Laser Weather Identifier: Present and Future

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ABSTRACT

Prototype Laser Weather Identifier (LWI) systems designed to detect fog, rain and snow were tested for several months at Stapleton International Airport in Denver, and at the AFGL Weather Test Facility at Otis Air Force Base, Massachusetts. We present a detailed analysis of the performance of these systems, compared with human weather observations and tipping-bucket raingages, and suggest modifications for future operational instruments.

1. Introduction

Traditional weather devices can measure only the total water content of precipitation; they are unable to identify the type of precipitation, such as rain, snow or hail, without the help of human observers. Many authors suggested that optical identification might provide an inexpensive and reliable method for unmanned automatic monitoring of weather conditions (Arnulf and Bricard, 1957; Atlas, 1953; Atlas and Ulbrich, 1974; Chu and Hogg, 1968; Earnshaw *et al.*, 1978; Folster *et al.*, 1975; Hogg, 1964; Kurnick *et al.*, 1960; Rensch and Long, 1970; Sheppard, 1970; Wang and Clifford, 1975; Wang *et al.*, 1977; 1978; 1979; 1980; Wang, 1982; Wilson and Penzias, 1966). When a visible or infrared light beam passes through an irregular medium, the irregularities in the medium produce changes in both the phase and the intensity (or irradiance) of the wave front. The intensity fluctuations are known as "scintillation." Different weather conditions produce different signatures of the detected scintillations and we use those differences to identify, for example, rain, hail and snow. Precipitation falling through a laser beam introduces finely structured interference patterns. These downward-moving interference patterns are unique and serve to identify precipitation by the increase in high-frequency components of irradiance scintillation as they sweep past a light detector.

Raindrops are several thousand times larger than the wavelength of light so their forward-scattered energy is concentrated in an angle less than a few milliradians. By contrast, fog particles, comparable in size with the optical wavelength, scatter light through relatively large angles of several degrees. The large scattering angle and the high number density of particles combine to average out individual scintillations, producing extinction and off-axis signals. Measurement of extinction and off-beam forward scatter are straightforward optical methods for detecting fog.

Two Laser Weather Identifier (LWI) systems were fabricated, each with the basic configuration shown in Fig. 1. The design permits detection and identification of precipitation and fog using scintillation, extinction, and off-axis forward scatter effects on the laser beam.

The transmitter contains a 4 mW He-Ne laser, expands the laser light into a uniform beam, and projects it onto the receiving telescope. A 400 Hz chopper-type light modulator interrupts the beam prior to its expansion and permits sensitive detection of precipitation- and fog-induced signals.

The receiver consists of three independently mounted detecting telescopes. The telescope used for detecting scintillation looks directly at the projected laser beam; its aperture is a narrow horizontal slit. Light incident on the slit is detected by a photodetector placed slightly behind the focal point of the objective lens. The two off-axis telescopes are aimed at approximately the midpoint of the laser beam. The telescopes are set to detect light scattered through angles of 0.6° and 1.2°, designated θ_1 and θ_2, respectively. The direct, on-axis signal A is filtered to obtain the spectral composition of the precipitation-induced scintillations in selected frequency bands. A 400 Hz chopper modulates the laser beam and permits sensitive, narrow-band detection of the scattered light at the two forward angles θ_1 and θ_2. All outputs are converted to slowly varying dc voltages suitable for low-speed chart recording or real-time computer processing.

