

**Conducting an SLCP Measurement Survey Campaign of Emissions
from Gas Flares: Final Technical Report on Black Carbon
Measurements in Mexico and Ecuador**

November 30, 2015

**Final Technical Report Prepared for the Petroleum Technology Alliance of Canada and the
United Nations Environment Programme**



Carleton
UNIVERSITY
Canada's Capital University

Mr. Bradley Conrad, Ph.D. Student,
Ms. Melina Jefferson, M.A.Sc. Candidate
Mr. Darcy Corbin, M.A.Sc.,
Prof. Matthew Johnson, Ph.D., P.Eng.,
Energy & Emissions Research Lab.
Mechanical & Aerospace Engineering,
Carleton University

PREFACE

This final report is submitted on behalf of the Energy & Emissions Research Lab. at Carleton University. The report summarizes work regarding the measurement of black carbon emission rate, flare gas flow rate, black carbon yield, and solid-phase flare efficiency under the research agreement from the Petroleum Technology Alliance Canada (PTAC) for the project entitled “Conducting an SLCP Measurement Survey Campaign of Emissions from Gas Flares” – specifically, sub-activity 1a. This final report is designed to satisfy the final deliverable due November 15, 2015. Additional support was provided by Petróleos Mexicanos, Petroamazonas, the World Bank Global Gas Flaring Reduction Partnership, and Carleton University. Future analyses of data obtained during the implementation of this research agreement is imminent – reporting on results from these remaining data (in the form of peer-reviewed journal article(s) and/or conference proceeding(s)) will be forwarded to stakeholders upon publication.

TABLE OF CONTENTS

1	BACKGROUND	5
2	PROJECT IMPLEMENTATION.....	7
2.1	Summary of Work.....	7
2.2	Measurements in Mexico	7
2.2.1	Background.....	7
2.2.2	Data Acquired In-Field	9
2.3	Measurements in Ecuador	11
3	RESULTS: MEASUREMENTS IN MEXICO	13
3.1	Black Carbon Emission Rate.....	13
3.2	Flare Gas Composition and Flow Rate	16
3.3	Black Carbon Yield.....	20
4	PRELIMINARY RESULTS: ECUADOR	22
5	SUMMARY	23
5.1	Future Work	24
6	REFERENCES	25
	APPENDIX A : SUMMARY OF DATA COLLECTED IN MEXICO.....	27
A.1	Pit Flare	27
A.1.1	Description of Flare	27
A.1.2	Sky-LOSA Acquisition.....	27
A.1.3	Simultaneous Flow and Composition Measurement	28
A.2	Southern Emergency Flare	31
A.2.1	Description of Flare	32
A.2.2	Sky-LOSA Acquisition.....	32
A.3	Northern Emergency Flare	33
A.3.1	Description of Flare	33
A.3.2	Sky-LOSA Acquisition.....	33
	APPENDIX B : FIELD REPORT FOR MEASUREMENTS IN ECUADOR	34

B.1	Project Background	35
B.2	Overview of Field Measurements in Ecuador.....	38
B.2.1	Black Carbon Measurements Using Sky-LOSA.....	38
B.3	Flare Gas Sampling for Compositional Analysis	47
B.4	References	50
B.5	Summary of Data Collected in the Field.....	52
B.5.1	Auca Central – October 26, 2015	52
B.5.2	Auca 27 – October 27, 2015	55
B.5.3	Auca Sur – October 28, 2015.....	60
B.5.4	Auca Sur 1 – October 27 & October 29, 2015.....	67
APPENDIX C : FLARE GAS FLOW RATE RESULTS IN ECUADOR.....		73
C.1	Project Background	74
C.2	Flare Gas Flow Rate Results	75
C.3	Flow Rate Results by Flare and Line	76
C.3.1	Auca 27	76
C.3.2	Auca Sur (Right Flare & Left Flare).....	79
C.3.3	Auca Sur 1.....	82
C.3.4	Auca Central	84
C.4	Preliminary Flare Gas Composition Results	86
C.5	References	88
C.6	Details of Measured Flow Rate Data and Results.....	89
C.6.1	Tracer-Dilution (TD) Technique Data	89
C.6.2	Optical Flow Meter (OFM) Data	89
C.6.3	Auca 27 – October 27, 2015	91
C.6.4	Auca Sur – October 28, 2015.....	96
C.6.5	Auca Sur 1 – October 29, 2015.....	98
C.6.6	Auca Central – October 26, 2015	101

1 BACKGROUND

Black carbon (BC) is an especially important atmospheric pollutant. Considered a PM_{2.5} species (particulate matter of less than 2.5 μm in diameter), BC is significantly correlated with both public health and anthropogenic climate forcing (US EPA 2012). A recent review by Graham et. al. (2014) suggests that BC is the component of PM_{2.5} primarily responsible for the causal relation of PM_{2.5} with cardiovascular and lung cancer mortality. Additionally, recent research, including Bond et. al. (2013), has implicated BC as the most potent anthropogenic climate forcer after carbon dioxide (CO₂). However, BC differs from CO₂ in that BC has a relatively short atmospheric lifetime; as such, BC is often classed as a Short-Lived Climate Pollutant (SLCP). While CO₂ is the focus for long-term mitigation of anthropogenic climate forcing, SLCPs are often regarded as a significant mitigation opportunity in the near term (IPIECA 2014).

Gas flaring, the activity of burning unwanted flammable gases deemed uneconomic to bring to market or utilize, is one important source of atmospheric BC. Satellite data suggest that annual volumes of flared gas are consistently above 140 billion m³ globally, as shown by Elvidge et. al. (2009). The impact of gas flaring on arctic climates is especially concerning, where the deposition of BC on snow or ice has the additional effect of reducing surface albedo (US EPA 2012). Stohl et. al. (2013) highlighted the magnitude of the impact of gas flaring in the arctic, suggesting flaring activities are responsible for 42% of BC surface deposition and more than 66% of airborne concentrations.

Although BC emissions from gas flaring are identified as crucially important, emission factor data relating BC emissions with various flare metrics are severely lacking. The review by McEwen and Johnson (2012) identifies critical shortcomings of emission factors used today, which have in general been based on very limited or even semi-quantitative data taken under a very narrow range of conditions. The very few available factors are starkly contrasted with the myriad types of flare designs, fuel compositions, flow rates, and environmental and operating conditions encountered in the field. As such, there is a critical need for quantitative field measurements to support development of science-based emission factors for in-field gas flares.

Until recently, BC yield (i.e. the ratio of BC mass emission rate to flare gas mass flow rate) has been impossible to quantify in the field due to an inability to perform in-situ

measurements of BC emission rate. This has changed with the development of sky-LOSA (**Line-Of-Sight Attenuation**) by Johnson et. al. (2010, 2011, and 2013). Sky-LOSA is an imaging technique that enables the quantification of the instantaneous BC emission rate through a specified control surface in the image plane. This is performed by using Rayleigh-Debye-Gans theory for Polydisperse Fractal Aggregates (RDG-PFA) to carefully consider visible-light extinction effects along the line-of-sight axis of the camera. The integrated BC volume fraction can then be calculated by computing the transmittance of the plume – i.e. the ratio between the measured intensity and the background skylight intensity. By coupling the integrated BC volume fraction with synchronized velocity data obtained via Image Correlation Velocimetry, the instantaneous BC emission rate can be directly quantified. In addition, quantitative measurement uncertainties can be calculated via a Monte Carlo method with a Latin Hypercube sampling technique to reduce processing time. Ultimately, the BC emission rate can be coupled with simultaneous flare gas flow rate and composition measurements to compute the BC yield and solid-phase flare efficiency (i.e. the efficiency of the flare in converting fuel to gas phase products). With support of the United Nations Climate and Clean Air Coalition (CCAC) and the World Bank Global Gas Flaring Reduction Partnership (GGFR), the 3rd generation sky-LOSA technique has now been deployed in three field trials; at Petroamazonas facilities in Ecuador in June 2014 (Conrad and Johnson 2015a) and October 2015 as well as at a compressor station under Petróleos Mexicanos' (PEMEX) jurisdiction in Campeche, Mexico in June 2015. Work relating to the latter two measurement campaigns, performed under the current research agreement, is detailed in this report.

2 PROJECT IMPLEMENTATION

2.1 Summary of Work

Work under the current research agreement included two field-measurement campaigns. The first measurement campaign, at PEMEX facilities in Mexico, was the initial motivation for the current work. A background of these field-measurements along with a summary of data collected in the field are presented in Section 2.2 and APPENDIX A, respectively. Final results and analysis are presented in Section 3. A second measurement campaign, at Petroamazonas facilities in Ecuador, was initiated in September 2015 and executed in October 2015. A background of these field-measurements can be found in Section 2.3 and a field report detailing the fieldwork performed and the data acquired can be found in APPENDIX B. Processing of data from this measurement campaign has just begun, however a report to Petroamazonas, CCAC, and the World Bank GGFR detailing preliminary volumetric flare gas flow rate data is provided in APPENDIX C.

2.2 Measurements in Mexico

2.2.1 Background

On June 11, 2015, Carleton University personnel were notified of a potential opportunity to perform sky-LOSA measurements of BC emission rates from flaring activities at PEMEX's Dos Bocas Marine Terminal (TMDB) in Tabasco, Mexico, with the support of PEMEX. Initial planning outlined the dates of June 29 and June 30, 2015 for execution of the proposed work. This work included the sky-LOSA measurement of BC emission rates and the simultaneous measurement of flare gas flow rate for a number of flares. Additionally, to support the calculation of BC yield and solid-phase flare efficiency, extractive samples of the flare gas were proposed to be acquired for compositional analysis in nearby Villahermosa.

Unfortunately, on June 23, 2015 (four days prior to departure) PEMEX reported an operational upset at TMDB, and ultimately PEMEX informed the Carleton team that the originally planned work could not proceed, citing safety concerns. Amid rapidly changing status updates, PEMEX personnel worked to identify an alternative measurement opportunity. Two

Carleton University personnel travelled to Villahermosa on June 27, 2015 to join PEMEX and Clearstone Engineering Ltd. personnel in case such an opportunity arose. On June 29, Carleton University personnel received word that access would be granted to the Atasta Compressor Station (located approximately 110 km northeast of Villahermosa – refer to Figure 1a and Figure 1b) in Campeche, Mexico for June 30, 2015. However, due to the rapid development of this opportunity, it was determined by PEMEX that Carleton University personnel would not be permitted access to the flare lines for flare gas flow rate measurements or extractive sampling. This precluded planned independent measurement of flare gas flow rate by Carleton University (to be performed simultaneously with the sky-LOSA measurements of BC emission rate) and detailed off-site chemical analysis of the flare gas composition. Fortunately, Clearstone Engineering of Calgary, Alberta was scheduled to perform flare gas flow rate and crude composition measurements of systems at the Atasta Compressor Station for the same date. This enabled the simultaneous acquisition of BC emission rate data (using sky-LOSA), flare gas flow rate data, and estimated concentrations of light hydrocarbon species in the flare stream. Ultimately the data acquired at the Atasta Compressor Station were sufficient to complete sub-activity 1a of the present contract.

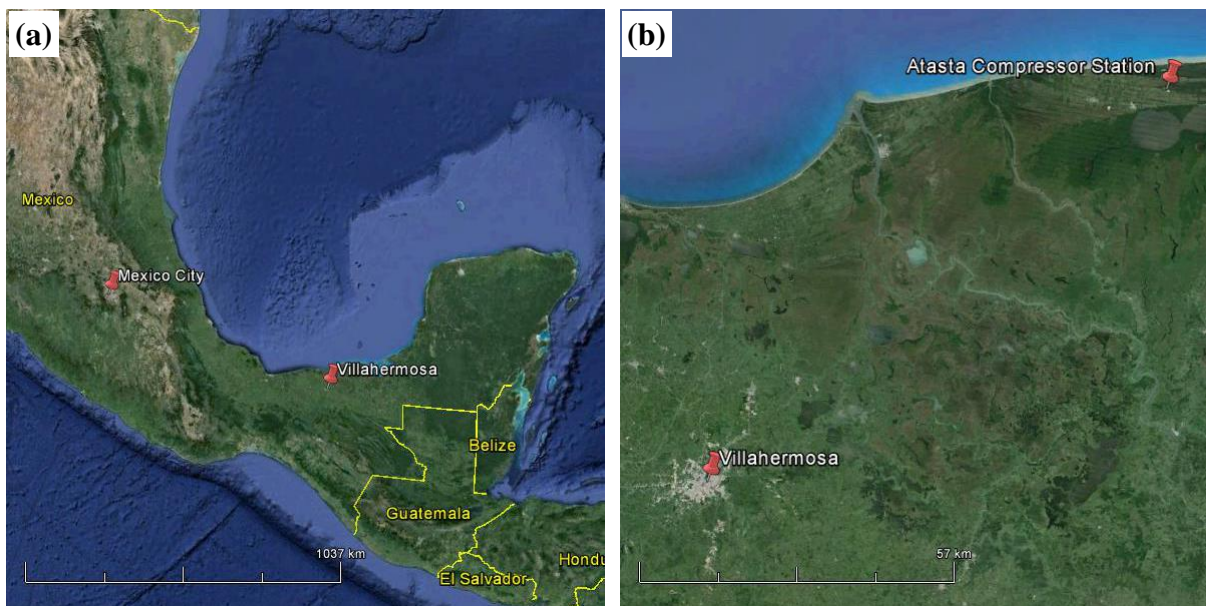


Figure 1: a) the location of Villahermosa, Tabasco with respect to Mexico City and b) the location of the Atasta Compressor Station in Campeche with respect to Villahermosa, Tabasco.

2.2.2 Data Acquired In-Field

Figure 2 shows a satellite image of the Atasta Compressor Station in Campeche, Mexico. Flaring activities at the Atasta Compressor Station were limited to the northwest corner of the site as shown in Figure 2a. In total, there were six flare installations, although only three had visible flames at the time of the site visit (the three flares at the left of Figure 2b). The three flares to the right were observed to be under construction.



Figure 2: Flaring infrastructure at the Atasta Compressor Station. a) the location of flaring activities with respect to the main site and b) the locations of active flares. The three easternmost flares were not in use during measurements as construction work was being performed. To the west were two stack flares composing the emergency system and a single horizontal pit flare composing the compressor purge system.

The three active flares were part of two separate flaring systems:

1. Two elevated flares (of approximately 50 m in height) made up the so-called “emergency system”, which was presumably fueled by overpressure events. The southern emergency flare (at $N18^{\circ} 38' 36.49''$, $W92^{\circ} 10' 14.80''$) was noted to be continuously operational while the northern emergency flare (at $N18^{\circ} 38' 44.90''$, $W92^{\circ} 10' 15.74''$) operated intermittently. As these two separate flares were fed by a single flare line, BC yield measurements on this flaring system could not be performed as two simultaneous sky-LOSA measurements would be required.

2. A pit flare (at N18° 38' 41.85", W92° 10' 16.15") was fueled by the purge gas of the on-site compressors. As shown in Figure 3a and Figure 3b, this flare consisted of three adjacent horizontal pipe exits situated within a triangular pit with sloped walls lined with refractory brick. The pit was also partially enclosed by refractory brick walls. Volumetric flow rate and composition measurements were performed upstream of the flare pit, where the flare line consisted of a single 30" diameter pipe.

Due to the separation of the emergency system (i.e. into two flares), the horizontal flare pit was selected as the primary focus for sky-LOSA measurements of BC emission rate and the subsequent calculation of BC yield.

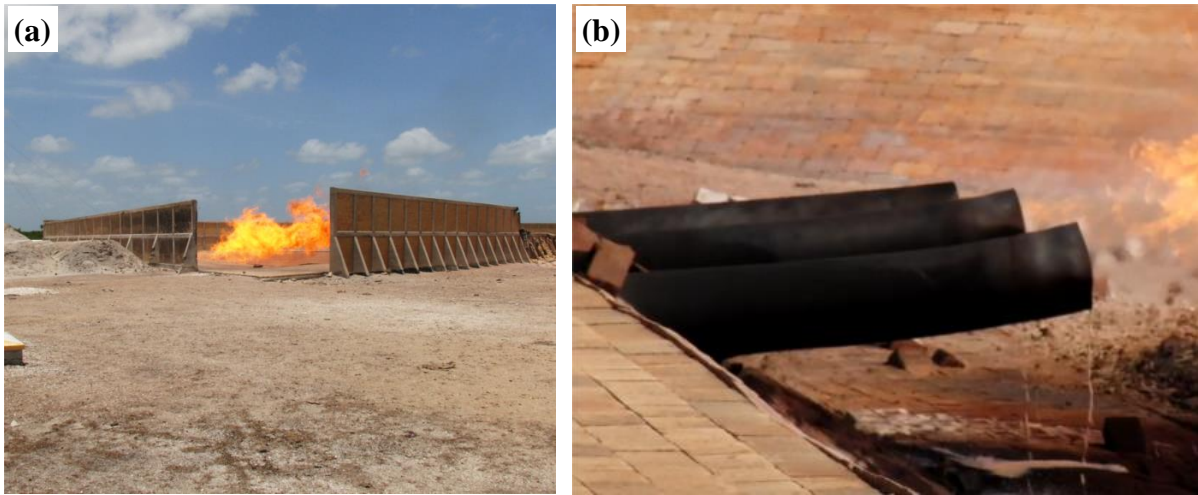


Figure 3: a) the horizontal pit flare at the Atasta Compressor Station – note the refractory brick lined pit and partial enclosure and b) the horizontal pit flare's exit.

During the late morning and early afternoon of June 30, 2015, sky-LOSA data of the pit flare were acquired simultaneously with flare gas volumetric flow rate and partial composition data obtained by Clearstone Engineering. Carleton University personnel acquired two ten-minute image sets of the flare and plume for BC emission rate quantification; three 30-second image sets of the sun for quantification of solar radiation; and one image set of sample skylight to support modelling of the skylight intensity distribution. A summary of data collected in the field alongside imaging parameters and sample images is provided in APPENDIX A.

Following the sky-LOSA measurement of the pit flare, Carleton University personnel began transferring the acquired image data to an external hard drive while Clearstone Engineering prepared for flow rate and composition measurements of the emergency flare system. While BC yield and flare efficiency data could not be computed for the emergency system, as previously noted, the sky-LOSA measurement equipment was prepared for measurement of the BC emission rate of the southern emergency flare. Upon setup, it was discovered that the power supply system had been damaged following the measurement of the pit flare and the subsequent teardown of equipment. Graciously, PEMEX offered to help troubleshoot the issue in their on-site electrical shop where it was discovered that the extension cord (used to provide power to the sky-LOSA camera and image acquisition computer from an inverter connected to a truck battery) was damaged. It was presumed that this damage was enabled by the intense heat from the sun and the nearby pit flare, which had compromised the mechanical strain relief of the extension cord. While considering repair options, it was brought to the attention of Carleton University personnel that a protest and road blockade of the nearby highway had been initiated. In the interest of ensuring a safe return to Villahermosa, PEMEX staff suggested that measurements be stopped and Carleton University and Clearstone Engineering personnel be evacuated immediately, thus bringing field measurements to a close.

2.3 Measurements in Ecuador

BC yield measurements were similarly performed at Petroamazonas facilities in Ecuador's amazon basin during October 26-29, 2015. Three Carleton University personnel traveled to Coca, Ecuador (approximately 175 km east of Quito, see Figure 4a) and performed measurements at four sites in Petroamazonas' Auca field (approximately 25 km south-southeast of Coca, see Figure 4b). Carleton University personnel obtained sky-LOSA image data, flare gas flow rate data, and gas samples for detailed off-site composition analysis for a total of five flares at the four measurement sites. APPENDIX B contains the field report submitted to Petroamazonas, CCAC, and the World Bank GGFR, which provides a detailed summary of data collected in Petroamazonas' Auca field during October 26-29, 2015.

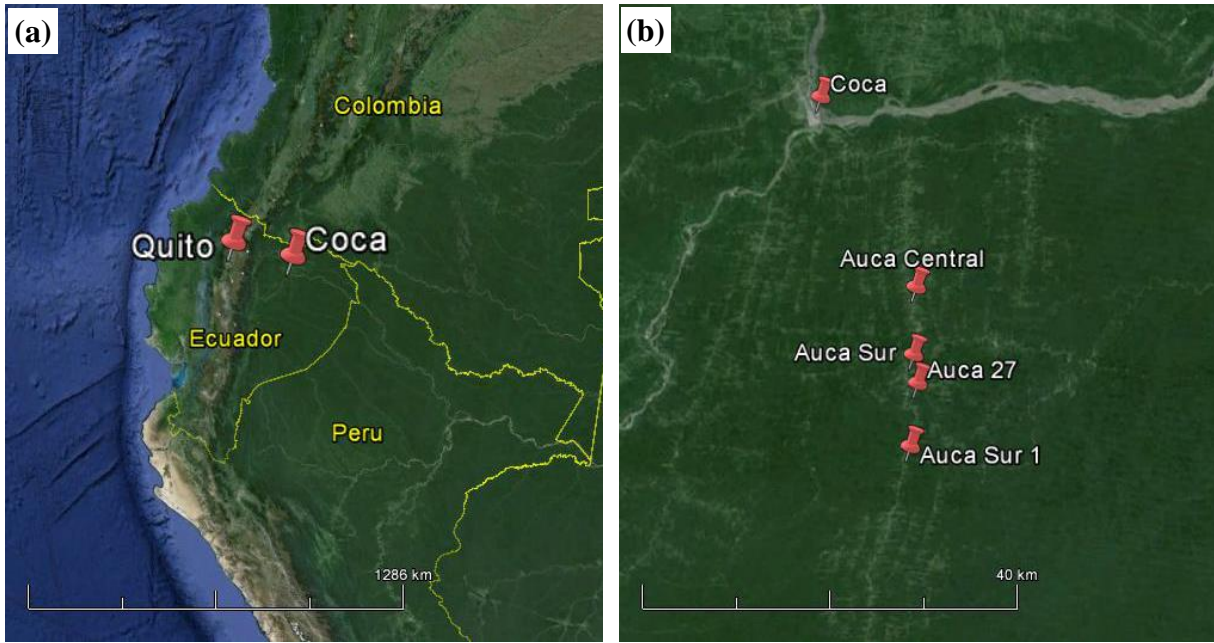


Figure 4: a) the location of Coca with respect to Ecuador's Capital, Quito and b) the location of the measurement sites in Petroamazonas' Auca Field with respect to Coca.

