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High Resolution Passive and Remote Detection and Measurements of CO2

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INTRODUCTION

Remote sensing confers several advantages over ground-based measurements that make it an important tool for developing CO2 emissions inventories. Anthropogenic CO2 monitoring requires a high degree of accuracy in order to detect changes against the natural background variations of CO2. While studies indicate that some satellites already have some level of CO2 measurement accuracy, it is unclear what instrument complexities might be responsible. Satellite instruments have been designed with a wide variety of spatial, temporal, and spectral resolutions depending on their original mission objectives, and any one or more of these properties might allow for a high CO2 measurement accuracy.

An essential requirement for an ideal system to detect and quantify CO2 is the ability to calibrate itself to a variety of system and atmospheric conditions that affects measurement. Monitoring for a safe none leaking CO2 storages in different geologic formations (including surface, near-surface, and subsurface areas) implies accurate quantifications for small leakages in areas with vast different environmental variables. The speeds of calibrations have to be fast enough to match the quick changing of the environmental conditions.

Another very important aspect is the resolution, the capability of differentiation between the target gas and other gases in the same vicinity. For this system to provide measurements that is comparable with a mass spectrometer, it has to have a very narrow bandwidth filtering (vertical sides down to a pixel level) to take advantage of very narrow IR transmittance.

For this deal system to be economically feasible, it must process the detection and quantification in minimum time limits. This is essential for the system to be able to multiplex its readings and measurements from many different sensors. Each area with different measurement ranges.

This is similar to the behavior of the human mind that quantifies data from variety of sensory inputs and makes decisions instantly. To make quantification as accurate as possible, each sensor data has to get calibrated with respect to its own location for different atmospheric conditions. Above all an effective system must calibrate and filter the data accurate enough to prevent false alarms.

OBJECTIVES

The objective of this paper is to determine the feasibility of a new technology of CO2 identification and concentration measurement. It provides for a very high resolution, and a new calibration methodology, that will drastically improve accuracy of measurement of CO2 remotely, even in the presence of other gases. It is also the goal of this paper is to show that much faster processing of sensor data (Digital Image Processing) allows fusion of data from many different sources for economic reasons.

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1- Filtering (differentiation)

The concept is simple. When we watch TV, we are watching pixels or combination of them. We watch the pixel colors (in visible light) and associate the colors with pre-recorded colors in our memories. The new filtering technology does what our eyes and brain do when we watch TV. It detects the pixels (primary) color intensities of the visible light and utilizes memories to identify a target by comparison of the color intensities with a known color intensities (that are pre-stored in memory); thus identification is made. There is no high mathematics involved to filter each or a group of pixels to identify a target. <u>This simple scheme will provide a new window of opportunities in very high resolution detection in the visible light and IR spectrum</u>.

Since it avoids complex and time consuming calculations, the filtering is fast enough for real time detection purposes. The filtering, detection and measurement of CO_2 is based upon the same concept.

Figure 2 show the new memory based filtering technique, consisting of three holding registers, Three memories and an AND gate. This simple hardware based Digital Tunable Filter opens a new window of opportunities in substance or target detection and identification not available with the present technology of image processing.

Current State of the Art

Current approaches in DSP technology relies on Fast Fourier Transforms, Kalman filters or similar techniques, to recognize, classify and quantify. They utilize pattern recognition, class or cluster recognition in which a variety of attributes are used for identification and measurements.

However, these techniques suffer from major setbacks of 1) very low speeds due to intensive computations and 2) low resolutions (lack of ability to differentiate a signal from a noise) due to utilization of group of pixels for identification and differentiation. The usual patterns are either 3x3 pseudo-Gaussian for dim points or 5x5 for brighter points. This process is called centroiding, in which the peak location of the pattern in pixel space is used as identification. They are not capable of delivering the required accuracies in measurements fast enough to service all sensors for the purposes of fusion.

The calibration process suffers from the same methodology of intensive mathematical calculations. This process results in inaccurate normalizations. They are too slow to be effective in fast changing environmental conditions. As the number of environmental variables increase, so does the time to normalize.

