Developing an optical sensor for local monitoring of air pollution in México

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This paper is devoted to the development of a prototype optical sensor for observing suspended particles in air at a local level on the territory of México City. The first part of the article discusses an urban atmospheric monitoring system, with special interest in $PM_{2.5}$ and PM_{10} particles because of their negative effect on human health and because they degrade the characteristics of optical communication. Its advantages and disadvantages are then analyzed, and it is shown that local monitoring is necessary. A new technical setup is proposed, based on the attenuation of the output optical signal as it is transmitted through open space. The data of official information sources, observational data bases, and interactive maps of the Sistema Nacional de Información de la Calidad del Aire and preliminary results of experiments are used to implement the work.

INTRODUCTION

Since the middle of the last century, rapid growth of urbanized territories in the world has been observed, including the appearance of megapolises (or magacities) with a population of more than 5–8 million inhabitants. It is predicted that by 2030 about 75% of the population will live in urbanized territories and, in the case of México, 53% of the population in thirty-five large cities, such as México City, Guadalajara, Monterrey, and Puebla.[1] It should be pointed out that this trend is closely associated with the appearance of problems of degradation of the natural environment both within the urbanized territories and beyond their limits, and this is intimately associated with contamination of the air, water, and soil.

The main contaminants ejected into the atmosphere of urban and industrial territories and presenting danger for the health of the population are ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and $PM_{2.5}$ and PM_{10}—suspended particles with a size less than 2.5 and 10 μm, respectively,[2] which are considered the most dangerous. They cannot be distinguished by odor nor by size, and they directly enter the organism by being breathed in and deposited in the lungs. In the course of time, a concentration increase can result in serious diseases of the air passages, cardiac insufficiency, and in some cases a fatal outcome.[3] Undoubtedly, the danger of the particles is determined by their composition and by the nature of the origin, which is mainly associated with soil erosion (5–10%), emissions from industrial enterprises (20–30%), exhaust gases of transport vehicles (about 50–70%), and the condensation of gases in photochemical processes in the atmosphere. Moreover, the presence of large concentrations of suspended particles in the air reduces visibility and the transmissibility of radio signals and as a result degrades the operation of optical communications.

There are currently air-quality observation networks in many large cities of México, combined into a single *Sistema Nacional de Información de la Calidad del Aire* (SINAICA) under the jurisdiction of the *Instituto Nacional de Ecología*. In particular, in México City, the air quality has been monitored since the mid-80s and in its achievements and scale currently represents an example for many countries of Latin America and even the world. However, one of the main problems of the observation system is that it is impossible to have accurate data on the degree of air contamination at the local level; this is especially important for warning the population in real time and in the immediate vicinity of their location.

THE MONITORING SYSTEM

The system for monitoring air pollution in México consists of one mobile center, a laboratory for calibration standards, and four operative subsystems:

- an automatic network of atmospheric monitoring (RAMA),
- a manual network of atmospheric monitoring (REDMA),
- a network of measurement of atmospheric precipitation (REDDA)
- a network meteorological observations (REDMET) (Fig. 1).

At present, all the networks include forty-nine stations (175 automatic and 39 manual installations), at many of which observations are carried out simultaneously for different subsystems.[4,5]

In particular, the RAMA subsystem was initiated in 1986 for atmospheric monitoring of ozone, sulfur dioxide, nitrogen oxides, carbon oxides, suspended particles (PM_{10} and $PM_{2.5}$), and hydrogen sulfide. By using the information obtained every hour from the thirty-six automatic RAMA stations [twenty-four in the Federal District (F.D.)], the mean

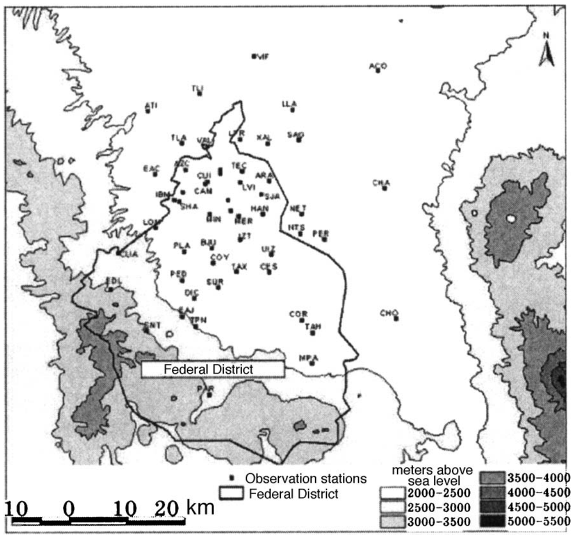

FIG. 1. Location of air-quality observation stations in Mexico.

air-quality index (IMECA) in México is calculated, which is shown in real time on the Internet page of the SINAICA system, with recommendations to the population, depending on its value, for taking definite precautionary measures.

