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Remote Detection of Leaks in Gas Pipelines with an Airborne Raman Lidar

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Introduction

Timely detection of gas leaks in gas pipelines is still an urgent problem, especially in exploitation of gas-main pipelines in vast unpopulated areas. For security reasons the same refers to pipelines in dense populated areas as well. In is quite obvious that it would be advantageous, if the detection were performed remotely by use of a contactless method. Among the methods that meet these requirements, there are lidar methods, which are based on the techniques of remote sensing of the atmosphere using laser radiation. Physically, various optical effects of interaction between the matter and laser radiation provide a good basis for constructing different instruments capable of solving the problem of gas leak detection [1, 2]. In this presentation, we discuss the approach to detection of gas leaks in gas pipelines by use of a Raman lidar installed onboard an aircraft or a helicopter. Information on the gas leak is acquired from Raman lidar return signals at the Raman line of methane. The estimates show that the version of an airborne Raman lidar discussed would enable detecting a gas leak from a carrier flying at the height of 300m using a single laser shot, if the concentration of methane in the air above the pipeline reaches one percent and higher.

Purpose

Detection of gas leaks in gas pipelines by use of an airborne Raman lidar.

Composition

Laser transceiver consisting of a pulsed laser, transmitting and receiving optics, a spectral device, a photodetector, an electron system for recording of lidar response, and a computer.

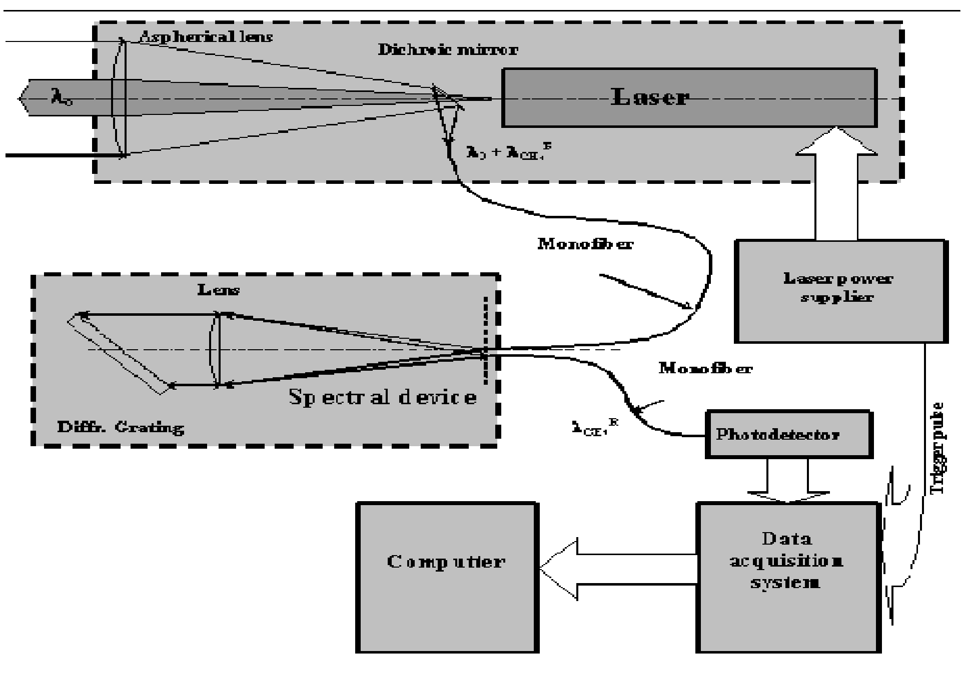
Operating principle

A pulse of laser radiation with the wavelength λ_0 is directed toward the sounded object using a transmitting-receiving lens (see Figure 1). In the atmosphere including the region adjacent to the gas pipeline, laser radiation is scattered by aerosols and molecular components of air. The scattered radiation propagates every which way including a rearward direction toward the transceiver. One of the processes contributing to the light scattering is Raman scattering, which manifests itself in the fact that in the spectrum of the radiation scattered by air, the spectral lines with the wavelengths λ_i appear that are shifted relative to the sounding radiation line. This shift is the spectral characteristic of the gas molecules present in the gas mixture of the sounded atmospheric volume, and their intensities are proportional to concentration of corresponding gas. Thus the spectral analysis of light scattered by a certain atmospheric volume enables qualitative and quantitative determining the composition of gas mixture in the sounded atmospheric volume.