3 RESULTS: MEASUREMENTS IN MEXICO

3.1 Black Carbon Emission Rate

Sky-LOSA image data acquired at PEMEX's Atasta Compressor Station in Campeche, Mexico were obtained under broken or partly cloudy sky conditions. As noted by Conrad and Johnson (2015b), sky-LOSA images acquired under overcast or broken skies are significantly more challenging and computationally intensive to process as compared to images with clear background skies. This is because the reconstruction of the skylight intensity distribution behind the plume can be especially complex, requiring the projection of cloud motion behind the plume. As both image sets of the pit flare and its atmospheric plume had similar partly cloudy background skies, there was no advantage to processing one set in priority over the other.

The first acquired image set, "PitPos1Run1", was arbitrarily selected for analysis and consisted of 30,000, 2560 by 2160 pixel, 16-bit intensity resolution images acquired at 50 frames-per-second, totaling ten minutes of data. It was noted during measurements and confirmed following the review of images that the atmospheric plume was quite chaotic – gusting wind coming off of the adjacent lagoon was found to change the direction of plume propagation by nearly 180°. Thus, to detect all BC emissions from the flare, the control surface used for the instantaneous BC emission rate measurement was necessarily centered near the middle of the flare pit with a radius of approximately 12.87 m (or 1100 pixels). Figure 5 shows a sample grayscale image with the control surface developed for sky-LOSA analysis of BC emission rate superimposed.



Figure 5: Sample grayscale image of the horizontal pit flare acquired using the sky-LOSA acquisition system with the control surface defining the instantaneous BC emission rate superimposed.

Figure 6 plots the time-resolved BC mass emission rate of the pit flare during the measurement period of the selected image set. In Figure 6a, the blue dots represent the instantaneous BC emission rate at one-second intervals while the red line indicates the cumulative average (i.e. the average mass emission rate using all instantaneous data to the left of a specified point on the horizontal axis). The stability of the red line at longer time intervals indicates that the 10-minute measurement window is sufficient to obtain a meaningful average emission rate.

Figure 6b shows a five-second subset of the instantaneous emission rate data at the full framerate of 50 measurements per second. Here, the blue line represents the same instantaneous emission rate plotted in Figure 6a (specifically it is the calculated mean from the Monte Carlo analysis), while the white band represents the 95% confidence interval in the calculated uncertainty of the BC emission rate.

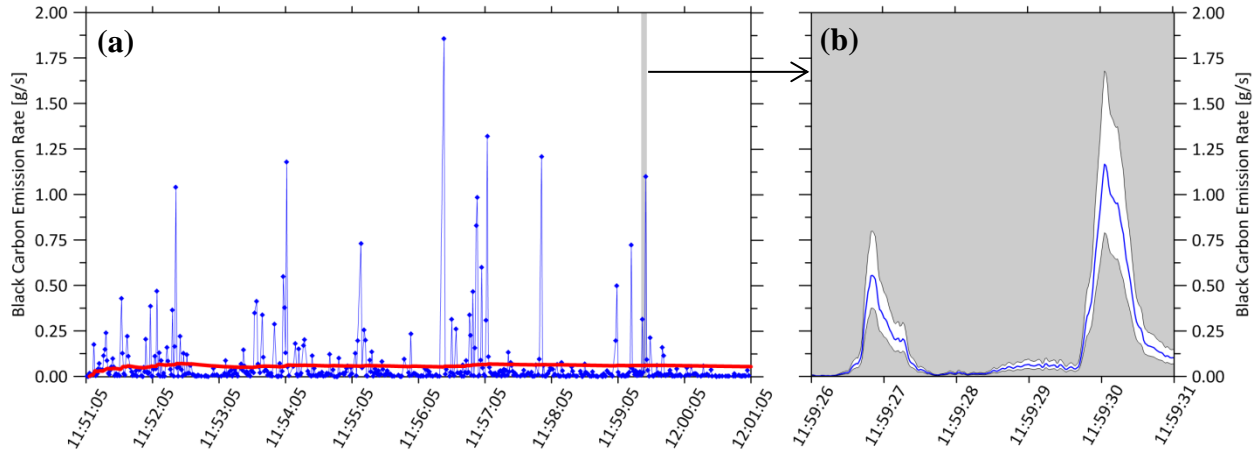


Figure 6: a) the instantaneous BC emission rate shown in one-second intervals (blue data) alongside the cumulative average (solid red line) and b) a five-second subset of the instantaneous BC emission rate shown at the full framerate of 50 frames-per-second. The blue line is the mean as computed by the Monte Carlo analysis while the white bands represent the 95% confidence interval.

Analysis of these data suggests that the time-averaged BC emission rate over this time interval was 0.054 g/s. The Monte Carlo method employed to assess the uncertainty of this result determined a 95% confidence interval of -33.1% to $+44.9\%$. The reported level of uncertainty is higher than previous sky-LOSA measurements due to a number of circumstances, including sky conditions during image acquisition, site access, and the layout/design of site infrastructure. In fact, the acquired image data represented the worst-case conditions for sky-LOSA measurements as explained in the following points:

- To minimize uncertainties, the sky-LOSA image acquisition system must be positioned such that the sun is located behind the viewer when facing the flare. While it was possible to achieve this at the Atasta Compressor Station, the available distance between the sky-LOSA camera and the flare pit was limited due to the location of site infrastructure relative to vegetation in the vicinity of the flare pit. This resulted in a larger uncertainty in the spatial scaling of the sky-LOSA images (which was already inherently high since the flare "tip" is ill-defined for a pit flare), thus increasing overall uncertainty in the BC emission rate calculation. A conservative uncertainty in the distance between the camera and flare tip was chosen in the analysis (45 ± 5 m), resulting in a relative uncertainty in the spatial scaling of $\pm 11.1\%$ being applied during implementation of the Monte Carlo method. As such, the resulting 95% confidence

interval on the resulting BC emission rate was notably larger than previous measurements (Conrad and Johnson 2015a; Johnson et al. 2013).

- Under partly cloudy sky conditions, the intensity of skylight behind the plume must be obtained by tracking cloud motion and projecting the position of cloud structures as they travel behind the plume. This procedure effectively extrapolates the trajectory of the clouds and therefore sees an increase in bias error as cloud structures are projected further from the plume edge. As such, it is considered ideal if the general direction of cloud motion is perpendicular to that of the atmospheric plume. Unfortunately, the directions of cloud motion and plume motion were nearly identical during the field-measurements in Campeche, which contributed to the increased measurement uncertainty.
- Post-processing of the acquired image data yielded an additional, not previously encountered, complication. The low elevation of the atmospheric plume (a consequence of which is a low inclination angle of the sky-LOSA camera) coupled with the near-horizontal propagation of the atmospheric plume necessitated use of a control surface that extended to the horizon in the sky-LOSA images. Near the horizon, under cloudy or partly cloudy conditions, the skylight intensity changes with a very high spatial frequency since numerous cloud structures can exist within a small region of the image – an effect that is visible at the right edge of Figure 5. This can cause the reconstruction of the background sky in this region to be more challenging as a small bias in the projection of cloud structures can lead to significant error.

While these issues made the measurements at the Atasta Compressor Station especially challenging, quantitative measurements were still achieved within the specified uncertainty ranges. The successful analysis of these data using algorithms further refined through this effort is a significant project outcome.

3.2 Flare Gas Composition and Flow Rate

Simultaneous measurements of flare gas flow rate as well as a partial gas composition analysis were obtained by Clearstone Engineering. Flare gas composition was estimated by drawing a gas sample through a Tunable Filter Spectroscopy measurement device that reports detectable

composition data every two seconds, on average. The specific instrument is capable of measuring volume fractions of C1-C5⁺ alkanes as well as carbon dioxide (CO₂) and hydrogen sulfide (H₂S). The instrument is not capable of quantifying other species in the flare gas, and specifically cannot detect additional diluents such as nitrogen and/or water vapour. Thus, it was necessary to assume the composition of undetectable species making up the significant balance of the measured flare gas. Table 1 shows the average flare gas composition as measured by Clearstone Engineering during the acquisition of the first sky-LOSA image set – also shown are the calculated mass fractions and select mixture properties assuming the balance composition consists of pure nitrogen. It was noted that this flare gas had a very high concentration of diluents (i.e. carbon dioxide and the balance composition) when compared to previous measurements during sky-LOSA field-work, which would be expected to reduce the emissions of BC.

Table 1: The average flare gas composition and select mixture properties during the acquisition of the first sky-LOSA image set, assuming the balance composition consists of pure nitrogen. Volume fractions are directly reported by the instrument, while mass fractions have been calculated. Note the large fraction of diluents in the flare gas stream.

Species	Volume Fraction	Mass Fraction *
Methane	68.12 %	53.43 %
Ethane	9.20 %	13.53 %
Propane	0.98 %	2.12 %
i-Butane	0.30 %	0.84 %
n-Butane	0.52 %	1.47 %
Pentanes +	0.00 %	0.00 %
Carbon Dioxide	0.00 %	0.00 %
Hydrogen Sulfide	0.09 %	0.16 %
Balance (additional diluents)*	20.79 %	28.45 %
Property *		
Molecular Weight (kg/kmol)	20.45	
Lower Heating Value (MJ/kg)	35.24	
Lower Heating Value (MJ/m ³)**	30.48	

*It is assumed that the balance composition consists of pure nitrogen

**At standard conditions – 15°C and 1 atm

Direct measurements of the volumetric (molar) flow rate of flare gas were also performed by Clearstone Engineering. The flow rate was directly measured on-site and in real-time via a tracer-dilution technique, whereby a stable tracer gas (acetylene in the present case) was injected into the flare gas stream and the concentration of the tracer gas was measured downstream, once it was fully mixed. A simple molar balance on the tracer gas provides the following governing equation for the tracer-dilution technique (it should be noted that at a fixed pressure and temperature, the volumetric flow rate can be trivially obtained from the molar flow rate):

$$\dot{n}_{tot} = \dot{n}_{injected} \left\{ \frac{X_{injected} - X_{background}}{X_{TD} - X_{background}} \right\} \quad (1)$$

where: \dot{n}_{tot} is the total molar flow rate of flared gas during tracer-dilution measurements,
 $\dot{n}_{injected}$ is the molar flow rate of the injection tracer gas,
 $X_{background}$ is the molar (volume) fraction of tracer gas in the background flare gas,
 $X_{injected}$ is the molar (volume) fraction of tracer gas in the injected gas (i.e. purity),
 X_{TD} is the molar (volume) fraction of tracer gas in the measured/flared gas.

By assuming the tracer is pure ($X_{injected} = 1$) and the tracer is non-existent in the background flare gas ($X_{background} = 0$), the governing equation can be reformatted more simply as:

$$\dot{n}_{tot} = \frac{\dot{n}_{injected}}{X_{TD}} \quad (2)$$

Ultimately, the flare gas mass flow rate can be calculated by correcting for the molecular weights of the injected and measured/flared gases. However, it should be noted that in the present case the molecular weight of the measured/flared gas required an assumed composition of the diluent species, thus introducing some additional uncertainty in the calculated mass flow rate:

$$\dot{m}_{tot} = \frac{\dot{m}_{injected}}{X_{TD}} \frac{M_{tot}}{M_{injected}} \quad (3)$$

where: \dot{m}_{tot} is the mass flow rate of flared gas during tracer-dilution measurements,
 $\dot{m}_{injected}$ is the controlled mass flow rate of injected tracer gas,

M_{tot} is the molecular weight of the measured/flared gas,

$M_{injected}$ is the molecular weight of the tracer gas.

Figure 7 shows the mass flow rate of flare gas calculated using this technique as measured by Clearstone Engineering, assuming the previously noted balance composition is pure nitrogen. Included in Figure 7a is the measured flare gas mass flow rate during the entire one-hour measurement period. The thin blue line represents the flow rate averaged over one-second intervals and the thick red line represents the 100-second running average (i.e. the average flow rate over the previous 100 seconds). Shaded in gray and provided in Figure 7b is the measurement during the sky-LOSA image set used to calculate the flare's BC emission rate. The calculated average mass flow rates over the entire measurement period and during the first sky-LOSA acquisition were 156.6 g/s and 153.2 g/s, respectively. As a matter of comparison, if the assumed balance composition consisted of water vapour only, the average mass flow rates would be 140.4 and 136.6 g/s, respectively – on the order of 10.15% less than the case of a pure nitrogen balance.

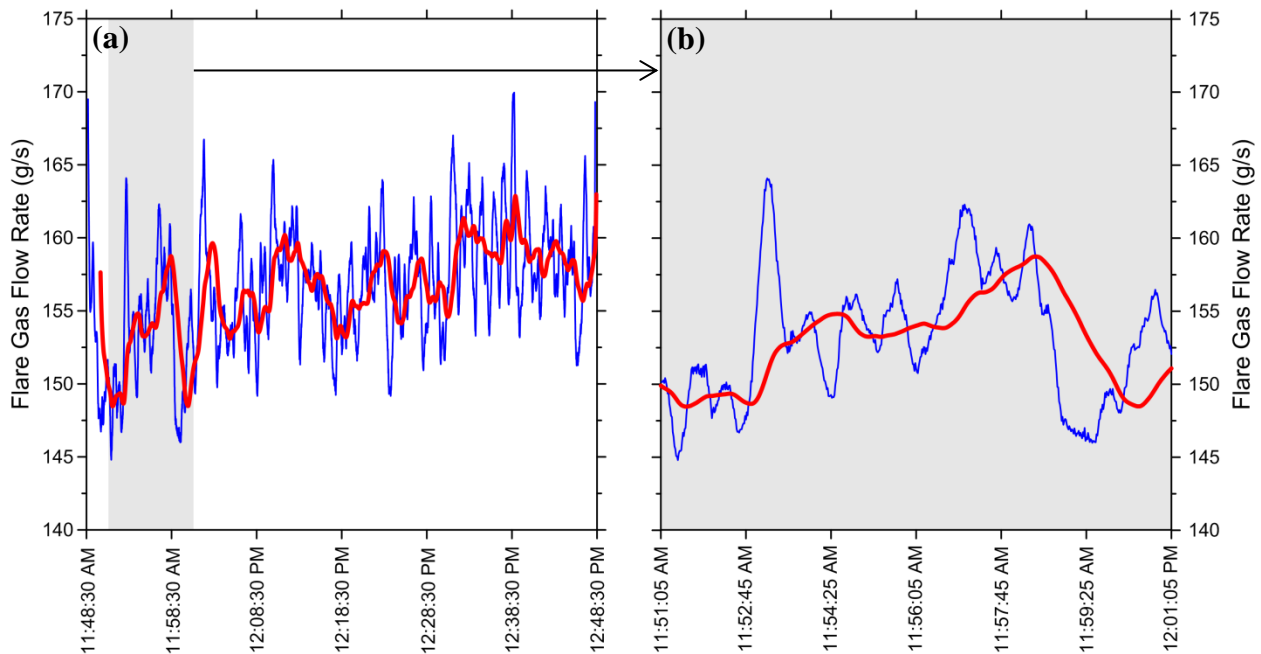


Figure 7: Calculated mass flow rate of flare gas measured by Clearstone Engineering using the tracer-dilution technique over the entire measurement interval (a) and during the first sky-LOSA acquisition (b).

The blue lines represent the average flow rate over one-second intervals, while the red lines indicate a running 100-second average. These data were calculated assuming the balance composition of the flare gas consisted of nitrogen only – comparatively, a balance composition of water vapour decreases the flow rate magnitude by 10.15% on average.

To report the BC yield of the horizontal pit flare at the Atasta Compressor Station with uncertainties, it was necessary to estimate the uncertainty of the flare gas mass flow rate as measured by Clearstone Engineering. It was assumed that the uncertainty in the flare gas mass flow rate was dominated by the unknown composition of the diluents in the flare gas stream as opposed to the instrument/technique-related contribution. Since nitrogen and water vapour are the two most likely diluents, it was assumed that the flare gas mass flow rate resulting from pure nitrogen dilution and pure water vapour dilution represented the 95% confidence interval in the flow rate. Consequently, the mean flare gas mass flow rate during the sky-LOSA image acquisition was assumed to follow a normal distribution with a mean of 144.9 g/s and a standard deviation of 4.15 g/s (2.86% of the mean).

3.3 Black Carbon Yield

The BC yield is an important parameter indicating the sooting propensity of a flare, normalized by the flare gas mass flow rate. Knowledge of this mass-to-mass ratio for a range of flaring designs and conditions is critical for the development of robust emission factors and inventories. The data acquired at the Atasta Compressor Station enable some of the global first calculations of BC yield from in-situ gas flares and the global first calculation for a horizontal pit flare.

The BC yield and its associated uncertainties were calculated using the mean and 95% confidence intervals of the BC emission rate and flare gas mass flow rate during the sky-LOSA image acquisition. The mean BC yield was calculated using the means of the BC emission rate and flare gas mass flow rate, while upper and lower uncertainty bounds were calculated independently by summing the respective bounds for the BC emission rate and flare gas mass flow rate in quadrature. The BC yield of the horizontal pit flare at the Atasta Compressor Station was ultimately found to be $0.373 \text{ g}_{\text{BC}}/\text{kg}_{\text{FG}}$ (where the subscript *FG* signifies flare gas) with a 95% confidence interval of -33.6% and $+45.3\%$. This result is equivalent to a solid-phase flare efficiency, i.e. the efficiency of the flare in converting fuel to gas phase products, of 99.96%.

The calculated BC yield for the horizontal pit flare is in-line with two previous measurements of heavily diluted and/or aerated flares, measured in Ecuador in June 2014

(Conrad and Johnson 2015a). Figure 8 compares the BC yield measurement at the Atasta Compressor Station alongside these previous measurements. Figure 8a shows the results on a logarithmic scale with the uncertainties listed as percentages of the mean, while Figure 8b shows the results on a linear scale with the range of absolute uncertainties listed.

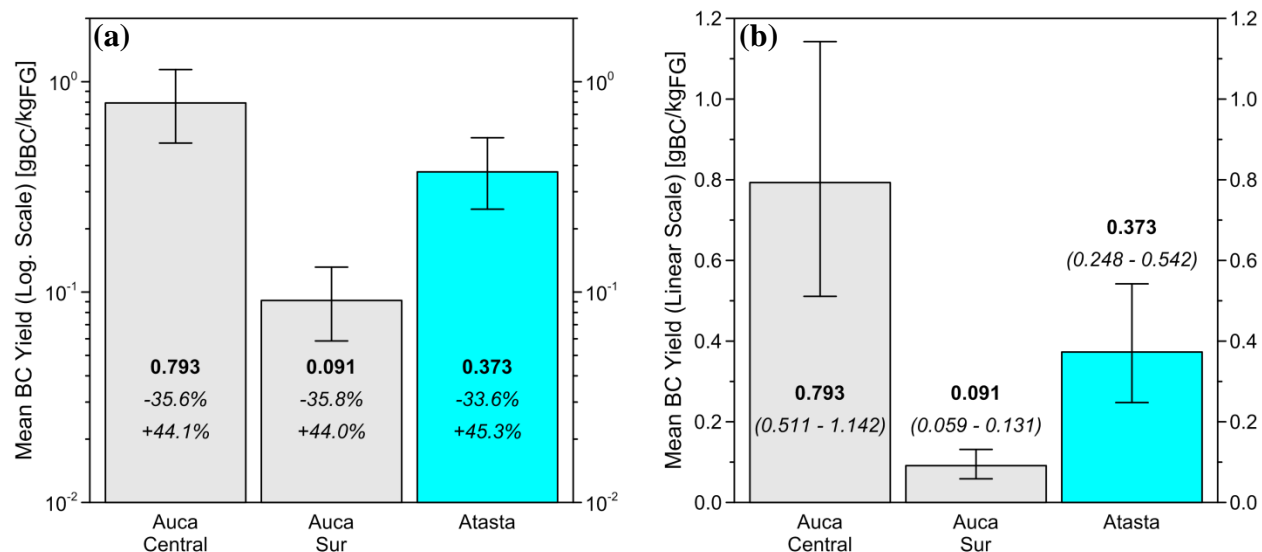


Figure 8: A comparison of the measured BC yield at the Atasta Compressor Station and two BC yield measurements from Ecuador in June 2014 that were also diluted or aerated. The results are shown on a logarithmic scale with relative uncertainties listed (a) and on a linear scale with the range of absolute uncertainties listed (b).

It is apparent that the relative uncertainties in these three measurements are quite close in magnitude. During the measurement campaign in Ecuador in June 2014, logistical issues in shipping gas samples to North America for detailed compositional analyses precluded the use of simultaneous composition data. Consequently, a conservative 95% confidence interval of $\pm 25\%$ on the flare gas mass flow rate data was applied, resulting in the large relative uncertainties visible in Figure 8. By contrast, the large relative uncertainties in the current analysis are due to uncertainty in the spatial scaling of the acquired images, necessary for calculating the BC emission rate (see section 3.1). Ultimately, it is expected that BC yield calculated using sky-LOSA and the tracer-dilution flow measurement technique could be reported with uncertainties less than $-27\%/+37\%$ when implemented without complication.

4 PRELIMINARY RESULTS: ECUADOR

As of the submission of this report, post-processing of data recently collected in the field at Petroamazonas facilities during October 26-29, 2015 has just begun. The large amount of acquired data from the various instruments have now been collated and documented as detailed in APPENDIX B. Current effort is focused on the calculation flare gas mass flow rate measurements in the lines feeding each of the five analyzed flares as well as initiating sky-LOSA post-processing to compute black carbon emission rates. While composition analysis of flare gas samples acquired in-field is still pending, a preliminary report of flare gas *volumetric* flow rate measurements to Petroamazonas has been prepared and is provided as APPENDIX C.

