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A MIE LIDAR SYSTEM FOR ATMOSPHERIC MONITORING: DESIGN CONSIDERATIONS

MINELLA C. ALARCON
Department of Physics
Ateneo de Manila University

ABSTRACT

With the growing urbanization of Metro Manila and other cities, there is an increasing need to monitor the atmosphere and environment. The laser radar or lidar technique has been shown to be highly flexible and capable of providing accurate multidimensional measurements of atmospheric and meteorological parameters over a wide area. LIDAR, the acronym for "light detection and ranging", is an active laser remote sensing system which employs the radar principle to give range-resolved measurements of the atmosphere from a single location. In particular, the Mie lidar system utilizes the phenomenon of elastic Mie scattering to monitor the atmosphere of aerosols, detect and measure particulate emissions from vehicles, observe clouds, and measure stratospheric aerosol layers consisting primarily of sulfate particles.

This paper discusses and analyzes the different parameters required to set up a highly sensitive two-wavelength Mie lidar system. Using the scattering lidar equation and known system specifications, the received power and signal-to-noise ratio are calculated and plotted with range, in order to predict the range capability and sensitivity of the system. The system is divided into the laser transmitter, the optical receiver, and the signal processing system, and the requirements of each are analyzed and discussed. Results of sensitivity measurements are presented. Because of their sensitivity and power, laser-based environmental sensors are able to provide high resolution and versatility.

INTRODUCTION

With the growing urbanization of Metro Manila and other cities, there is an increasing need to monitor the atmosphere and environment. Monitoring of pollutants near the ground level is necessary in order to determine the quality of air that man breathes. Both ground-level and higher-level monitoring must be performed in order to develop mathematical models for predicting air quality for varying circumstances. Stratospheric gases and particles affect man in a less direct, but equally important way.

In general, laser remote sensing is one of the active areas of laser applications and it benefits a major sector of the general populace. It is one area where lasers can make a significant impact in the Philippines.

A result of careful and thorough study, this paper gives an overview of the LIDAR technique and Mie lidar systems, and discusses and analyzes the different parameters required to set up a highly sensitive two-wavelength Mie lidar system.

THE LIDAR TECHNIQUE FOR ENVIRONMENTAL SENSING

Advances in the field of lasers gave rise to the active remote sensing technique called the Laser Radar or LIDAR, the acronym for "light detection and ranging". The LIDAR technique is characterized by the introduction into the atmosphere of well-collimated laser beams of high irradiance and spectral purity.

In a manner analogous to the microwave radar technique, the time between the transmission of the laser pulse and the arrival of the scattered return signal can be directly related to the range at which the scattering occurred. Thus, the laser radar is capable of range-resolved measurements.

The atmosphere, in addition to the major gases N_2, O_2, Ar, water vapor and CO_2, contains trace constituents, solid particles, and aerosols. Most of these constituents modify the transmission of electromagnetic radiation through the atmosphere. There are various ways by which the transmitted light interacts with the atmospheric constituents. These processes include Rayleigh scattering, Mie scattering, Raman scattering, resonance scattering, fluorescence, absorption, and differential absorption and scattering. The decision to use a particular technique is based on the information required from environmental species. This is obtained from measurements of physical parameters of the scattered radiation.

Lasers afford great flexibility of operation and can monitor with high resolution a wide variety of pollutants. The scope of lasers in environmental sensing is extensive. They can be used to undertake concentration measurements of both major and minor constituents in the atmospshere, detection and mapping of specific constituents as required in pollution monitoring, and airborne mapping of fluorescent substances such as chlorophyll or oil slicks in or on lakes and oceans. Furthermore, these observations can be made remotely with both spatial and temporal resolution from the ground or from mobile platforms such as boats, helicopters, aircraft, or satellites.