A problem with scintillation measurements is the need to measure the small fluctuations superimposed on the much larger unperturbed irradiance. Any small changes of laser output or beam position might completely mask the scintillation measurement. To

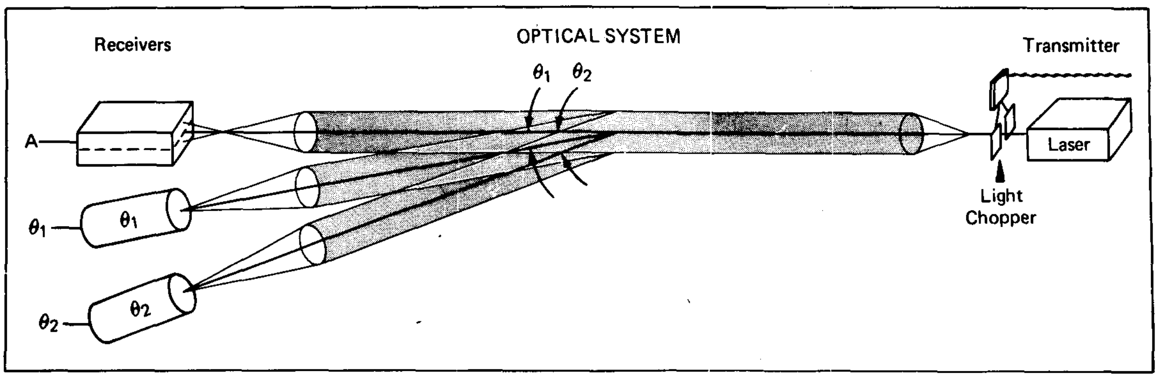

FIG. 1. Schematic diagram of the prototype Laser Weather Identifier (LWI).

avoid this we used a logarithmic amplifier as a normalizer. The input irradiance can be decomposed into a fluctuating part I_1 and an unperturbed part I_0. The photodetector converts these to voltages V_1 and V_0, respectively. When we pass the voltages through a log-amplifier, the output is

$$\ln(V_0 + V_1) = \ln V_0 + \ln\left(1 + \frac{V_1}{V_0}\right). \quad (1)$$

After transmission through a blocking capacitor, the final output is $\ln(1 + V_1/V_0)$. Under ordinary conditions $V_1 \ll V_0$, and

$$\ln(1 + V_1/V_0) \simeq V_1/V_0 . \quad (2)$$

Therefore the final output is the percentage fluctuations, independent of the absolute irradiance.

An LWI was installed at Stapleton International Airport in Denver, Colorado, in June of 1978. The optical path length was ~75 m. The transmitting and receiving systems were housed in unheated shelters. The instruments were mounted on stable steel platforms bolted to separate concrete foundations. Ten months of accumulated data were analyzed. Signals from fog and from rain-, snow- and turbulence-induced scintillations were recorded on a low-speed chart recorder. The direct on-axis signal was separated into frequency bands of 20–200 Hz, 500–1000 Hz, 1–2 kHz and 2–4 kHz. The received irradiance of the on-axis laser light was also monitored to measure the attenuation of laser light caused by fog, dust or heavy precipitation. The signal from the off-axis detector at θ_2 was also recorded. The chopper operated automatically for ~8 min of each hour. The information recorded on frequency bands above 500 Hz was not used while the chopper was operating because of high-frequency contamination induced by the harmonics of the 400 Hz chopper.

A similar system using an optical path length of 200 m was installed at the Weather Test Facility at Otis AFB, Massachusetts, in the fall of 1976. Three months of continuous data were analyzed. Signals were processed into five selected frequency bands (200–500 Hz, 500–1000 Hz, 1–2 kHz, 2–4 kHz, and 4–10 kHz), digitized and recorded. A voltage proportional to the irradiance of the on-axis laser was monitored when the chopper, along with channels θ_1 and θ_2 was activated. Unlike the Colorado unit, the chopper was started manually and remained on for extended periods of time. The log-amplifier was not used in the receiving system.

