Zbigniew MOTYKA, Tadeusz SMOŁA
GŁÓWNY INSTYTUT GÓRNICTWA, 1 Gwarków Sq., 40-166 Katowice, Poland

A new system of retroreflectors for methanometry of extended sources

Abstract

Past, new and future metrological applications in the area of methanometry for mining and environment show the necessity of developing wider metrological basis for methane emission from extended sources. Some solutions and tendencies developed in parallel in GIG and in the world are presented in the paper. A plane set of changing geometry approximating spherical mirrors of different radii is proposed. The visual results of introductory comparative tests are also presented.

Keywords: retroreflectors, laser beam, methanometry, municipal waste dumps.

1. Introduction

Past, new and future metrological applications in the area of methanometry developed in GIG for mining and environment show the necessity of developing still wider metrological basis of measuring systems for methane emission from extended sources, such as municipal waste dumps. One possible tool for such measurements is to use a laser beam being selectively absorbed by methane, emitted along a path of length L towards the detector or some kind of a reflector, e.g., cube corner type or cat-eye retroreflector. An average methane concentration along this path of length L is measured.

Some, developed in parallel with GIG works, world solutions and tendencies show that there exists an extensive technical base sufficient for such measurements up to distances ca. 100 m [1-3]. However, the modern communal wastedumps achieve areas of several hectares [4]. Apart of methane, also other Earth's hydrocarbons emission from extended sources may be of interest [5] as well as other gases increasing the greenhouse effect, e.g., carbon dioxide [6]. The light-source and receiver separated with a measurement path are known for decades solutions enabling measurements up to distances ca.1000 m and more [7]. However, the well collimated light beams of big enough optical power have to be used there in combination with costly analytical instruments (spectrophotometers). In parallel, much simpler devices using lasers have been developed for detection of particular gases [8]. In general, they do not need additional collimating optics up to ca. 100 m path lengths.

It will be considered here, if and how the applicability of these already developed laser measuring solutions of moderate costs may be extended for significantly longer than 100 m distances L without additional beam collimation and without separation of a transmitter and a receiver by placing them at points lying at the opposing ends of path length.

The possible solution is the use of mirrors reflecting the measuring beam back to the measurement system. The effectiveness of different constructional solutions of such mirrors will be discussed below. The target is the distance of at least ca. 300 m, which would may enable development of present methods into more complex ones of significant meaning for many important areas of applications.

Hollow gold infrared retroreflectors of as big as 127 mm aperture (offered, e.g., by Edmund Optics) and their clusters seems to be a natural proposal for significant extension of the range of existing devices for remote measurements of methane and other greenhouse gas emissions. However, for distances much longer than 100 m, the interference effects of beams retroreflected from neighbouring walls of corner cubes together with diffraction on their three inner edges are becoming of particular importance.

The similar solution of cat's-eye retroreflectors of big enough aperture is in principle almost free of the disturbances caused by diffraction. However, for greater distances the increasing aperture is needed, resulting with increased costs of the applied there IR-grade lenses of increasing diameters.

A similar solution of the Newtonian (Jones-Bird) telescope using a concave parabolic (or less-costly, spherical) mirror of increasing with foreseen distances diameter also demands costly IR optics of high precision. Such a telescope can work as a very effective cat-eye type retroreflector when one replaces its ocular with a reflecting mirror (Fig. 1).

Taking into account the high costs of the above-mentioned solutions, an entirely new proposal of effective retroreflectors of especially good costs to effects ratio is proposed here. It is a plane set of mirrors of changing geometry, approximating concave mirrors of different radii. It is elastic enough to be applied for different distances without increasing the loss of light energy density with the path length typical for plane mirrors (the returned reflected beam is twice as big as the mirror dimensions only due to geometrical optics). On the contrary, additional mirrors are included into geometry with increase in the distance the diameter of laser beam to be reflected. These peripheral mirrors may be suitably tilted, at the measure of necessity, to achieve necessary returning beam final concentration.

In the paper, some resulting pictures of performance of different quality and construction retroreflected mirrors obtained for the described above different solutions are presented, discussed and compared with the results for the tested sets of plane mirrors within the visible range of spectra.

