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(54) Title: HYDROCARBON LEAK IMAGING AND QUANTIFICATION SENSOR

### Multispectral Absorption Imaging for Natural Gas Leak Detection

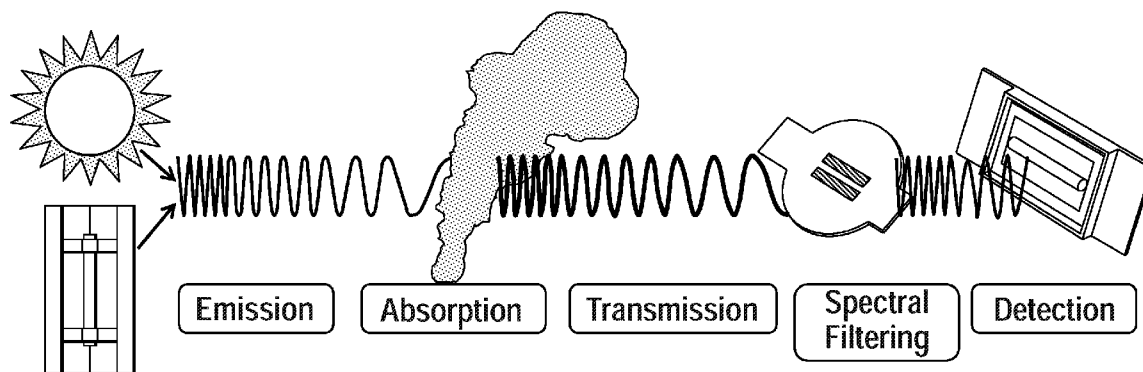


Fig. 1A

(57) Abstract: This invention consists of sensors and algorithms to image, detect, and quantify the presence of hydrocarbon gas (for example from leaks) using a short-wave infrared radiation detector array with multiple spectral filters under natural sunlight or artificial illumination, in combination with the hydrodynamics of turbulent gas jets and buoyant plumes. Multiple embodiments are recited and address detection and quantification of methane gas leaks. Quantification includes gas column densities, gas concentration estimates, total mass, hole size estimates, and estimated emission flux (leak rate) of gas from holes and cracks in pressurized vessels, pipes, components, and general gas infrastructure, and from surface patches (for example due to gas leaks in underground pipes) under the action of buoyancy and wind. These and similar embodiments are applicable more generally to natural gas and other hydrocarbon gases, liquids, emulsions, solids, and particulates, and to emissions monitoring of greenhouse gases methane and carbon dioxide.



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## HYDROCARBON LEAK IMAGING AND QUANTIFICATION SENSOR

### CROSS-REFERENCE TO RELATED APPLICATIONS

- 5 This application claims priority from provisional patent applications US 62/338,255 filed 2016 May 18, and US 62/472,463 filed 2017 March 16, both by the present inventors.

### TECHNICAL FIELD of INVENTION

- 10 This invention refers generally to optical detection and quantification of natural gas and other hydrocarbon gas leaks, from holes and cracks in pressurized vessels, pipes, components, and general gas infrastructure, and from emissions emanating from surfaces due to gas leaks in underground gas infrastructure or naturally occurring surface emissions. It may also be useful in assessing methane emissions from
- 15 livestock.

### BACKGROUND – PRIOR ART

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## BACKGROUND ART

10 Natural gas leaks create both safety and environmental hazards, and occur along the entire gas supply chain from the well to the street (so-called upstream, midstream, and downstream sectors). Methane, the primary constituent of natural gas is combustible in air, and is also a potent greenhouse gas. Other hydrocarbons found in natural gas, as well vapors emanating from liquids separated from gas and oil include ethane, propane, butane, pentane, hexane, octane, and heavier hydrocarbons, 15 which form volatile organic compounds that generate smog which is a health hazard. Thus, there are compelling reasons to detect leaks of methane gas and other hydrocarbon gases, so that such leaks can be repaired. However, in order to repair such leaks, it is necessary to also localize the leak, and in order to prioritize repairs it is desirable to quantify the leak in terms of leak rate or emission flux. Estimating gas 20 emission flux is also needed to assess environmental impact of greenhouse gases. Moreover, it is desirable to have a means to monitor or inspect wide areas for such leaks and do so quickly from a safe and practical standoff distance, while maintaining the ability to pinpoint the leak location and estimate the leak rate. It is also desirable to conduct effective leak monitoring in the presence of naturally occurring ambient 25 gases and vapors, such as water vapor, and regardless of the relative temperature between leaked gas and the background environment. A cost-effective solution is also necessary if such solutions are to be broadly adopted and utilized.

Gas detectors can be classified according to their coverage extent, as either spot sensors, line sensors or area sensors. Spot sensors, often referred to as sniffers, 30 draw in a local sample of air and detect the presence of a combustible or toxic gas by means of various analytical methods. They can be fixed in place for continuous monitoring, or hand portable for inspections, but they require direct sampling in place and provide very limited coverage. They may provide concentration measurements, but do not provide leak rate estimates. Other instrumentation is available to locally

sample (as opposed to image) known leaks in order to provide an estimate of leak rate, but they too provide only local coverage and require direct collection of gas from the leaking component.

Optical line sensors, also known as open-path gas detectors, employ optical  
5 means to detect gas that lies along the line between a dedicated light emitter (e.g., laser, tunable laser, or narrowly focused broadband source) and a dedicated photo-detector (or multiple photo-detectors). Such detectors exploit the absorption of light (typically in different parts of the infrared spectrum) at select wavelengths characteristic of the molecular composition of the gas of interest. These sensors detect  
10 gas present anywhere along the line between the light emitter and the photo-detector (or between combined emitter/detector assembly and a remote reflector if the optical path is folded), but they cannot determine where along the path the gas is, nor from where it came, and has limited coverage to only the narrow open path between emitter and detector. By utilizing multiple wavelengths of light, such sensors can measure  
15 column density of gas along the open path, but cannot measure or estimate concentration nor leak rate. Open-path sensors can be installed in place, hand portable, or mobile aboard ground and air vehicles. In order to achieve area coverage from a standoff distance, it is recognized that imaging sensors offer many advantages over spot and line sensors, in that they can detect the presence of gas and possibly  
20 localize the leak source.

Several gas imaging technologies have been proposed, developed, patented, and are commercially available. They are all based on the absorption of infrared light at wavelengths characteristic of the molecules of interest. For methane and hydrocarbons in general, most imagers operate in select bands of the mid-wave  
25 infrared and long-wave infrared spectrum. The leading commercially available gas imaging sensors operate in only a single narrow band of the mid-wave infrared spectrum, and do not provide quantitative data, only pictures to be interpreted by the human operator. Other imaging sensors utilize multiple spectral bands in the long-wave infrared (the so-called “molecular fingerprint region”) to detect and discriminate  
30 among different hydrocarbon gases, and to quantify the column density of gas at each pixel of the image. Such systems have proven to be both expensive and have significant shortcomings. These mid-wave and long-wave infrared sensors rely on thermally emitted light from the background to illuminate the gas that will absorb at select wavelengths as detected by the imaging sensors. This requires that the

background and gas differ in temperature by at least several degrees Celsius, otherwise the light absorbed (or emitted) by the gas will not provide sufficient signal contrast to be reliably detected by the human operators of these thermal sensors. For example, in the case of surface emissions of natural gas due to an underground pipe leak, or methane emissions from a landfill, the gas percolates up through the soil and reaches thermal equilibrium with the soil by the time it emerges from the ground. Thus, there is little or no thermal contrast between the gas and the ground, and so cannot be reliably detected by a thermal infrared sensor. Another major shortcoming of mid-wave and long-wave gas imaging sensors is their poor performance in the presence of water vapor (high humidity, steam), fog and light rain. This is because the spectrum of water overlaps with key spectral features of methane in both the mid-wave and long-wave infrared spectral regions. Thus, water vapor will mask the presence of a methane leak, and conversely, water vapor will trigger a false alarm for methane. As both water vapor and methane are less dense than air, they both rise due to buoyancy and look alike in a spectrally filtered mid-wave or long-wave infrared image. Additionally, all mid-wave infrared and some long-wave infrared gas imaging sensors require cryogenic cooling, which is both expensive and unreliable. It is preferable to utilize only thermo-electric cooling to reduce dark current in gas imaging sensors. Finally, none of the available gas imaging sensors provides a capability to estimate leak rate from a hole, or emission flux from a surface. Some can provide column density of gas at each pixel, and using spatial information of the imaged gas jet, plume or cloud, one can then estimate local or average gas concentration.

In order to overcome the above-cited shortcomings of thermal infrared based imaging sensors for gas detection, it is possible to utilize differential absorption gas imaging in the short-wave infrared part of the spectrum. Atmospheric scientists using satellite-borne sensors like Landsat and SCIAMACHY have exploited this. It enables the detection of methane, other hydrocarbons, carbon dioxide, and other gases in the atmosphere based on molecular absorption of natural sunlight, without confusion of intervening water vapor. Such space-based imaging technologies provide synoptic scale maps of column densities of greenhouse gases and other air pollutants.

It is the purpose of this invention to provide sensors and methods that enable gas leak detection, localization, imaging, and quantification of leak rate or emission mass flux, utilizing multispectral imaging in the short-wave infrared in combination

with the hydrodynamics of turbulent gas jets and buoyant plumes. Multiple embodiments of the invention are described and have been developed, that are applicable more generally to natural gas and other hydrocarbon gases, liquids, emulsions, solids, and particulates, and to emissions monitoring of greenhouse gases  
5 such as methane and carbon dioxide.

### **SUMMARY of the INVENTION and its ADVANTAGES**

This invention consists of sensors and algorithms for imaging, detection, localization, and quantification of hydrocarbon leaks by means of multispectral  
10 sensing using non-thermal infrared radiation from natural sunlight or artificial illumination sources. More specifically, several embodiments of sensor systems are described that incorporate short-wave infrared (SWIR) detector arrays sensitive in the range of approximately 1.0 through 2.6 microns, in combination with two or more spectral filters selected to create *Core and Wings* spectral bands with respect to a  
15 hydrocarbon feature complex in the vicinity of 2.3 microns. Detection is accomplished via absorption spectroscopy using natural sunlight or artificial illumination in direct transmission through a gas to the sensor, or reflected off a background surface with gas located between the background and the sensor. With the system properly calibrated, the resulting multispectral data can be processed in real-  
20 time to yield an absorption map or image related to the differential optical depth, or equivalently column density, of an intervening hydrocarbon gas such as methane, the major constituent of natural gas.

The resulting absorption imagery is color mapped to render the degree of gas absorption across the scene, and overlaid on an optically registered color visible  
25 image that provides context. In the case of gas leaking from a hole or crack in a pressurized pipe or vessel, the escaping gas forms a turbulent jet or plume that is visible in the absorption image and from which the leak can be localized. The invented methods estimate both the diameter of the effective hole and the mass flux of leaking methane (or other gas) from the data present in this absorption image, if the  
30 internal pressure driving the leak is known approximately. In the case of underground gas leaks, such as due to municipal gas infrastructure or gathering lines from gas wells, the gas percolates through the subsurface soil and emerges at the surface, often in disconnected surface patches. These surface emissions diffuse into a thin layer next to the ground and rise (in the case of natural gas) due to buoyancy, but are often

blown by ground-level winds. The invented methods estimate both the mass of gas and the mass flux from a surface patch by combining the absorption imagery with wind speed and direction measured near ground level. Flux estimation methods are developed for cases of both steady winds and gusting winds.

5           Functional prototypes of two embodiments of leak imaging and quantification sensors have been built, and graphical user interfaces to control these sensors and view (and store or transmit) their real-time outputs have been implemented on touch-screen tablet displays. One such embodiment supports video-rate imaging and quantification of gas leaks. A second such embodiment supports scan-based imaging  
10 over a programmable and variable wide field-of-regard, trading away video-rate imaging for a lower cost embodiment of an imaging gas sensor. Imagery of gas leaks from holes and surfaces, and leak rate estimates, are shown in the figures to confirm the viability of the invention.

          This invention has several key advantages over thermal infrared gas imaging  
15 sensors that operate in the mid-wave (MWIR) or long-wave (LWIR) infrared parts of the spectrum. This includes the ability to detect and quantify leaked gas with small or no temperature difference relative to the background, as the invention utilizes SWIR light provided by natural sunlight or by lamps of appropriate color temperature, and does not rely on a thermal contrast between gas and the background or a background  
20 of varying temperature. The detectors suitable for use in this invention do not require cryogenic cooling, using instead thermo-electric cooling that is more reliable and less expensive than cryogenic coolers such as a Stirling engine or liquid nitrogen. Finally, the invention can also detect gas leaks in the presence of humidity, steam, fog, and light rain, as the hydrocarbon features detected in the SWIR do not overlap spectral  
25 regions where water vapor absorption is significant, which is important as one cannot control the presence of water vapor or fog in the atmosphere between the sensor and the leak source, and many industrial processes purposely mix steam with hydrocarbon gases.

          This invention and its various embodiments will be useful in imaging,  
30 detecting, localizing, and quantifying natural gas leaks from components along the entire gas supply chain, from the well head to compressors to transmission pipelines to gate stations and underground distribution networks. Detection and quantification of volatile organic compounds (VOCs) in or near refineries, petrochemical plants, hydrocarbon storage tanks, or other industrial and commercial facilities will be

possible. Landfill methane emissions mapping will be possible using this invention in combination with tomographic imaging around the periphery of a landfill. Similar tomographic three-dimensional mapping of gas over a refinery is possible, utilizing an airborne variant of this invention. This invention has also been shown to be capable of  
5 detecting liquid oil spills on land, sand, seawater, and sea ice. Other embodiments of the invention will prove useful in detecting and mapping oil films and emulsions at sea, oil spills in arctic waters, tar balls on beach sand, and damage to wetlands from oil spills. The embodiments of the invention described herein are suitable for packaging in the form of, for example, hand-portable imaging sensors, ground  
10 vehicle-mounted inspection systems, vessel-mounted sensing systems, airborne surveying systems, relocatable trailer-mounted and fixed-site monitoring systems.

### DRAWINGS – FIGURES

FIG. 1A illustrates the physical principles that underlie multispectral absorption  
15 imaging for natural gas detection.

FIG. 1B illustrates the methane spectrum in the infrared region from 1.5 to 10 microns, its primary spectral absorption features in the short-wave, mid-wave, and long-wave infrared regions, and the ratio of these methane absorption features to the corresponding water-vapor absorption features.

20 FIG. 2A illustrates the short-wave infrared spectra of the primary constituents of natural gas – methane, ethane, propane, butane, and carbon dioxide, as well as the spectrum of water vapor.

FIG. 2B illustrates the detailed methane spectral features in the range 2.1 to 2.6 microns, and its decomposition into a *Core Band* and *Wings Band*, along with the  
25 value of the average absorption cross-sections for this choice of *Core* and *Wings Bands*.

FIG. 3 shows a prototype user interface for a gas imaging sensor implemented on a touch-screen tablet, displaying a methane gas jet exiting a 1.5mm orifice at 130  
psig.

30 FIG. 4A illustrates an example of real-time video imaging of natural gas exiting a 10mm orifice from a pipe pressurized at a low levels of only  $\frac{1}{4}$  psig in a mild crosswind.

FIG. 4B illustrates an example of real-time video imaging of methane jets emanating from a loosened hammer union pressurized to 500 psig in a 9kph crosswind.

FIG. 4C illustrates an example of real-time imaging of ground surface emissions due to an underground natural gas pipe leak beneath a street in the Boston area.

FIG. 5A is a one-dimensional photo-detector array with its read-out circuitry, together with a pair of spectral filters that overlays the detector array and alternates  
5 between each of the two filters covering the detector array.

FIG. 5B is a pair of one-dimensional photo-detector arrays, each with its own read-out circuitry, and each with a different spectral filter positioned over it.

FIG. 6A is a two-dimensional photo-detector array and its read-out circuitry, with four different spectral filters, each filter overlaying one or more rows of detectors.

10 FIG. 6B is an array of four discrete photo-detectors with their individual read-out circuits, each detector covered with a separate spectral filter island. The spectral filters form a spectral filter mosaic.

FIG. 7A is a system diagram of the video leak imaging and quantification sensor system.

15 FIG. 7B is a system diagram of the scan leak imaging and quantification sensor system.

FIG. 8A diagrams the imaging geometry for leak detection with sunlight ahead of the leak in direct transmission, passing once through a gas jet towards the sensor.

20 FIG. 8B diagrams the imaging geometry for leak detection with a source of artificial illumination from behind the leak (near the sensor), reflecting off a background material, passing twice through a gas jet and then to the sensor.

FIG. 9A shows a real-time absorption image of a methane gas jet exiting a 1mm orifice from a test manifold pressurized to 1300 psig.

25 FIG. 9B shows three profiles of differential optical depth across the methane gas jet of FIG. 9A, corresponding to the pixel values sampled along the lines labeled a, b, and c.

FIG. 10A shows a graph of the estimated jet width along the axis of the methane jet of FIG. 9A, and a least-squares linear regression to these data points.

30 FIG. 10B shows a graph of the integrated differential optical depth across the width of the jet, along the axis of the methane jet of FIG. 9A, and a least-squares linear regression to these data points.

FIG. 10C shows a graph of the ratio of integrated differential optical depth to estimated jet width (i.e., the average differential optical depth) along the axis of

the methane jet of FIG. 9A, and a least-squares linear regression to these data points.

FIG. 11 shows a graph of the integrated differential optical depth across the width of a methane jet exiting a narrow slit orifice of width 50 microns and length 1cm, and various least-squares regressions to these data points.

FIG. 12A illustrates for a set of experiments, a graph of the intercept value of average differential optical depth normalized by orifice diameter vs. the internal pressure driving a methane jet from orifices of 1mm and 0.75mm, and compares the data to a smooth power-law curve.

FIG. 12B illustrates data from an extensive set of experiments of methane exiting round and slit orifices of various sizes across a large range of pressures. The graph shows the measured mass flux per unit area of orifice vs. the internal pressure driving the methane jet, and a least-squares linear regression to these data points.

FIG. 13A illustrates an outdoor test setup used for imaging and estimating leak rate (mass outflow) of methane exiting round orifices under pressure in a crosswind in sunlight, in which the mass flowing into the release manifold is measured.

FIG. 13B shows a graph of estimated mass outflow compared to the measured mass inflow for twelve experiments using the test setup shown in FIG. 13A.

FIG. 14A illustrates (side view) geometry of an elevated LIQS sensor imaging ground surface gas emission in the presence of ground-level winds.

FIG. 14B illustrates (plan view) geometry of gas emission from a surface patch in the presence of ground-level winds.

## **DETAILED DESCRIPTION of the INVENTION**

### **25 Principals of Gas Absorption Imaging**

This invention detects gas leaks via differential absorption imaging spectroscopy in the range 1.0 to 2.6 microns, exploiting spectral features of hydrocarbons in the short-wave infrared (SWIR) region, primarily in the wavelength range of 2.0 to 2.5 microns. These wavelengths are not typically associated with those in the thermal emission regions of the mid-wave infrared (MWIR) and long-wave infrared (LWIR) for objects at terrestrial temperatures. Appreciable thermal emission at around 2.0 microns requires objects at temperatures of around 1000°C. Instead, this invention relies on illumination sources like natural sunlight and lamps of color temperature near 1000°C. Thus, the invention can detect hydrocarbons at the same

temperatures as their backgrounds by using external illumination instead of thermally emitted light.

The principals underlying non-thermal infrared multispectral imaging of a gas leak are shown in FIG. 1A. SWIR radiation from the sun or broadband artificial illumination, directly or in reflection off background objects, transmits through the ambient atmosphere, passes through a gas jet or plume emanating from a source such as for example a leak, continues towards the sensor where it is filtered into multiple spectral bands and detected on a photo-detector array that is sensitive to SWIR photons. Both the atmosphere and the gas absorb some of the light at wavelengths characteristic of the materials that comprise these media. In the case of natural gas the primary absorber is methane, while for the atmosphere the primary absorbers are water vapor and other ambient gases that may include methane as well as carbon dioxide. Incident light is also scattered out of the transmission path by particulates in the atmosphere and the gas leak itself. Light that is absorbed by the gas is subsequently reemitted in all directions, resulting in a reduction of light at characteristic wavelengths that is transmitted in the direction from the light source towards the sensor.

