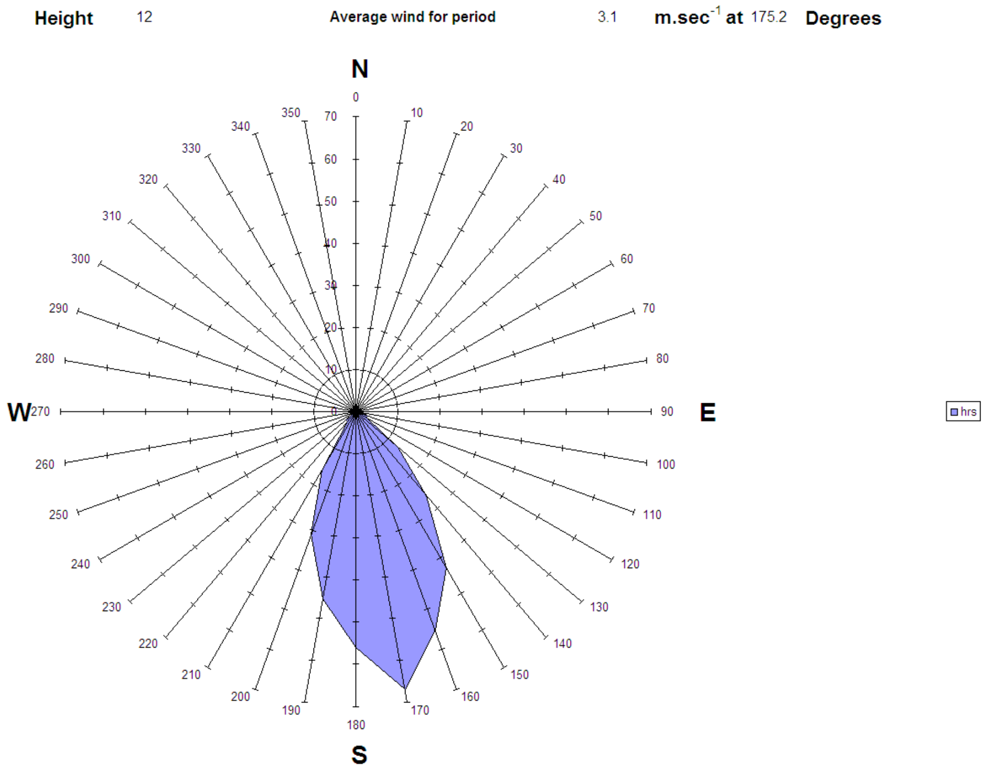

Figure A3.36 Wind rose for 23rd March during measurements from SDP33, 10:18 - 17:05

