REMOTE ESTIMATION OF SULFUR CONTENT IN FUEL FROM SO_2 AND CO_2 QUANTIFICATION OF SHIP EXHAUST PLUMES

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ABSTRACT

Sulfur oxide (SOx) from seagoing ships contribute to local air pollution in cities and coastal areas around the world. Sulfur dioxide (SO_2) emissions in particular, are a precursor to acid rain and atmospheric particulates leading to ocean acidification which can contribute to negative human health outcomes[2]. The International Convention for the Prevention of Pollution from Ships (MARPOL) defines limits on the sulfur content in ship fuel oils, since the sulfur is ultimately released into the atmosphere through the ship's exhaust system as sulfur dioxide (SO_2). This application note describes the use of remote hyperspectral imaging data collected using the Telops Hyper-Cam along with signal processing techniques to provide rapid and accurate estimation of sulfur content in fuel oils. Comparison between the retrieved sulfur content in the fuel of several ships with data from bunker delivery notes provided by the ship's owner and in situ measurements performed by Transport Canada are presented.

Index Terms— Sulfur dioxide, Sulfur, Hyperspectral, Hyper-Cam, Remote sensing, Ship plume

1. INTRODUCTION

Sulfur oxide (SOx) from seagoing ships contribute to local air pollution in cities and coastal areas around the world. There are 13 sulfur oxides, the most stable being sulfur dioxide (SO_2) and sulfur trioxide (SO_3)[1]. Sulfur dioxide emissions in particular, are a precursor to acid rain and atmospheric particulates which can lead to environmental acidification and contribute to negative human health outcomes[2].

SOx emissions from ships are purely a function of the sulfur content of the fuel being used. The combustion process converts most of the sulfur in the fuel oil to SO_2 and around 3% to SO_3. Sulfur trioxide, reacts very quickly with H_2O in the exhaust to form sulfuric acid (H_2SO_4)[3].

The International Convention for the Prevention of Pollution from Ships (MARPOL) defines limits on allowable sulfur content in ship fuel oils. In January 2020, the limit for SOx and particulate matter emissions decreased from 3.5% m/m to 0.5% m/m. Ship fuel oils Emission Control Areas (ECAs), an even more restrictive limit of 0.10% m/m has been enforced since January 1st 2015.

Figure 1 Hyper-Cam monitoring a ship on the Saint Lawrence seaway.

The current approved method to verify compliance to these limits requires direct sampling and analysis of on-board fuel storage tanks by regulatory personnel, a complex, time consuming and costly task. More recently, arrays of point sensors have been installed under bridges as well as on drones and other airborne platforms to determine the SO_2 concentration within the ship exhaust plume, and from that, infer the sulfur content within the fuel. Although these methods have the potential to increase testing efficiency, they have challenging operational constraints. For example, they suffer from the fact that it is very difficult to ensure that the ship's plume will pass through the sensor array to be sampled. Imaging-format remote sensing techniques present a distinct advantage in this case as a result of superior spatial resolution. Additionally, remote sensing techniques offer a potential supporting validation method, since remote sensing techniques do not require direct sampling of the fuel or the ship exhaust emissions.

Fourier transform infrared spectroscopy (FTIR) is a sensitive technique used for the detection, identification and quantification of infrared active molecules such as SO_2.

Telops Hyper-Cam is a passive infrared hyperspectral imaging camera based on FTIR technology capable of both identification and quantification of various chemical species in complex gas mixtures. The usefulness of the Telops Hyper-Cam as a sulfur monitoring tool in a maritime environment is illustrated in this paper, where several ships were monitored. The Hyper-Cam was used to quantitatively measure the SO_2 content of the ship exhaust and this data was used to successfully retrieve the sulfur content of the fuel burned by the ship.

2. EXPERIMENTAL INFORMATION

The Telops Hyper-Cam (Figure 1) is a lightweight and compact hyperspectral imaging instrument utilizing Fourier Transform Infrared (FTIR) technology. It provides a unique combination of spatial, spectral, and temporal resolution for a complete characterization of the substances being monitored. Its high performance and efficiency as a remote chemical agent detector has been proven through numerous field campaigns since 200.