2. Laser methanometers for extended surface methane sources

A dozen years ago, in 2004, Laser Laboratory of CMI developed a laser methanometry system for methane emission detection from extended sources. It was tested then for monitoring such emissions from municipal waste dump in chosen location in West Poland. It used a two-wavelength (3392 nm for the measurement beam and 632.8 nm for the reference beam) He-Ne laser. Its measurement range was 0.005 – 2% CH_4 with the possibility of its modification. Its accuracy was $\pm$0.001% CH_4. The maximal measurement distance L achieved during field tests was 100 m.

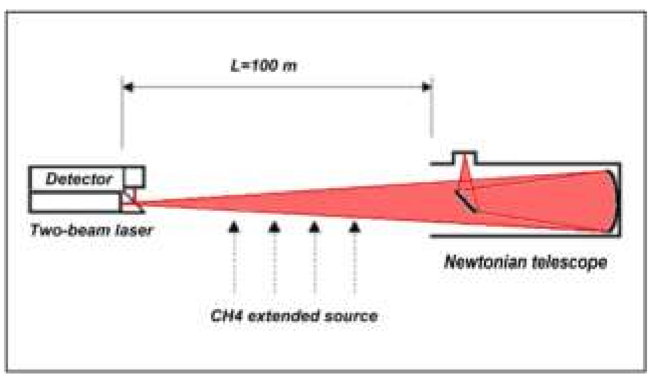


Fig. 1. The principle of operation of the developed in 2004 by GIG Laser Technology Laboratory laser system for methane emission detection from extended sources

When there is an associate detector (in the place of ocular) with the Newtonian telescope on the right in Fig. 1a, the measurement distances *L* can be significantly increased, especially for well collimated laser beams. Similar separated solutions for broad-range visible light sources have been commonly used for decades, e.g., in DOAS (Differential Optical Absorption Spectroscopy) systems manufactured by the Swedish company OPSIS AB. These systems, working in the visible range, allow the measurement paths as long as 300 m or even 1000 m, and more. E.g., the measuring channel of 1243 m length was reported for visible range for SO_2, NO_2 and some aromatic compounds measurements [7]. In recent times, this manufacturer has informed about a similar solution (FTIR DOAS) based on Fourier Transform Infrared Spectroscopy, including the possibility of CH_4 monitoring.

For many years Tohoku Anritsu Corporation Ltd. has offered, based on TDLAS (Tunable Diode Laser Absorption Spectroscopy) method, the LaserMethane mini methanometer [8]. It was designed for remote detection of methane leaks with the use of laser wavelength 1653 nm being absorbed by methane.

Its measuring range is 0 – 10% of methane concentration (with relative accuracy $\pm$10%) for the distance 1 m (0 – 5% in the mini-G version). It means that for a distance of 100 m it can measure uniform methane concentration up to 0.1% The single measurement time is 0.1 s. Its distance measurement range is 0.5 – 30 m without a mirror and 30 – 100 m with the reflecting surface.

The LaserMethane mini incorporates both laser source and detector in a single portable measurement unit. However, it does not use advanced collimation optics.

Therefore, the use of this and similar devices, needs appropriate concentration of the reflected back beam, of typical for this class of laser devices angular divergences.

Below, there will be discussed the new solutions enabling extension of the 100 m distance range without separating laser and detector by such a distance, and using complex reflecting mirrors rather than corner or cat-eye type retroreflectors.

3. A laser system with retroreflector for methane detection

The basic parameters of the IR reflecting systems have to be defined, which will allow increase the scope of the utility of the systems similar to those described in the previous paragraph, in the potential areas of application for methane sources of linear extension comparable with at least 150 m distance range.

In Tab. 1, the data has been collected for the possible increases in the size of the laser beam with the distance, resulted only from the maximum angular displacement of the beam due to imperfect manufacture of true retro-reflectors. The reftroreflectors of special hollow construction are considered, with a cavity covered with gold, ensuring 97% efficient reflecting operation within the infrared range of 900 - 2000 nm. Such requirements are met by coated with gold, hollow infrared retroreflectors offered by Edmund Optics, with the largest currently offered by the company aperture of 127 mm.