In accordance with this principle, detection of gas leaks in gas pipelines is performed by observation of the spectral line of methane in the Raman spectrum of light scattered by the air adjacent to pipeline.

For this purpose, a pulse of laser radiation with the wavelength λ_0 is directed toward the pipeline (Figure 1). Radiation scattered in the rearward direction is collected by the transceiver lens and directed to the input of spectral device using a flexible optical monofiber. In the spectral device, the light arrived at its input is decomposed in the spectrum, from which a spectral Raman line of methane $\boldsymbol{\lambda_{CH4}^R}$[3] is selected using another flexible optical monofiber. Then, this radiation arrives at photodetector that transforms the signal in a digital form using an electron system of recording of lidar response. Application of pulse sounding radiation in the lidar enables selecting signals from required atmospheric volume adjacent to pipeline using the time passing from the moment of sending the pulse in the atmosphere up to the incoming of scattered radiation. For this purpose, a synchronization pulse produced in the laser system is used for initial startup of the system of lidar response recording. Computer software makes it possible to analyze the photodetector signal and produce the signal announcing the presence of a leak as soon as the photodetector signal generated by the Raman line of methane $\boldsymbol{\lambda_{CH4}^R}$ is arrived from the atmospheric volume adjacent to pipeline.

Figure 1: Block diagram of the airborne Raman lidar detector of gas leaks in gas pipe



Specifications

Transmitter: Nd:YAG - laser

Wavelength l 0, nm 532

Pulse energy, J 0.1

Pulse repetition rate, Hz 20
Receiver: aspheric lens

Diameter, cm 10

Focal length, cm 60

Spectral device: diffraction monochromator

Transmission, % 50

Width of selected region of spectrum, nm 0,5

Photodetector: photoelectronic multiplier

Quantum efficiency at λ_{CH4}^{R}, % 30.

Spatial length of the strobe above the Earth surface within which optical signal can be recorded is 10 m (66 ns in time expression).

Estimated distance (or the height of carrier fly) of detecting a gas leak is >300 m at the CH 4 volume concentration of 2 percent and the vertical range of visibility in the atmosphere ~10 km. Horizontal distance between the successive sounded volumes does not exceed 3 meters at the carrier speed of about 180 km/h.

Detection Ability of the Facility

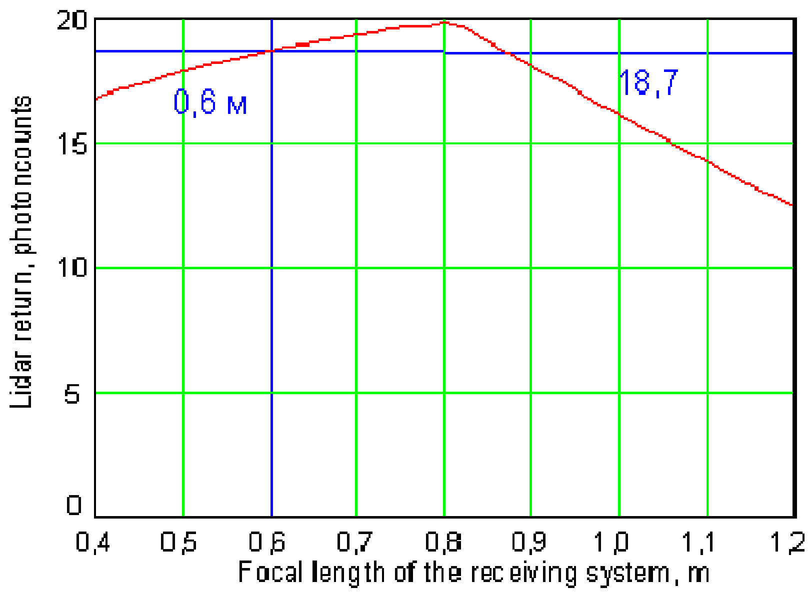
Analysis of the ability of the Raman lidar detector to detect methane gas near the Earth surface at the methane volume concentration of 2 percent is based on the calculation of the Raman lidar response as a function of some lidar parameters as well as on the calculation of the contribution from the factors hindering the detection of the signal from methane. Assuming that the proposed device should be a compact unit, but it should be able to solve a problem of detecting a methane leak using one sounding pulse, in these calculations, we fixed the diameter of detecting optics on the level of 10 cm and varied the focal length of detecting optics and pulse energy of sounding laser radiation.