Observations of the overall index of suspended particles (PST) and of PM_{10} and $PM_{2.5}$ for 24 hours are presented on REDMA every six days, as well as the concentrations of certain heavy metals (lead and manganese) in the air. The network has fourteen remote stations available, nine of which are in the F.D.

Air and rainwater tests have been reported weekly on REDDA since 1987 for the analysis of dry and moist residues, respectively, and for determining the chief physicochemical characteristics of the water: the pH, the electrical conductivity, and the concentrations of anions (nitrates, sulfates, and chlorides) and cations (ammonium, calcium, sodium, magnesium, potassium). This makes it possible to establish and compare the dependences between the concentrations of toxic substances in the air and in rainwater. There are currently sixteen semiautomatic stations (twelve in the F.D.).

The REDMET subsystem has the function of monitoring the meteorological air index, which in turn can be used to make climatological predictions and when calculating spatial and temporal models of contaminant propagation. It also presents information on the UV index, in order to warn the population of the level of solar radiation and limitation of activity in the open air. Wind speed and direction, temperature, relative humidity, and overall and UV radiation are observed at fifteen stations.

Suspended particles $PM_{2.5}$ and PM_{10} are thus monitored in México by means of twenty-three installations at the RAMA and REDMA stations.[6] However, a number of current problems should be pointed out.[7] These include the nonuniform distribution of the stations over the territory and the averaging of the parameters over large territorial sectors. This fails to reflect the actual situation at the local level and becomes meaningless for warning the population in the immediate vicinity of their location.

PROSPECTS OF LOCAL MONITORING

In planning the development of the system of atmospheric monitoring[7] in México in 2012 and in the assumed program of specific actions of the Environmental Department of the Federal District (EDFD),[6] the following points are envisaged for improving the operation of the network, directly associated with the theme of studies of this paper:

- increasing the number of stations, including movable installations, and expanding the zone in which the monitoring acts;
- including new contaminants in the list of measurements being made;
- constantly monitoring the operation of the apparatus for measuring the $PM_{2.5}$ and PM_{10} concentrations;
- introducing video cameras into the monitoring system to determine in real time the "visibility" parameter in open space;
- enhancing the quality of the statistical processing when predicting the ozone and $PM_{2.5}$ concentrations in 24 hours;
- taking measures to spread the information;
- developing equipment for a monitoring program in microspaces in order to estimate the health risk of the population.

It should be pointed out that the EDFD equipment for measuring the concentration of suspended particles under steady-state conditions (at the stations of the monitoring network) currently includes apparatus based on sucking in volumes of air and suspended particles through filters of a definite size. The AccuScan™ Remote Sensing system product, made by ESP, is used to measure the concentration of hydrocarbons, CO, CO_2, and NO_x on movable objects. This is based on the optical principle of IR or UV reflection and is used to measure the concentrations of the indicated substances in automotive exhaust gases on city streets. The device is made in the USA[8] and has been successfully used not only in México, but also in other countries of the world, such as Australia, Canada, Egypt, Germany, Taiwan, and England. The concentrations were calculated from the variation of the absorption frequency of an optical signal when it passes through a medium with various contaminants. For the key elements of contaminants such as hydrocarbons, CO, CO_2, and NO_x, the wavelengths are established, and this signal comes from a personal radiation source for each of them[9] and is subsequently transformed into an electric signal. In this connection, the device is unwieldy and, moreover, expensive.

