MEASUREMENT TOOLS FOR ATMOSPHERIC SYSTEMS

W. K. Graber and M. Furger
Paul Scherrer Institute, CH-5232 Villigen-PSI, Switzerland

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Summary

The article presents techniques, instruments, and sensors used to measure parameters in atmospheric physics and chemistry. First, an overview over fundamental techniques frequently realized in many instruments is given. These techniques are often based on interactions of either electromagnetic or sound waves with the atmosphere. They are used for instrumental techniques in the laboratory, or in the open atmosphere. The latter gained attraction in remote sensing to cover large areas with highly resolved data on land surface cover or atmospheric characteristics. The description of the techniques is

followed by a presentation of meteorological and chemical properties of the atmosphere. The presentation takes into consideration instruments for measuring temperature, humidity, cloud properties, precipitation, wind, pressure and different aspects of radiation. Measurement tools for chemical parameters separate gas concentration and aerosol measurements.

1. Introduction

Among the environmental systems, the Earth's atmosphere is the system that transports pollutants most rapidly and dilutes them most efficiently. A volatile pollutant emitted into the atmosphere can reach any place on Earth within typically 10 days, even up to a height of some 20 km. Because of the turbulent nature of atmospheric motion, it is extremely difficult to forecast the dispersion of anthropogenic pollutants brought into the atmosphere.

The reason for disposing anthropogenic wastes into the atmosphere is given by its simplicity and efficiency with respect to the dilution capability of the atmosphere. Beside this disposal, three additional ways for removing anthropogenic pollutants are practiced, but all with some risk on a local scale. First, concentration of waste material, followed by recycling or storing in a safe containment. Second, controlled release into ecosystems such that their capacity of biodegradation is not exceeded. Third, dilution of the pollutants in water or in soil.

Deposing wastes into the atmosphere was a good solution, as far as not too much and not too poisonous emission sources were present. But during the last decades the widespread practice of this solution lead to a world-wide contamination of the atmosphere, with a couple of well-known key problems such as stratospheric ozone depletion, global warming, deposition of sulfur and nitrogen followed by acidification and eutrophication of the soil and leading to a reduction of biodiversity, etc.

The complexity of the dispersion processes and the interconnection of various feedback cycles are the reasons why the impact of anthropogenic air pollutants on soil, water, plant and human is not evident as a causal chain. In addition to the complex structure of atmospheric motion, anthropogenic primary pollutants can be transformed chemically into secondary pollutants during their travel time in the atmosphere: the fate of an air mass moving from highly polluted urban areas to remote locations shows production of tropospheric ozone, peroxi-acetyl-nitrate and other toxic gases or aerosols.

On a wide field of interdisciplinary work and with tremendous effort the interplay of forces in this context was studied with experimental and model-based approaches.

The traditional way of gaining knowledge in physics and chemistry is by arranging reproducible experiments in a laboratory where a few processes are isolated from further influences. Addressing the atmosphere as a huge laboratory, this isolation is not possible and therefore measuring strategies and instruments were invented to explore individual processes.This is often done in the framework of large field campaigns or long-term monitoring networks. (see *Field Techniques for Atmospheric Systems*). This present article focuses on some standard measurement tools and instruments for specific parameters widely used in today's atmospheric research from the surface up to the stratosphere.

Three types of measurements for evaluating atmospheric parameters are distinguished: in-situ measurements, remote sensing techniques and, mainly for chemical quantities, off-line techniques with air sampling followed by laboratory analysis. In-situ point sensors gain information about a specific quantity of the air in a very small volume of typically a few cubic-centimeters.

With remote sensing, mainly involving electromagnetic radiation, averages of parameters over large surface areas or air volumes are evaluated. Both types of sensors can be mounted either on ground stations, such as towers, or on moving platforms, such as vehicles, aircraft, satellites or balloons. In the following overview, sensors are categorized according to the quantity they measure. The categories exhibit the two principal approaches of specifying the atmosphere by either its dynamic properties of moving air masses and their exchange, generally addressed as meteorological parameters, or by their chemical properties and constituents. Besides the dynamic properties of the atmosphere the meteorological parameters also describe thermodynamic variables of state, radiation and energy.

Because often a physical or chemical technique can be applied for evaluating a variety of parameters, an overview of the most frequently used techniques is given in advance.