When imaging methane and other hydrocarbons, it is common to exploit their strong features in the MWIR and LWIR, as the absorption in those spectral regions is greater than in the SWIR. However, it is important to consider the effects of water vapor absorption by the intervening atmosphere. In most applications, the physical extent of a gas jet, plume or cloud is small compared to the length of atmosphere that the light will propagate through on its way to the sensor. Thus, appreciable absorption may occur at wavelengths characteristic of water vapor, depending on the humidity of the air or the presence of fog or steam in optical field-of-view. It is therefore important to consider the relative absorption of methane to water vapor at the wavelengths that characterize methane. FIG. 1B illustrates this by plotting the methane absorption cross-section, and the ratio of water vapor to methane absorption cross-sections in narrow spectral bands where methane possesses strong spectral features, shown here on semi-logarithmic scales for wavelengths from 1.5 to 10 microns. It is clear that, despite the relatively weaker absorption cross-section for methane in the SWIR compared to the MWIR and LWIR, it has significantly higher absorption ratio to water vapor in the SWIR. Thus, for imaging gas in the presence of humidity or fog or steam, the SWIR region has particular advantage over both the

MWIR and LWIR spectral regions. For many applications, this is an advantage, despite the lower absorption cross-section in the SWIR.

FIG. 2A shows a plot of absorption cross-section (on a linear scale) in the SWIR spectrum from 1.8 to 2.6 microns, for the various constituents comprising natural gas: methane, ethane, propane, butane, and carbon dioxide, as well as for water vapor. From FIG. 2A it can be seen that the hydrocarbons possess broad feature complexes from 2.2 to 2.5 microns with much overlap in the range of 2.2 to 2.4 microns. Methane can be separated from the other hydrocarbons by its reduced absorption in the 2.4 to 2.5 micron range. It is also apparent that the constituents of natural gas have spectral features in the SWIR that lie between the strong water vapor features below 2.0 microns and above 2.5 microns. As is well known in the art, similar absorption features are present in the SWIR for liquid crude oil, oil-water emulsions, asphalt and tar.

In order to detect and quantify the hydrocarbons present in natural gas, it is advantageous to use multiple spectral bands in the SWIR. This can be accomplished using spectral filters designed to selectively transmit preferred wavelength bands while rejecting other SWIR radiation. Such spectral filters can be narrow bandpass filters, broadband filters, notched filters, edge filters, and combinations of such filters. For example, to preferentially detect methane, the primary constituent of natural gas, the invention utilizes a minimum of two spectral bands; one called the *Core Band* which spans the spectral feature complex from approximately 2.25 to 2.45 microns (200nm bandwidth), and the other called the *Wings Band* (serving as a reference band) which spans an interval of approximately 100nm to either side of the *Core Band*. These spectral intervals are shown as the rectangular boxes in FIG. 2A. The average absorption cross-section across the *Core* and *Wings Bands* are plotted over the methane spectrum in FIG. 2B. By imaging in these two bands, the presence of methane can be both detected and quantified in terms of column density of methane. As is well known in the art of spectral image processing, other SWIR spectral bands can be selected to preferentially detect and quantify the other constituents of natural gas shown in FIG. 2A and related volatile organic compounds of interest in gas and oil production. The exact location and extent of any of these bands is not critical to enabling a functional sensor, as long as they span regions both on and off the strong spectral features of the gas of interest. In order to quantify the column density of gas present at each pixel in the imagery, and account for absorption by trace gases in the

atmosphere, it is shown below that comparison between regions with gas present and gas absent is preferred, and this is achieved through proper on-site adaptive calibration of the system before inspecting for gas leaks.

### Prototype Gas Imaging Sensor

5           The invention described here has been reduced to practice by building functional prototypes of a multispectral video imager and a scan imager for methane imaging, detection and quantification. The prototype dual-band video sensor images at 20 frames per second and displays gas absorption imagery overlaid on color visible imagery of the scene on a touch-screen user display. The prototype system is hand-  
10   portable and interfaces to external networks via both wireless and wired interfaces. The prototype 6-band scan sensor creates imagery of gas over a programmable and variable field-of-regard, by combining raster scanning with super-resolution image processing. The flexibility of switching among a variety of scan patterns enables this sensor to support both gas safety applications and emissions monitoring applications,  
15   in a cost-effective manner. This scan imager is suitable for mast-mounting to overlook wide-area installations, using a programmable pan-tilt unit to effect scanning. An alternative embodiment replaces the pan-tilt unit with scanning mirrors or a combination of scanning mirror and rotating optics, to enable compact packaging for a hand-portable gas imaging and quantification camera.

20           FIG. 3 illustrates a prototype graphical user interface for the video gas imager, showing touch-screen controls of the sensor and displaying an image of natural gas emanating from a 1.5mm round orifice at a pressure of 130 psig (pounds per square inch gauge), taken outdoors in sunlight. The color rendering of the gas jet absorption corresponds to pixel-level differential optical depth between the *Core* and *Wings*  
25   *Bands*, which can be converted to column density of methane and expressed in a variety of common units (molecules/cm<sup>2</sup>, %LEL-meters, ppm-meters). FIG. 4A is another example of gas imaging, showing a natural gas plume emanating from a 10mm round ball valve orifice inside a 16mm pipe at a low (household) gas pressure of ¼ psig in a mild crosswind, outdoors using artificial illumination. This low-  
30   pressure release of natural gas is dominated by the buoyancy of methane in air, and accelerates upwards under gravity as a buoyant turbulent plume. FIG. 4B shows a pair of momentum dominated methane jets driven out of a loose threaded hammer union by high internal pressure of 500 psig; they form turbulent gas jets a short distance

from slit-like orifices. By exploiting the self-similar dynamics of gas jets and plumes, it is shown how this absorption imagery can be used to estimate the diameter of the release orifice and the mass flux of methane from the hole. A final example of gas imaging is shown in FIG. 4C, where natural gas is leaking from an underground pipe in municipal gas infrastructure in Boston, MA. By the time the gas percolates up through the soil, it is approximately the same temperature as the ground itself. The prototype system can image the gas emissions from the surface in sunlight as shown, or alternatively using artificial illumination (possibly mixed with sunlight) from above reflecting off the ground, which is absorbed as it passes through the gas twice. FIG. 4C illustrates the patchy nature of ground surface emissions, with gas emerging from manholes, storm gratings, cracks in road asphalt and concrete sidewalks, as well as along the side of the road where the asphalt meets dirt and grass. All of these surface emissions may be due to a single leak in a pipe at the bottom of the hill near the end of the street. The spatial distribution of surface leak patches can be useful in bounding the actual leak location in the underground pipe.

### **Imaging Sensor Embodiments**

Several different embodiments of SWIR imaging sensors for hydrocarbon imaging are described next. There are several different semiconductor materials that can be used to fabricate the basic photo-detector sensitive to the SWIR spectrum of light from approximately 1.0 to 2.6 microns, with a dark-current that can be suitably reduced by thermo-electric cooling. These include so-called extended-response indium gallium arsenide (extended-InGaAs) commonly grown on an indium phosphide (InP) lattice-mismatched substrate, and the recently developed type-II quantum wells made from alternating layers of InGaAs and gallium arsenide antimonide (GaAsSb) grown on an InP lattice-matched substrate. These two materials have different spectral response characteristics, but both can be used for detecting the hydrocarbons that comprise natural gas, and in particular, methane as well as VOCs. They also have different manufacturing yields due to their lattice structures. Thus, extended-InGaAs photo-detectors are only available as discrete photo-detectors and one-dimensional arrays but not as two-dimensional arrays, while type-II InGaAs/GaAsSb photo-detectors have been successfully fabricated and demonstrated as two-dimensional arrays. Mercury cadmium telluride (MCT) is a common infrared detector material that can also be used for imaging in the extended SWIR; however,

its high dark-current requires cryogenic cooling with, for example, a Stirling engine to achieve useful signal-to-noise ratios.

There are several embodiments of photo-detector arrays in combination with multiple spectral filters that yield a suitable sensor for use in a gas leak imaging and quantification system. FIGS. 5A and 5B illustrate the use of one-dimensional SWIR photo-detector arrays in combination with two spectral filters called *F-A* and *F-B*, which can be used to create the *Core Band* and *Wings Band* filters for methane detection or other hydrocarbons of interest. A one-dimensional (i.e., linear) 2.5- $\mu\text{m}$ -SWIR InGaAs array with 512 detectors is used in the functional prototype methane gas imager. The configuration of FIG. 5A shows a single linear array of photo-detectors with its read-out integrated circuit (ROIC) together with a pair of filters in a frame that is designed to overlay the photo-detector array and alternate between the filters *F-A* and *F-B* positioned in front of the detector array. In this example, the photo-detector array and its ROIC are mounted on a small thermo-electric cooler and enclosed inside a hermetically sealed package with a transparent window located above the photo-detectors. The alternating filter assembly is positioned outside the package so that each filter overlays the window as the filters alternate in position. This configuration uses a mechanical means to move the respective filters into place at a sufficiently fast rate to support the desired imaging requirements. Other means of alternating spectrally separated bands of light onto a linear detector array are also possible. The prototype gas imager operates at 20 frames/second.

FIG. 5B shows another configuration of one-dimensional SWIR photo-detector arrays and filters, where two separate linear arrays with their own ROICs are configured in parallel layout on a common thermo-electric cooler inside a hermetically sealed package with a window located above the pair of photo-detector arrays. Filters *F-A* and *F-B* are mounted either in a frame or glued directly to the window, each filter being fixed in place and located above one of the photo-detector arrays. This configuration eliminates the need to mechanically move the filters rapidly and lends itself to higher frame rates. This configuration of two parallel linear arrays of photo-detectors can also be used with an alternating or otherwise changeable filter array such that a new pair of filters is moved into place to overlay the detector arrays. For example, a four-band imager would be created from a dual-linear detector array with alternating pairs of filters in a quad-filter frame, and could, for example, support

separate detection and quantification of methane and volatile organic compounds or methane and carbon dioxide.

FIG. 6A illustrates the use of a two-dimensional SWIR photo-detector array and ROIC, where an array of four filters, *F-A*, *F-B*, *F-C*, and *F-D* are configured as stripes that overlay the detector array. The filter stripes can extend across most of the array, with each stripe covering one or more rows of detectors. The detector array and ROIC is to be mounted on a thermo-electric cooler and enclosed in a hermetically sealed package with a transparent window over the detector array. The filter stripes can be configured into an array as a mosaic of individual filters in a frame, or fabricated as a monolithic array, and it is clear that more than four different filters can comprise the array. Two-dimensional 2.5 $\mu$ m-SWIR type-II InGaAs/GaAsSb imaging arrays of size 320x256 pixels are now commercially available. This configuration can be viewed as a collection of many linear arrays covered by a set of spectral filters.

FIG. 6B shows a configuration of four discrete SWIR photo-detectors, *PD1*, *PD2*, *PD3*, and *PD4*, arranged in a 2x2 array, each with its own analog read-out circuit and (possibly shared) analog-to-digital converter, and each covered with a separate spectral filter island. In practice, the four discrete photo-detectors are to be mounted on a common thermo-electric cooler and enclosed in a hermetically sealed package (e.g., a TO-8 “transistor-outline” metal can) with a transparent window. The spectral filters can be assembled from discrete filters into a spectral filter mosaic, or fabricated as a monolithic array of filter islands, and located outside the window aligned with the photo-detectors below. With the appropriate lens, this configuration forms the equivalent of a single multi-spectral SWIR pixel. This configuration can clearly be extended to more or fewer discrete photo-detectors, each with its own spectral filter. A minimum of two spectrally filtered photo-detectors is required to construct a scanner that can image and quantify gas emissions. This same type of spectral filter mosaic can also be combined with the two-dimensional photo-detector array shown in FIG. 6A, whereby each filter island of the mosaic overlays a small two-dimensional sub-array of even smaller pixels. Upon read-out of the entire detector array, each sub-array of pixels corresponding to the same filter island can be combined into a macro-pixel. This configuration trades off reduced spatial resolution for increased signal in a two-dimensional array of very small photo-detectors.

All of the multi-spectral SWIR detector configurations described and shown in FIGS. 5 and 6 utilize additional scanning and focusing optics in order to create two-

dimensional spectral imagery from which a gas detection imager can be created. As is known to one of ordinary skill in the art, all the detector embodiments shown in FIG. 5 and 6 lend themselves to packaging in hand-held systems, and can also be configured to operate on moving platforms such as ground vehicles, airborne rotorcraft and fixed-wing platforms, ships, rotating mast-mounted systems, and translating rail-mounted systems.

### Gas Imaging Sensor Systems

FIG. 7A illustrates a first system diagram for the video gas imaging sensor system. Beginning with the SWIR camera (SWIR), it consists of one of the SWIR photo-detector arrays (linear, dual-linear, or two-dimensional) as shown in FIG. 5A, 5B and 6A, together with its corresponding read-out circuitry and video timing circuitry. This SWIR camera has a SWIR lens (L) that is transmissive to at least the spectral range spanning the wavelengths of interest to sense the hydrocarbon features, approximately 1.0 through 2.6 microns. Positioned between the SWIR lens (L) and the SWIR camera (SWIR) is the spectral filter array positioner (F) which may include a motor and/or mechanical fixture to properly locate the correct filter(s) in front of the photo-detector array(s) during the exposure of each frame. This combination of SWIR detector array plus filter array corresponds to the various embodiments as shown in FIG 5A, 5B, and 6A. The SWIR imaging sub-system also includes a scanning mirror (SM) which sweeps the scene across the spectrally filtered photo-detector array so as to create a two-dimensional field-of-regard. The scanning mirror (SM) is typically a one-dimensional scanner that sweeps in a directional perpendicular to the orientation of the filters positioned over one-dimensional detector arrays or the stripes over the two-dimensional detector array. An electronic driver (D) controls the scanning mirror (SM). Synchronization between the scanning mirror (SM), filter positioner (F), and SWIR camera (SWIR) is provided by a micro-controller (C). Two-dimensional image assembly is performed on a micro-processor (P1).

FIG. 7B illustrates a second system diagram for the scan gas imaging sensor system. In this case, the discrete photo-detectors and spectral filter mosaic (SFM) of FIG. 6B form a single multispectral pixel by means of a defocusing lens (L), and this sensor is scanned across the scene in two directions by mounting it atop a high-accuracy pan-tilt unit (PTU) controlled by micro-controller (C2). Two-dimensional imagery is created by raster scanning across a desired, and possibly variable, field-of-

regard. In order to create imagery of higher resolution than that obtained directly by scanning this sensor with its own narrow field-of-view, it is useful to employ spatial over-sampling in combination with super-resolution image processing, which is widely discussed in the literature. Two-dimensional scanning can be accomplished in a compact configuration, for example, by a pair of scanning mirrors or a pair of rotating prisms. Two-dimensional imaging can also be achieved using a single scanning mirror combined with physical movement of the imaging sensor (e.g., translation or rotation in a direction perpendicular to the scan mirror motion) such as by mounting the sensor upon a moving platform (e.g., truck-mounted, airborne, rail-mounted) or rotating the sensor in a mast-mounted configuration.

Each imaging sensor system of FIG. 7A and 7B may also include one or more visible color (RGB) or black and white cameras, laser range finder (LRF) to measure distance from the sensor to a detected leak, global positioning system (GPS) sensor to determine sensor location (and indirectly leak location), inertial measurement unit (IMU) to sense linear and rotational accelerations including direction of gravity, magnetic sensor (Mag) to sense the earth's magnetic field acting as a compass, and/or weather sensors (Wx) to relay local atmospheric conditions including wind speed and direction, all of which is packaged together with one or more processors (P1, P2). In order to optically register the visible imagery with the SWIR imagery and resulting gas absorption imagery, as shown in FIG. 7A, a beam splitter (BS) is incorporated that is preferably dichroic, such that the incident light along the line-of-sight (LOS) is mostly transmitted through the beam splitter for visible wavelengths 0.4 through 0.7 microns, and mostly reflected for SWIR wavelengths 1.0 through 2.6 microns. The reflected SWIR light is subsequently reflected by the scanning mirror (SM) towards the SWIR lens (L) that focuses this light onto the SWIR camera (SWIR) behind the spectral filter assembly (F). Alternatively, as shown in FIG. 7B, in the absence of a beam splitter, the measured range to each SWIR sample can be used to correct the parallax offset between that SWIR sample and its corresponding location in the visible RGB image, using the known spacing of the SWIR, RGB, and LRF sensors.

As shown in FIG. 7A and 7B, one processor (P1) is associated with the multispectral SWIR camera and is responsible for real-time or near real-time processing of the SWIR multispectral data to create the gas absorption imagery. A separate processor (P2) has a path for accepting the visible camera (RGB) imagery and triggers the other low-bandwidth sensors (LRF, GPS, IMU, Mag). This processor

(P2) also communicates wirelessly (or wired) with an external weather sensor (Wx) and a graphical user interface (GUI) implemented on a touch-screen tablet computer. The tablet, in turn, provides wireless access to an Ethernet or data cloud (E/C), which in turn can be accessed by a remote personal computer (PC). This arrangement  
5 enables remote (PC) access and control of one or more gas imaging sensor systems. Finally, an artificial illuminator (Lum), as explicitly shown in FIG. 7B, is controlled by a micro-controller (C2) and incorporated to enable gas imaging in the absence of sufficient sunlight or for indoor locations. Alternative implementations are possible, such as for example (but not limited to) a configuration with:

- 10       • the display or the controls or the complete user interface physically attached to the imaging device,
- the display or the controls or the complete user interface physically remote from the imaging device,
- the user interface implemented with physical knobs, buttons, sliders, dials,  
15       selectors or similar on the imaging device or separate from it
- the user interface implemented with digital representations of knobs, buttons, sliders, dials or similar using a display where this display can be either physically attached to the imaging device or connected by wired or wireless means
- 20       • a combination of physical and digital user interface described above
- processors P1 and P2 combined into a single processor or their functions distributed over multiple processors,
- some or all of the low-bandwidth sensors being integrated into (a) the imaging device, (b) into a separate unit, or (c) into a display unit,
- 25       • some or all of a single set of low-bandwidth sensors being connected to one or several processors that is (are) providing data for use by multiple imaging sensor systems.

#### **OPERATION OF ALL SENSOR EMBODIMENTS**

30       The various sensor embodiments described above can be operated in many different modes. In one mode the data gathered from the sensor is analyzed by a processor and used for automatic analysis and decisions (such as triggering of an alarm signal or different operating mode, because a certain limit of gas detection is

exceeded) by the processor without being displayed in real-time or near real-time on a display. In another mode an image of the received data can be shown on a display (for example for monitoring by a human operator) however no real-time analysis like gas quantification is performed. In a third mode an image is displayed and automatic gas  
5 quantification is performed, and significant results are automatically stored or sent to remote locations. Other combinations and modes of operation are possible as well, for example in conjunction with the use of low-bandwidth sensors like range and weather sensors.

### **Imaging Turbulent Gas Jets and Absorption Profiles**

10 FIGS. 8A and 8B illustrate two alternative imaging geometries of a potential gas leak, shown as a gas jet exiting a hole in a pressurized pipe and expanding into an ambient atmosphere. Illumination provided by the sun is shown in FIG. 8A to transmit directly through the gas jet and ambient atmosphere towards the SWIR  
imaging sensor, i.e., the sun is roughly in front of the sensor and the gas leak. In FIG.  
15 8B, artificial illumination comes from near the SWIR imaging sensor behind the gas leak, passes through the gas jet and ambient atmosphere, reflects off background material and heads back to the sensor while passing through the gas jet and ambient atmosphere a second time. A hybrid of these imaging geometries is where the sun is out in front of the sensor beyond the gas leak, but first reflects off the ground then up  
20 through the gas towards the sensor. These various imaging geometries differ in three ways; the number of passes through the gas jet (once vs. twice), the optical path length through the ambient atmosphere to be considered ( $L_J$  vs.  $2L_R$ ), and change in spectral illumination of the source  $S_\lambda$  due to the reflectivity of the background  $R_\lambda$ .  
The spectral response of the SWIR sensor will be affected by the solar (or artificial)  
25 SWIR illumination, reflectivity of the background, absorption by the gas jet, absorption by the ambient atmosphere, the quantum efficiency of the photo-detector array  $Q_\lambda$ , and transmission of the filters  $F_\lambda$  in combination with the SWIR lens.