Among the factors interfering with the detecting, we take into account a background generated by the sun light reflected from the Earth surface in the direction of the optical detection system of the lidar installed onboard an aircraft. In so doing, we made these calculations for most adverse conditions where the Earth surface is covered with white snow, the sky is cloudless, and the sun is at a height of 22° above horizon. Obviously, inter fering action of sun should be weaker for other conditions of the sun background generation.

It was assumed in calculations that the laser beam is focused on the Earth surface from the height of 100 meters, which enables to reduce the sunlight background reflected from the Earth surface and collected by the lidar receiving lens.

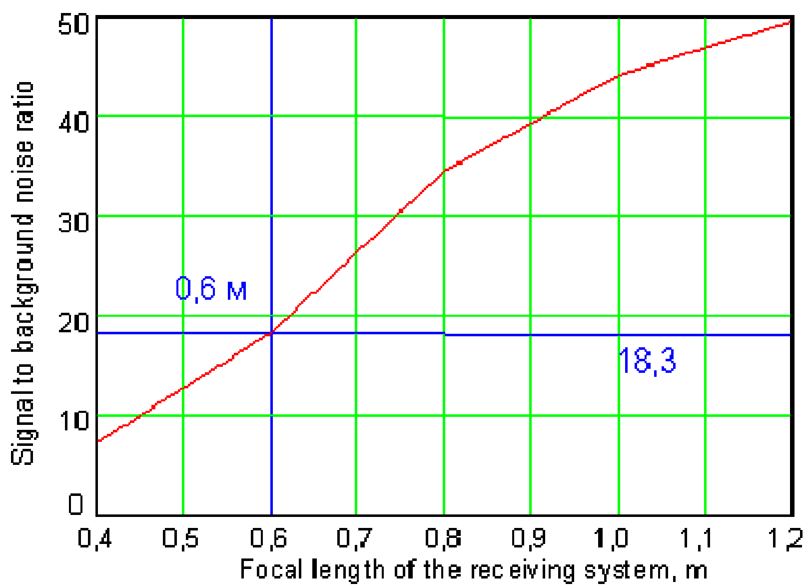
Thus, Figure 2 shows the dependence of the methane Raman lidar response on the focal length of the receiving lens 10 cm in diameter. It is seen from figure that at the focal length of 0.6 m, lidar can record 18.7 photocounts per shot in the mean from the atmospheric volume 10 meters long along the beam near the Earth surface at a distance of 100 meters.

Figure 2: Raman lidar response from methane as a function of focal length of the receiving lens 10 cm in diameter



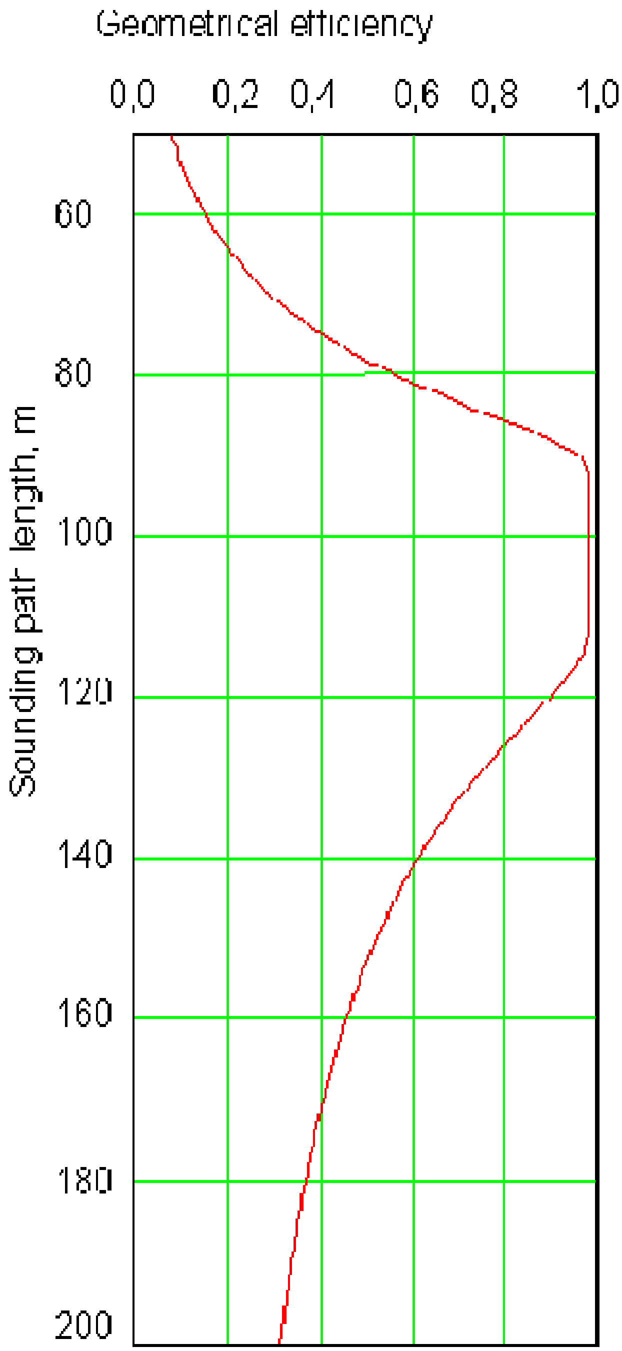
In so doing, the signal-to-noise ratio (sunlight background) is 18.3, as follows from Figure 3, where this parameter is represented as a function of the focal length of the receiving lens.