The Hyper-Cam Long-Wave features a Focal Plane Array (FPA) detector containing 320×256 pixels over a basic 6.4°×5.1° field of view. The spectral resolution is user-selectable between 0.25 and 150 cm-1 over the 8.0 to 11.8 µm spectral range. The Hyper-Cam offers a high sensitivity for each pixel of the scene under observation, and its lightweight makes it ideal for field operation.

For the measurements presented below, the camera was located on the shore of the Saint-Lawrence river at distances ranging between 500 m to 1.5 km away from the ship's exhaust plume. The instrument field of view was narrowed in order to keep the measurement rate at ~1 sec/datacube.

3. DATA ANALYSIS

Since the Hyper-Cam is not mounted on a tracking platform, the ship displacement during one acquisition (datacube) causes strong variations in the raw data (interferogram) measurements, also called scene change artifacts. The ship movement across the image must be corrected before applying SO_2 quantification algorithms. To this end, a digital image correlation algorithm based on a frequency-domain representation of the data is used. The algorithm estimates the relative translation offset between sets of edge pixels from successive non-uniformity corrected interferogram images[4].

In order to exploit the rich information content of Hyper-Cam datacubes, Telops has developed a suite of gas identification and quantification algorithms suitable for distant ship emissions monitoring (Figure 2). These algorithms are based on previous work related to distant smokestack emissions monitoring[5,6]. These applications account for turbulences in the exhaust plume induced by unsteady/uneven gas streams and/or fluctuating wind conditions.

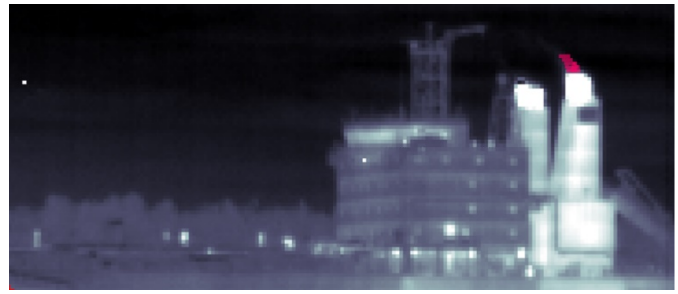

Figure 2 SO2 detection of a moving ship. The ship is moving eastward (toward the left) on the Saint-Lawrence seaway.

In order to calculate the amount of sulfur in the fuel, we make the following assumptions.

1. Sulfur content in the fuel is converted almost completely to SO_2 in the exhaust gas. Combustion of fuel in marine vessels is usually complete and most of the sulfur emitted is in the form of SO_2. Therefore, SO_2 can be used as a proxy for the sulfur content in the emission plumes[3].
2. All of the carbon in the fuel is converted to CO_2[7].
3. The average mass fraction of the carbon in the fuel is 0.865 (around 87%)[8].

Based on these assumptions, the percentage of sulfur in the fuel can be calculated using equation 1:

$$\%S = \frac{C_{SO_2}}{C_{CO2}} \times \frac{M_S}{M_C} \times W_c \times 100\%$$

where M_S and M_C are the atomic weights of sulfur and carbon, C_{SO2} and C_{CO2} are the concentration of SO_2 and CO_2 retreived from quantification algorithm, and Wc is the fractional composition of carbon in the fuel.

4. RESULTS AND DISCUSSION

Four different ships were measured. To preserve confidentiality, the ship's names will not be revealed, they are instead code named A, B, C and D. In this first section, the results from ship A will be presented.

The upper image in Figure 3 presents the broadband infrared image of ship A on the Saint Lawrence seaway after displacement correction. The quantification algorithm requires the user to select several pixels in specified areas of the image (refer to ref. 2-3). These pixels are shown in red, blue and green on Figure 3, corresponding to pixels in the exhaust plume, on the ship chimney body, and the background (sky), respectively. The infrared radiance spectra of these selected pixels are displayed on the middle graph in Figure 3.

