Microwave Radar Sensing of Gas Pipeline Leaks

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Abstract: With the growing demand for natural gas and the aging of the natural gas infrastructure in the U.S., remote sensing systems are needed to inspect nearly 2 million miles of natural gas transmission systems for potential leaks and ensure safety and reliability of service to the public. Current leak detection techniques based on sniffing are labor-intensive and impractical for inspecting the vast network of pipes around the country. This report presents a state-of-the-art survey of remote sensing techniques in the context of detection and location of natural gas leaks. There is a wealth of literature on optical remote sensing techniques that include laser-based spectroscopic systems. These optical techniques are briefly described along with their advantages and limitations. Even though microwaves are routinely used for satellite-based weather forecasting and remote sensing of earth resources, there is not much published literature about their use for leak detection. Stemming from our past work in microwave and millimeter-wave chemical detection, we have described the basis of a leak detection method based on microwave pulsed radars and discussed their potential for gas pipeline leak imaging.

I. INTRODUCTION

The U.S. natural gas infrastructure is large and expansive, covering the country over 2 million miles of transmission and distribution pipelines from bore wells to homes and industries. Also, the natural gas demand is projected to increase by 50% by the year 2020.[1] This coupled with the fact that most of the existing infrastructure is old and aging, raises a great concern for long-term gas reliability and infrastructure integrity. Leaks, for example, can develop in any part of the transmission and distribution lines due to pipe corrosion, third party damage, or failure of valves and joints. Because of the flammable nature of the gas, leaks can be deadly and disrupt service to thousands of customers. Remote and fast inspection tools are, therefore, of paramount importance for early detection and prevention of gas leaks.

Current leak detection systems are based on sniffing or drawing of air samples from inspection location. These point-sensing devices, although they may work well, are labor intensive and impractical for inspecting the vast network of pipes. The nature and scale of the problem calls for remote sensing techniques that can monitor the gas pipelines around the clock to image/locate minute leaks. Wave techniques using visible, infrared, ultraviolet, microwave, or millimeter wave bands of the electromagnetic spectrum offer potential for remote sensing. While these techniques are routinely used in satellite-based remote sensing and imaging of the earth resources and weather forecasting, their application to chemical detection is still in their early stages.

Argonne proposes to develop a microwave radar method for remote and fast imaging of gas leaks. The underlying principle is the change in radar reflection, refraction, and scattering properties of leak plumes with respect to the surrounding air. The objective is to build a van-mounted or airborne microwave imaging radar to detect above- or underground pipe leaks.

II. CURRENT LITERATURE ON GASEOUS LEAK DETECTION

The natural gas composition consists of mostly methane (70-95% by volume) and the rest are ethane, propane, and butane (0-20% combined), so the chemical of choice for gas leak detection is methane. From the leak detection point of view, gas sensors can be classified into two groups: point-sensors and remote sensors. A point-sensor draws samples from the desired location into the sensor apparatus and measures the sample concentration by using physical, chemical, electrochemical, or spectroscopic principles. A remote sensor invariably uses wave techniques such as visible, infrared, ultraviolet, microwave, or millimeter wave bands for remote detection of the chemical cloud near the leak location.

A. Point Sensors

A gamut of analytical techniques[2] such as gas chromatographs, mass spectrometers, and Fourier transform infrared (FTIR) spectrometers are available for very sensitive measurement of specific gases in a complex mixture; however, they are generally complex and expensive laboratory instruments and impractical for field measurements. The field sensors must be portable, sensitive and selective to the leak gas, and provide fast measurements with low false-positives. Gas industries have used the following point sensors for manual or vehicle-mounted leak surveys with varying degrees of success.[3]

1. Flame-ionization detector
2. Optical methane detector
3. Metal-oxide semiconductor sensor

Flame ionization detector consists of a hydrogen flame chamber into which the sample under test is drawn. Hydrocarbons such as methane get easily ionized in the H_2 flame. When a potential is applied between two electrodes placed across the flame chamber, the ionized or charged particles establish a current flow that is an indication of the amount of hydrocarbons present in the air sample. Although it responds to any hydrocarbon including methane and thus is not selective, commercially available field units claim a sensitivity of 0.1 ppm.