Based on the preliminary review of these recently acquired data and the in-field experience, it is anticipated that the BC yield can be calculated for all of the measured flares with levels of uncertainty better than that of the BC yield measurement at the Atasta Compressor Station. Extractive gas samples were acquired in each of the flare lines feeding the measured flares and, as of the submission of this report, are being prepared for shipment by Petroamazonas to a laboratory in Edmonton, Alberta. Gas chromatographic analysis at this laboratory will provide highly detailed gas composition data for each of the flare lines; the scheduled analysis is capable of isolating volume fractions of paraffins (alkanes), olefins (alkenes), naphthenes (cycloalkanes), and aromatics up to C₁₅; residual hydrocarbons from C₄ to C₁₅⁺; and fixed gases (diluent). This highly-resolved analysis will aid in the reduction of uncertainty in the flare gas mass flow rate and will help provide insight into key factors driving the BC yield. Sky-LOSA image data also suggest that ideal conditions (clear sky or flat overcast sky) existed for two of the five measured flares and that the remaining three flares were obtained under partly cloudy or overcast conditions. It is expected that the data for the latter three flares will be easier to analyze than the pit flare at the Atasta Compressor Station since the measured flares in Petroamazonas' Auca field were all stack flares, enabling larger sky-LOSA camera inclination angles. Review of the acquired sky-LOSA images suggests that the high spatial frequency of cloud structures near the horizon will not be an issue in the post-processing of the image data acquired in the Auca field.

5 SUMMARY

Sky-LOSA measurements of BC emission rate were performed on the horizontal pit flare at the Atasta Compressor Station in Campeche, Mexico. Simultaneous measurements of flare gas flow rate and flare gas composition were obtained by Clearstone Engineering, enabling one of the global-first measurements of BC yield and solid-phase flare efficiency from in-field flares.

Although there were three active flares at the Atasta site during the measurement campaign, ultimately only one flare was deemed suitable for the quantification of BC yield. A horizontal pit flare was fueled by the compressors' purge gas, while two additional stack flares composed an “emergency system”, which could not be considered for BC yield quantification as this system would necessitate two simultaneous measurements of BC emission rate using sky-LOSA. As such, the horizontal pit flare was selected for analysis. The horizontal pit flare's average BC emission rate was calculated to be 0.054 g/s with a 95% confidence interval of $-33.1/+44.9\%$. The width of the 95% confidence interval is larger than previous sky-LOSA measurements as the uncertainty in the spatial scaling of the sky-LOSA images was increased by the location of site infrastructure relative to vegetation in the vicinity of the flare pit.

Simultaneous flare gas flow rate and flare gas composition measurements were performed by Clearstone Engineering during the sky-LOSA measurement of the horizontal pit flare. Real-time flare gas composition estimates were obtained with a Tunable Filter Spectroscopy instrument, which showed that the flare gas fueling the horizontal pit flare was a slightly sour gas composed of mainly C1-C2 hydrocarbons with over 20% unidentified diluents on a volume basis. Consequently, an assumed composition of these diluents was necessary to calculate the flare gas mass flow rate. The mass flow rate of flare gas during the acquisition of the sky-LOSA image set used for BC emission rate calculation was estimated assuming two different assumptions; that the diluent composition was pure nitrogen and that it was pure water vapour. By taking the mean of these two extreme conditions and treating them as the 95% confidence interval of the flow rate, the flare gas mass flow rate during the acquisition of sky-LOSA images was assumed to follow a normal distribution with a mean of 144.9 g/s and a standard deviation of 4.15 g/s.

The BC emission rate and flare gas mass flow rate during the analyzed sky-LOSA image set was used to calculate the BC yield of this flare. The mean BC yield was calculated using the means of the emission and flow rates and the uncertainty in the BC yield was estimated by independently summing the lower and upper uncertainty bounds in quadrature. The BC yield of the horizontal pit flare at PEMEX's Atasta Compressor Station was calculated to be $0.373 \text{ g}_{\text{BC}}/\text{kg}_{\text{FG}}$ with a 95% confidence interval of $-33.6/+45.3\%$. This result was found to be in-line with previous measurements of BC yield from diluted or aerated flares.

More detailed measurements of BC yield were performed during October 26-29, 2015 at Petroamazonas facilities in the Auca field near Coca, Ecuador. Sky-LOSA image data, flare gas flow rate data, and extractive gas samples were acquired by Carleton University personnel to enable the calculation of BC yield for a total of five flares located at four sites. As of the submission of this report, detailed analysis is underway and an interim project report (detailing data collected in-field) is appended to this report.

5.1 Future Work

All sub-activities of the present research agreement have been satisfied as of the submission of this final report. However, significant additional work will be performed analyzing recently acquired field-data to derive additional BC yield data. Reported results (in the form of peer-reviewed journal article(s) and/or conference proceeding(s)) from future work will be forwarded to PTAC and CCAC when complete.

6 REFERENCES

- Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S. (2013). “Bounding the role of black carbon in the climate system: A scientific assessment.” *Journal of Geophysical Research: Atmospheres*, 118(11), 5380–5552.
- Conrad, B. M., and Johnson, M. R. (2015a). “Sky-LOSA Measurement of Soot Yield of Gas Flares in Ecuador’s Amazon Basin.” *Proceedings of Combustion Institute - Canadian Section*, 1–6.
- Conrad, B. M., and Johnson, M. R. (2015b). “Uncertainties in Overcast Sky Reconstruction for Open-Path Attenuation Measurements.” *Air & Waste Management Association (AWMA) 108th Annual Conference, June 22-25 (ID #74)*, Raleigh, NC.
- Elvidge, C. D., Ziskin, D., Baugh, K. E., Tuttle, B. T., Ghosh, T., Pack, D. W., Erwin, E. H., and Zhizhin, M. (2009). “A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data.” *Energies*, 2, 595–622.
- Grahame, T. J., Klemm, R., and Schlesinger, R. B. (2014). “Public health and components of particulate matter: The changing assessment of black carbon.” *Journal of the Air & Waste Management Association*, 64(6), 620–660.
- IPIECA. (2014). *Understanding short-lived climate forcers*. London, UK.
- Johnson, M. R., Devillers, R. W., and Thomson, K. A. (2011). “Quantitative Field Measurement of Soot Emission from a Large Gas Flare Using Sky-LOSA.” *Environmental Science & Technology*, 45(1), 345–350.
- Johnson, M. R., Devillers, R. W., and Thomson, K. A. (2013). “A Generalized Sky-LOSA Method to Quantify Soot/Black Carbon Emission Rates in Atmospheric Plumes of Gas Flares.” *Aerosol Science and Technology*, 47(9), 1017–1029.
- Johnson, M. R., Devillers, R. W., Yang, C., and Thomson, K. A. (2010). “Sky-Scattered Solar Radiation Based Plume Transmissivity Measurement to Quantify Soot Emissions from Flares.” *Environmental Science & Technology*, 44(21), 8196–8202.
- McEwen, J. D. N., and Johnson, M. R. (2012). “Black Carbon Particulate Matter Emission Factors for Buoyancy Driven Associated Gas Flares.” *Journal of the Air & Waste Management Association*, 62(3), 307–321.

Stohl, A., Klimont, Z., Eckhardt, S., Kupiainen, K., Shevchenko, V. P., Kopeikin, V. M., and Novigatsky, A. N. (2013). “Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions.” *Atmospheric Chemistry and Physics*, 13(17), 8833–8855.

US EPA. (2012). *Report to Congress on Black Carbon*. United States Environmental Protection Agency, Research Triangle Park, NC.

APPENDIX A: SUMMARY OF DATA COLLECTED IN MEXICO

A.1 *Pit Flare*



Figure A.1: Pit flare at the Atasta compressor station in Campeche, Mexico.

A.1.1 *Description of Flare*

- This horizontal pit flare was fed by a single 30" diameter flare line that was split into three separate lines prior to combustion
- Combustion occurred in a triangular pit with sloped walls lined with refractory brick
- The triangular pit was partially enclosed by refractory brick walls

A.1.2 *Sky-LOSA Acquisition*

- Sky-LOSA was setup approximately 30m NNE of the edge of the flare pit; a low-height tripod was employed to achieve an appropriate camera inclination angle

- Two ten-minute image sets of the flare and atmospheric plume were acquired for calculation of the BC emission rate
- Three sets of sun images were acquired to discern solar irradiance (when obstructed and unobstructed by cloud cover) during the measurement
- A short set of reference sky images were acquired to support the selection of an appropriate skylight intensity distribution model

A.1.3 Simultaneous Flow and Composition Measurement

- Flare gas flow rate data and composition data were acquired by Clearstone Engineering simultaneously with collection of Image Set 1 and Image set 2

Image Set 1 (N18° 38' 43.56" W92° 10' 15.36")

Time @ Start: 11:51:05 Local
 File Prefix: PitPos1Run1
 File Type: Multi-Tiff
 # of Images: 30,000
 Framerate: 50 fps
 Length: 10 minutes
 Dist. to Flare: 45 m
 Azimuth: 189.8°
 Inclination: 16.4°
 Lens: Zeiss 25 mm
 Filtering: 67 mm 531/40 FF01
 Aperture: 3.4
 Exposure: 0.8 ms
 Image Size: 2560 x 2160



Sky Conditions: Semi-clear sky conditions with large white clouds. Sun intermittently blocked during acquisition due to cloud motion.
 Comments: Simultaneous consumer-grade video was acquired. Occasional saturation of small cloud regions.

Image Set 2 (N18° 38' 43.56" W92° 10' 15.36")

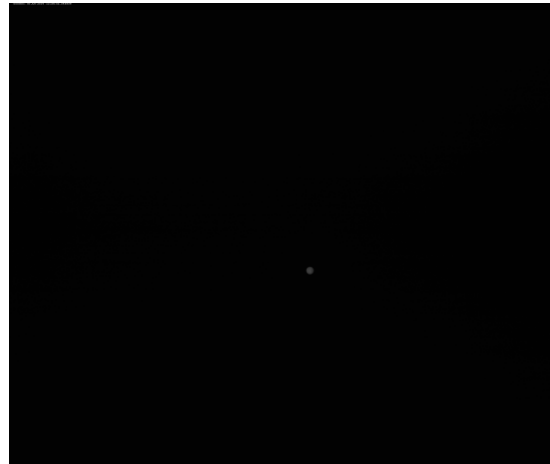
Time @ Start: 12:03:05 Local
File Prefix: PitPos1Run2
File Type: Multi-Tiff
of Images: 30,000
Framerate: 50 fps
Length: 10 minutes
Dist. to Flare: 45 m
Azimuth: 189.8°
Inclination: 16.4°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: 3.4
Exposure: 0.8 ms
Image Size: 2560 x 2160



Sky Conditions: Semi-clear sky conditions with large white clouds. Sun intermittently blocked during acquisition due to cloud motion.
Comments: Simultaneous consumer-grade video was acquired. Occasional saturation of small cloud regions.

Sun Image Set 1 (N18° 38' 43.56" W92° 10' 15.36")

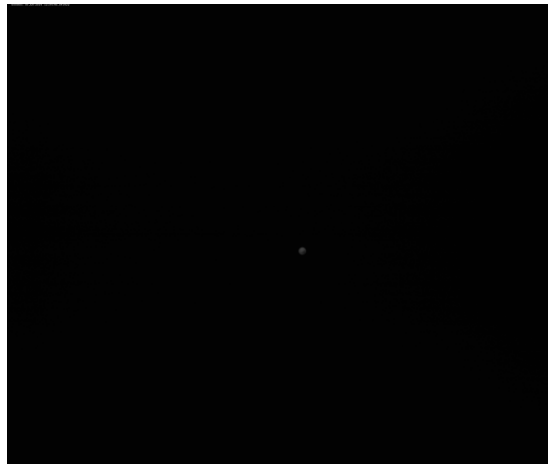
Time @ Start: 12:28:32 Local
File Prefix: PitSun1
File Type: Multi-Tiff
of Images: 1,500
Framerate: 50 fps
Length: 30 seconds
Azimuth: 64.32°
Inclination: 78.82°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01 + ND 5.3
Aperture: 3.4
Exposure: 0.8 ms
Image Size: 2560 x 2160



Comments: Sun became partially blocked during acquisition

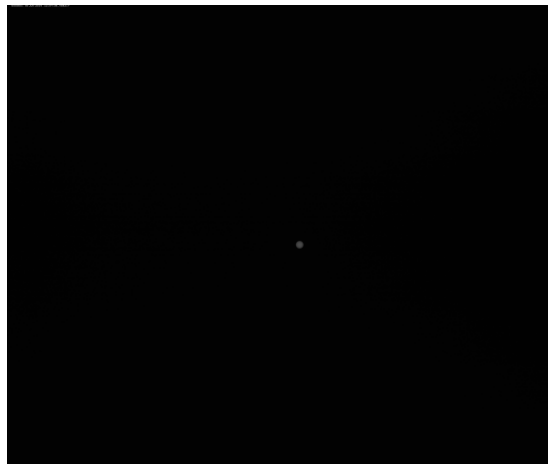
Sun Image Set 2 (N18° 38' 43.56" W92° 10' 15.36")

Time @ Start: 12:34:51 Local
File Prefix: PitSun2
File Type: Multi-Tiff
of Images: 1,500
Framerate: 50 fps
Length: 30 seconds
Azimuth: 64.32°
Inclination: 78.82°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01 + ND 5.3
Aperture: 3.4
Exposure: 0.8 ms
Image Size: 2560 x 2160
Comments: Sun became partially blocked during acquisition



Sun Image Set 3 (N18° 38' 43.56" W92° 10' 15.36")

Time @ Start: 12:37:06 Local
File Prefix: PitSun3
File Type: Multi-Tiff
of Images: 1,500
Framerate: 50 fps
Length: 30 seconds
Azimuth: 64.32°
Inclination: 78.82°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01 + ND 5.3
Aperture: 3.4
Exposure: 0.8 ms
Image Size: 2560 x 2160
Comments: Sun became partially blocked during acquisition



Reference Sky Image Set 3 (N18° 38' 43.56" W92° 10' 15.36")

Time @ Start: 12:41:18 Local
File Prefix: PitSky1
File Type: Multi-Tiff
of Images: 773
Framerate: 10 fps
Length: 1 minute and 17.3 seconds
Azimuth: 311.0°
Inclination: 18.4°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: 3.4
Exposure: 0.8 ms
Image Size: 2560 x 2160
Comments: Semi-clear sky conditions with large white clouds – similar to condition during acquisition of plume images



A.2 Southern Emergency Flare



Figure A.2: Southern emergency flare at the Atasta compressor station in Campeche, Mexico.

A.2.1 Description of Flare

- This vertical flare of approximately 50 m in height was part of a two flare emergency system
- The flare was fed by a single flare line of unknown diameter split from a main line feeding both emergency flare – the flare line system was reduced in diameter upstream of the flare stack

A.2.2 Sky-LOSA Acquisition

- The above noted issues regarding the sky-LOSA power supply system and the requirement for early site evacuation due to a protest and road blockade in the area precluded acquisition of sky-LOSA data for this flare
- Image data were acquired using a consumer-grade camera to enable a potential crude sky-LOSA analysis, however it has been concluded that results from such an analysis would yield know benefit due to the expectedly larger uncertainties

A.3 Northern Emergency Flare



Figure A.3: Northern emergency flare (operational flare at the right of the image) at the Atasta compressor station in Campeche, Mexico.

A.3.1 Description of Flare

- This flare was of similar design to the southern emergency flare, and was also fed by a flare line of unknown diameter which split from a main line feeding both emergency flares

A.3.2 Sky-LOSA Acquisition

- The intermittent nature of the flare and the above noted issues regarding the sky-LOSA power supply system and the requirement for early site evacuation due to a protest and road blockade in the area precluded the acquisition of image data for sky-LOSA analysis

APPENDIX B: FIELD REPORT FOR MEASUREMENTS IN ECUADOR

**Field Measurements of Black Carbon Emissions from Flaring in
Coca, Ecuador, October 26-29, 2015**

INTERIM PROJECT REPORT I: SUMMARY OF DATA COLLECTED DURING FIELD MEASUREMENTS

Report submitted to World Bank Global Gas Flaring Reduction (GGFR)
Partnership, United Nations Environment Programme (UNEP) Climate & Clean
Air Coalition (CCAC), and Petroamazonas

November 13, 2015



Matthew Johnson, Ph.D., P.Eng.
Melina Jefferson, M.A.Sc. Candidate
Darcy Corbin, M.A.Sc.
Bradley Conrad, Ph.D. Candidate
Energy & Emissions Research Laboratory
Mechanical & Aerospace Engineering,
Carleton University
Ottawa, ON, Canada

© 2015

B.1 Project Background

Emissions of black carbon (BC) from flares are of significant concern given the very large volumes of gas flared globally. Based on satellite observations of visible light emission, it is estimated that global flare volumes are on the order of 140 billion m³ annually (NOAA, 2012; Elvidge et al., 2009). Recent studies have identified BC as a powerful climate forcer with a total warming effect in the atmosphere second only to that of CO₂ (e.g. Bond et al., 2013; Ramanathan & Carmichael, 2008). Flaring is further implicated as a prominent emitter of atmospheric BC, especially in Arctic regions where it is the dominant anthropogenic source and is responsible for 42% of BC surface deposition north of 66 degrees latitude (Stohl et al., 2013).

Local effects of BC emissions are also a significant concern. While airborne particulate less than 2.5 microns in size (PM_{2.5}) is a known health hazard linked directly to human mortality (e.g. US EPA, 2010), recent studies have directly implicated BC as the key component of PM_{2.5} responsible for the majority of adverse health effects (Grahame et al., 2014). BC emissions from flaring are thus both a global and local concern.

Despite the significance of flaring and the potential impacts of global flare generated BC emissions, current data for flare BC emissions are scarce. The few available emission factors for estimating PM_{2.5} are of questionable accuracy and are not well-suited for broad applicability to the range of flare designs, flow rates, fuel compositions, and operating conditions seen globally (McEwen and Johnson, 2012). This critical lack of data reflects historic challenges in accurately measuring BC emissions rates in the field, and the difficulty of designing more detailed lab-scale experiments without the guidance of reliable measurements. However, this is changing through recent work in the Energy & Emissions Research Laboratory at Carleton University developing a new measurement technology known as sky-LOSA (Line-Of-Sight Attenuation using skylight, see Johnson et al., 2013; Johnson et al., 2011; Johnson et al., 2010), which enables quantitative remote optical measurement of BC mass emission rates in flare plumes under field conditions.

With co-support of the World Bank Global Gas Flaring Reduction (GGFR) partnership, sky-LOSA has now been successfully deployed in four field trials:

1. 1st-generation proof-of-concept measurement on a large, sooting flare in Uzbekistan (Johnson et al., 2011) supported by World Bank and Natural Resources Canada in July 2008.
2. 2nd-generation technology demonstration on two smaller, lightly-sooting flares near Poza Rica, Mexico (Johnson and Devillers, 2012; Johnson et al., 2013) with PEMEX in December 2011.
3. First attempt at 3rd-generation sky-LOSA with simultaneous flow measurement in Coca, Ecuador with Petroamazonas in June 2014. Due to logistical issues in the transfer of field-collected flare gas samples through Ecuadorian and United States customs for gas chromatographic analysis at the contracted Texas-based laboratory, BC yield estimates were necessarily calculated using low-resolution composition data from Auca field samples that were collected non-concurrently with sky-LOSA data; this was noted to introduce significant uncertainties into the field-measured BC yield.
4. Second attempt at 3rd-generation sky-LOSA with PEMEX in Campeche, Mexico in June 2015. Simultaneous flow rate measurements and on-site low-resolution gas analysis were performed by a third-party to support estimate of BC yield for a single horizontal pit flare.

Through these efforts, and associated peer-reviewed journal publications and national and international conference presentations, sky-LOSA is emerging as a vital new and disruptive technology with the ability to enable global efforts to quantify and demonstrably mitigate atmospheric emissions of BC. The primary objectives of this project were to improve upon the results of field measurements conducted in Ecuador in 2014 (Trial 3) and obtain the first ever quantitative measurements of BC yield (i.e. mass of BC emitted per mass of fuel delivered to the flare) based on simultaneous measurements of BC emission rate, flare gas flow rate(s), and detailed flare gas composition(s). These data are imperative for assessing the global importance of flare-generated BC, for developing new measurement procedures enabled by the pioneering sky-LOSA technology, for providing new data to improve BC emission inventories, and most critically, for identifying mitigation opportunities and developing procedures to validate future mitigation efforts.

Working in close collaboration with Petroamazonas and the World Bank GGFR partnership, and with additional funding support from the United Nations Environment Programme (UNEP) Climate & Clean Air Coalition (CCAC), the Carleton University Energy & Emissions Research Laboratory was invited to perform field measurements at four active sites in Petroamazonas' Auca field. Field measurement data were collected during October 26-29, 2015. This initial field report provides an overview of the measurement techniques deployed in the field and summarizes the range of data collected. Detailed data analysis is currently underway, and subsequent reports will present quantitative measurement results and discuss potential mitigation opportunities as appropriate.

B.2 Overview of Field Measurements in Ecuador

Located south-east of Coca, Ecuador in the Amazon basin, the Auca field is one of several active production regions under development by Petroamazonas. Four sites with active flare operations were visited during the period of October 26-29, 2015; these were Auca Central, Auca 27, Auca Sur, and Auca Sur 1. The Carleton University team in the field included Prof. Matthew Johnson, Ms. Melina Jefferson, and Mr. Darcy Corbin. They were accompanied by Mr. David Neira and Mr. David Herrera (Petroamazonas) during field measurements. Additional logistical support was provided by several other key Petroamazonas personnel including Javier Villacis, Christian Gutierrez, and Holguer Naranjo. A general overview of the methods and instruments used during the measurement campaign is provided in the sections that follow. Section B.5 provides a detailed summary of the specific field measurements performed at each site and the range of initial data collected.