2. Analysis

Previous research (Wang and Clifford, 1975; Earnshaw *et al.*, 1978; Wang *et al.*, 1978, 1979) has shown that turbulent temperature gradients, rain and snow all induce irradiance scintillations in a projected laser beam. Precipitation-induced scintillations usually contain more high-frequency components than clear air turbulence (Wang and Clifford, 1975; Wang *et al.*, 1978). Rain-induced scintillations contain substantial frequency components above 1 kHz, clear air turbulence frequencies are mostly below 1 kHz, and snow-induced scintillations contain frequencies between those of rain and clear air. This presents the possibility of separately identifying rain, snow and turbulence by determining the relative frequency composition of the induced signals. We found that the low-frequency channel (20–200 Hz) is sensitive to turbulence and is negligibly affected by precipitation (Wang *et al.*, 1980). The frequency band between 500 and 1000 Hz responds to both turbulence and precipitation, whereas high-frequency channels (1–2 kHz and 2–4 kHz) respond solely to precipitation.

Our analysis is based on official surface weather observations taken at Otis AFB and Stapleton Airport. Threshold levels for selected frequency bands were established (see details in Section 3) and signal excursions above these levels, for more than two consecutive minutes, were interpreted as positive indications of precipitation. For fog, the signal integration time was increased to 5 min because of the slowly varying nature of the fog-induced optical signal. For both systems, surface weather observations were made 1.5 km from the experimental sites so that localized precipitation could have produced misleading results. Frequently, discrepancies were noted between surface weather observations and experimental indications of the beginning and ending times of a storm. The Colorado data were analyzed on an hourly basis. For instance, if the human observer recorded precipitation at some time during a given hour, experimental data were examined for a positive indication of precipitation at any time during that hour. Timing for Massachusetts data was more precise with an accuracy of approximately ±1 min. This allowed analysis of the data using ±10 min of the indicated tipping-bucket raingage recorded time, and the human observing time.

3. Precipitation identification

Our initial objective was to determine how reliably our instrument could detect precipitation. Results from the Colorado system, given in terms of the number of missed and false alarm occurrences, are shown in Table 1. Missed cases for measurable precipitation (>0.25 mm h^{-1}) are essentially negligible, indicating that the difficulty lies in the detection of trace amounts of precipitation. Statistics shown in Table 1 were obtained by observing the length of time that the induced signal was above a predetermined threshold. The high error rates (the sum of missed and false alarm cases normalized to the total number of precipitation occurrences), along with the large discrepancy between the number of missed and false alarm cases, prompted further analysis of the data at varying threshold levels. This proved extremely difficult because of the graphical nature of the Colorado data, whereas the digitized output from Massachusetts data lent itself to this kind of analysis.

TABLE 1. A comparison of the identification of precipitation by Laser Weather Identifier and conventional raingage at Stapleton Airport, Denver, Colorado.

Weather type	Identification	LWI	Tipping bucket raingage
Clear	Correct	~5000 h (99.1%)	
	False	46 h (0.9%)	
Rain (>0.25 mm h^{-1})	Correct	8 h (100%)	8 h (100%)
	Missed	0 (0%)	
Snow (>0.25 mm h^{-1})	Correct	55 h (98.2%)	56 h (100%)
	Missed	1 h (1.8%)	
Trace (<0.25 mm h^{-1})	Correct	345 h (61.4%)	92 h (16.3%)
	Missed	217 h (38.6%)	470 h (83.7%)
Total precipitation	Correct	408 h (65.2%)	156 h (24.9%)
	Missed	218 h (34.8%)	470 h (75.1%)

NOTE: The National Weather Service's surface weather observer data sheets provided the ground truth for the comparison. Tipping bucket raingage records were used as the basis for precipitation >0.25 mm h^{-1}.