The present system of DSP (calibration and filtering) cannot deliver the speeds and resolutions demanded by a proper fusion system. The resolutions are so low that some systems require a mass spectrometer as an added cost and complexity.

2. CALIBRATION OF CHANNELS

The new calibration methodology is to calibrate channels on a continuous, pixel by pixel or a frame to frame timing to meet the rapid changes of adverse environment conditions, with the results of far accurate identification, concentration measurements and fusion of data. To achieve this goal, memories are used to store pre calculated data

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from existing mathematical or experimental results to calibrate (normalize) without resorting to time consuming calculations of equations during measurements.

Preliminary Test Results on the Proof of Concept

Simulation of the proposed Tunable Filter in visible light has provided much higher resolutions and faster processing times. The tunable filter was used for counting of hundreds of NOAA's sea lions (and penguins), Figure 1 below. The preliminary proof of concept is based upon visible light RGB spectrum of three primes and 8 bit per prime. The same concept will provide the same result for the IR spectrum with different number of channels and different number of A/D converters.
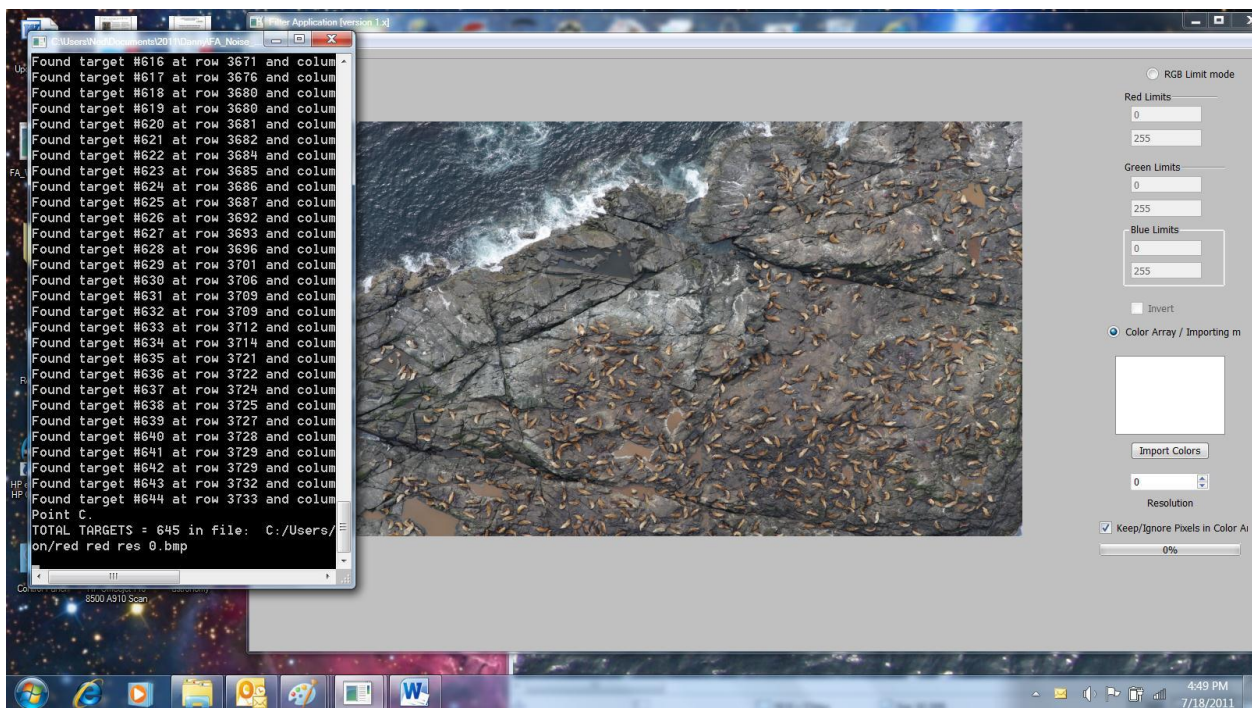