B.2.1 Black Carbon Measurements Using Sky-LOSA

Sky-LOSA is a recently-developed measurement technique that permits in situ quantification of BC emissions from gas flares (Johnson et al., 2010; Johnson et al., 2011; Johnson et al., 2013). The sky-LOSA technique involves two main concurrent tasks: first, high-speed image data is used to determine the time-resolved two-dimensional velocity field of the BC-laden flare plume in the image plane of the camera using Image Correlation Velocimetry (Figure B.1:), and second, the extinction of narrowband skylight and solar radiation along a high-resolution scientific-grade camera's line-of-sight axis are quantified (Figure B.2). These data, along with reference sky luminance and solar irradiation measurements taken at the time of the field measurements, are used in conjunction with Rayleigh-Debye-Gans theory for Polydisperse Fractal Aggregates to determine cumulative BC concentrations along a chord normal to the spatially-resolved image plane of the camera. Finally, by combining the two-dimensional velocity field with the cumulative BC concentration data along a control surface spanning the plume, and employing an extensive Monte Carlo analysis with literature-derived probability distributions of BC properties, the time-resolved BC mass emission rate can be computed within quantified uncertainty limits. The world's first sky-LOSA field measurement was performed on a large-scale flare at a gas plant in Uzbekistan (Johnson et al., 2011). High-speed, low-resolution image data were acquired using a CMOS camera and high-resolution image data were acquired

using a separate thermoelectrically-cooled scientific-grade CCD camera and narrow band-pass filter. Measured emissions from this large-scale flare averaged to 2.0 g/s, estimated at the time to be approximately equivalent to 500 diesel buses driving at 50 km/h.

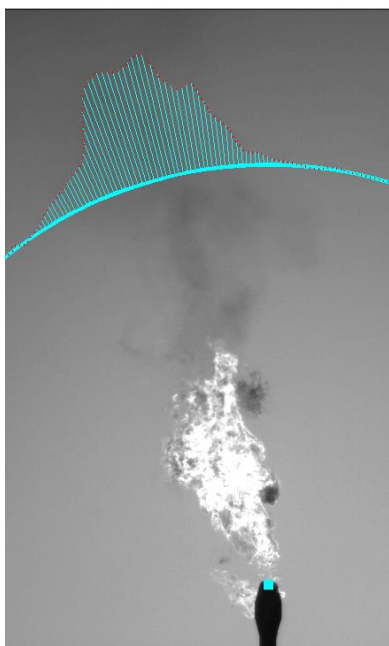


Figure B.1: Sample result showing the instantaneous two-dimensional velocity field of a BC laden flare plume.

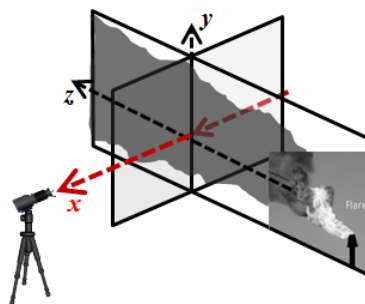


Figure B.2: Schematic illustrating the measurement of skylight optical extinction through the plume of a gas flare.

There have been several significant improvements to the sky-LOSA technique since the initial proof-of-concept measurements in Uzbekistan, as fully detailed in Johnson et al. (2013). Notably, the sky-LOSA algorithms were modified to precisely quantify within specified uncertainties any potential measurement bias as a result of in-scattered skylight and solar radiation, as well as the out-scattering of the line-of-sight skylight by the plume (Figure B.3). Additionally, with the introduction of scientific-CMOS (or sCMOS) camera sensors, it became possible to use a single camera to simultaneously acquire high-speed and high-resolution image data. Using this 2nd-generation technology, Johnson et al. (2013) performed high-sensitivity measurements on a small-scale flare (approximately 30 times smaller than the Uzbekistan flare on a BC emission rate basis) located at a turbo-compressor station in Poza Rica, Mexico. Time-averaged emission rates were quantified at 0.067 g/s within an uncertainty range of -24.8% to

+34.9%. Duration of image acquisition was limited by the field computer's memory (24 GB of RAM, the maximum achievable at the time), which at an image framerate of 50 frames/s producing 550 MB/s of data allowed for only 34.4 s of continuous measurements.

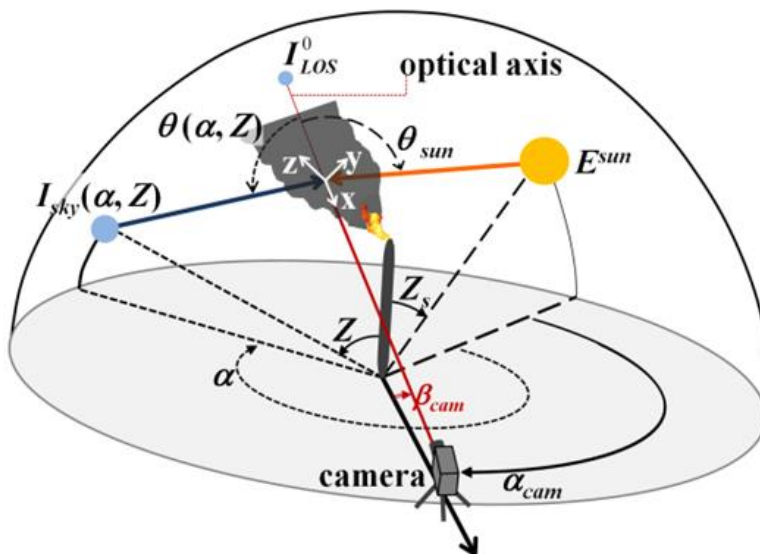


Figure B.3: Sky-LOSA camera set up, and illustrative skylight illuminance, solar irradiation, velocity field measurements.

Prior to the measurement campaigns at Petroamazonas facilities in 2014 and 2015, further sky-LOSA system hardware improvements were implemented and tested. A PCI-based solid state drive (Virident model FlashMax II 1.1 TB Performance) was added to the field computer, which when used in conjunction with the frame grabber (Silicon Software model microEnable IV VD4-CL), allowed the continuous acquisition of image data at the maximum camera speed (550 MB/s). This allowed for the acquisition of multiple 10-minute (30,000 frames at 50 frames/s) image sets before needing to offload the data to secondary hard drives. In addition to the image acquisition and storage improvements, parallel instrumentation for measuring flare gas flow rates and extracting samples for compositional analysis were acquired. This flow measurement instrumentation was used in conjunction with the 3rd-generation sky-LOSA technology during recent measurements at Petroamazonas sites conducted during October 26-29, 2015, in which data sufficient to quantify BC yields for several flares were acquired.



Figure B.4: Sky-LOSA setup at Auca 27. From left to right - rugged portable field computer, tripod with laser rangefinder, sCMOS camera, and consumer-grade video camera, and case for additional lenses and optical filters as necessary during measurements. The system is powered through an inverter connected to the battery system of a nearby vehicle located to the right of the image.

B.2.2 Flare Gas Flow Rate Measurement Methods

Four complementary flow measurement techniques were deployed for field measurements, each having different advantages and disadvantages in specific measurement conditions. These included a tracer-dilution (TD) measurement system, as well as three different insertion probe systems which included an optical flow meter (OFM), a thermal mass flow meter (TMF), and a wheel vane anemometer (WVA). The extra effort in transporting the four different systems helped maximize the potential for collecting high quality flow data in all encountered conditions. All four techniques were deployed at various times during the four days of measurement.

Tracer-Dilution (TD) Technique

The TD technique uses conservation of moles in a non-reacting flow to relate the measured concentration of an injected tracer species to the molar flow rate of gas in a flare line. The deployed measurement system used acetylene (C_2H_2) as a tracer species, as it is stable, readily obtained in the field, and could be precisely measured when mixed into the flare gas

stream. During measurements, acetylene was injected at a prescribed rate from a pressurized gas bottle into the flare gas line at an upstream location. At a downstream location where the flare gas and injected tracer were fully mixed, a sample was withdrawn from the line and the mole fraction of tracer in the flare gas was measured using a cavity ringdown analyzer (CRD). With knowledge of the purity of the tracer, injected flow rate via a mass flow controller, and the background mole fraction of tracer in the flare gas stream prior to injection, the total molar flow rate delivered to the flare could be determined using Equation (4).

$$\dot{n}_{tot} = \dot{n}_{injected} \left\{ \frac{X_{injected} - X_{background}}{X_{TD} - X_{background}} \right\} \quad (4)$$

where: \dot{n}_{tot} is the total molar flow rate of flared gas during tracer-dilution measurements,
 $\dot{n}_{injected}$ is the molar flow rate of the injection tracer gas,
 $X_{background}$ is the molar (volume) fraction of tracer gas in the background flare gas,
 $X_{injected}$ is the molar (volume) fraction of tracer gas in the injected gas (i.e. purity),
 X_{TD} is the molar (volume) fraction of tracer gas in the measured/flared gas.

The total mass flow rate delivered to the flare can be derived from Equation (5) using the known molecular mass of the injected tracer and the molecular mass of the flare gas obtained from the detailed chromatographic analysis of gas samples drawn from the relevant flare line.

$$\dot{m}_{tot} = \dot{m}_{injected} \frac{M_{tot} (X_{injected} - X_{back})}{M_{inj} (X_{TD} - X_{back})} \quad (5)$$

where: \dot{m}_{tot} is the mass flow rate of flared gas during tracer-dilution measurements,
 $\dot{m}_{injected}$ is the controlled mass flow rate of injected tracer gas,
 M_{tot} is the molecular weight of the measured/flared gas,
 $M_{injected}$ is the molecular weight of the tracer gas.

The TD flow measurement technique is advantageous since, unlike the other measurement techniques, it does not require the assumption of a specific velocity profile within the flare line. However, it does require that the injected tracer gas and flare gas stream are fully mixed. It is therefore important that the injection and sampling points are sufficiently spaced, otherwise additional procedures must be implemented to promote mixing of the tracer gas and flare stream between injection and sampling locations. To further promote rapid and complete mixing during field measurements, multi-hole injection probes were used. These probes were made from ¼" outer diameter stainless steel tubing (0.35" wall thickness); one end of the tube was plugged and two orthogonally oriented rows of fifteen injection holes (1/32" diameter) were drilled into each probe. The holes were spaced uniformly over 4", 6", 8", and 10" to ensure that the ports would span the entire diameter of common flare line sizes. Two probes of each size were created (one for injection and one for sampling).

Figure B.5 and Figure B.6 show photos of the tracer-injection and sampling systems. The instruments and equipment used in the TD flow measurement technique were as follows:

- Methane (CH₄) / Acetylene (C₂H₂) / Water (H₂O) CRD Gas Analyzer (Los Gatos Research, model 915-0043)
- Acetylene (C₂H₂) Mass Flow Controller (Brooks, model SLAMF50S1BAB1K2A1)
- Acetylene (C₂H₂) Tracer Gas – 99 % Purity (Supplied by Linde Ecuador S.A. and purchased after arrival in Coca on October 26, 2015)

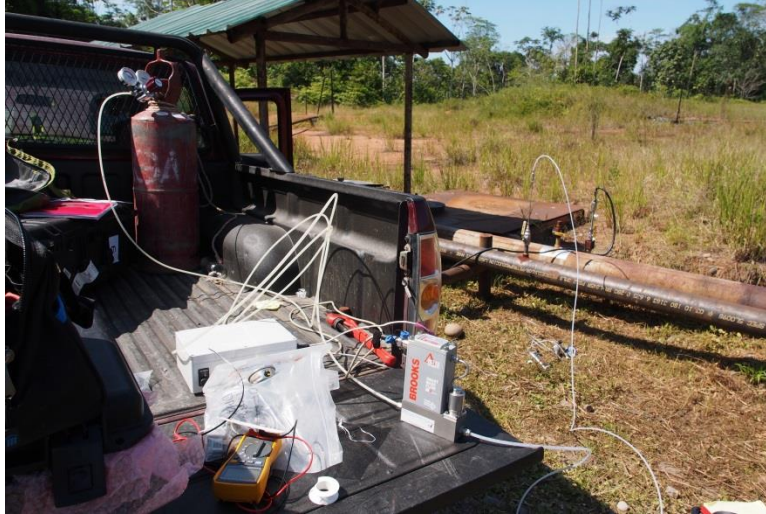


Figure B.5: Injection of acetylene with a mass flow controller from a bottle of 99% pure acetylene at Auca Sur 1.



Figure B.6: Downstream sampling of the acetylene in the flare line at Auca Sur 1 using a multi-hole sampling probe connected to the CRD gas analyzer.

Optical Flow Meter (OFM)

An optical flow meter (Focus 2.0 - Photon Controls) was also employed in the field measurements at Petroamazonas facilities, as shown in Figure B.7. The OFM consists of two precisely spaced lasers housed within a 3/4" diameter, 21-3/8" long probe. As entrained dust or liquid aerosols transect each beam, a signal is detected. By cross-correlating the two laser signals, the transit time and hence the velocity of the entrained aerosols moving with the flare stream can be precisely measured. An advantage of the OFM is that it only requires a single insertion point into the flare line (unlike the tracer-dilution method). Also, like the TD method,

the OFM does not require the flare gas stream to be clean and aerosol free (unlike the TFM discussed below), but in fact requires impurities within the flare gas to create a measureable signal. However, a key disadvantage of the OFM (that is shared with the TFM and vane wheel anemometer discussed below) is that the velocity profile in the line must be known, as well as the temperature and pressure, to calculate the line's volume flow rate. In addition, there is a limit to the amount of aerosol contamination that the OFM can accommodate, as excess accumulation of liquids or solid particles tend to degrade the effectiveness of optical components within the probe, thus decreasing the quality and frequency of valid measurements. This issue is partially mitigated via an integrated heater element on key optical components within the OFM probe.

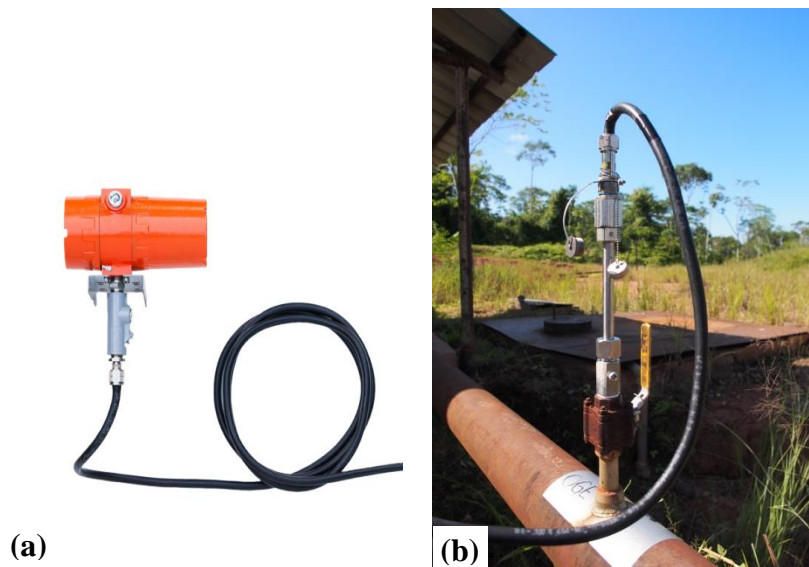


Figure B.7: OFM system. (a) Image showing the control head of the OFM and fiber optic cable system that connects to (b) the OFM insertion probe, shown installed in a flare line at Auca Sur 1.

Constant Temperature Thermal Mass Flow Meter (TFM)

A SAGE Metering Integral Prime thermal mass flow meter (with an 18" long 1/2" diameter probe) was also employed in the field measurements at Petroamazonas facilities, as illustrated in Figure B.8. TFMs use the heat transfer properties of a flowing gas to determine a flow velocity. The sensor consists of two closely located resistance temperature detectors (RTDs). One RTD is variably heated to transfer heat into the gas stream, while the second RTD measures the change in flow temperature. The TFM's processor attempts to maintain a constant temperature at the second RTD by controlling heat released from the first RTD. The power required to maintain this temperature is indicative of the velocity of the fluid in which it is

immersed. The TFM is calibrated based on the geometry of the RTDs and the specific thermodynamic properties of the calibration fluid. Because TFM measurements are strongly dependent on the properties of the gas, uncertainties tend to be large and back-calibration is generally necessary following gas composition analysis. As detailed below, gas samples were extracted at each line with installed sample ports which could be used for this purpose.

Calculation of the total mass flow rate from a measured velocity further requires knowledge of the velocity profile, pressure, and temperature in the line being measured. Additionally, TFM probes are susceptible to bias errors due to probe contamination with liquid aerosols and debris, which are often present in flare gas lines at upstream production sites. Prior to use of TFM, a cleanable probe was inserted to test for the presence of condensable aerosols or entrained solids to ensure the viability of the TFM in measuring the flare line's flow rate.



Figure B.8: Measuring flow with the constant temperature TFM at Auca 27.

Vane Wheel Anemometer (VWA)

A vane wheel anemometer (VWA, model ZA18 GE MC 40T 240-2 P10/Ex - Hoentzsch), shown in Figure B.9, was the fourth complementary flow/velocity measurement device deployed during field measurements at Petroamazonas facilities. Like the OFM and the TFM, the VWA measures velocity at the tip of a probe and requires additional knowledge or assumptions about

the velocity profile in the flare gas line to calculate volumetric flow rates. The VWA consists of a small propeller (wheel) of known geometry near the end of a 3/4" diameter probe. The induced angular velocity of the propeller is proportional to the linear velocity of the gas stream. The mass flow rate of the gas stream can be calculated from the measured velocity at the specific radial location combined with the field measured temperature and pressure, molecular weight data from the gas sample analysis, and an assumed velocity profile. As with the TFM, measurement accuracy is degraded by the presence of liquids in the flare gas stream (and/or liquids/solids that may be deposited on the walls of flare lines which can lead to contamination of the probe during insertion), which can impede the rotation of propeller, introducing bias errors relative to the internal calibration. The primary advantage of the VWA is its simplicity of use in situations where two access points for the TD system are not available, there are insufficient entrained aerosols for reliable operation of the OFM, and a complementary measurement to the TFM that is less sensitive to variations in the composition of the flare stream is desired.



Figure B.9: Vane wheel anemometer.

B.3 Flare Gas Sampling for Compositional Analysis

Detailed flare gas composition data is essential for the calculation and interpretation of fuel-mass-specific BC emission rates. In addition, detailed composition data is critical for proper assessment of potential flare and BC mitigation opportunities. Because of significant challenges and delays in transporting sample containers and collected gas sample into and out of Ecuador and the United States during the first phase of field measurements in June 2014, two separate gas sample collection plans were implemented.

Two-dozen 300 mL stainless steel sample cylinders were brought into Ecuador to facilitate flare gas sample collection from each line with an available hot tap. The cylinders were filled using a combination of positive pressure in the flare lines (when available) and a small hand-operated sample pump (as being used in Figure B.10), which could pressurize the cylinders to the desired 60 psig. Tedlar® bags were also brought to Ecuador as back-up in the event that the sample cylinders were delayed in transiting various customs agencies as happened in both the 2014 Ecuador campaign and the 2015 Mexico campaign. Fortunately, there were no issues in bringing the empty sample cylinders from Ottawa to Coca, and as detailed in Table B.1, gas samples were successfully collected from all accessible flare lines at the four sites producing a total of 10 samples for export back to Canada for detailed analysis. On October 29, these ten cylinders and the remaining 14 unused cylinders were shipped by bus from Coca to Quito, and the following day were hand-delivered to David Neira's Petroamazonas office in Quito. As of November 12, 2015, Mr. Neira is preparing to ship the cylinders via DHL Global Forwarding to Maxxam Analytics in Edmonton, AB for compositional analysis. The selected analysis will be highly detailed, capable of isolating volume fractions of alkanes, alkenes, cycloalkanes, and aromatics up to C₁₅; residual hydrocarbons from C₄ to C₁₅⁺; and fixed gases. Due to DHL's dangerous goods shipment regulations, a corporation rather than an individual must be the shipper, which prohibited Carleton University staff from initiating the shipment directly.

The second (parallel) sample collection plan entailed contracting an Ecuadorian company, SGS del Ecuador S.A., to analyze a second set of samples collected in cylinders provided by SGS in Ecuador. The SGS lab was only capable of providing analysis to up to C₆⁺ species, so the intent was to use these results as a backup only. SGS was unfortunately only able to provide six sample cylinders, which were used to collect samples at Auca Central, Auca 27, and Auca Sur 1 as indicated in Table B.1. The cylinders were picked up and returned to SGS in Coca for transport to Quito for analysis.

Table B.1: Collected gas samples for Carleton University and SGS analysis

Site Name	Line Number (Flare)	Carleton University Cylinder Number	SGS Sample Number
Auca Central	Line 1 (Right)	8	1
Auca 27	Line 1	5	2
	Line 2	4	3
	Line 3	7	4
	Line 4	16	5
Auca Sur	Line 2 (Right)	13	--
	Line 3 (Right)	10	--
	Line 1 (Left)	9	--
Auca Sur 1	Line 1	11	6
	Line 3	2	--



Figure B.10: Filling a sample cylinder from a hot tap with hand pump at Auca Sur.