Figure 1 is a diagram of the basic laser radar configuration. In most systems, a pulsed laser is employed as transmitter and the laser radiation is collimated and transmitted into the atmosphere. As the laser energy passes through the atmosphere, it interacts with various scatters such as aerosols, gas molecules and solids. A fraction of this energy is backscattered and collected by a receiving telescope, transmitted through an optical filter or monochromator, and transferred to a photodetector. The electrical signal is recorded by a transient memory recorder in a range-gated fashion and then transferred to a computer. The spatially-resolved data of the atmospheric scatters are calculated by a signal processing computer and recorded on a display terminal. The range of the scattering volume can be uniquely determined from the recorded signal as a function of time, and the backscattering properties, such as particle concentrations, are derived from the magnitude of the signal.

THE MIE SCATTERING LIDAR

The Mie LIDAR system uses the developed technique of Mie scattering. This is the efficient elastic scattering process whose cross section can be so large that even low concentrations of dust or aerosols can be detected. The Mie scattering scheme provides direct observation of the transmitted frequency of atmospheric elastic backscattering from which the presence, location and distribution of particles, such as dust, smoke and cloud, can be determined. This lidar system, either mobile or stationary, is capable of observing the tropospheric environment and collecting information over a wide area.

Since the first laser radar observations were reported in 1963, the Mie scattering lidar has been studied and developed as a new tool for understanding atmospheric processes in connection with the transport and convection of pollutants and aerosols from natural and man-made sources. Early laboratory experiments with the lidar, such as those of Fiocco and de Wolf (1968), and Fernald et al. (1972), attest to the system's capability to measure aerosols in the atmosphere with high spatial and temporal resolution. On the other hand, Davis (1969) used the lidar to observe clouds and obtain direct information on cloud heights and thicknesses.

Single-wavelength Mie lidar observations lead to measurements of the volume backscattering coefficient which provide direct information on the presence and location of smoke plumes, dust, among others. Collis and Russell (1976) point out that this measurement has little practical significance in itself for air pollution monitoring. Information on mass concentration, or number concentration of particle size distribution, is of far greater importance. Such information, however, can not be directly obtained by remote single-wavelength lidar observations. Multiple wavelength or bistatic lidar observations can provide information on these quantities. Two-wavelength lidar systems consist of long and short wavelengths, and explore the wavelength dependence of the backscattering and extinction coefficients to provide such direct information as mean particle size. A convenient choice is a single laser system such as the Nd: YAG which has emissions at 1.06 µm and its second harmonic at 532 nm. For example, Uthe (1982) has shown that the Nd:YAG laser system would be useful in evaluating particles of sizes less than 1 µm from the ratio of long wavelength to short wavelength extinction coefficients.

Any preliminary analysis of the system begins with the lidar equation which is classified according to the target and optical interaction process. For Mie scattering, the equation is:

$$P(R) = P_0\, l\, K\, A_r\, \beta(R)\, Y(R)\, T_0(R)^2/R^2,$$

where P(R) is the received power, l is the effective length of the scattering volume corresponding to one-half of the laser pulse length ($l = ct/2$, t is the laser pulse duration), K is the optical efficiency of the transmitting and receiving optics, Y(R) is the geometrical overlap factor between the laser and telescope receiver field of view, A_r is the receiving telescope area, β(R) is the volume backscattering coefficient of the target scatterers, $T_0(R)$ is the single path transmittance of the laser beam through the atmosphere which depends on the total extinction coefficient of the atmospheric scatterer at the laser wavelength and R is the range.

The detection sensitivity of the system can be determined by the voltage signal-to-noise ratio (S/N), which is simply the ratio of the signal to noise current. The signal current is the number of photoelectrons generated by the detector per unit time and is directly proportional to the power received P(R). In this context, noise represents the false signals received by the system and can reduce the accuracy of the measurements. In laser sensing, noise may come from statistical fluctuations of signal and background radiation, thermal generation of photoelectrons in the absence of light and the thermal agitation of photoelectrons. Depending on various conditions, all these contribute to the noise current and can affect the detection sensitivity of the lidar system. In the case of the photomultiplier tube (PMT) as detector, considering shot-noise limited conditions, the governing equation is