Based on the spectral signature information from the specified pixels, the quantitative algorithm utilizes a radiative transfer model to extract gas plume properties such as plume temperature, H_2O, SO_2, CO_2, NO_2 and HNO_3 concentrations. An example of the resulting fit of a single plume pixel is presented in Figure 4. The fit obtained from the algorithm is in good agreement with the measured spectrum. The retrieved SO_2 and CO_2 concentrations were 30,3 and 10000 ppm×m respectively. Only column density results (expressed in ppm×m units) can be retrieved from remote sensing when the path length is unknown and cannot be efficiently estimated from a single perspective. Performing the same procedure for several pixels reveal the spatial concentration of SO_2 within the entirety of the exhaust plume (Figure 5).

The average percentage of sulfur in the fuel for this specific ship measured on February 26th 2020 obtained by using equation 1, is 0.7%. in order to verify this estimate, the percentage of sulfur in the fuel was obtained using two other methods. The first one is based on the Bunker Delivery Note (BDN). This is a standard document required by the authorities for MARPOL compliance which contains information on the sulfur content in the embarked fuel oil. The BDN provided by the company for this vessel indicate a sulfur percentage of 0.79%. The second method relies on measurements performed by Transport Canada (T.C.). To make those measurements, marine safety inspectors from Transport Canada used portable fuel analyzers to sample and measure the sulfur content of the vessel's fuel oil. For this ship, T.C. measured a sulfur content value of 0.78%, corroborating the value from the BDN and in good agreement with the value obtained from remote hyperspectral data.

In addition to the example illustrated above, three other ships (code name B, C and D) were measured and their data analyzed to calculate the percentage of sulfur within the fuel. The results are summarized in Table 6. For three of the ships (A, B and D), the measurements were performed on the same day by both Telops and Transport Canada (T.C.). Similar to ship A, there is a good agreement between values measured by Telops and Transport Canada for vessel D. However, values differ for ship B. To understand why there might be a difference, it is worth noting that the marine safety inspector from Transport Canada measures the sulfur content in the fuel oil feeding the main engines whereas we measure the SO_2 gas emitted from the exhaust (which may come from different combustion sources). Moreover, the ship is equipped with hydraulic units which can be driven by either an electric motor, via ship's generator or by a smaller diesel engine which burns fuel oil containing <0.1% sulfur. Since this specific ship was docked when it was simultaneously measured by Telops and Transport Canada, it could have been relying on its hydraulic units and less on its main engines, this could very well explain the difference.

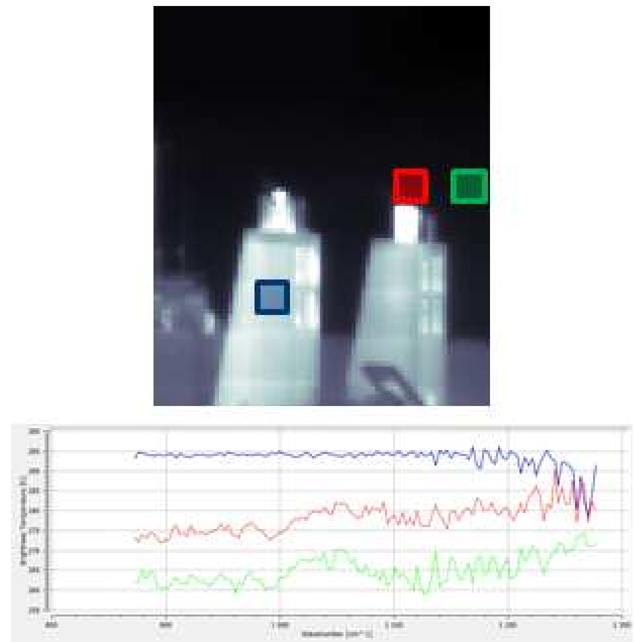

Figure 3 Broadband infrared imagery of the ship's chimneys showing the three selected pixels required by the algorithm with their corresponding spectra.

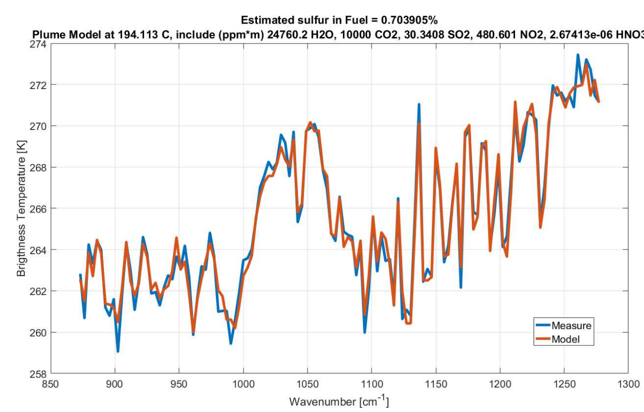

Figure 4 Measurement spectrum from a pixel within the plume (blue curve). Best fit from the algorithm (red line).