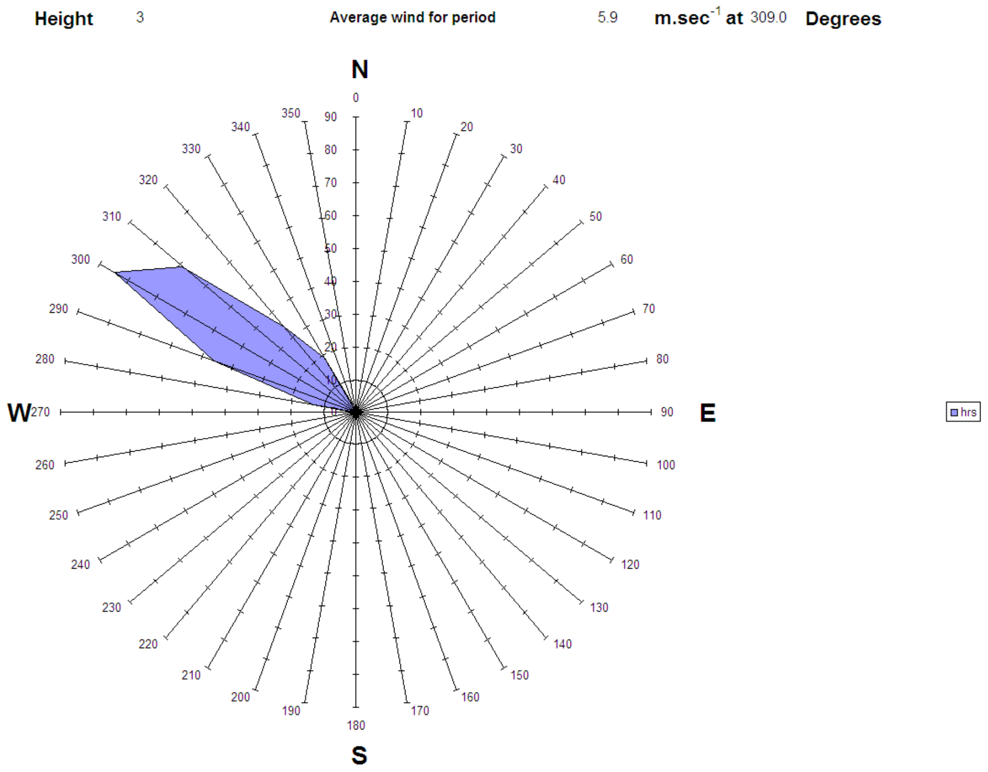

Figure A3.37 Wind rose for 25th March during measurements from SDP34, 10:53 - 16:54

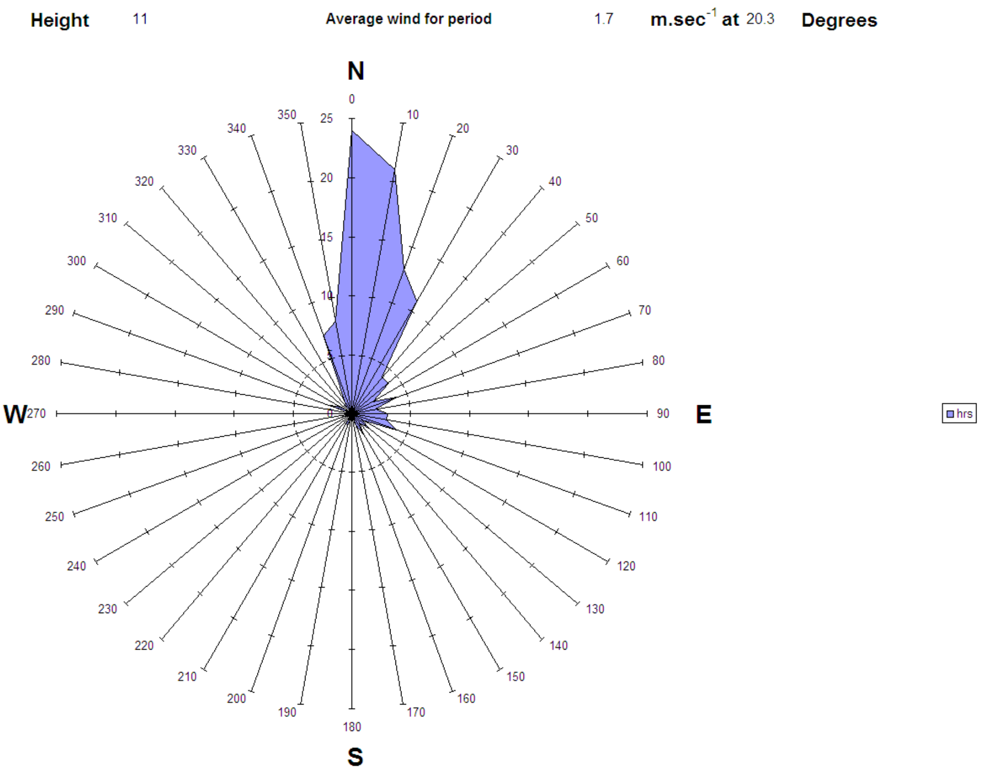

Figure A3.38 Wind rose for 26th March during measurements from SDP35, 10:53 - 13:33