Figure 1- Counting of Sea Lions (645) lying on a beach (the original picture is the courtesy of NOAA)

CO2 Spectrum

The long wave IR CO_2 slicing channels between approximately 13.2 and 14.5 μm have beenimplemented in a number of meteorological satellite instruments [1. Smith, W.L.; Woolf, H.M.; Hayden, C.M.; Wark, D.Q.; McMillin, M. The TIROS-N operational vertical sounder. Bull. Amer. Meteor. Soc. **1979**, 60, 1177-1187. Smith, W.L.; Suomi, V.E.; Menzel, W.P.; Woolf, H.M.; Sromovsky, L.A.; Revercomb, H.E.;Hayden, C.M.; Erickson, D.N.; Mosher, F.R. First sounding results from VAS-D. Bull. Amer.] Multi-years of high cloud statistics obtained from a series of satellite sensors of National Oceanic and Atmospheric Administration (NOAA) have beenreported [Wylie, D.P.; Menzel, W.P.

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*Eight years of high cloud statistics using HIRS. J. Climate **1999**, 12,170-184].* The CO_2 slicing technique is a well accepted method for inferring cloud height frompassive IR remote sensing observations *[Smith, W.L.; Frey, R. On cloud altitude determinations from high resolution interferometer*

Filtering and Detection Hardware

Figure 2 (below) is the hardware block Diagram of Tunable Filter for visible light as a part of patent (7,529,404) related to filtering, identification and tracking.
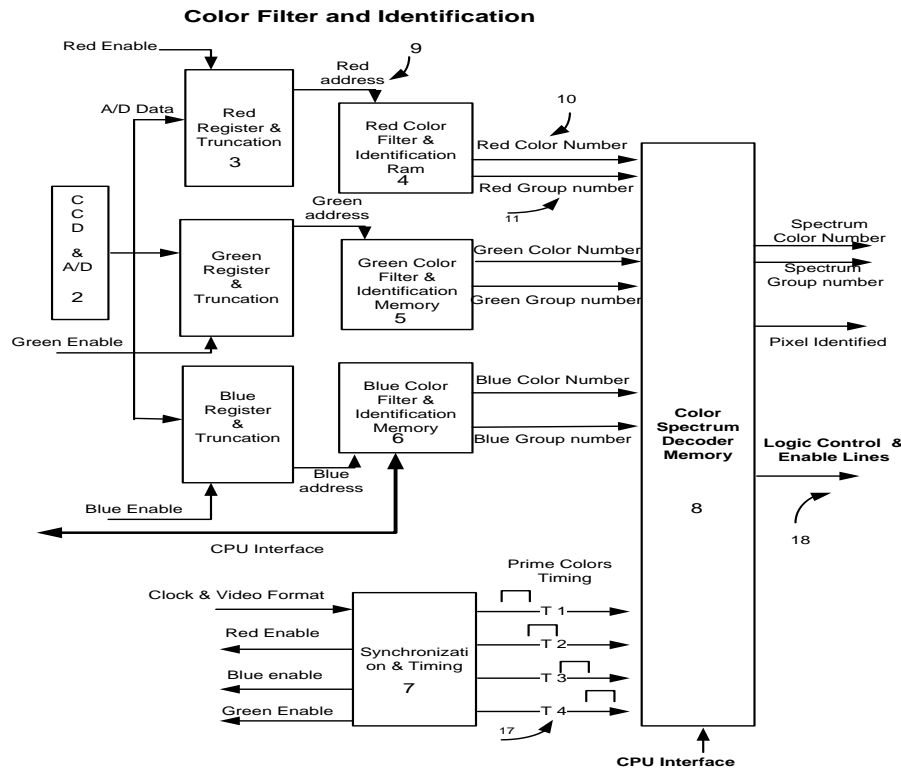
Color Filter and Identification

Figure 2- Tunable Filter hardware block diagram for visible light

Tunable Filter bandwidth settings

- The bandwidth can be any band of frequencies or a group of different (not adjacent) bands. It encompasses from the lowest narrow-band, which is a single pixel to broadband frequencies for many pixels.
- There is no limitation to the spectral frequencies spacing. Any frequency can be detected as long as their intensity values are per-loaded in the filter memory.
- For scientific instrumentation, unlike the human retina's non linarites, the detection can be as linear (flat) as one might expect it to be. Any band of electromagnetic signals either continuous or disjoint is detected. The filtering and its linearity are dependent on the optical filters properties used to filter.