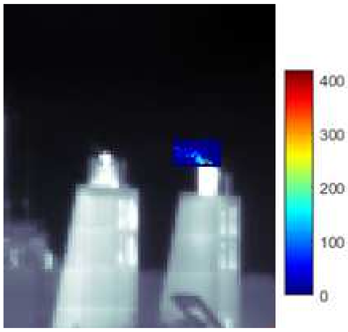

Figure 5 Spatial concentration of SO2 in ppm×m within the ship's plume.

Ship Code Name	Sulfur % measured by Telops	Sulfur % Measured by T.C.	Sulfur % Obtained from BDN
Ship A	0.70	0.7824 0.7791	0.79
Ship B	0.45	0.8287 0.8363	0.79
Ship C	1.8	*No Data*	1.94*
Ship D	0	0.0608	*No Data*

Table 6 Sulfur percentage results measured by Telops, Transport Canada and from bunker delivery notes for the four measured ships.

* Indicate the average value (The BDN provided by the company for this vessel indicate a sulfur percentage of 1.45% on November 28th, 2.11% on November 10th and 2.27% on October 25th 2019. Since the amount of fuel remaining after each delivery is unknown, the exact amount of sulfur at the time of measurement cannot be determined (note that a simple mean of the BDNs values give 1.94%).).

5. CONCLUSIONS

Remote estimation of sulfur content in fuel from quantitative SO_2 and CO_2 measurements of ship plume exhaust using the hyperspectral imagery was demonstrated. Obtained values agree with values declared in bunker delivery notes (BDN) and measurements performed by Transport Canada. Remote, passive hyperspectral imagery offers unmatched benefits for MARPOL compliance as it allows monitoring in a quick, safe, and non-invasive way. Data recorded and analyzed with processing tools developed in this work demonstrate the strength of a hyperspectral imaging system for estimating sulfur content in ship fuel.

9. REFERENCES

[1] N.N Greenwood, "Chemistry of the elements", vol. 2, Butterworth Heinemann, chapter 15 - Sulfur.

[2] "Sulfur Dioxide (SO_2) Pollution." https://www.epa.gov/so2-pollution, accessed on 30 Mar. 2020.

[3] Khanbabakhani. Aida. (2018). Determining Emission Factors from Marine Vessels Employing Differential Optical Absorption Spectroscopy (DOAS) and Tunable Diode Laser Absorption Spectroscopy (TDLAS) (master's thesis). Atmospheric Chemistry, York University, Toronto, Ontario.

[4] Savary, S., Tremblay, P., Villemaire, A., "System and method to remotely measure the directional velocity map of gaseous emissions", U.S. Patent pending No. 61/332,260 (2010).

[5] Pierre Tremblay et al., Standoff gas indentification and quantification from turbulent stack plumes with an imaging Fourier-transformed spectrometer, Proc. of SPIE, 7673, 76730H.

[6] Savary, S., Gagnon, J.-P., Gross, K., Tremblay, P., Chamberland, M., Farley, F., "Standoff identification and quantification of flare emissions using infrared hyperspectral imaging," Proc. SPIE 8024, Advanced Environmental, Chemical, and Biological Sensing Technologies VIII, 80240T (26 May 2011).

[7] Williams, E.J., Lerrier, B.M., Murphy, P.C., Herndon, S.C., Zahniser, M.S. (2009). Emissions of NO_X, SO_2, CO, and HCHO from commercial marine shipping during Texas Air Quality Study (TexAQS) 2006, J. Geophys. Res. Atmos, 114, D21306.

[8] Cooper D.A., Exhaust emissions from ships at berth Atmospheric Environment, Atmospheric Environment Volume 37, Issue 27, September 2003, Pages 3817-3830.