GUIDELINES FOR THE DEVELOPMENT OF A REMOTE MULTISPECTRAL SENSING-BASED VESSEL EMISSIONS MONITORING SYSTEM

by

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A THESIS

Submitted to the Faculty of the Stevens Institute of Technology
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE – MARITIME SYSTEMS

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2018

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ABSTRACT

Since January 8, 2009, U.S. and foreign-flagged vessels operating in the waters of the United States have been subject to Annex VI of MARPOL, which sets limits on sulfur oxides and nitrogen oxides emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances. In a Memorandum of Understanding with the U.S. Environmental Protection Agency, the United States Coast Guard is responsible for the enforcement of MARPOL regulations. Currently, the USCG conducts enforcement through onboard compliance inspections. A remote, mobile vessel emissions monitoring system capable of identifying and quantifying ship exhausts, and determining fuel sulfur content can make enforcement much more efficient. Multispectral sensing-based technology, which captures image data at specific frequencies across the electromagnetic spectrum, can be applied to enforce emission regulations. The thesis seeks to respond to the following research question: How can multispectral imaging technology be used to develop a vessel emissions monitoring system capable of remote and mobile operation? To develop the proposed vessel emissions monitoring system, the operational problem was first described. A literature review was then performed to determine the status of similar research conducted. The fundamentals behind multispectral technology were uncovered. Bands specific to those used for carbon monoxide, carbon dioxide, sulfur oxides, and nitrogen oxides detection and quantification were then determined. Mobility and accessibility design considerations were investigated. A market survey was performed which concluded that imagers suitable for vessel emissions monitoring were not commercially available. A vessel emissions monitoring system therefore will require specialized design and consideration. It was ultimately found that while there is no system available that meets our needs, a multispectral sensing-based vessel emissions monitoring system as detailed in the study has the potential to provide a small, lightweight, and efficient enforcement system for use on various mobile detection platforms.

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Date: April 30, 2018

Department: Maritime Systems

Degree: Master of Science

ACKNOWLEDGMENTS

I would like to express my very great appreciation to all those without whom this thesis would not have been possible. I express my deep gratitude to Dr. Barry Bunin and Dr. Thomas Wakeman for their patient guidance, enthusiastic encouragement, and useful critiques of this research work. I would like to thank Beth Austin-DeFares for her unwavering support and her role as my personal cheerleader. Finally, I wish to thank my parents for inspiring me to always follow my dreams.

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This material is based upon work supported by the U.S. Department of Homeland Security under Grand Award Number 2014-ST-061-ML0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

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LIST OF ABBREVIATIONS

ABBREVIATION	MEANING
AIS	Automatic Identification System
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ECA	Emissions Control Area
EPA	Environmental Protection Agency
FT-IR	Fourier-Transform Infrared
GHG	Greenhouse Gases
GPS	Global Positioning System
HC	Hydrocarbon
HCFC-22	Chlorodifluoromethane (Freon)
IR	Infrared
LA	Lost Angeles
LB	Long Beach
LWIR	Long-wave Infrared

MARPOL	International Convention for the Prevention of Pollution from Ships
MODTRAN	Moderate Resolution Atmospheric Transmission Model
MOU	Memorandum of Understanding
MWIR	Mid-wave Infrared
N_2O	Nitrous Oxide
N_2O	Nitrous Oxide
NASA	National Air and Space Administration
NIR	Near Infrared
NIST	National Institute of Standards and Technology
NO	Nitric Oxide
NO_x	Nitrogen Oxides
NYPD	New York Police Department
NYU	New York University
$PM_{2.5}$	Particulate Matter less than 2.5 micrometers
PPM	Parts Per Million
RoRo	Roll On Roll Off Vessel
SF_6	Sulfur Hexafluoride
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides

UAV	Unmanned Aerial Vehicle
USCG	United States Coast Guard
USGS	United States Geological Survey
UV	Ultraviolet
VEMS	Vessel Emissions Monitoring System
VIS	Visible Light

LIST OF SYMBOLS

Symbol	Meaning
α	Absorbance
α_{bb}	Absorbance of Blackbody
α_s	Absorbance of Sample
A_{Lens}	Area of Lens
A	Area of Plume
L_b	Background Radiation
C	Continuum Curve
S_{cr}	Continuum-removed Spectra
R_1	Detection Distance (Radius)
ε_s	Emittance of Sample
R	Instrument Response Function
L_{se}	Instrument Self-Emission
I_0	Intensity of Plume
I_1	Intensity of Plume at Distance
L_{bb}	Luminance of Blackbody
L_s	Luminance of Sample
L'_{sky}	Luminance of Sky
L_a	Luminance of the Atmosphere

L_s	Luminance of the Plume
N	Noise-equivalent Power
L'_s	Observed Radiance
S	Original Spectrum
P	Power of Plume
$P_{Exhaust}$	Power of Plume Exhaust
P_{Lens}	Power Plume Exhaust at Lens
R_0	Radius of Plume
ρ	Reflectance
SNR	Signal-to-Noise Ratio
σ	Stefan-Boltzmann's Constant
T	Temperature
T_C	Temperature of Atmosphere
T_H	Temperature of Plume
τ	Transmittance
τ_s	Transmittance of Sample
ν	Wave Number

1 INTRODUCTION

Ocean going vessels may emit significant pollution that affects populations living near ports and coastlines, as well as those living hundreds of miles inland. Marine diesel engines can generate significant nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$), and sulfur dioxide (SO_2) emissions that contribute to nonattainment of the National Ambient Air Quality Standards for $PM_{2.5}$ and ozone. In addition, these engines emit hydrocarbons (HC), carbon monoxide (CO), and other hazardous air pollutants and toxins that are associated with adverse health effects and climate change. Emissions from marine diesel engines cause harm to the public welfare, and contribute to visibility impairment and other detrimental environmental impacts across the United States [1].

For the year 2012, international carbon dioxide (CO_2) maritime shipping emissions were approximately 796 million metric tons, and greenhouse gas (GHG) emissions combining carbon dioxide, methane (CH_4), and nitrous oxide (N_2O) were 816 million metric tons. International shipping accounts for approximately 2.2% of global CO_2 emissions, and 2.1% of global GHG emissions. Annually, international shipping is estimated to produce approximately 18.6 million metric tons of NO_x in the form of nitrogen dioxide (NO_2), and 10.6 million metric tons of sulfur oxides (SO_x) in the form of SO_2. NO_x and SO_x emissions from the maritime shipping industry represent approximately 13% and 12% of worldwide NO_x and SO_x emissions [2].

MARPOL, developed through the International Maritime Organization, is a United Nations agency that regulates maritime safety and security, as well as marine pollution from ships. Annex VI of MARPOL is the main international treaty addressing air pollution prevention requirements from ships. Annex VI requirements comprise both engine-based and fuel-based standards, and apply to U.S. flagged ships wherever located and to non-U.S. flagged ships operating in U.S. waters.

Annex VI, adopted on January 8, 2009 in the United States, establishes significant and progressive limits for NO_x and SO_x emissions from marine engines, and for the first time addresses PM emissions. Beginning in 2015, fuel used by all ships operating up to 200 nautical miles off of U.S. shores must use marine diesel that cannot exceed 0.1% fuel sulfur content, or 1,000 ppm. This geographic area is designated under Annex VI as the Emissions Control Area (ECA). Beginning in 2016, new engines on ships operating in ECAs must use emission controls that achieve an 80% reduction in NO_x emissions.

On June 27, 2011, the U.S. EPA and USCG entered into a Memorandum of Understanding to enforce Annex VI of MARPOL. The MOU provides that the EPA and USCG will jointly and cooperatively enforce the provisions of Annex VI. Efforts to be conducted by the USCG and EPA include inspections, investigations, and enforcement actions if a violation is detected. The efforts to ensure compliance include oversight of marine fueling facilities, onboard compliance inspections, and record reviews. Violations of MARPOL Annex VI may result in criminal or civil liability. Persons found to have violated MARPOL Annex VI or any implementing regulation may be liable for a civil penalty up to $25,000 for each violation, and each day of a continuing violating may constitute a separate offense [3].

USCG Marine Inspectors and Port State Control Officers may request a bunker fuel sample if non-compliance is suspected. A sealed sample of bunker fuel is given to the ship crew by the bunker supplier. The sample is to be retained on board for at least one year to allow for inspection by Port State Control as required [4]. In accordance with MARPOL Annex VI, Regulation 18.8.2, the United States government requires the MARPOL fuel oil representative sample to be analyzed at an independent laboratory to determine whether the bunker fuel meets the requirements of Regulation 14 [5].

The United States Coast Guard is limited to the amount of inspections it can perform each year. In 2016, out of 81,877 ship visits to the United States, only 9,390 or 11.5% of total ships were inspected for safety issues [6]. Safety-related inspections include those that present a danger to the vessel, its crew, the port, or the environment. Therefore, an even smaller percentile of inspections are performed to check for Annex VI compliance. A need exists to develop a system that can detect, identify and quantify ship emissions remotely and in real-time, allowing for more frequent inspections with limited resources. The system must be compact and lightweight to allow for deployment on mobile sources such as unmanned aerial vehicles, patrol boats, and smart buoys.

The goal of this work is to prepare guidelines for the development of a multispectral sensing-based vessel emissions monitoring system. Multispectral sensing-based technology will be explored and its fundamental operation principles will be detailed. Spectroscopic bands used for NO_x, SO_x and CO_2 detection will be determined from spectral data. These bands will then be used amongst other requirements to determine if there is a multispectral sensing-based imager commercially available through a market survey. Mobility and system accessibility considerations will then be investigated. Ultimately, the development guidelines proposed for the creation of a remote vessel emissions monitoring system will have the potential be leveraged to provide enforcement of MARPOL Annex VI and EPA emission regulations.

2 LITERATURE REVIEW

Researchers have been active in the field of air emissions. However, only a few academic references discuss the remote sensing of ship emissions. An extensive literature review indicates that an operational, mobile non-vessel based monitoring system ready for use by emissions enforcement agencies does not currently exist.

A 2011 study [7] discusses the results of measurements in the Hamburg port area from the remote sensing of gases by hyperspectral imaging. Remote sensing by infrared spectroscopy allows detection and identification of hazardous clouds in the atmosphere from long distances. An infrared hyperspectral imager based on a Michelson interferometer, in combination with a focal plane array detector, was deployed to measure gas emissions in the port area. Emissions from ships, industrial sources, as well as gases released intentionally were measured. Using algorithms for remote sensing by infrared spectroscopy, it was possible to identify, visualize, and track plumes of SO_2, CO_2, and SF_6 from distances in the order of three kilometers. Although the system shows robust operation, the hyperspectral imager is excessive for our needs and non-mobile, resulting in a larger and more expensive system than for what is required.

A 2014 study [8] for the first time evaluates the usage of an ultraviolet (UV) camera to measure the low concentrations and emission rates of SO_2 in plumes from moving and stationary ships. Over the last few years, fast-sampling ultraviolet imaging cameras have been developed to measure SO_2 emissions from industrial and natural sources. Generally, measurements have been made from sources rich in SO_2 with high concentrations and emission rates. Field experiments were conducted at Kongsfjorden, Svalbard, where emissions from cruise ships were measured, and at the port of Rotterdam, Netherlands, measuring emissions from more than ten different container and cargo ships. In all trials, SO_2 path concentrations were estimated and emission rates determined. Accuracies were compromised in some cases due to the presence of particulates in ship emissions and the restriction of single-filter UV imagery. Despite the ease of use and ability to determine SO_2 emission rates from the UV camera system, limitations in accuracy and precision suggest that the system may only be used under ideal circumstances, and is therefore not suitable for regular emissions enforcement.

A 2016 study [9] uses the Telops Hyper-Cam standoff mid-wave 3-5 μm infrared hyperspectral imager to record ship plumes from an operating ferry 115 meters away. The Telops Hyper-Cam was chosen due to its high level of performance and efficiency that has been proven through numerous field campaigns. Passive remote sensing technologies were used since they are non-invasive and do not involve installing any additional equipment on the ship itself. Temperature maps from the ship plumes as well as column density maps of exhaust gases such as CO and CO_2 were successfully determined. Combustion efficiency maps and mass flow rates were derived from the data. The selectivity provided by the Telops Hyper-Cam hyperspectral technology allows identification and quantification of various chemicals, which can vary by engine type, fuel grades, and engine revolution. The system proposed by this study is effective for ship plume characterization and serves as an exploratory tool for researchers and scientists.

Serving as a research tool, it is not suitable for day-to-day operation by the USCG, EPA and other law enforcement agencies.

A 2017 [10] study performed by the NYU Center for Urban Progress and Science uses longwave infrared hyperspectral imaging to study the ongoing leakage of refrigerant gases in New York City. The imaging system employed was the GBSS-2 manufactured by the Aerospace Corporation. Post-processing was performed by HyperSEAL software for plume identification, as well as an analysis procedure using MODTRAN 12 together with a Digital Surface Model of New York City for atmospheric compensation and concentrated analysis. The spectral range of the imaging system, 7.6-13.2 µm, covers a region where many polyatomic molecules have well-defined spectral features, and the high spectral resolution, 40 nm, allows the compounds to be identified with high selectivity. Large quantities of HCFC-22 refrigerant and ammonia along with a number of other gases were successfully detected. The results suggest that long-term spectroscopic imaging campaigns will be instrumental for estimating gaseous refrigerant emissions for the purpose of both research and policy. In terms of vessel emissions enforcement, the system proposed in this study is not suitable since it is large, expensive, and requires an external liquid nitrogen cooling system. In addition, the system has been developed primarily for refrigerant gas leakage detection in an urban landscape. Despite these differences, research and associated data from the study can be applied to this thesis for the development of an operational vessels emissions monitoring system.