The geometry of the gas jet, as shown in FIGS. 8, is indicative of a momentum-dominated jet forced from an orifice of effective diameter  $D_o$  under  
30 pressure. If the internal pipe pressure is approximately twice the external atmospheric pressure, the jet will exhibit critical flow (also termed “choked flow”) at the orifice where it just reaches the local speed of sound. The internal pressure and temperature

determines the density of the gas at the exit, and hence, the mass-flow of gas out the hole. Beyond the exit hole the gas expands rapidly and adiabatically, and beyond an initial zone of complex acoustic waves, the resulting slip flow of the gas relative to the ambient air goes unstable and transitions to turbulence. This turbulence penetrates across the entire gas jet, entraining air into the jet from the sides, which causes the gas to dilute and the jet to expand in a predictable self-similar flow that is invariant to scale. The gas exiting the hole thus shares its initial momentum with the entrained air, thereby losing initial momentum while buoyancy acts to add momentum in the direction of gravity. In the case of natural gas, the buoyancy force acts upwards as the methane at atmospheric pressure is less dense than air. The heavier hydrocarbons will gain downward momentum due to negative buoyancy. The orientation of the pipe and location of the hole will affect the angle of the jet relative to gravity, and the presence of crosswinds will cause the jet to bend with the wind. The self-similar structure of this turbulent gas jet, its variation along the jet axis and cross-sectional profiles, are well known. For thin cracks, as opposed to approximately round holes, there is also a self-similar solution to the turbulent jet. And at low pressures, where the exit flow is sub-sonic, the jet will rapidly become a buoyant plume that also generates turbulence and exhibits a self-similar structure. Since the variations in jet geometry, gas concentration, and gas density, will all affect the absorption of the SWIR illumination passing through the jet, the absorption imagery of a gas jet can be used from different viewpoints to probe the geometry of the orifice, and determine its approximate shape and size. Combining this information with the internal pressure of the pipe (assumed known from reading a nearby pressure gauge or knowledge of the plumbing network), it is possible to estimate the mass-flow out of the orifice. Thus, the invention provides both imagery of the gas leak and quantification in terms of gas present in the jet and mass-flow out the hole along with estimates of hole shape and size.

FIG. 9A illustrates an absorption image of a methane gas jet exiting a 1mm diameter round orifice with an internal pressure of 1300 psig (pounds per square inch – psi “gauge”, i.e., relative to external atmospheric pressure of approximately 14.5psi). The absorption image is colored according to a pixel-level *differential optical depth* scale shown to the right. This corresponds to the degree of absorption in the *Core Band* relative to the *Wings Band* for the filters used in the functional prototype of FIG. 3A. This pixel-level *differential optical depth* is directly proportional to the number of methane molecules along each cone of rays between the

light source and the photo-detector corresponding to each pixel; this is the so-called *pixel column density* of the gas. The turbulent structure of the jet is apparent near the top of the jet image. It is clear from the absorption image that the jet diameter grows linearly along the jet axis, as is consistent with the theoretical self-similar solution for turbulent jets. In this image, it is the noise level of the background differential optical depth that determines the boundary of the jet and so limits the visible diameter.

FIG. 9B shows cross-sectional profiles of the jet absorption image. The graphs plot *differential optical depth* vs. pixel number across a row of 512 pixels corresponding to the horizontal lines labeled *a, b, c* in FIG. 9A. It is apparent from these plots that the diameter of these absorption profiles is increasing along the jet axis, and that the turbulence creates fluctuations in absorption through the jet. The general shape of these plots is entirely consistent with the path length through a cross-section of a round jet in combination with a radial concentration profile of Gaussian shape. Superposed on this smooth theoretical profile are fluctuations in concentration due to turbulence.

The maximum of the absorption on each profile should occur on axis of the jet, if the imaging line-of-sight is perpendicular to the jet axis, as this is where the path length through the jet is a maximum and the gas concentration is largest. Based on the self-similar solution for turbulent round jets, the gas concentration on axis will decrease linearly along the jet as it expands, while the diameter increases linearly along the axis, and so the product of axial gas concentration with diameter should remain a constant, suggesting the column density along the jet axis should remain constant. However, due to the turbulent fluctuations, these profiles change over time, and so individual pixel values fluctuate. To cope with these turbulent fluctuations, it is suggested to use spatial averages of quantities across the jet, and then calculate the total absorption of a slice of jet, as it is due to the total mass of gas in that slice and not sensitive to the exact distribution of mass throughout the slice. Each row of pixels along consecutive cross-sections through the jet corresponds to a constant thickness slice, and since the jet diameter varies linearly with axial distance, hence, the slice volume increases as the square of the axial distance. But since the gas concentration dilutes linearly with axial distance in a self-similar round jet, the mass of gas in constant thickness slices is expected to increase linearly with axial distance along the jet. That is, the gas at the front of a jet slice flows slower than the gas at the rear of the jet slice, causing mass to build up between slices of constant thickness. And since the

mass of gas in slices increases linearly along the jet axis, so should the absorption due to that mass. Thus, the *integrated differential optical depth* across each cross-section of the jet image should increase linearly along the jet. Similarly, the jet width in the absorption image should increase linearly along the jet, where the jet boundary is  
5 determined by the noise in the background image. Integrating the absorption across jet cross-sections acts to smooth out the effect of turbulent fluctuations on gas concentration in the jet.

FIG. 10A and 10B plot the automatically extracted jet width and  
10 corresponding *integrated differential optical depth* (integrated-dOD), respectively, along the axial distance (approximately the image row number) for the jet image in FIG. 9A. It is apparent that both quantities follow clear linear trends, and so a least-squares regression line is fit to each quantity. Forming the ratio of *integrated differential optical depth* to *jet width* yields an *average differential optical depth* (*average-dOD*) value at each axial location along the jet. This ratio is plotted in FIG.  
15 10C, to which a least-squares regression line is fit (starting away from the orifice to exclude the complex acoustic region just outside the hole). It is apparent from FIG. 10C that the slope of this regression line is very small, and that the *intercept* of the regression line then corresponds to the *average differential optical depth* extrapolated back to the *effective orifice* from which the gas leaks under pressure.

20 FIG. 11 plots the integrated differential optical depth (integrated-dOD) along the axis of a natural gas jet emanating from a narrow (50 micron) slit orifice that is 1cm long, meant to emulate a crack (instead of a hole) in a pressurized line at 60 psig. Following the same reasoning as above but for a plane turbulent jet (instead of a round turbulent jet), one finds that the integrated-dOD should scale with the square-root of the distance along the axis, as is apparent from the least-squares regression fits  
25 in FIG. 11. And since the integrated-dOD across a plane jet is independent of the orientation of the slit relative to the line-of-sight of the sensor, one can use this square-root versus linear behavior to distinguish between a gas leak emanating from a crack or a hole.

### 30 **Absorption and Mass Flow Across a Range of Pressures and Orifice Sizes**

Experiments have been conducted to image the release of methane gas under a range of pressures (50 – 1400 psig) exiting from round orifices (diameters of 0.75mm and 1.0mm). Gas jet boundaries are automatically extracted from the imagery, and the

average differential optical depth (*Avg-dOD*) along the jet axis is computed. Fitting a least-squares regression line to this data determines the intercept of this regression line, which indicates the degree of absorption of the methane at the effective orifice.

FIG. 12A plots the value of this *Avg-dOD intercept* (scaled by orifice diameter)

5 against the internal pressure  $P$  (in units of *Bar*, where 1 *Bar* = 14.5psi, the atmospheric pressure at sea level). The data points are consistent with a power-law behavior of pressure, for which the scaling constant and exponent values are shown on the graph. This is expected since the absorption by the methane gas at the effective exit hole (extrapolating back from the linear boundaries of the jet) will be

10 proportional to the product of the effective orifice diameter and the local gas density, while the gas density is proportional to a power-law of the pressure through the adiabatic equation of state using the ratio of heat capacities for methane. Further experiments will determine the general utility of this specific power-law relationship across a range of orifice diameters and (approximately round) shapes.

15 FIG. 12B plots the measured methane mass flow per orifice area (in grams/sec, divided by orifice area) against internal pressure for numerous experiments using round and slot orifices of different sizes. It is clear they follow the expected linear relationship, with a slope determined by the data. The mass flow out of the orifice is proportional to the product of the area of the orifice and the methane gas

20 density in the pipe (which is proportional to the pressure in the pipe). Thus, while the *Avg-dOD intercept* curve scales linearly with effective diameter of a round orifice (as implied by FIG. 12A), the mass flow scales like the square of the effective diameter of a round orifice (as implied by FIG. 12B). These relationships taken together are therefore used to estimate the orifice size and mass flow of gas directly from the

25 observed absorption image of a gas jet leaking from a hole under known internal pressure. Thus, it is possible to estimate the size of a leak hole directly from a gas jet absorption image, even if the leak hole itself is not visible in the image. And this leads directly to a leak rate or mass flow estimate. Similar relationships apply to a planar gas jet leaking from a narrow crack.

30 FIG. 13A shows a test setup for imaging and estimating methane mass flow exiting from small round orifices of various sizes at a range of internal pressures up to 1000 psig. Experiments were conducted outdoors in natural sunlight under varying crosswinds. FIG. 13B graphs the data obtained using the setup in FIG. 13A, showing strong correlation between the mass outflows estimated directly from the gas

absorption imagery with the measured mass flowing into the gas release manifold, in the presence of crosswinds (Low = 0-5kph, Med = 5-10kph, High > 10kph). This validates the method for estimating gas leak rate from absorption imagery, for holes in pressurized lines.

5           Next, the mathematical formulation of absorption imaging and quantification of gas leaks is described, using methane or natural gas as a specific example.

**Defining the SWIR Spectral Bands**

Spectral imagery is taken through at least two filters with transmission exceeding about 5% over wavelength regions that cover the 2350nm methane feature complex.

10          One filter is narrow (bandwidth approximately 200nm) and centered at about 2350nm; call this the *Core Filter* with transmission  $F_C(\lambda)$  and integrated transmission  $F_C$ . The other filter is broad (bandwidth approximately 400nm), transmitting between approximately 2100 – 2500nm; call this the *Surround Filter* with transmission  $F_S(\lambda)$  and integrated transmission  $F_S$ .

15          Remove the overlapping *Core Band* spectral transmission from the *Surround Filter*, in order to image the intensity in the spectral *Wings Band* of methane. Alternatively, use two separate filters that transmit in bands on either side of the *Core Band*, and combine them into a *Wings Band* filter. Or use a single broadband filter that spans both sides of the *Core Band* with a low-transmission notch in the region of  
 20          the *Core Band*. It is recommended to use *Core Band* and *Wings Band* filters with approximately equal transmission-bandwidth product to balance the dynamic range of the signal in both spectral bands.

Define the *core integrated* transmission of the *Surround Filter* as  $F_{SC}$  and of the *Core Filter* as  $F_C$ , and the imaged intensities in the core and surround pass-bands as  $I_C$   
 25          and  $I_S$ , then the intensity in the *Wings Band*  $I_W$  is obtained as

$$I_w = I_s - \left[ \frac{F_{SC}}{F_C} \right] I_c \tag{Eq. 1}$$

**Calibrating the Sensor in the Ambient**

**Environment**

Define the *optical depth* in the *Core Band* as  $\tau_c^{(a)}$  and the optical depth in  
 30          the *Wings*  $\tau_w^{(a)}$  *Band* as Each is the product of the respective absorptivity and path length through the environment (approximating integrals across wavelength bands). Noting the superscript (*a*) to connote the ambient atmosphere, and using the

symbols defined previously and shown in FIG. 8B, the intensities in both bands are given by:

$$I_c^{(a)} = S_c(r) Q_c F_c R_c \exp[-\tau_c^{(a)}] \quad (\text{Eq. 2a})$$

$$I_w^{(a)} = S_w(r) Q_w F_w R_w \exp[-\tau_w^{(a)}] \quad (\text{Eq. 2b})$$

Next form the ratio of these spectral intensities, and note the spectral illumination source function *ratio*  $S_c/S_w$  is independent of distance and only a function of wavelength.

Then define the cross-channel *Core-to-Wings gain*  $G_{CW}$  as the ratio of bracketed terms in Eq. 3a, the atmospheric differential absorption  $\delta\alpha^{(a)}$  coefficient, and path length from sensor to the reflector panel  $L_R$ . The ratio of *Core* to *Wing* intensities is then

$$\frac{I_c^{(a)}}{I_w^{(a)}} = \frac{[S_c(0) Q_c F_c R_c]}{[S_w(0) Q_w F_w R_w]} \exp[-\tau_c^{(a)} + \tau_w^{(a)}] \quad (\text{Eq. 3a})$$

$$\frac{I_c^{(a)}}{I_w^{(a)}} = G_{CW} \exp[-\alpha_c^{(a)} + \alpha_w^{(a)}] 2L_R = G_{CW} \exp[-\delta\alpha^{(a)}] 2L_R \quad (\text{Eq. 3b})$$

To adaptively calibrate the sensor in the ambient atmosphere, first measure the SWIR illumination bouncing off a reflector panel at two or more distances, calculate the image average intensities, and form the log of their ratio to solve for the unknowns  $\delta\alpha^{(a)}$ ,  $G_{CW}$  and (if using more than two distances, solve for the two unknowns via method of least-squares). The resulting value for the gain  $G_{CW}$  incorporates the ratio of *Core-to-Wings* reflectivities of the calibration panel. When the sensor is sufficiently close to the potential leak site, it is not required to account for absorption by the ambient atmosphere, therefore one can forego measurement of reflected light from calibration panels at measured distances, and instead adopt a value of zero distance to such panels. Practical application for methane sensing suggests that distances from 5 to 15 meters are sufficiently close under conditions of a fair atmosphere, however, under foggy conditions, even distances below 5 meters might require the above process to compensate for atmospheric absorption.

Next, rescale the gain  $G_{CW}$  using in-scene reflector materials (i.e., background materials). Use a pair of *Core* and *Wings Band* images of the in-scene reflector materials (concrete, wood, asphalt, dirt, grass, etc.) together with Eq. 3b to determine an adaptive gain  $G_{CW}$  for each reflecting material. It is also possible to generate a

library of these gain values for a variety of background materials, and have the user select from a menu the appropriate gain value, or have the sensor system automatically select the appropriate gain value to use while conducting a leak inspection. For direct transmission of sunlight through gas, as in FIG. 8A, the new gain value is obtained by simply imaging in a direction without a background and ignoring atmospheric absorption, using Eq. 3b.

**Imaging Possible Gas Leaks (Detection Mode)**

To inspect for a possible gas leak, image in the direction of interest. Using the symbols of FIG. 8b for a gas leak of extent (jet width)  $D_J$ , measure range  $L_R$  to the reflecting surface in the background (either the reflector panel or an in-scene reflector).

Let  $\tau^{(g+a)}$  be the optical depth of the combined gas jet in the ambient environment from the sensor to the reflector at  $L_R$  and back to the sensor. Then the intensities in the

*Core* and *Wings Bands* are given by

$$I_c^{(g)} = S_c(r) Q_c F_c R_c \exp[-\tau_c^{(g+a)}] \tag{Eq. 4a}$$

$$I_w^{(g)} = S_w(r) Q_w F_w R_w \exp[-\tau_w^{(g+a)}] \tag{Eq. 4b}$$

Form the ratio of *Core* to *Wings Bands* from equations (4), substitute the expression for the cross-channel gain  $G_{CW}$  (appropriate for the background surface reflector), define the differential spectral absorption  $\delta\alpha^{(g)}$  coefficient of methane or natural gas, and rearrange terms (the superscript “(g)” connotes gas may be present),

$$\frac{I_c^{(g)}}{I_w^{(g)}} = G_{CW} \exp\{-[\delta\alpha^{(g)} - \delta\alpha^{(a)}]2D_J + [\delta\alpha^{(a)}]2L_R\} \tag{Eq. 5}$$

Define the *Excess Differential Spectral Absorptivity* of the gas jet (diluted methane or natural gas) over that of the ambient atmospheric environment as

$$\Delta_{CW}^{g-a} \equiv \delta\alpha^{(g)} - \delta\alpha^{(a)} = [\alpha_c^{(g)} - \alpha_w^{(g)}] - [\alpha_c^{(a)} - \alpha_w^{(a)}] \tag{Eq. 6}$$

Therefore, the *Differential Optical Depth (dOD)* image due to the gas jet is obtained from the measured spectral intensities and calibration parameters via equations (5) and (6) as

$$dOD = \left[ \Delta_{CW}^{g-a} \right] D_j = -\frac{1}{2} \ln \left[ \frac{1}{G_{cw}} \frac{I_c^{(g)}}{I_w^{(g)}} \right] - \left[ \delta \alpha^{(a)} \right] L_R \quad (\text{Eq. 7a})$$

In the case of negligible atmospheric absorption as compared to the gas leak (e.g., imaging sufficiently close to a potential leak), the second term on the right can be eliminated by setting  $L_R$  to zero, thus

$$dOD = -\frac{1}{2} \ln \left[ \frac{1}{G_{cw}} \frac{I_c^{(g)}}{I_w^{(g)}} \right] \quad (\text{Eq. 7b})$$

The factor of  $\frac{1}{2}$  in equation (7b) comes from the double path length through the gas due to reflection of incident light from near or behind the sensor, off the background surface, and back to the sensor. In the case of single pass transmission (e.g., sunlight ahead of the gas leak, passing directly through the gas to the sensor), this factor is simply dropped.

### Estimating Jet Mass, Orifice Size, and Methane Mass Flux

From the differential optical depth ( $dOD$ ) image for a detected jet (or plume or cloud), compute the average- $dOD$  across the jet profiles along its axis, and sum along the axis to obtain the total optical depth of the visible jet according to

$$dOD_{jet} = \sum_{axis} D_j(z) \overline{dOD}(z) \quad (\text{Eq. 8})$$

Relating  $dOD$  to the methane molecular column density via the absorption cross-sections  $\sigma_C$  and  $\sigma_W$  in the *Core* and *Wings Bands* (see FIG. 2B), obtain the total number of methane molecules, and multiply by the mass of a methane molecule  $m_{CH_4}$  to obtain the total mass of methane gas in the visible jet (or plume or cloud) via the expression

$$Mass_{CH_4} = \left[ \frac{dOD_{jet}}{\sigma_C - \sigma_W} \right] m_{CH_4} \quad (\text{Eq. 9})$$

From the differential optical depth ( $dOD$ ) image for a detected jet, derive the  $Avg-dOD$   $\overline{dOD}_0$  intercept by linear regression along the jet axis as explained above and shown in FIG. 10C, and combine with a power-law equation of the form (see FIG. 12A)

$$\overline{dOD}_0 = \frac{1}{S} D_o P^k \quad (\text{Eq. 10a})$$

Solve for (an approximately round) orifice diameter  $D_o$  and substitute for the scale factor and exponent as obtained from the experimental data as shown in FIG. 12A,

$$D_o = S \frac{\overline{dOD}_0}{P^k} \cong 110 \frac{\overline{dOD}_0}{(P/14.7)^{0.34}} \quad (\text{Eq. 10b})$$

Use this orifice diameter  $D_o$  to estimate the methane mass flow rate from the orifice flow formula using the linear regression formula shown in FIG. 12B,

$$Q_m = \frac{\pi}{4} D_o^2 (0.68P) \cong 0.53 D_o^2 P \quad (\text{Eq. 11})$$

- 5 This mass flow estimate is valid for internal pressures  $P$  greater than approximately 1.8 bar (26psi), such that choked flow occurs at the leak orifice, with outflow speed at the local sound speed and adiabatic expansion of the gas. The units for the physical quantities in equations (8) through (11) are: optical  $\overline{dOD}_0$  depth intercept is dimensionless, diameter  $D_o$  in millimeters, pressure  $P$  in psig, and methane mass  
10 flux  $Q_m$  in grams/min.

