A Feasibility Study of Identifying Weather by Laser Forward Scattering

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ABSTRACT

The possibility of identifying weather through the observation of forward scatter of a laser beam has been investigated. Preliminary observations with a prototype instrument suggest that it is possible to distinguish clear air, rain, snow, hail and fog using laser weather identification. After additional measurements are made in various weather conditions, it should be practical to design a simple automatic instrument to provide such information.

1. Introduction

Techniques for identifying weather have traditionally relied on human judgment. In recent years devices have been introduced to make automatic weather observations but their ability to identify weather is quite limited. For example, most of the automatic devices can only measure the total water content of the precipitation, and are unable to identify the type of precipitation such as rain, snow or hail without the help of human observers. Recent efforts devoted to the effects of wind (Lawrence *et al.*, 1972; Clifford *et al.*, 1975, Ochs *et al.*, 1976) and precipitation (Hogg, 1964; Chu and Hogg, 1968; Atlas, 1953; Wilson and Penzias, 1966; Atlas and Ubrich, 1974; Kurnick *et al.*, 1960; Arnulf and Bricard, 1957; Wang and Clifford, 1975; Wang *et al.*, 1977, 1978; Wang and Earnshaw, 1977; Derr *et al.*, 1974) on optical and infrared wave transmissions through the atmosphere suggest that optical identification of weather may provide an inexpensive and reliable method for monitoring weather conditions, making possible more complete remote weather sensing at automatic unmanned weather stations.

When a visible or infrared light beam passes through an irregular medium, the irregulatities in the medium produce changes in both the phase and the intensity (or irradiance) of the wave front. This phenomenon has long been known as "scintillation." The twinkling of stars is a familiar example. Different weather conditions produce different signatures of the detected scintillations. Here we discuss the use of weather-induced scintillations to identify, for example, wind, rain, hail and snow. Either phase or irradiance scintillations might be used but phase measurements at optical wavelengths are more difficult than irradiance measurements. We discuss only the use of irradiance fluctuations. In clear air, turbulence combined with temperature gradients causes scintillations of a projected optical beam. The scintillations, which result from variations of refractive index in the air, are similar to the irregular moving patterns on the bottom of a swimming pool in direct sunlight. The turbulence scintillations are always present but often decrease during extended periods of rain or snow. A principal challenge of laser weather identification is to identify the weather-induced signals, usually small in amplitude, in the presence of the larger turbulence-scintillation signals.

A distinctive characteristic of precipitation is that the particles introduce finely structured interference patterns (Wang and Clifford, 1975; Wang *et al.*, 1977, 1978; Wang and Earnshaw, 1977) that are moving downward through the projected laser beam. These moving patterns suggest that weather can be identified by measuring the speed of pattern movement, and by observing the increase in high-frequency components caused by the fine interference patterns as they sweep past a light detector. We have observations to indicate that the terminal velocities can be measured optically, and can be used to identify separately rain, snow and hail. In fact, even the simpler measurement of the frequency spectrum of the scintillation signals may permit separate identification of snow, rain and clear-air turbulence. Raindrops are several thousand times larger than the wavelength of light so their forward-scattering angle is only a few milliradians. By contrast, fog particles are comparable in size to the optical wavelength, so light is forward-scattered to relatively large angles of several degrees. The large scattering angle and the high number density of particles combine to average out individual scintillations, producing attenuation and off-axis forward-scattering signals. Measurement of attenuation and off-beam forward scatter are straightforward optical methods for detecting fog.