There has been some research in remote detection and identification of vessel emissions but none have suggested an operational system ready for day-to-day use by enforcement agencies. Authors have studied the problems of detecting, identifying, and quantifying ships emissions. The systems proposed are categorized as exploratory and scientific research tools; they are large, impractical, overcomplicated, and unsuitable for operational use by emission enforcement agencies. Therefore, the need exists to create a practical and ready-to-use system for emissions enforcement.

3 MULTISPECTRAL IMAGING TECHNOLOGY

3.1 INTRODUCTION

Multispectral sensing-based technology has been investigated to determine if it can be applied to enforce emissions regulations. Multispectral imaging captures spatial-spectral data in cubes of scenes, illustrated in Figure 1A, which contains a set of two-dimensional images at different frequencies. Multispectral detectors operate in 3 to 10 bands, opposed to hyperspectral detectors, which operate in hundreds or thousands of bands. For this study, the focus will be on multispectral sensing-based technology, as it may show promise to detect vessel emissions in a mobile and lightweight package.

For gas detection-based multispectral imaging, image data can be collected at specific frequencies across the electromagnetic spectrum using a process called Fourier-transform infrared (FT-IR) emission spectroscopy. FT-IR emission spectroscopy is a technique based on the determination of infrared radiation from a gas. It measures the frequencies and intensities at which the gas emits thermal radiation remotely. Fourier-transform infrared spectroscopy has been the dominant technique used for measuring the infrared emission spectra of many gases [13].

Data collected from FT-IR emission spectroscopy can be processed to create a continuous spectrum for each image cell, as shown in Figure 1B. After adjustments for sensor, atmospheric, and terrain effects are applied, image spectra can be compared with lab reference spectra in order to recognize and map particular materials [11], such as CO,

CO_2, NO_x, and SO_x, for vessel emissions monitoring. These techniques can be used to answer the following research question: How can multispectral imaging technology be used to develop a vessel emissions monitoring system capable of remote and mobile operation?

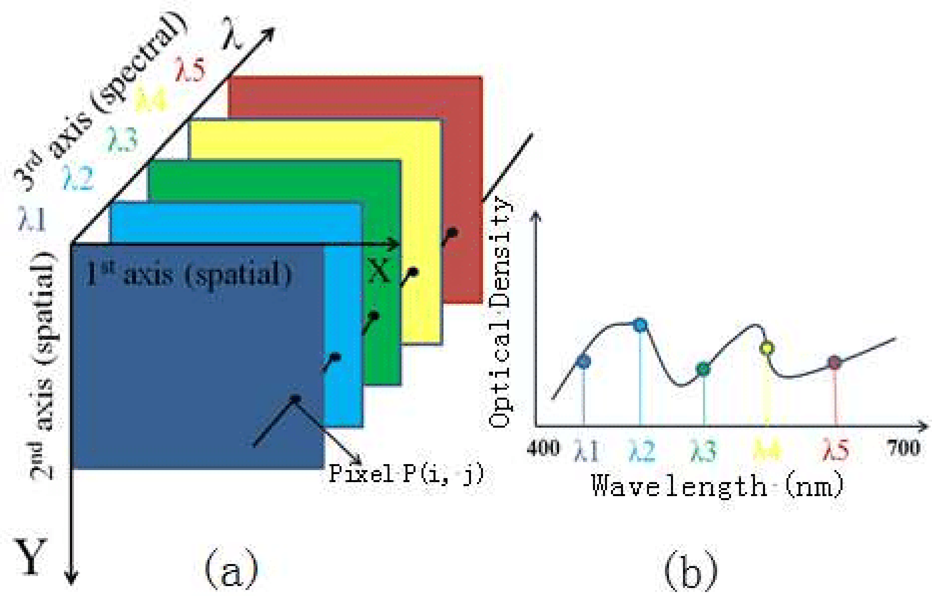


FIGURE 1: MULTISPECTRAL IMAGE: (A) DATA CUBE; (B) SPECTRUM [12]

3.2 INFRARED SPECTROSCOPY

For vessel emissions monitoring, a specific type of emission FT-IR spectroscopy can be used, called passive open-path Fourier-transform infrared (OP FT-IR) emission spectroscopy. Open-path FT-IR emission spectroscopy allows for the measurement of the concentration of gases over long optical paths open to the atmosphere. Passive techniques do not use an artificial IR light source, but instead measure only the energy of IR radiation present within the field-of-view of the instrument. Since passive open-path FT-

IR monitoring systems do not introduce any IR radiation into the gas monitored, detection of gaseous molecules within the detector's field-of-view depends on the radiance contrast (temperature gradient) between the gas and the background. Large temperature differences will produce higher signal-to-noise ratios and a greater detection range [13].

The ability to remotely analyze and characterize a chemical plume such as one from a vessel smokestack is of great interest to the military and civilian communities. FT-IR emission spectroscopy can be used in a variety of different applications, such as the measurement of the composition of volcanic gases, analysis of smokestack emissions, analysis of engine exhaust gases, detection of warfare agents under battlefield conditions, and more. In the case of chemical accidents, acts of terrorism, or war, hazardous compounds are often released into the atmosphere. FT-IR spectrometers can be used for the detection and identification of these hazardous clouds [13].

3.2.1 ADVANTAGES AND CHALLENGES

There are several advantages to passive open-path FT-IR emission spectroscopy for our study. No infrared source is necessary; the radiation source is the hot gas emitted by the ships studied. Passive FT-IR emission spectroscopy shows potential to be used for mobile enforcement applications, such as unmanned aerial vehicles, smart buoys, or handheld devices, and allows for fast operation. It can be used at remote-sensing distances of up to several kilometers. These potential advantages will be investigated further in our study.

Challenges of passive open-path FT-IR emission spectroscopy techniques are present as well. FT-IR instruments measure interferograms; interferograms are difficult to interpret without first performing a Fourier transform to produce a spectrum, which requires computing power. The sensitivity of the passive method is generally less than that of the active method, which uses an artificial IR source and measures the absorption and reflection of its radiation. In addition, the passive method suffers from disadvantages connected with field measurements including weather-related problems such as wind, temperature, cloud conditions and their fast changes [13]. For highly sensitive work, and lengthy experiments, changes in infrared-absorbing gas concentrations can affect the results [14].

3.2.2 BASIC PRINCIPLES OF THERMAL RADIATION

To create a model for passive open-path FT-IR emission spectroscopy, the basic principles of thermal radiation must first be investigated. If a monochromatic beam of light of unit intensity falls on a slab of material, some fraction of the light is reflected, another is absorbed, and the remainder is transmitted so that these fractions add up to unity [13]:

$$\alpha_s + \rho_s + \tau_s = 1 \qquad (1)$$

where α_s, ρ_s, and τ_s are the absorbance, reflectance, and transmittance of the sample, expressing its fractional absorption, reflection, and transmission. A blackbody absorbs all radiation falling on it, therefore, for a blackbody:

$$\alpha_s = 1 \qquad \text{and} \qquad \rho_s = \tau_s = 0 \qquad (2)$$

Kirchoff's law states that the ratio of the radiant flux (or luminance) of any sample, L_s, at any given temperatue, T, to its absorbance, α_s, is equal to the luminance of the blackbody, L_{bb}, at the same temperature:

$$\frac{L_s}{\alpha_s} = L_{bb} \qquad (3)$$

which implies that the absorbance of the blackbody is unity ($\alpha_{bb} = 1$). An important consequence of this law is the principle of equivalence between absorbance and emittance, where the emittance of the sample is equal to its absorbance, $\varepsilon_s = \alpha_s$. Therefore, Equation (3) can be rewritten as:

$$\varepsilon_s = \frac{L_s}{L_{bb}} \qquad (4)$$

Thus, substiting emittance for absorbance in Equation (1), the basic relation of optical emission spectroscopy is:

$$\varepsilon_s + \rho_s + \tau_s = 1 \qquad (5)$$

In gaseous samples such as CO_2, NO_x, and SO_x for vessel emissions monitoring, reflection effects are usually negligible ($\rho = 0$), therefore Equation (5) simplifies to:

$$\varepsilon_s + \tau_s = 1 \qquad (6)$$

For remote passive open-path FT-IR emission spectroscopy, emittance (and absorption) are the only possible detection methods. Transmittance requires an active infrared source, which is not feasible for remote detection. As Equation 6 illustrates, transmittance and emittance add to 1 in perfect conditions, therefore, if transmittance values are known, emittance (or absorption) values can theoretically be calculated, and vice-versa.

3.2.3 MODEL FOR PASSIVE REMOTE SENSING

The sensitivity of passive open-path FT-IR remote sensing depends on the radiometric temperature difference between the plume under observation and the background beyond it. The background for vessel emissions monitoring may be the sky, or the sea, depending on the elevation angle. We will assume that the background is the sky for this model. It must be noted that background emissivity of the sky will be different from the background emissivity of the sea.

As illustrated in Figure 2A, the IR signal reaching the interferometer can be attributed to three zones of gaseous samples, the atmosphere between the spectrometer and the emissions plume, the emissions plume itself, and the sky background. Emission and absorption from all three zones will affect the IR beam spectrum measured for the emissions plume [13].

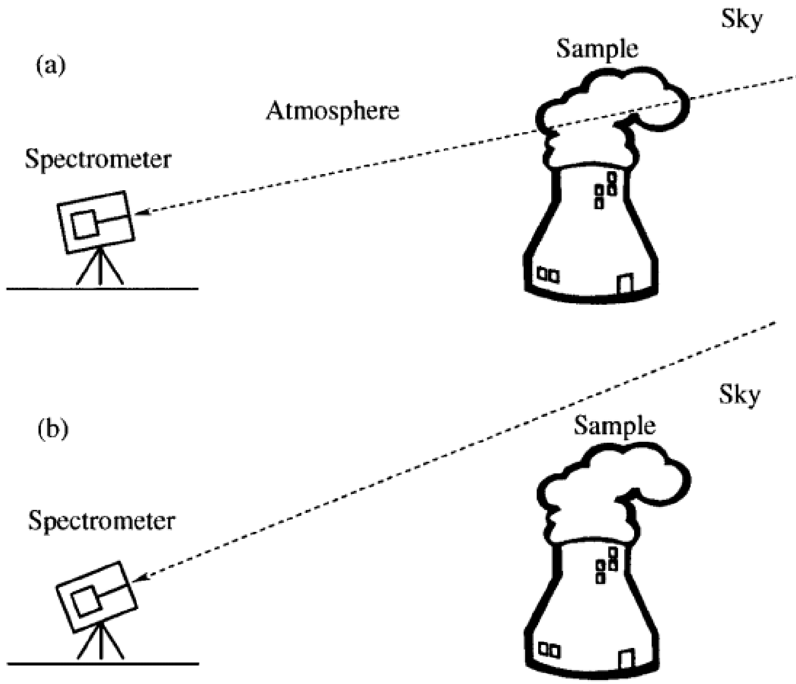


FIGURE 2: MEASUREMENT SETUP OF PASSIVE REMOTE SENSING OF HOT PLUMES: (A) DETECTION OF EMISSION SPECTRUM OF THE PLUME; (B) DETECTION OF THE SKY BACKGROUND RADIATION [13]

Accordingly, Equation 7 describes the passively collected spectrum of an emissions plume, L'_s, taking into account contribution from the instrument's self-emission as well as the spectrometer's overall response time:

$$L'_s = R(L_s + L_a + L_{sky}\tau_s + L_{se}) = R(L_{bb} - L_{bb}\tau_s + L_{sky}\,\tau_s + L_{se}) \qquad (7)$$

where R is the instrument response time, L_s is the luminance of the plume, L_a is the luminance of the atmosphere between the spectrometer and the emissions plume, L_{sky} is the radiance of the sky background, L_{se} is the radiance due to the instrument's self-emission, L_{bb} is the radiance of the blackbody, and τ_s is the transmittance of the sample plume.

When the infrared spectrometer is pointed away from the plume to an area of the sky, as illustrated in Figure 2B, a spectrum of the sky can be obtained, denoted as L'_{sky}:

$$L'_{sky} = R(L_{sky} + L_{se}) \tag{8}$$

where *R* is the infrared spectrometer's response function, L_{sky} is the radiance of the sky, and L_{se} is the radiance due to the instrument's self-emission. Since the IR radiance of the sky can vary considerably with the viewing angle, different regions of the sky, and change by time, it should be assumed that the sky background spectra are collected in close temporal and spatial proximity to the sample hot gas spectra, under the same elevation angle.

An emission spectrum of a blackbody source, L'_{bb}, at the same temperature of the plume can be written as:

$$L'_{bb} = R(L_{bb} + L_{se}) \tag{9}$$

where *R* is the infrared spectrometer's response function, L_{bb} is the radiance of the blackbody, and L_{se} is the radiance due to the instrument's self-emission.