Optical methane detector is based on nondisperive infrared (NDIR) technique, which uses infrared absorption that occur at one of the absorption bands of methane.[4] An infrared light source such as a xenon lamp is used to radiate wideband infrared radiation over a short pathlength between the transmitter and an IR detector. A filter with its passband tuned to methane absorption is built into the IR detector. If methane is present

in the beam path, the detector signal decreases with gas concentration in accordance with the Beer-Lambert's law. In a Gas Research Institute sponsored study, a prototype NDIR sensor, mounted on the front bumper of a utility truck, provided a sensitivity level of 1 ppm at a speed of up to 48 km/hour. Limitations of the technique include calibration drifts, sensitivity to vehicle vibration, environmental effects such as rain, snow, and ice, and maintaining cleanliness of the optics.

Metal-oxide semiconductor[5] is a solid-state sensor in which a film of tin oxide or iron oxide is deposited on a substrate with two pairs of electrodes built into it. With one pair of electrodes, the film is heated and with the other, the resistance of the film is measured. When the metal-oxide film is exposed to a reducing agent such as methane, its resistance decreases depending on the gas concentration. Like the flame-ionization detector, primary limitation of this sensor is the lack of selectivity.

B. Remote Optical Sensors

Remote chemical sensors are generally based on molecular spectroscopy principles.[6-7] Figure 1 is a plot of methane absorption spectra for 100 ppm-m (e.g., 10 ppm methane extended over 10 m), obtained from the HITRAN database.[8] There exist two strong absorption bands at ~3.33 µm and at ~7.65 µm. Besides strong lines of molecular absorption, the wavelength selection must take into account the optical transmission of the atmosphere. Figure 2 gives the HITRAN transmission spectrum of the atmosphere for a 60° slant, 500m pathlength in the optical wavelength regime 1-15 µm. Two atmospheric windows exist in the IR band between 3 to 5 µm and 8 to 14 µm. Fortuitously, the two methane absorption bands coincide with the atmospheric windows in spite of the possibility for some level of interference between methane and atmospheric molecules. Upon a close look of the two overlaid plots, methane lines at ~3.45 µm show least interference with atmospheric molecules, see Figure 3. Even so, the interference problem cannot be overlooked especially because path-integrated measurements are made over a long path.

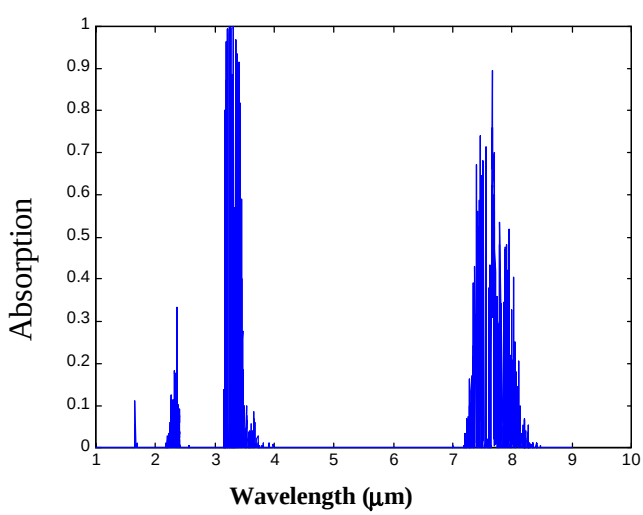

Fig. 1. Methane absorption spectra for 100 ppm-m.

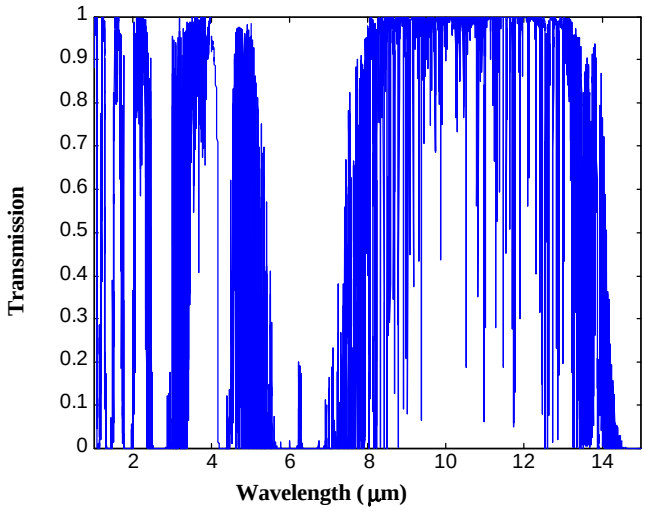

Fig. 2. Atmospheric transmission in the 1-15 µm range.