B.4 References

- Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., et al. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res. Atmos.*. 118:5380–5552.
- Elvidge, C.D., Ziskin, D., Baugh, K.E., Tuttle, B.T., Ghosh, T., Pack, D.W., Erwin, E.H., and Zhizhin, M. (2009). A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data. *Energies*. 2:595–622.
- Grahame, T.J., Klemm, R., and Schlesinger, R.B. (2014). Public health and components of particulate matter: The changing assessment of black carbon. *J. Air Waste Manage. Assoc.*. 64:620–660.
- Johnson, M.R. and Devillers, R.W. (2012). Field Measurement of Black Carbon Emissions from Gas flares near Poza Rica , Mexico using Second Generation sky-LOSA Technology. Report submitted to Petroleum Technology Alliance of Canada, Natural Resources Canada, and the World Bank Global Gas Flaring Reduction (GGFR) Partnership, Ottawa, ON, Carleton University Energy & Emissions Research Lab.
- Johnson, M.R., Devillers, R.W., and Thomson, K.A. (2011). Quantitative Field Measurement of Soot Emission from a Large Gas Flare Using Sky-LOSA. *Environ. Sci. Technol.*. 45:345–350.
- Johnson, M.R., Devillers, R.W., and Thomson, K.A. (2013). A Generalized Sky-LOSA Method to Quantify Soot/Black Carbon Emission Rates in Atmospheric Plumes of Gas Flares. *Aerosol Sci. Technol.*. 47:1017–1029.
- Johnson, M.R., Devillers, R.W., Yang, C., and Thomson, K.A. (2010). Sky-Scattered Solar Radiation Based Plume Transmissivity Measurement to Quantify Soot Emissions from Flares. *Environ. Sci. Technol.*. 44:8196–8202.
- McEwen, J.D.N. and Johnson, M.R. (2012). Black Carbon Particulate Matter Emission Factors for Buoyancy Driven Associated Gas Flares. *J. Air Waste Manage. Assoc.*. 62:307–321.
- NOAA (2012). Global Gas Flaring Estimates.
http://www.ngdc.noaa.gov/eog/interest/gas_flares.html
- Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nat. Geosci.*. 1:221–227.
- Stohl, A., Klimont, Z., Eckhardt, S., Kupiainen, K., Shevchenko, V.P., Kopeikin, V.M., and Novigatsky, A.N. (2013). Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions. *Atmos. Chem. Phys.*. 13:8833–8855.
- US EPA (2010). Integrated Science Assessment for Particulate Matter. EPA/600/R-08/139F,

Research Triangle Park, NC, National Center for Environmental Assessment-RTP
Division, U.S. Environmental Protection Agency.

B.5 Summary of Data Collected in the Field

B.5.1 Auca Central – October 26, 2015



Figure B.11: Flare setup at Auca Central with the Venturi air-entrainment circled in red.

Description of Site Flaring

There were four flare stacks and two active flares at the Auca Central site. The three flare stacks to the left of Figure B.11 were connected to a header fed by one 4" line and one 8" line. The middle of these three stacks had a visible flame present at the time personnel were on site. These flares did not have hot taps available on either the 4" or 8" feed line which precluded the ability to conduct flow rate or gas composition measurements. The rightmost flare in Figure B.11 had a visible flame present and was fed from a dedicated 10" line. This flare was the subject of simultaneous sky-LOSA, flow rate, and gas composition measurements. The flare employed an open entrainment section at the base (circled in red in Figure B.11). The 10" line

feeding the flare terminated in a converging nozzle which was directed into the open base of the 8” diameter vertical flare stack. Presumably, the intent of this arrangement was to induce ambient air entrainment into the vertical flare stack via the Venturi effect as a means to reducing visible BC emissions.

Sky-LOSA Acquisition

The sky-LOSA apparatus was setup on a gravel/sand pad situated in front and to the left of the truck seen in Figure B.11. All sky-LOSA data at Auca Central were collected from this position as further detailed below. Sun images to determine solar intensity were not obtained as the sun was blocked by clouds for the duration of all measurements.

Line Access

The 10" line feeding the rightmost flare had two 1" hot taps approximately 5.5 m apart.

Details of Collected Data at Auca Central

Image Set 1 (S00° 38' 36.48" W76° 56' 07.56")

Time @ Start: 17:12:11 Local
File Prefix: AucaCentralF1Pos1Run1BC
File Type: Multi-TIFF
of Images: 3,000
Framerate (Hz): 50
Acquisition Length: 1 minute
Distance to Flare: 21.8 m
Azimuth: 113.6°
Inclination: 19.8°
Lens: Nikkor 50 mm
Filtering: 52 mm 531/40 FF01
Aperture: f/1.8
Exposure: 1.2 ms
Image Size: 2560 x 2160

Sky Conditions: Flat sky to human eyes, sun fully blocked by clouds

- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Incomplete data set taken (3,000 of 30,000 images)
 - Simultaneous flow rate data were acquired at 17:12:11 to 17:13:11 local



Image Set 2 (S00° 38' 36.48" W76° 56' 07.56")

Time @ Start: 17:17:03 Local
File Prefix: AucaCentralF1Pos1Run2BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 21.8 m
Azimuth: 113.6°
Inclination: 19.8°
Lens: Nikkor 50 mm
Filtering: 52 mm 531/40 FF01
Aperture: f/1.8
Exposure: 1.2 ms
Image Size: 2560 x 2160
Sky Conditions: Flat sky to human eyes, sun fully blocked by clouds
Comments:

- Consumer-grade video acquired simultaneously in standard definition
- Simultaneous flow rate data were acquired at 17:17:03 to 17:27:03 local



Flow Rate Measurements and Gas Samples

- Line 1
- Line pressure: Negative pressure –not logged
 - Line temperature: 25.7 °C
 - Tracer-dilution measurements
 - Test started at time 17:10:52 to 17:31:15 local
 - Simultaneous with sky-LOSA measurements at 17:12:11 to 17:13:11 and 17:17:03 to 17:27:03 local (Image Sets 1 and 2)
 - Control of acetylene injection was set digitally at 0.1 SLPM and gas analyzer data were logged to computer
 - 8” multi-point injection probes were used at the injection and sampling points – end of probe was against the bottom of pipe
 - No solids or liquids were seen on probe when removed from the hot taps
- Other
- Atmospheric pressure: 97.49 kPa
 - File name(s): Auca_Central_Mon26_Afternoon.xls
 - Flare gas samples taken
 - Line 1 – Cylinder Number 8 and Sample Number 1 (for Maxxam Analytics in Edmonton, AB and SGS in Ecuador respectively)

B.5.2 Auca 27 – October 27, 2015



Figure B.12: Flare setup at Auca 27

Description of Site Flaring

A single flare was present and operating with a large visible flame at the Auca 27 site as shown in Figure B.12. The flare was fed by two 4" and two 6" lines, which were numbered for our records as Lines 1 through 4 from left to right as seen in Figure B.12. Markings on Lines 2 and 4 indicated that they were 6-5/8" OD with 0.29" wall thickness.

Sky-LOSA Acquisition

Sky-LOSA equipment was set up in the large open area surrounding the well-heads at Auca 27, as seen in Figure B.4. The ground was hard-packed gravel and sand. Two positions were used to take measurements and sun images were not taken due to full cloud coverage during sky-LOSA acquisition.

Line Access

Lines 1 and 3 (4-1/2" OD) each had a single 1" hot tap in the flare area as seen in Figure B.12. Lines 2 and 4 (6-5/8" OD) each had 1" hot taps in the flare area and a second set of 1" hot taps approximately 150 m upstream.

Details of Collected Data at Auca 27

Image Set 1 (S00° 44' 07.80" W76° 52' 50.46")

Time @ Start: 08:06:15 Local
File Prefix: Auca27Run1BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 96 m
Azimuth: 55.4°
Inclination: 20.3°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4
Exposure: 1.2 ms
Image Size: 2560 x 2160



Sky Conditions: Relatively flat, clouds started to break during test, sun completely blocked
Comments:

- Consumer-grade video acquired in standard definition although time is not synched
- Time on computer and consumer-grade camera were synched after this test
- No simultaneous flow measurements were taken

Image Set 2 (S00° 44' 07.80" W76° 52' 50.46")

Time @ Start: 08:40:51 Local
File Prefix: Auca27R2P2BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 96 m
Azimuth: 57.9°
Inclination: 20.3°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4
Exposure: 1.2 ms
Image Size: 2560 x 2160



Sky Conditions: Sun blocked at beginning of test – started to break during test. Overcast, slight variation in cloud brightness.

- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM flow measurements acquired at 08:47:33 to 08:50:51 local

Flow Rate Measurements and Gas Samples

- Line 1
- Line pressure: 186.3 kPa
 - Line temperature: 34.9 °C
 - Optical measurements
 - Test start at 08:29:43 to 08:38:45 local
 - Not simultaneous with sky-LOSA measurements
 - Top of OFM fitting was 12" from top outside wall; OFM knuckle 7-1/8" from top of fitting; therefore estimated depth from outside wall is 2-1/4"
 - Master delay was 1000 ms in acquisition software
 - Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Average reading over several minutes was 2207.16 FPM from six hand-recorded readings
 - Probe length: 17-1/2"; hot tap: 12-1/4"; outer diameter of pipe: 4-1/2"; therefore for probe to be in centre of pipe, insertion depth 1-7/8" nut to nut
 - Tracer-dilution flow measurements were not taken – only single hot tap available
 - No solids or liquids were seen on probes when removed from the hot taps

- Line 2
- Line pressure: 103.42 kPa
 - Line temperature: 37.3 °C
 - Optical measurements
 - Test start at 08:47:33 to 08:52:55 local
 - Simultaneous with sky-LOSA measurements at 08:47:33 to 08:50:51 local (Image Set 2)
 - OFM probe length: 21-3/8"; hot tap height: 12"; outer diameter of pipe: 6-5/8"; therefore for probe to be in centre of pipe, knuckle fitting is 6" from top of hot tap
 - Master delay of 1000 ms in data acquisition software
 - Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Average reading over several minutes was 3393.8 FPM from five hand-recorded readings
 - Probe length: 17-1/2"; hot tap height: 12-1/4"; outer diameter of pipe: 6-5/8"; therefore for probe to be in centre of pipe, insertion depth 3" nut to nut
 - Tracer-dilution measurements
 - Test start time: 13:09:22 to 13:19:02 local
 - Not simultaneous with sky-LOSA measurements
 - Mass flow control of acetylene at 2.01V (corresponding to 2.01 SLPM)
 - No solids or liquids were seen on probes when removed from the hot taps
- Line 3
- Line pressure: 100.66 kPa
 - Line temperature: 38.1 °C
 - Optical measurements
 - Test start at 09:01:23 to 09:11:38 local
 - Not simultaneous with sky-LOSA measurements
 - OFM probe insertion depth calculations were identical to Line 1 measurements
 - Master delay of 1000 ms in data acquisition software
 - Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Insertion depth calculations identical to Line 1
 - Pinned at 5000 SFPM – possible solids in line
 - Tracer-dilution flow measurements were not taken – only single hot tap available
 - No solids or liquids were seen on probes when removed from the hot taps

- Line 4
 - Line pressure: 103.07 kPa
 - Line temperature: 34.8 °C
 - Optical measurements
 - Test start at 09:19:04 to 09:27:24 local
 - Not simultaneous with sky-LOSA measurements
 - OFM probe insertion calculations were identical to Line 2
 - Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Insertion depth calculations identical to Line 2
 - Pinned at 5000 SFPM – possible solids in line
 - Tracer-dilution measurements
 - Test start at 12:43:17 to 12:53:43 local
 - Not simultaneous with sky-LOSA measurements
 - Mass flow control of acetylene at 2.01V (corresponding to 2.01 SLPM)
- No solids or liquids were seen on probes when removed from the hot taps
- Other
 - Atmospheric pressure: 98.51 kPa
 - File name(s): Auca27_Line1_OFM.xls, Auca27_Line2_OFM.xls, Auca27_Line3_OFM.xls, Auca27_Line4_OFM.xls, Auca27_line2_crd_2SLPM_TI.xls, Auca27_line4_crd.xls, Auca27_line4_crd_2SLPM_TI.xls
 - Flare gas samples taken
 - Line 1 – Cylinder Number 5 and Sample Number 2 (for Maxxam Analytics in Edmonton, AB and SGS in Ecuador respectively)
 - Line 2 – Cylinder Number 4 and Sample Number 3 (for Maxxam Analytics in Edmonton, AB and SGS in Ecuador respectively)
 - Line 3 – Cylinder Number 7 and Sample Number 4 (for Maxxam Analytics in Edmonton, AB and SGS in Ecuador respectively)
 - Line 4 – Cylinder Number 16 and Sample Number 5 (for Maxxam Analytics in Edmonton, AB and SGS in Ecuador respectively)

B.5.3 Auca Sur – October 28, 2015



Figure B.13: Flare setup at Auca Sur

Description of Site Flaring

A total of four stacks were installed at the Auca Sur site. Two flares were in operation at the time of measurements (the rightmost and third from right as seen in Figure B.13) and two flares were inactive (second from right as seen in Figure B.13 and one out of frame on the left). The left active flare was fed by a single 8” line. As seen in Figure B.14, this flare employed a similar Venturi arrangement at its base as seen at Auca Central; however, the line feeding the converging nozzle at the base of the left flare at Auca Sur was significantly misaligned from the open base of the flare stack. At this degree of misalignment it is expected that a significant portion of the gas flow exiting the line may not be reaching the flame.

The right flare was connected to three lines. Staff on site indicated that the leftmost line (12-3/4” OD) was no longer operational and there were no hot taps in that line. The 8” center line (mostly obscured by the larger non-operational line to the left in the image) and the 12” rightmost line were both active. Sky-LOSA measurements were performed on both flares. Because of operation issues with the computers in the extreme heat of the sun, there were several partial sky-LOSA data sets recorded. Once the vehicle was repositioned to allow the computer equipment to operate out of the air-conditioned cabin, longer data sets were successfully obtained.

Sky-LOSA Acquisition

Sky-LOSA was setup adjacent to the hot taps on the lines feeding the right flare. One position was used to obtain sky-LOSA data for each flare and sun images were taken to determine solar intensity.

Line Access

For the right flare, line 1 (leftmost line) had no hot taps and was reported to be inactive by on site personnel. Line 2 (centre line) had a single 1” hot tap into which the OFM was installed. Line 3 (rightmost line) had two 1” hot taps spaced approximately 9.14 m apart which were used for tracer-dilution flow measurements. The single line feeding the left active flare had a single 1” hot tap which allowed flow measurement via the OFM.



Figure B.14: Ambient air entrainment (premixing) technique using converging nozzle and vertically offset flare stack.

Details of Collected Data at Auca Sur

Image Set 1 – Right Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 10:19:36 Local
File Prefix: AucaSurRFRun1Pos1BC
File Type: Multi-TIFF
of Images: 20,372
Framerate (Hz): 50
Acquisition Length: 6 minutes 47.44 seconds
Distance to Flare: 48 m
Azimuth: 25.9 °
Inclination: 25.3°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4
Exposure: 1.0 ms
Image Size: 2560 x 2160
Sky Conditions: Blue sky, puffy clouds,
Comments: • Consumer-grade video acquired simultaneously in standard definition



Sun Image Set 1 (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 11:31:06 Local
File Prefix: AucaSurSun
File Type: Multi-TIFF
of Images: 1,000
Framerate (Hz): 50
Acquisition Length: 20 seconds
Azimuth: 158.32°
Inclination: 76.58°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: 1.0 + 4.0 ND
Exposure: 1.0 ms
Image Size: 2560 x 2160

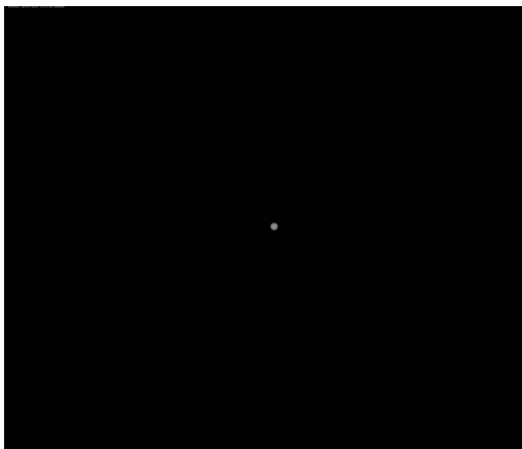


Image Set 2 – Right Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 11:39:37 Local
File Prefix: AucaSurRFRun2BC
File Type: Multi-TIFF
of Images: 1,000
Framerate (Hz): 50
Acquisition Length: 20 seconds
Distance to Flare: 48 m
Azimuth: 25.9°
Inclination: 25.3°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4
Exposure: 1.0 ms
Image Size: 2560 x 2160

Sky Conditions: Blue sky, puffy clouds

- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM and TD flow rate data from 11:39:37 to 11:39:57 local



Image Set 3 – Right Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 11:43:50 Local
File Prefix: AucaSurRFRun3BC
File Type: Multi-TIFF
of Images: 8,891
Framerate (Hz): 50
Acquisition Length: 2 minutes 57.82 seconds
Distance to Flare: 48 m
Azimuth: 35.9°
Inclination: 26.8°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4.8
Exposure: 1.0 ms
Image Size: 2560 x 2160

Sky Conditions: Blue sky, puffy clouds

- Comments:
- Consumer-grade video acquired 10 seconds earlier than sky-LOSA in standard definition
 - Simultaneous OFM and TD flow rate data from 11:43:50 to 11:46:48 local
 - System crashed at 8,891 saved images due to heat



Image Set 4 – Right Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 11:56:30 Local
File Prefix: AucaSURRun4RFBC
File Type: Multi-TIFF
of Images: 14,102
Framerate (Hz): 50
Acquisition Length: 4 minutes 42.04 seconds
Distance to Flare: 48 m
Azimuth: 35.9°
Inclination: 26.8°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/4.8
Exposure: 1.0 ms
Image Size: 2560 x 2160
Sky Conditions: Blue sky, puffy clouds



- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM and TD flow rate data from 11:56:30 to 12:01:12 local
 - System crashed at 14,102 images due to heat

Image Set 5 – Left Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 16:19:12 Local
File Prefix: AucaSurLFRun1BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 26.5 m
Azimuth: 3.4°
Inclination: 19.7°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/2.8
Exposure: 1.0 ms
Image Size: 2560 x 2160
Sky Conditions: Sun partially to fully blocked, mixed clouds



- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM flow rate data from 16:19:23 to 16:29:12 local

Image Set 6 – Left Flare (S00° 42' 26.64" W76° 53' 09.30")

Time @ Start: 16:34:34 Local
File Prefix: AucaSurLFRun2Exp2BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 26.5 m
Azimuth: 3.4°
Inclination: 19.7°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/2
Exposure: 1.2 ms
Image Size: 2560 x 2160



Sky Conditions: Sun fully blocked by cloud, mixed clouds
Comments:

- Consumer-grade video acquired simultaneously in standard definition
- Simultaneous OFM flow rate data from 16:34:34 to 16:44:34 local

Flow Rate Measurements and Gas Samples

- Line 2
 - Line pressure: 98.52 kPa
- Right
 - Line temperature: 44.4 °C
- Flare
 - Optical measurements
 - Test start at 11:05:55 to 12:05:37 local
 - Simultaneous with sky-LOSA measurements at 11:39:37 to 11:39:57, 11:43:50 to 11:46:47, and 11:56:30 to 12:01:12 local (Image Sets 2, 3, and 4)
 - Probe length: 21-3/8"; outer radius: 4-5/16"; therefore 17-1/16" top of pipe to knuckle
 - No solids or liquids were seen on probe when removed from the hot taps
- Line 3
 - Line pressure: 98.11 kPa
- Right
 - Line temperature: 48.0 °C
- Flare
 - Tracer-dilution measurements
 - Test start at 11:39:37 to 12:05:02 local
 - Simultaneous with sky-LOSA measurements at 11:39:37 to 11:39:57, 11:43:50 to 11:46:47, and 11:56:30 to 12:01:12 local (Image Sets 2, 3, and 4)
 - 10" multi-point injection probes were used
 - Injected 0.1 SLPM of acetylene
 - No solids or liquids were seen on probes when removed from the hot taps

- Line 1
 - Line pressure: 97.84 kPa
- Left
 - Line temperature: 45.7 °C
- Flare
 - Optical measurements
 - Test start at 16:19:23 to 16:55:16 local
 - Simultaneous with sky-LOSA measurements at 16:19:23 to 16:29:12 and 6:34:34 to 16:44:34 local (Image Sets 5 and 6)
 - 17-1/16” outer wall to OFM knuckle
 - Readings primarily near 0 with occasional reading of 0.6 FPS (possible clean flow)
 - No solids or liquids were seen on probes when removed from the hot taps
- Other
 - Atmospheric pressure: 98.13 kPa (during Right Flare data collection)
 - Atmospheric pressure: 97.35 kPa (during Left Flare data collection)
 - File names(s): AucaSur_skyLosa.xls, AucaSur_OFM-L2_TD-L3.xls, AucaSur_flare2_OFM.xls
 - Flare gas samples taken
 - Line 2 (Right Flare) – Cylinder Number 13 (for Maxxam Analytics in Edmonton, AB)
 - Line 3 (Right Flare) – Cylinder Number 10 (for Maxxam Analytics in Edmonton, AB)
 - Line 1 (Left Flare) – Cylinder Number 9 (for Maxxam Analytics in Edmonton, AB)

B.5.4 Auca Sur 1 – October 27 & October 29, 2015



Figure B.15: Flare setup at Auca Sur 1.

Description of Site Flaring

A single flare was present and operating with a visible flame at Auca Sur 1. Three lines lead toward the flare labeled as Lines 1 to 3 (left to right when looking downstream towards flare), although Line 2 terminated in a blind flange prior to reaching the flare. Lines 1 and 3 were 6" lines.

Sky-LOSA Acquisition

Sky-LOSA was set up on a hard-packed gravel road, adjacent to the hot taps, behind the truck in Figure B.15. Measurements were performed over two separate days, October 27 and 29, 2015. A single sky-LOSA image set was obtained on October 27 prior to the end of daylight. The Auca Sur 1 site was revisited on October 29, 2015 and a total of three sky-LOSA plume image sets (Image Sets 2, 3, and 4) and one reference sun image set were recorded in conjunction with simultaneous flow measurements.

Line Access

Lines 1 and 3 each had two 1" hot taps, spaced an estimated 10 m apart. Initially upon arrival at the site, the downstream hot taps were interconnected with threaded pipe, but the onsite operator was kindly able to quickly remove the connected piping providing access to the taps for measurement. The downstream hot tap on Line 3 would not allow passage of the OFM, which suggests it may not have been a fully ported valve. As illustrated in Figure B.16, there were significant solids in the bottom ~2-1/8" of Line 3. This initially caused contamination problems when deploying the flow measurement probes. However, successful measurements were

obtained in the remaining vapour space of the line once proper insertion lengths were determined.