Using the three measured spectra, L'_s, L'_{sky}, and L'_{bb} from Equations (7), (8), and (9), the transmittance of the emissions plume, τ_s, can be modelled as:

$$\tau_s = \frac{L'_s - L'_{bb}}{L'_{sky} - L'_{bb}} \tag{10}$$

Emittance can then be modelled, using the principles in equation (6):

$$\varepsilon_s = 1 - \tau_s = 1 - \frac{L'_s - L'_{bb}}{L'_{sky} - L'_{bb}} \tag{11}$$

Since all compounds show characteristic emittance in unique infrared spectral regions, they can be analyzed both qualitatively and quantitatively using passive open-path FT-IR emission spectroscopy. The equations modeled in this section provide the researcher insight on the thermal radiation concepts used for passive remote sensing. These fundamental concepts illustrate how passive infrared spectrometers operate.

3.3 SPECTRAL LIBRARIES

Libraries of reference spectra for natural and synthetic materials are available for public use. These libraries provide a source of reference spectra that can aid the interpretation of multispectral images. The USGS Spectral Library [15], compiled by the United States Geological Survey Spectroscopy Lab in Denver, Colorado has a database of about 400 spectra of minerals and plants. NASA has made the ASTER Spectral Library [16] available as part of the Advanced Space-borne Thermal Emission and Reflection Radiometer imaging instrument program. The ASTER Spectral Library contains over 2,400 spectra, including minerals, rocks, soils, gases, man-made materials, water, and snow. The ASTER Spectral Library includes data from other spectral libraries as well: the Johns Hopkins University Spectral Library and the Jet Propulsion Laboratory Spectral Library.

For the purposes of CO_2, NO_x, and SO_x detection and identification, standard reference data provided by the National Institute of Standards and Technology will be utilized. Data from NIST is certified as reference material and can be used to help develop accurate methods of analysis, and to calibrate measurements systems used to measure a property at the state-of-the-art limit. The NIST Chemistry WebBook Standard Reference Database Number 69 contains infrared spectra for over 16,000 compounds [17]. Infrared spectra from this resource will be used to determine which bands are most appropriate for multispectral sensing-based vessel emissions monitoring.

3.4 PROCESSING TECHNIQUES

Processing techniques generally identify the presence of materials through the measurement of spectral absorption (or emittance) features. Often multispectral data is post-processed to remove atmospheric effects using methods such as the Air Force Phillips Laboratory computer code MODTRAN (Moderate Resolution Atmospheric Transmission Model).

The MODTRAN computer code is used worldwide by research scientists in government agencies, commercial organizations, and educational institutions for the prediction and analysis of optical measurements through the atmosphere. The code is embedded in many operational and research sensor and data processing systems, particularly those involving the removal of atmospheric effects, commonly referred to as atmospheric correction, in remotely sensed multispectral and hyperspectral imaging [18]. The MODTRAN computer code was utilized in the NYU CUSP study [10] for the atmospheric correction of thermal-infrared imagery of the urban environment.

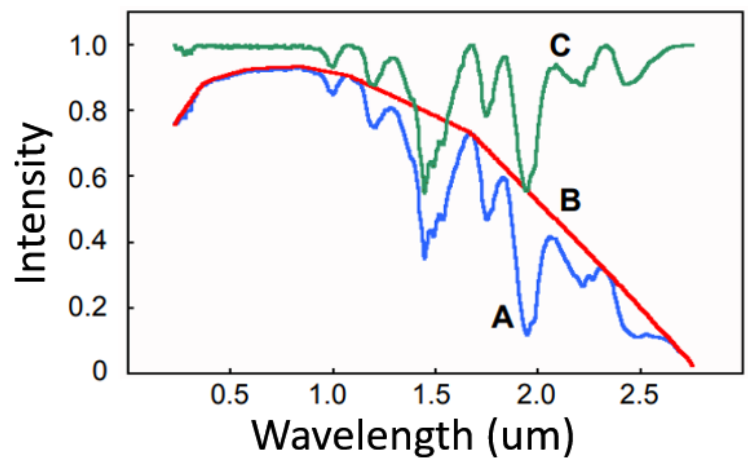
Many emission-related gases can be recognized by the position, strength, and shape of their emittance features. One matching strategy attempts to compare only the emittance maximum values to reference transmittance minimum values and ignore the other parts of the spectrum. A unique set of wavelength regions is therefore examined for each reference candidate, determined by the locations of its maximum and minimum intensity values. The local position and slope of the spectrum can affect the strength and shape of an emittance feature, so these parameters are usually determined relative to the continuum (the upper limit of the spectrum's general shape).

The continuum is the curve that fits "over the top" of the spectrum [21], illustrated as Curve B in Figure 3 below. The continuum curve is calculated using computer software algorithms, such as ENVI, resulting in a convex full fit over the top of the spectrum that connects local maxima with straight-line segments. After the continuum is computed for each wavelength subset, it is removed by dividing the intensity at each spectral channel by its corresponding continuum value. Equation 12 illustrates the formula for calculating the continuum-removed spectra [22]:

$$S_{cr} = \frac{S}{C} \qquad (12)$$

where: S_{cr} is the continuum-removed spectra, S is the original spectrum, and C is the continuum curve.

After continuum removal, shown as Curve C in Figure 3, a part of the spectrum with less intensity will have a lower value, whereas a higher intensity will have a value closer to 1.0, with most intensities falling somewhere in between. Removing the continuum removes the overall curvature of the spectrum, and normalizes it for comparison with reference data. Emittance features can then be matched to reference transmittance features using a set of derived values, or by using the complete shape of the feature.



Intensity spectrum for a gas (Curve A). Curve B shows the continuum for the spectrum, and Curve C shows the spectrum after removal of the continuum

FIGURE 3: CONTINUUM MATCHING STRATEGY [20]

4 BAND DETERMINATION

To determine which frequency bands are required for vessel emissions monitoring, reference data from the NIST Chemistry WebBook Standard Reference Database Number 69 was used. The NIST catalog provides IR spectral reference data for over 16,000 compounds, including CO_2, NO_x, and SO_x. Reference spectra data, which is presented using transmittance values as intensity, will be plotted and analyzed to determine the unique IR signature of each pollutant. Since transmittance minimum values align with emittance maximum values, reference transmittance data can be used for this study, as we are just identifying the peaks and troughs on the chart, and nothing else. The locations of the transmittance features, represented by the minimum values on the graph, will be calculated to determine the range of the wavelength bands required for an emittance-based multispectral imager capable of vessel emissions monitoring.

IR spectral data from the NIST catalog is presented in the JCAMP-DX format. JCAMP-DX is a standard file form for the exchange of infrared spectra and related chemical and physical information between spectrometer data systems, main-frame systems, and lab computers. JCAMP-DX files are intended for the ease of exchange of data. While JCAMP-DX files are also used for building data banks and archiving spectra, they are not designed to rapid-research or other special uses. Rather, they are viewed as a source for creating data bases, as well as for informal exchange of data [23].

A MATLAB code was developed to convert the JCAMP-DX files into IR spectral charts for analysis. Below is a sample of the code used:

```
1 %First, download the JCAMP.DX file into MATLAB
2 %The script on lines 4 and 5 extracts the data from the
3 %JCAMP.DX file and converts it into a matrix readable by MATLAB
4 jcampStruct = jcampread('FILE_NAME.jdx')
5 data = jcampStruct.Blocks(1);
6 %Line 8 plots the data, Transmittance as the Y-Axis, and
7 %Wavenumber (1/CM) as the X-Axis
8 plot(data.XData, data.YData,'LineWidth',2);
9 %Lines 10, 11, and 12 label the axes and title of the graph
10 title(jcampStruct.Title);
11 xlabel(data.XUnits);
12 ylabel(data.YUnits);
13 %Line 14 returns the axes of the chart for the current figure
14 ax=gca
15 %Line 16 and 17 sets the ranges for the X-Axis and Y-Axis
16 ax.XTick = [0:200:4000];
17 ax.YTick = [0:.1:1.0];
18 %Line 19 sets the limits of the Y-Axis
19 ax.YLim = [0 1.1];
20 %Line 21 sets the chart background to white
21 set(gcf,'color','w');
22 %Line 24 reverses the axis for better interpretation of the
23 %results
24 set(gca,'xdir','reverse')
```

Charts created using the MATLAB code were plotted with transmittance as the y-axis, ranging from 0.0 to 1.0, and wavenumber as cm^{-1} plotted as the x-axis, ranging from

4000 cm^{-1} to 0 cm^{-1}. Carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitric oxide (NO), and nitrous oxide (N_2O) were analyzed below, representing CO, CO_2, and select SO_x and NO_x gas emissions from ships. The NIST database did not have any IR spectral data for nitrogen dioxide (NO_2), therefore the gas was not analyzed in this study. The data cursor tool was used to calculate the exact minimum values of the transmittance data.

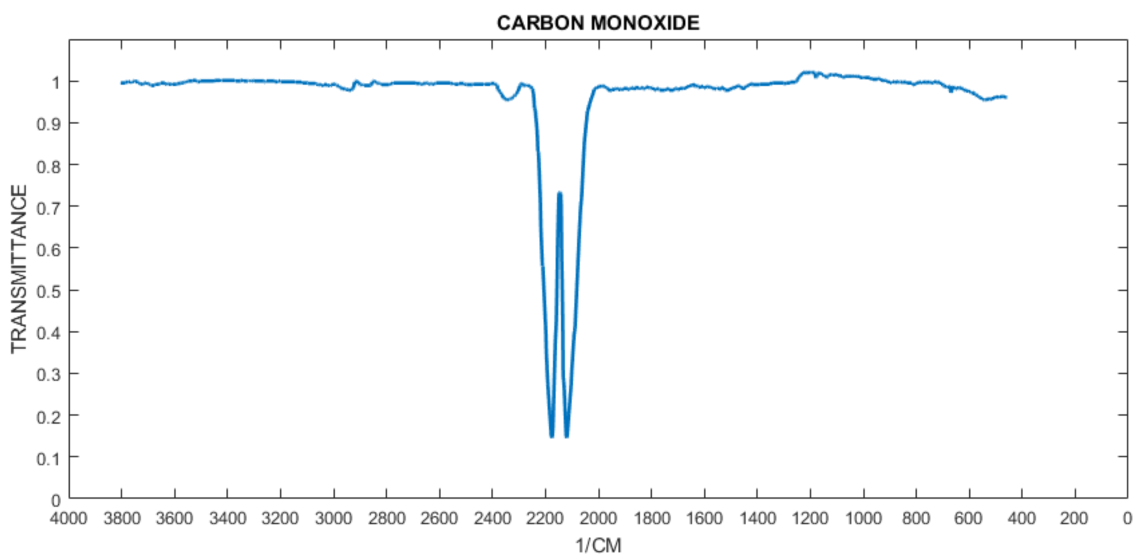


CHART 1: CARBON MONOXIDE REFERENCE IR SPECTRA

Absolute minima for carbon monoxide (Chart 1) occurred at 2120 cm^{-1} and 2176 cm^{-1}.

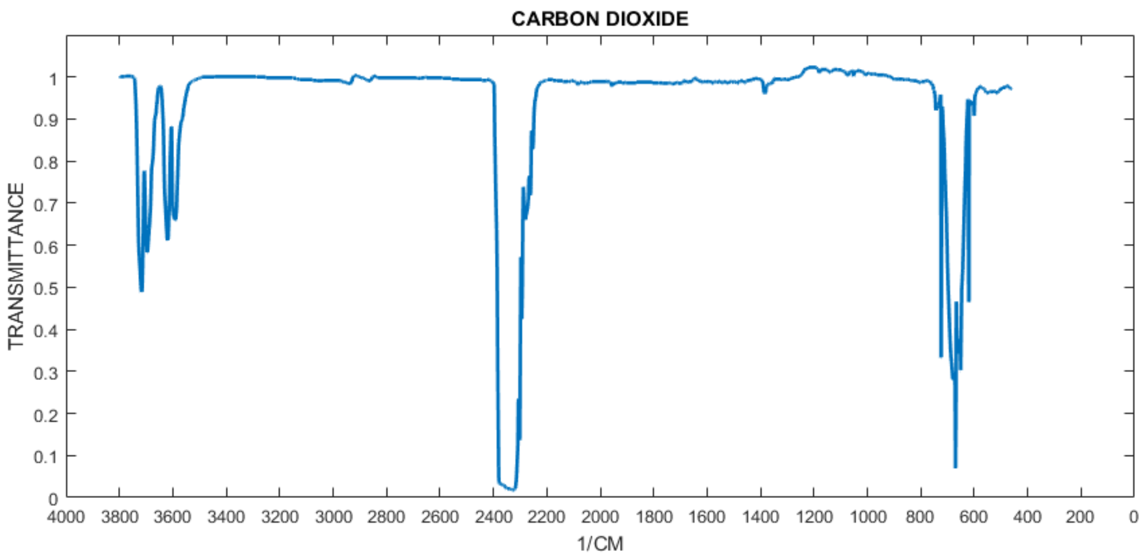


CHART 2: CARBON DIOXIDE REFERENCE IR SPECTRA

Absolute minima for carbon dioxide (Chart 2) occurred at 2332 cm^{-1}, 2379 cm^{-1}, and 670.1 cm^{-1}. Local minima occurred at 3717 cm^{-1}, 3695 cm^{-}1, 3620 cm^{-1}, 3589 cm^{-1}, 724.3 cm^{-1}, 650.5 cm^{-1}, and 619.6 cm^{-1}.