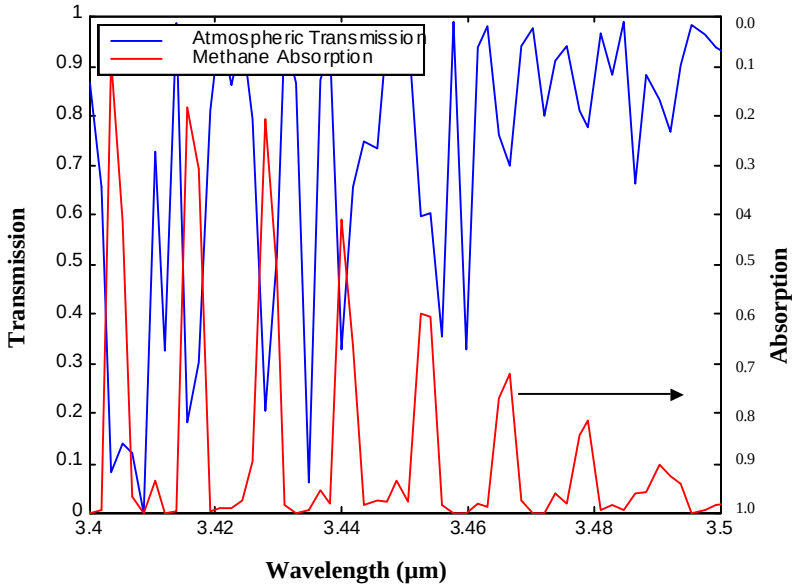

Fig. 3. Composite plot of methane absorption lines under atmospheric transmission window.

Remote sensors may be either active or passive depending on whether or not a radiation source is used to interrogate the target area. In the active case, lasers are increasingly used as the source of radiation because of their coherence, high spectral brightness, spectral purity, tunability, and directivity.[9-10] A typical chemical laser system transmits a laser beam toward the target area and receives the terrain-reflected radiation. By modulating the laser wavelength around one of the absorption lines of the chemical, an absorption line can be measured with high sensitivity. Differential absorption lidar, called DIAL, is another laser approach in which two wavelengths are used, one corresponding to the gas line and the other at the base of the line; the difference between

these two return signals will indicate the level of spectral absorption. Besides high sensitivity, the small footprints of laser systems allow high-resolution imaging of chemical plumes.

A major difficulty with the laser approach in general is the limited availability of lasers in the infrared region; molecular gas lasers such as CO_2 and CO lasers are available at a limited number of wavelengths. Compact, narrowly-tunable diode lasers are beginning to be available at infrared wavelengths between 1 to 25 µm.[11] SRI International has developed a mobile diode-laser-based gas leak sensor for short ranges using one of the weak absorption lines of methane at 1651 nm. They claim a detection sensitivity of 18 ppm-m with a natural topographic target at the range of 10 to 15 m. Diode lasers, however, suffer from low power and limited tunability.

Passive remote sensors use either the sun-reflected radiation or the blackbody radiation of the background scene. The braodband radiation through the plume is received by a multispectral or FTIR receiver.[12] The plume contrast or sensitivity depends on the temperature difference between the plume and the background, absorption properties of the plume, and the background emisivity. Because there is no active illumination, the detection range is essentially unlimited, allowing the use of satellite based systems.

The advantages of optical remote sensing include high sensitivity and selectivity to chemicals, plume imaging capability, and airborne (possibly satellite-based) leak surveys. The disadvantages are sensitivity of the system to weather conditions (e.g., cloud, haze, dust, and rain), interference from atmospheric molecules (predominantly water vapor), lack of suitable lasers in methane absorption bands, sensitivity to terrain reflectivity, glint and speckle effects in laser systems, and sensitivity to temperature and emissivity of the background in passive systems. Furthermore, because the optical systems measure path-integrated concentration, the minimum detectable leak concentration is limited by the presence of 1.7 ppm of methane in the natural background.

III. MICROWAVE LEAK DETECTION

The fact that the wavelengths of microwaves (e.g., 3 cm in X band radars) are much longer than their optical counterparts (micrometers) gives them a unique advantage for remote sensing. Microwaves are less affected by weather conditions such as cloud, fog, storm, and rain. Airborne or satellite-based microwave remote sensing is routinely used for several applications including weather forecasting, communications, navigation, and mapping of the earth resources.[13] Doppler radars have become an essential tool of weather forecasters to help predict impending storm hazards.[14] Advanced synthetic aperture radar (SAR) technology has enabled high-resolution mapping of earth terrain and targets from airborne or satellite platforms.

Microwaves can be used for remote detection of airborne chemicals in two possible ways that are based on microwave or millimeter-wave spectroscopy and microwave pulsed radars.