2. Techniques

Among the physical techniques used in meteorological and chemical measurements the interactions of electromagnetic waves with the atmosphere play a primary role. Considering the growing importance of remote sensing techniques, the wide use of these interactions become evident.

The atmospheric interaction phenomena are refraction and reflection, most often used for meteorological measurements, and absorption and emission, predominantly used for chemical measurements. In addition to electromagnetic waves, interactions of acoustic waves are also involved in atmospheric measurements.

Frequently used methods for chemical analysis are outlined very briefly in subsection 2.4. Simple techniques or techniques used for analyzing specific parameters are considered in the description of the meteorological and chemical measurement tools.

2.1. Interaction of Electromagnetic Radiation with the Atmosphere

Interaction of electromagnetic radiation with atmospheric inhomogeneities leads to refraction, while interaction with aerosols and gases leads to scattering or reflection. Both types of interactions are used for instruments to retrieve information on the atmosphere, e.g. lidars, radars, scintillometers and electromagnetic profilers.

The *lidar* (light detection and ranging) technique uses a laser beam reflected at topographical targets or backscattered by aerosols in the atmosphere. These laser techniques were developed together with modern laser technology with very powerful lasers. Lidars operate with laser light sources beamed into the atmosphere as shown in Figure 1.

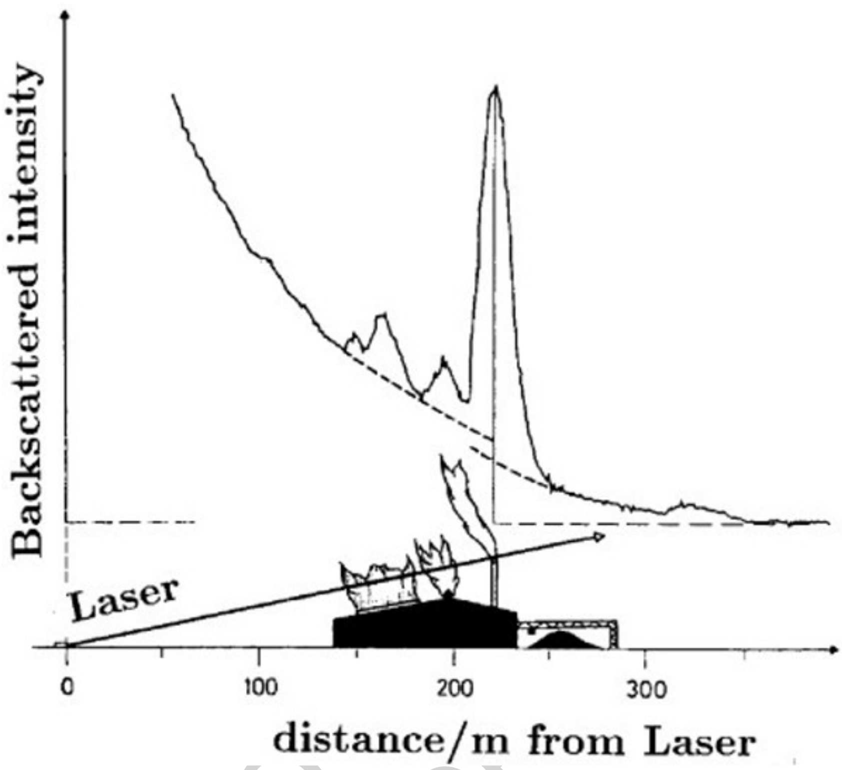

Figure 1. Mie scattering lidar particle monitoring at an iron-alloy plant (from Fredriksson K., Lindgren I., Svanberg S., Weibull G. (1976). *Measurements of the emission from industrial smoke-stacks using laser radar techniques*, Rep. GIPR-121, Göteborg Institute of Physics, CTH, Göteborg, Sweden).

The beam is typically focused with a Cassegrain telescope. The backscattered signal is sampled usually with the same telescope in a coaxial arrangement and measured with a photomultiplier. The backscattering is dominated by Mie scattering at aerosols. Additionally, Rayleigh scattering and resonant backscattering at wavelengths close to absorption lines of the molecules also contribute to the total backscattering. Besides the elastic Rayleigh scattering, the inelastic Raman scattering at wavelengths different from the incident light is observed with *Raman Lidars*.