$$\left(\frac{S}{N}\right)_v = \sqrt{\tau_g \eta \lambda m}\,/hc\mu P_r\,/\,\sqrt{P_r + 2P_b}$$

where τ_g is the gate time of observation for a single laser pulse, η is the quantum efficiency of the photodetector, m is the total number of laser shots within some predetermined observation time, μ is the photomultiplier noise factor. P_b is the background power, and is

$$P_b = B(\lambda)\,\Delta\Omega_r A_r K\,\Delta\lambda$$

where B(λ) is the spectral radiance of background light, ΔQ_r is the solid angle of the receiver field of view, and Δλ is a the spectral width of the receiver. Here the boxcar integration technique is to be preferred to accommodate a wider range of optical signals for lidar operation. The range capability of the system is determined from a plot of $(S/N)_v$ vs. R, as in Figure 2. Note from the graph that a system using a flashlamp-pumped Nd:YAG laser emitting at 532 nm as specified may reach a maximum altitude of 40 km at nighttime under clear air conditions.

Figure 3 presents a schematic diagram of the highly sensitive two-wavelength Mie scattering lidar system that is to be developed locally. The system consists of three main parts: the laser transmitter, the optical receiver and the signal processing system. For the purposes of system design, it is essential to consider the requirements of each.

The Laser System

In general, the choice of the laser transmitter must consider the following for highly sensitive laser remote sensing: atmospheric optical transmittance; optical interaction involved; availability of high power and efficient laser sources and highly sensitive detectors and detection techniques; and eye-safety conditions. For the two-wavelength Mie lidar, a flashlamp-pumped Nd:YAG laser is a suitable choice because it satisfies the requirements of power and wavelength.

The beam emitted by the laser is directed through appropriate output optics toward the target of interest. The function of the output optics is threefold: to improve the beam collimation; provide spatial filtering; and block the transmission of any unwanted broadband radiation, including the emission that arises from some lasers.

The design of the beam collimator and expander system is mainly determined by the laser beam divergence, the beam spot size and the opening angle of the telescope. The components of the system are so chosen to satisfy the condition on the geometrical overlap factor. The geometrical overlap factor is unity where the field of view of the receiver optics overlaps the laser beam. In practical terms, this is so, provided the divergence angle of the laser beam is less than the opening angle of the telescope. The other required optics are reflectors with high reflectivities at the laser wavelength. Often a small fraction of the laser pulse is sampled to provide a zero-time marker (a reference signal with which the return signal can be normalized should the laser's output reproducibility be inadequate) and a check on the laser wavelength where this is important.

The Optical Receiver

The telescope mirror collects the backscattered radiation and reflects it onto the detector via an aperture or iris, and a dielectric interference filter. The size of the receiver's aperture is directly proportional to the power received and it depends to a large extent on the technique and range involved. Majority of lidar systems make use of reflecting (Newtonian or Cassegrainian) telescopes and require some kind of secondary mirror to direct the backscattered signal onto the detector. Such secondary mirror is not employed in the receiving optical system shown in Figure 4. As mentioned earlier, the opening angle of the telescope is a significant parameter to consider and can be readily measured. The same parameter determines the size of the iris which is placed at the focal spot. The radiation gathered by the receiver optics is passed through some form of spectrum analyzer on its way to the photodetection system. The spectrum analyzer serves to select the wavelength interval of observation and to provide adequate rejection of all off-frequency radiation. It can take the form of a monochromator, polychromator or a set of narrowband spectral filters.

The choice of the photodetector is determined by basic characteristics which include spectral response, quantum efficiency, frequency response, current gain and dark current. The wavelength of the signal to be detected constitutes the primary factor in selecting the photodetector to be employed. Usually, a photomultiplier tube (PMT) is used as detector, particularly at visible laser wavelengths where the detector quantum efficiency is 10%, or better. In the near-infrared, the quantum efficiency of PMTs is about 0.1% or less. Thus, in this wavelength region, it is practical to consider another type of detector such as the photodiode. A few systems (Hansen and Spinhirne, 1982; Salemink et al., 1985) have considered this idea. For the near-infrared component of the backscattered signal, this system uses a high responsivity silicon avalanche photodiode-preamplifier module with noise equivalent power of 8×10^{-14} $W/\sqrt{Hz}$ at 1060 nm. The module consists of a silicon avalance photodiode, a high frequency amplifier, a temperature sensing element and associated circuity for temperature compensation of the photodiode responsivity – all of which are in hybrid form and in a hermetically-sealed modified 25-mm diameter package.