The manufacturer provides only retroreflectors with 1”, 2” , 5” and 30” deflection. The dependence of possible increase in the laser beam radius with the distance due to the angular displacement of these particular retro-reflectors is presented in Tab. 1.

When we assume that the radius of the retroreflected beam increase due to the angular displacement should not exceed 20 mm being the “blind” one-side border of a single Edmund Optics retroreflector, with the largest currently offered by the company aperture of 127 mm, Tab. 1 shows that such a single retroreflector, having an outer diameter of 167 mm and a deflection angle 30", would be useful for geometric acquiring of laser beam with divergence angle of ca. 1.5 mrad, at a distance of 100 m. Taking into account the optical geometry alone, it should ensure the returning from this distance beam with the additional to the double external retroreflector active diameter “blur” of not more than 14.5 mm width. This also means that the laser beam will be geometrically fully included in the effective diameter of the retroreflector at the distance 85 m and retroreflected with a 12 mm width blur at the retroreflected image on the level of the laser source.

Tab. 1. Laser beam radius increase as a function of the distance and angular displacement of the retroreflector

Distance *L*, m	Retroreflector angular displacement			
	1”	2”	5”	30”
	Laser beam radius increase, mm			
100	0.5	1.0	2.4	14.5
200	1.0	1.9	4.8	29.1
300	1.5	2.9	7.3	43.6
500	2.4	4.8	12.1	72.7
900	4.4	8.7	21.8	130.9
1500	7.3	14.5	36.4	218.2

Two similar retroreflectors, placed in line, have the total length of 334 mm, including 20 mm borders on both sides. The effective length of 294 mm differs from 300 mm diameter of laser beam of 1.5 mrad divergence at a distance 200 m on merely 6 mm. When the retroreflectors with a deflection angle of 5" will be used, then, as before taking into account the optical geometry alone, the width of "blurred" ring of retroreflected beam of up to 1.5 mrad divergence will not exceed 5 mm at the level of the laser source.

However, an effective mirror of four such retroreflectors placed in square has an outer diameter of 403 mm and the effective 363 mm. The latter means that the laser beam of 1.5 mrad divergence exceeds the effective diameter of such a mirror at a distance of 242 m. This also means that the laser beam will be geometrically fully included in the effective diameter of the retroreflector at the distance 242 m and retroreflected with a 6 mm width blur at the retroreflected image on the level of the laser source.

In a similar way, three such retroreflectors, placed in line, have the total length of 501 mm, including 20 mm borders on both sides, suitable for 300 m distance and a laser beam of 1.5 mrad divergence. When the retroreflectors with a deflection angle of 5" will be used, then, taking into account the optical geometry alone, the width of "blurred" ring around retroreflected beam will not exceed 7.3 mm.

An effective mirror of nine such retroreflectors placed in square has an outer diameter of 639 mm and the effective diameter of 599 mm. The latter means that the laser beam of 1.5 mrad divergence exceeds the effective diameter of such a mirror at a distance of 399 m. This also means that the laser beam will be geometrically fully included in the effective diameter of the retroreflector at the distance 399 m and retroreflected with a 10 mm width blur at the retroreflected image on the level of the laser source. Such a system of 9 retroreflectors with 5” deflection angle cost for 400 m distance increases the value of methanometer system based on LaserMethane mini only by 50%. However, this additional cost can be significantly (even ten times) reduced when using an alternative mirror of changing geometry construction with the great efficiency discussed later in this paper.

The another trouble with corner retroreflectors is that they do not behave in accordance with geometrical optics rules only, but the interference and diffraction effects become of particular importance starting from distances well below 100 m [9]. The impact of the wave character of light on the image of laser beams retroreflected by such devices is demonstrated in the following paragraph.

Alternatively to the gold hollow retroreflectors, there also can be used, e.g., the Thorlabs retroreflectors of maximum diameter of 50 mm, made of borosilicate glass N-BK7, with good transmission in both the visible spectrum and the near infrared range, up to

2000 nm. This makes them to be particularly suitable for methane detecting devices operating at a wavelength of 1653 nm.