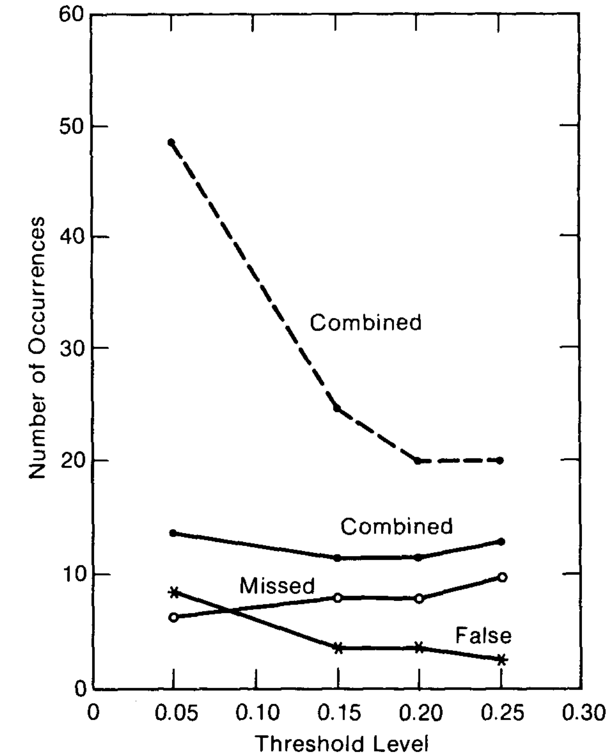

FIG. 2. Results for rain in the 1–2 kHz frequency bands as a function of predetermined threshold. The solid lines indicate the number of occurrences excluding turbulence contaminations. The optimal threshold is around 0.20 (arbitrary units). The dashed line indicates the combined number of occurrence without removing the turbulence contaminations.

Examination of the Massachusetts data revealed that much of what was interpreted as a positive indication of precipitation was actually elevated turbulence and wind activity. This condition produced frequent false alarms, especially in the lower frequency channels. It was found that increased turbulence and strong winds at times masked the snow spectrum and occasionally contaminated that of rain. To remove the ambiguity caused by clear air turbulence, a ratio of the turbulence-dominant channel (20–200 Hz) to the signal in the precipitation-dominant frequency band (1–2 kHz) was established. Values of this ratio above a predetermined threshold indicated turbulence contamination, and a negative indication of precipitation was assumed. Lower ratios indicated negligible turbulence contamination, and data were analyzed in the manner previously discussed.

Fig. 2 shows results for rain in the 1–2 kHz frequency band as a function of a predetermined threshold. The solid lines indicate the number of occurrences excluding turbulence contamination as out-

TABLE 2. A comparison of the identification of rain by Laser Weather Identifier and conventional raingage at Otis AFB, Massachusetts.

Weather type	Identification	LWI	Tipping bucket raingage
Clear	Correct	~1000 h (99.5%)	
	False	5 h (0.5%)	
Rain (>0.25 mm h^{-1})	Correct	29 h (100%)	29 h (100%)
	Missed	0 (0%)	
Trace (<0.25 mm h^{-1})	Correct	40 h (83.3%)	15 h (31.3%)
	Missed	8 h (16.7%)	33 h (68.7%)
Total precipitation	Correct	69 h (89.6%)	44 h (57.1%)
	Missed	8 h (10.4%)	33 h (42.9%)

NOTE: Results correspond to data analyzed at the optimal threshold with turbulence contamination removed.

lined above. The optimal threshold is about 0.20 (arbitrary units). The dashed line shown in Fig. 2 is the combined number of occurrences without removing the turbulence contamination. It is obvious that, in this case, the error rates are intolerably high, especially for low thresholds. Table 2 shows results at the optimal threshold for minimal error rates. The turbulence contamination has been removed to obtain these results. It is clear that the optical rain detection is much more sensitive to trace precipitation than the tipping-bucket raingage techniques in use today.

4. Rain and snow discrimination

Because the rain-induced signal possesses more high-frequency components than that induced by snow, the ratio of the 2–4 kHz channel to the 1–2 kHz channel should discriminate rain from snow (Wang *et al.*, 1980). Fig. 3 shows the behavior of this ratio during a continuous period of snow followed by rain. A transition from snow to rain occurred during a storm on 13 January 1978, at Otis AFB, Massachusetts. A separate period of snow, occurring on 14 December 1976 was inserted to provide a comparison. The top two curves of Fig. 3 represent the output signals of the 2–4 kHz and 1–2 kHz channels; the third is the ratio of the signal of 2–4 kHz to the signal of 1–2 kHz. The ratio is insensitive to minor fluctuations of the two component signals but reflects the transition from snow to rain at a ratio value of ~0.18 (from Fig. 4). However, at a different location, this value may change. When we compare these results with the given surface weather observations, it becomes evident that, by establishing threshold levels for this ratio, we can distinguish rain from snow for this storm. The transition period between 2048 and 2109 EST clearly indicates a mixture of rain and snow though the change in precipitation type was not recorded by the surface weather observer.