If the lidar is to be efficient in long-range observations, the detector's sensitive surface should be located in the focal plane of the telescope. The detector must be centered on the optical axis of the collecting mirror such that each point on its sensitive surface receives radiation from the mirror. Focusing optics may be required to compress the lidar signal down to the detector size.

In a two-wavelength lidar measurement using an Nd:YAG laser, the emitted beam consists of the fundamental at 1.06 μm and its second harmonic at 532 nm. In such a set-up, the collected backscatter passes through a harmonic separator so that the near-infrared portion is focused on the photodiode while the visible received signal is imaged on the photomultiplier tube. In front of each photodetector is a bandpass interference filter centered at the corresponding wavelengths.

Signal Processing System

The signal from the photodetector may be processed through analogue or digital techniques. In the analogue approach, raw data is displayed as the backscattered signal intensity as a function of elapsed time on a wide-bandwidth oscilloscope. The data can be digitized by means of fast dual-waveform digitizers which together with a computer make real-time data processing possible.

OPERATION AND PERFORMANCE OF THE SYSTEM

After the Mie lidar system is put together, it is then ready for alignment and measurements. The lidar system alignment proceeds by adjusting the optical components for optimum overlap of the laser beam and the receiving telescope at the farthest range possible with the emitted laser power. The position of the detector assembly is also adjusted in search of the optimum position of the telescope's focal point. The corresponding changes are monitored with the oscilloscope. The main object of the system alignment is to receive the maximum signal from the farthest range possible with the emitted laser power. Figure 5 presents typical oscilloscope data resulting from sensitivity measurements. One was obtained under clear air conditions from 500 meters, while the other was obtained with clouds from an altitude of 2.4 km.

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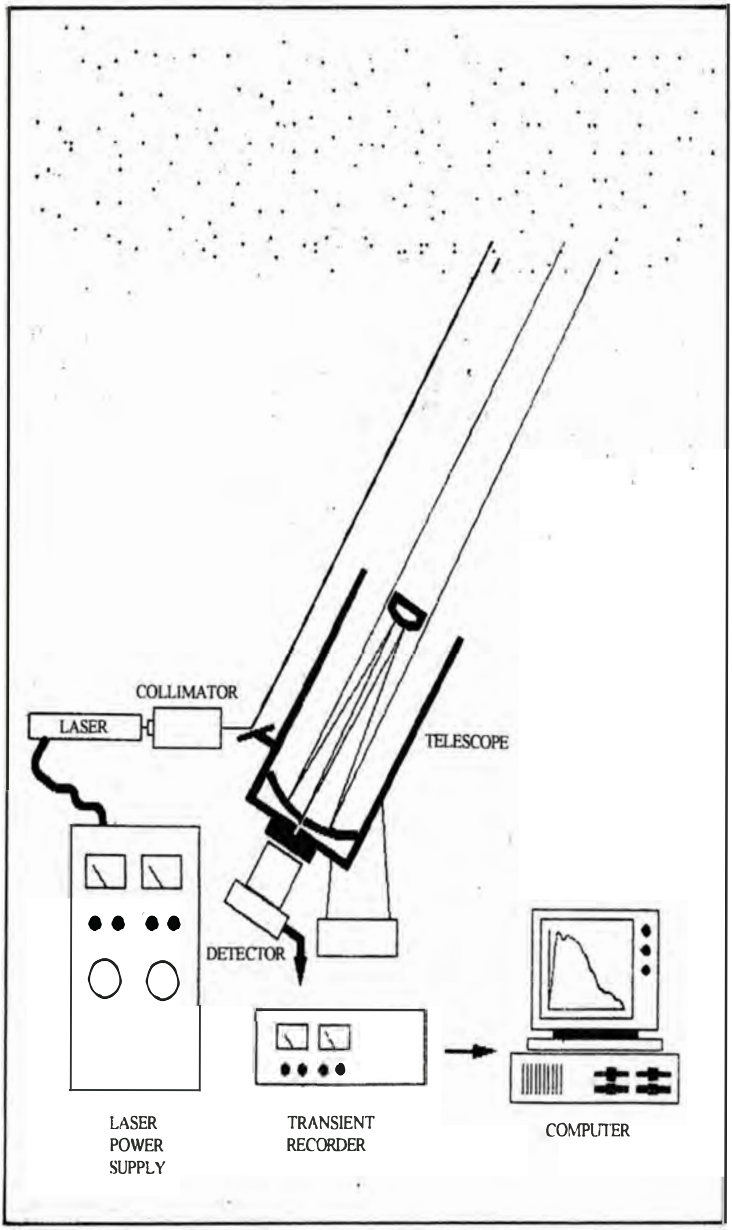