This inelastic scattering varies with the scattering molecule, but is one to three orders of magnitudes smaller than the Rayleigh cross-section. Knowledge of the atmospheric density profile from measurements of the temperature profile and the surface pressure is used for the determination of the Rayleigh scattering. At greater altitudes, where aerosols are negligible (upper stratosphere and mesosphere), the temperature profile can be deduced from the backscattered signal. Lidar backscatter signals are analyzed with respect to their time of travel, their intensity and their Doppler shift in frequency. From these three properties the range (distance), the quantity and the radial velocity of the backscattering medium is evaluated.

The range resolution is given by the duration of the laser pulse emitted into the atmosphere: a 100 ns pulse gives a resolution of 15 m. The repetition rate of the laser is usually 10 to 100 pulses per second. With continuous wave lidars (*CW lidars*) the range is resolved by runtime discrimination with a transient recorder. Lidars used for wind sensing by evaluating the Doppler shift of the backscattered signal are called *Doppler lidars*. For concentration measurements of atmospheric trace gases differential optical absorption lidars (*DIAL*) are used.

They emit radiation at two wavelengths, one on a specific absorption line of a molecule (λ_{on} in Figure 2) and the other in close proximity (λ_{off}). The absorption of this molecule is determined by the difference of both measurements.

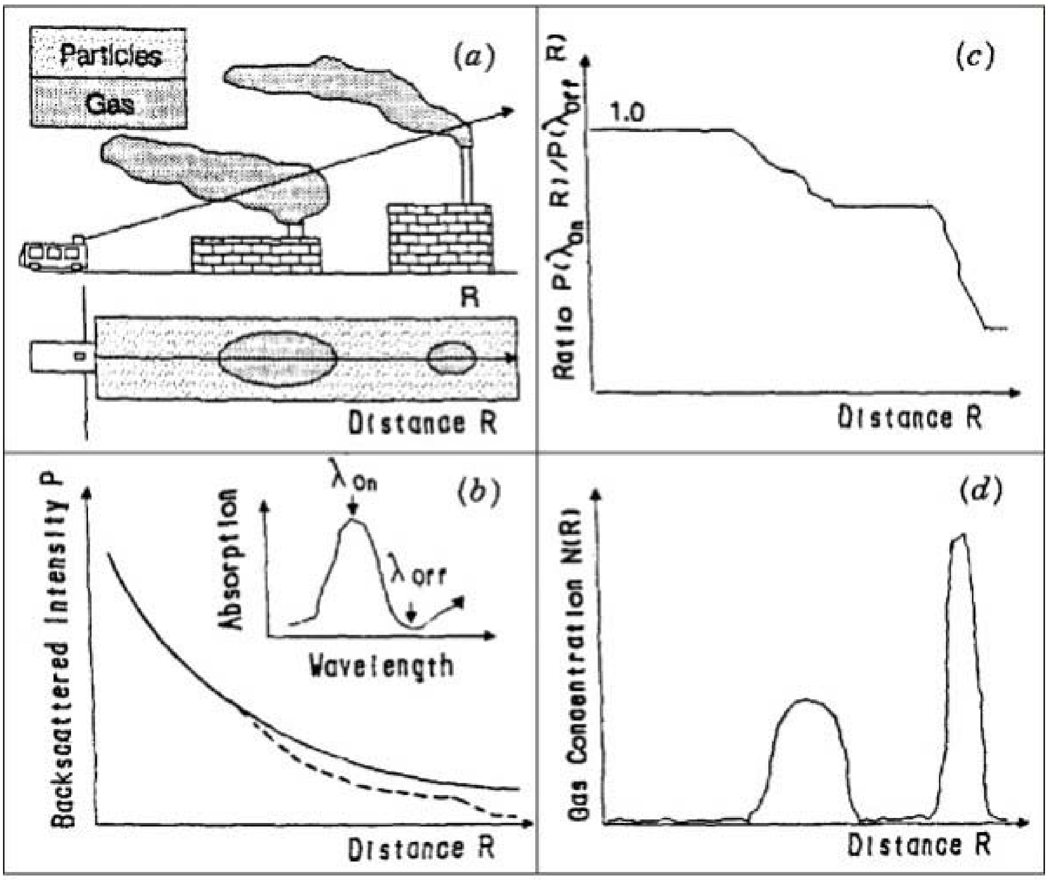

Figure 2. The principle of differential absorption lidar (from Edner H., Fredriksson K., Sunesson A., Svanberg S., Uneus L., and Wendt W. (1987) Mobile remote sensing system for atmospheric monitoring, *Appl. Opt.,* **26**, 4330–4338).