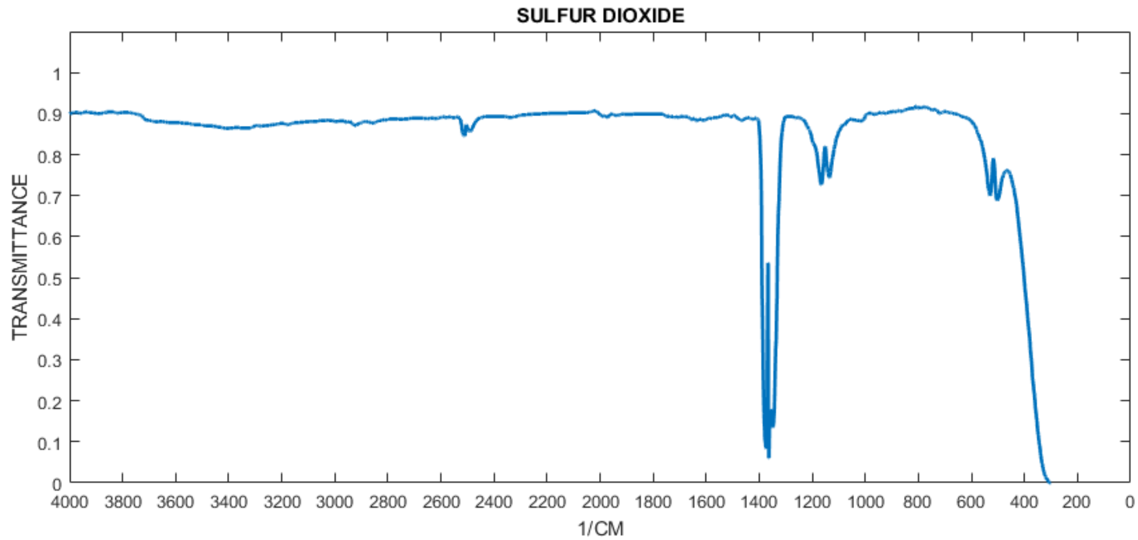


CHART 3: SULFUR DIOXIDE REFERENCE IR SPECTRA

Absolute minimum for sulfur dioxide (Chart 3) occurred at 1364 cm^{-1}. Local minima occurred at 1167 cm^{-}1, 1134 cm^{-1}, 529.7 cm^{-1}, and 502.5 cm^{-1}.

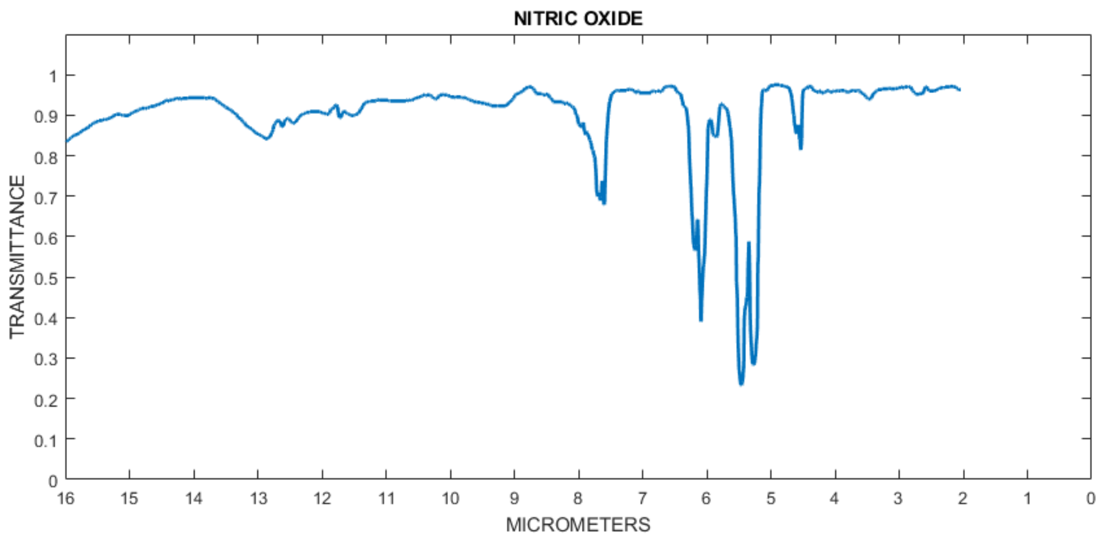


CHART 4: NITRIC OXIDE REFERENCE IR SPECTRA

For nitric oxide (Chart 4), reference data was collected in micrometers (µm). Absolute minimum occurred at 5.46 µm. Local minima occurred at 7.60 µm, 6.12 µm, 6.10 µm, 5.7 µm, and 4.53 cm^{-1}. The data in micrometers will be later converted to wavenumber for analysis.

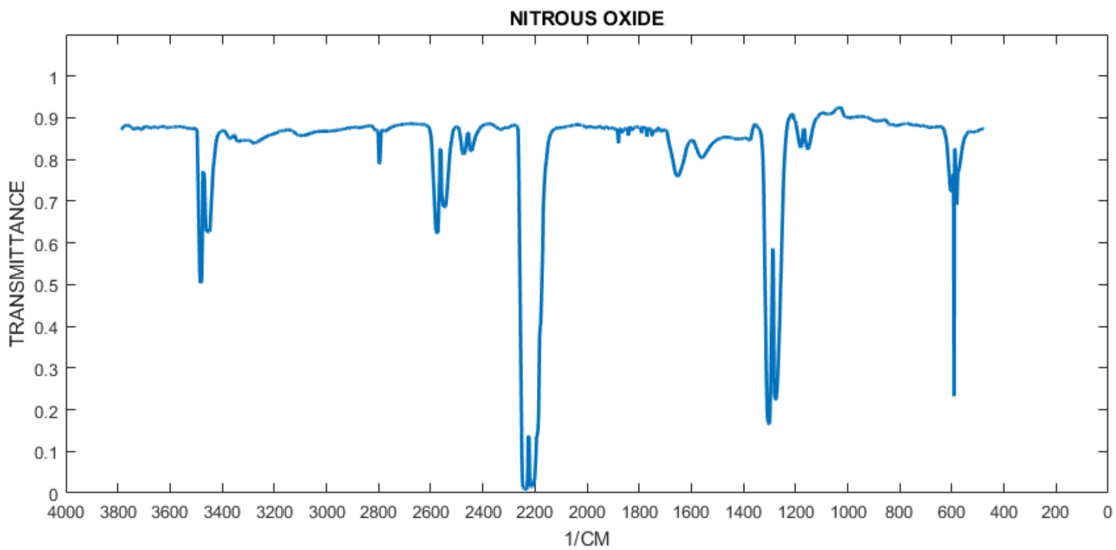


CHART 5: NITROUS OXIDE REFERENCE IR SPECTRA

Absolute minima for nitrous oxide (Chart 5) occurred at 2234 cm^{-1}, and 2205 cm^{-1}. Local minima at 3480 cm^{-1}, 3449 cm^{-1}, 2576 cm^{-1}, 2542 cm^{-1}, 1301 cm^{-1}, 1276 cm^{-1}, and 592 cm^{-1}.

To standardize this data, Table 1 was constructed, converting wavenumber, cm^{-1}, to wavelength, µm, using Equation 13 [24]:

$$Wavelength\ (\mu m) = \frac{10{,}000}{Wavenumber\ (cm^{-1})} \qquad (13)$$

Gas	Transmittance	Wavenumber (cm-1)	Wavelength (µm)
Carbon Monoxide	Absolute Minima	2120	4.72
		2176	4.60
Carbon Dioxide	Absolute Minima	2332	4.29
		2379	4.20
		670.1	14.92
	Local Minima	3717	2.69
		3695	2.71
		3620	2.76
		3589	2.79
		724.3	13.81
		650.5	15.37
		619.6	16.14
Sulfur Dioxide	Absolute Minima	1364	7.33
	Local Minima	1167	8.57
		1134	8.82
		529.7	18.88
		502.5	19.90
Nitric Oxide	Absolute Minima	1831	5.46
	Local Minima	1315	7.60
		1633	6.12

		1639	6.10
		1754	5.70
		2207	4.53
Nitrous Oxide	Absolute Minima	2234	4.48
		2205	4.54
	Local Minima	3480	2.87
		3449	2.90
		2576	3.88
		2542	3.93
		1301	7.69
		1276	7.84
		592	16.89

TABLE 1: REFERENCE SPECTRA TRANSMITTANCE MINIMA VALUES

Utilizing wavelength values calculated in Table 1, Chart 6 was the constructed, showcasing minima reference transmittance values for the emission gases studied.

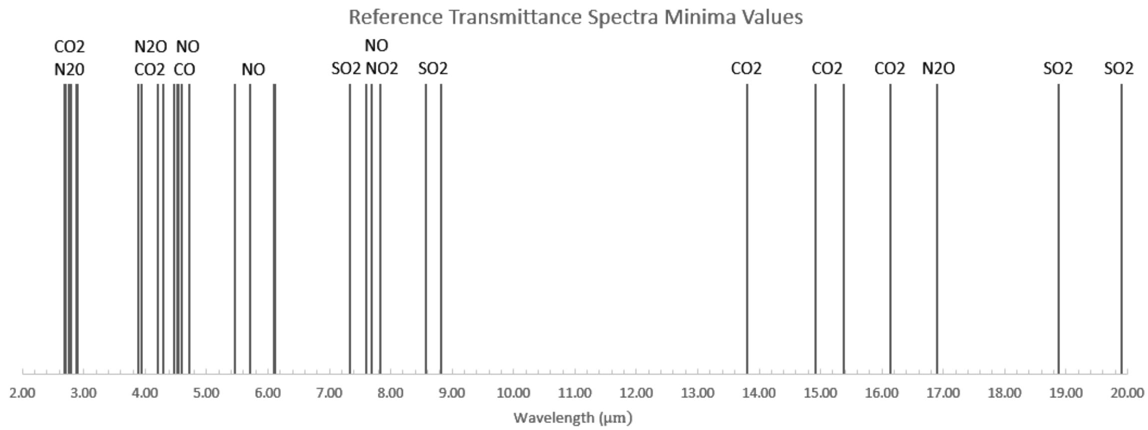


CHART 6: REFERENCE TRANSMITTANCE SPECTRA MINIMA VALUES

Chart 6 yields noteworthy results. Emission gases tend to have similar bands of transmittance minima values in the lower end of the infrared spectrum. Carbon dioxide and nitrous oxide both have wavelengths within the 2.6 µm – 3.0 µm band. Nitrous oxide, nitric oxide, carbon monoxide, and carbon dioxide show multiple wavelengths within the 3.8 µm – 4.8 µm band. Nitric oxide occupies wavelengths between the 5.4 µm – 6.2 µm band. Wavelengths between 7.3 µm – 7.9 µm can be assembled into a band as sulfur dioxide, nitric oxide, and nitrous oxide show minima transmittance values there. Sulfur dioxide occupies wavelengths between the 8.5 µm – 8.9 µm band. It is interesting to note that between 9.0 µm – 13.8 µm, there are no transmittance minima values for any of the emission gases.

From the 13.8 µm – 20.0 µm upper wavelength range, minima transmittance values do not occur at concentrated wavelengths, therefore, there are no obvious bands. Carbon dioxide has minima transmittance values at 13.81 µm, 15.37 µm, and 16.14 µm. Nitrous oxide exhibits a minimum transmittance value at 16.89 µm, while sulfur dioxide minima transmittance values occur at 18.88 μm and 19.90 μm. The carbon dioxide wavelength at 13.81 μm is the only absolute minima transmittance value at the upper wavelength range. The other wavelengths represent local minima transmittance values, therefore, wavelengths above 13.81 μm are not necessary for emissions detection.

Band Number	Wavelength Range	Gas Detection
1	2.6 μm – 3.0 μm	CO_2, N_2O
2	3.8 μm – 4.8 μm	CO, CO_2, NO, N_2O
3	5.4 μm – 6.2 μm	NO
4	7.3 μm – 7.9 μm	SO_2, NO, N_2O
5	8.5 μm – 8.9 μm	SO_2
6	13.81 μm	CO_2

TABLE 2: BAND DETERMINATION FOR VESSEL EMISSIONS DETECTION

Table 2 showcases the wavelength bands required for the development of a vessel emissions monitoring system. The 6 proposed detection bands span both the mid-wave infrared (MWIR) and long-wave infrared (LWIR) bands of the electromagnetic spectrum. MWIR and LWIR detection techniques can used because at terrestrial temperatures, gases emit IR energy in these bands.

5 DETECTION DISTANCE ESTIMATION

To discover how detection distance is estimated for various imagers, Equation 14 [25] can be used, which calculates thermal radiative intensity in terms of power per unit area emitting from a body:

$$I_0 = \frac{P}{A} = \varepsilon\sigma T^4 \tag{14}$$

where I_0 is thermal radiation, P is power of the emitting body, A is surface area of the emitting body, ε is the emissivity of the body, σ is the Stefan-Boltzmann constant, and T is the absolute temperature of the body surface in Kelvin.

