Remote Estimation of Sulfur Content in fuel from SO_2 Quantification from Ship Exhaust Plume

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.

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.

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.

Experimental Information

The Telops Hyper-Cam

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 2006.

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.

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

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.

Figure 2. SO_2 detection of a moving ship. The ship is moving eastward (toward the left) on the Saint-Lawrence seaway.

Remote Quantification

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.

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_{SO_2} and C_{CO2} are the concentration of SO_2 and CO_2 retreived from quantification algorithm, and W_c is the fractional composition of carbon in the fuel.

Results and Discussion

Results from ship A

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, gray and green on Figure 3, corresponding to pixels in the exhaust plume, sky, on the ship chimney body, and the background (vegetation), respectively. The unprocessed infrared radiance spectra of these selected pixels are displayed on the middle graph in Figure 3. Examination of the infrared spectrum corresponding to the pixel in the ship exhaust plume (red trace on middle graph) reveals a slight increase in the brightness temperature value between approximately 1100 and 1250 cm^{-1}. If we compare the red trace to the collection of reference library spectra shown at the bottom of Figure 3, we can see that the observed increase in brightness temperature value in the red trace corresponds to a similar feature in the reference spectrum for SO_2. This similarity between the signature of the ship exhaust plume pixel and the reference library spectrum of SO_2 suggests that we can detect the presence of SO_2 by examining which pixels contain a spectral signature similar to the SO_2 library spectrum. In this way, the spatial distribution of multiple gases inside an exhaust plume can be documented.

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

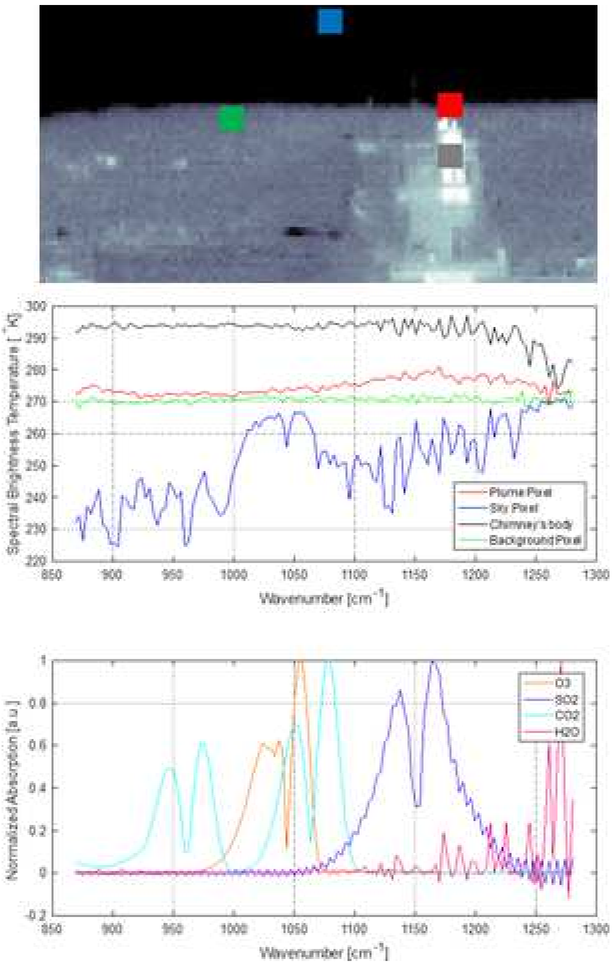

Figure 3. Infrared Image of the ship (upper) with selected pixels for the algorithm with their spectra plotted (middle). Spectra of library active molecules.

Figure 4. The fit obtained from the algorithm is in good agreement with the measurements. The retrieved SO_2 and CO_2 concentrations were 33.5 and 10,000.2 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).

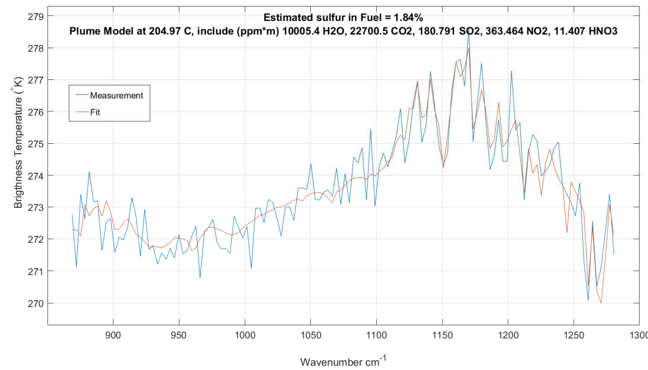

Figure 4. Plume pixel measurement (blue curve). Best fit from the algorithm (red line).

The average percentage of sulfur in the fuel for this specific ship measured on November 29th, obtained by using equation 1, is 1.84%. The Bunker Delivery Note (BDN) is a standard document required for MARPOL compliance which contains information on fuel oil delivery. 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%). Nevertheless, there is a good agreement between the measured value by Telops and the values obtained from the BDNs.

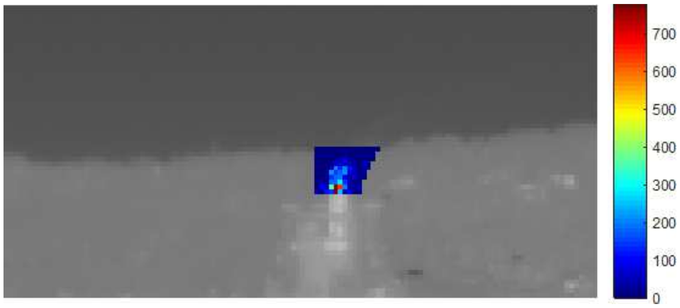

Figure 5. Spatial concentration of SO2 in ppm×m within the ship's plume.

Results from all measured ships

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 Figure 6. For three of the ships (B, C and D), the measurements were performed on the same day by both Telops and Transport Canada (T.C.). For these measurements, marine safety inspectors from Transport Canada used portable fuel analyzers to measure the sulfur content of the vessel's fuel oil. Similar to ship A, there is a good agreement between values measured by Telops and Transport Canada for vessels B and D. However, values differ for ship C. 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.

Ship Code Name	Sulfur % measured by Telops	Sulfur % Measured by T.C.	Sulfur % Obtained from BDN
Ship A	1.8	*No Data*	1.94*
Ship B	0.70	0.7824 0.7791	0.76
Ship C	0.45	0.8287 0.8363	0.76
Ship D	0	0.0608	*No Data*

Figure 6. Sulfur percentage results measured by Telops, Transport Canada and from bunker delivery notes for the four measured ships. * Indicate the average value (exact values are stated in the text).

Conclusions

Remote estimation of sulfur content in fuel from quantitative SO_2 measurements in ship plume exhaust using the Telops Hyper-Cam offers unmatched benefits for MARPOL compliance as it allows monitoring in a quick, safe, and non-invasive way. Hyperspectral images recorded and analyzed with processing tools developed by Telops demonstrate the strength of a Hyper-Cam system for monitoring sulfur content in ship fuel and other similar industrial applications.

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