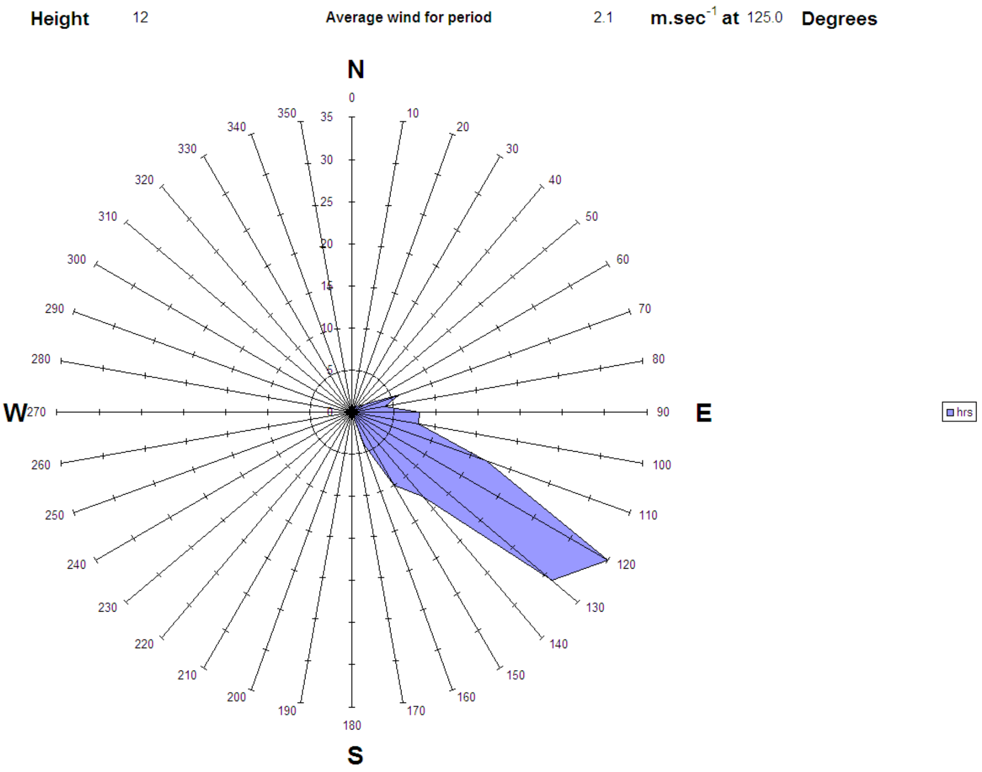

Figure A3.39 Wind rose for 26th March during measurements from SDP36, 14:38 - 17:05