Figure 1. **The basic laser radar configuration consists of the laser transmitter, the optical receiver and the signal processing system.**

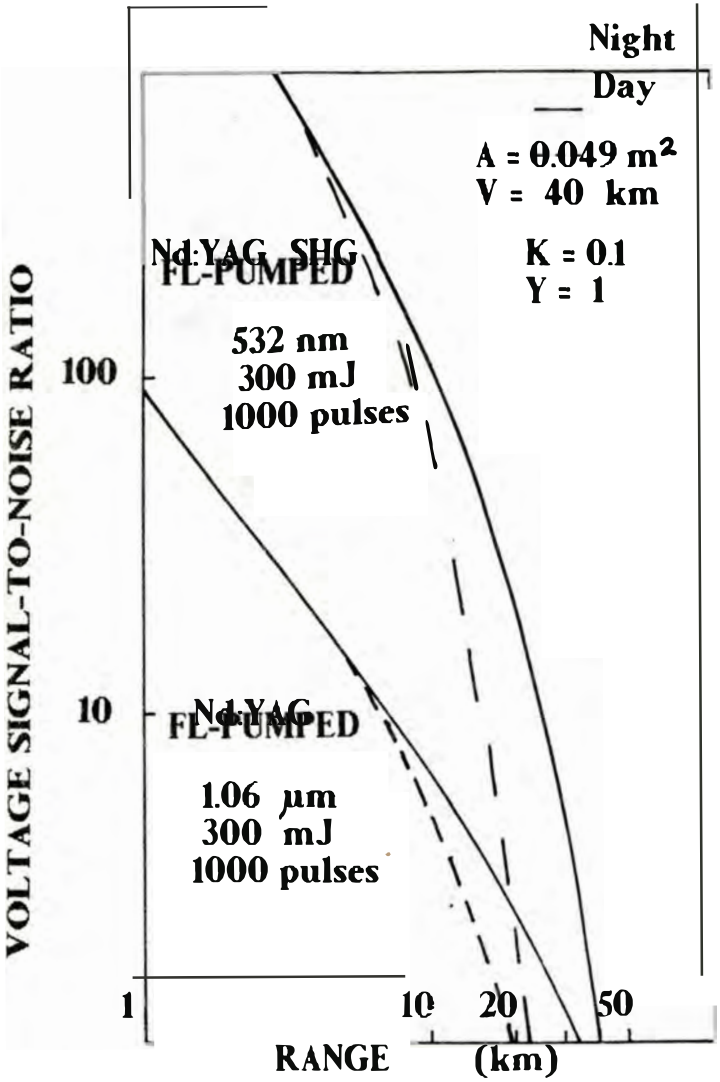

Figure 2. Range dependence of voltage signal-to-noise ratio for detecting molecular Rayleigh scattering with a two-wavelength Mie lidar using the fundamental and second harmonic beams of a flashlamp-pumped Nd: YAG laser