Fig. 4 shows the probability density function (pdf) of the ratio for each type of precipitation. It is clear that rain can be distinguished from snow. The ratio corresponding to periods of rain mixed with snow overlapped into both the snow and rain regions to an extent determined by the composition of the precipitation (between 0.1 and 0.3). Snowstorms occurring at a temperature of 2°C introduce further ambiguities and are designated by the dashed lines in Fig. 4. It is likely that snowflakes at these temperatures had a high water content or were accompanied by rain at some point, although these facts were not recorded by the surface weather observer.

Fig. 4 demonstrates that this ratio is confined essentially to non-overlapping regions in identifying the type of precipitation. We see that the probability density functions for snow and rain have a Gaussian-like appearance resulting in a tendency for the ratio to be localized around a certain median value. Any ambiguities in the intermediate region would occur only a very small percentage of the time. These results confirm the practicality of using spectral techniques to distinguish rain from snow once the presence of precipitation has been indicated.

5. Fog detection

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 the directly received beam. Measurement of this extinction is a straightforward optical

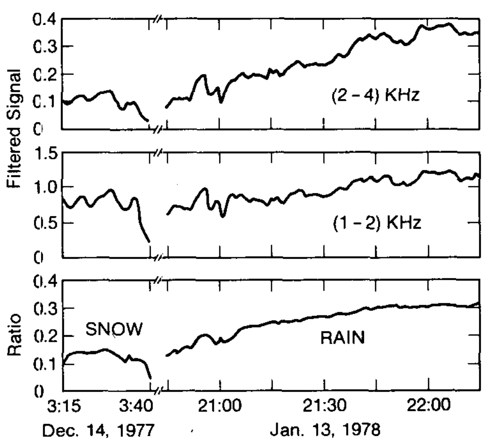

FIG. 3. The behavior of two high-frequency channels during a continuous period of snow followed by rain. A transition from snow to rain occurred on 13 January 1978, at Otis AFB, Massachusetts. The separate period of snow, occurring on 14 December 1976, was inserted to provide a comparison. The top two curves represent the signals presented in the 2–4 kHz and 1–2 kHz channels, respectively; the lowest curve is the ratio of the signal of 2–4 kHz to the signal of 1–2 kHz.

method for detecting fog, but we have found that off-axis forward scattering is more sensitive (Earnshaw *et al.*, 1978). Most of the light scattered by a particle of diameter d larger than the wavelength λ of the light occurs at scattering angles $\leqslant\lambda/d$ rad. For raindrops with $d \approx 2$ mm, forward scattering for optical wavelengths is limited to angles $<3 \times 10^{-4}$ rad, whereas fog particles with $d \approx 6$ μm produce significant scattering out to angles as great as 0.1 rad. Thus an off-axis detector arranged to detect the forward scattering at about 1° ($\theta_1 \approx 0.6°$, $\theta_2 \approx 1.2°$) is sensitive to particle sizes <20 μm (e.g., fog, haze, dust and smoke) and insensitive to larger particles (e.g., rain and hail). To discriminate against the background light, the laser was modulated by a 400 Hz chopper, and narrow-band 400 Hz filters were used to process the received signals.