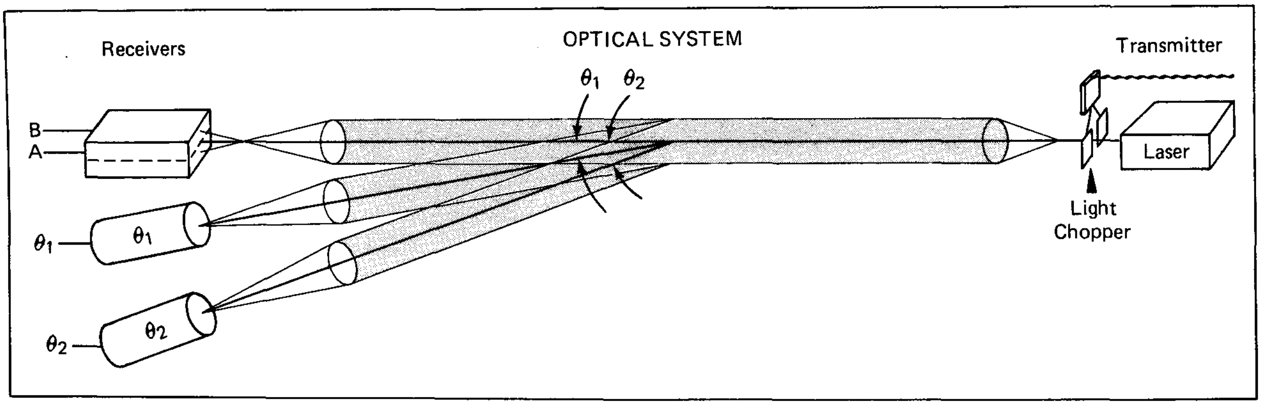

FIG. 1. Schematic diagram of the prototype laser weather identifier.

2. The prototype laser weather identifier

We built an optical system to detect the scintillations in a projected laser beam and to measure the light scattered from the beam at two forward-scattering angles. A chopper-type light modulator in the optical transmitter permits sensitive detection of light in the forward-scatter detectors when the beam is strongly attenuated by fog or heavy precipitation. Fig. 1 is a schematic diagram of the optical system. An earlier prototype instrument has been described in detail by Earnshaw and Keebaugh (1977). The laser transmitter simply collimates light from the laser beam and projects it onto one of the receiving telescopes. The modulator chops the laser beam prior to beam expansion, and may be switched on or off at the signal processing chasis. Fig. 2 is a photograph of the transmitter.

The receiver system consists of three independently mounted detecting telescopes. The scintillation-measuring telescope is aligned with the transmitted laser beam and is apertured by two narrow horizontal slits that are spaced 2 cm apart vertically. Light from the slits is detected by a dual-diode photodetector placed slightly behind the focus of the telescope objective lens. The signals from the upper and lower photo-detectors, designated A and B, respectively, are amplified and transmitted to the signal-processing circuits. The two off-axis forward-scatter telescopes detect light within 0.06° conical volumes. The telescope axes are aimed at the midpoint of the laser beam and are set to detect the forward-scatter light at angles of approximately 0.5° and 1°. The detected forward-scatter light signals, designated θ_1 and θ_2, are amplified and transmitted to the signal-processing circuits. Fig. 3 is a photograph of the optical receiver. The A and B signals from the

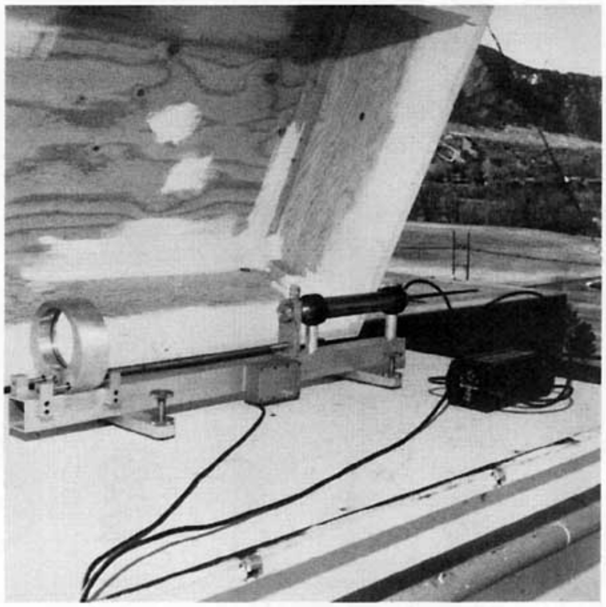

FIG. 2. The laser transmitter.

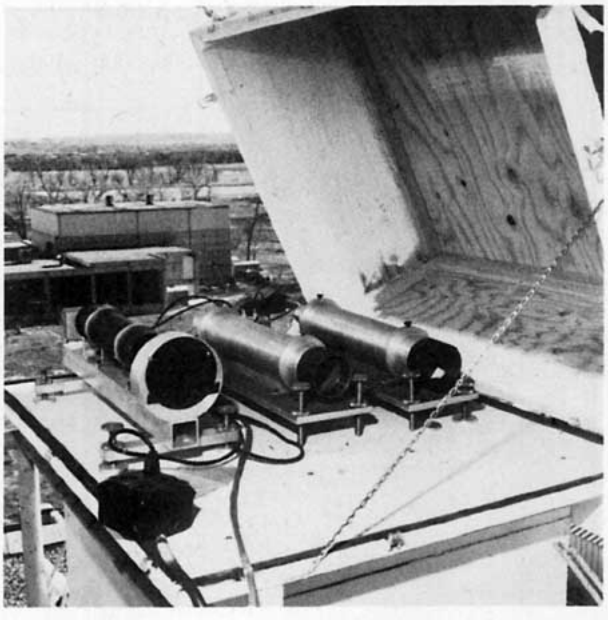

FIG. 3. The three optical-detecting telescopes of the receiver system. The one at left is aimed to detect the direct beam through two horizontal entrance slits. The two other telescopes are off-axis detectors.