A. Millimeter-wave spectroscopy

Millimeter-wave spectroscopy is similar to optical spectroscopy but uses molecular rotational energy instead of vibrational and electronic energy changes. Molecular specificity is nearly 100% with the millimeter-wave technique if the sample can be introduced into a vacuum system. Argonne has developed a millimeter-wave radar system for remote detection of airborne chemicals.[15-17] It uses swept-frequency continuous-wave technique in the atmospheric frequency window 200-300 GHz. The system was field tested at the Nevada Test Site from a trailer at a distance of 60 m from the release point. The system detected polar chemicals like methyl chloride to a sensitivity level of 10 ppm.

Additionally, we investigated the feasibility of millimeter-wave spectroscopy for detection of automobile leaks such as from refrigeration components. One method consisted of charging the test part by a polar gas and scanning the part by a millimeter-wave beam for the presence of one of the spectral lines of the gas. Using nitrous oxide as a charger gas, the millimeter-wave system detected the 251.2 GHz spectral line of N_2O down to 10^{-5} scc/s. In another method, we used an open-path system in which freon leak was introduced behind a metal target and the system detected freon leaks down to 10^{-3} scc/s based on their absorption features in the return signals. The sensitivity of detection was limited by the available power (30 mW) of the continuous-wave system; a pulsed system with high power can improve the sensitivity.

The chemical to be detected with this technique must be polar in nature. Because methane is nonpolar, this method is generally not viable for natural gas leak detection. However, the wet natural gas appears to contain 0 to 5% of hydrogen sulfide, which is a strong polar molecule. For example, 1% H_2S absorbs 12% of power at 300 GHz.[18] Hence, the millimeter-wave leak absorption technique may be used in those situations where H_2S is present in the gas stream.

B. Microwave pulsed radars

The problem of radar detection of gas leaks from a point source is in many ways similar to that of weather prediction — both deal with gas-phase media and their dielectric property changes. The source of radar returns in meteorological radars is the change of reflectivity, refraction, and scattering caused by storms, rain, cloud, atmospheric turbulence, and wind movement. Even in the absence of contrasting dielectric materials such as water and ice droplets in the atmosphere, the radars can detect clear-air turbulence and wind shear due to wave scattering caused by index of refraction inhomogeneities.[14]

MW imaging radars have been used in the past for locating underground oil and gas deposits based on (a) distinct changes in the topographic features above the deposits and (b) seepage of hydrocarbon gases into the atmosphere from underground.[19] While the underlying physics of the radar detection of gas seepage was not quite understood or

explained, the investigators claimed a success rate of 75% as verified by drilling. The radar backscatter in this case appears to stem from the dielectric contrast of the hydrocarbon gases and the index of refraction inhomogeneities caused by their movement and local turbulence.

Recently, under the auspices of a Newly-Independent-States Initiatives-for-Proliferation Prevention (NIS-IPP) program, Argonne has been working with a Russian company, AOZT FINN-TRADE, St. Petersburg, Russia, on a MW pulsed radar for detecting radioactive plumes. By modifying a 3.2-cm MW weather radar and using special signal processing, they successfully detected radioactive clouds 8 km from the exhaust stacks of a nuclear power plant during normal operation at a release level of 25-50 Ci in a 24-h period.[20] The source of radar return is the enhanced reflectivity of ionized clouds caused by radioactive particles. The same technique has also been applied for detection of chemical exhaust plumes from industrial stacks of an aluminum plant; Fig. 1 gives the radar blips from stacks and the image of chemical plume from a distance of 12 km. The chemical plume clearly offered detectable backscatter, even though the individual chemical constituents were not identified. The radar signal appears to be mainly due to index of refraction inhomogeneities of the chemicals in relation to that of air.