If the hot body, in our case the ship exhaust, is at temperature T_H, and is radiating in a colder atmospheric environment, of temperature T_C, then the net thermal radiative intensity is:

$$I_0 = \frac{P}{A} = \varepsilon\sigma(T_H^4 - T_C^4) \tag{15}$$

The power from the ship exhaust is therefore:

$$P_{Exhaust} = (4\pi {R_0}^2)\varepsilon\sigma(T_H^4 - T_C^4) \tag{16}$$

where area A is a sphere of radius R_0 considering the body a point source radiating according to spherical spreading. The radiation energy at a distance R_1, follows the inverse square law, and the power intensity at this distance R_1 is [26]:

$$I_1 = \frac{(4\pi {R_0}^2)\varepsilon\sigma(T_H^4 - T_C^4)}{(4\pi {R_1}^2)} \tag{17}$$

The power of the exhaust that reaches the lens of the imager, with an area of A_{Lens}, is therefore:

$$P_{Lens} = I_1 * A_{Lens} \tag{18}$$

The imager has a system noise, called noise-equivalent power, *N*. The internal noise of the imager may be limiting, especially in an IR camera, which generates its own thermal energy. In order for the detection to be made, the power generated by the hot exhaust, at *R* distance away, must be greater than the noise-equivalent power, *N*. Hence, the threshold is:

$$P_{Lens} \geq N \tag{19}$$

where detection distance, *R*, can then be estimated when $P \geq N$.

Furthermore, Equation 19 can be expanded if a signal-to-noise ratio, *SNR*, for the imager is known, where:

$$SNR = \frac{P_{Lens}}{N} \tag{20}$$

5.1 SAMPLE CALCULATION

To illustrate how Equation 20 can be used to estimate detection distance, a sample calculation will be performed.

1. Radius, R_o, of the exhaust emissions plume leaving the vessel smokestack, is estimated to be 5 m.

2. Temperature of the hot exhaust gas at the funnel top, T_H, is 266°C [27]. This temperature was previously recorded on a 292 meter long and 32 meter wide RoRo/Containership while the vessel was at cruising speed.
3. Temperature of the atmospheric environment, T_C, is assumed to be 20°C.
4. Emissivity, ε, is estimated to equal 0.17, assuming an exhaust of 100% pure CO_2, at a pressure of 1 ATM (sea level) and a temperature of 266°C [28].
5. Stefan-Boltzmann's constant, σ, is 5.67×10^{-8} W/m^2 K^4.
6. For a detection to be made, the signal-to-noise ratio, *SNR*, must be at least 1 [29].
7. The noise-equivalent power, N, of the imager is estimated to be 7.92×10^{-5} W/m^2. This figure was determined using specifications from the Block Engineering PORTHOS detector [31].
8. A_{Lens} is estimated to equal about 0.0144 m^2.

Figure 4 below illustrates the experimental setup of the sample calculation.

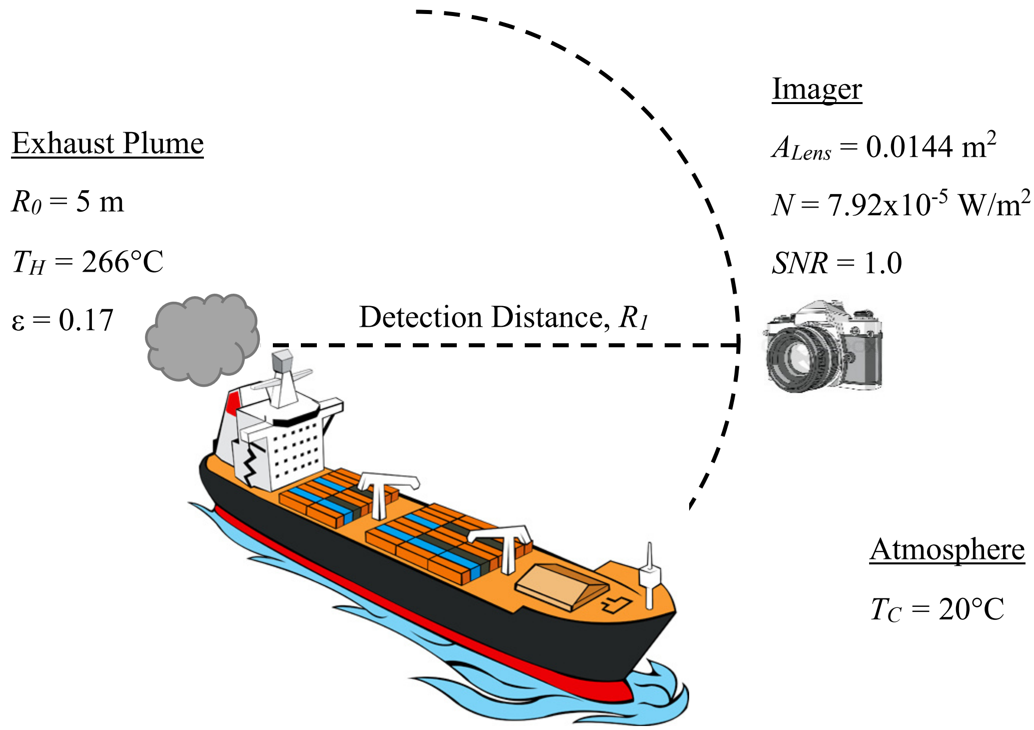


FIGURE 4: SAMPLE CALCULATION EXPERIMENTAL SETUP

With these parameters defined, detection distance for the hypothetical imager can be estimated. Equation 20 rearranges Equation 19 to solve for detection distance, R_1:

$$\sqrt{\frac{(4\pi {R_0}^2)\varepsilon\sigma(T_H^4 - T_C^4)A_{Lens}}{4\pi * SNR * N}} = R_1 \tag{20}$$

Equation 21 solves for detection distance using the predefined parameters:

$$\sqrt{\frac{4*\pi*1m^2*0.17*5.67*\frac{10^{-8}W}{m^2K^4}*((266+273°\mathrm{K})^4-(20+273°\mathrm{K})^4)*0.0144m^2}{4*\pi*1*7.92*10^{-5}W/m^2}} = 1{,}837\ meters \tag{21}$$

The estimated detection range of this hypothetical imager is above the minimum range of at least half a mile required for vessel emissions detection, at 1,837 meters or 1.14 miles. To further increase detection distance, a larger exhaust plume surface area, a higher exhaust temperature, a lower atmospheric temperature, or a lower noise-equivalent power is required.

6 MARKET SURVEY

To determine if there is a passive system capable of remote vessel emissions monitoring that is commercially available, a market survey has been conducted. The system requirements must include:

1. The ability for operation in the 2.6 µm – 3.0 µm, 3.8 µm – 4.8 µm, 5.4 µm – 6.2 µm, 7.3 µm – 7.9 µm, 8.5 µm – 8.9 µm, and 13.81 µm spectral regions;
2. The ability for remote operation, with a range of at least half a mile;
3. The ability for mobile operation, with a weight less than 50 pounds; and
4. A cost that is as low as possible.

Other parameters that are important for equipment selection but are more subjective for the purposes of this report include equipment footprint, spectral resolution, and data format. Detection range will be further investigated later on in this chapter.

6.1 PRODUCT INFORMATION

Several different types of devices available on the market were investigated with key features outlined in the next few sections. These include hyperspectral imagers, multispectral imagers, and infrared point detectors. The difference between these three detector types is the number of bands they can detect in and how narrow the bands are. Hyperspectral imagers can detect in hundreds or thousands of bands, while multispectral detectors generally operate in 3 to 10 bands. Infrared point detectors are limited to just one band.

While hyperspectral sensing-based imagers have a greater spectral operating range than multispectral sensing-based imagers, they often require large, expensive systems, and at times, exterior cooling systems. They will still be considered in this survey as it may be feasible to limit the spectral operating region to a desired frequency range, allowing for a smaller, more efficient system tailored for emission monitoring. Infrared point detectors were included as a source for comparison.

6.1.1 HYPERSPECTRAL IMAGERS

6.1.1.1 BERTIN TECHNOLOGIES SECOND SIGHT MS

The Bertin Technologies Second Sight MS is a $220,000, uncooled, hyperspectral LWIR imager that is ruggedized for field deployment. It operates in the 7 µm to 12 µm spectral region. The sensor images the scene by using filters, acquiring images in different bands, then changing the filter and acquiring the next band. Detections are overlaid on a visual image for analysis.

Pictured in Figure 5, the camera and processing unit weigh about 23 pounds. The unit includes a chemical library of 35 chemicals including blister agents such as mustard gas, nerve agents, and toxic industrial chemicals such as ammonia, carbonyl chloride, and hydrogen cyanide. Detection time is 2 seconds, while time to alarm is under 8 seconds. The system is capable of monitoring up to 15 different gases simultaneously while displaying up to 4 gases. Stated detection range is up to 3 miles, while the system can support 3 hours of operation with the optional battery pack [30].

FIGURE 5: BERTIN TECHNOLOGIES SECOND SIGHT MS

6.1.1.2 BLOCK ENGINEERING PORTHOS

The Block Engineering PORTHOS is a FT-IR scanning detector that operates in the 7.5 μm to 13 μm spectral region. The detector, viewed in Figure 6, scans a scene with a single pixel and overlays results into a visual image for analysis. The processing unit, integrated with the detector, uses MESH software to analyze the captured data. The detector weights about 17 pounds and is capable of detecting a range of gases with alarm times as low as 2 seconds. Detectable gases include Military C-Agents (Nerve, Blood, and Blister) such as ammonia, arsine, carbon disulfide, and hydrogen cyanide. Additional chemicals can be programmed as needed. Stated detection range is up to 3 miles, and the built-in battery has an approximate run-time of about 4 hours. The unit cost is $325,000 [31].

FIGURE 6: BLOCK ENGINEERING PORTHOS

6.1.1.3 BRUKER RAPID PLUS

The Bruker Rapid Plus is a hyperspectral FT-IR scanning detector that operates in the 7.5 μm to 14 μm LWIR spectral region. Detections and analysis are performed using the Bruker OPUS RS, a proprietary processing software. Weighing about 66 pounds, the system costs $225,000. Stated detection range depends on gas concentrations and field conditions, but can be greater than 3 miles. The system, pictured in Figure 7, includes several libraries needed for chemical, biological, nuclear, radiological, and explosive emissions detection [32].

FIGURE 7: BRUKER RAPID PLUS

6.1.1.4 BRUKER SIGIS-II

The Bruker Sigis-II is a hyperspectral FT-IR scanning detector based on a Michelson interferometer. The cooled detector operates in the 6.6 μm to 14.5 μm LWIR spectral region. The detector is capable of scanning up to 360 degrees, using Bruker OPUS RS software for detection and analysis.

The system, illustrated in Figure 8, weighs 143 pounds, costs about $300,000 and has several chemical libraries available specifically for chemical, biological, nuclear, radiological, and explosive events. With alarm times as low as 2 seconds, the detector has a high spectral resolution, which increases the ability to differentiate compounds with similar spectra. The stated detection range depends on gas concentrations and field conditions, but can be greater than 6 miles [33].

FIGURE 8: BRUKER SIGIS-II

6.1.1.5 CHEMRING I-SCAD

The Chemring I-SCAD is a hyperspectral FT-IR scanning detector based on a Michelson interferometer capable of operation within the 7 μm to 14 μm spectral region. The detector can scan up to 360 degrees, but the scan time can be shortened with a narrower scan range. Analysis for the detection of chemical warfare agents and toxic industrial chemicals is integrated into the detector. Weighing about 40 pounds, the stated detection range is up to 3 miles. The system costs $550,000 and is pictured in Figure 9 [34].

FIGURE 9: CHEMRING I-SCAD

6.1.1.6 FLIR GF304/GF306/GF320/GF343/GF346

The FLIR GF series comprises of hand-held, single-band, filter-based imagers. The detectors, illustrated in Figure 10, are internally cooled, calibrated (except the GF 343), and provide temperature data. Thermal data is shown as a visual image for analysis. The standard lens has a field of view of 10.8 to 14.5 degrees, with an optional lens available with a field of view of 24 degrees. The detectors each weigh about 4 pounds, and cost less than $100,000. They each have a stated detection range of up to 1.2 miles [35].

FIGURE 10: FLIR GF SERIES

6.1.1.7 MESH INC. IMCAD

The Mesh iMCAD (improved Mobile Chemical Agent Detector) is a hyperspectral FT-IR scanning detector based on a Michelson interferometer capable of operation within the 7 μm to 13 μm spectral region. The detector, viewed in Figure 11, can scan up to 360 degrees, and the display for the instrument includes an inset showing the detector field of vision. The detector system comprising of the sensor, scanner, and power supply weigh about 88 pounds. The hyperspectral system allows for in-depth analysis that provides detection for a large number of chemicals simultaneously. The stated detection range depends on gas concentrations and field conditions, but can detect from up to 4 miles away. The system costs $225,000 [36].

FIGURE 11: MESH INC. IMCAD

6.1.1.8 TELOPS HYPER-CAM MWE/METHANE/LW

The Telops Hyper-Cam series of detectors are hyperspectral imagers based on Michelson interferometers. They operate in both the MWIR and LWIR spectral range depending on the detector. All detections are overlaid on a visual image for analysis, with the field of vision spanning 5.1 to 6.4 degrees, and stated detection range of up to 3 miles.

The detectors, viewed in Figure 12, cost about $600,000 each, come with several chemical libraries, and offer alarm times as low as 2 seconds. The spectral resolution can be adjusted, with lower resolutions resulting in quicker scan times. Data analysis is performed independently of the sensor, requiring additional software. Telops offers both REVEAL PRO and REVEAL D&I software for research and real-time detection at an additional cost [37].