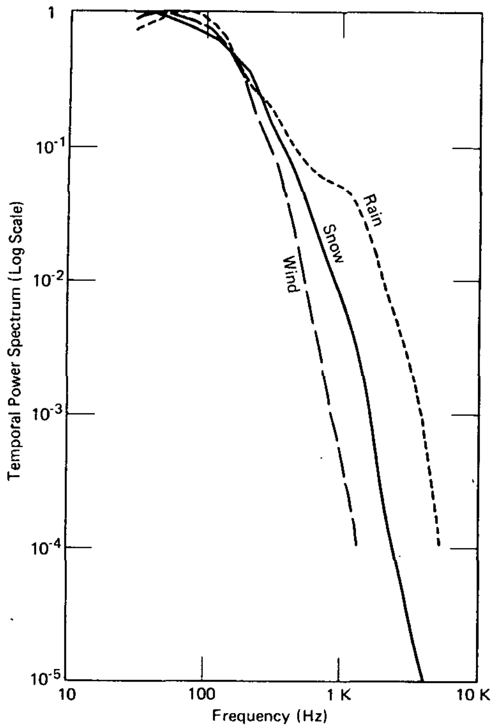

FIG. 4. Temporal power spectra of rain-, snow- and wind-induced scintillation detected by a horizontal line detector on a 50 m line-of-sight path.

upper and lower slit apertures are processed in a correlator to obtain the time-lagged covariance and, from it the terminal velocity distribution of falling particles (Wang *et al.*, 1977; Wang and Earnshaw, 1977). The B signal is also used to analyze the spectrum of the scintillations by selecting six frequency bands (0~200, 200~500, 500~1000, 1000~2000, 2000~4000, 4000~10000 kHz). As an option, the beam can be modulated by a 400 Hz chopper. The B signal and the two off-axis detected signals (θ_1 and θ_2) are amplified by 400 Hz narrow-band amplifier filters and converted to dc signals. All outputs are slowly varying voltages suitable for low-speed chart recording.

3. Results and interpretations

The instrument was used during the summer and fall of 1976 in Boulder, Colorado. Unprocessed signals from rain, hail, snow, fog and turbulence-induced scintaillations were detected and recorded on an audio stereo tape recorder. These data were later replayed through the processing electronics. Because of the uneventful weather of Colorado, we could not obtain enough data for convincing statistical analysis, but our measurements do provide enough samples to encourage us to continue to pursue this approach.

Turbulence, combined with temperature gradients, causes scintillation of a projected optical beam passing through clear air. If the beam is observed by a thin horizontal line detector, the typical spectrum (labeled "wind" in Fig. 4) of atmospheric turbulence-induced optical scintillation signals observed over a path length of 50 m shows large signals at low frequencies with rapidly decreasing amplitudes at higher frequencies. This frequency spectrum is typical for most clear weather, though increased wind speed shifts the spectrum to somewhat higher frequencies. Methods for using the optical scintillations to make quantitative path-averaged crosswind velocity measurements are available at the present time (Lawrence *et al.*, 1972; Clifford *et al.*, 1975; Ochs *et al.*, 1976).

Precipitation-induced scintillation has more high-frequency components than that induced by turbulence