The off-axis method of fog detection was employed in both systems. We found that the agreement between the on-axis laser attenuation and the off-axis forward scatter signal was very good. Table 3 shows the statistics of fog identification at both sites. The high number of missed cases and low number of false alarm cases at Colorado were a consequence of the comparatively short pathlength (75 m) which yielded an insufficient capture volume for satisfactory fog detection. The results from Massachusetts reveal two basic problems with optical fog detection. An increased optical pathlength (200 m) yielded fewer missed cases but also increased the number of false alarm cases. We have also included the extinction as a positive identification when it is above a preset threshold. A second problem was the inability of our instrument to distinguish snow-induced signals from those produced by fog. Snow scattered light at both detection angles (θ_1 and θ_2). We found no straightforward way to eliminate snow contamination from the off-axis scattering in the present system.

6. Summary

One major advantage of the laser weather identifier is that it is an automated system capable of continuously monitoring weather. The overall evaluation

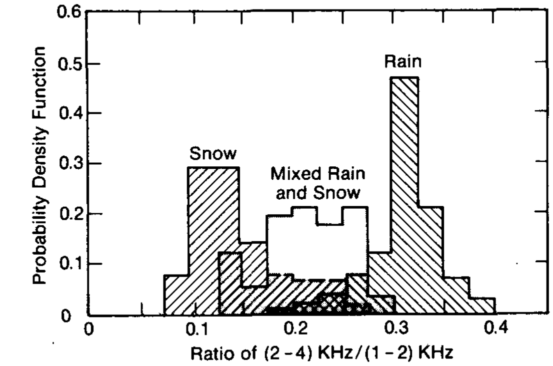

FIG. 4. Probability density function of rain and snow as a function of the ratio of the signal of 2–4 kHz to the signal of 1–2 kHz.

of the performance of the present system is discussed in detail according to different types of weather as follows.

a. Rain

The performance of the system for identifying rain is excellent. It has never missed any rain rates >0.25 mm/h^{-1}. At Massachusetts, the system occasionally identified rain traces 2–3 h before the first tip of the tipping-bucket raingage. For extremely light rain (no recorded amount of water), the system indicates a 15% error rate compared with the human observer's record. However, it should be pointed out that, at both locations, the weather identifiers were located 1.5 km from the observer, so spatial variation of precipitation may contribute to the discrepancy. No attempt was made to estimate and correct for human observer errors. On one occasion at Massachusetts, the record of the human observer indicated there was no precipitation; however, the tipping-bucket raingage registered 16 tips during that hour, and our instrument also indicated heavy rain signals. In addition to identifying rain, it has been shown that the system is capable of quantitative measurements of rain rates (Wang *et al.*, 1979).

TABLE 3. A comparison of the identification of fog by Laser Weather Identifier at Stapleton Airport, Denver, Colorado and at Otis AFB, Massachusetts.

			Otis AFB	
Weather type	Identification	Stapleton 1.2°	0.6°	1.2°
Clear	Correct	~5000 h (99.7%)	~1000 h (98%)	
	False	15 h (0.3%)	23 h (2.3%)	19 h (1.9%)
Snow-induced		7 h (0.1%)	18 h (1.8%)	16 h (1.6%)
Fog	Correct	34 h (12.1%)	45 h (93.7%)	44 h (91.7%)
	Missed	246 h (87.9%)	3 h (6.3%)	4 h (8.3%)

TABLE 4. Subjective estimates of error rates with and without the vertical velocity measurements for precipitation identification.

	Weather		
Techniques	Snow	Rain	Hail
Spectra only	30% (turbulence contamination)	20%	100% (cannot be separated from rain)
Spectra and vertical velocity	Less than 10%	Less than 10%	Less than 10%

b. Snow

Because the spectra of snow-induced scintillation are close to that of turbulence-induced scintillation (especially for the case of strong wind), occasional ambiguity may occur. We identified snow less accurately than rain without introducing more information channels. If precipitation can be positively identified, the discrimination between rain and snow is good.

c. Fog

Heavy fog can be identified by the extinction of the on-axis signals whereas light fog can be identified by the off-axis scattering signals. Because the optical path is short (usually less than 200 m), it is extremely difficult to identify light fog when visibility is better than 1 km even using the off-axis scattering technique. Increased pathlengths can increase sensitivity but also will increase the number of false alarms, especially for those signals induced by snow. The high error rate suggests that more information channels are needed for fog identification.