### Surface Emission Mass Flux Under Steady Winds

To estimate surface emission mass flux under conditions of buoyancy and ground-level winds, we consider the imaging geometry shown in FIG. 14A overlooking a ground area upon which gas is detected, similar to the example shown  
15 in FIG. 4C. Each emitting surface patch is analyzed using the notation shown in FIG. 14B, and the total surface emission flux is obtained by summing the individual patch emissions.

As illustrated in FIG. 14B, a surface patch by definition is isolated, surrounded by ambient clear air, with winds that are assumed steady in direction and speed  $V$  (the  
20 case of gusting winds will be considered below). Gas emerges from the ground, diffuses into the air above, and rises (methane) or falls/lingers (for heavier hydrocarbons) due to buoyancy forces. The wind convects the gas downwind as it continues to disperse and rise (as is typically the case for a natural gas leak from an underground pipe). The mass of methane associated with a surface patch is estimated  
25 from spectral imaging, which provides the differential spectral optical depth of methane over the entire patch. Summing the pixels over the entire patch, similar to Eq. 8 for the gas jet, and convert to methane mass over the patch as in Eq. 9.

Measure the wind speed  $V$  and direction near ground/surface level, and assume it is representative of the wind at the emitting surface patch. Also measure range from  
30 the sensor to the surface patch, so that pixel dimensions of the patch can be converted

to linear dimensions. The steady wind  $V$  (cm/sec) blows methane across the patch and away, as it diffuses out of the ground into the air above the patch, and an equilibrium is established in which the surface emission mass flux  $Q_m$  (grams/sec) is balanced by the windblown mass crossing the downwind boundary of the patch. The methane layer above the surface patch has a characteristic thickness  $D$  and concentration  $c$  which give rise to the measured differential optical depth  $dOD$  at each pixel. By adjusting the threshold on the optical depth to a low level above the noise floor, the spatial extent of an emitting patch is defined. Construct the bounding rectangle around that patch such that one axis of the rectangle aligns with the wind direction, as illustrated in FIG. 14B. Using the range measured to the patch, convert pixel dimensions of this bounding rectangle to linear dimensions  $L$  and  $W$ . The volume flux ( $\text{cm}^3/\text{sec}$ ) across the downwind boundary of the patch is equivalent to the volume flux  $DWV$  across side  $W$  of the rectangle. The methane mass flux  $Q_m$  (grams/sec) is obtained from the product of the methane concentration in air, methane density, and volume flux across the downwind boundary;

$$Q_m = c\rho_{CH_4}DWV \tag{Eq. 12a}$$

Expressing  $c\rho_{CH_4}D$  in terms of the differential spectral optical depth  $dOD$ , obtain the estimate of methane mass flux from a patch in steady wind:

$$Q_m = \left[ \frac{m}{\sigma_B - \sigma_{ref}} \right]_{CH_4} WV(dOD) \tag{Eq. 12b}$$

As the imaging geometry shown in FIG. 14A suggests possible oblique sensing, at an angle of  $\phi$  relative to the vertical, through the gas layer above the ground surface, the measured differential optical depth should be scaled by cosine ( $\phi$ ) so as to relate to the physical thickness of the layer as denoted by  $D$ . The same oblique imaging geometry results in a foreshortening of the ground surface in the down-range direction in the imagery. One can correct the measured optical depth and surface patch dimensions by projecting all sensor data and imagery to the ground plane using the known tilt of the sensor relative to the ground plane (as is commonly done when ortho-rectifying imagery), as if viewing the surface patch from directly above.

### Surface Emission Mass Flux Under Gusting Winds

Similar to the formulation for steady winds, gas diffuses out of the ground into the air above the surface patch and builds up a gas layer as the wind blows it away. However, when a gust occurs, the wind rapidly blows the entire layer of methane away. In gusting winds, the methane layer alternates between building itself up (in steady winds of speed  $V$ ) and being rapidly destroyed by a sudden gust. This allows the build-up of a methane layer to be observed over time. The build-up of methane mass above the patch is the surface emission mass flux  $Q_m$  minus the mass flux due to steady wind  $V$  as in Eq.12B,

$$\frac{dM_{CH_4}}{dt} = Q_m - \left[ \frac{m}{\sigma_B - \sigma_{ref}} \right]_{CH_4} WV(dOD) \quad (\text{Eq. 13a})$$

However, direct observation of the accumulation of methane is possible by imaging the time-varying differential optical depth over the patch, since

$$\left. \frac{dM_{CH_4}}{dt} \right]_{obs} = A_p \rho_{CH_4} \frac{d}{dt}(cD) = \left[ \frac{m}{\sigma_B - \sigma_{ref}} \right]_{CH_4} A_p \frac{d}{dt}(dOD) \quad (\text{Eq. 13b})$$

Here  $A_p$  is the area of the patch observed before the gust,  $D$  is the changing thickness of the methane layer above the patch, and  $c$  is the increasing concentration of methane as the layer grows until the next gust. Equating expressions Eq. 13a and Eq. 13b, we obtain an estimate of the methane mass flux  $Q_m$  (grams/time) from a surface patch in gusting wind by observing the time-varying differential optical depth as the methane layer is reestablished under steady wind conditions;

$$Q_m = \left[ \frac{m}{\sigma_B - \sigma_{ref}} \right]_{CH_4} \left\{ A_p \frac{d}{dt}(dOD) + WV(dOD) \right\} \quad (\text{Eq. 13c})$$

## CONCLUSION, RAMIFICATIONS AND SCOPE

The embodiments as described above consist of both multispectral SWIR sensors for imaging, detecting and localizing methane and other hydrocarbon gases, and methods to estimate the leak rate or mass flux. Multiple embodiments of sensor systems have been described to enable imaging of gas leaks, and multiple methods have been disclosed for estimating methane mass flux from holes in pressurized lines, and from surface patch emissions due to underground gas pipe leaks. Example imagery and leak rate estimates across a wide variety of conditions illustrate the viability of the sensors and methods.

Summarizing the advantages of the invention over existing alternative gas imaging technologies, we note the ability to image and quantify gas leaks using natural sunlight without the need for any thermal contrast between the gas and the background, the ability to image and quantify methane in the presence of water vapor and fog, and the ability to quantify leak rates and surface emission flux in order to assess leak severity and prioritize repairs. These capabilities have application in gas safety, gas leak inspection, and greenhouse gas emissions monitoring.

While the above description contains much specificity, these should not be construed as limitations on the scope, but rather as exemplification of several embodiments thereof. Many other variations are possible. For example, by selecting the appropriate spectral filters in the SWIR, the invention can be used for detecting and quantifying other gases, liquids, emulsions, powders, and solids, in addition to the ones cited above and discussed in detail. Thus, multiple spectral filters can be selected to detect ammonia gas, which is both combustible and toxic. Also fertilizers can be detected and quantified, as can soil wetness and general plant health, thus other embodiments may be well suited for agricultural assessments. Yet other embodiments can be constructed that are well suited for detection of ammonium nitrate and its variants as used in the making of homemade explosives. Additionally, the methods developed for leak rate quantification of gases can be utilized for detecting gases and other substances in other spectral bands, in addition to the SWIR band. Accordingly, the scope should be determined not by the embodiments illustrated, but by the appended claims and legal equivalents.

**CLAIMS**

What is claimed is:

1. An imaging device to detect hydrocarbon compounds, comprising:
  - 5 a. one or more one-dimensional arrays of photo-detectors appreciably responsive to light in a wavelength range of approximately 1.0 to 2.6 microns, each said one-dimensional array having an associated electronic read-out circuit,
  - 10 b. at least two spectral filters associated with said one-dimensional arrays of photo-detectors, such that at least one of said spectral filters is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and such that at least one other of said spectral filters is appreciably transmissive to light of wavelengths not spanned by said spectral feature complex of said hydrocarbon compound of interest,
  - 15 c. a mechanical device selected from the group consisting of stationary frames, sliding frames, spinning frames, swinging blades, and rotating wheels, so that the filters can be disposed in a first position and a second position, in the first position light passes through the first filter before striking any of said one-dimensional arrays of photo-detectors, in the second position light passes through the second filter before striking any of said one-dimensional arrays of photo-detectors, and the mechanical device can move the filters between the first and second positions,
  - 20 d. an optical element selected from the group consisting of lenses, curved mirrors, diffractive surfaces, and combinations of said elements, to gather and focus incident illumination such that light at least in a wavelength range of approximately 1.0 to 2.6 microns is directed at said one-dimensional array(s) of photo-detectors so as to first pass through said spectral filters located in front of said one-dimensional photo-detector arrays,
  - 25 e. an opto-mechanical scanning device selected from the group consisting of resonant oscillating mirrors, galvanometric driven mirrors, rotating multi-faceted mirrors, and electrically actuated micro-mirror arrays, to scan a field-of-view one portion at a time relative to the one-dimensional photo-detector array(s),
  - 30

- f. at least one electronic circuit to control the integration time of said photo-detector array(s) and to convert signals generated by said photo-detector array(s) into amplified and digitized signals,
- g. at least one electronic circuit to synchronize said opto-mechanical scanning device, said mechanical device to dispose said filters in said positions relative to said photo-detector array(s), and said electronic circuit to read-out and convert said signals generated by said photo-detector array(s), so as to generate two-dimensional digital multispectral imagery,
- h. a processor coupled to receive said multispectral imagery and a value representative of a distance to a reflective calibration target, so as to calibrate said imagery of each said spectral band relative to imagery of said spectral band associated with said spectral feature complex of said hydrocarbon compound of interest, whereby such processing determines calibration parameters consisting of a dark level offset and a relative gain for image pixels of interest between said spectral bands, and a relative absorption coefficient for each said spectral band characterizing the local atmosphere under conditions of the ambient environment,
- i. a processor coupled to said multispectral imagery, in combination with said calibration parameters, to generate an adaptive relative gain across spectral bands, adapted to in-scene reflectors, and a differential optical depth absorption image, so as to determine the possible presence of said hydrocarbon compound of interest in said field-of-view, employing the Beer-Lambert Law of absorption across the multiple spectral bands,
- j. electronic circuitry to control the operation of said photo-detector arrays, said mechanical device to dispose said filters in said positions relative to said photo-detector arrays, said opto-mechanical scanning device, said processor to calibrate said multispectral imagery, and said processor to generate said absorption image.
2. The imaging device of claim 1 in which said spectral filters includes a *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both shorter and longer than the *Core* filter, said *Wings Band* filter created from a broadband *Surround* filter that includes said *Core Band*, by subtracting said *Core*

*Band* filter measurements from said *Surround* filter measurements, accounting for the relative transmission characteristics of said *Core Band* and *Surround* filters.

3. The imaging device of claim 1 in which said spectral filters includes a *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an  
5 extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both shorter and longer than said *Core* filter, said *Wings Band* filter created from a broadband filter with a low-transmission notch spanning the wavelengths of said *Core Band* filter.
- 10 4. The imaging device of claim 1 in which said spectral filters includes a *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter created from one or more filters that are appreciably transmissive to light of wavelengths either shorter or longer than those  
15 appreciably transmitted by said *Core Band* filter.
5. The imaging device of claim 1 in combination with a processor coupled to receive said absorption image, and a value of internal pressure of objects from which the detected hydrocarbons compounds being imaged originate, so as to estimate at  
20 least one quantity selected from the group consisting of the total absorption in said multispectral imagery of said hydrocarbon of interest, the total mass visible in said absorption imagery of said hydrocarbon of interest, the diameter of an approximately round hole from which said hydrocarbon of interest leaks, and the mass flow rate of said hydrocarbon of interest, by at least one method selected from the group consisting of the summation along the axis of said absorption  
25 image of said hydrocarbon gas jet of said average differential optical absorption weighted by the diameter of said imaged hydrocarbon gas jet, the scaling of total differential optical absorption of said hydrocarbon gas jet by said differential spectral absorption cross-section weighted by the mass of said hydrocarbon gas molecule, the relationship between said average differential optical depth along  
30 said hydrocarbon gas jet extrapolated back to the vertex of said hydrocarbon gas jet and said internal pressure as it relates to the diameter or area of said leak hole, and the mass flow of said hydrocarbon gas out of said leak hole of known area and said internal pressure.

6. The imaging device of claim 1 in combination with a processor coupled to receive said absorption image from a ground surface patch, and a value of near ground-level wind speed and direction, so as to estimate surface emission mass flux of said hydrocarbon of interest, by at least one method selected from the group
- 5 consisting of the relationship between said mass flux and said average differential optical depth imaged across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction, the relationship between said mass flux and said differential optical
- 10 depth imaged along the downwind edges of said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction, and the relationship between said mass flux and said
- 15 absorption imagery inferred rate-of-change of said average differential optical depth weighted by the area of said surface patch in combination with said average differential optical depth across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction.
7. The imaging device of claim 1 in combination with a visible light camera such that both said imaging devices possess approximately parallel lines-of-sight and share principally overlapping fields-of-view, by which said absorption image of
- 20 said hydrocarbon of interest is overlaid on the visible light image, thereby providing spatial context of where in the scene a possible hydrocarbon leak is detected.
8. The imaging device of claim 1 in combination with any of the following ancillary sensors: global positioning sensor to determine said device positional coordinates
- 25 on the earth, inertial measurement unit to determine said device linear or rotational acceleration components, magnetometer to determine said device orientation with respect to the earth's magnetic field, range finder to determine range of said device from reflecting surfaces in the scene, and weather measurement unit to determine local environmental conditions in proximity to
- 30 said device.
9. The imaging device of claim 1 in combination with electronic circuits capable of acting on data in ways selected from the group consisting of storing, saving, and transmitting said multispectral imagery, said absorption image, and associate with said imagery data selected from the group consisting of said estimated quantities

recited in claim 5 and claim 6, said visible light camera recited in claim 7, and said sensors recited in claim 8.

10. An imaging device to detect hydrocarbon compounds, comprising:
- a. a two-dimensional array of photo-detectors appreciatively responsive to light  
5 in a wavelength range of approximately 1.0 to 2.6 microns, having associated electronic read-out circuitry,
  - b. a spectral filter array organized as a set of stripes forming a two-dimensional surface that approximately covers the extent of said photo-detector array,  
10 whereby each stripe has its long dimension oriented across one dimension of said photo-detector array and the short dimension of each stripe spans one or more detectors of said photo-detector array, such that at least one of said spectral filter stripes is appreciably transmissive to light of wavelengths  
15 spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and such that at least one other of said spectral filter stripes is appreciably transmissive to light of wavelengths not spanned by said spectral feature complex of said hydrocarbon compound of interest,
  - c. a mechanical frame to hold said spectral filter array in front of said photo-detector array, such that light passes through said spectral filter array before striking said photo-detector array,
  - 20 d. an optical element selected from the group consisting of lenses, curved mirrors, diffractive surfaces, and combinations of said elements, to gather and focus incident illumination such that light at least in a wavelength range of approximately 1.0 to 2.6 microns is directed at said photo-detector array so as to first pass through said spectral filter array located in front of said photo-  
25 detector array,
  - e. an opto-mechanical scanning device selected from the group consisting of resonant oscillating mirrors, galvanometric driven mirrors, rotating multi-faceted mirrors, and electrically actuated micro-mirror arrays, to scan in a direction perpendicular to the orientation of said filter array stripes, thereby  
30 establishing a two-dimensional field-of-view to be imaged by said photo-detector array,
  - f. at least one electronic circuit to control the integration time of said photo-detector array and to convert signals generated by said photo-detector array into amplified and digitized signals,

- g. at least one electronic circuit by which to synchronize said opto-mechanical scanning device, and said electronic circuit to read-out and convert said signals generated by said photo-detector array, so as to generate a sequence of two-dimensional digital multispectral imagery,
- 5 h. a processor coupled to receive said multispectral imagery and a value representative of a distance to a reflective calibration target, so as to calibrate said imagery of each spectral band relative to imagery of said spectral band associated with said spectral feature complex of said hydrocarbon compound of interest, whereby such processing determines calibration parameters
- 10 consisting of a dark level offset and a relative gain for image pixels of interest between said spectral bands, and a relative absorption coefficient for each spectral band characterizing the local atmosphere under conditions of the ambient environment,
- i. a processor coupled to said multispectral imagery, in combination with said
- 15 calibration parameters, to generate an adaptive relative gain across spectral bands, adapted to in-scene reflectors, and a differential optical depth absorption image, so as to determine the possible presence of said hydrocarbon compound of interest in said field-of-view, employing the Beer-Lambert Law of absorption across the multiple spectral bands,
- 20 j. electronic circuitry to control the operation of said photo-detector array, said opto-mechanical scanning device, said processor to calibrate said multispectral imagery, and said processor to generate said absorption image.
11. The imaging device of claim 10 in which said spectral filters includes a *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an
- 25 extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both shorter and longer than the *Core* filter, said *Wings Band* filter created from a broadband *Surround* filter that includes said *Core Band*, by subtracting said *Core Band* filter measurements from said *Surround* filter measurements, accounting for
- 30 the relative transmission characteristics of said *Core Band* and *Surround* filters.
12. The imaging device of claim 10 in which said spectral filters includes a *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both

shorter and longer than said *Core* filter, said *Wings Band* filter created from a broadband filter with a low-transmission notch spanning the wavelengths of said *Core Band* filter.