Figure B.16: Solids in bottom of Line 3 at Auca Sur 1 on OFM probe.

Details of Collected Data at Auca Sur 1 – October 27, 2015

Image Set 1 (S00° 47' 36.30" W76° 53' 09.54")

Time @ Start: 17:26:56 Local
File Prefix: AucaSur1Go
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 43 m
Azimuth: 152.9°
Inclination: 22.1°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/2
Exposure: 1.2 ms
Image Size: 2560 x 2160

Sky Conditions: Small clouds – mostly clear, time of test near sundown

Comments: • Consumer-grade video acquired simultaneously in standard definition



Flow Rate Measurements and Gas Samples – October 27, 2015

- Line 1
 - Line pressure: 100.25 kPa
 - Line temperature: 47.0 °C
 - Vane anemometer
 - Several minutes of flow data was logged intermittently by hand for an average of 9.35 FPM
- Line 3
 - No flow measurements taken
- Other
 - Atmospheric pressure: 97.39 kPa
 - No flow measurement data logged digitally
 - Flare gas samples taken
 - Line 1 – Sample Number 6 (for SGS in Ecuador)

Details of Collected Data at Auca Sur 1 – October 29, 2015

Image Set 2 (S00° 47' 36.42" W76° 53' 09.54")

Time @ Start: 09:03:39 Local
File Prefix: AucaSur1Day4R1BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 39.1 m
Azimuth: 155.6°
Inclination: 26.1°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/3.3
Exposure: 1.2 ms
Image Size: 2560 x 2160



Sky Conditions: Wispy clouds – clouds disappeared soon after test started

- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM and TD flow rate data from 09:03:39 to 09:13:39 local

Image Set 3 (S00° 47' 36.42" W76° 53' 09.54")

Time @ Start: 09:26:51 Local
File Prefix: AucaSur1Day4Run2BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 39.1 m
Azimuth: 156.0°
Inclination: 26.3°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/3.3
Exposure: 1.2 ms
Image Size: 2560 x 2160
Sky Conditions: Wispy clouds



- Comments:
- Consumer-grade video acquired simultaneously in standard definition
 - Simultaneous OFM and TD flow rate data from 09:26:51 to 09:36:51 local

Sun Image Set 1 (S00° 47' 36.42" W76° 53' 09.54")

Time @ Start: 09:40:29 Local
File Prefix: AucaSur1Day4Sun
File Type: Multi-TIFF
of Images: 3,000
Framerate (Hz): 50 fps
Acquisition Length: 1 minute
Azimuth: 112.87°
Inclination: 55.25°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/3.3
Exposure: 1.2 ms
Image Size: 2560 x 2160

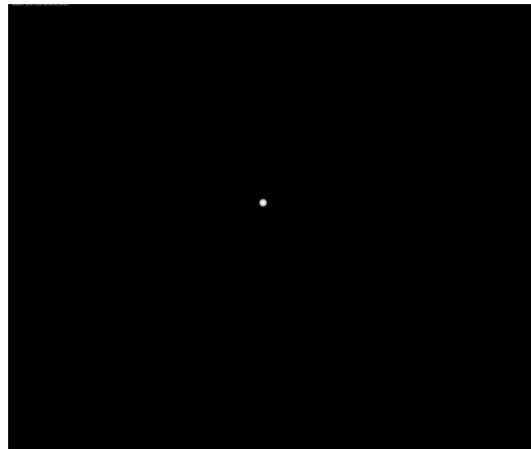


Image Set 4 (S00° 47' 36.42" W76° 53' 09.54")

Time @ Start: 10:33:47 Local
File Prefix: AucaSur1R3P2BC
File Type: Multi-TIFF
of Images: 30,000
Framerate (Hz): 50
Acquisition Length: 10 minutes
Distance to Flare: 39.1 m
Azimuth: 155.8°
Inclination: 25.6°
Lens: Zeiss 25 mm
Filtering: 67 mm 531/40 FF01
Aperture: f/3.3
Exposure: 1.2 ms
Image Size: 2560 x 2160
Sky Conditions: Clear blue sky
Comments:

- Consumer-grade video acquired simultaneously in standard definition
- Simultaneous OFM and TD flow rate data from 10:33:47 to 10:43:47 local



Flow Rate Measurements and Gas Samples – October 29, 2015

- Line 1
- Line pressure: 98.56 kPa
 - Line temperature: 33.8 °C
 - Optical measurements
 - Test start at 09:50:56 to 10:44:45 local
 - Simultaneous with sky-LOSA measurements at 10:33:47 to 10:43:47 local (Image Set 4)
 - OFM probe length – 21-3/8"; for probe to be in middle of line, knuckle to pipe outer wall is 18-3/8"
 - Master delay was 1000 ms in acquisition software
 - Tracer-dilution measurements
 - Test start at 08:59:50 to 09:37:00 local
 - Simultaneous with sky-LOSA measurements at 09:03:39 to 09:13:39 and 09:26:51 to 09:36:51 local (Image Sets 2 and 3)
 - Master delay was 1000 ms in acquisition software
 - 8" multi-hole probe was used to test for solids and liquids in line – the probe showed no thick solids, though many liquid droplets were present

- Line 3
 - Line pressure: 102.73 kPa
 - Line temperature: 46.5 °C
 - Optical measurements
 - Test start at 08:52:34 to 09:47:42 local
 - Simultaneous with sky-LOSA measurements at 09:03:39 to 09:13:39 and 09:26:51 to 09:36:51 local (Image Sets 2 and 3)
 - Inserted multi-point probe to test depth of oil/dirt in line – measured solids 2-1/8” from bottom (see Figure B.16)
 - For an insertion depth of 2/3 into the vapour space, probe is 2-3/4” into pipe from outer wall
 - OFM probe length – 21-3/8”; knuckle fitting is 18-5/8” from top of pipe outer wall
 - Master delay was 1000 ms in acquisition software
 - Tracer-dilution measurements
 - Test start at 10:29:31 to 10:43:57 local
 - Simultaneous with sky-LOSA measurements at 10:33:47 to 10:43:47 local (Image Set 4)
 - Master delay was 1000 ms in acquisition software
- Other
 - Atmospheric pressure: 97.97 kPa
 - File name(s): AucaSur1_Oct29_OFMandTD_dup_161508155.xls, AucaSur1_Oct29_OFMandTD_linesswitched.xls
 - Flare gas samples taken
 - Line 1 – Cylinder Number 11 (for Maxxam Analytics in Edmonton, AB)
 - Line 3 – Cylinder Number 2 (for Maxxam Analytics in Edmonton, AB)

APPENDIX C: FLARE GAS FLOW RATE RESULTS IN ECUADOR

**Field Measurements of Black Carbon Emissions from Flaring in
Coca, Ecuador, October 26-29, 2015**

INTERIM PROJECT REPORT II: SUMMARY OF FLOW RATE AND COMPOSITION RESULTS

Report submitted to World Bank Global Gas Flaring Reduction (GGFR)
Partnership, United Nations Environment Programme (UNEP) Climate & Clean
Air Coalition (CCAC), and Petroamazonas

November 30, 2015



Carleton
UNIVERSITY

Canada's Capital University

Matthew Johnson, Ph.D., P.Eng.

Melina Jefferson, M.A.Sc. Candidate

Darcy Corbin, M.A.Sc.

Energy & Emissions Research Laboratory

Mechanical & Aerospace Engineering,

Carleton University

Ottawa, ON, Canada

© 2015

C.1 Project Background

This report is the second in a series of reports summarizing the recent field measurement campaign near Coca, Ecuador taking place from October 26–29, 2015. The previous report, Interim Project Report I (Johnson et al., 2015), summarized the goals of the project and the technologies and methods used to measure black carbon (BC) emission rates, flare gas flow rates, and composition of the flare gases at the various sites visited. It also included a summary of the raw data collected at each site, including dates, times, and the nature of the data collected. The current report presents preliminary results of flare gas flow rate measurements and composition analysis. Specific objectives of this report are to:

- provide the results of flow rate measurement tasks on flare lines that were subject to related sky-LOSA measurement of BC emission rate;
- present preliminary results of gas composition analysis performed by SGS on a limited number of samples from the lines subject to flow rate measurement; and
- update the status of the primary gas samples, which are awaiting shipment from Ecuador to Maxxam Analytics for composition analysis that will provide detailed data for all lines subject to flow rate measurement.

The collection of flow rate measurements and extractive gas samples concurrent with sky-LOSA BC emission measurements was a key goal of this project. The successful collection of corresponding measurements of BC emission rate, flow rate, and gas composition represents the most substantive effort to date to quantify flare generated BC yields.

C.2 Flare Gas Flow Rate Results

Flare gas flow rates were separately measured in each of the lines feeding each of the five flares subject to sky-LOSA measurements. As fully detailed in the first interim project report (Johnson et al., 2015), four different measurement techniques were available to determine flare gas flow rates, depending on which approach was best suited to each specific flare line. The techniques included a tracer-dilution technique (TD), an optical flow meter (OFM), a thermal mass flow meter (TMF), and a vane wheel anemometer (VWA).

Figure C.1 plots summary volumetric flow rate results for each of the five measured flares. Volumes are reported at a standard temperature and pressure of 15°C (288.15 K) and 101.325 kPa, and are shown in standard cubic metres per day on the left axis and standard cubic metres per year on the right axis. The total flare gas volume flow for all five flares was 81,512 m³/day (equivalent to 29.77 million m³/year). The single large flare at Auca 27 represents over 73% of this volume. As a means of comparison, the annual gas volume for this one flare is larger than that of any of the more than 2600 flares reporting data at upstream production sites in Alberta, Canada (Johnson and Tyner, 2015). As noted above, flare gas samples for detailed compositional analysis are awaiting shipment from Quito back to Canada; these data will be very valuable in assessing potential opportunities for flare mitigation driven both by the potential value of the gas and its constituents and through offsetting of black carbon emissions.

Line specific flow rate measurements for each line feeding flares at each site are discussed in subsequent sections of this report. In addition, Section C.6 presents the detailed measurement data for each line comprising either the raw velocities as measured by the OFM or the raw concentrations and tracer flow rate pertaining to deployment of the tracer dilution technique. Section C.6 also contains details of the data processing used to discern time frames over which the raw data should be parsed to produce the summary results presented in Figure C.1, and for each line as presented below.

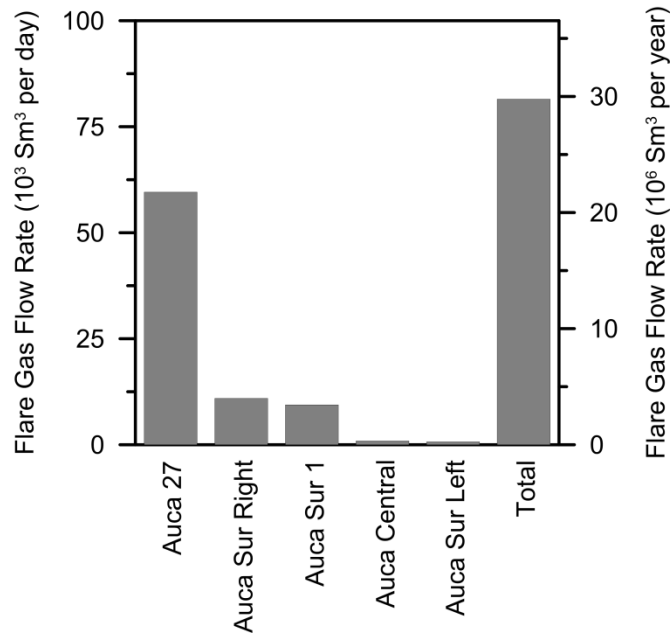


Figure C.1: Measured flared volumes for each flare and total flared volume for all five flares. Flared volumes at Auca 27, Auca Sur Right, and Auca Sur 1 are a summation of the volumetric flow rates of lines measured individually. Where multiple techniques were used on a given line, TD results were used preferentially over OFM measurements.

C.3 Flow Rate Results by Flare and Line

Brief descriptions of the flares at each site are presented below, including relevant details of the flare lines (diameters, number of hot taps) feeding each flare. Results are presented in summary only. Raw data, processing details, and time-resolved flow rate results are presented in greater detail in Section C.6.

C.3.1 Auca 27

Figure C.2 shows the flare at Auca 27, which was measured on October 27, 2015. This was the largest of the five flares measured in the Auca field. There were four separate lines feeding the flare at Auca 27 (visible in Figure C.2) and flow rate measurements were obtained on all four lines. Lines 1 and 3 (counting left to right in Figure C.2) were 4" lines (4.5" OD), whereas Lines 2 and 4 were 6" lines (6.625" OD). The two 4" lines each had only one hot tap available, and flow rate measurements were completed using the OFM. The two 6" lines each had a pair of hot taps, with one hot tap in the immediate vicinity of the flare and a second hot tap far upstream (> 150 metres) at the other side of the production site. For each of the 6" lines, flow rate

measurements were performed using both the OFM as well as with the tracer dilution technique. The measured flow rates in each of the four lines are plotted in Figure C.3. Available measurement results using both the OFM and tracer-dilution technique are shown, as well as the combined totals for all lines. The agreement between the optical flowmeter and tracer dilution techniques is very good, especially considering that the measurements were performed at different times and the raw data shown in Section C.6 reveal that flow rates in each line were continually varying.



Figure C.2: The flare at Auca 27 had the largest flare gas flow rates of the measurement campaign. Pictured are the four lines feeding the flare, all of which were the subject of one or more flow rate measurements as well as extractive gas sampling.

In Figure C.3, the combined total flow rate for the flare is shown as the sum of individual OFM readings (red column) for each line, as well as the sum of OFM data for Lines 1 and 3 and available TD data for Lines 2 and 4 (red and blue stacked column). As could be expected, these two different combined total flow rate results are nearly identical at $59.6 \times 10^3 \text{ Sm}^3/\text{day}$. Line 4 had the highest flow rate at $22.99 \times 10^3 \text{ Sm}^3/\text{day}$ as measured by the OFM, whereas Line 3 has the lowest flow rate at $10.00 \times 10^3 \text{ Sm}^3/\text{day}$. The measured volume flow rate results for each line are summarized as follows:

- Line 1 (leftmost) had an average centreline velocity of 11.61 m/s as measured with the OFM, which equated to a bulk-average velocity of 9.48 m/s when calculated using a 1/7 power law relation for a turbulent velocity profile. The measured line temperature and pressure were 34.9°C and 186.30 kPa respectively. Utilizing the assumed velocity profile to equate centreline and bulk velocities, and correcting to standard temperature and pressure (15°C, 101.325 kPa), the calculated flow rate in Line 1 at was 11.41×10^3 Sm³/day.
- The flare gas flow rate in Line 2 (second from left) was measured using both the OFM and the tracer dilution technique. During the five-minute analysis period starting at 08:47:33 local time, the OFM measured an average centreline velocity of 12.30 m/s and a bulk-average velocity of 10.04 m/s (based on an assumed 1/7 power law turbulent velocity profile). The line temperature and pressure were 37.3°C and 103.42 kPa. Based on these data, the calculated flow rate was 15.15×10^3 Sm³/day. The tracer dilution technique was subsequently deployed; acetylene was injected at a flow rate of 2.12 SLPM into the upstream tap, producing an average measured concentration at the downstream tap 152.84 ppmv. Prior to injection, the acetylene concentration in the line was measured at an average of 0.86 ppmv. During the ten-minute analysis period starting at 13:09:08 local time, the calculated flow rate using these tracer dilution measurements was 19.89×10^3 Sm³/day.
- The average centreline velocity of Line 3 was 19.03 m/s as measured with the OFM, equating to a bulk-average velocity of 15.54 m/s (again using a 1/7 power law relation for a turbulent velocity profile). The measured line temperature and pressure were 38.1°C and 100.66 kPa, and the final calculated volumetric flow rate was 10.00×10^3 Sm³/day.
- Both the OFM and tracer dilution measurements were performed in Line 4 (rightmost line). OFM readings were analyzed for an eight-minute period starting at 09:19:04 local time. The average OFM-measured centreline velocity during this period was 18.57 m/s corresponding to a bulk-average of 15.17 m/s assuming a 1/7 power law relation for a turbulent velocity profile. Corrected to standard conditions from the measured temperature and pressure of 34.8°C and 103.07 kPa, the measured flare gas flow rate was 22.99×10^3 Sm³/day. Tracer dilution results were computed over a ten-minute period

starting at 12:43:39 local time. Acetylene was injected at 2.12 SLPM, producing a measured downstream concentration of 166.83 ppmv which compared to an initial background concentration of 1.35 ppmv. These data corresponded to a measured flow rate of $18.27 \times 10^3 \text{ Sm}^3/\text{day}$.

Further details of the measurements at Auca 27 are provided in Section C.6.

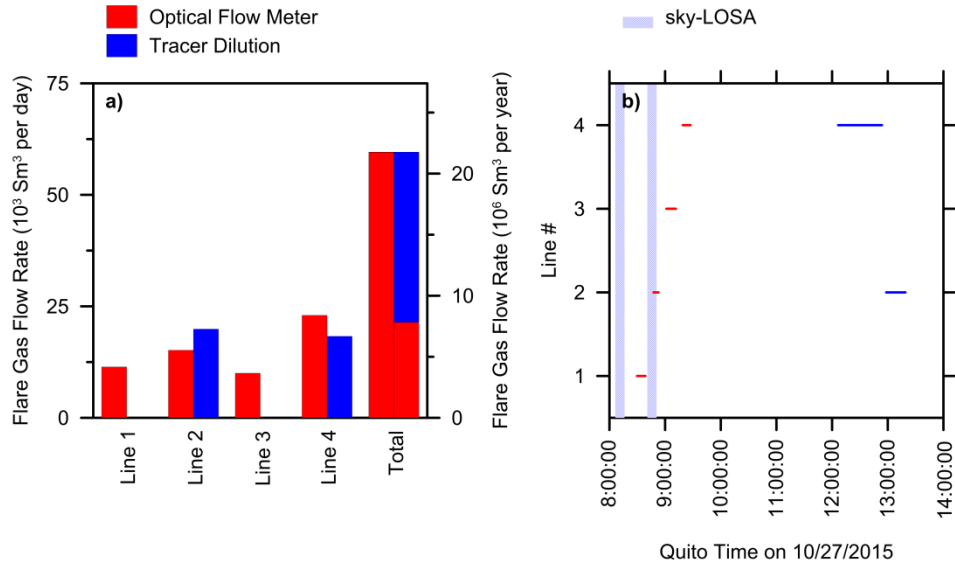


Figure C.3: Flow rate measurement results at Auca 27. a) Measured flowrates for individual lines are shown by instrument where applicable as well as combined totals for the flare. The combined total for the tracer dilution technique includes OFM measurements in Lines 1 and 3 combined with TD measurements from Lines 2 and 4. b) Timing diagram showing when flowrate measurements were performed in each flare line with overlaid shading to indicate the timing of sky-LOSA measurements of BC emission rate. Note that the OFM and TD measurements in each of Lines 2 and 4 were not simultaneous and apparent discrepancies in the measured flow rate may simply be an artifact of flow rate variations throughout the day.

C.3.2 Auca Sur (Right Flare & Left Flare)

There were two active flares at Auca Sur, a larger flare to the right as shown in Figure C.4 (identified as Auca Sur Right), and a smaller flare to the left (identified as Auca Sur Left). The Auca Sur site was visited on October 28, 2015 and flow rate measurements, gas sample collection, and sky-LOSA measurements of BC were performed on both flares. As shown in Figure C.4, Auca Sur Right was fed by three lines. However, the leftmost of these lines (Line 1) was inactive as reported by Petroamazonas staff on site. This line had no hot taps which precluded confirmation by measurement. Line 2 (centre) was an 8" line (8.625" OD) with a

single hot tap, which was used for flow rate measurement with the OFM. Line 3 (rightmost) was a 12” line (12.75” OD) with two hot taps, which were used for simultaneous flow rate measurement via the tracer dilution technique. Auca Sur Left was fed by a single 8” line (8.625” OD) that had a single hot tap. Flow rate measurements in that line were completed using the OFM.



Figure C.4: Flares at Auca Sur. Both flares visible were measured as Auca Sur Right (pictured right) and Left (pictured left). The rightmost two lines had hot taps installed and fed the rightmost flare. Site staff informed Carleton personnel that the adjacent line was inactive, there were also no hot taps which precluded confirmation by measurement. The leftmost flare was fed by a single line which enters the lefthand side of the image.

Figure C.5 plots the measured flow rates for the lines feeding the two active flares at Auca Sur along with the combined total for the site ($11.63 \times 10^3 \text{ Sm}^3/\text{day}$). Details of the measurements at Auca Sur including the raw data obtained during flow rate measurements can be found in the relevant sub-section of Section C.6. The measured volume flow rate results for each line are summarized as follows:

- Auca Sur Right – Line 2 (centre) had an average centreline velocity of 5.33 m/s as measured with the OFM which equates to a bulk-average velocity of 4.35 m/s when calculated using a 1/7 power law relation for a turbulent profile. The line temperature

and pressure were recorded as 44.4°C and 98.52 kPa. The calculated flow rate in Line 2 at standard temperature and pressure was $10.60 \times 10^3 \text{ Sm}^3/\text{day}$.

- Auca Sur Right – Line 3 (rightmost) was measured using the tracer dilution technique, and data were collected simultaneously with the OFM measurements in Line 2. The flow rate in Line 3 was measured by injecting 0.105 SLPM of acetylene into the line producing a downstream measured mole fraction of 472.94 ppmv, starting from an initial background measured mole fraction of 4.37 ppmv. These data equated to flow rate of $0.33 \times 10^3 \text{ Sm}^3/\text{day}$.
- Auca Sur Left – The average centreline velocity in the single line feeding the left flare was measured at 0.35 m/s which equates to a bulk-average velocity of 0.29 m/s when calculated using a 1/7 power law relation for a turbulent profile. The measured line temperature and pressure were 45.7°C and 97.84 kPa. Converted to standard temperature and pressure, the volumetric flow rate feeding the flare was $0.70 \times 10^3 \text{ Sm}^3/\text{day}$.