4. Corner cube test measurement sets

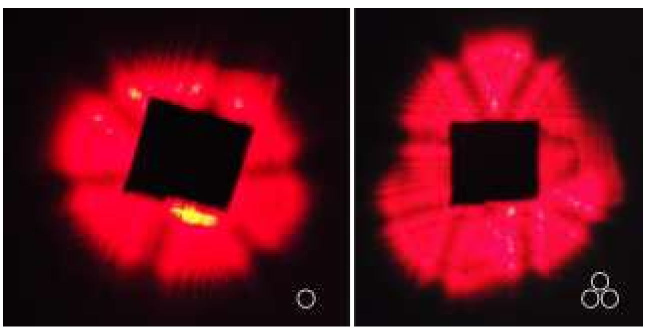
To verify the usefulness of retroreflectors, the tests in visible range of spectra were performed (Fig. 2).

Fig. 2. Geodetic mirror TPS30, offered by South, composed of 3 retroreflectors, 64 mm diameter each, two of which are blind covered at this photo for partial test

The wave nature of light causes that two plane waves of close wave vectors interfere with fringes space frequency increasing with the increasing angle of the two vectors. It may be of particular importance for longer distances, for which the angles generally decrease resulting in the possibility of negative interference within the area of the receiver.

The resulting interference picture can be easily observed in the returning laser beam cross-sections (Fig. 3). It is also extremely sensitive to atmospheric refraction causing its rapidly changing dynamical behaviour.

Fig. 3 presents the examples of retroreflected laser beam visual pictures obtained with the red laser in the far-field conditions, for 75 m distance from triple corner TPS30 cube glass retroreflector of 64 mm diameter each. Fig.3a presents the image obtained for 75 m from single prism of this triple retroreflector (two others were closed). In both cases, the TPS30 set was illuminated by a laser beam of ca. 1.5 mrad divergence from 100 m distance.



(a) (b)

Fig. 3. Examples of laser beams visual pictures obtained on a screen with rectangular central hole for the red laser beam reflected under the laboratory conditions from 75 m distance by single (a) and triple (b) corner South TPS30 cube glass retroreflector

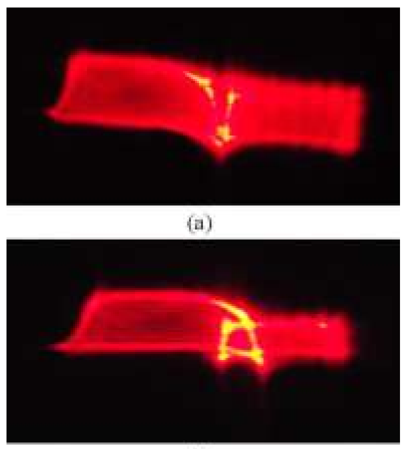
5. Plane mirror test measurement sets

The data from Table 1 influence also the final dimensions of images reflected by plane mirrors. Therefore, also the precision of their flatness has to be taken into account. The two reflecting plane 100×150 mm holographic 100% reflecting mirrors, type ZHL-PL of PZO production, being GIG's Laser Technology Laboratory equipment, were used to develop long measuring base for tests, extended 75 m distance three-folds to 225 m without intertwining laser beam twice at the same reflecting surface. The model of a reflecting mirror set composed of two poor quality 40×60 mm plane mirrors with 40 mm gap between them with independently course and precision regulation of their off plane X-Y inclinations was tested. The 1 mW red laser beam of 1.5 mrad divergence was used for testing the effectiveness of the laser beam propagation through the set without any additional optics.

The 180 mm diameter Gaussian beam was obtained at the level of reflecting two poor quality mirrors model set of changing geometry. The two-mirror testing set was placed within the beam area (Fig. 4).

Fig. 4. The reflecting simple two-mirror testing set of changing geometry illuminated with the laser beam after traveling 225 m distance from the laser source

The use of two intermediate reflecting mirrors of very good quality for prolonging the 75 m path three-times gave additional visual results regarding the effects of far-field propagation of the laser beam reflected by sequential plane mirror surfaces. It can be seen from Fig.4 that the diffraction effects on the mirror edges did not change significantly the Gaussian character of the central beam picture on the distance of 225 m path with two subsequent reflections at 75 m and 150 m.