Figure 3: Signal-to-noise ratio (background) as a function of the focal length of the lidar receiving lens.



By varying the focal length of the lidar receiving lens, we sought for a certain compromise relative to the facility dimensions and to a provision of relatively free demands to the consistency of the flying height of aircraft. These demands are shown in Figure 5 as the dependence of the signal interception efficiency on the sounding (flying) height.

Fig. 5: Signal interception efficiency as a function of the flying height



Sounding beam is focused at 100 m.

This calculation is performed for focal length of the lidar lens of 0.6 m. It is seen from Figure 5 that in this case, the for the interception efficiency of 0.8, tolerance to the flying height variations is kept in the range from 85 to 125m.

Below (Figure 6), we present the detection and false-alarm probabilities calculated for different sounding pulse energies in terms commonly used in detection problems.

Figure 6: Detection and false-alarm probabilities calculated for different sounding pulse energies

False Alarm Probability

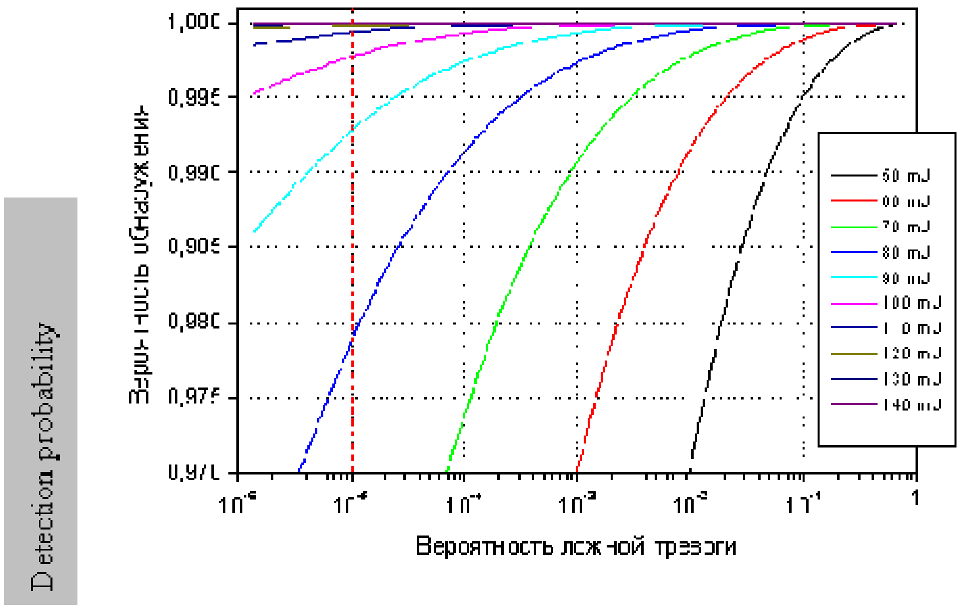


Figure 7: Leak omission and false-alarm probabilities calculated for different sounding pulse energies