There are a fair number of publications at the international level concerning devices based on an optical principle, although most of them have other purposes. Even in the middle of the last century, White[10,11] proposed a layout that was subsequently widely used in spectroscopy, in which a light ray passed through a long optical path in an open but restricted space by means of multiple reflections from mir-

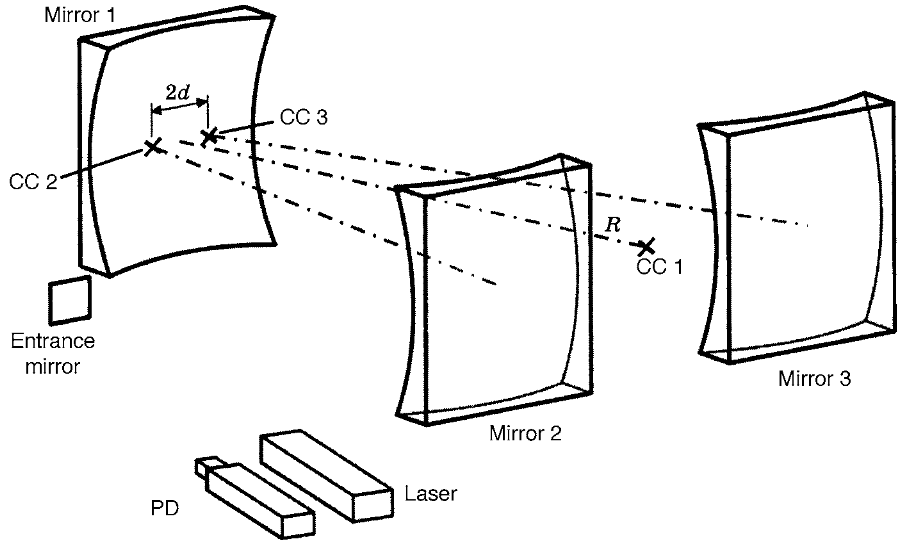

FIG. 2. Layout of optical-based sensor for determining suspended particles in air.

rors. The attenuation of the output optical signal is associated in this case (when the mirrors are technically installed and adjusted correctly) exclusively with the absorption of light by the particles suspended in the air. This principle was discussed in detail in Ref. 12 and was used to develop a new microelectromechanical system to improve optical communications. It is shown in Ref. 13 that a light signal can be used to measure the degradation of the characteristics of optical communication when it passes through free space during bad weather, in particular, under an elevated concentration of water vapor—with fog, rain (up to 80 mm/h), and snow. The layout of the device is fairly simple in this case and includes a laser diode with a lens, a reflector, and a signal detector. The authors propose to use this device under urban conditions to make observations on the visibility between high buildings. The same principle was used in Ref. 14 to measure the losses of the output optical signal from backup systems (10–100 Mbit/sec, distance to 1000 m) under bad local weather conditions. This idea subsequently formed the basis of Ref. 15 for measuring the concentrations of suspended particles in air at the local level.

In practice, the equipment for observing suspended particles for purposes of personal monitoring, developed in the USA 20 yr ago[16] and used in recent years in México,[17] has the same basis as the stationary equipment installed at stations for observing the air quality in the F.D. This small device is based on the principle of sucking in volumes of air at the level of the human breathing apparatus and subsequently processing the results in the laboratory by weighing the particles that have passed through a definite size of filters for PM_{10} and $PM_{2.5}$, followed by chemical absorption to determine the limited number of contaminants of which these particles consist. However, the device is distinguished by being physically inconvenient to use because of its bulk and weight, by the necessity of constantly being worn by a person, by the exclusively individual zone of action, and by an extremely high price.

A LOCAL OPTICAL SENSOR

Starting from everything said above, this paper proposes a new economical setup for a local sensor for measuring the PM_{10} and $PM_{2.5}$ concentration per area of operation up to 10 m^2 and based on the operating principle of the cell.[10,11]

The optical layout of the sensor consists of three identical hemispherical mirrors (reflectors), with one mirror facing the other two at a distance of the concavity radius R $=40$ cm, identical for all the mirrors. The center of concavity (CC) of mirror 1 in this case is centered between 2 and 3, whose centers in turn are located on mirror 1 at an equal distance from each other ($2d$). The apparatus is placed horizontally, although it is understood that this setup can subsequently be used on surfaces with a small slope for prechosen angles of reflection (Fig. 2). Laser radiation with wavelength 632 nm is used as the input signal in operation, and air pollution is simulated by water vapor, whose concentration increase reduces the output optical signal, converted at the photodetector (PD) into an electric signal.