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Future Advancements in Achieving Higher Degree of Resolutions

The resolution (discrimination) of the IR spectrum that needs to be distinguished from one another is dependent on the number of tuples (channels) and the number of bits of the A/D converter. The mathematical equation for the resolution is given by:

Resolution = D^P
Where D is the number of different combinations of a given bits in an A/D converter.
P is the number of channels in different bands that are used for detection of a target.

For example, with four channels of IR target data and a 9 bit A/D converter, the resolution is 512^4= 68,719,476,736 number of different values of the received IR to differentiate a target signature from surrounding noise. The effects of discrete quantum frequency spacing have not been considered in the above resolution calculations. This resolution will drastically improve the discrimination of target signature from background noise (clutter).There is no limitation to the spectral frequency spacing. Any frequency can be detected as long as the intensity values are pre-loaded in the filter memory.

CALIBRATION

The new calibration methods use memories to avoid time consuming calculations of calibration. Detected strengths of data signals in their respective bands are compared to the known values (first method) and the results are used to normalize regular data channels accordingly eliminating calculations. Calibration takes place continuously on 50 to 70 nanoseconds (high speed electronics) time limits for a channel and for a variable. A large density sequencing memory RAM structure (Figure 3) is used for calibration. The adverse environments conditions (variable data) are used as an address to the sequencing RAM to fetch previously loaded calibration factors. The calibration factors are derived mathematically or by empirical tests. The recent advancements in memory densities increases allows for high addresses to implement this addressing scheme.

CONTINUOUS CALIBRATION

Two methodologies for calibrations are recommended. One method is to calibrate based upon the calibration channel such as gray scale in visible light. It sets aside one or more calibration channels for IR systems. The second method is to calibrate the data channels based upon the availability of the adverse conditions (data) that affect regular data channels. In the first method, the received data from calibrating channels are compared to a known (ideal) value and calibration factors are generated to normalize and calibrate the regular data channel. In the second method the known (measured) adverse environmental conditions like temperature, humidity, fog, brightness, etc. are used to retrieve a pre-loaded calibration factor from memory to calibrate the regular data channel sequentially (Figure 3 below). For both methods calibration takes place continuously within pixel timing periods (Estimated times of 50 to 70 nanoseconds time limits per channel and one environmental variable). The above methods are the result of the awarded patent for calibration and measurement of various gases remotely. See