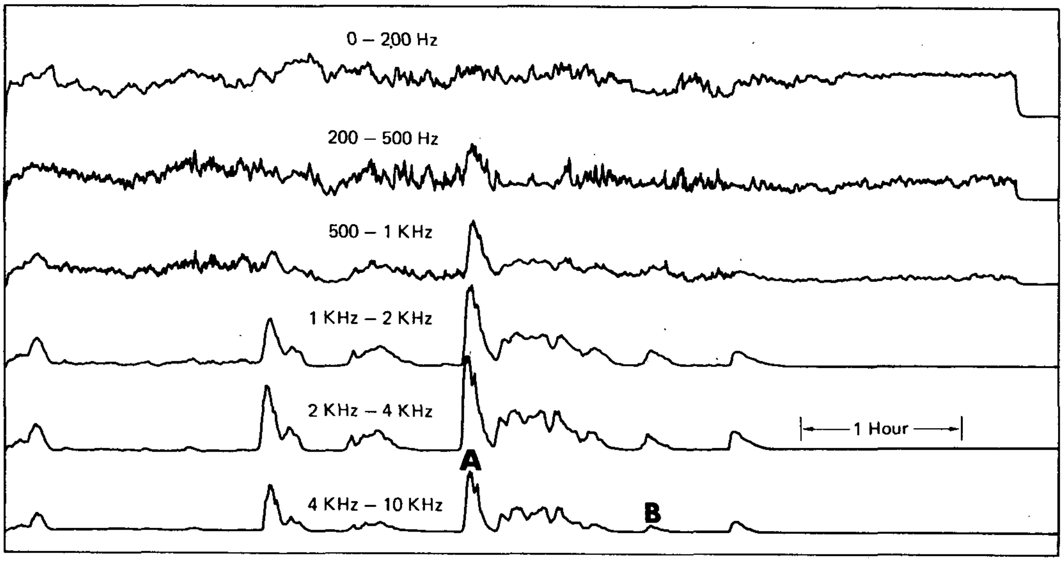

FIG. 5. Sample six-band analyzer recording of rain-induced scintillation, using a horizontal line detector and a 50 m path length. Signals in the three highest frequency bands are produced by rain.

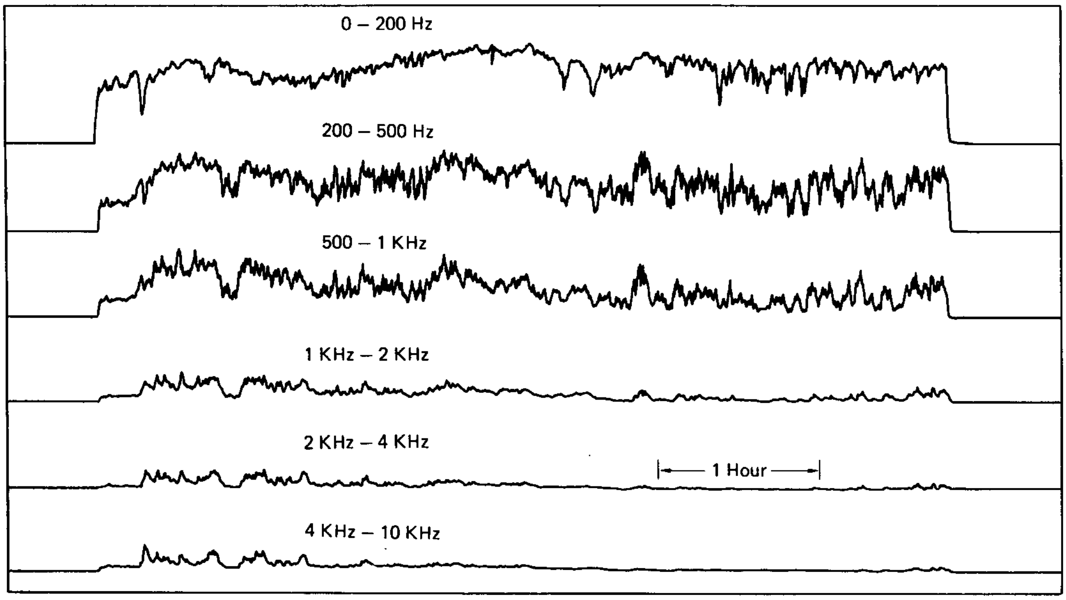

FIG. 6. As in Fig. 5 except for snow-induced scintillation. Signals in the three highest frequency bands are produced by snow. Compared to rain (Fig. 5), snow signals are stronger in band 4 than in band 5.