The IR signal arrives at a small input mirror mounted under the first mirror in such a way that the reflection from it passes to mirror 2. Since the given distance is the focal length, the light ray is reflected to mirror 1 (the first reflection), from which it goes to mirror 3 and returns to the first (second reflection), subsequently repeating the entire reverse path (Fig. 3). As a whole, a setup was worked out experimentally for which the optical path of the light signal reaches 14.8 m, being reflected from the mirrors thirty-seven times.

Taking into account that the suspended particles have a complex chemical composition, calculations were carried out in Ref. 18 to determine the absorption coefficient of the optical signal for elemental carbon and sulfur (as some of the most significant contaminants associated with organic and industrial effluents). Based on the studies of Ref. 19, the authors established the wavelengths at 7.46, 6.29, and 5.45 μm to determine SO_2, NO_2, and NO and for 2.5-μm

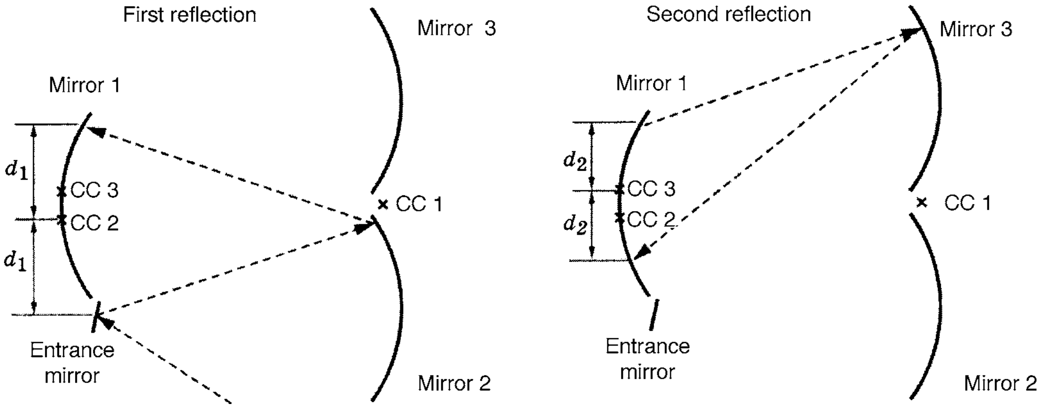

FIG. 3. Operating diagram of optical sensor.

particles. These data, nevertheless, need to be experimentally confirmed further.

CONCLUSION

This paper has pointed out that there has been a fairly well-developed monitoring system in México since 1986 as part of the National Information System on Air Quality. The four operative subsystems include forty-nine observation stations, at twenty-three of which suspended particles are observed. Even though this network is preeminent in achievements and operating efficiency in Latin America, the number of stations does not meet the needs of a megapolis, because they are nonuniformly distributed over the territory and because they average the air-pollution parameters over large territorial sectors. This does not reflect the actual situation at the local level.

In this connection, this paper has proposed a new economical setup of a local sensor for measuring the concentration of PM_{10} and $PM_{2.5}$, calculated per area of action up to 10 m^2 under stationary conditions—for example, in government and academic institutions, offices, and plants. This sensor is based on the principle of attenuating an optical signal transmitted in free space and is associated with the absorption of light by suspended particles. Calculations have also been carried out to determine the absorption coefficient of the optical signal for elemental carbon and sulfur, and the wavelengths 7.46, 6.29, and 5.45 μm have been established for determining SO_2, NO_2, NO, and for 2.5-μm particles.

Further studies on the given device are proposed to experimentally determine the wavelengths for other elements that make up suspended particles and are of interest from the viewpoint of their negative effect on health. An optical sensor is to be created for measuring multielement concentrations, with periodic transmission of a light signal with a given wavelength from a single source to avoid an unwieldy design.