13. The imaging device of claim 10 in which said spectral filters includes a *Core*  
5 *Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter created from one or more filters that are appreciably transmissive to light of wavelengths either shorter or longer than those appreciably transmitted by said *Core Band* filter.
- 10 14. The imaging device of claim 10 in combination with a processor coupled to receive said absorption image, and a value of internal pressure of objects from which the detected hydrocarbons compounds being imaged originate, so as to estimate at least one quantity selected from the group consisting of the total absorption in said multispectral imagery of said hydrocarbon of interest, the total  
15 mass visible in said absorption imagery of said hydrocarbon of interest, the diameter of an approximately round hole from which said hydrocarbon of interest leaks, and the mass flow rate of said hydrocarbon of interest, by at least one method selected from the group consisting of the summation along the axis of said absorption image of said hydrocarbon gas jet of said average differential optical  
20 absorption weighted by the diameter of said imaged hydrocarbon gas jet, the scaling of total differential optical absorption of said hydrocarbon gas jet by said differential spectral absorption cross-section weighted by the mass of said hydrocarbon gas molecule, the relationship between said average differential optical depth along said hydrocarbon gas jet extrapolated back to the vertex of  
25 said hydrocarbon gas jet and said internal pressure as it relates to the diameter or area of said leak hole, and the mass flow of said hydrocarbon gas out of said leak hole of known area and said internal pressure.
15. The imaging device of claim 10 in combination with a processor coupled to receive said absorption image from a ground surface patch, and a value of near  
30 ground-level wind speed and direction, so as to estimate surface emission mass flux of said hydrocarbon of interest, by at least one method selected from the group consisting of the relationship between said mass flux and said average differential optical depth imaged across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said

- wind direction, the relationship between said mass flux and said differential optical depth imaged along the downwind edges of said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction, and the relationship between said mass flux and said absorption imagery inferred rate-of-change of said average differential optical depth weighted by the area of said surface patch in combination with said average differential optical depth across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction.
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- 10 16. The imaging device of claim 10 in combination with a visible light camera such that both said imaging devices possess approximately parallel lines-of-sight and share principally overlapping fields-of-view, by which said absorption image of said hydrocarbon of interest is overlaid on the visible light image, thereby providing spatial context of where in the scene a possible hydrocarbon leak is
- 15 detected.
17. The imaging device of claim 10 in combination with any of the following ancillary sensors: global positioning sensor to determine said device positional coordinates on the earth, inertial measurement unit to determine said device linear or rotational acceleration components, magnetometer to determine said device
- 20 orientation with respect to the earth's magnetic field, range finder to determine range of said device from reflecting surfaces in the scene, and weather measurement unit to determine local environmental conditions in proximity to said device.
18. The imaging device of claim 10 in combination with electronic circuits capable of
- 25 acting on data in ways selected from the group consisting of storing, saving, and transmitting said multispectral imagery, said absorption image, and associate with said imagery data selected from the group consisting of said estimated quantities recited in claim 14 or claim 15, said visible light camera recited in claim 16, and said sensors recited in claim 17.
- 30 19. An imaging device to detect hydrocarbon compounds, comprising:
- a. An array of at least two discrete photo-detectors, each responsive to light in a wavelength range of approximately 1.0 to 2.6 microns, each having an associated electronic read-out circuit,

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- b. a spectral filter mosaic organized as a set of filter islands that approximately covers the extent of said array of discrete photo-detectors, whereby each said filter island covers only one discrete photo-detector, such that at least one of said filter islands is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and such that at least one other of said spectral filter islands is appreciably transmissive to light of wavelengths not spanned by said extended spectral feature complex of said hydrocarbon compound of interest,
  - c. a mechanical frame to hold said spectral filter mosaic in front of said array of discrete photo-detectors, such that light passes through said spectral filter array before striking said array of discrete photo-detectors,
  - d. an optical element selected from the group consisting of lenses, curved mirrors, diffractive surfaces, and combinations of said elements, to gather and focus incident illumination such that light at least in a wavelength range of approximately 1.0 to 2.6 microns is directed at said array of discrete photo-detectors so as to first pass through said spectral filters located in front of said array of discrete photo-detectors,
  - e. a mechanical scanning device selected from the group consisting of resonant oscillating mirrors, galvanometric driven mirrors, rotating multi-faceted mirrors, electrically actuated micro-mirror arrays, and dual-axis pan-tilt unit, to scan in two perpendicular directions, thereby establishing an optical field-of-regard to be imaged by said array of discrete photo-detectors,
  - f. at least one electronic circuit to control the integration time of said array of discrete photo-detectors and to convert signals generated by said array of discrete photo-detectors into amplified and digitized signals,
  - g. at least one electronic circuit to synchronize said mechanical scanning device, and said electronic means to read-out and convert said signals generated by said array of discrete photo-detectors, so as to generate a sequence of two-dimensional digital imagery of multiple spectral bands,
  - h. a processor coupled to receive said multispectral imagery and a value representative of a distance to a reflective calibration target, so as to calibrate said imagery of each spectral band relative to imagery of said spectral band associated with said spectral feature complex of said hydrocarbon compound of interest, whereby such processing determines calibration parameters

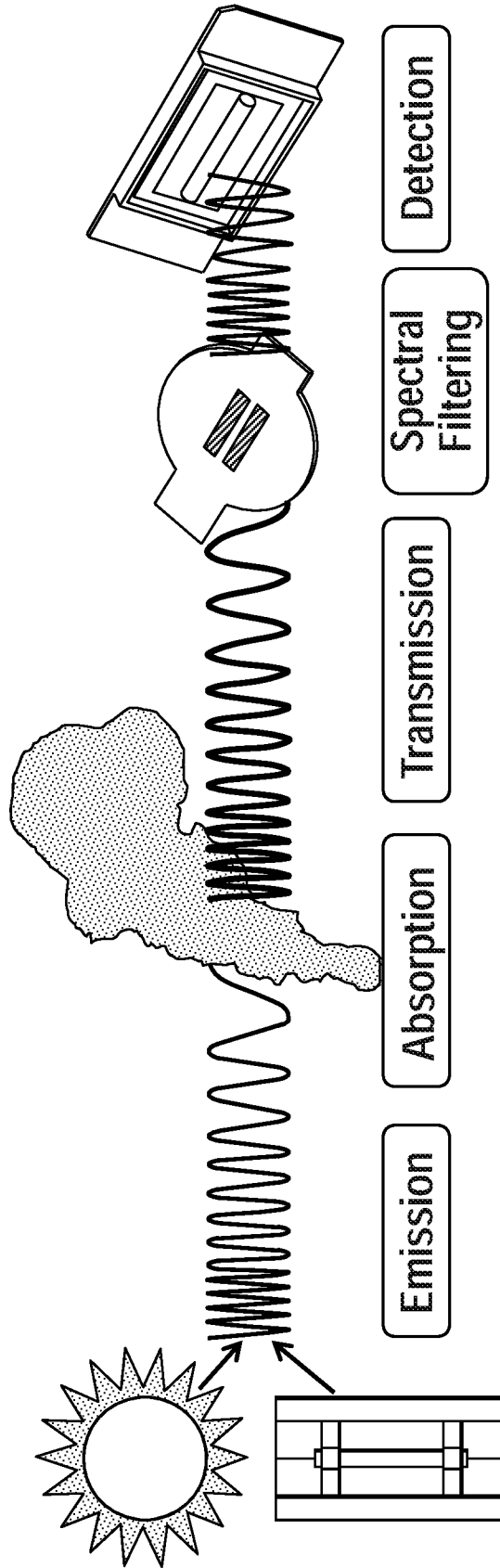
- consisting of a dark level offset and a relative gain for image pixels of interest between said spectral bands, and a relative absorption coefficient for each spectral band characterizing the local atmosphere under conditions of the ambient environment,
- 5 i. a processor coupled to said multispectral imagery, in combination with said calibration parameters, to generate an adaptive relative gain across spectral bands, adapted to in-scene reflectors, and a differential optical depth absorption image, so as to determine the possible presence of said hydrocarbon compound of interest in said field-of-regard, employing the Beer-
- 10 Lambert Law of absorption across the multiple spectral bands,
- j. electronic circuitry to control the operation of said discrete photo-detectors, said mechanical scanning device, said processor to calibrate said multispectral imagery, and said processor to generate said absorption image.
20. The imaging device of claim 19 in which said spectral filter islands includes a
- 15 *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both shorter and longer than the *Core* filter, said *Wings Band* filter created from a broadband *Surround* filter that includes said *Core Band*, by subtracting said *Core*
- 20 *Band* filter measurements from said *Surround* filter measurements, accounting for the relative transmission characteristics of said *Core Band* and *Surround* filters.
21. The imaging device of claim 19 in which said spectral filter islands includes a
- Core Band* filter that is appreciably transmissive to light of wavelengths spanned
- 25 by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter that is appreciably transmissive to light of wavelengths both shorter and longer than said *Core* filter, said *Wings Band* filter created from a broadband filter with a low-transmission notch spanning the wavelengths of said *Core Band* filter.
22. The imaging device of claim 19 in which said spectral filter islands includes a
- 30 *Core Band* filter that is appreciably transmissive to light of wavelengths spanned by an extended spectral feature complex of a hydrocarbon compound of interest, and a *Wings Band* filter created from one or more filters that are appreciably transmissive to light of wavelengths either shorter or longer than those appreciably transmitted by said *Core Band* filter.

23. The imaging device of claim 19 in combination with a processor coupled to receive said absorption image, and a value of internal pressure of objects from which the detected hydrocarbons compounds being imaged originate, so as to estimate at least one quantity selected from the group consisting of the total absorption in said multispectral imagery of said hydrocarbon of interest, the total mass visible in said absorption imagery of said hydrocarbon of interest, the diameter of an approximately round hole from which said hydrocarbon of interest leaks, and the mass flow rate of said hydrocarbon of interest, by at least one method selected from the group consisting of the summation along the axis of said absorption image of said hydrocarbon gas jet of said average differential optical absorption weighted by the diameter of said imaged hydrocarbon gas jet, the scaling of total differential optical absorption of said hydrocarbon gas jet by said differential spectral absorption cross-section weighted by the mass of said hydrocarbon gas molecule, the relationship between said average differential optical depth along said hydrocarbon gas jet extrapolated back to the vertex of said hydrocarbon gas jet and said internal pressure as it relates to the diameter or area of said leak hole, and the mass flow of said hydrocarbon gas out of said leak hole of known area and said internal pressure.
24. The imaging device of claim 19 in combination with a processor coupled to receive said absorption image from a ground surface patch, and a value of near ground-level wind speed and direction, so as to estimate surface emission mass flux of said hydrocarbon of interest, by at least one method selected from the group consisting of the relationship between said mass flux and said average differential optical depth imaged across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction, the relationship between said mass flux and said differential optical depth imaged along the downwind edges of said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction, and the relationship between said mass flux and said absorption imagery inferred rate-of-change of said average differential optical depth weighted by the area of said surface patch in combination with said average differential optical depth across said surface patch weighted by said wind speed and the extent of said surface patch in the direction perpendicular to said wind direction.

25. The imaging device of claim 19 in combination with a visible light camera such that both said imaging devices possess approximately parallel lines-of-sight and share overlapping fields-of-view, by which said absorption image of said hydrocarbon of interest is overlaid on the visible light image, thereby providing spatial context of where in the scene a possible hydrocarbon leak is detected.
26. The imaging device of claim 19 in combination with any of the following ancillary sensors: global positioning sensor to determine said device positional coordinates on the earth, inertial measurement unit to determine said device linear or rotational acceleration components, magnetometer to determine said device orientation with respect to the earth's magnetic field, range finder to determine range of said device from reflecting surfaces in the scene, and weather measurement unit to determine local environmental conditions in proximity to said device.
27. The imaging device of claim 19 in combination with electronic circuits capable of acting on data in ways selected from the group consisting of storing, saving, and transmitting said multispectral imagery, said absorption image, and associate with said imagery data selected from the group consisting of said estimated quantities recited in claim 23 and claim 24, said visible light camera recited in claim 25, and said sensors recited in claim 26.
28. A method for characterizing the mass flow of a hydrocarbon gas jet leaking from a leak hole in an object:
- whereby the internal pressure of said object is approximately known,
  - obtaining a differential absorption image of said hydrocarbon gas jet leaking from said object utilizing a multispectral imaging sensor sensitive to two or more spectral bands in which at least one of said spectral bands is appreciably transmissive to light of wavelengths spanned by one or more spectral features of said hydrocarbon compound of interest, and at least one other of said spectral bands is highly transmissive of light of wavelengths not spanned by said one or more spectral features of said hydrocarbon compound of interest, and
  - estimating at least one quantity selected from the group consisting of the total absorption in said multispectral imagery of said hydrocarbon of interest, the total mass visible in said absorption imagery of said hydrocarbon of interest, the diameter of an approximately round hole from which said hydrocarbon of

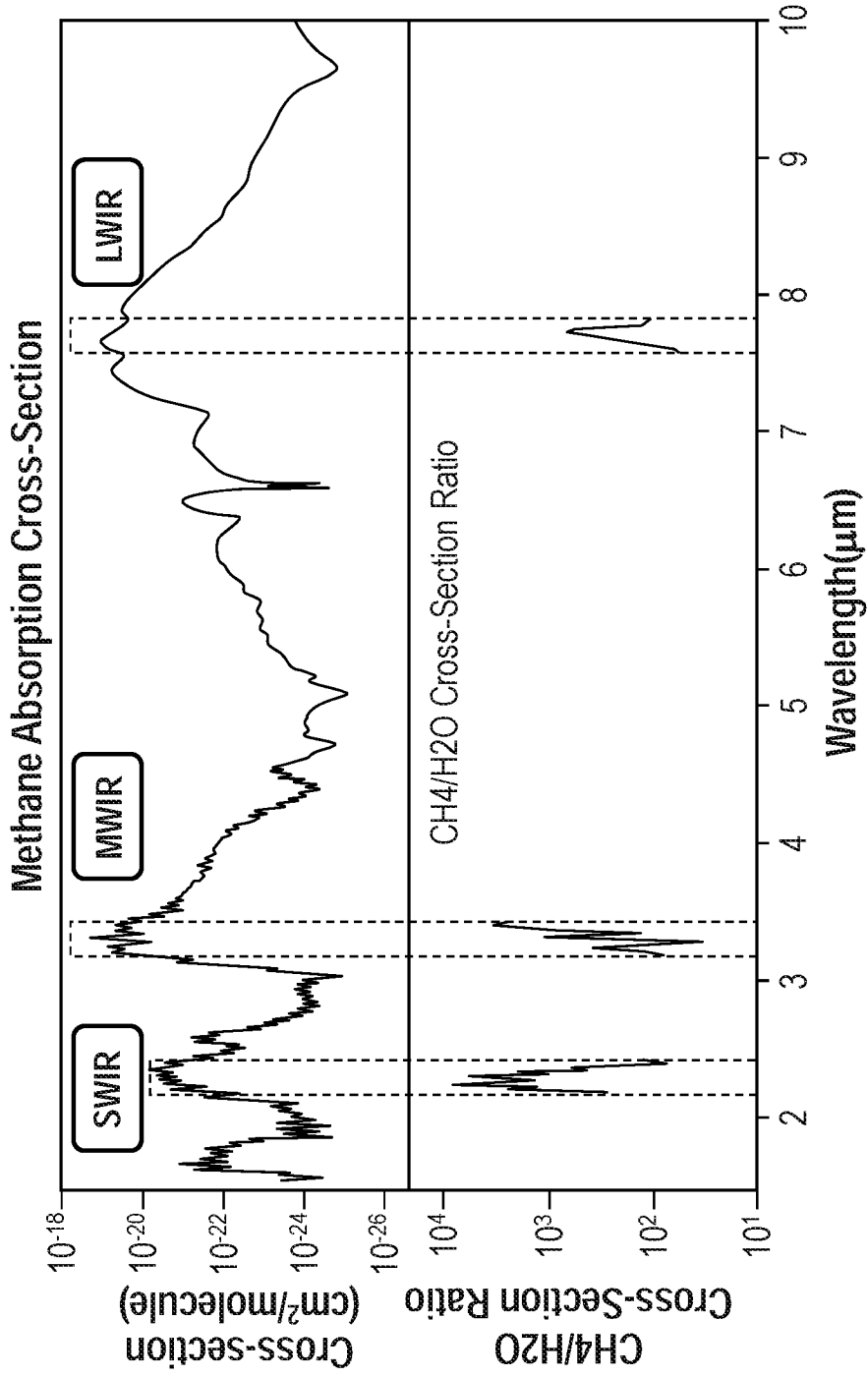
interest leaks, and the mass flow rate of said hydrocarbon of interest by at least one method selected from the group consisting of the summation along the axis of said absorption image of said hydrocarbon gas jet of said average differential optical absorption weighted by the diameter of said imaged hydrocarbon gas jet, the scaling of total differential optical absorption of said hydrocarbon gas jet by said differential spectral absorption cross-section weighted by the mass of said hydrocarbon gas molecule, the relationship between said average differential optical depth along said hydrocarbon gas jet extrapolated back to the vertex of said hydrocarbon gas jet and said internal pressure as it relates to the diameter or area of said leak hole, and the mass flow of said hydrocarbon gas out of said leak hole of known area and said internal pressure.

# Multispectral Absorption Imaging for Natural Gas Leak Detection



*Fig. 1A*

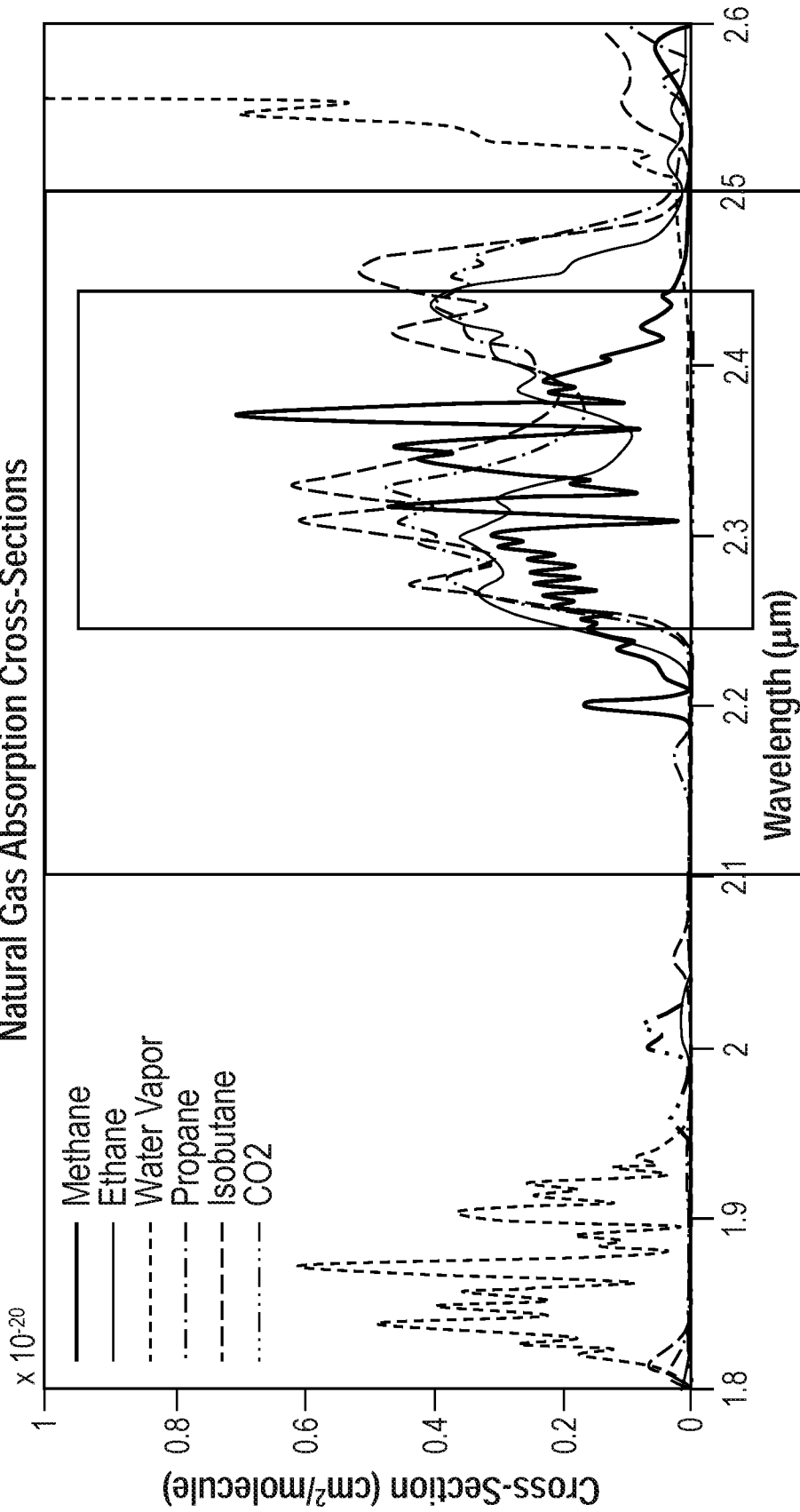
2/18  
Absorption of Methane & Ratio to Water Vapor in the  
SWIR, MWIR and LWIR Spectrum