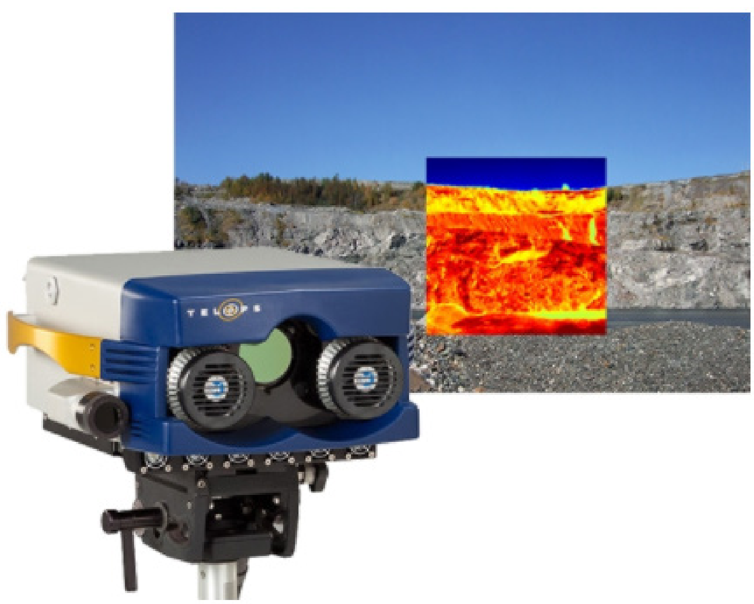


FIGURE 12: TELOPS HYPER-CAM SERIES

6.1.2 MULTISPECTRAL IMAGERS

6.1.2.1 AGROWING MULTI-SPECTRAL EVAULATION PACKAGE

The AgroWing Multi-Spectral Evaluation Package includes two multispectral Sony E-mount lenses, the NDVI and Red-Edge, that feature dual optical paths which split the visible spectrum for analyzing specific agricultural phenomena using AgroSense software. The AgroWing system is designed to be mounted on an unmanned aerial vehicle. Each lens allows for capturing different parts of the spectrum. The NDVI separates the 450, 550, 650, and 850 nm frequencies, while the Red-Edge lens separates the 450, 550, 710, and 850 nm frequencies. The multispectral imager system, illustrated in Figure 13, is specifically designed for agricultural surveying, costs $2,800, and weighs a total of 0.6 pounds. Stated detection range is up to two miles [38].

FIGURE 13: AGROWING MULTI-SPECTRAL EVAULATION PACKAGE

6.1.2.2 PIXELTEQ'S SPECTROCAM VIS-SWIR

Pixelteq's SpectroCam VIS-SWIR is an aerial-based multispectral wheel camera that offers a flexible platform for development and deployment for various imaging applications. The SpectroCam, viewed in Figure 14, features a high speed, continuously rotating filter wheel containing 6 to 8 interchangeable optical filters. The VIS-SWIR model includes detection in a spectral region of 500 nm to 1700 nm, and has a weight of 2.0 pounds. The camera has a stated detection range of 2 miles, and costs $57,508.50 [39].

FIGURE 14: PIXELTEQ'S SPECTROCAM VIS-SWIR

6.1.2.3 SILIOS TECHNOLOGIES CMS-S

The Silios Technologies CMS-S is a VIS/NIR multispectral camera system capable of detecting in the 650 nm to 930 nm spectral region. The camera has applications in precision farming, cosmetics, earth observation, medicine, and in autonomous vehicle technology. The system has a weight of 0.13 pounds and stated detection range of 2 miles. Price for the unit, pictured in Figure 15, is $8,890 [40].

FIGURE 15: SILIOS TECHNOLOGIES CMS-S

6.1.2.4 SLANTRANGE 3P

The SlantRange 3P is a multispectral sensor specifically designed for agricultural purposes. The unmanned aerial vehicle-based system, viewed in Figure 16, includes operation in the 410 nm to 950 nm spectral region. The unit weighs 0.77 pounds, and is capable of operation at up to two miles. Costing $3,950, the system is able to determine specific crop types and stages of growth. The 3P is also capable of determining different agricultural populations and pinpoint weed locations [41].

FIGURE 16: SLANTRANGE 3P

6.1.2.5 TELOPS MS-M2k/MS-V350

The Telops MS series includes multispectral infrared cameras equipped with a fast-rotating filter wheel, which allows the scene signal to be split into different spectral bands rather than one broadband image, enabling spectral signature analysis. The MS-M2k (Figure 17) operates in the spectral range of 3 μm to 5 μm, while the MS-V350 operates in the 7.5 μm to 12 μm spectral region. The cameras weigh about 29 pounds each, and have a stated detection range of 3 miles. Price is unknown for each of the cameras [42].

FIGURE 17: TELOPS MS SERIES

6.1.3 INFRARED POINT DETECTORS

6.1.3.1 GENERAL MONITORS MODEL IR400/IR2100

The General Monitors IR series point detectors are microprocessor-based hydrocarbon detectors that continuously monitor combustible gases and vapors, and provide alarm indication. The model IR 400 and IR 2100 detection principle is based on measuring the absorption of infrared radiation passing through a volume of gas using a dual beam, single detector method. The infrared detector measures the intensity of two specific wavelengths, one at an absorption wavelength, and the other outside of the absorption wavelength. The gas concentration is then determined by a comparison of these two values.

The IR point detectors are capable of detecting methane, propane, ethane, ethylene, butane, hexane, pentane, and benzene. The aluminum model weighs 3 pounds, while the stainless steel model weighs 6 pounds (Figure 18). The devices are active detectors suited for installation in pipe and smokestack systems. Since they measure the infrared radiation passing through the detector, the detection range is 0 miles. The IR400 model costs $275, while the IR2100 model costs $150 [43].

FIGURE 18: GENERAL MONITORS IR SERIES

6.2 SURVEY FINDINGS

The market survey identifies 22 unique detection systems currently sold on the market, ranging in price from about $150 to $600,000. Systems vary in detection method, cost, spectral range, weight, and stated detection range. Some detectors target a single gas, while others are capable of identifying a large number of gases. Some detectors have on-board, real-time data processing, while others require processing through a separate computer. Table 3 illustrates the survey findings for 22 detection systems and their key parameters.

Product Name	Spectral Region (µm)	Weight (lb)	Stated Detection Range (mi)	Cost (USD)	Suitable for VEMS?
HYPERSPECTRAL IMAGERS					

Bertin Technologies Second Sight MS	7 - 12	23	3	$220,000	O
Block Engineering PORTHOS	7.5 - 13.5	17	3	$325,000	O
Bruker Rapid Plus	7.5 - 14	66	3	$225,000	X
Bruker Sigis-II	6.6 - 14.5	143	6	$300,000	X
Chemring I-SCAD	7 - 14	40	3	$550,000	O
FLIR GF304	8.0 - 8.6	4	.6 - 1.2	$100,000	X
FLIR GF306	10.3 - 10.7	4	.6 - 1.2	$100,000	X
FLIR GF320	3.2 - 3.4	4	.6 - 1.2	$100,000	X
FLIR GF343	4.0 -4.4	4	.6 - 1.2	$100,000	O
FLIR GF346	4.52 - 4.67	4	.6 - 1.2	$100,000	O
MESH Inc. iMCAD	7 - 13	88	4	$225,000	X
Telops Hyper-Cam MWE	1.5 - 5.4	68	3	$600,000	X
Telops Hyper-Cam Methane	7.4 - 8.3	68	3	$600,000	X
Telops Hyper-Cam LW	7.7 - 11.8	68	3	$600,000	X
MULTISPECTRAL IMAGERS					
AgroWing Multi-Spectral Ev. Package	0.45 - 0.85	0.6	2	$2,800	X

Pixelteq's SpectroCam VIS-SWIR	0.5 - 1.7	2	2	$57,509	X
Silios Technologies CMS-S	0.65 - .93	0.13	2	$8,890	X
SlantRange 3P	0.41 - 0.95	0.77	2	$3,950	X
Telops MS-M2k	3 - 5	29	3	NA	O
Telops MS-V350	7.5 - 12	29	3	NA	O
INFRARED POINT DETECTORS					
General Monitors Model IR400	Methane, Propane, Ethane, Ethylene, Butane, Hexane, Pentane, Benzene	3	0	$275	X
General Monitors Model IR2100	Methane, Propane, Ethane, Butane, Hexane,	3	0	$150	X

	Pentane, Benzene					
Notes: VEMS - Vessel Emissions Monitoring System ✓ - Suitable O - Partially Suitable X - Not Suitable						

TABLE 3: SURVEY FINDINGS

The market survey demonstrates that out of the best 22 contenders, there is no detection system in production that can provide complete vessel emissions monitoring. 7 detection systems, the Bertin Technologies Second Sight MS, Block Engineering PORTHOS, Chemring I-SCAD, FLIR GF343, FLIR GF346, Telops MS-M2k, and Telops MS-V350 are classified as “Partially Suitable”. While all 7 systems comply with weight, stated detection range, and cost requirements, they do not cover the complete spectral range required for vessel emissions detection. The remaining 15 detection systems are classified as “Not Suitable”. The Bruker Sigis-II/Rapid Plus, MESH Inc. iMCAD, and Telops Hyper-Cam MWE/Methane/LW all exceed weight limits, rendering them immobile. The FLIR GF304/306/320, AgroWing Multi-Spectral Evaluation Package, Pixelteq's SpectroCam VIS-SWIR, Silios Technologies CMS-S, and SlantRange 3P operate at spectral ranges inadequate for vessel emissions monitoring. The General Monitors Model

IR400/IR2100 infrared point detectors are active devices that are not capable remote and passive operation, rendering them unsuitable for our purposes.

The majority of the hyperspectral systems are specially designed for chemical, biological, nuclear, radiological, and explosive emissions detection. Typical customers include police departments, homeland security-related agencies, and the military. In addition, many multispectral systems on the market are specially designed for agricultural purposes, and therefore cannot detect vessel emissions. These systems are effective at detecting different types of solid materials, but are unable to detect gases. Infrared point detectors actively detect gases, and must be placed inside the emissions plume, rendering this technology unsuitable for our remote and passive system.

The market survey indicates that a system completely suited for vessel emissions enforcement does not currently exist. A passive, infrared detection system capable of vessel emissions monitoring therefore cannot readily be purchased on the market, and will require specialized design and consideration. While there is not a system that completely meets our needs, the MS Series by Telops represents the most suitable detection system available. An interested emissions enforcement agency should contact the manufacturer directly to see if it is feasible to alter the imager's operating spectral region to the bands appropriate for CO, CO_2, NO_x, and SO_x detection as detailed in this study.

7 MOBILITY CONSIDERATIONS

7.1 MODULAR DESIGN

The vessel emissions monitoring system (VEMS) must have a standardized design scheme that can be used on a variety of mobile detection platforms (Figure 19) that operate within close proximity to shipping channels. These detection platforms include typical assets from enforcement agencies such as patrol boats and ground-based vehicles, helicopters and planes, and land-based tripod systems. Upcoming detection platforms include the use of smart buoys and unmanned aerial vehicles.

Modular design is a design approach that subdivides a system into smaller parts, called modules. These modules can be independently created and used in different systems interchangeably. Modularity offers benefits in cost savings due to less customization across platforms and shorter learning times, and the ability to be easily replaced or interchanged [44]. It is imperative the vessel emissions monitoring system use modular architecture in its design scheme to allow for easy interchangeability between detection platforms. This will allow for a single unit that can operate seamlessly with many detection platforms, allowing the system to be quickly swapped depending on mission requirements. For example, a unit can be disconnected from a ground patrol vehicle and seamlessly reconnected to a helicopter if the mission focus changes, from port to offshore emissions monitoring. This is a cost-effective approach for enforcement agencies, as it eliminates the need to have a dedicated system for each detection platform; one unit can be shared within the array of detection platforms.