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Hardware implemented pixel level digital filter and processing of electromagnetic signals. Apr, 17, 2012: US 8159568 Ned M Ahdoot:
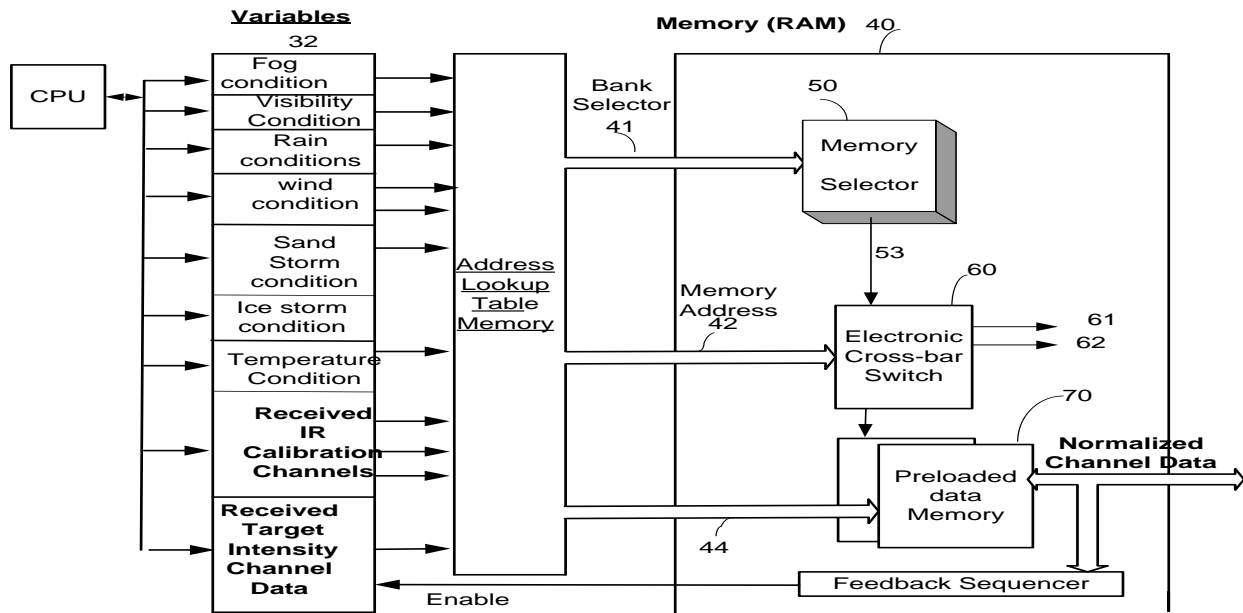

Figure 3 - Sequencer RAM for calibration due to many variables including environmental conditions

Calibration Principals

The Figure 3D depicts the percent transmittance of various elements such as H_2O, O_2, O_3, and CO_2 in 0.4 to 2.5 micrometer spectrum wavelength. H_2O and CO_2 energy transmittance is zero in wavelengths 1.3 to 1.4, and 1.8 to 1.9 micrometer wavelengths. The element CO_2 has the heights transmittance in wavelengths 2.0 to 2.4 micrometers.
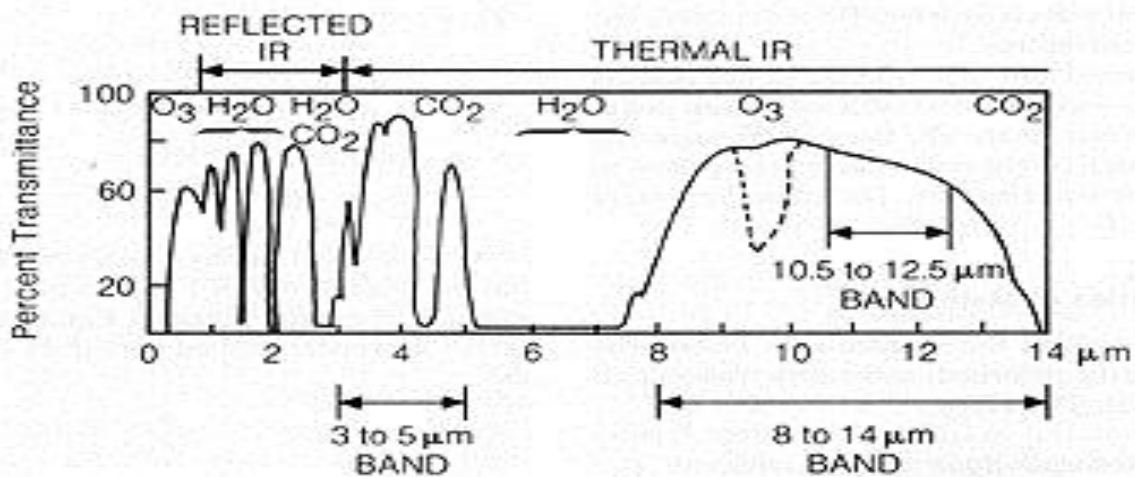
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CONCENTRATION MEASUREMENT

The following analysis is for the concentration measurements of CWAs and TICs in a closed environment. The same methodology can be used, to remotely (open system) measure concentration of CO_2 in the presence of other gases utilizing high resolution IR detection methodology described above.