(Wang and Clifford, 1975; Wang, *et al.*, 1978). Typical temporal power spectra of rain- and snow-induced irradiance scintillation observed with a horizontal line detector appear in Fig. 4. Rain-induced scintillations have substantial frequency components above 2 kHz; for snow the scintillations are usually below 2 kHz and for turbulence, below 1 kHz. Figs. 5 and 6 show sample results from the six-band analyzer in the presence of rain and snow, respectively. The gains of the six bands are arbitrarily set, but they remain fixed for comparison between the two figures. The low-frequency signal of band 1 indicates the strength of turbulence-induced scintillations and very little effect of precipitation appears in this band. Bands 2 and 3 respond to both turbulence (wind) and precipitation. The three upper frequency bands respond for this storm to precipitation only, and we found that the signal in band 6 is sensitive to precipitation. For example, at Point B in Fig. 5, the rain rate was about 0.1 mm h^{-1}; at point A, it was about 7.5 mm h^{-1}. It appears that, to distinguish rain from snow, the ratio of band 4 to band 5 can be used whenever band 6 indicates that some kind of precipitation is present, though additional observations are needed to see if such discrimination is invariably successful. Although the spectrum seems to be able to discriminate precipitation from clear air, strong wind might occasionally produce enough high-frequency components to be comparable to snow-induced scintillation. The reliability of identifying precipitation by spectrum analysis must still be assessed by collecting more weather data in various locations and seasons.

A more reliable method for identifying precipitation involves the fact that particles are falling with noticeable vertical speed. We have demonstrated a technique (Wang *et al.*, 1977; Wang and Earnshaw, 1977) for measuring the path-averaged terminal velocity distribution of raindrops with two horizontally oriented, vertically spaced line detectors. The technique measures accurately the path-averaged rain rate and the drop-size distribution. The same technique can be used to measure the fall velocity of snow or hail. Typical path-averaged velocity distributions of snow, rain and hail appear in Fig. 7, though the values may vary in storms having different hail or drop sizes. The terminal velocity of raindrops usually ranges from 3 to 8 m s^{-1}. For snow, it is usually less than 2 m s^{-1} and for hail, greater than 8 m s^{-1}. Thus, with only occasional ambiguity, the measured terminal velocities can be used to identify separately rain, snow and hail. For

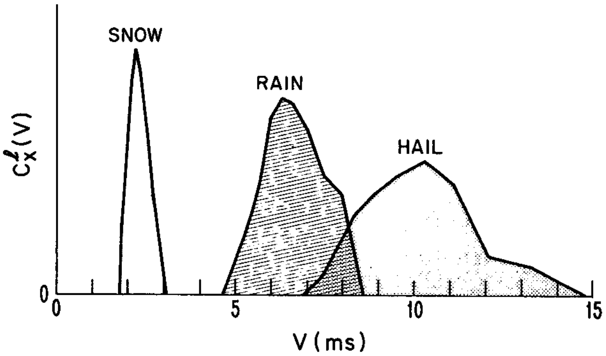

FIG. 7. The optically measured, path-averaged (pathlength, 200 m) terminal velocities of snow, rain and hail. Each curve represents only one 40 s average of a specific storm.

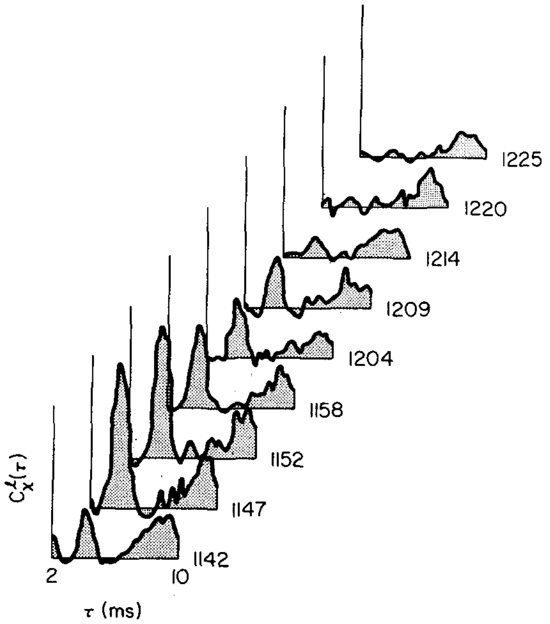

FIG. 8. The time-lagged covariance functions of the signals detected by two vertically separated line detectors with a separation of 4 cm on a 200 m path at Table Mountain during a mixture of rain and hail on 23 June 1976.

example, a bimodal velocity distribution was detected on 23 June 1976 during a mixture of rain and hail. The time-lagged covariance functions, each averaged over 5 min and taken with a slit spacing of 4 cm, are shown in Fig. 8. The peak at 4 ms contributed by hail-induced scintillations corresponds to a terminal velocity of 10 m s^{-1}. The 9 ms peak is caused by raindrops with terminal velocity of 4.5 m s^{-1}. Near the end of the storm the hail disappeared while small raindrops were still falling.