7. Modifications for future systems

We have developed another technique using optical scintillations to measure path-averaged terminal velocity distributions of falling precipitants (Earnshaw *et al.*, 1978; Wang *et al.*, 1979). The general approach is to measure the precipitation-induced irradiance scintillations with two horizontally oriented, vertically spaced, line detectors. The temporal covariance function of the signals detected by the two sensors yields the path-averaged terminal velocity distribution of the precipitants. The measured vertical velocity can be used to identify rain, snow and hail (Earnshaw *et al.*, 1978). Because of the complexity of the data analysis involved in obtaining the vertical velocity distributions, we did not include the measurements of vertical velocities in the two LWI systems discussed above. We found that the use of spectra only was insufficient to identify hail from rain because of their similarity in the temporal spectra of the induced scintillations. The spectrum of snow may be confused with that of clear-air turbulence, especially with strong wind. Therefore, we recommend adding a vertical velocity measurement to future systems. An estimate of the error rates with and without the velocity measurements, based on our own judgment, is shown in Table 4. The off-axis scattering induced by the finestructure of snowflakes also contaminates the identification of fog (see Table 3). We believe that, with the help of a vertical velocity channel, the contamination of snow can be removed (see Table 5).

A recent study (Wang, 1982) has shown that the correlation technique can be used in the near-field region as well as in the far-field region of precipitants. This enables us to use the scintillation correlation technique to measure terminal velocity distributions for path lengths from a few centimeters to a few hundred meters.

Quantitative measurement of total water content for precipitation is also possible (Wang *et al.*, 1978, 1979). Although the technique was developed to measure path-averaged rain rates, it gives a reasonable estimate for total water content for both snow and hail. An estimated accuracy for each type of precipitation, again based on our own judgment, is shown in Table 6. In addition, if rain is positively identified, the raindrop size distribution can be obtained (Wang *et al.*, 1979).

We have used a 400 Hz mechanical chopper modulating the laser to obtain enough signal-to-noise ratio for the off-axis detectors. Because of the high-order harmonics generated by the chopper, any on-axis channel sensitive to frequencies of 400 Hz or higher has to be turned off when the chopper is operating. The mechanical chopper and the electronic switches used to control the various channels were unreliable for unattended operations in the field, and caused many maintenance problems. However, if we can modulate the source above 10 kHz, all channels can be operated continuously, thus eliminating the trouble caused by the chopper and switches. To modulate a laser above 10 kHz is always a troublesome and expensive task. A light emitting diode (LED) is easy to modulate but its large injection area destroys the spatial coherence needed for scintillation measure-

TABLE 5. Subjective estimates of error rates for different combinations of techniques for fog/haze.

Off-axis scattering only	60% (extinction loss and snow contamination)
Off-axis scattering and extinction	50% (snow contamination)
Off-axis scattering, extinction, and vertical velocity	15%

TABLE 6. Subjective estimates of accuracy of measurement of total water content for precipitation.

	Snow	Rain	Hail
Accuracy	Order of magnitude	10%	Within a factor of 2

ments. The recently developed cw laser diode has the advantages of both the coherence and the modulation. We have used a laser diode (type LCW-10 by Laser Diode Laboratories, Inc.) instead of a laser as the source in a laboratory test. Although the coherence of the laser diode is inferior to that of the laser, it is good enough to produce scintillation patterns induced by artificially generated water drops. The modulation and demodulation circuits are very simple for frequencies up to several hundred kilohertz. A narrow bandpass filter centered at the modulation frequency can be used to increase the signal-to-noise ratio; therefore, the sensitivity of fog or haze detection can be improved. The durability and reliability of the laser diode may even exceed that of a laser.

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