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[1]*CONAGUA (Comisión Nacional del Agua). Estadísticas del agua en México* (CONAGUA, México City, 2007).
[2]"AMC (Academia Mexicana de Ciencias). Ambiente y salud," Revista Ciencia **57**, No. 4, 96 (2007).
[3]*SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). Informe de la situación del medio ambiente en México. Compendio de estadísticas ambientales* (SEMARNAT, México City, 2005).
[4]*INEGI (Instituto Nacional de Estadística, Geografía e Información). Estadísticas del Medio Ambiente del Distrito Federal y Zona Metropolitana 2002* (INEGI, SMA-GDF, México City, 2005.
[5]"SIMAT (Sistema de Monitoreo Atmosférico). Mapa interactivo," Página web, 2008: http://www.sma.df.gob. mx/simat/pnrednueva.htm.
[6]*SMA-GDF (Secretaría de Medio Ambiente del Gobierno Distrito Federal). La calidad del aire en la Zona Metropolitana del Valle de México 1986–2006. Informe del estado y tendencias de la contaminación atmosférica* (SM-GDF, México City, 2007).
[7]M. Perevochtchikova, "Environmental monitoring in the México City metropolitan area: the current situation," in *Environmental quality in the large cities and industrial zones: problems and management*, ed. RSHU, 2009. [in press].
[8]"ESP. ESP AccuScan™ Remote Sensing (RSD3000) Device," Environmental Systems Products Holding Inc. East Granby, CT, USA, Web site, 2008: www.etest. com.
[9]"RSD. RSD Calculations: a Brief Description. The remote sensing device," Web site, 2008: www.rsdremotesensing. com.
[10]J. U. White, "Long optical paths of large aperture," J. Opt. Soc. Am. **32**, 285 (1942).
[11]J. U. White, "Very long optical paths in air," J. Opt. Soc. Am. **66**, 411 (1976).
[12]B. L. Anderson, V. Argueta-Diaz, F. Abou-Galala, G. Radhakrishnan, and R. J. Higgins, "Optical cross connect switch based on tip/tilt micromirrors in a White cell," IEEE J. Sel. Top. Quantum Elec. **9**, 579 (2003).
[13]V. Kukshya, T. S. Rappaport, H. Izadpanah, G. Tangonan, R. A. Guerrero, J. K. Mendoza, and B. Lee, "Freespace optics and high-speed RF for next generation networks propagation measurements," in *IEEE 56th Proceedings of Vehicular Technology Conference. VTC 2002-Fall*, vol. 1, pp. 616–620.
[14]E. Leitgeb, J. Bregenzer, P. Fasser, and M. Gebhart, "Free-space optics extension to fiber-networks for the 'last mile'," Proc. Lasers Electro-Optics Soc. **2**, 459 (2002).
[15]G. E. Sandoval Romero and V. Argueta Diaz, "Mid-infrared gas sensor for pollutants: case study, Mexico City," in Poster presentations of RIAO-OPTICALSE'07 Conference, 2007.
[16]M. T. Morandi, T. H. Stock, and C. F. Contant, "A comparative study of respirable particulate microenvironmental concentrations and personal exposures," Envir. Monit. Assessment **10**, No. 2, 105 (1988).
[17]G. González de la Luz, "Evaluación de exposición personal a contaminantes atmosféricos (Ozono, dióxido de nitrógeno, partículas menores a 10 y 2.5 micrómetros) en adultos mayores que habitan en la Zona Metropoli-

tana del Valle de México," in Memorias del Congreso XVI FEMISCA, 2008.
[18]V. Argueta Diaz and G. E. Sandoval Romero, "Effects of pollutants in free-space optical communication: case study, México City," in *Abstracts of the International Conference Fundamentals of Laser-Assisted Micro- and Nanotechnologies, 2007*.
[19]G. Schkolnik, D. Chand, A. Hoffer, M. Andreae, C. Erlick, E. Swietlicki, and Y. Rudich, "Constraining the density and complex refractive index of elemental and organic carbon in biomass burning aerosol using optical and chemical measurements," Atmos. Environ. **41**, 1107 (2007).
[20]V. Kukshya, T. S. Rappaport, H. Izadpanah, G. Tangonan, R. A. Guerrero, J. K. Mendoza, and B. Lee, "Freespace optics and high-speed RF for next generation networks propagation measurements," in *Proceedings of Vehicular Technology Conference, 2002*, vol. 1, pp. 616–620.
[21]G. Schkolnik, D. Chand, A. Hoffer, M. Andreae, C. Erlick, E. Swietlicki, and Y. Rudich, "Constraining the density and complex refractive index of elemental and organic carbon in biomass burning aerosol using optical and chemical measurements," Atmos. Environ. **41**, 1107 (2007).