**Fig. 1B**

3/18

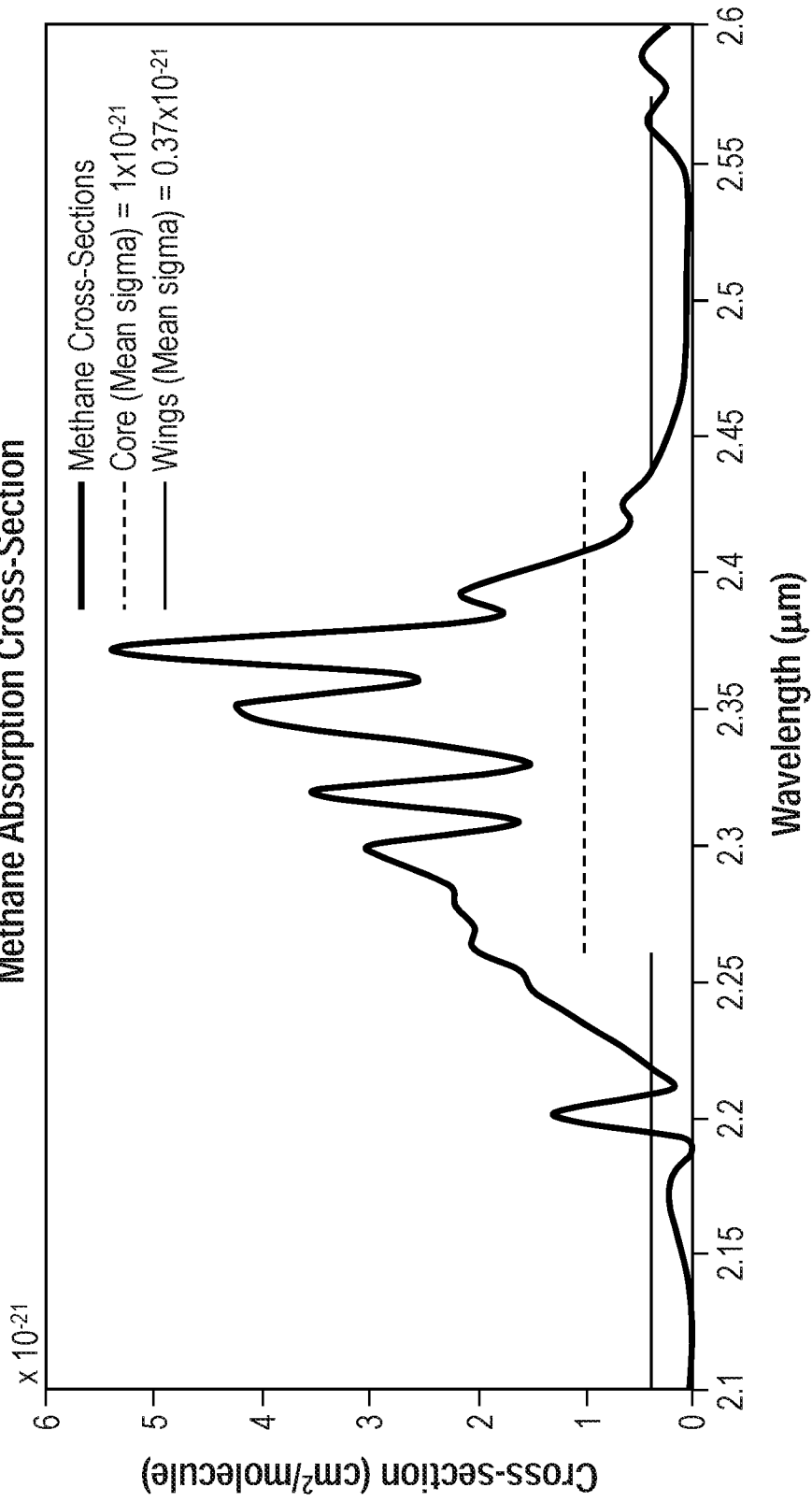
### Spectra of Natural Gas Constituents Natural Gas Absorption Cross-Sections



**Fig. 2A**

4/18

### Methane Spectrum Core & Wing Bands Methane Absorption Cross-Section



**Fig. 2B**

5/18

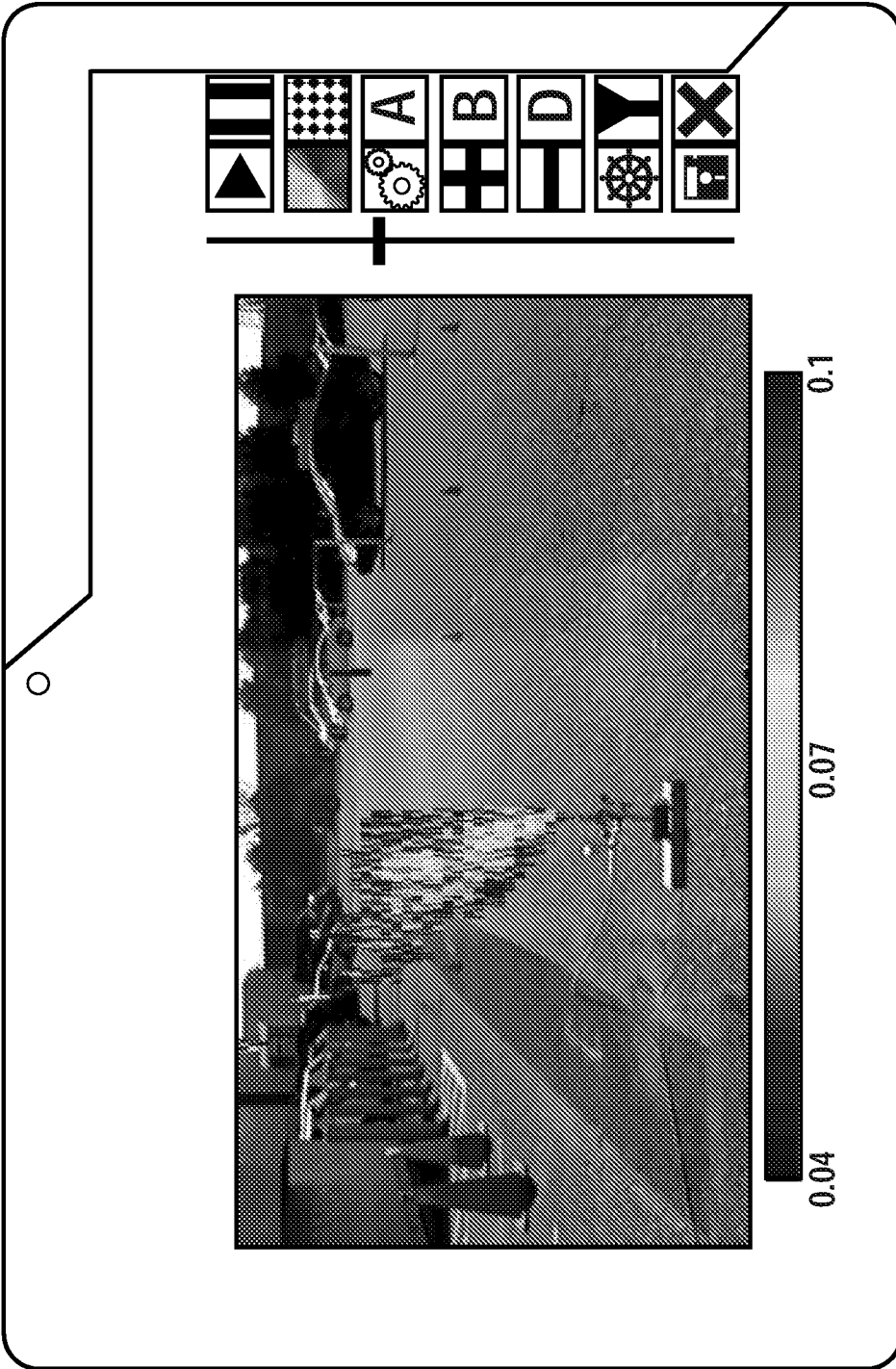
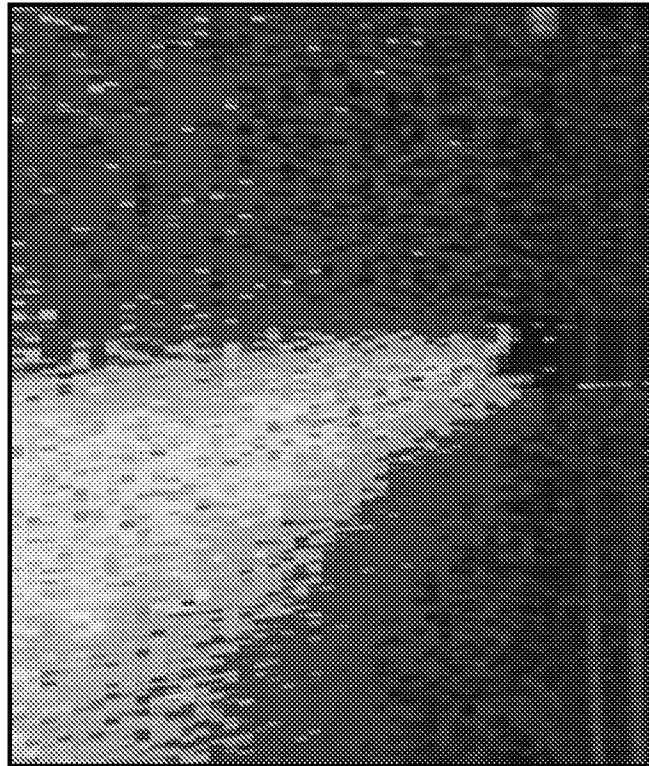


Fig. 3

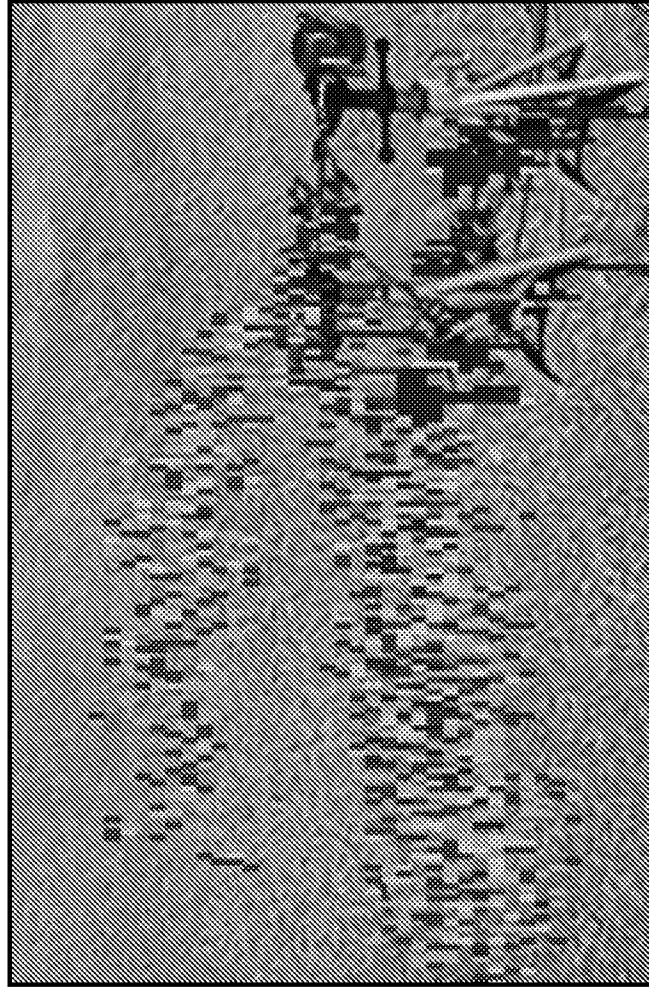
6/18

Natural Gas Plume from 10mm  
Orifice at 1/4 psig in Mild Wind



*Fig. 4A*

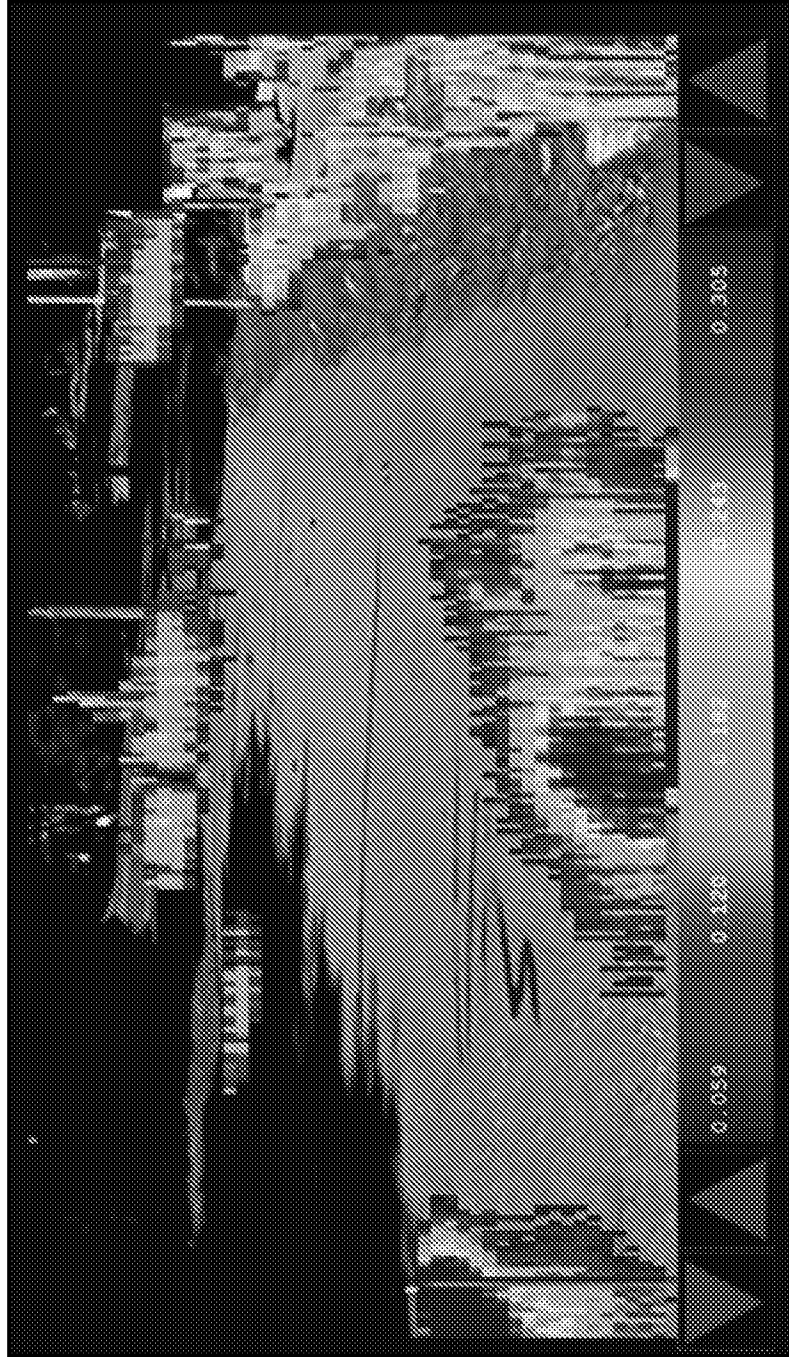
Methane Jet from a Loose Hammer  
Union at 500 psig in 9kph Wind



*Fig. 4B*

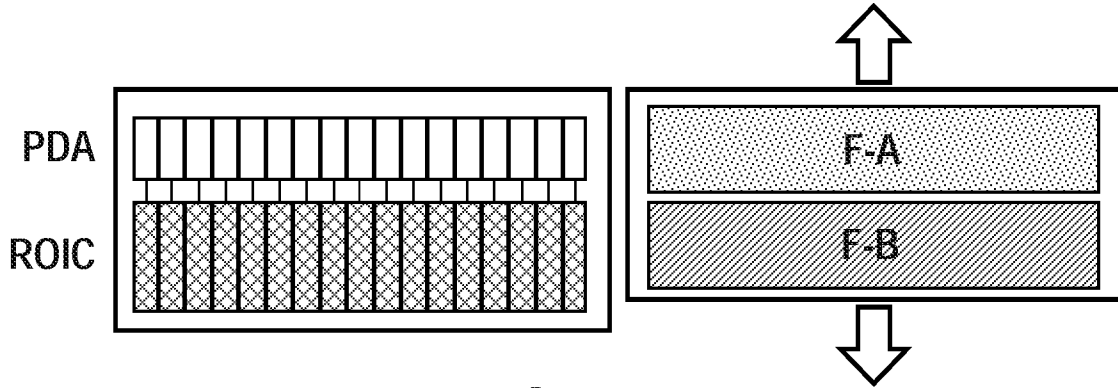
7/18

Surface Emissions from an Underground  
Gas Pipe Leak on a Boston Area Street



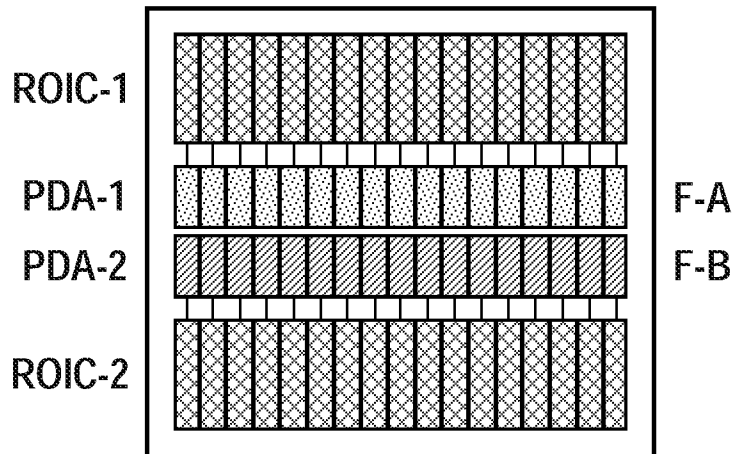
*Fig. 4C*

Single Linear Detector Array with Alternating  
Dual-Band Spectral Filter Overlay



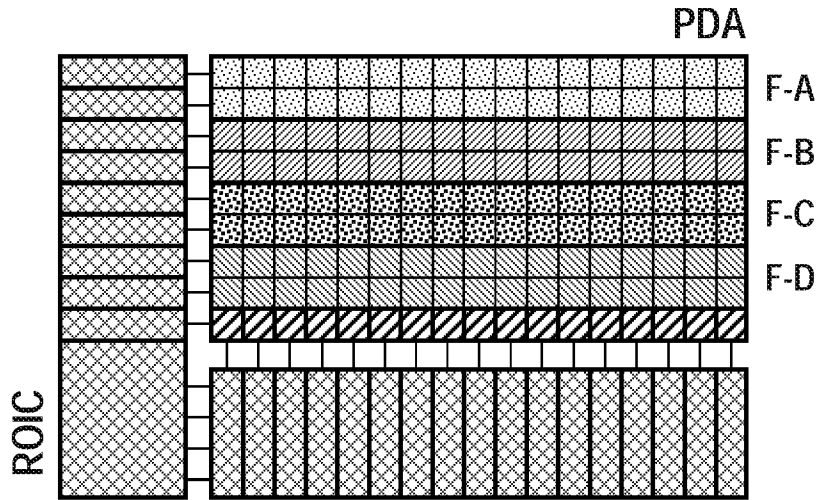
*Fig. 5A*

Dual Linear Detector Arrays with Fixed  
Individual Spectral Filter Overlays



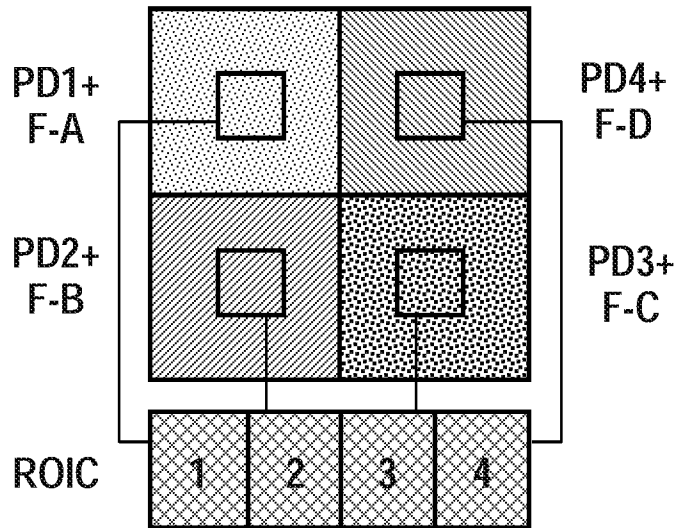
*Fig. 5B*

### 2D Detector Array with Quad-Band Spectral Filter Stripes Overlay



*Fig. 6A*

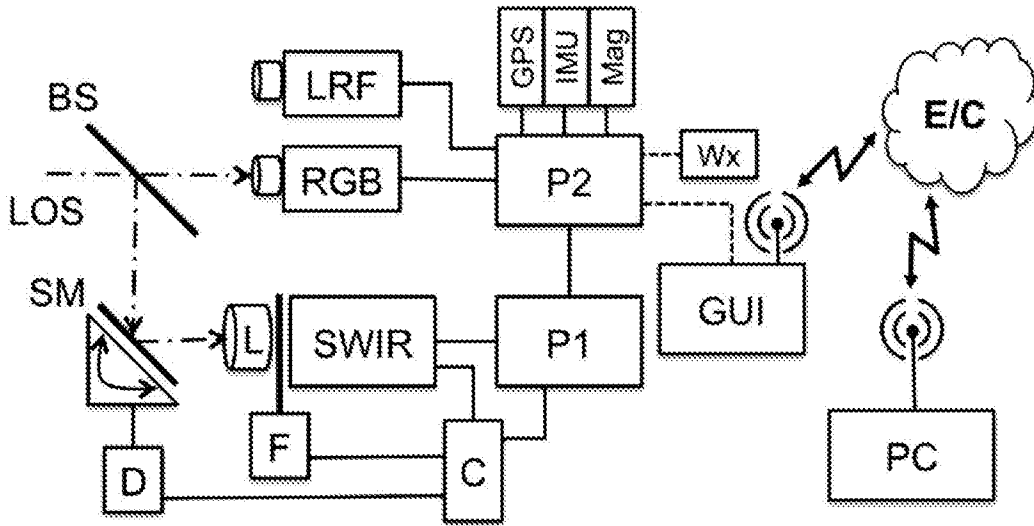
### 2x2 Array of Discrete Photo-Detectors with Quad-Band Spectral Filter Overlay