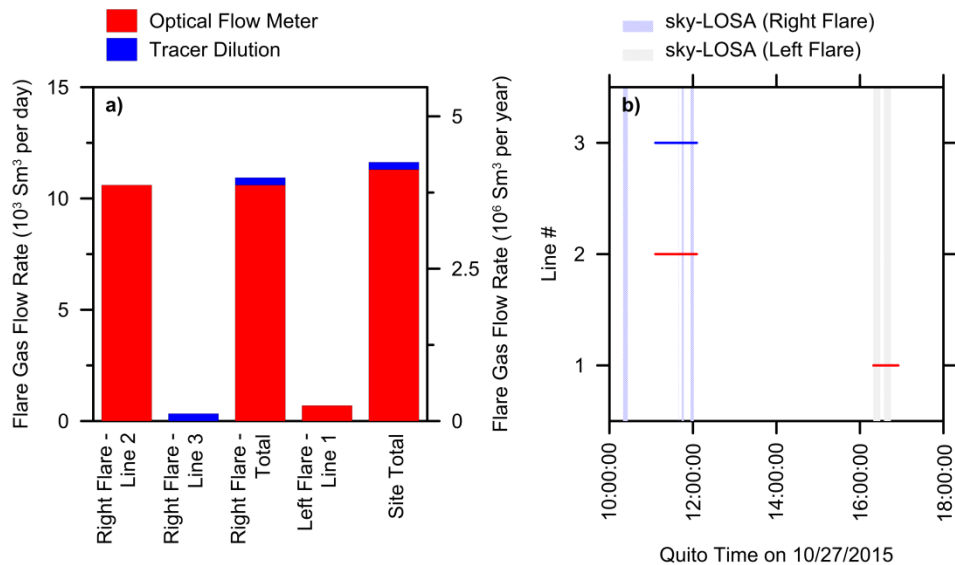


Figure C.5: Flow rate measurement results on Auca Sur Right. a) Flow rate results are shown for each line by the instrument used for measurement. The combined total is the sum of the flow rates in Lines 2 and 3 as measured by the OFM and tracer dilution technique respectively. b) Timing diagram showing when flowrate measurements were performed in each flare line with overlaid shading to indicate the timing of sky-LOSA measurements of BC emission rate.

C.3.3 Auca Sur 1

There was a single active flare at Auca Sur 1 which was visited on both October 27 and October 29, 2015. The flare was subject to sky-LOSA measurement on both dates, however complete flow rate measurements were only made on October 29, 2015. There were three lines leading to the flare as shown in Figure C.6, and each had two hot taps. Line 2 (centre) terminated at a blind flange just downstream of the second hot tap. Lines 1 (left) and 3 (right) were 6" lines (6.625" OD) and the flow rate in each line was measured using both the OFM and the tracer dilution technique.



Figure C.6: Flare at Auca Sur 1. Pictured are three hot taps on three adjacent lines, each line had an additional hot tap upstream (not shown). The centre line of the three terminated at a blind flange just after the hot tap pictured. The other two lines were the subject of flow rate measurements.

The measured flow rate of Lines 1 and 3 are displayed in Figure C.7 along with the combined totals. Measured flowrates in Line 3 were very similar using either of the measurement approaches. For Line 1, flow rates determined using the tracer-dilution technique were approximately 30% less than the flow rate derived using the OFM. However, given the agreement of the results for Line 1 and since the OFM and TD data are non-simultaneous, it is expected that this discrepancy is more an indication of flow rate variability in the line rather than inaccuracies in either approach. Using the TD technique, the combined total flow rate for both

lines was $9.41 \times 10^3 \text{ Sm}^3/\text{day}$. Details of the measurements at Auca Sur 1 including the raw data obtained during flow rate measurements can be found in the relevant sub-section of Section C.6. The measured volume flow rate results for each line are summarized as follows:

- Line 1 had an average centreline velocity of 9.32 m/s as measured by the OFM, corresponding to a bulk-average velocity of 7.61 m/s assuming a standard 1/7 power law turbulent velocity profile. The measured temperature and pressure in the line were 33.8°C and 98.56 kPa. This corresponded to a measured volumetric flow rate of $11.06 \times 10^3 \text{ Sm}^3/\text{day}$ at standard conditions. For the tracer-dilution technique, the background acetylene fraction in the line was measured at 63.24 ppmv, and the acetylene tracer gas was injected first at 0.211 SLPM and later at 0.527 SLPM. The resulting average concentrations of 111.16 ppmv and 146.05 ppmv during the periods of injection corresponded to an average measured flow rate of $8.22 \times 10^3 \text{ Sm}^3/\text{day}$.
- Line 2 had an average centreline velocity of 1.04 m/s as measured by the OFM, corresponding to a bulk-average velocity of 0.85 m/s. Measured temperature and pressure were 46.5°C and 102.73 kPa. This corresponded to a measured flow rate of $1.24 \times 10^3 \text{ Sm}^3/\text{day}$. For the tracer-dilution technique, the background acetylene fraction in Line 2 was measured at 60.02 ppmv. The acetylene tracer gas was injected at 0.211 SLPM resulting in an average downstream mole fraction of 313.79 ppmv. From these data, the average measured flow rate in Line 2 was determined to be $1.19 \times 10^3 \text{ Sm}^3/\text{day}$.

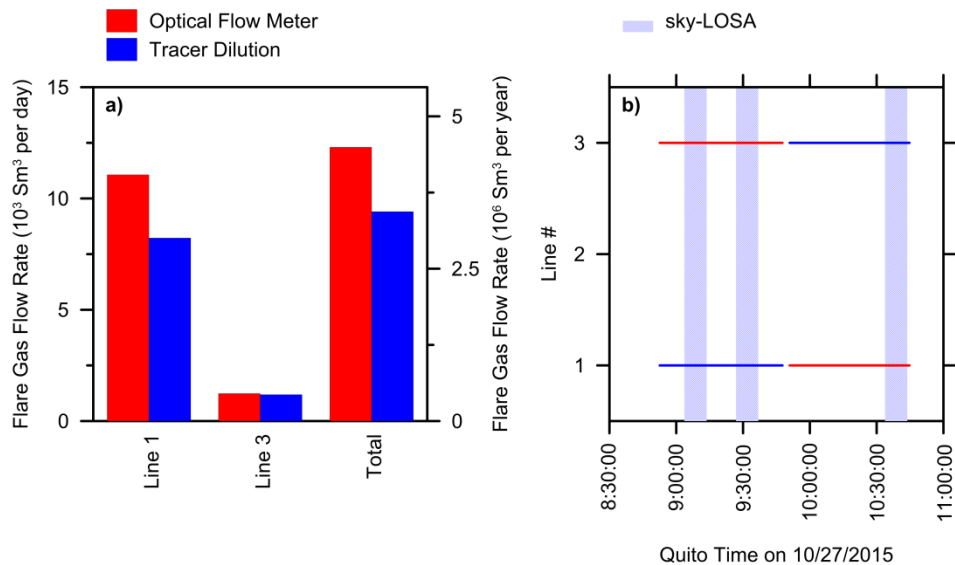


Figure C.7: Flow rate measurement results at Auca Sur 1. a) The flow rate in each line was measured by both the OFM and tracer dilution technique and the totals are summed from the flow rates in each line as measured by that technique. b) Timing diagram showing when flowrate measurements were performed in each flare line, with overlaid shading to indicate the timing of sky-LOSA measurements of BC emission rate. Note that the difference in flow rates measured with the OFM and TD methods in Line 1 may simply be a result of measurement over different time periods.

C.3.4 Auca Central

Auca Central was the site of two active flares as shown in Figure C.8 and was visited on October 26, 2015. Only the rightmost flare pictured was subject to sky-LOSA BC and flow rate measurements. This flare was fed by a single 10" line (10.75" OD) that had two hot taps installed. Flow measurements were made using the tracer dilution technique, during which acetylene was injected at 0.105 SLPM into the upstream tap, and the average acetylene mole fraction at the downstream tap was measured to be 169.69 ppm_v. Prior to injection the background mole fraction of acetylene was measured to be 0.76 ppm_v. The calculated flow rate of gas to the flare during the measurement period is $0.89 \times 10^3 \text{ Sm}^3/\text{day}$. Figure C.9 indicates the timing of flowrate measurements and parallel sky-LOSA BC emission rate measurements at Auca Central. Details of the measurements at Auca Central including the raw data obtained during flow rate measurements are provided in Section C.6.



Figure C.8: Flares at Auca Central. Hot taps were available only for the line feeding the right flare in the image and only this flare was the subject of sky-LOSA BC and flow rate measurements.

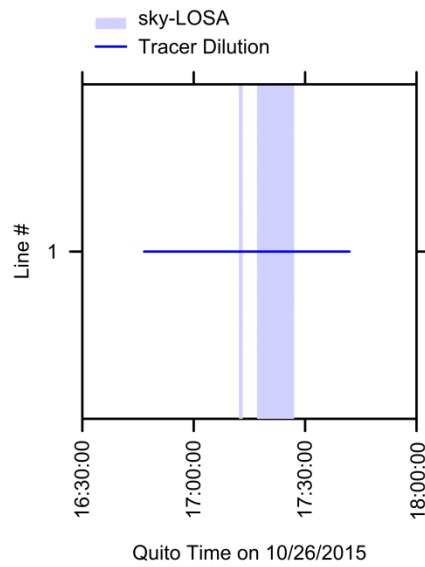


Figure C.9: Timing diagram comparing timing of TD flowrate measurements (blue line on figure) with timing of parallel sky-LOSA measurements of BC emission rate (indicated with overlaid shading).

C.4 Preliminary Flare Gas Composition Results

Flare gas for composition analysis is essential for converting flare gas volumetric flow rates to mass flow rates, and more importantly for deriving fuel-specific mass yields of black carbon from the raw black carbon emission rate measured by sky-LOSA. Detailed flare gas composition data are also critical for providing insight into mitigation potential, both in terms of potential economic value of the flare stream in different scenarios, as well as for determining potential for emission reduction credits. As noted in our previous report (Johnson et al., 2015), two sets of gas samples were acquired during field measurements. The primary samples were collected using a set of twenty-four 300 mL stainless steel sample cylinders brought to the field by Carleton University personnel. A total of ten samples, one from each of the ten measured flare lines, were collected and are intended for analysis by Maxxam Analytics. These cylinders are in the process of being transported to Maxxam Analytics in Edmonton, AB for detailed analysis capable of isolating volume fractions of alkanes, alkenes, cycloalkanes, and aromatics up to C15, residual hydrocarbons from C4 to C15⁺; and fixed gases.

In light of past experience from the 2014 Ecuador campaign in which the international transport of samples proved difficult and led to the loss of viable gas composition data, as a backup, a second partial set of samples were obtained for local analysis using an Ecuadoran company, SGS. Unfortunately SGS was only able to provide 6 sample collection cylinders for use in the field so that backup samples could not be collected from all lines. Table C.1 identifies the primary and backup samples collected. As of this writing, the primary samples are still awaiting shipment by Petroamazonas from Quito. However, all of the SGS samples have now been analyzed as reported in Table C.2.

Table C.1: Gas cylinders submitted to Maxxam Analytics and SGS for compositional analysis.

Site Name	Line Number (Flare)	Carleton University Cylinder Number	SGS Sample Number
Auca Central	Line 1 (Right)	8	1
Auca 27	Line 1	5	2
	Line 2	4	3
	Line 3	7	4
	Line 4	16	5
Auca Sur	Line 2 (Right)	13	--
	Line 3 (Right)	10	--
	Line 1 (Left)	9	--
Auca Sur 1	Line 1	11	6
	Line 3	2	--

Table C.2: Flare gas composition data from backup samples analyzed by SGS

Property	Auca Central [1000 mL]	Auca 27 – Line 1 [1000 mL]	Auca 27 – Line 2 [1000 mL]	Auca 27 – Line 3 [250 mL]	Auca 27 – Line 4 [250 mL]	Auca Sur 1 – Line 1 [1000 mL]
Nitrogen, N ₂ [% mole]	7.09	4.20	2.53	1.42	1.99	4.43
Methane, CH ₄ [% mole]	48.18	61.53	40.98	34.46	45.81	54.18
Carbon Dioxide, CO ₂ [% mole]	14.81	7.00	5.93	5.75	6.98	9.73
Ethane, C ₂ H ₆ [% mole]	7.70	7.25	8.56	8.53	9.85	7.00
Propane, C ₃ H ₈ [% mole]	11.13	9.85	17.74	19.05	18.80	10.70
i-butane, C ₄ H ₁₀ [% mole]	2.39	2.22	5.13	5.42	4.40	2.87
n-Butane, C ₄ H ₁₀ [% mole]	4.18	3.89	9.22	10.00	7.40	4.51
i-pentane, C ₅ H ₁₂ [% mole]	1.74	1.34	3.49	3.40	1.87	2.17
n-Pentane, C ₅ H ₁₂ [% mole]	1.41	1.04	2.58	2.51	1.32	1.46
Hexanes, C ₆ [% mole]	1.37	1.68	3.84	9.46	1.58	2.95
Ideal Relative Density [kg/m ³]	1.3807	1.2289	1.6414	1.8514	1.4761	1.3711
Ideal Gross Calorific Value [MJ/m ³]	51.96	54.46	76.10	86.93	67.62	58.29
Ideal Net Calorific Value [MJ/m ³]	47.40	49.58	69.72	79.78	61.82	53.20
Apparent Molecular Weight [g/mol]	30.73	27.37	36.32	40.80	32.75	30.47

C.5 References

- Johnson, M.R., Jefferson, A.M., Corbin, D.J., and Conrad, B.M. (2015). Field Measurements of Black Carbon Emissions from Flaring in Coca, Ecuador - INTERIM PROJECT REPORT I: SUMMARY OF DATA COLLECTED DURING FIELD MEASUREMENTS. Ottawa, ON, Carleton University Energy & Emissions Research Lab.
- Johnson, M.R. and Tyner, D.R. (2015). Techno-economic Analysis of Flaring and Venting Mitigation Potential in Western Canada. Ottawa, ON, Carleton University Energy & Emissions Research Lab.

C.6 Details of Measured Flow Rate Data and Results

C.6.1 Tracer-Dilution (TD) Technique Data

The tracer dilution technique utilizes two distinct measurements to produce a calculated flow rate: the flow rate of the injected tracer gas and the measured concentrations of the tracer in the gas stream (both before and during the injection of the tracer). Once the tracer injection is started, there is a time-delay for the injection flow rate to reach a steady state as well as a required transit time for the tracer to mix and reach the downstream sample port. Once a steady injection flow rate was verified, the required delay time for analysis of the downstream readings was determined by monitoring the trend of the measured tracer concentration in the line. For Auca 27 Lines 2 and 4, Auca Sur 1 Line 3, and Auca Central where sharp increases or decreases in measured concentration was readily apparent preceding a relatively stable concentration reading, the start of data analysis interval was defined as time at which the measured concentration reached within 5% of the average over the measurement interval. For Auca Sur Right Line 3 and Auca Sur 1 Line 1, where the flow rates in the line were more variable, the valid interval was defined as beginning 5 minutes after the start of stable tracer injection.

C.6.2 Optical Flow Meter (OFM) Data

The raw OFM data requires post-processing to give an accurate velocity measurement. If particles are not present in the flow at a given instant, the OFM will return a zero value for velocity and it is reasonable that these data be discarded. Additionally, debris (solid or liquid) in the measurement orifice may cause unrealistic or unreasonable measurements of the bulk gas velocity. Figure C.10 shows the data obtained using the OFM on a line-by-line basis. These plots illustrate the level of thresholding required to exclude non-physical low-value or zero velocity readings during the measurements. The x-axis spans the range of velocities measured for a given line a specified flare. The y-axis indicates the corresponding average measured velocity in a given line, as a function of the x-axis threshold velocity value used to exclude non-physical low value OFM readings. Each of these plots shows a similar trend in that there is a flat region on the left (beginning near 0.1 m/s) where the calculated average velocity is insensitive to the choice of threshold value used to exclude non-physical low values during post-processing. The onset of the flat region in Figure C.10 corresponds with the lower limit of the

manufacturer's specified measurement range for the OFM of 0.1 – 150 m/s; based on this a lower limit threshold value of 0.1 m/s was applied to all raw data, where any readings below this limit were ignored.

As shown in Figure C.10b, the OFM data for Auca Sur Line 1 were a possible exception to the trend discussed previously, showing much greater sensitivity to the chosen threshold value in the vicinity of the 0.1 m/s cutoff as compared to all other lines. This is indicative of the high number of readings just above the threshold value as illustrated in Figure C.22. The plotted cumulative average of the velocities above the 0.1 m/s threshold bisects what appear to be two distinct clusters of data (one near the threshold and one around 2 m/s). This suggests the flow rate in the line was pulsating, which would tend to increase the uncertainty of the measurement. Nevertheless, the average flow rate calculated from OFM measurements agrees very well with a subsequent measurement of the same line obtained using the TD technique. Moreover, the flow rate measured in Line 3 by either technique represents only 10-12% of the total flow rate at Auca Sur 1. As such, any increased uncertainty in the OFM measurements of Auca Sur Line 1 has negligible impact on the accuracy of the measured total flow rate delivered to the flare.

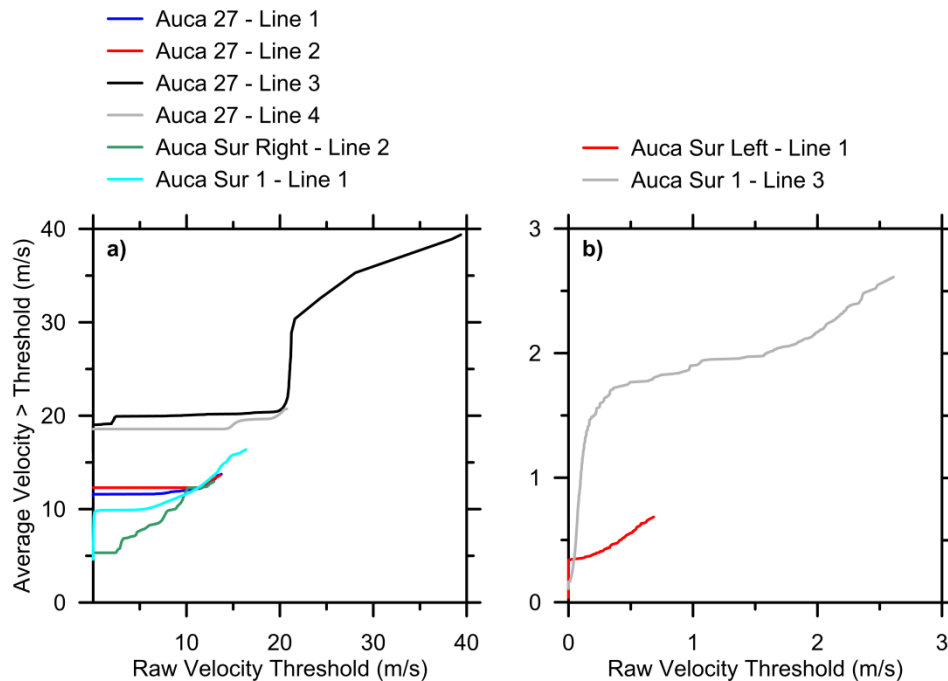


Figure C.10: OFM thresholding showing a) data for Auca 27 which was generally higher velocities, and b) data for other flare lines where velocities were generally lower.

C.6.3 Auca 27 – October 27, 2015

Line 1

- Line pressure: 186.3 kPa
- Line temperature: 34.9 °C
- Optical measurements
 - Test start at 08:29:43 to 08:38:45 local
 - Not simultaneous with sky-LOSA measurements
 - Threshold of > 0.1 m/s selected, nine zero-value data points removed

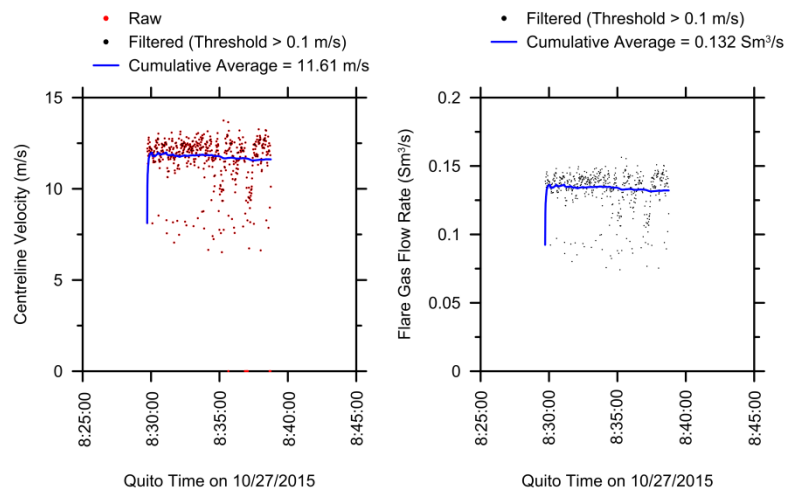


Figure C.11: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca 27 Line 1.

- Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Average reading over several minutes was 2207.16 FPM from six hand-recorded readings
 - Probe length: 17-1/2"; hot tap: 12-1/4"; outer diameter of pipe: 4-1/2"; therefore for probe to be in centre of pipe, insertion depth 1-7/8" nut to nut

Line 2

- Line pressure: 103.42 kPa

- Line temperature: 37.3 °C
- Optical measurements
 - Test start at 08:47:33 to 08:52:55 local
 - Simultaneous sky-LOSA measurements at 08:47:33 to 08:50:51 local (Image Set 2)
 - Threshold of > 0.1 m/s selected, no data points removed

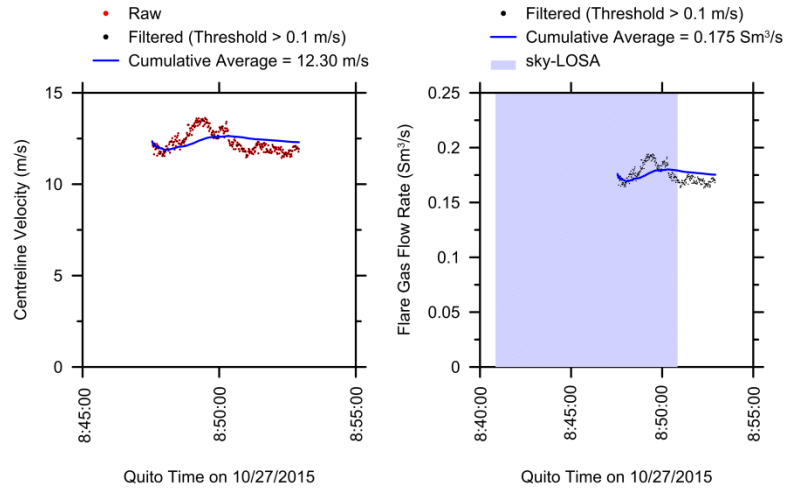


Figure C.12: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca 27 Line 2.

- Tracer dilution measurements
 - Test start time: 13:09:08 to 13:19:02 local
 - Not simultaneous with sky-LOSA measurements

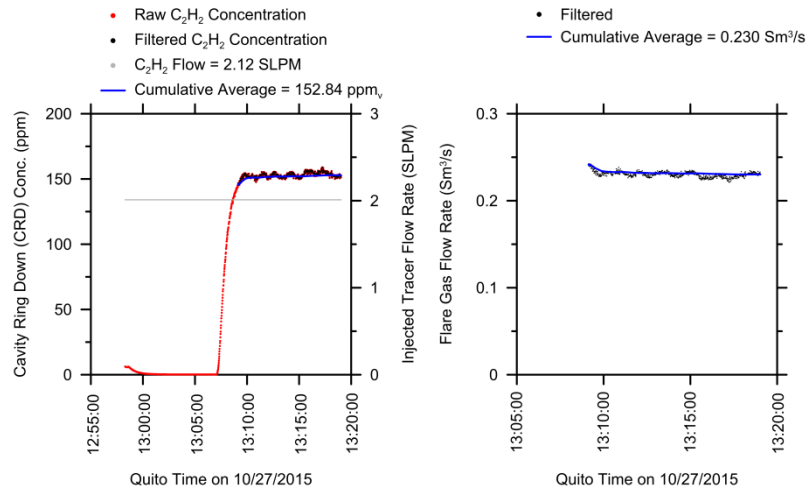


Figure C.13: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca 27 Line 2.

- Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Average reading over several minutes was 3393.8 FPM from five hand-recorded readings
 - Probe length: 17-1/2"; hot tap height: 12-1/4"; outer diameter of pipe: 6-5/8"; therefore for probe to be in centre of pipe, insertion depth 3" nut to nut

Line 3

- Line pressure 100.66 kPa
- Line temperature: 38.1 °C
- Optical measurements
 - Test start at 09:01:23 local to 09:11:38
 - Not simultaneous with sky-LOSA measurements
 - Threshold of > 0.1 m/s selected, ninety zero-value and two non-zero data points removed

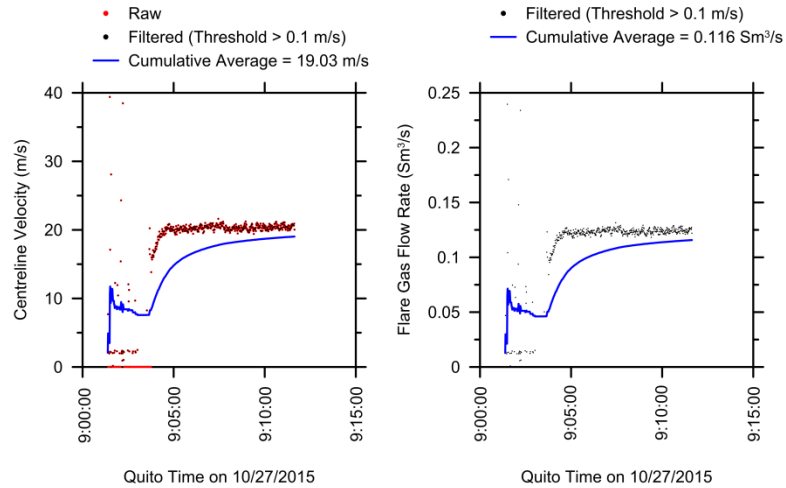


Figure C.14: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca 27 Line 3.

- Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements
 - Insertion depth calculations identical to Line 1
 - Pinned at 5000 SFPM – possible solids in line

Line 4

- Line pressure: 103.07 kPa
- Line temperature: 34.8 °C
- Optical measurements
 - Test start at 09:19:04 to 09:27:24 local
 - Not simultaneous with sky-LOSA measurements
 - Threshold of > 0.1 m/s selected, no data points removed

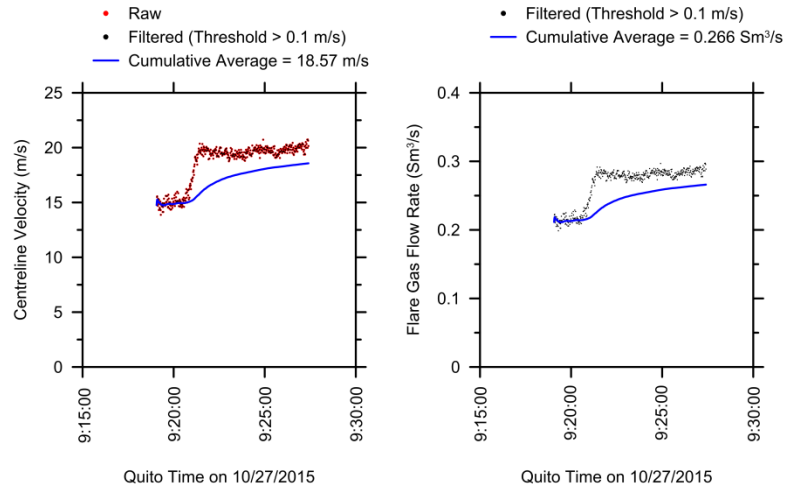


Figure C.15: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca 27 Line 4.

- Tracer dilution measurements
 - Test start at 12:43:39 to 12:53:43 local
 - Not simultaneous with sky-LOSA measurements

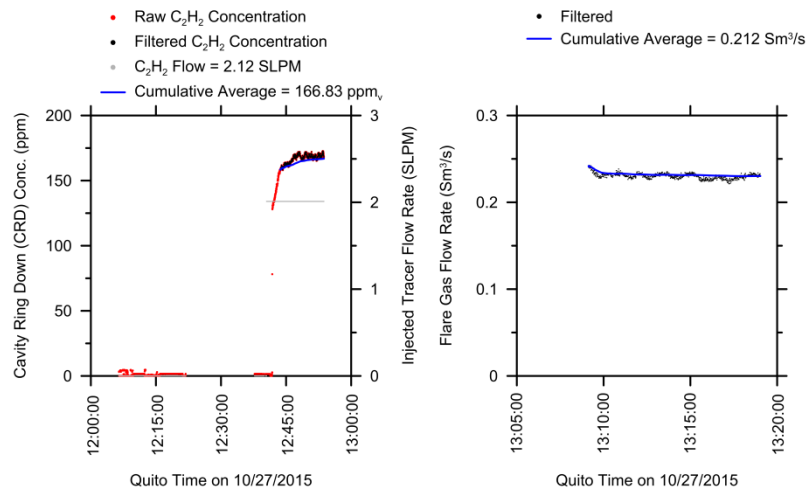


Figure C.16: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca 27 Line 4.

- Thermal measurements
 - Test start between 10:00:00 to 11:00:00 local
 - Not simultaneous with sky-LOSA measurements

- Insertion depth calculations identical to Line 2
- Pinned at 5000 SFPM – possible solids in line

C.6.4 Auca Sur – October 28, 2015

Line 2 (Right Flare)

- Line pressure: 98.52 kPa
- Line temperature: 44.4 °C
- Optical measurements
 - Test start at 11:05:55 to 12:05:37 local
 - Simultaneous with sky-LOSA measurements at 11:39:37 to 11:39:57, 11:43:50 to 11:46:47, and 11:56:30 to 12:01:12 local (Image Sets 2, 3, and 4)
 - Threshold of > 0.1 m/s selected, twenty-nine zero-value and one non-zero data points removed

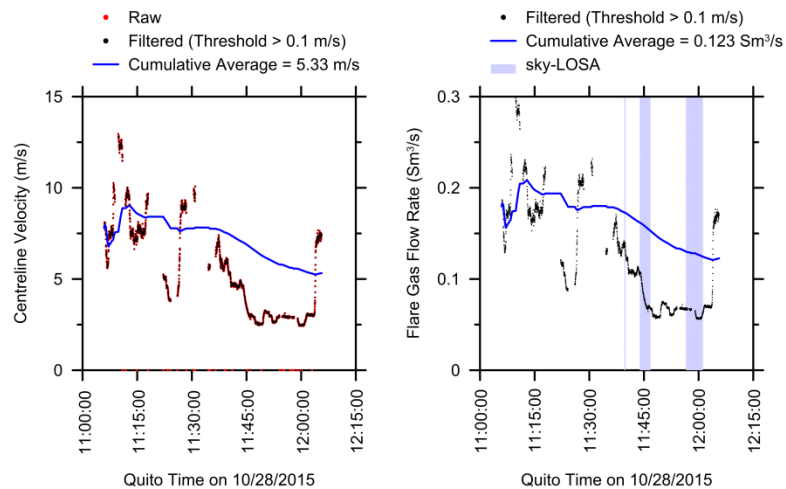


Figure C.17: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca Sur Right Line 2.

Line 3 (Right Flare)

- Line pressure: 98.11 kPa
- Line temperature: 48.0 °C
- Tracer dilution measurements
 - Test start at 11:34:34 to 12:05:02 local

- Simultaneous with sky-LOSA measurements at 11:39:37 to 11:39:57, 11:43:50 to 11:46:47, and 11:56:30 to 12:01:12 local (Image Sets 2, 3, and 4)

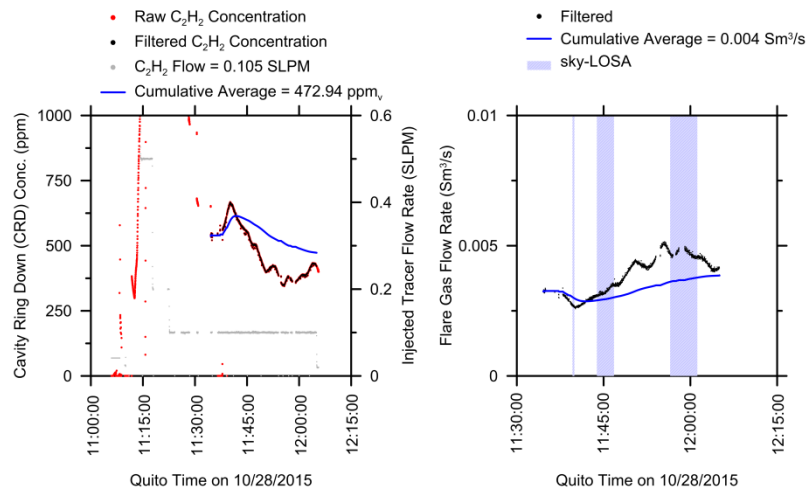


Figure C.18: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca Sur Right Line 3.

Line 1 (Left Flare)

- Line pressure: 97.84 kPa
- Line temperature: 45.7 °C
- Optical measurements
 - Test start at 16:19:23 local to 16:55:16
 - Simultaneous with sky-LOSA measurements at 16:19:23 to 16:29:12 and 6:34:34 to 16:44:34 local (Image Sets 5 and 6)
 - Threshold of > 0.1 m/s selected, 1922 zero-value and ten non-zero data points removed

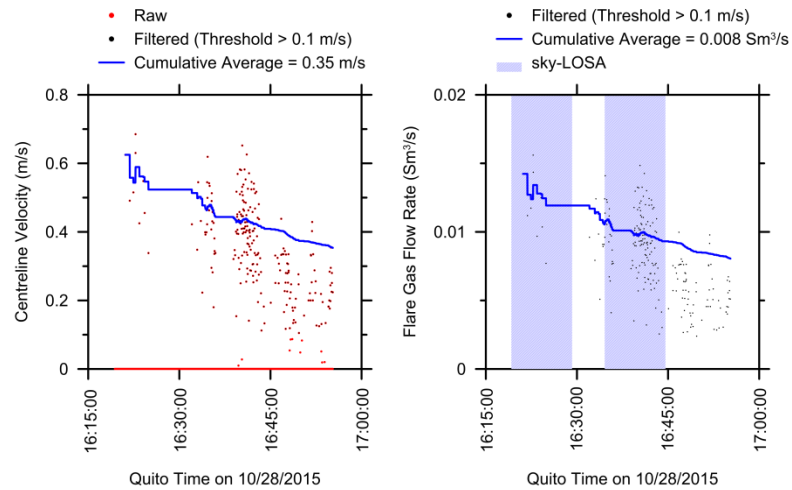


Figure C.19: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca Sur Left Line 1.

C.6.5 Auca Sur 1 – October 29, 2015

Line 1

- Line pressure: 98.56 kPa
- Line temperature: 33.8 °C
- Optical measurements
 - Test start at 09:53:47 to 10:44:18 local
 - Simultaneous with sky-LOSA measurements at 10:33:47 to 10:43:47 local (Image Set 4)
 - Threshold of > 0.1 m/s selected, 610 zero-value and 609 non-zero data points removed

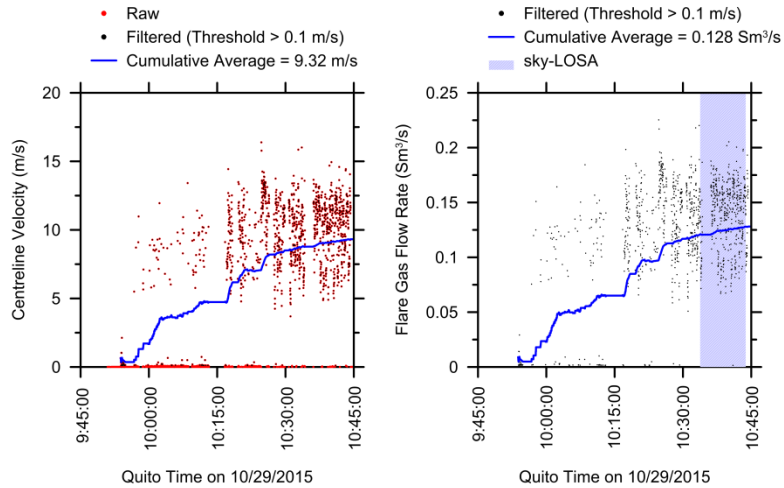


Figure C.20: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca Sur 1 Line 1.

- Tracer dilution measurements
 - Test start at 09:04:55 to 09:36:59 local
 - Simultaneous with sky-LOSA measurements at 09:04:55 to 09:13:39 and 09:26:51 to 09:36:51 local (Image Sets 2 and 3)

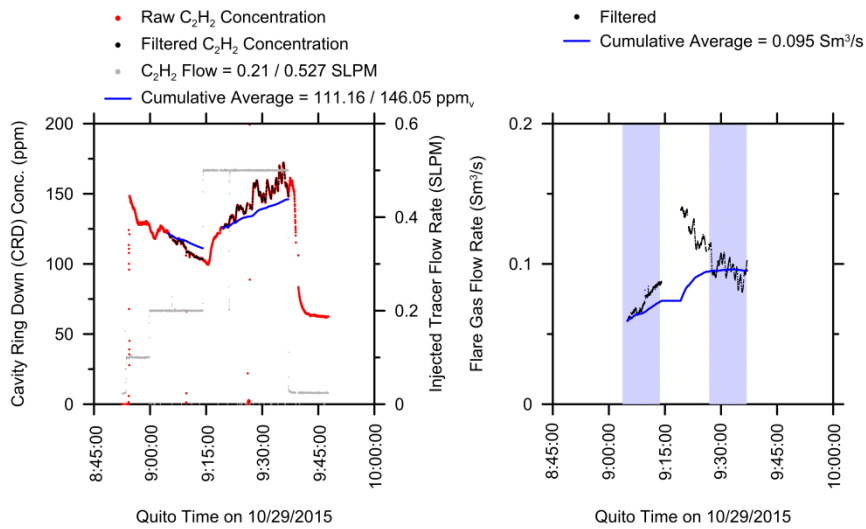


Figure C.21: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca Sur 1 Line 1.

Line 3

- Line pressure: 102.73 kPa
- Line temperature: 46.5 °C
- Optical measurements
 - Test start at 08:52:34 to 09:43:20 local
 - Simultaneous with sky-LOSA measurements at 09:03:39 to 09:13:39 and 09:26:51 to 09:36:51 local (Image Sets 2 and 3)
 - Threshold of > 0.1 m/s selected, 1048 zero-value and 1809 non-zero data points removed

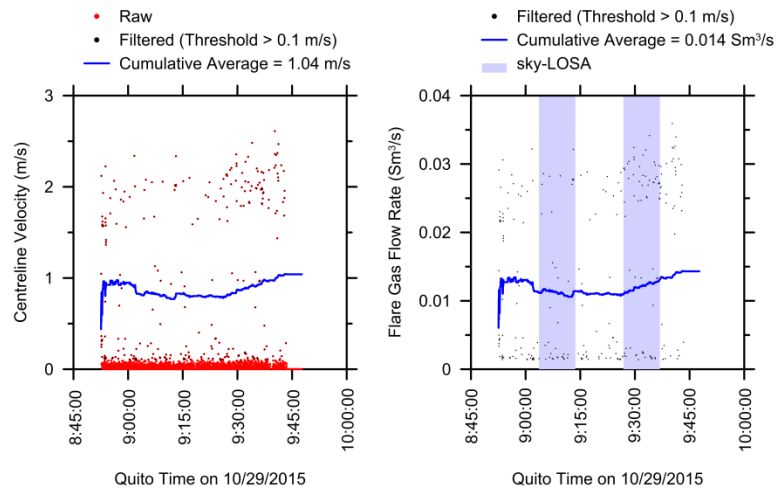


Figure C.22: Measured raw velocities, filtered velocities, and calculated flare gas flow rate for Auca Sur 1 Line 3.

- Tracer dilution measurements
 - Test start at 10:29:43 to 10:43:56 local
 - Simultaneous with sky-LOSA measurements at 10:33:47 to 10:43:47 local (Image Set 4)

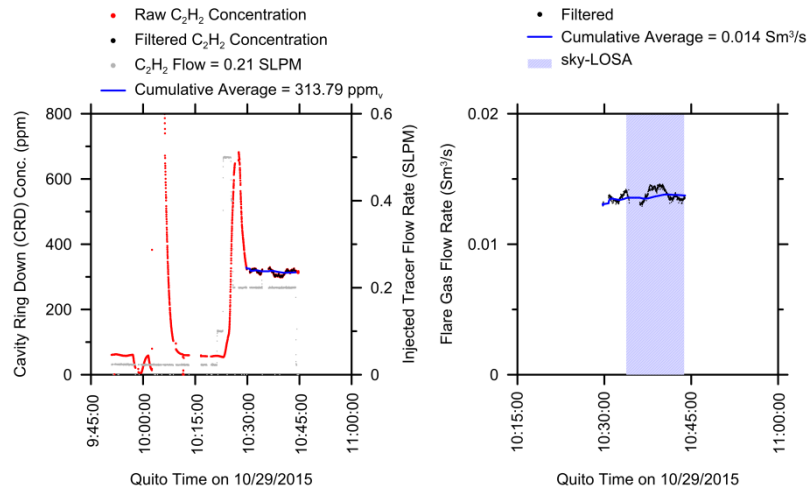


Figure C.23: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca Sur 1 Line 3.

C.6.6 Auca Central – October 26, 2015

Line 1

- Line pressure: Negative pressure –not logged (assumed 101.325 kPa)
- Line temperature: 25.7 °C
- Tracer dilution measurements
 - Test started at time 17:14:30 to 17:29:13 local
 - Simultaneous with sky-LOSA measurements at 17:17:03 to 17:27:03 local (Image Sets 2)

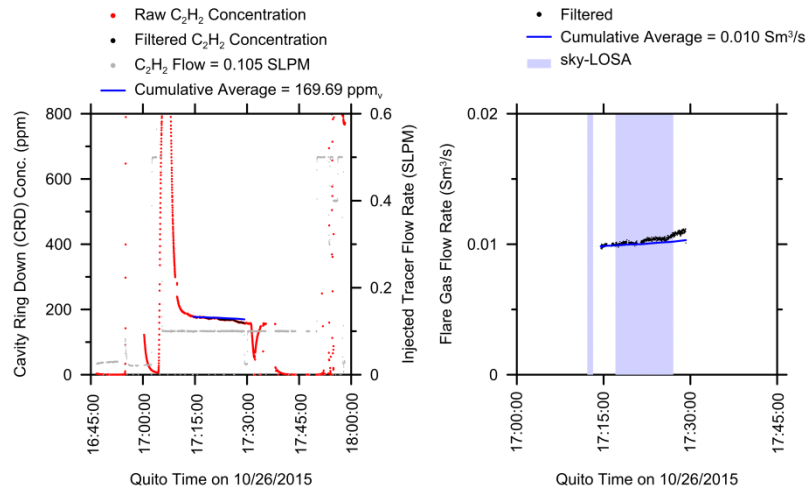


Figure C.24: Measured raw concentrations, filtered concentrations, tracer flow rate, and calculated flare gas flow rate for Auca Central Line 1.