False Alarm Probability

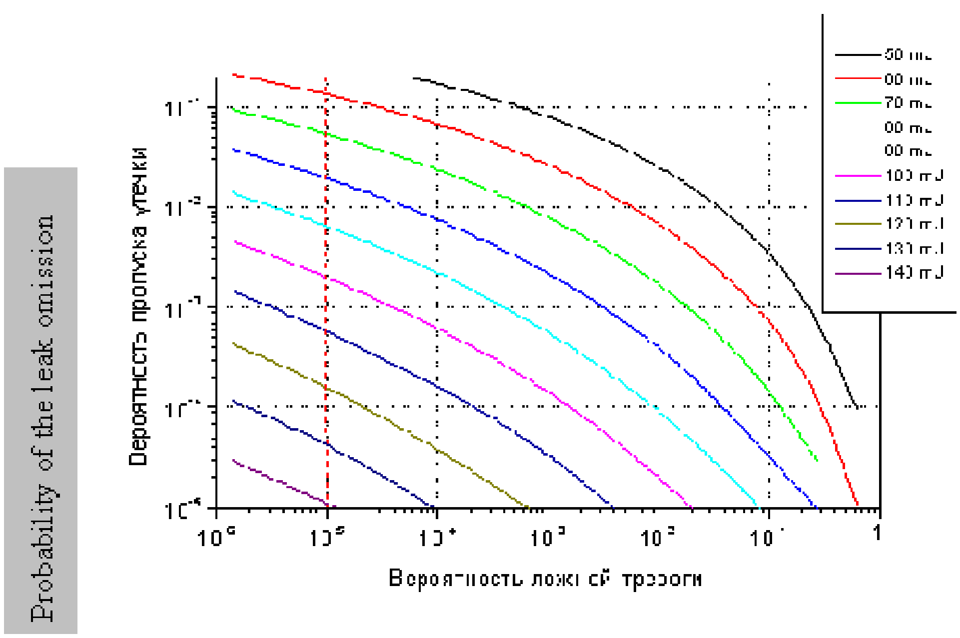


Figure 7 shows similar calculations in terms of the undetection probability in the logarithmic scale along both axes.

A vertical line in Figure 6 and Figure 7 shows that for preset false alarm probability of 10^{-5} and sounding pulse repetition rate of 20 Hz, the false alarm should be announced, in the mean, once in every one hour and 20 minutes. In so doing, the gas leak undetection probability is of 2×10^{-3}. We note that the data presented in Figure 6 and Figure 7 are calculated on the assumption of the Poisson statistics for photocounts recorded with a lidar.

The following preliminary conclusions can be made:

- Manufacturing the Raman lidar detector of methane leaks in accordance with the performance specification seems to be quite real both relative to the sounding pulse energy (100 mJ) and to the dimensions of the (diameter 10 cm, focal length 60 cm).
- Project made using the MathCad package enables on-the-fly performing the calculation for various sounding conditions (day, night, atmospheric visibility, and different parameters of the transmitting and receiving lidar sections).
- The schematic of the lidar detector proposed represents a remote spectrometer that enables, if needed, enhancing its functions for investigation of properties of underlying surface by adding the spectral channels at the output of the spectral device and channels of the lidar response recorder.

References

1. Ioan Balin, Valentin Simeonov, Ilia Serikov, Sergei Bobrovnikov, Bertrand Calpini, Yuri Arshinov and Hubert van den Bergh, "Simultaneous Measurement of Temperature, Water Vapor, Aerosol Extinction and Backscatter by Raman Lidar," Reviewed and Revised Papers Presented at the 22nd International Laser Radar Conference (ILRC 2004), 12–16 July 2004, Matera, Italy. Gelsomina Pappalardo, Aldo Amodeo, eds.

2. Arshinov Yu, S. Bobrovnikov, Ilia Serikov, A. Vorozhtsov, N. Eisenreich, "Remote Detection of Chemical Agents with a Lidar in the Solar-Blind Spectral Region," 36th International Annual Conference of ICT and 32nd International Pyrotechnics Seminar June 28-July 1, 2005, Karlsruhe, Germany.

3. *Raman Spectroscopy of Gases and Liquids*, edited by A. Weber (Berlin: Springer/New York: Heidelberg, 1979.)