The preferred method for the measurement outlined in the paper is based upon a recent study and recommendation for measurements of chemical agents by, Michael B. Pushkarsky1, Michael E. Webber1, Tyson MacDonald1 and C. Kumar N. Patel and Department of Physics & Astronomy, University of California. Los Angeles, CA 90095.and US patent 8159568 by Ned M Ahdoot.

The UCLA study presents an analytical model for evaluating the suitability of optical absorption based spectroscopic techniques for detection of chemical warfare agents (CWAs) and toxic industrial chemicals (TICs) in a ambient air (closed system in which the sampled contaminated air is introduced to measurement system). The study is based upon sensor performances that are modeled by simulating absorption spectra of a sample containing both the target and multitude of interfering species as well as an appropriate stochastic noise for determining the target concentrations from the simulated spectra via a least square fit (LSF) algorithm. The distribution of the LSF target concentrations determines the sensor sensitivity, probability of false positives (PFP) and probability of false negatives (PFN). Their model was applied to CO_2 laser based photoacosutic (L-PAS) CWA sensor and predicted single digit ppb sensitivity with very low PFP rates in the presence of significant amount of interferences. This approach will be useful for assessing sensor performance by developers and users alike; it also provides methodology for inter-comparison of different sensing technologies.

Feasibility Discussions of Calibration

This proposal utilizes the calculation methodology of the UCLA paper. It need to be emphasized that the paper is for a closed system of measurements and use of lasers to achieve measurements of harmful gases in the presence of other gases. This paper seeks the feasibility of CO_2 measurement, utilizing the stated and proven UCLA paper along with the very high resolutions and calibrations (discussed above) of this technology for remote sensing measurements.

The essential reason and argument that can establish such identification and measurement remotely are:

- Very high resolution capabilities of the new filtering technology for visible light and IR.
- ✓ Feasibility of providing much higher resolutions (compared to the proposed above), by increasing the number of channels and the number of bits in A/D converters.
- Recommended approaches for correcting system imperfections and calibration due to adverse environment conditions.
- Recommended approaches for calibration, even in the presence of adverse environmental conditions.

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Please refer to the patent April, 17, 2012: US 8159568 Ned M Ahdoot: for measurements of the concentrations of chemicals even in the presence of adverse environment conditions. The technology provides for a detection and measurement system to be deployed on satellites or a high flying plane, for immediate detection and measurements

Measurements of harmful Chemical Intensities

IR absorption spectroscopy is a powerful tool for trace gas detection because a vast majority of polyatomic molecules including CWAs, TICs and explosives absorb light in the wavelength region from 3 to 14 um. Table 1 show the IR spectra of nerve and mustard gases and gives more comprehensive list of both CWAs and TICs absorbing between 3 and 11.5 um. The required sensitivity for CWA detection is determined by the toxicity levels of particular agents, most of which reasonably well documented. The concentrations and related health effects for Sarin (GB), a typical nerve agent CWA, are summarized in Table 1.

The characteristics that allows for the proposed system to measure chemical agents (from very long distances) are as follows:

- The extremely high resolution in detection as explained above.
- The ability to automatically calibrate and correct the effects of distortions (pixel by pixel in real time), caused by the effects of adverse environment condition.
- The ability to make automatic adjustments of the system imperfections and the system temperature changes (Such as FPA) that affects measurement.

Method

The approach is based upon utilizing multispectral IR detection technique similar co2 lasers to achieve required sensitivity in the desired 9-11.5 nm spectral range.