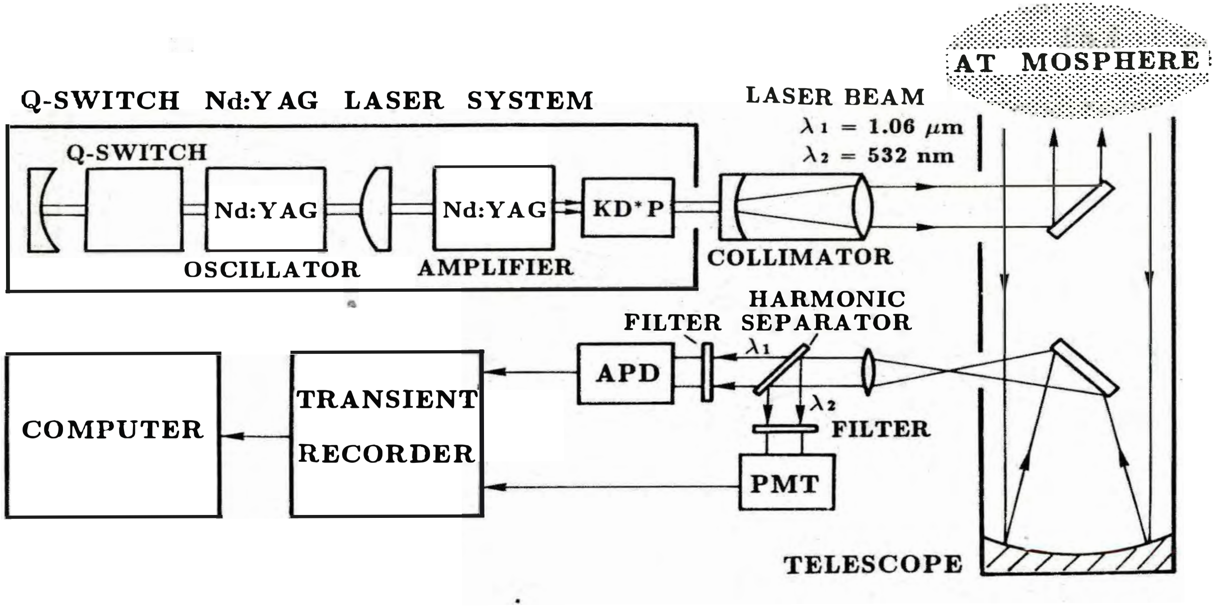

Figure 3. The highly sensitive two-wavelength Mie scattering lidar system

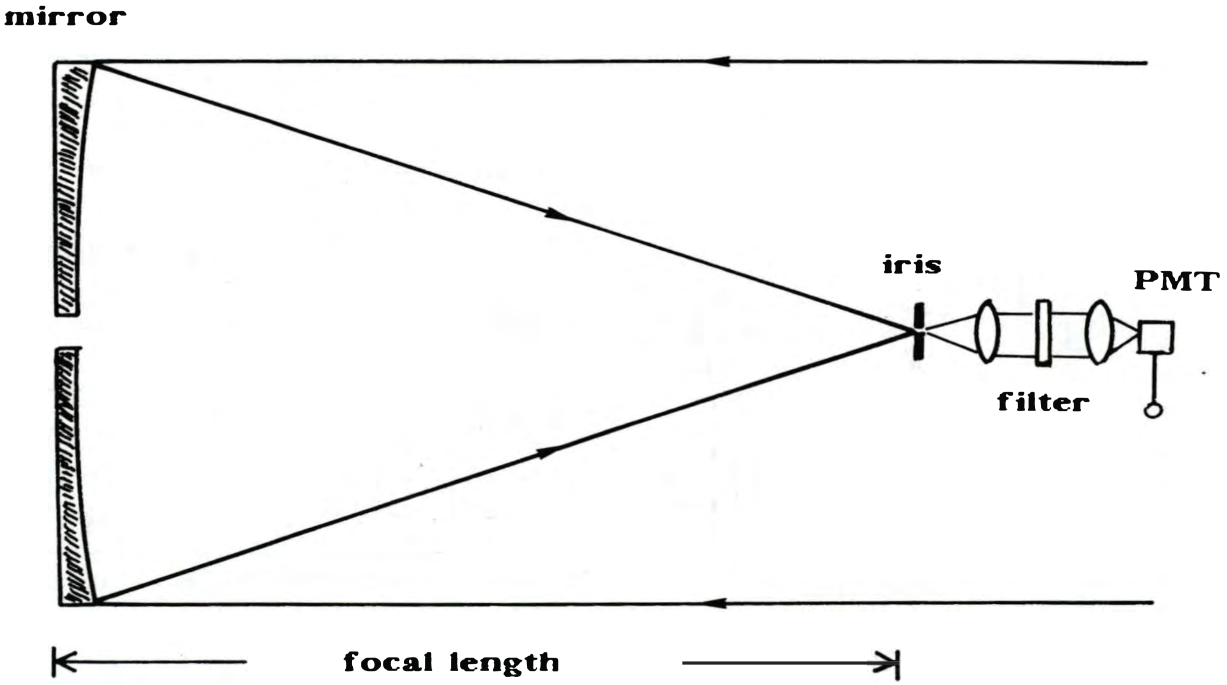

Figure 4. The telescope mirror collects the backscattered signal and reflects it onto the