*Fig. 6B*

10/18

LIQS Video Imager System Diagram

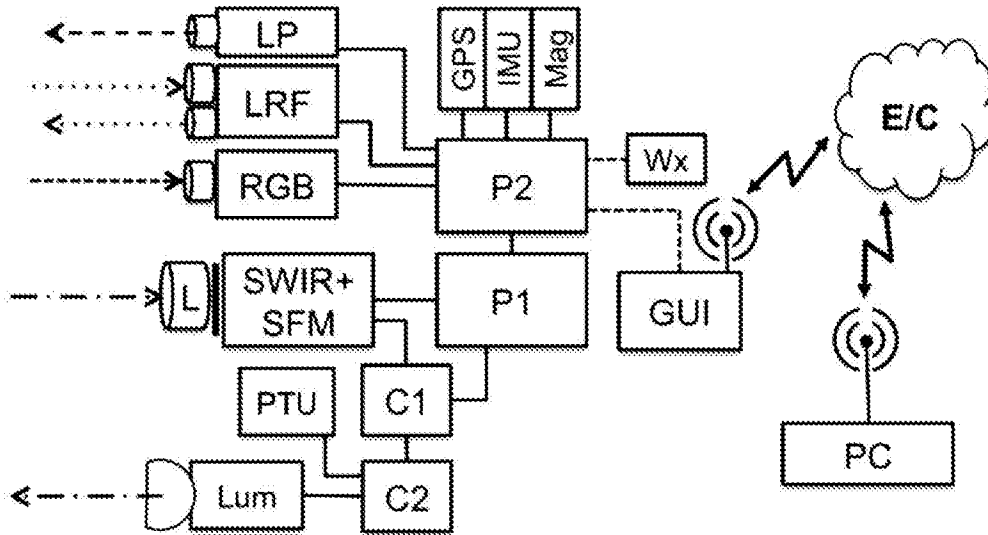


- SWIR – SWIR photo-detector array with read-out imaging electronics
- L – Lens for SWIR photo-detector array (located in front of filters)
- RGB – Color visible micro-camera with lens
- LRF – Laser Range Finder
- LOS – Line of sight from coincident optical axes of imagers
- BS – Beam Splitter (dichroic)
- SM – Scanning mirror
- D – Driver electronics for scanning mirror
- F – Filter changer (as required for moving filter holder)
- C – micro-Controller for synchronization signals
- P1 – micro-Processor #1 (real-time SWIR processor)
- P2 – micro-Processor #2 (all other sensors & GUI requests)
- GPS – Global Positioning System receiver
- IMU – Inertial Measurement Unit (6 degrees-of-freedom)
- Mag – Magnetometer compass
- Wx – Weather sensors (T, P, RH, wind speed & direction)
- GUI – Graphical User Interface on touchscreen tablet
- E/C – Ethernet / Cloud
- PC – Personal Computer remotely running system via cloud

**Fig. 7A**

11/18

LIQS Scan Imager System Diagram

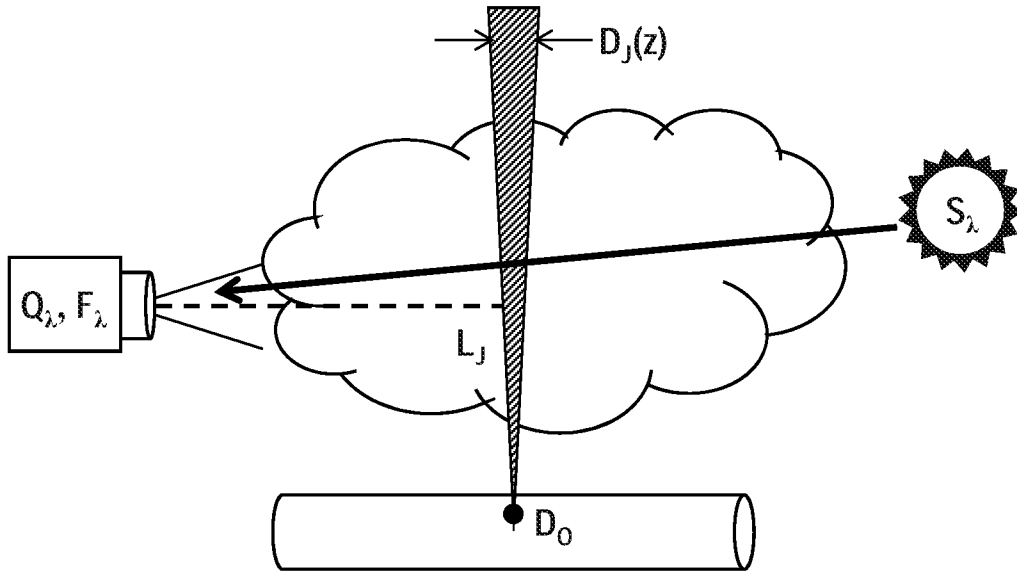


- SWIR – SWIR photo-detector array with read-out electronics
- SFM – Spectral Filter Matrix located over SWIR detector array
- L – Lens for SWIR photo-detector array (located in front of SFM)
- RGB – Color visible micro-camera with lens
- LRF – Laser Range Finder (near-IR)
- LP – Laser Pointer (visible “red dot”)
- PTU – Pan-Tilt Unit scans sensors across site in two-dimensions
- Lum – SWIR broadband illuminator to augment solar illumination
- C1 – micro-Controller with A/D converter samples SWIR signals
- C2 – micro-Controller controls PTU motion and illuminator brightness
- P1 – micro-Processor #1 (real-time SWIR signal processor)
- P2 – micro-Processor #2 (all other sensors & GUI requests/display)
- GPS – Global Positioning System receiver
- IMU – Inertial Measurement Unit (6 degrees-of-freedom)
- Mag – Magnetometer compass
- Wx – Weather sensors (T, P, RH, wind speed & direction)
- GUI – Graphical User Interface on touchscreen tablet
- E/C – Ethernet / Cloud
- PC – Personal Computer remotely running system via cloud

**Fig. 7B**

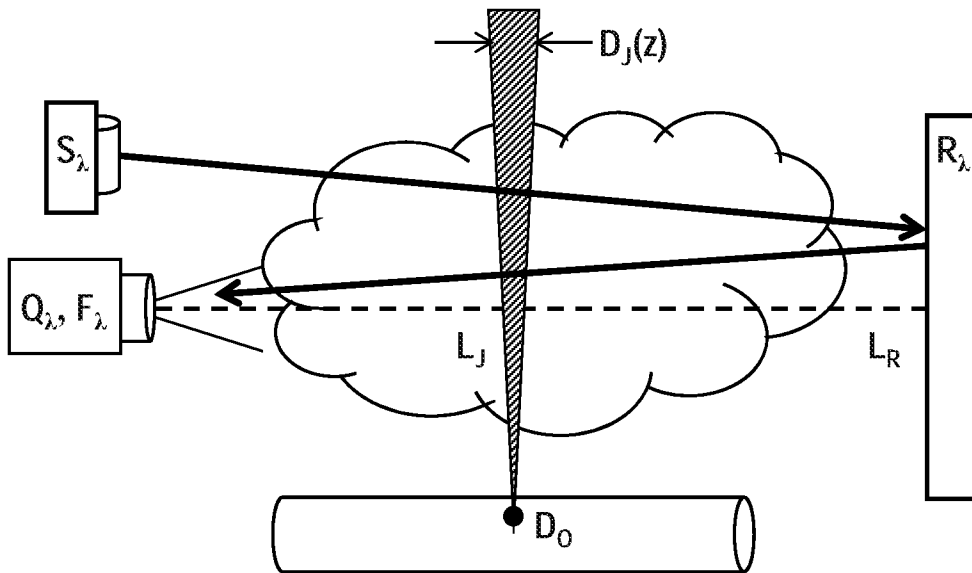
12/18

Imaging Geometry in Transmission



*Fig. 8A*

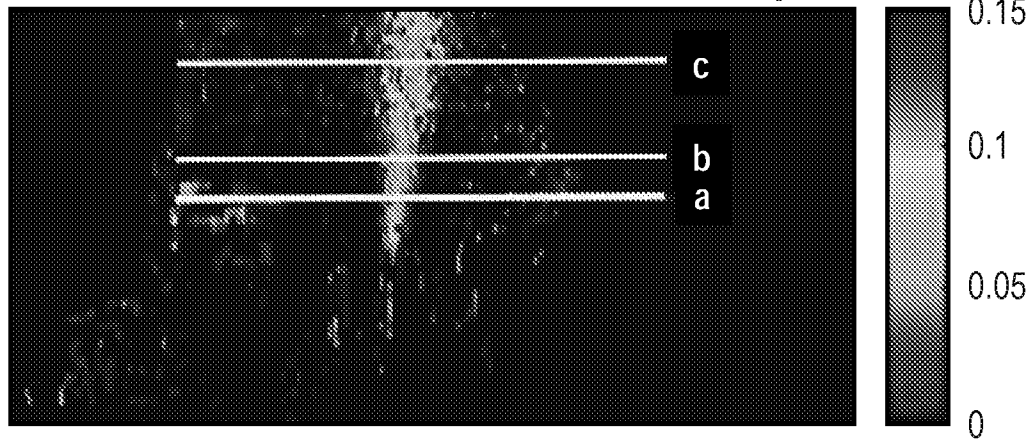
Imaging Geometry with Reflective Background



*Fig. 8B*

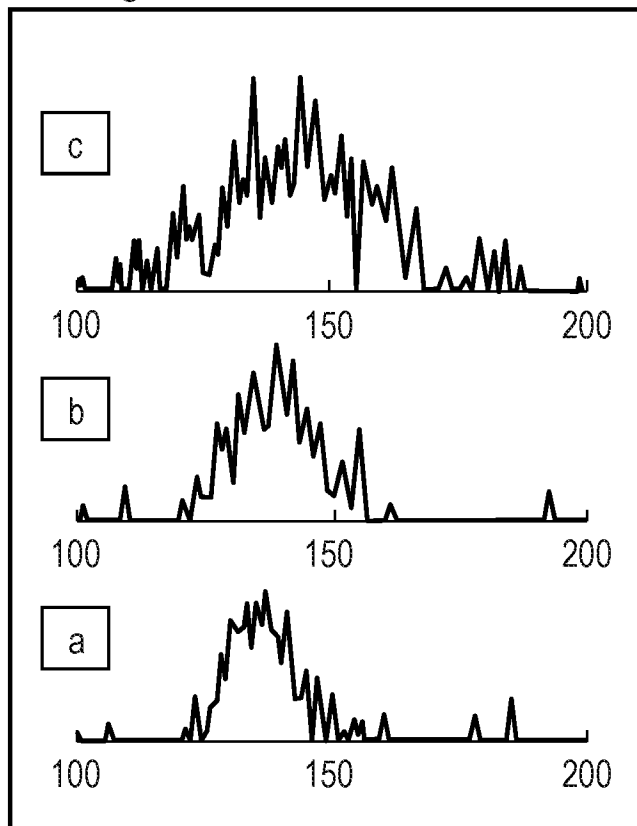
13/18

Methane Jet from a 1mm Orifice at 1300psi



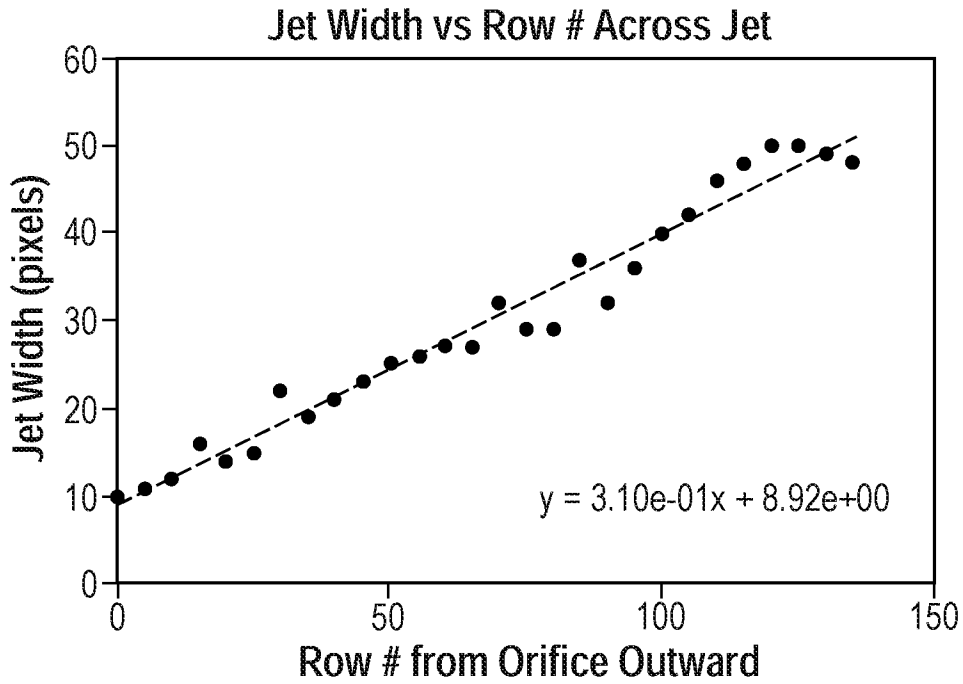
*Fig. 9A*

Profiles of Differential Optical Depth Along the Axis of a Methane Jet

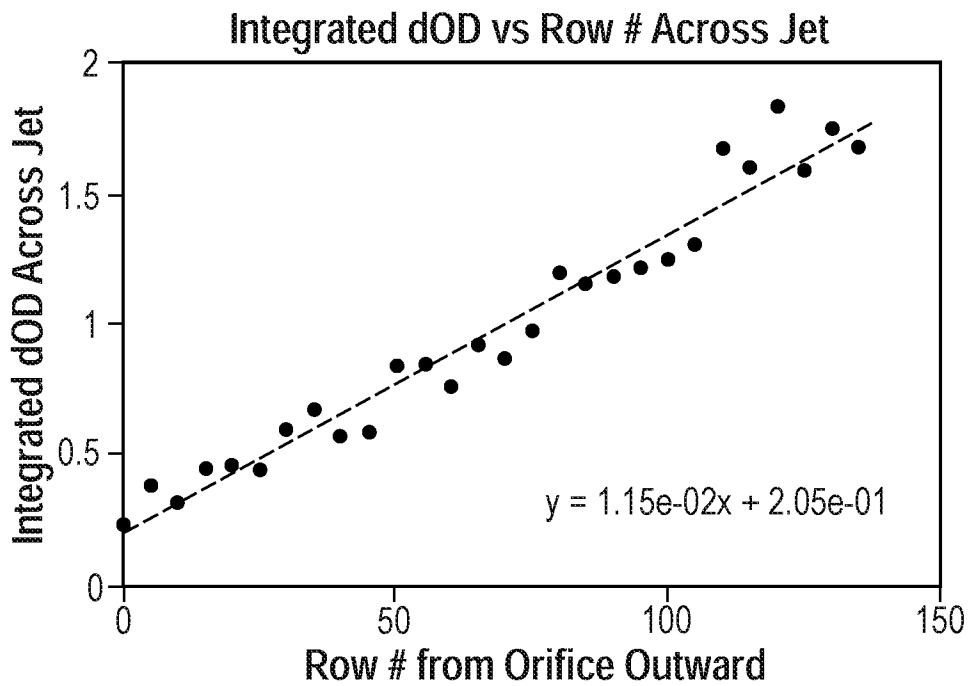


*Fig. 9B*

14/18  
Jet Width, Integrated Optical Depth and  
Average Optical Depth Axial Plots  
(1mm round hole @ 1000psig)