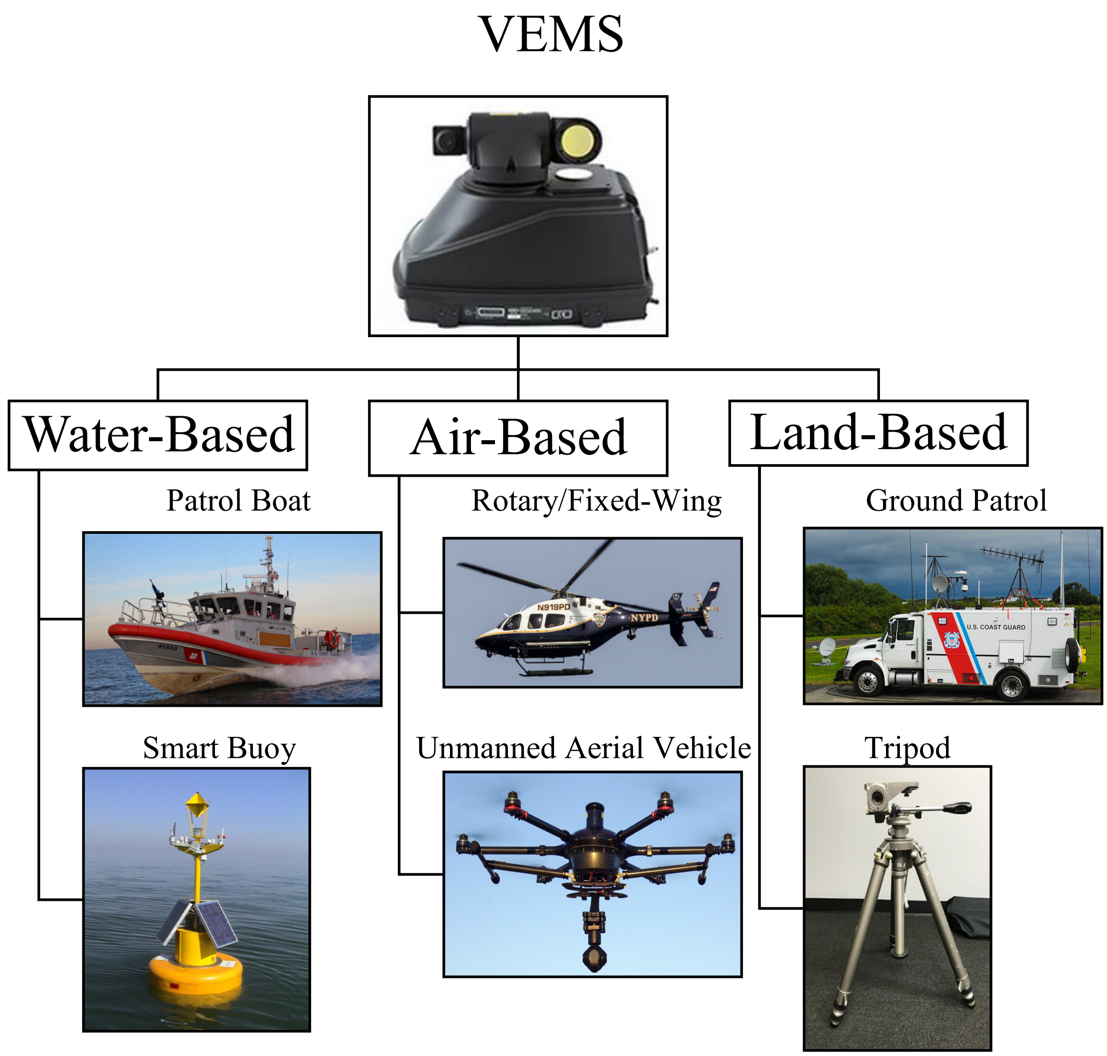


FIGURE 19: MOBILE DETECTION PLATFORMS

7.1.1 PATROL BOAT

The United States Coast Guard, a vessel emissions enforcement agency, operates a fleet of 25-foot boats that regularly patrol harbor entrances and shipping channels. The Defender Class boats were procured under an emergency acquisition authority in a direct response to the need for additional Homeland Security assets in wake of the September 11th terrorist attacks.

The 400-vessel Defender Class fleet is assigned to the Coast Guard's Maritime Safety and Security Teams, Maritime Security Response Team, Marine Safety Units, and Boat Stations throughout the Coast Guard. With two 225 horsepower outboard engines, a unique turning radius, and gun mounts forward and aft, the Defender Class boats are exceptional waterborne assets for conducting fast and high-speed maneuvering tactics in a small and deployable package [45].

With these attributes, the patrol boat represents a perfect candidate for use as a detection platform for a vessel emissions monitoring system. It is important to note that the vessel emissions monitoring system must be waterproof, corrosion resistant for saltwater spray, and have the ability to withstand intense vibrations, and forces associated with the vessel slamming into waves. Figure 20 illustrates an adequate location for placement of VEMS, denoted by the yellow box on the roof of the cabin, within clear and unrestricted sight of vessels forward the patrol boat. It is important to place the vessel emissions monitoring system in a position that will not impede or interfere with radar and communications. Additionally, the system must have a self-cleaning component that will free the lens of any sea spray or debris.

FIGURE 20: VEMS PLACEMENT ON PATROL BOAT

7.1.2 SMART BUOY

Smart buoys are increasingly gaining attention in the maritime industry. Smart buoys provide a large amount of information that can be accessed remotely, and often in real-time. The buoys, which usually collect water samples, such as temperature, salinity, and current information, have ever-expanding applications [46].

Clever Buoy [47] is a marine monitoring platform that contains a shark detection and response system that autonomously identifies large sharks and sends warning signals to shore for human intervention response. The ASC SCOUT [48] is a smart buoy that is autonomous, self-propelled, and GPS-positioned, eliminating the need for mooring hardware and therefore reducing installation cost. In addition, a Summer Research Institute team at the Maritime Security Center [49] identified the feasibility of the creation of a smart buoy for the purposes of an underwater passive acoustic detection system.

Installation of the vessel emissions monitoring system on a smart buoy positioned at the entrance of a shipping channel is possible pending further research. The smart buoy must have an adequate power supply to allow for frequent operation of the monitoring system. In addition, the power supply, which is fed by wind power, solar cells, or wave motion, must be capable of sending emissions information remotely via satellite or cellular communications links. Figure 21 illustrates potential placement of VEMS on a smart buoy, as denoted by the yellow box.

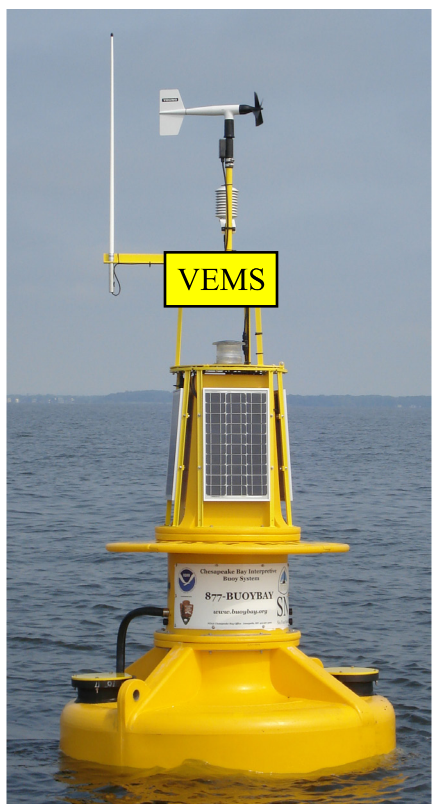


FIGURE 21: VEMS PLACEMENT ON SMART BUOY

7.1.3 ROTARY/FIXED-WING

Air-based detection methods include both rotary and fixed-wing in the form of helicopters and planes. Helicopters, however, are preferred for the vessel emissions monitoring system as they have the ability to hover in place and are more versatile than airplanes. The New York Police Department (NYPD), a potential vessels emissions enforcement agency for the Port of New York and New Jersey, has a fleet of helicopters at their disposal. The NYPD Air Support and Air Sea Rescue Unit operates 4 medium-lift helicopters, and 4 light helicopters. The Bell 412 medium-lift helicopters are used for missions such as tactical support, fast roping, firefighting, port security and rescue operations [50].

The NYPD helicopters are equipped with radiation detectors. The helicopters regularly scan critical infrastructure and landmarks, and have the capability to "fly over a container, cargo, or tanker ship and accurately detection a radiation signature from an altitude of 200 feet" [51]. This is significant since the radiation detector and a vessel emissions monitoring system deployed on the helicopter can help complete two missions in one scan.

Using a helicopter as a detection platform, VEMS must be able to withstand high winds and intense vibrations. The monitoring system may be placed on the underside of the nose of the aircraft, or on the belly of the aircraft, as shown in Figure 22.

FIGURE 22: VEMS PLACEMENT ON HELICOPTER

7.1.4 UNMANNED AERIAL VEHICLE

Unmanned aerial vehicles (UAVs) are creating paradigm shifts across all sectors, ranging from real estate and home delivery, to search and rescue and safety inspections. An unmanned aerial vehicle is an aircraft without a human pilot aboard. The flight of UAVs may operate with various degrees of autonomy, either under remote control by a human operator, or autonomously by onboard computers.

An unmanned aerial vehicle may be a suitable detection platform for the vessel emissions monitoring system pending additional research. While the usage of UAVs represent a huge cost reduction in contrast to a helicopter, there are a limited number of UAVs commercially available that can lift up to the 50-pound VEMS upper-bound weight limit.

In addition, it is not clear if the selected UAV will have enough power to supply both the VEMS and a communication link within a meaningful detection time frame.

The Vulcan UAV Airlift series represent one of the heaviest lift UAVs commercially available. Supporting loads of up to 66 pounds for up to 30 minutes, the UAV features eight electric brushless motors, which allow the UAV to reach a maximum speed of 30 miles per hour. Depending on the goal, the Vulcan UAV Airlift can be equipped with electro-optical, infrared, and thermal cameras. The aircraft has the ability to be folded for transportation or storage [52].

Figure 23 illustrates the Vulcan UAV Airlift with a vessel emissions monitoring system as its payload denoted by the yellow box. Since flight-time is limited, the unmanned aerial vehicle must be operated in a timely and precise manner. Depending on port activity and vessel frequency, a fleet of UAVs may be required so one is operational at all times (while the others may be charging). The UAVs may also be programmed to intercept and scan emissions autonomously using vessel AIS and GPS information.

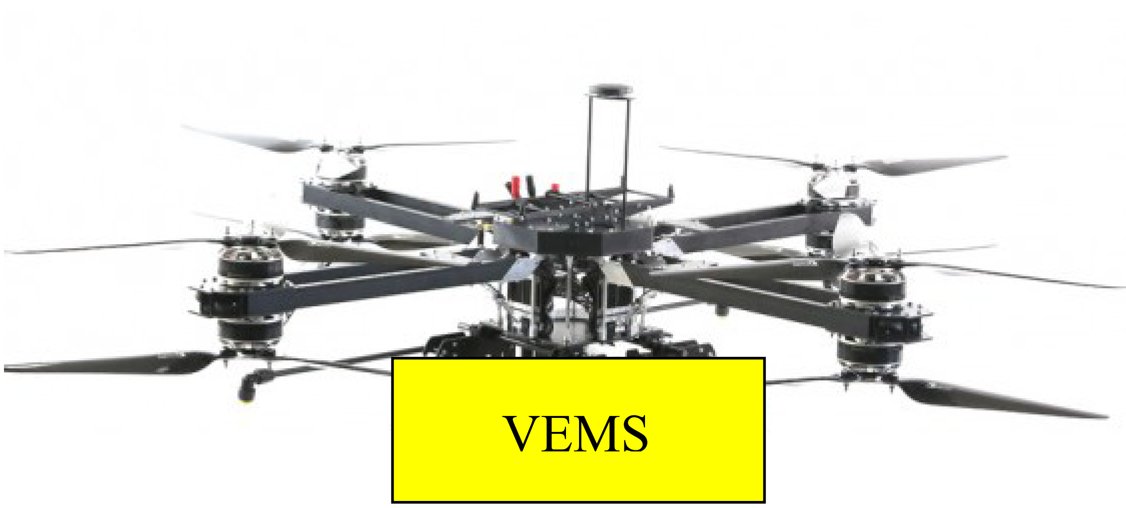


FIGURE 23: VEMS PLACEMENT ON UNMANNED AERIAL VEHICLE

Unmanned aerial vehicles are significant because they can be used to intercept vessels offshore before they enter the port area and pollute the region if noncompliance is detected. Analysis of the three largest ports in the United States shows that heavy lift drones such as the Vulcan UAV Airlift are powerful enough as described by the manufacturer to intercept and scan vessels within a reasonable range and fly back ashore. The Vulcan UAV Airlift can fly for 30 minutes with a 66-pound load at 30 miles per hour. The range of the UAV is:

$$\frac{30\ miles}{60\ minutes} * 30\ minutes = 15\ miles \qquad (22)$$

However, since the UAV must intercept and scan a vessel out at sea and return back to base, the effective range of the UAV in perfect conditions is therefore:

$$\frac{15\ miles}{2} = 7.5\ miles \qquad (23)$$

For the three largest ports in the United States, the Port of Los Angeles, the Port of Long Beach, and the Port of New York and New Jersey, the effective UAV range of 7.5 miles is satisfactory for scanning vessels away from population centers, and within range of potential UAV landing and operational bases.

For the joint Port of Los Angeles (LA) and Port of Long Beach (LB), a potential UAV-equipped VEMS base is stationed right at the center of the port, on San Pedro Island, California. USCG Sector LA/LB operates a major facility in the port, equipped with vessels and personnel. Figure 24 below illustrates the location of the base on the map, which includes an overlay of ship density over the year 2017 for the port. The intercept area is an arc with a radius of 7.5 miles away from Sector LA/LB. The map indicates that a maximum effective range of 7.5 miles is suitable to scan any ship desired away from the population center and within range of the potential UAV operational base.