The following Figure is showing the absorption spectra of eight target nerve agents and surrogates at wavelengths accessible with close to 80 channel multispectral channel.
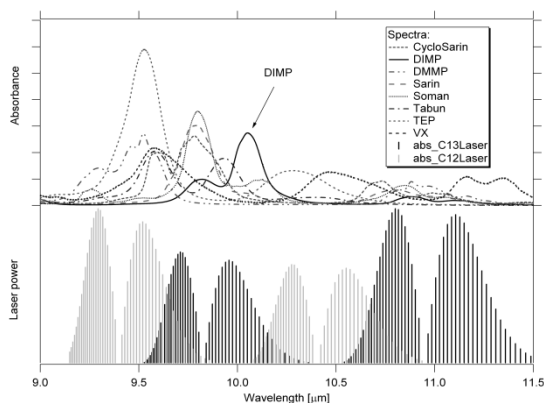

Figure 4 Spectra of nerve agents and 88 channels IR spectral wavelengths

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Consequently 88 channels IR spectral from 9.6 to 11.4 micron were chosen as spectral range for the spectral libraries for DIMP all listed in above Table 1. Detections will produce the concentrations measurements by evaluating the absorption coefficients from the available libraries at 88 channel IR spectral wavelengths.

Concentration measurements of Harmful Gases

In addition to sensitivity and fast response time, the very important parameter of a sensor is selectivity i.e. an ability to operate with acceptably low probability of false positive (PFP) readings in the presence of interferences typical in indoor and outdoor environments. In fact, the lack of selectivity may become a critical problem when sensing realistically contaminated air because of high economic costs of frequent false alarms. Therefore a model allowing prediction of the sensor PFP as well as the probability of false negative (PFN) would be very valuable tool for sensor developers and users alike. This paper presents an analytical model allowing to quantitatively evaluating performance, i.e. sensitivity and selectivity of absorption spectroscopy based techniques for the detection of CWAs and TICs in realistically contaminated ambient air.

IR absorption spectroscopy is a powerful tool for trace gas detection because a vast majority of polyatomic molecules including CWAs, TICs and explosives absorb light in the wavelength region from 3 to 14 um. Table 1 shows the IR spectra of nerve and mustard gases and Table 1 gives more comprehensive list of both CWAs and TICs absorbing between 3 and 11.5 um. The required sensitivity for CWA detection is determined by the toxicity levels of particular agents, most of which reasonably well documented.

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Table .1 CWAs, TICs and explosives that can be detected in specific spectral regions.

9-11.5 um	
CWAs	Lewisite, Nitrogen Mustard (HD), Mustard (H-N3), Sulfur mustard 4-Dithiane, Diisopropyl methylphosphonate (DIMP), Dimethyl methylphosphonate (DMMP), Isoamyl alcohol,
TIC	Ammonia, Arsine, Boron trichloride, Ethylene oxide, Nitric acid
4-9 um	
CWA	Mustard (H-N3), Sulfur mustard (HD), 4-Dithiane,

$$
\begin{bmatrix}
\sigma_{\lambda_1,1} & \sigma_{\lambda_1,2} & - & - & \sigma_{\lambda_1,M} \\
\sigma_{\lambda_2,2} & \sigma_{\lambda_2,2} & - & - & \sigma_{\lambda_2,M} \\
- & - & - & - & - \\
\sigma_{\lambda_N,M} & - & - & - & \sigma_{\lambda_N,M}
\end{bmatrix}
\begin{Bmatrix} X_1 \\ X_2 \\ - \\ X_M \end{Bmatrix}
+
\begin{Bmatrix} Noise_1 \\ Noise_2 \\ - \\ Noise_N \end{Bmatrix}
=
\begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ - \\ \alpha_N \end{Bmatrix}
$$

$$
\begin{bmatrix}
\sigma_{\lambda_1,1} & \sigma_{\lambda_1,2} & - & - & \sigma_{\lambda_1,M} \\
\sigma_{\lambda_2,2} & \sigma_{\lambda_2,2} & - & - & \sigma_{\lambda_2,M} \\
- & - & - & - & - \\
\sigma_{\lambda_N,M} & - & - & - & \sigma_{\lambda_N,M}
\end{bmatrix}
\begin{Bmatrix} X_1 \\ X_2 \\ - \\ X_M \end{Bmatrix}
+
\begin{Bmatrix} Noise_1 \\ Noise_2 \\ - \\ Noise_N \end{Bmatrix}
=
\begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ - \\ \alpha_N \end{Bmatrix}
$$