Scintillometers measure the intensity fluctuations of an electromagnetic wave travelling through some portion of the atmosphere. They exist in two configurations, one with only a receiver detecting the scintillation of an independent light source, e.g. a star or a natural scene, the other more common configuration with a transmitter as an artificial source of electromagnetic radiation and a receiver.

Their measurements are based on the inhomogeneities of the refractive index along the optical path, which are caused by variations in atmospheric density (temperature) and composition (humidity). Scintillometers are used to measure the spatially averaged crosswind component perpendicular to the optical path, or the refractive index structure parameter, C_n^2, from which important turbulence quantities like energy dissipation rates or turbulent heat fluxes can be derived.

Radars (radio wave detection and ranging) are mainly used for area-covering determination of precipitation, thunderstorms and hail. Radars make use of the backscatter of microwave radiation in the region between 1.5 and 30 GHz. *Wind profilers* are used for vertical profiles of wind velocity and direction. The scattering elements for both instruments are any kind of larger atmospheric suspensions, preferably water droplets, but also insects and even inhomogeneities of the refractive index for microwaves. Incoherent and coherent radars are in use: The receiver of an *incoherent radar* detects the range dependence of the average backscattered power. A *coherent radar* additionally detects phase and amplitude of the signal.

With a *Doppler radar* the radial velocity component of the motion of the scattering elements is deduced from measuring the Doppler shift in frequency. Airborne radars on satellites or aircraft often use the synthetic aperture Radar (*SAR*) technique. The longer the antenna of a radar, the finer the resolution in this dimension.

The SAR concept refers to a technique used to synthesize a very long antenna by combining echoes received by the radar as it moves along its flight track. Aperture means the opening used to collect the reflected energy that is converted into an image. Because the radar wavelengths are much longer than those of visible or infrared light, SARs can also 'see' through cloudy and dusty conditions that visible and infrared instruments cannot.

With the set-up of the satellite-borne global positioning system (*GPS*) a few applications came up for atmospheric research. The distortion of these waves, for example, is used to retrieve humidity.

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Biographical Sketches

Werner Karl Graber was born on 14 December 1951, Basel, Switzerland. He received Diplom fuer Physiker and Ph.D. Degrees from Eidgenoessische Technische Hochschule Zuerich in 1977 and 1985 respectively. He is presently Head of the Atmospheric Pollution Section , Paul Scherrer Institute, Villigen-PSI, Switzerland. His research interests include application of instruments for measurements in environmental research, mainly aircraft measurements, field measurements to investigate the production of photo-oxidants, modeling for the description of the link between local and regional wind systems, deposition of atmospheric pollution to the vegetation and interaction with the vegetation, and soil solution modeling and calculation of critical loads and levels of nitrogen (eutrophication) and sulfur (acidification).

Markus Furger was born on 26 Aug 1958. He received a physics Diploma from Eidgenoessische Technische Hochschule (ETH), Zuerich in 1983 and a Ph.D in Geography from the University of Bern in 1990. He received the 1990 Meteotest Award for the latter. During Aug. 1992 - July 1993 he was Adjunct Environmental Scientist at Washington State University, Tri-Cities Campus, spent at Pacific Northwest Laboratory, Richland, Washington. He is presently with Paul Scherrer Institut, Villigen PSI, Switzerland. He took part in various field experiments in the Alps (ALPEX, Pollumet, VOTALP, Ecomont, MAP) and worked on the development of remote sensing applications in mountainous terrain (scintillometer, sodar, radar wind profilers).His research activities include climatological studies of the wind field in the lower troposphere in the vicinity of mountain ranges, Monte Carlo simulation technique to estimate the uncertainties in boundary layer heat budgets obtained from wind profiler data. He is member of American Meteorological Society, American Geophysical Union, Swiss Society of Meteorology, and European Geophysical Society.