detector through an aperture and an optical filter.

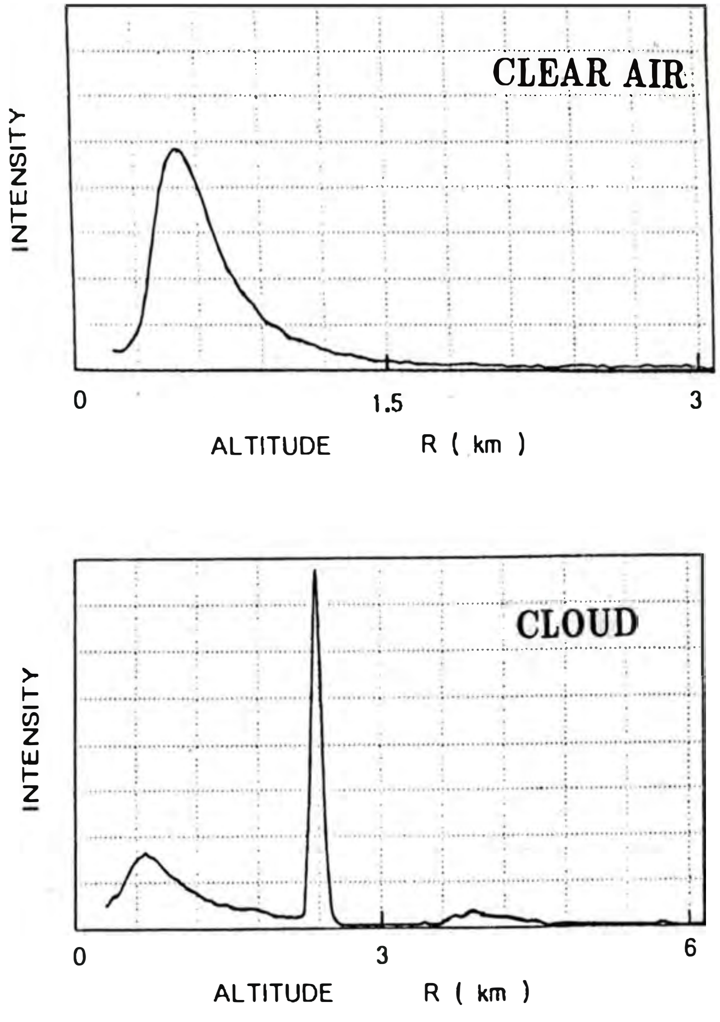

Figure 5. Typical oscilloscope data resulting from sensitivity measurements of aerosols and clouds

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