$$
\begin{Bmatrix} X_1 \\ X_2 \\ - \\ X_M \end{Bmatrix}_{LSF}
=
\begin{bmatrix}
\vec{\sigma}_1\cdot\vec{\sigma}_1 & \vec{\sigma}_2\cdot\vec{\sigma}_1 & - & \vec{\sigma}_M\cdot\vec{\sigma}_1 \\
\vec{\sigma}_1\cdot\vec{\sigma}_2 & \vec{\sigma}_2\cdot\vec{\sigma}_2 & - & \vec{\sigma}_M\cdot\vec{\sigma}_2 \\
- & - & - & - \\
\vec{\sigma}_1\cdot\vec{\sigma}_M & \vec{\sigma}_2\cdot\vec{\sigma}_M & - & \vec{\sigma}_M\cdot\vec{\sigma}_M
\end{bmatrix}^{-1}
\times
\begin{bmatrix}
\sigma_{\lambda_1,1} & \sigma_{\lambda_2,1} & - & - & \sigma_{\lambda_N,1} \\
\sigma_{\lambda_1,2} & \sigma_{\lambda_2,2} & - & - & \sigma_{\lambda_N,2} \\
- & - & - & - & - \\
\sigma_{\lambda_1,M} & - & - & - & \sigma_{\lambda_N,M}
\end{bmatrix}
\times
\begin{Bmatrix} \alpha_{\lambda_1} \\ \alpha_{\lambda_2} \\ - \\ \alpha_{\lambda_N} \end{Bmatrix}
\quad (5)
$$

The above equation provides needed mathematical tools for concentration measurements of multi sensor which relies upon acquisition and analysis of a complex spectrum. For practical application of the presented model one needs to specify the following parameters:

1. A set of concentrations, X_i, of all expected targets and interferences

2. The spectral range of a spectrometer and the absorption spectral library of all the expected ambient air constituents that absorb appreciably within an identified spectral range.

The details for the measurement of CO2 (firmware and hardware) is not considered for this document due to limitation of pages.

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PRINCIPAL INVESTIGATOR AND OTHER KEY PERSONNEL

Ned M. Ahdoot, Project Manager, senior scientist and investigator
Education:
BEE., Electrical Engineering New York City college, New York, N.Y. 1970
MSEE., Electrical Engineering New York University New York, N.Y. 1973
Secret Clearance

Ned Ahdoot has over 35 years of experience in the aerospace and electronics field including design and development of communication and recommence satellite for the United States Air Force. As a program manager, Ahdoot has extensive experience in GPS Satellites design with responsibility for definition of technical requirements (Requirement Specification), definition of scope of the work, planning of schedule and budget, and assigning key personnel to specific positions. As project manager, his managerial and technical experience includes his work on the DSP satellite, Milstar Satellite, and STSS. Mr. Ahdoot has received several company (TRW and others) letters of commendations for the hard work to finish a project on time with the goal to meet United States Government needs.

Ahdoot has proven experience providing project's requirement specifications, negotiating technical as well as financial aspect for the vendor (to build and deliver) and oversee work in progress. Over his career, he has a long history interfacing with outside contractors, and customers such as Air Force. He has extensive experiences in working with Government personnel as well as sub-contractors. Ned Ahdoot has provided valuable recommendations and assistance for resolving complex technical issues. As a key member of Independent Readiness Review Team (IRRT System Lead Engineer) for STSS, WGS and DMSP satellites, Ahdoot has uncovered and resolved many high profile technical issues, benefiting the team and the Air Force.

Facilities/Equipment

TRI D System will team with SARA, Inc. located in Cyprus, California to develop the proposed technology. SARA, Inc. has a large facility equipped with the most advanced electronic equipment. A laboratory in this facility, as well as all necessary equipment, will be leased to TRI D System for the development. The company facility is also authorized by DOD to for sensitive and secret work. There is a letter of commitment and NDA agreement on file.

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