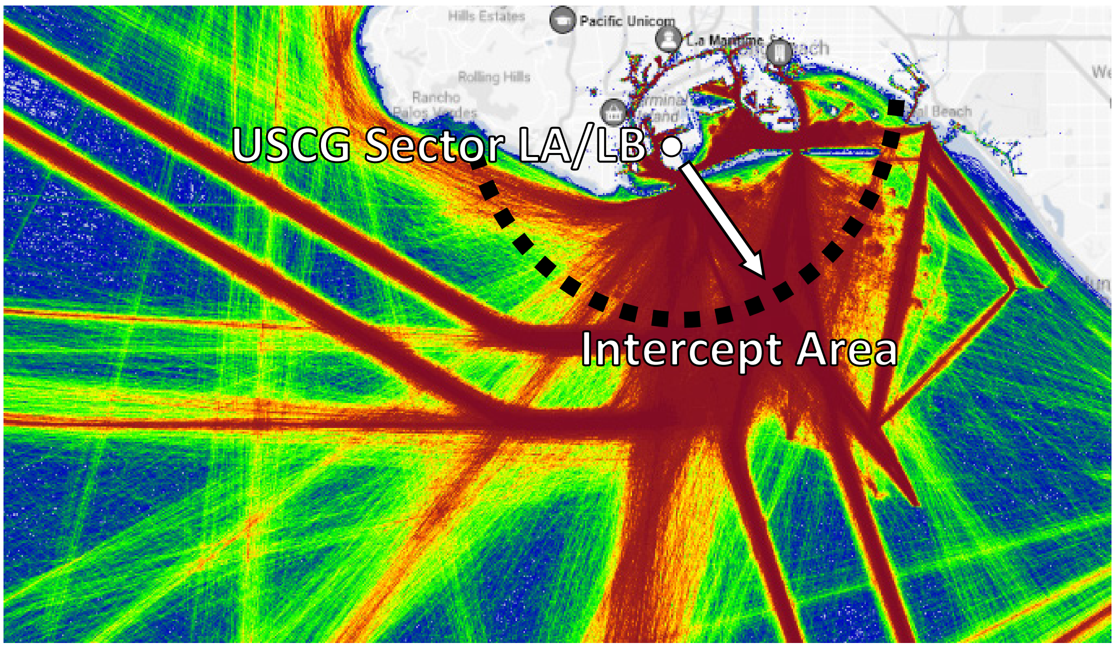


FIGURE 24: UAV OPERATING DIAGRAM FOR PORT OF LOS ANGELES AND LONG BEACH [SOURCE: MARINETRAFFIC]

For the Port of New York and New Jersey, potential vessel emissions enforcement agencies have operating facilities approximate to the Ambrose Channel, the main shipping channel. The NYPD Aviation Unit is stationed at Floyd Bennett Field in Brooklyn, New York, and represents a perfect base for UAV operations. All NYPD helicopters are stationed at this location. Another potential base for VEMS-equipped UAVs is at the USCG base at the tip of Sandy Hook Island in Monmouth County, New

Jersey. Coast Guard cutters and personnel are stationed at this site. While air-operations do not currently occur here, the site is well-situated within close proximity to the shipping channel. The intercept area in Figure 25 below is about 7 miles away from both NYPD and USCG bases.

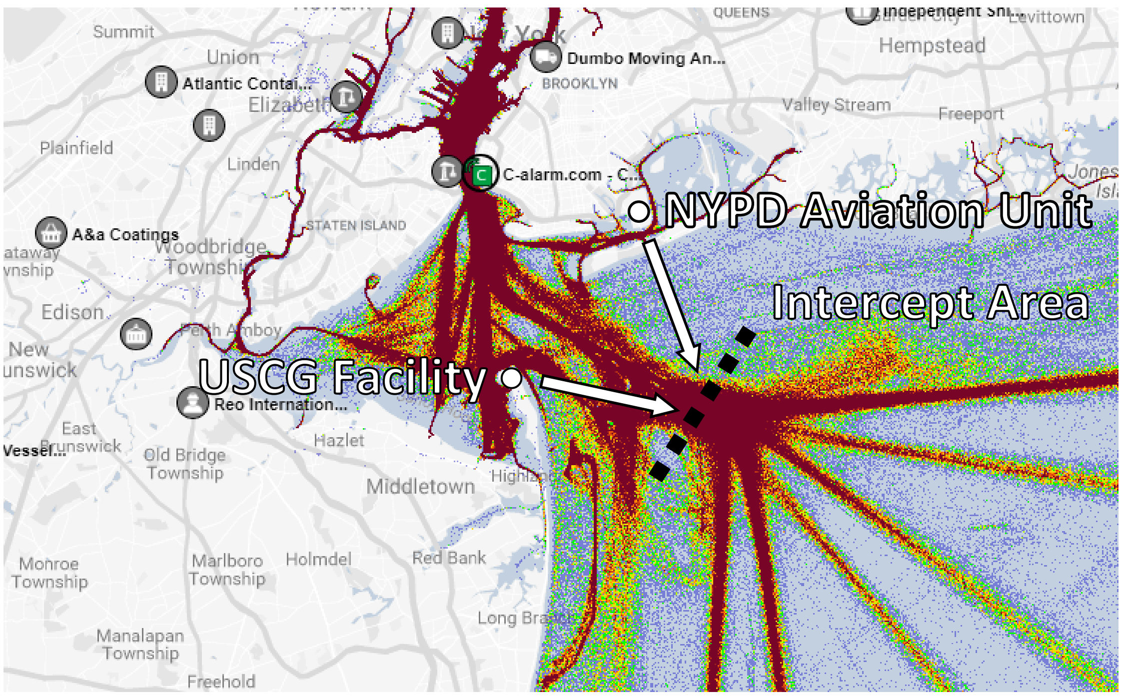


FIGURE 25: UAV OPERATING DIAGRAM FOR PORT OF NEW YORK AND NEW JERSEY [SOURCE: MARINETRAFFIC]

7.1.5 GROUND PATROL VEHICLE

The United States Coast Guard, Environmental Protection Agency, and other potential emissions enforcement agencies maintain a fleet of ground patrol vehicles at their disposal. These vehicles, which range from cars to sport utilities, vans to trucks, may serve as potential vessel emissions detection platforms if placed within proximity to shipping channels. Ground patrol vehicles are regularly found in the port environment and perform safety and security monitoring for maritime operations. Often equipped with chemical and radiological detectors, cameras, and scanners, patrol vehicles may serve as a primary detection platform for the vessel emissions monitoring system. Figure 26 illustrates potential placement for the monitoring system, as denoted by the yellow box, for a ground patrol vehicle common to a port area.

FIGURE 26: VEMS PLACEMENT ON GROUND PATROL VEHICLE

7.1.6 TRIPOD

Tripods have the highest degree of mobility of detection platforms discussed. They can be deployed at moment's notice, are able to support a large load, and can be repositioned within minutes or less. Similar to patrol vehicles and other land-based detection platforms, they must be placed on the coastline within proximity to the shipping channel. Opposed to vehicles, tripods are not self-powered; a vessel emissions monitoring system mounted on a tripod requires an external power source. The power source can be in the form of a battery or direct connection to the power grid. A communications link can send vessel emissions data to a central monitoring station, eliminating the need for constant staffing. The tripod and monitoring system must be weighed down in extreme weather conditions, or can be taken inside if necessary. In certain situations, a tripod can be used in conjunction with a helicopter, patrol boat, or ground patrol vehicle for vessel emissions monitoring. Figure 27 illustrates typical tripod setup for the monitoring system, denoted by the yellow box.

FIGURE 27: VEMS PLACEMENT ON TRIPOD

7.2 SYSTEM ACCESSIBILITY

Along with a high degree of mobility, the vessel emissions monitoring system must possess a high degree of accessibility; it must be easy to use. The system must include both hardware and software that is practical and user-friendly. It is not assumed that the operators of the monitoring system will derive from engineering or scientific backgrounds. Therefore, it is imperative to design and select an intuitive system that can be learned in the quickest time possible. In addition, upmost care must be taken when handling the system; a ruggedized system design must be selected that is able to withstand drops and rough handling.

7.3 MOBILITY & ACCESSBILITY OUTCOMES

The vessel emissions monitoring system should be built using modular design architecture to allow for interoperability between detection platforms. This will allow for one unit that can be operated and exchanged seamlessly amongst many detection platforms depending on mission requirements. This design approach is advantageous as detection platform sharing will lead to a reduction in equipment and training costs. Since at least one unit is needed and can be shared amongst air, water, and land-based vehicles, crews will only need to learn how to operate one device regardless of detection platform.

The detection platforms most suitable for vessel emissions monitoring include patrol boats, smart buoys, helicopters, unmanned aerial vehicles, ground-based vehicles, and tripods. Various detection platforms require different design considerations. For one device capable of complete interchangeability between all detection platforms, the vessel emissions monitoring system must be able to withstand intense vibrations, be waterproof, resist corrosion from saltwater spray, resist forces associated with slamming into waves, be ruggedized to withstand drops and rough handling, and have a system capable of clearing the lens of salt and debris. It is critical to add that the system must be accessible to the user. It should be intuitive and easy to operate, and should require as less training as possible

8 CONCLUSIONS & RECOMMENDATIONS

Vessels in the maritime transportation system can emit significant amounts of pollution that affects populations living near the water as well as those living hundreds of miles inland. The vessel emission gases, in the form of nitrogen oxides, sulfur oxides, carbon monoxide and carbon dioxide, contribute to adverse health effects and climate change. International shipping accounted for approximately 2.2% of global CO_2 emissions, and 2.1% of global greenhouse gas emissions in 2012. In addition, NO_x and SO_x emissions from the maritime shipping industry represent approximately 13% and 12% of worldwide NO_x and SO_x emissions in 2012.

MARPOL Annex VI, adopted on January 8, 2009 in the United States, establishes significant limits for NO_x and SO_x emissions from marine engines. Beginning in 2015, fuel used by all ships operating up to 200 nautical miles off of U.S. shores must use marine diesel that cannot exceed 0.1% fuel sulfur content, or 1,000 ppm. Beginning in 2016, new engines on ships operating in ECAs must use emission controls that achieve an 80% reduction in NO_x emissions. While the U.S. EPA and USCG entered into a Memorandum of Understanding to enforce Annex VI MARPOL in 2011, it is evident that a limited amount of compliance inspections are performed. In 2016, out of 81,877 ship visits to the United States, only 9,390 or 11.5% of total ships were inspected by the USCG for safety issues, which includes issues that present a danger to the vessel, its crew, the port, or the environment. An even smaller percentile of vessels are inspected for Annex VI compliance.

A literature review was performed to determine the status of research in the remote sensing of ship emissions. While there has been some research in the remote detection and identification of vessel emissions, none present an operational system ready for use by enforcement agencies. The systems proposed are exploratory and primarily used as scientific research tools. They are large, impractical, overcomplicated, overly-expensive, and are therefore unsuitable for operational use by emission enforcement agencies. The literature review ultimately finds that a vessel emissions monitoring system able to operate remotely and in real-time does not currently exist.

A need therefore exists to develop a system that can detect, identify and quantify ship emissions remotely and in real-time to allow for more frequent inspections with limited resources. The system must be compact and lightweight to allow for deployment on a variety of mobile sources that operate within the port region. Multispectral-sensing technology, which captures image data at specific frequencies across the electromagnetic spectrum, can be applied to enforce emission regulations. The thesis responds to the following research question: How can multispectral imaging technology be used to develop a vessel emissions monitoring system capable of remote and mobile operation?

Multispectral-sensing technology was investigated to determine if it could be applied to enforce emissions regulations. It was discovered that passive open-path Fourier-transform infrared emission spectroscopy was well suited for vessel emissions detection. This detection method measures the frequencies and intensities at which the emission gas emits thermal radiation, remotely over long optical paths to the atmosphere. Since the system can operate passively without a second device acting as an infrared source, the technology shows potential to be used for a variety of mobile enforcement applications.

To determine which frequency bands were required for the multispectral-sensing based vessel emissions monitoring, reference data from the NIST Chemistry WebBook Standard Reference Database Number 69 was used. Since infrared spectral data from the NIST catalog is presented in the JCAMP-DX format, a MATLAB code was developed to convert the JCAMP-DX files into infrared spectral charts for analysis. Charts created were plotted with transmittance as the y-axis, ranging from 0.0 to 1.0, and wavenumber as cm^{-1} plotted as the x-axis, ranging from 4000 cm^{-1} to 0 cm^{-1}. Carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitric oxide (NO), and nitrous oxide (N_2O) were analyzed. It was found that frequencies required for vessel emissions monitoring comprise of the following six bands: 2.6 µm – 3.0 µm, 3.8 µm – 4.8 µm, 5.4 µm – 6.2 µm, 7.3 µm – 7.9 µm, 8.5 µm – 8.9 µm, and 13.81 µm.

A market survey was then conducted to determine if there were any systems commercially available suitable for vessel emission monitoring. Besides operation in the above six spectral regions, it was determined that the system must also have the ability for remote operation, with a range of at least half a mile, for mobile operation, with a weight less than 50 pounds, and with a cost that is as low as possible. The market survey demonstrates that out of the best 22 contenders, there is no detection system in production that can provide complete vessel emissions monitoring. While there is not a system that completely meets our needs, the Hypercam Series by Telops represents the most suitable detection system available. The study recommends modifying this system to allow operation in the desired spectral region.

The study then determines the detection platforms most suitable for vessel emissions monitoring include patrol boats, smart buoys, helicopters, unmanned aerial vehicles, ground-based vehicles, and tripods. Design considerations were investigated for each detection platform. A modular design architecture was recommended to allow for interoperability between detection platforms, reducing the cost of equipment and training. Finally, accessibility considerations were discussed. The chosen system design must be as intuitive and user-friendly as possible.

An operational, real-world problem involving MARPOL Annex VI compliance enforcement was identified and a potential solution was recommended through the development of a multispectral sensing-based vessel emissions monitoring system. This research has served to lay the groundwork behind the fundamental principles and design considerations involved for the development of such a system. These guidelines act as an initial probe and are by no means complete; therefore, the study recommends further research and consideration into both hardware and software design. Additionally, interested parties should contact multispectral imager manufacturers directly to determine the possibility of modifying existing equipment for the purposes of vessel emissions monitoring as outlined in this report. Ultimately, the development guidelines for a multispectral sensing-based vessel emissions monitoring system as proposed in this report shows plausibility to provide enforcement of MARPOL Annex VI and EPA emission regulations.

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