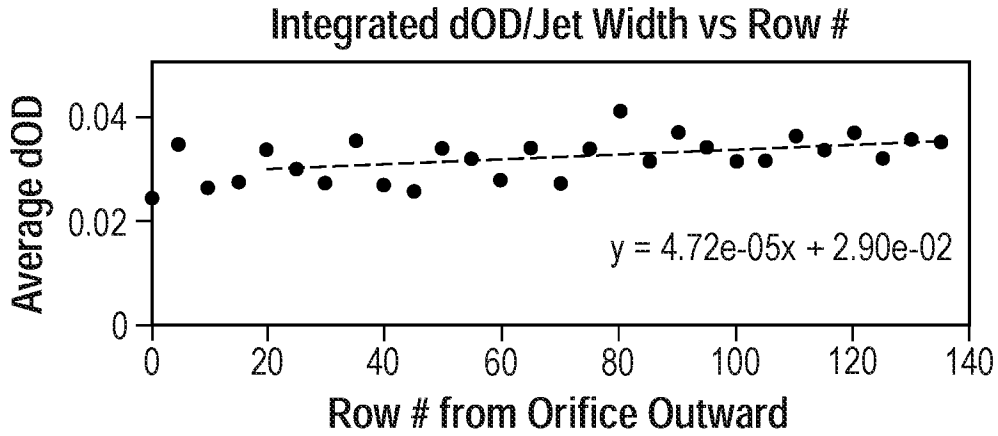


**Fig. 10A**



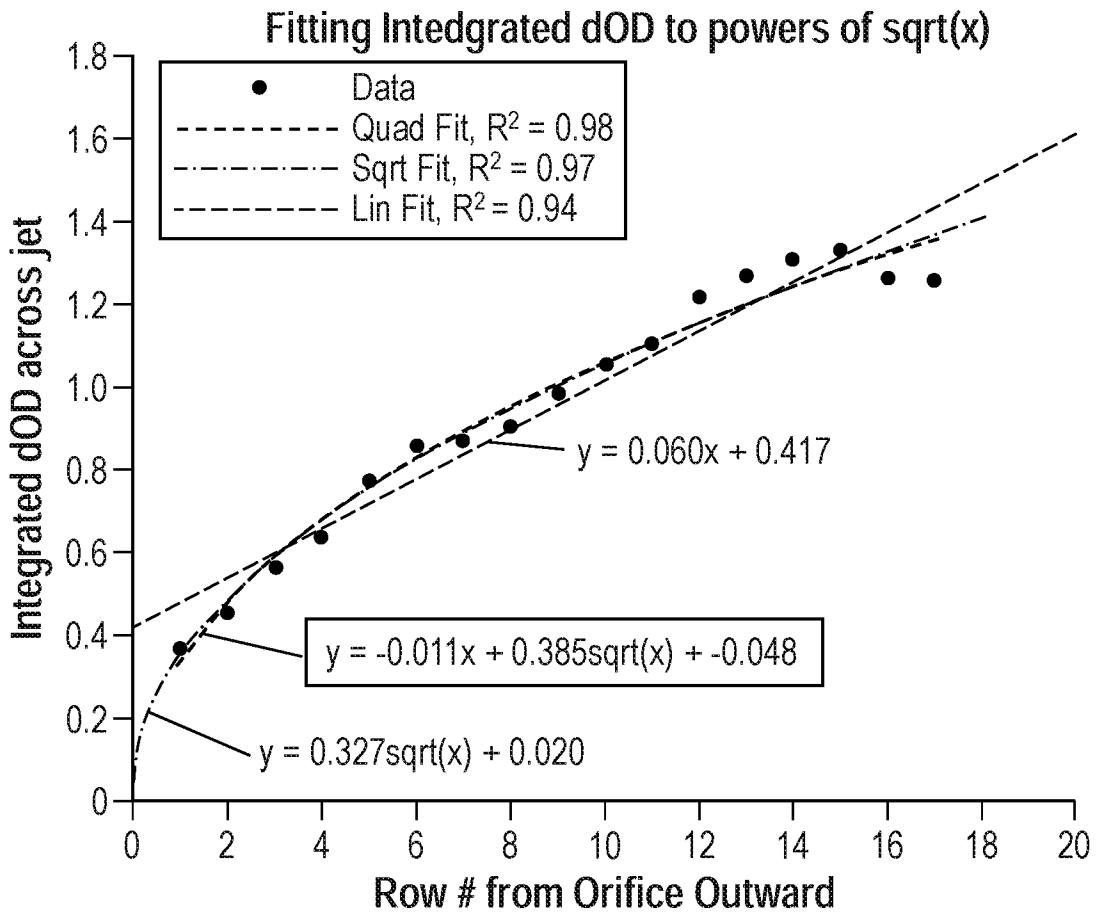
**Fig. 10B**

15/18



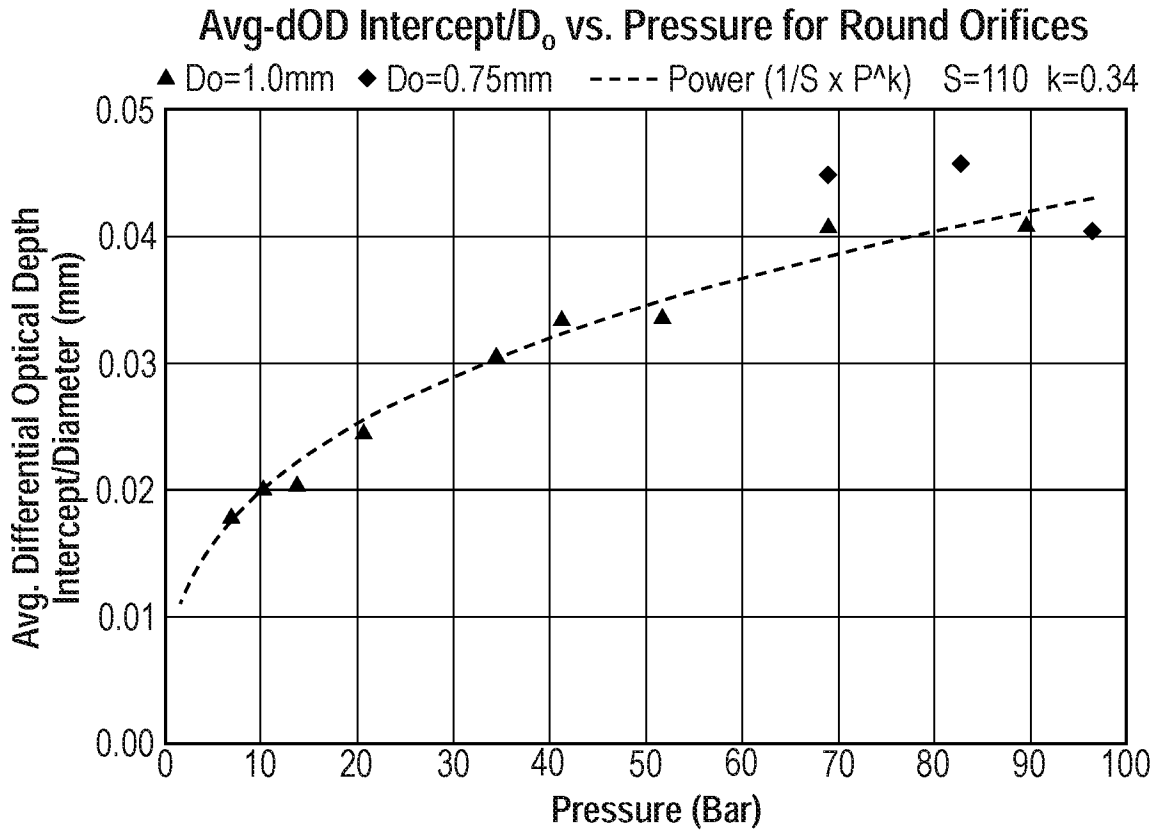
**Fig. 10C**

**Integrated Optical Depth Across Jet from a 50um Slit (1cm long) at 60psig Shows Square-Root Behavior**

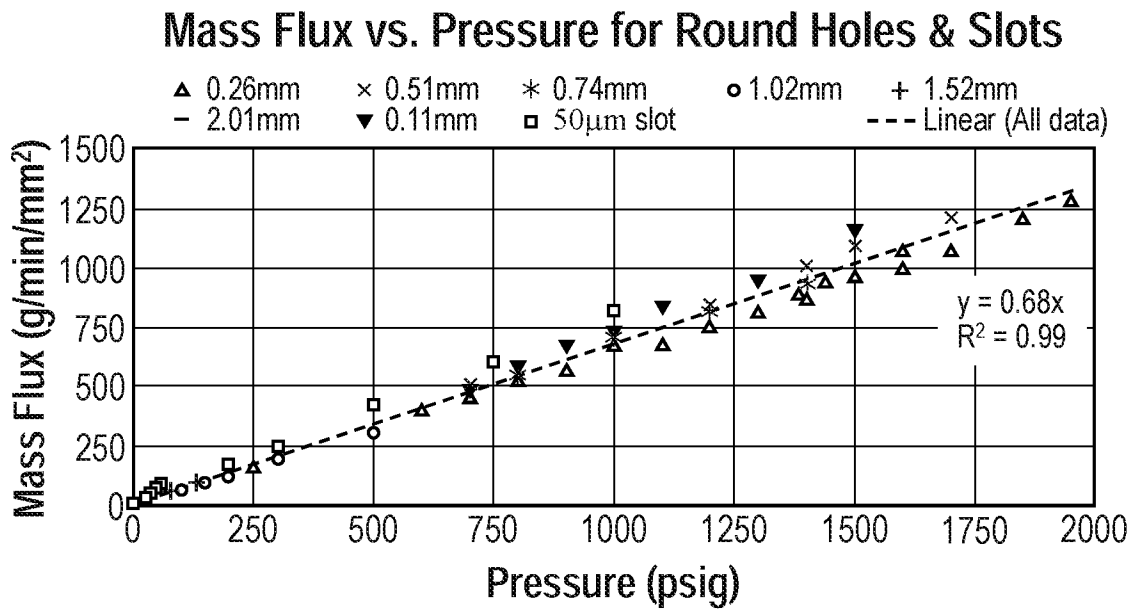


**Fig. 11**

16/18



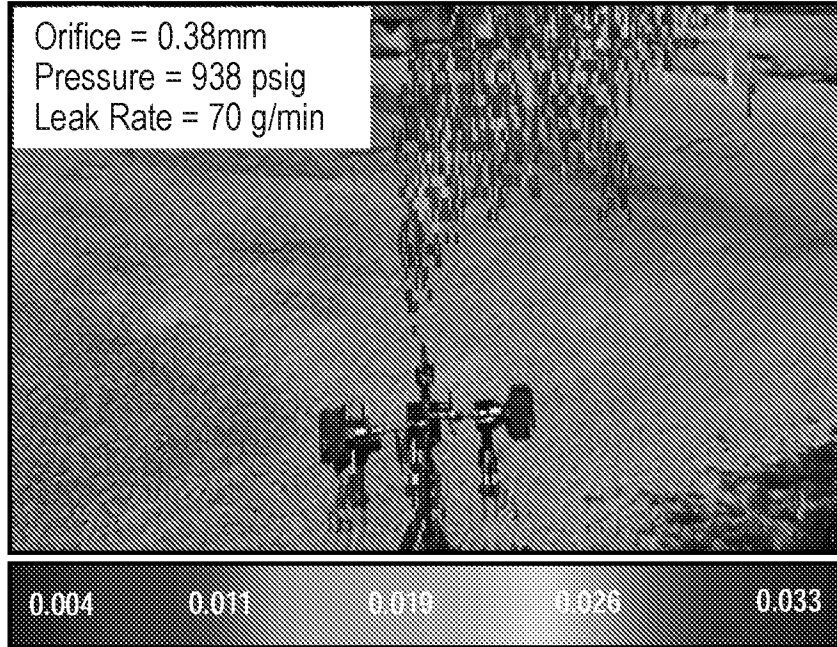
**Fig. 12A**



**FIG. 12B**

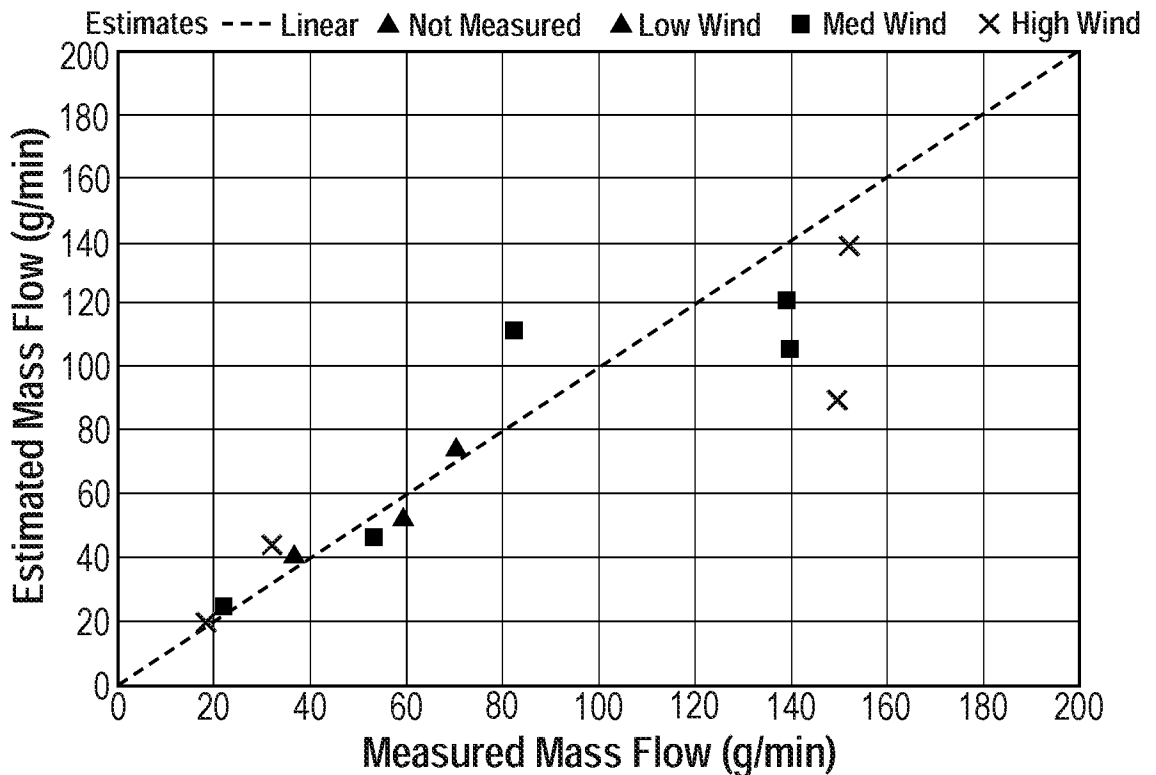
17/18

### Mass Flow (Leak Rate) Estimation in Wind



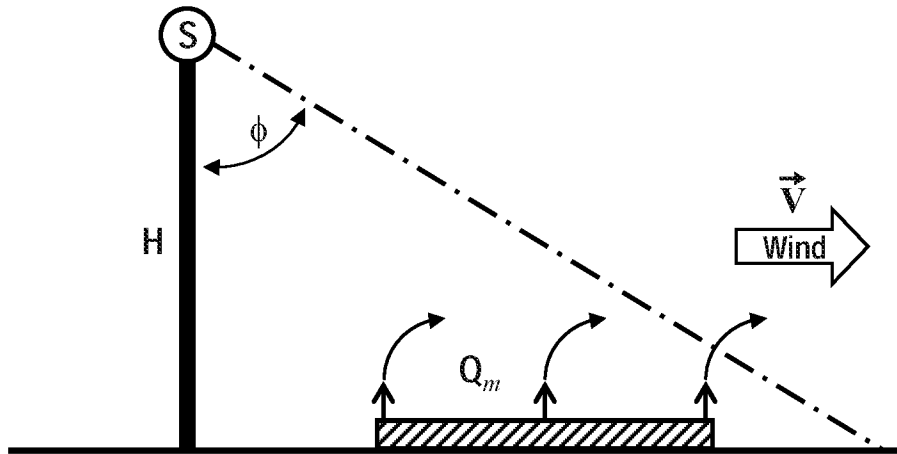
**Fig. 13A**

### Estimated vs. Measured Mass Flow in Wind



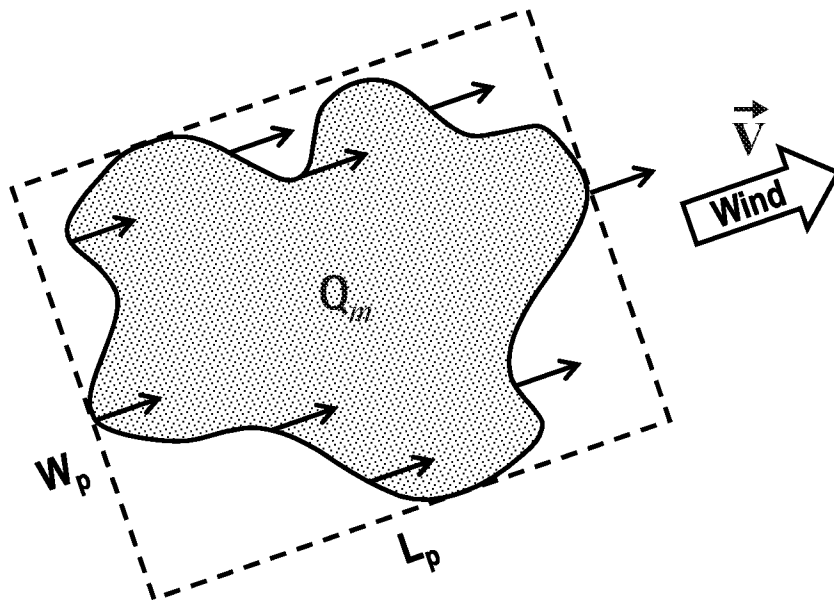
**Fig. 13B**

Methane Surface Patch Imaging Geometry (Side View)



*Fig. 14A*

Methane Surface Patch Emission Geometry (Plan View)



*Fig. 14B*

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/033157

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01N 21/35; E21B 47/10; G01J 5/02; G01N 21/3504 (2017.01)

CPC - G01N 21/359; E21B 47/1015; G01J 3/02; G01J 5/0014; G01N 21/3563 (2017.02)

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2016/0131576 A1 (CI SYSTEMS (ISRAEL), LTD.) 12 May 2016 (12.05.2016) entire document	1-28
A	US 2015/0316473 A1 (REBELLION PHOTONICS, INC.) 05 November 2015 (05.11.2015) entire document	1-28
A	US 2013/0327942 A1 (SILNY et al) 12 December 2013 (12.12.2013) entire document	1-28
A	US 2006/0202122 A1 (GUNN et al) 14 September 2006 (14.09.2006) entire document	1-28
A	US 5,281,816 A (JACOBSON et al) 25 January 1994 (25.01.1994) entire document	1-28

 Further documents are listed in the continuation of Box C. See patent family annex.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

29 August 2017

Date of mailing of the international search report

14 SEP 2017

Name and mailing address of the ISA/US

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Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300  
PCT OSP: 571-272-7774

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/033157

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2.  Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3.  Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:  
See extra sheet(s).

1.  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2.  As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3.  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4.  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

- Remark on Protest**
- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
  - The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
  - No protest accompanied the payment of additional search fees.

Continued from Dox No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-27, drawn to an imaging device to detect hydrocarbon compounds.

Group II, claim 28, drawn to a method for characterizing the mass flow of a hydrocarbon gas jet leaking from a leak hole in an object.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: c. a mechanical device selected from the group consisting of stationary frames, sliding frames, spinning frames, swinging blades, and rotating wheels, so that the filters can be disposed in a first position and a second position, in the first position light passes through the first filter before striking any of said one dimensional arrays of photo-detectors, in the second position light passes through the second filter before striking any of said one-dimensional arrays of photo-detectors, and the mechanical device can move the filters between the first and second positions, d. an optical element selected from the group consisting of lenses, curved mirrors, diffractive surfaces, and combinations of said elements, to gather and focus incident illumination such that light at least in a wavelength range of approximately 1.0 to 2.6 microns is directed at said one-dimensional array(s) of photo-detectors so as to first pass through said spectral filters located in front of said one-dimensional photo-detector arrays, e. an opto-mechanical scanning device selected from the group consisting of resonant oscillating mirrors, galvanometric driven mirrors, rotating multifaceted mirrors, and electrically actuated micro-mirror arrays, to scan a field of view one portion at a time relative to the one-dimensional photo-detector array(s), f. at least one electronic circuit to control the integration time of said photodetector array(s) and to convert signals generated by said photo-detector array(s) into amplified and digitized signals, as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: c. estimating at least one quantity selected from the group consisting of the total absorption in said multispectral imagery of said hydrocarbon of interest, the total mass visible in said absorption imagery of said hydrocarbon of interest, the diameter of an approximately round hole from which said hydrocarbon of interest leaks, and the mass flow rate of said hydrocarbon of interest by at least one method selected from the group consisting of the summation along the axis of said absorption image of said hydrocarbon gas jet of said average differential optical absorption weighted by the diameter of said imaged hydrocarbon gas jet, the scaling of total differential optical absorption of said hydrocarbon gas jet by said differential spectral absorption cross-section weighted by the mass of said hydrocarbon gas molecule, the relationship between said average differential optical depth along said hydrocarbon gas jet extrapolated back to the vertex of said hydrocarbon gas jet and said internal pressure as it relates to the diameter or area of said leak hole, and the mass flow of said hydrocarbon gas out of said leak hole of known area and said internal pressure as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of obtaining absorption image of said hydrocarbon gas utilizing a multispectral imaging sensor sensitive to two or more spectral bands in which at least one of said spectral bands is appreciably transmissive to light of wavelengths spanned by one or more spectral features of said hydrocarbon compound of interest, and at least one other of said spectral bands is highly transmissive of light of wavelengths not spanned by said one or more spectral features of said hydrocarbon compound of interest, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2015/0316473 A1 (REBELLION PHOTONICS, INC) 5 November 2015 (05-11.2015) teaches obtaining absorption image of said hydrocarbon gas utilizing a multispectral imaging sensor sensitive to two or more spectral bands in which at least one of said spectral bands is appreciably transmissive to light of wavelengths spanned by one or more spectral features of said hydrocarbon compound of interest, and at least one other of said spectral bands is highly transmissive of light of wavelengths not spanned by said one or more spectral features of said hydrocarbon compound of interest (to detect a hydrocarbon gas cloud of propylene, para. 0092. The method can include capturing multispectral infrared (IR) image data at the FPA unit from at least two optical channels that are spatially and spectrally different from one another. The method can include acquiring multispectral optical data representing the target species from the IR radiation received at the FPA, para. 0008. The plurality of photo-sensitive devices may comprise a two-dimensional imaging sensor array that is sensitive to radiation having wavelengths between 1  $\mu\text{m}$  and 20  $\mu\text{m}$  (for example, in near infra-red wavelength range, mid infra-red wavelength range, or long infra-red wavelength range,). In various embodiments, the plurality of photo-sensitive devices can include CCD or CMOS sensors, bolometers, microbolometers or other detectors that are sensitive to infra-red radiation, para. 0041).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.