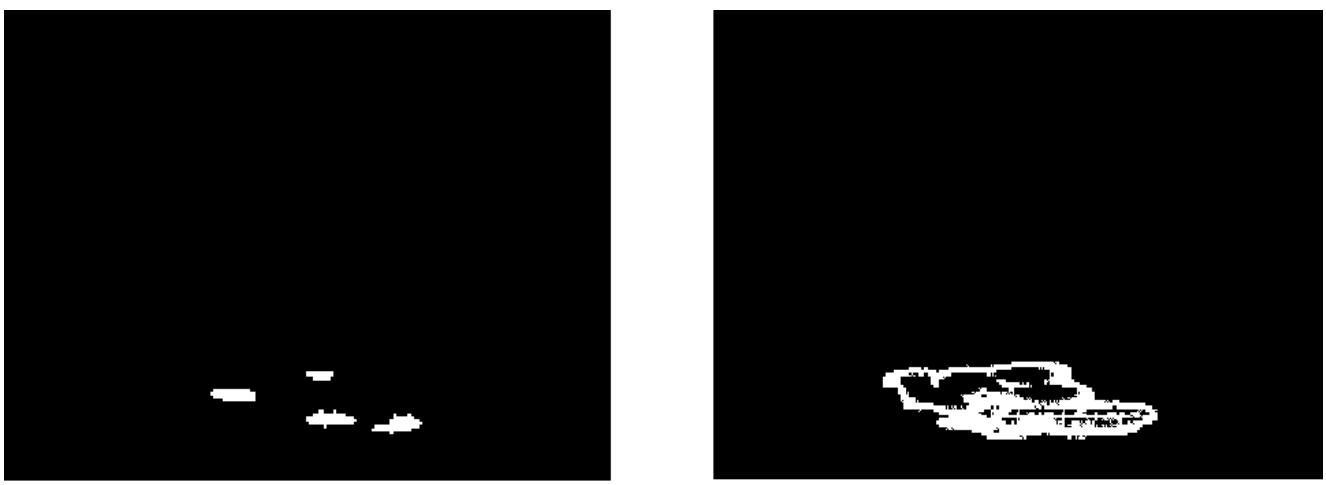

Image of stacks Image of chemical exhaust plume

Fig. 1. Radar detection of chemical plume (AOZT FINN TRADE, St. Petersburg, Russia)

The key to MW radar measurements is the radar equation:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4},$$

where P_r is the received power, P_t the transmitter power, G the gain of the transmit/receive antenna, λ the wavelength, R the distance to the plume, and σ the radar cross section of the plume. The radar cross section of the gas plume depends on its complex dielectric constant denoted by $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part, ε', is the relative permittivity (responsible for reflection and refraction ($n^2=\varepsilon'$)) and the imaginary part, ε'', is the loss factor (responsible for absorption). It also depends on the scattering from the

index of refraction fluctuation caused by the gas cloud. Other factors that can play a role in the radar return include wavelength, incident angle, and polarization diversity.

The natural gas constituents, because of their nonpolar or weakly polar nature, do not absorb much MW energy but show contrasts in their relative permittivity and index of refraction constants with respect to air, e.g., ε' of methane is 1.00081, ethane 1.0014, propane 1.002, butane 1.00258, and dry air 1.0005364. With high-power pulsed radars and low-noise, high-gain receivers, a change in permittivity or the index of refraction in the fifth or sixth decimal place is adequate to make a detectable change in the backscatter cross section. For example, the National Severe Storms Laboratory's 10-cm radar with a peak power of 10^6 W and antenna gain of 40,000, the receiver can detect an echo power of 10^{-14} W; at a range of 20 km, a cross section as small as 2.10^{-7} m^2 can be detected.[14] Efforts, however, must be made in the radar signal processing area to discriminate the signal from background clutter, landcover, and weather effects. For example, observation of echoes between scans that change in size and shape but remain at the same location will distinguish the leak echoes from a stationary clutter.

The advantages of MW technique for gas leak detection include availability of high power radars with built-in sophisticated radar imaging techniques and the continuous around-the-clock leak monitoring/infrastructure protection capability with possibly satellite-based systems. Although the technique does not offer chemical selectivity to methane per se, the probability of false positives is less because of the prior knowledge of the general location of pipelines and less likelihood of finding any other leaks in those areas.

IV. CONCLUSIONS

A state-of-art the survey is presented in the context of remote sensing of gas pipeline leaks, in general, and microwave radar sensing, in particular. A wealth of literature is available in optical remote sensing of trace gas detection in the atmosphere, which has direct relevance to gas leak detection. Laser-based detection is an active area of research in remote sensing and imaging of gas plumes because it offers good sensitivity and specificity. However, it suffers from a lack of adequate lasers in the methane absorption bands and atmospheric molecular interference. Furthermore, the optical systems are generally affected by weather conditions such as cloud, dust, fog, and rain.

Because of their long wavelengths, microwaves are less affected by weather conditions and are routinely used for remote sensing of earth resources and weather forecasting from airborne and satellite platforms. Microwave gas leak detection is based on reflection, refraction, and scattering changes of gas plumes in relation to the surrounding air. With the availability of low-cost high-power microwave pulsed radars and sophisticated radar signal processing and imaging software, microwave leak detection system can be built for remote and fast inspection of thousands of miles of transmission and distribution gas pipelines.

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