(a)

(b)

Fig. 5. The two merging beam cross-section pictures obtained by the use of suitably modified geometry of the resulting complex test mirror composed of two elementary plane mirrors, at the 50 m (a) and 60 m (b) distance from the test mirror

Fig. 5 demonstrates that even for poor quality mirrors the geometry effects prevailed over the interference and diffraction. When superimposed, such laser beams form the mixture of high enough density energy to be collected by the receiver.

6. The prototype set of plane mirrors of changing geometry for distant remote methane emission measurements

The performed tests determined the form of the final prototype reflecting device of changing geometry to be built (Fig. 6). The central mirror of high quality (1”) will be used solely to reflect with minor only distortions of the laser beam of ca.1 mrad diameter up to 100 m distance, and to collect the essential (e.g., Gaussian) central part of the beam from twice as big distance.

For distances up to 200 m the peripheral mirrors of much poorer quality (30”) will be used to direct the part of the beam from its peripheral cross-section part to the receiver. They will increase the final light density approaching the detecting system simultaneously providing it by random and therefore more uniform mixture than the picture interfered by optical interference and diffraction in the case of using cube corner retroreflectors (Fig. 3). From the data in Table 1 for 200 m distance it follows that a “blur” of not more than 30 mm width will be present at the rectangular cross-section of the reflected laser beam at the level of the laser source. That is why the narrower mirrors than the central one may be used.

As far as construction from mirrors with gold reflecting surface is concerned, the presented project solution of the plane mirror prototype set of changing geometry can be suitable for distant remote methane emission measurements both with the use of lasers working at the 3390 nm (Fig. 1) or 1653 nm (Fig. 2). They will be also suitable for visual rangefinders.

It is foreseen that all 5 mirrors will be pre-adjusted (calibrated) under laboratory conditions. In the field, the system of 4 peripheral simultaneously adjustable mirrors will be adjusted to the necessary measurement distance with the use of a single micrometer screw gauge.

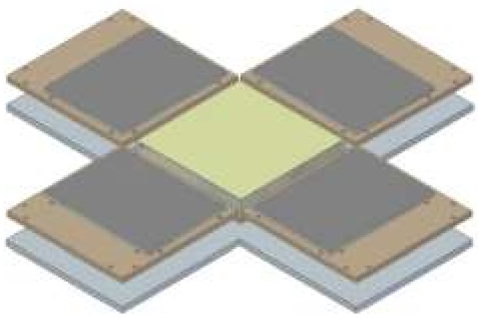


Fig. 6. The project of a mirror with changing geometry for stationary systems for distant remote measurements of methane emission from extended sources

7. Summary and conclusions

The introductory considerations and visual tests show the usefulness of the proposed plane model set of mirrors of changing geometry approximating different-radius spherical mirrors. The projected mirror seems to be useful as a retroreflector for extended distances of line measurements of air chemical parameters (e.g., methane concentration) with the use of low-energy laser beams. It can be especially suitable for the stationary stands for low methane emission control from extended sources. The visual results of the introductory comparative tests also suggest the foreseen advantages of the presented solution.

The long-distance stationary measurements may provide important data for methane and other Earth’s hydrocarbon emissions from extended sources. Also such gases as carbon dioxide may be considered on a similar base.

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Zbigniew MOTYKA, PhD

Adiunct GIG working in optoelectronics and laser techniques, and especially LDV, fiber optics, UV-Vis and IR spectroscopy, optical filtration and interference methods, acoustical and seismic imaging, laser control of sound emission, laser alignment, methanometry and other implementation of laser, acoustics and vibration techniques in mining, industry and environment.

e-mail: zmotyka@gig.eu

Tadeusz SMOŁA, eng.

Senior specialist GIG working in Laser Technology Laboratory. He specializes in applied mechanics, engineering, and designing of technical solutions with the use of CAD programs, especially SolidEdge.

e-mail: tsmola@gig.eu