In fog the relatively large scattering angles and the high number density of particles combine to average out individual scintillations, producing only extinction of light in a directly received beam. Measurement of this extinction is a straightforward optical method for detecting fog, through it should also be practical to use off-beam forward scattering. Significant light scattering by a particle of diameter d larger than the wavelength λ of the light occurs at all scattering angles less than about λ/d rad. For raindrops with $d \approx 2$ mm, the scattering angles for optical wavelengths extend to about 3×10^{-4} rad, while fog particles with $d \approx 6$ μm produce scattering angles as great as about 0.1 rad. Thus an off-beam detector arranged to detect the forward scattering at about 1° (actually 0.64° was used) will be sensitive to particles <20 μm (e.g., fog, haze, dust and smoke) and insensitive to larger particles (e.g., rain, snow and hail). To discriminate against the background light, the laser was modulated by a 400 Hz chopper and a narrow-band 400 Hz filter was used to process the received signals. Fig. 9 shows measurements of direct transmission and scattered light during a very light fog. The upper trace is the transmittance and the lower trace the off-axis scattering. Because the fog was extremely light, no loss of transmittance was detected on the 50 m path (the small dips shown in the upper diagram were caused by manual beam blocking) but the off-axis signal clearly showed the presence of fog. The effect of a heavier fog is shown in Fig. 10. Here the agreement between the attenuation and the off-axis signal is good. The slow drift of the transmittance trace was caused by the beam wandering as a result of a change in vertical temperature gradient of the atmosphere. The off-axis signal is less affected by beam wandering and is more sensitive to light fog, so we believe this is the more reliable method for identifying the presence of fog.

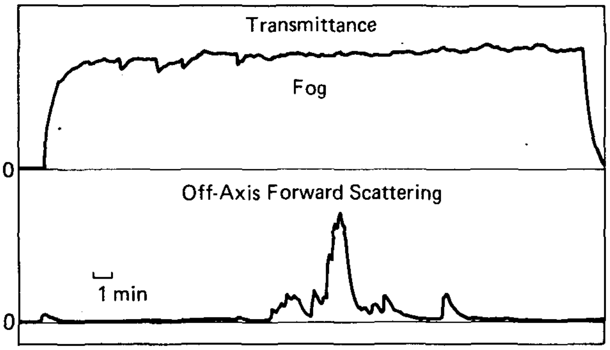

FIG. 9. Transmittance and off-axis forward-scattering measurements during a light fog. (The small dips shown in the upper diagram were caused by manual beam blocking.)

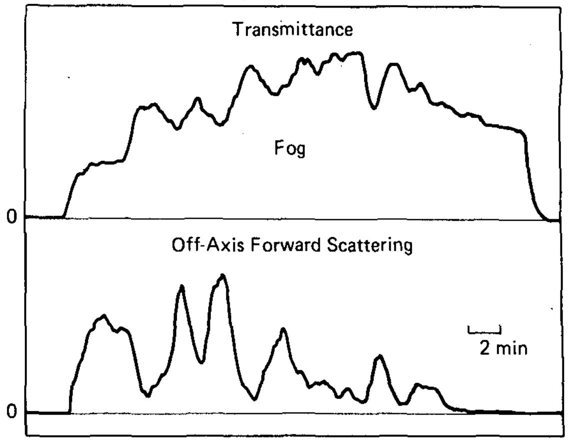

FIG. 10. Transmittance and off-axis forward-scattering measurements during a heavy fog. (The slow change in the transmittance was caused by the beam wandering as a result of a change in vertical temperature gradient of the atmosphere.)

4. Summary

It appears that signals from a laser forward-scattering system can indeed identify different types of weather. Preliminary results show that clear air (wind), snow, rain and hail can be identified by the unmodulated forward-scattered signal. With the help of a modulator and an off-axis receiver, fog and haze can be detected. Because of the large capture volume of this system, the time resolution of the observations is very short, typically 20 s.

Any remaining ambiguity in the identification of weather could be removed by adding to the system additional information channels. The detected signals at the rainbow angle (~138°) can be used to positively identify raindrops. This would discriminate rain from fast-falling snow pellets. Depolarization measurements can surely be helpful in separating spherical from irregular particles (in the single-scattering regime) and may occasionally be necessary to separate rain from snow or hail. We have made no attempt to build an instrument that will serve as an automatic weather identifier because optimum design of such a system requires extensive data collection in various types of weather. We expect that a reliable identifier can be developed using the results of measurements like those we have described.

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