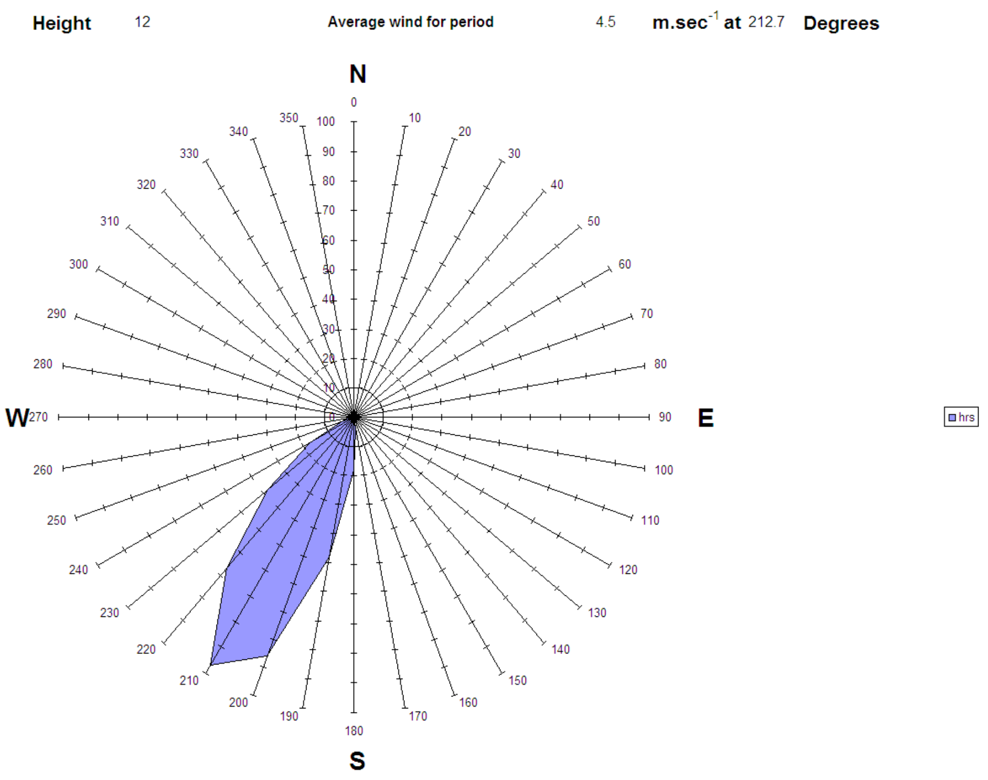

Figure A3.40 Wind rose for 27th March during measurements from SDP37, 9:58 - 16:51

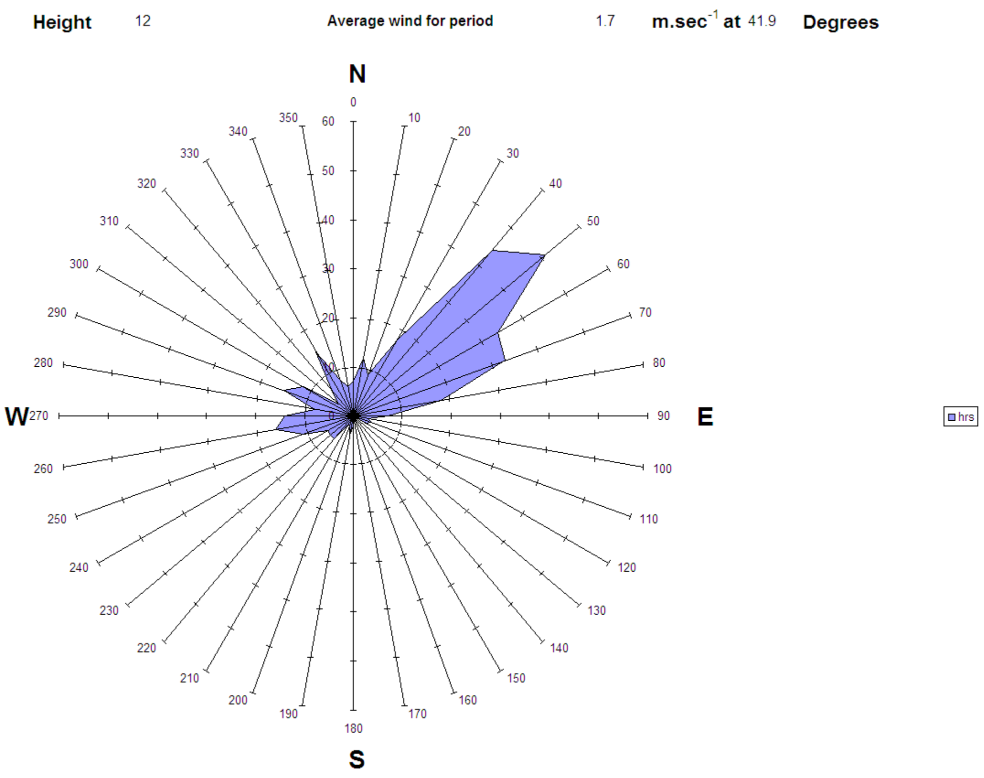

Figure A3.40 Wind rose for 29th March during the last day of the campaign, 9:00 - 16:30